realized using capacitor elements, distributed capacitance, networks, arrays, series and parallel combinations of capacitances, and the like. The capacitance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[00162] It is to be understood that the inductance and capacitance in an electromagnetic resonator 102 may be lumped, distributed, or a combination of lumped and distributed inductance and capacitance and that electromagnetic resonators may be realized by combinations of the various elements, techniques and effects described herein.

[00163] Electromagnetic resonators 102 may be include inductors, inductances, capacitors, capacitances, as well as additional circuit elements such as resistors, diodes, switches, amplifiers, diodes, transistors, transformers, conductors, connectors and the like.

[00164] **Resonant Frequency of an Electromagnetic Resonator**

[00165] An electromagnetic resonator 102 may have a characteristic, natural, or resonant frequency determined by its physical properties. This resonant frequency is the frequency at which the energy stored by the resonator oscillates between that stored by the electric field, W_E, ($W_E=q^2/2C$, where q is the charge on the capacitor, C) and that stored by the magnetic field, W_B, ($W_B=Li^2/2$, where i is the current through the inductor, L) of the resonator. In the absence of any losses in the system, energy would continually be exchanged between the electric field in the capacitor 104 and the magnetic field in the inductor 108. The frequency at which this energy is exchanged may be called the characteristic frequency, the natural frequency, or the resonant frequency of the resonator, and is given by ω,

$$\omega = 2\pi f = \sqrt{\frac{1}{LC}}.$$

[00166] The resonant frequency of the resonator may be changed by tuning the inductance, L, and/or the capacitance, C, of the resonator. The resonator frequency may be design to operate at the so-called ISM (Industrial, Scientific and Medical) frequencies as specified by the FCC. The resonator frequency may be chosen to meet certain field limit specifications, specific absorption rate (SAR) limit specifications, electromagnetic compatibility (EMC) specifications, electromagnetic interference (EMI) specifications, component size, cost or performance specifications, and the like.

[00167] **Quality Factor of an Electromagnetic Resonator**

[00168] The energy in the resonators 102 shown in Fig. 6 may decay or be lost by intrinsic losses including absorptive losses (also called ohmic or resistive losses) and/or radiative losses. The Quality Factor, or Q, of the resonator, which characterizes the energy decay, is inversely proportional to these losses. Absorptive losses may be caused by the finite conductivity of the conductor used to form the inductor as well as by losses in other elements, components, connectors, and the like, in the resonator. An inductor formed from low loss materials may be referred to as a "high-Q inductive element" and elements, components, connectors and the like with low losses may be referred to as having "high resistive Q's". In general, the total absorptive loss for a resonator may be calculated as the appropriate series and/or parallel combination of resistive losses for the various elements and components that make up the resonator. That is, in the absence of any significant radiative or component/connection losses, the Q of the resonator may be given by, Q_{abs},

$$Q_{abs} = \frac{\omega L}{R_{abs}},$$

where ω, is the resonant frequency, L, is the total inductance of the resonator and the resistance for the conductor used to form the inductor, for example, may be given by $R_{abs} = l\rho / A$, (l is the length of the wire, ρ is the resistivity of the conductor material, and A is the cross-sectional area over which current flows in the wire). For alternating currents, the cross-sectional area over which current flows may be less than the physical cross-sectional area of the conductor owing to the skin effect. Therefore, high-Q magnetic resonators may be composed of conductors with high conductivity, relatively large surface areas and/or with specially designed profiles (e.g. Litz wire) to minimize proximity effects and reduce the AC resistance.

[00169] The magnetic resonator structures may include high-Q inductive elements composed of high conductivity wire, coated wire, Litz wire, ribbon, strapping or plates, tubing, paint, gels, traces, and the like. The magnetic resonators may be self-resonant, or they may include external coupled elements such as capacitors, inductors, switches, diodes, transistors, transformers, and the like. The magnetic resonators may include distributed and lumped capacitance and inductance. In general, the Q of the resonators will be determined by the Q's of all the individual components of the resonator.

[00170] Because Q is proportional to inductance, L, resonators may be designed to increase L, within certain other constraints. One way to increase L, for example, is to use more than one turn of the conductor to form the inductor in the resonator. Design techniques and trade-offs may depend on the application, and a wide variety of structures, conductors, components, and resonant frequencies may be chosen in the design of high-*Q* magnetic resonators.

[00171] In the absence of significant absorption losses, the *Q* of the resonator may be determined primarily by the radiation losses, and given by, $Q_{rad} = \omega L / R_{rad}$, where R_{rad} is the radiative loss of the resonator and may depend on the size of the resonator relative to the frequency, ω, or wavelength, λ, of operation. For the magnetic resonators discussed above, radiative losses may scale as $R_{rad} \sim (x/\lambda)^4$ (characteristic of magnetic dipole radiation), where x is a characteristic dimension of the resonator, such as the radius of the inductive element shown in Fig. 6b, and where $\lambda = c / f$, where c is the speed of light and f is as defined above. The size of the magnetic resonator may be much less than the wavelength of operation so radiation losses may be very small. Such structures may be referred to as sub-wavelength resonators. Radiation may be a loss mechanism for non-radiative wireless energy transfer systems and designs may be chosen to reduce or minimize R_{rad}. Note that a high-Q_{rad} may be desirable for non-radiative wireless energy transfer schemes.

[00172] Note too that the design of resonators for non-radiative wireless energy transfer differs from antennas designed for communication or far-field energy transmission purposes. Specifically, capacitively-loaded conductive loops may be used as resonant antennas (for example in cell phones), but those operate in the far-field regime where the radiation *Q*'s are intentionally designed to be small to make the antenna efficient at radiating energy. Such designs are not appropriate for the efficient near-field wireless energy transfer technique disclosed in this application.

[00173] The quality factor of a resonator including both radiative and absorption losses is $Q = \omega L / (R_{abs} + R_{rad})$. Note that there may be a maximum *Q* value for a particular resonator and that resonators may be designed with special consideration given to the size of the resonator, the materials and elements used to construct the resonator, the operating frequency, the connection mechanisms, and the like, in order to achieve a high-Q resonator. Fig. 7 shows a plot of *Q* of an exemplary magnetic resonator (in this case a coil with a diameter of 60 cm made of copper pipe with an outside diameter (OD) of 4 cm) that may be used for wireless power transmission at MHz frequencies. The absorptive *Q* (dashed line) 702 increases with frequency, while the radiative Q (dotted line) 704 decreases with frequency, thus leading the overall Q to peak 708 at a particular frequency. Note that the Q of this exemplary resonator is greater than 100 over a wide frequency range. Magnetic resonators may be designed to have high-Q over a range of frequencies and system operating frequency may set to any frequency in that range.

[00174] When the resonator is being described in terms of loss rates, the Q may be defined using the intrinsic decay rate, 2Γ, as described previously. The intrinsic decay rate is the rate at which an uncoupled and undriven resonator loses energy. For the magnetic resonators described above, the intrinsic loss rate may be given by $\Gamma = (R_{abs} + R_{rad})/2L$, and the quality factor, Q, of the resonator is given by $Q = \omega/2\Gamma$.

[00175] Note that a quality factor related only to a specific loss mechanism may be denoted as $Q_{mechanism}$, if the resonator is not specified, or as $Q_{1,mechanism}$, if the resonator is specified (e.g. resonator 1). For example, $Q_{1,rad}$ is the quality factor for resonator 1 related to its radiation losses.

[00176] **Electromagnetic Resonator Near-Fields**

[00177] The high-Q electromagnetic resonators used in the near-field wireless energy transfer system disclosed here may be sub-wavelength objects. That is, the physical dimensions of the resonator may be much smaller than the wavelength corresponding to the resonant frequency. Sub-wavelength magnetic resonators may have most of the energy in the region surrounding the resonator stored in their magnetic near-fields, and these fields may also be described as stationary or non-propagating because they do not radiate away from the resonator. The extent of the near-field in the area surrounding the resonator is typically set by the wavelength, so it may extend well beyond the resonator itself for a sub-wavelength resonator. The limiting surface, where the field behavior changes from near-field behavior to far-field behavior may be called the “radiation caustic”.

[00178] The strength of the near-field is reduced the farther one gets away from the resonator. While the field strength of the resonator near-fields decays away from the resonator, the fields may still interact with objects brought into the general vicinity of the resonator. The degree to which the fields interact depends on a variety of factors, some of which may be controlled and designed, and some of which may not. The wireless energy transfer schemes described herein may be realized when the distance between coupled resonators is such that one resonator lies within the radiation caustic of the other.

[00179] The near-field profiles of the electromagnetic resonators may be similar to those commonly associated with dipole resonators or oscillators. Such field profiles may be described as omni-directional, meaning the magnitudes of the fields are non-zero in all directions away from the object.

[00180] Characteristic Size of An Electromagnetic Resonator

[00181] Spatially separated and/or offset magnetic resonators of sufficient Q may achieve efficient wireless energy transfer over distances that are much larger than have been seen in the prior art, even if the sizes and shapes of the resonator structures are different. Such resonators may also be operated to achieve more efficient energy transfer than was achievable with previous techniques over shorter range distances. We describe such resonators as being capable of mid-range energy transfer.

[00182] Mid-range distances may be defined as distances that are larger than the characteristic dimension of the smallest of the resonators involved in the transfer, where the distance is measured from the center of one resonator structure to the center of a spatially separated second resonator structure. In this definition, two-dimensional resonators are spatially separated when the areas circumscribed by their inductive elements do not intersect and three-dimensional resonators are spatially separated when their volumes do not intersect. A two-dimensional resonator is spatially separated from a three-dimensional resonator when the area circumscribed by the former is outside the volume of the latter.

[00183] Fig. 8 shows some example resonators with their characteristic dimensions labeled. It is to be understood that the characteristic sizes 802 of resonators 102 may be defined in terms of the size of the conductor and the area circumscribed or enclosed by the inductive element in a magnetic resonator and the length of the conductor forming the capacitive element of an electric resonator. Then, the characteristic size 802 of a resonator 102, x_{char}, may be equal to the radius of the smallest sphere that can fit around the inductive or capacitive element of the magnetic or electric resonator respectively, and the center of the resonator structure is the center of the sphere. The characteristic thickness 804, t_{char}, of a resonator 102 may be the smallest possible height of the highest point of the inductive or capacitive element in the magnetic or capacitive resonator respectively, measured from a flat surface on which it is placed. The characteristic width 808 of a resonator 102, w_{char}, may be the radius of the smallest possible circle through which the inductive or capacitive element of the magnetic or electric resonator respectively, may pass while traveling in a straight line. For example, the characteristic width 808 of a cylindrical resonator may be the radius of the cylinder.

[00184] In this inventive wireless energy transfer technique, energy may be exchanged efficiently over a wide range of distances, but the technique is distinguished by the ability to exchange useful energy for powering or recharging devices over mid-range distances and between resonators with different physical dimensions, components and orientations. Note that while k may be small in these circumstances, strong coupling and efficient energy transfer may be realized by using high-Q resonators to achieve a high U, $U = k\sqrt{Q_s Q_d}$. That is, increases in Q may be used to at least partially overcome decreases in k, to maintain useful energy transfer efficiencies.

[00185] Note too that while the near-field of a single resonator may be described as omni-directional, the efficiency of the energy exchange between two resonators may depend on the relative position and orientation of the resonators. That is, the efficiency of the energy exchange may be maximized for particular relative orientations of the resonators. The sensitivity of the transfer efficiency to the relative position and orientation of two uncompensated resonators may be captured in the calculation of either k or κ . While coupling may be achieved between resonators that are offset and/or rotated relative to each other, the efficiency of the exchange may depend on the details of the positioning and on any feedback, tuning, and compensation techniques implemented during operation.

[00186] High-*Q* Magnetic Resonators

[00187] In the near-field regime of a sub-wavelength capacitively-loaded loop magnetic resonator ($x \ll \lambda$), the resistances associated with a circular conducting loop inductor composed of N turns of wire whose radius is larger than the skin depth, are approximately $R_{abs} = \sqrt{\mu_o \rho \omega / 2} \cdot Nx / a$ and $R_{rad} = \pi / 6 \cdot \eta_o N^2 (\omega x / c)^4$, where ρ is the resistivity of the conductor material and $\eta_o \approx 120\pi\ \Omega$ is the impedance of free space. . The inductance, L, for such a N-turn loop is approximately N^2 times the inductance of a single-turn loop given previously. The quality factor of such a resonator, $Q = \omega L / (R_{abs} + R_{rad})$, is highest for a particular frequency determined by the system parameters (Fig. 4). As described previously, at lower frequencies the Q is determined primarily by absorption losses and at higher frequencies the Q is determined primarily by radiation losses.

[00188] Note that the formulas given above are approximate and intended to illustrate the functional dependence of R_{abs}, R_{rad} and L on the physical parameters of the structure. More accurate numerical calculations of these parameters that take into account deviations from the strict quasi-static limit, for example a non-uniform current/charge distribution along the conductor, may be useful for the precise design of a resonator structure.

[00189] Note that the absorptive losses may be minimized by using low loss conductors to form the inductive elements. The loss of the conductors may be minimized by using large surface area conductors such as conductive tubing, strapping, strips, machined objects, plates, and the like, by using specially designed conductors such as Litz wire, braided wires, wires of any cross-section, and other conductors with low proximity losses, in which case the frequency scaled behavior described above may be different, and by using low resistivity materials such as high-purity copper and silver, for example. One advantage of using conductive tubing as the conductor at higher operating frequencies is that it may be cheaper and lighter than a similar diameter solid conductor, and may have similar resistance because most of the current is traveling along the outer surface of the conductor owing to the skin effect.

[00190] To get a rough estimate of achievable resonator designs made from copper wire or copper tubing and appropriate for operation in the microwave regime, one may calculate the optimum Q and resonant frequency for a resonator composed of one circular inductive element ($N=1$) of copper wire ($\rho=1.69\cdot 10^{-8}\ \Omega m$) with various cross sections. Then for an inductive element with characteristic size $x=1\ cm$ and conductor diameter $a=1$ mm, appropriate for a cell phone for example, the quality factor peaks at $Q=1225$ when $f=380$ MHz. For $x=30\ cm$ and $a=2\ mm$, an inductive element size that might be appropriate for a laptop or a household robot, $Q=1103$ at $f=17$ MHz. For a larger source inductive element that might be located in the ceiling for example, $x=1$ m and $a=4$ mm, Q may be as high as $Q=1315$ at $f=5$ MHz. Note that a number of practical examples yield expected quality factors of $Q\approx 1000\text{-}1500$ at $\lambda/x\approx 50\text{-}80$. Measurements of a wider variety of coil shapes, sizes, materials and operating frequencies than described above show that Q's >100 may be realized for a variety of magnetic resonator structures using commonly available materials.

[00191] As described above, the rate for energy transfer between two resonators of characteristic size x_1 and x_2, and separated by a distance D between their centers, may be given by κ. To give an example of how the defined parameters scale, consider the cell phone, laptop, and ceiling resonator examples from above, at three (3) distances; D/x=10, 8, 6. In the examples considered here, the source and device resonators are the same size, x_1=x_2, and shape, and are oriented as shown in Fig. 1(b). In the cell phone example, $\omega / 2\kappa$ =3033, 1553, 655 respectively. In the laptop example, $\omega / 2\kappa$ =7131, 3651, 1540 respectively and for the ceiling resonator example, $\omega / 2\kappa$ =6481, 3318, 1400. The corresponding coupling-to-loss ratios peak at the frequency where the inductive element Q peaks and are κ / Γ =0.4, 0.79, 1.97 and 0.15, 0.3, 0.72 and 0.2, 0.4, 0.94 for the three inductive element sizes and distances described above. An example using different sized inductive elements is that of an x_1=1 m inductor (e.g. source in the ceiling) and an x_2=30 cm inductor (e.g. household robot on the floor) at a distance D=3 m apart (e.g. room height). In this example, the strong-coupling figure of merit, $U = \kappa / \sqrt{\Gamma_1 \Gamma_2}$ =0.88, for an efficiency of approximately 14%, at the optimal operating frequency of f=6.4 MHz. Here, the optimal system operating frequency lies between the peaks of the individual resonator Q's.

[00192] Inductive elements may be formed for use in high-Q magnetic resonators. We have demonstrated a variety of high-Q magnetic resonators based on copper conductors that are formed into inductive elements that enclose a surface. Inductive elements may be formed using a variety of conductors arranged in a variety of shapes, enclosing any size or shaped area, and they may be single turn or multiple turn elements. Drawings of exemplary inductive elements 900A-B are shown in Fig. 9. The inductive elements may be formed to enclose a circle, a rectangle, a square, a triangle, a shape with rounded corners, a shape that follows the contour of a particular structure or device, a shape that follows, fills, or utilizes, a dedicated space within a structure or device, and the like. The designs may be optimized for size, cost, weight, appearance, performance, and the like.

[00193] These conductors may be bent or formed into the desired size, shape, and number of turns. However, it may be difficult to accurately reproduce conductor shapes and sizes using manual techniques. In addition, it may be difficult to maintain uniform or desired center-to-center spacings between the conductor segments in adjacent turns of the inductive elements. Accurate or uniform spacing may be important in determining the self capacitance of the structure as well as any proximity effect induced increases in AC resistance, for example.

[00194] Molds may be used to replicate inductor elements for high-Q resonator designs. In addition, molds may be used to accurately shape conductors into any kind of shape without creating kinks, buckles or other potentially deleterious effects in the conductor. Molds may be used to form the inductor elements and then the inductor elements may be removed from the forms. Once removed, these inductive elements may be built into enclosures or devices that may house the high-Q magnetic resonator. The formed elements may also or instead remain in the mold used to form them.

[00195] The molds may be formed using standard CNC (computer numerical control) routing or milling tools or any other known techniques for cutting or forming grooves in blocks. The molds may also or instead be formed using machining techniques, injection molding techniques, casting techniques, pouring techniques, vacuum techniques, thermoforming techniques, cut-in-place techniques, compression forming techniques and the like.

[00196] The formed element may be removed from the mold or it may remain in the mold. The mold may be altered with the inductive element inside. The mold may be covered, machined, attached, painted and the like. The mold and conductor combination may be integrated into another housing, structure or device. The grooves cut into the molds may be any dimension and may be designed to form conducting tubing, wire, strapping, strips, blocks, and the like into the desired inductor shapes and sizes.

[00197] The inductive elements used in magnetic resonators may contain more than one loop and may spiral inward or outward or up or down or in some combination of directions. In general, the magnetic resonators may have a variety of shapes, sizes and number of turns and they may be composed of a variety of conducing materials.

[00198] The magnetic resonators may be free standing or they may be enclosed in an enclosure, container, sleeve or housing. The magnetic resonators may include the form used to make the inductive element. These various forms and enclosures may be composed of almost any kind of material. Low loss materials such as Teflon, REXOLITE, styrene, and the like may be preferable for some applications. These enclosures may contain fixtures that hold the inductive elements.

[00199] Magnetic resonators may be composed of self-resonant coils of copper wire or copper tubing. Magnetic resonators composed of self resonant conductive wire coils may include a wire of length l, and cross section radius a, wound into a helical coil of radius x, height h, and number of turns N, which may for example be characterized as $N=\sqrt{l^2-h^2}/2\pi x$.

[00200] A magnetic resonator structure may be configured so that x is about 30 cm, h is about 20 cm, a is about 3 mm and N is about 5.25, and, during operation, a power source coupled to the magnetic resonator may drive the resonator at a resonant frequency, f, where f is about 10.6 MHz. Where x is about 30 cm, h is about 20 cm, a is about 1 cm and N is about 4, the resonator may be driven at a frequency, f, where f is about 13.4 MHz. Where x is about 10 cm, h is about 3 cm, a is about 2 mm and N is about 6, the resonator may be driven at a frequency, f, where f is about 21.4 MHz.

[00201] High-Q inductive elements may be designed using printed circuit board traces. Printed circuit board traces may have a variety of advantages compared to mechanically formed inductive elements including that they may be accurately reproduced and easily integrated using established printed circuit board fabrication techniques, that their AC resistance may be lowered using custom designed conductor traces, and that the cost of mass-producing them may be significantly reduced.

[00202] High-Q inductive elements may be fabricated using standard PCB techniques on any PCB material such as FR-4 (epoxy E-glass), multi-functional epoxy, high performance epoxy, bismalaimide triazine/epoxy, polyimide, Cyanate Ester, polytetraflouroethylene (Teflon), FR-2, FR-3, CEM-1, CEM-2, Rogers, Resolute, and the like. The conductor traces may be formed on printed circuit board materials with lower loss tangents.

[00203] The conducting traces may be composed of copper, silver, gold, aluminum, nickel and the like, and they may be composed of paints, inks, or other cured materials. The circuit board may be flexible and it may be a flex-circuit. The conducting traces may be formed by chemical deposition, etching, lithography, spray deposition, cutting, and the like. The conducting traces may be applied to form the desired patterns and they may be formed using crystal and structure growth techniques.

[00204] The dimensions of the conducting traces, as well as the number of layers containing conducting traces, the position, size and shape of those traces and the architecture for interconnecting them may be designed to achieve or optimize certain system specifications such as resonator Q, $Q_{(p)}$, resonator size, resonator material and fabrication costs, U, $U_{(p)}$, and the like.

[00205] As an example, a three-turn high-Q inductive element 1001A was fabricated on a four-layer printed circuit board using the rectangular copper trace pattern as shown in Fig. 10(a). The copper trace is shown in black and the PCB in white. The width and thickness of the copper traces in this example was approximately 1 cm (400 mils) and 43 μ m (1.7 mils) respectively. The edge-to-edge spacing between turns of the conducting trace on a single layer was approximately 0.75 cm (300 mils) and each board layer thickness was approximately 100 μ m (4 mils). The pattern shown in Fig. 10(a) was repeated on each layer of the board and the conductors were connected in parallel. The outer dimensions of the 3-loop structure were approximately 30 cm by 20 cm. The measured inductance of this PCB loop was 5.3 μ H. A magnetic resonator using this inductor element and tunable capacitors had a quality factor, *Q*, of 550 at its designed resonance frequency of 6.78 MHz. The resonant frequency could be tuned by changing the inductance and capacitance values in the magnetic resonator.

[00206] As another example, a two-turn inductor 1001B was fabricated on a four-layer printed circuit board using the rectangular copper trace pattern shown in Fig. 10(b). The copper trace is shown in black and the PCB in white. The width and height of the copper traces in this example were approximately 0.75 cm (300 mils) and 43 μ m (1.7 mils) respectively. The edge-to-edge spacing between turns of the conducting trace on a single layer was approximately 0.635 cm (250 mils) and each board layer thickness was approximately 100 μ m (4 mils). The pattern shown in Fig. 10(b) was repeated on each layer of the board and the conductors were connected in parallel. The outer dimensions of the two-loop structure were approximately 7.62 cm by 26.7 cm. The measured inductance of this PCB loop was 1.3 μ H. Stacking two boards together with a vertical separation of approximately 0.635 cm (250 mils) and connecting the two boards in series produced a PCB inductor with an inductance of approximately 3.4 μ H. A magnetic resonator using this stacked inductor loop and tunable capacitors had a quality factor, *Q*, of 390 at its designed resonance frequency of 6.78 MHz. The resonant frequency could be tuned by changing the inductance and capacitance values in the magnetic resonator.

[00207] The inductive elements may be formed using magnetic materials of any size, shape thickness, and the like, and of materials with a wide range of permeability and loss values. These magnetic materials may be solid blocks, they may enclose hollow volumes, they may be formed from many smaller pieces of magnetic material tiled and or stacked together, and they may be integrated with conducting sheets or enclosures made from highly conducting materials. Wires may be wrapped around the magnetic materials to generate the magnetic near-field. These wires may be wrapped around one or more than one axis of the structure. Multiple wires may be wrapped around the magnetic materials and combined in parallel, or in series, or via a switch to form customized near-field patterns.

[00208] The magnetic resonator may include 15 turns of Litz wire wound around a 19.2 cm x 10 cm x 5 mm tiled block of 3F3 ferrite material. The Litz wire may be wound around the ferrite material in any direction or combination of directions to achieve the desire resonator performance. The number of turns of wire, the spacing between the turns, the type of wire, the size and shape of the magnetic materials and the type of magnetic material are all design parameters that may be varied or optimized for different application scenarios.

[00209] **High-*Q* Magnetic resonators using magnetic material structures**

[00210] It may be possible to use magnetic materials assembled to form an open magnetic circuit, albeit one with an air gap on the order of the size of the whole structure, to realize a magnetic resonator structure. In these structures, high conductivity materials are wound around a structure made from magnetic material to form the inductive element of the magnetic resonator. Capacitive elements may be connected to the high conductivity materials, with the resonant frequency then determined as described above. These magnetic resonators have their dipole moment in the plane of the two dimensional resonator structures, rather than perpendicular to it, as is the case for the capacitively-loaded inductor loop resonators.

[00211] A diagram of a single planar resonator structure is shown in Fig. 11(a). The planar resonator structure is constructed of a core of magnetic material 1121, such as ferrite with a loop or loops of conducting material 1122 wrapped around the core 1121. The structure may be used as the source resonator that transfers power and the device resonator that captures energy. When used as a source, the ends of the conductor may be coupled to a power source. Alternating electrical current flowing through the conductor loops excites alternating magnetic fields. When the structure is being used to receive power, the ends of the conductor may be coupled to a power drain or load. Changing magnetic fields induce an electromotive force in the loop or loops of the conductor wound around the core magnetic material. The dipole moment of these types of structures is in the plane of the structures and is, for example, directed along the Y axis for the structure in Figure 11(a). Two such structures have strong coupling when placed substantially in the same plane (i.e. the X,Y plane of Figure 11). The structures of Figure 11(a) have the most favorable orientation when the resonators are aligned in the same plane along their Y axis.

[00212] The geometry and the coupling orientations of the described planar resonators may be preferable for some applications. The planar or flat resonator shape may be easier to integrate into many electronic devices that are relatively flat and planar. The planar resonators may be integrated into the whole back or side of a device without requiring a change in geometry of the device. Due to the flat shape of many devices, the natural position of the devices when placed on a surface is to lay with their largest dimension being parallel to the surface they are placed on. A planar resonator integrated into a flat device is naturally parallel to the plane of the surface and is in a favorable coupling orientation relative to the resonators of other devices or planar resonator sources placed on a flat surface.

[00213] As mentioned, the geometry of the planar resonators may allow easier integration into devices. Their low profile may allow a resonator to be integrated into or as part of a complete side of a device. When a whole side of a device is covered by the resonator, magnetic flux can flow through the resonator core without being obstructed by lossy material that may be part of the device or device circuitry.

[00214] The core of the planar resonator structure may be of a variety of shapes and thicknesses and may be flat or planar such that the minimum dimension does not exceed 30% of the largest dimension of the structure. The core may have complex geometries and may have indentations, notches, ridges, and the like. Geometric enhancements may be used to reduce the coupling dependence on orientation and they may be used to facilitate integration into devices, packaging, packages, enclosures, covers, skins, and the like. Two exemplary variations of core geometries are shown in Figure 11(b). For example, the planar core 1131 may be shaped such that the ends are substantially wider than the middle of the structure to create an indentation for the conductor winding. The core material may be of varying thickness with ends that are thicker and wider than the middle. The core material 1132 may have any number of notches or cutouts 1133 of various depths, width, and shapes to accommodate conductor loops, housing, packaging, and the like.

[00215] The shape and dimensions of the core may be further dictated by the dimensions and characteristics of the device that they are integrated into. The core material may curve to follow the contours of the device, or may require non-symmetric notches or cutouts to allow clearance for parts of the device. The core structure may be a single monolithic piece of magnetic material or may be composed of a plurality of tiles, blocks, or pieces that are arranged together to form the larger structure. The different layers, tiles, blocks, or pieces of the structure may be of similar or may be of different materials. It may be desirable to use materials with different magnetic permeability in different locations of the structure. Core structures with different magnetic permeability may be useful for guiding the magnetic flux, improving coupling, and affecting the shape or extent of the active area of a system.

[00216] The conductor of the planar resonator structure may be wound at least once around the core. In certain circumstances, it may be preferred to wind at least three loops. The conductor can be any good conductor including conducting wire, Litz wire, conducting tubing, sheets, strips, gels, inks, traces and the like.

[00217] The size, shape, or dimensions of the active area of source may be further enhanced, altered, or modified with the use of materials that block, shield, or guide magnetic fields. To create non-symmetric active area around a source once side of the source may be covered with a magnetic shield to reduce the strength of the magnetic fields in a specific direction. The shield may be a conductor or a layered combination of conductor and magnetic material which can be used to guide magnetic fields away from a specific direction. Structures composed of layers of conductors and magnetic materials may be used to reduce energy losses that may occur due to shielding of the source.

[00218] The plurality of planar resonators may be integrated or combined into one planar resonator structure. A conductor or conductors may be wound around a core structure such that the loops formed by the two conductors are not coaxial. An example of such a structure is shown in Figure 12 where two conductors 1201,1202 are wrapped around a planar rectangular core 1203 at orthogonal angles. The core may be rectangular or it may have various geometries with several extensions or protrusions. The protrusions may be useful for wrapping of a conductor, reducing the weight, size, or mass of the core, or may be used to enhance the directionality or omni-directionality of the resonator. A multi wrapped planar resonator with four protrusions is shown by the inner structure 1310 in Figure 13, where four conductors 1301, 1302, 1303, 1304 are wrapped around the core. The core may have extensions 1305,1306,1307,1308 with one or more conductor loops. A single conductor may be wrapped around a core to form loops that are not coaxial. The four conductor loops of Figure 13, for example, may be formed with one continuous piece of conductor, or using two conductors where a single conductor is used to make all coaxial loops.

[00219] Non-uniform or asymmetric field profiles around the resonator comprising a plurality of conductor loops may be generated by driving some conductor loops with non-identical parameters. Some conductor loops of a source resonator with a plurality of conductor loops may be driven by a power source with a different frequency, voltage, power level, duty cycle, and the like all of which may be used to affect the strength of the magnetic field generated by each conductor.

[00220] The planar resonator structures may be combined with a capacitively-loaded inductor resonator coil to provide an omni-directional active area all around, including above and below the source while maintaining a flat resonator structure. As shown in Figure 13, an additional resonator loop coil 1309 comprising of a loop or loops of a conductor, may be placed in a common plane as the planar resonator structure 1310. The outer resonator coil provides an active area that is substantially above and below the source. The resonator coil can be arranged with any number of planar resonator structures and arrangements described herein.

[00221] The planar resonator structures may be enclosed in magnetically permeable packaging or integrated into other devices. The planar profile of the resonators within a single, common plane allows packaging and integration into flat devices. A diagram illustrating the application of the resonators is shown in Figure 14. A flat source 1411 comprising one or more planar resonators 1414 each with one or more conductor loops may transfer power to devices 1412,1413 that are integrated with other planar resonators 1415,1416 and placed within an active area 1417 of the source. The devices may comprise a plurality of planar resonators such that regardless of the orientation of the device with respect to the source the active area of the source does not change. In addition to invariance to rotational misalignment, a flat device comprising of planar resonators may be turned upside down without substantially affecting the active area since the planar resonator is still in the plane of the source.

[00222] Another diagram illustrating a possible use of a power transfer system using the planar resonator structures is shown in Figure 15. A planar source 1521 placed on top of a surface 1525 may create an active area that covers a substantial surface area creating an "energized surface" area. Devices such as computers 1524, mobile handsets 1522, games, and other electronics 1523 that are coupled to their respective planar device resonators may receive energy from the source when placed within the active area of the source, which may be anywhere on top of the surface. Several devices with different dimensions may be placed in the active area and used normally while charging or being powered from the source without having strict placement or alignment constraints. The source may be placed under the surface of a table, countertop, desk, cabinet, and the like, allowing it to be completely hidden while energizing the top surface of the table, countertop, desk, cabinet and the like, creating an active area on the surface that is much larger than the source.

[00223] The source may include a display or other visual, auditory, or vibration indicators to show the direction of charging devices or what devices are being charged, error or problems with charging, power levels, charging time, and the like.

[00224] The source resonators and circuitry may be integrated into any number of other devices. The source may be integrated into devices such as clocks, keyboards, monitors, picture frames, and the like. For example, a keyboard integrated with the planar resonators and appropriate power and control circuitry may be used as a source for devices placed around the keyboard such as computer mice, webcams, mobile handsets, and the like without occupying any additional desk space.

[00225] While the planar resonator structures have been described in the context of mobile devices it should be clear to those skilled in the art that a flat planar source for wireless power transfer with an active area that extends beyond its physical dimensions has many other consumer and industrial applications. The structures and configuration may be useful for a large number of applications where electronic or electric devices and a power source are typically located, positioned, or manipulated in substantially the same plane and alignment. Some of the possible application scenarios include devices on walls, floor, ceilings or any other substantially planar surfaces.

[00226] Flat source resonators may be integrated into a picture frame or hung on a wall thereby providing an active area within the plane of the wall where other electronic devices such as digital picture frames, televisions, lights, and the like can be mounted and powered without wires. Planar resonators may be integrated into a floor resulting in an energized floor or active area on the floor on which devices can be placed to receive power. Audio speakers, lamps, heaters, and the like can be placed within the active are and receive power wirelessly.

[00227] The planar resonator may have additional components coupled to the conductor. Components such as capacitors, inductors, resistors, diodes, and the like may be coupled to the conductor and may be used to adjust or tune the resonant frequency and the impedance matching for the resonators.

[00228] A planar resonator structure of the type described above and shown in Fig. 11(a), may be created, for example, with a quality factor, *Q*, of 100 or higher and even *Q* of 1,000 or higher. Energy may be wirelessly transferred from one planar resonator structure to another over a distance larger than the characteristic size of the resonators, as shown in Fig. 11(c).

[00229] In addition to utilizing magnetic materials to realize a structure with properties similar to the inductive element in the magnetic resonators, it may be possible to use a combination of good conductor materials and magnetic material to realize such inductive structures. Fig. 16(a) shows a magnetic resonator structure 1602 that may include one or more enclosures made of high-conductivity materials (the inside of which would be shielded from AC electromagnetic fields generated outside) surrounded by at least one layer of magnetic material and linked by blocks of magnetic material 1604.

A structure may include a high-conductivity sheet of material covered on one side by a layer of magnetic material. The layered structure may instead be applied conformally to an electronic device, so that parts of the device may be covered by the high-conductivity and magnetic material layers, while other parts that need to be easily accessed (such as buttons or screens) may be left uncovered. The structure may also or instead include only layers or bulk pieces of magnetic material. Thus, a magnetic resonator may be incorporated into an existing device without significantly interfering with its existing functions and with little or no need for extensive redesign. Moreover, the layers of good conductor and/or magnetic material may be made thin enough (of the order of a millimeter or less) that they would add little extra weight and volume to the completed device. An oscillating current applied to a length of conductor wound around the structure, as shown by the square loop in the center of the structure in Figure 16 may be used to excite the electromagnetic fields associated with this structure.

[00230] Quality factor of the structure

[00231] A structure of the type described above may be created with a quality factor, *Q*, of the order of 1,000 or higher. This high-Q is possible even if the losses in the magnetic material are high, if the fraction of magnetic energy within the magnetic material is small compared to the total magnetic energy associated with the object. For structures composed of layers conducting materials and magnetic materials, the losses in the conducting materials may be reduced by the presence of the magnetic materials as described previously. In structures where the magnetic material layer's thickness is of the order of 1/100 of the largest dimension of the system (e.g., the magnetic material may be of the order of 1 mm thick, while the area of the structure is of the order of 10 cm x 10 cm), and the relative permeability is of the order of 1,000, it is possible to make the fraction of magnetic energy contained within the magnetic material only a few hundredths of the total magnetic energy associated with the object or resonator. To see how that comes about, note that the expression for the magnetic energy contained in a volume is $U_m = \int_V d\mathbf{r}\mathbf{B}(\mathbf{r})^2 / (2\mu_r\mu_0)$, so as long as $\boldsymbol{B}$ (rather than $\boldsymbol{H}$) is the main field conserved across the magnetic material-air interface (which is typically the case in open magnetic circuits), the fraction of magnetic energy contained in the high-μ_r region may be significantly reduced compared to what it is in air.

[00232] If the fraction of magnetic energy in the magnetic material is denoted by *frac*, and the loss tangent of the material is $tan\delta$, then the Q of the resonator, assuming the magnetic material is the only source of losses, is $Q=1/(frac \times tan\delta)$. Thus, even for loss tangents as high as 0.1, it is possible to achieve *Q's* of the order of 1,000 for these types of resonator structures.

[00233] If the structure is driven with *N* turns of wire wound around it, the losses in the excitation inductor loop can be ignored if *N* is sufficiently high. Fig. 17 shows an equivalent circuit 1700 schematic for these structures and the scaling of the loss mechanisms and inductance with the number of turns, *N,* wound around a structure made of conducting and magnetic material. If proximity effects can be neglected (by using an appropriate winding, or a wire designed to minimize proximity effects, such as Litz wire and the like), the resistance 1702 due to the wire in the looped conductor scales linearly with the length of the loop, which is in turn proportional to the number of turns. On the other hand, both the equivalent resistance 1708 and equivalent inductance 1704 of these special structures are proportional to the square of the magnetic field inside the structure. Since this magnetic field is proportional to *N*, the equivalent resistance 1708 and equivalent inductance 1704 are both proportional to N^2. Thus, for large enough N, the resistance 1702 of the wire is much smaller than the equivalent resistance 1708 of the magnetic structure, and the Q of the resonator asymptotes to $Q_{max} = \omega L_\mu / R_\mu$.

[00234] Fig. 16 (a) shows a drawing of a copper and magnetic material structure 1602 driven by a square loop of current around the narrowed segment at the center of the structure 1604 and the magnetic field streamlines generated by this structure 1608. This exemplary structure includes two 20 cm x 8 cm x 2 cm hollow regions enclosed with copper and then completely covered with a 2 mm layer of magnetic material having the properties $\mu_r' = 1{,}400$, $\mu_r'' = 5$, and $\sigma = 0.5$ S/m. These two parallelepipeds are spaced 4 cm apart and are connected by a 2 cm x 4 cm x 2 cm block of the same magnetic material. The excitation loop is wound around the center of this block. At a frequency of 300 kHz, this structure has a calculated Q of 890. The conductor and magnetic material structure may be shaped to optimize certain system parameters. For example, the size of the structure enclosed by the excitation loop may be small to reduce the resistance of the excitation loop, or it may be large to mitigate losses in the magnetic material associated with large magnetic fields. Note that the magnetic streamlines and *Q's* associated with the same structure composed of magnetic material only would be similar to the layer conductor and magnetic material design shown here.

[00235] **Electromagnetic Resonators Interacting with Other Objects**

[00236] For electromagnetic resonators, extrinsic loss mechanisms that perturb the intrinsic Q may include absorption losses inside the materials of nearby extraneous objects and radiation losses related to scattering of the resonant fields from nearby extraneous objects. Absorption losses may be associated with materials that, over the frequency range of interest, have non-zero, but finite, conductivity, σ , (or equivalently a non-zero and finite imaginary part of the dielectric permittivity), such that electromagnetic fields can penetrate it and induce currents in it, which then dissipate energy through resistive losses. An object may be described as lossy if it at least partly includes lossy materials.

[00237] Consider an object including a homogeneous isotropic material of conductivity, σ and magnetic permeability, μ . The penetration depth of electromagnetic fields inside this object is given by the skin depth, $\delta = \sqrt{2/\omega\mu\sigma}$. The power dissipated inside the object, P_d , can be determined from $P_d = \int_V d\mathbf{r}\,\sigma\,|\,\mathbf{E}\,|^2 = \int_V d\mathbf{r}\,|\,\mathbf{J}\,|^2/\sigma$ where we made use of Ohm's law, $\mathbf{J} = \sigma\mathbf{E}$, and where $\mathbf{E}$ is the electric field and $\mathbf{J}$ is the current density.

[00238] If over the frequency range of interest, the conductivity, σ , of the material that composes the object is low enough that the material's skin depth, δ, may be considered long, (i.e. δ is longer than the objects' characteristic size, or δ is longer than the characteristic size of the portion of the object that is lossy) then the electromagnetic fields, $\mathbf{E}$ and $\mathbf{H}$, where $\mathbf{H}$ is the magnetic field, may penetrate significantly into the object. Then, these finite-valued fields may give rise to a dissipated power that scales as $P_d \sim \sigma V_{ol} \left\langle |\mathbf{E}|^2 \right\rangle$, where V_{ol} is the volume of the object that is lossy and $\left\langle |\mathbf{E}|^2 \right\rangle$ is the spatial average of the electric-field squared, in the volume under consideration. Therefore, in the low-conductivity limit, the dissipated power scales proportionally to the conductivity and goes to zero in the limit of a non-conducting (purely dielectric) material.

[00239] If over the frequency range of interest, the conductivity, σ, of the material that composes the object is high enough that the material's skin depth may be considered short, then the electromagnetic fields, $\mathbf{E}$ and $\mathbf{H}$, may penetrate only a short distance into the object (namely they stay close to the 'skin' of the material, where δ is smaller than the characteristic thickness of the portion of the object that is lossy). In this case, the currents induced inside the material may be concentrated very close to the material surface, approximately within a skin depth, and their magnitude may be approximated by the product of a surface current density (mostly determined by the shape of the incident electromagnetic fields and, as long as the thickness of the conductor is much larger than the skin-depth, independent of frequency and conductivity to first order) $K(x,y)$ (where x and y are coordinates parameterizing the surface) and a function decaying exponentially into the surface: $\exp(-z/\delta)/\delta$ (where z denotes the coordinate locally normal to the surface): $J(x,y,z) = K(x,y)\exp(-z/\delta)/\delta$. Then, the dissipated power, P_d, may be estimated by,

$$P_d = {}^{V} d\mathbf{r} \, |\mathbf{J}(\mathbf{r})|^2 / \sigma \simeq \left({}^{S} \mathbf{dxdy} \, | \mathbf{K}(\mathbf{x},\mathbf{y}) |^2 \right) \left({}^{\infty}_{0} \mathbf{dz} \exp(\mathbf{2z}/\delta) / (\sigma \delta^2) \right) = \sqrt{\mu\omega / 8\sigma} \left({}^{S} dxdy \, | K(x,y) |^2 \right)$$

[00240] Therefore, in the high-conductivity limit, the dissipated power scales inverse proportionally to the square-root of the conductivity and goes to zero in the limit of a perfectly-conducting material.

[00241] If over the frequency range of interest, the conductivity, σ, of the material that composes the object is finite, then the material's skin depth, δ, may penetrate some distance into the object and some amount of power may be dissipated inside the object, depending also on the size of the object and the strength of the electromagnetic fields. This description can be generalized to also describe the general case of an object including multiple different materials with different properties and conductivities, such as an object with an arbitrary inhomogeneous and anisotropic distribution of the conductivity inside the object.

[00242] Note that the magnitude of the loss mechanisms described above may depend on the location and orientation of the extraneous objects relative to the resonator fields as well as the material composition of the extraneous objects. For example, high-conductivity materials may shift the resonant frequency of a resonator and detune it from other resonant objects. This frequency shift may be fixed by applying a feedback mechanism to a resonator that corrects its frequency, such as through changes in the inductance and/or capacitance of the resonator. These changes may be realized using variable capacitors and inductors, in some cases achieved by changes in the geometry of components in the resonators. Other novel tuning mechanisms, described below, may also be used to change the resonator frequency.

[00243] Where external losses are high, the perturbed Q may be low and steps may be taken to limit the absorption of resonator energy inside such extraneous objects and materials. Because of the functional dependence of the dissipated power on the strength of the electric and magnetic fields, one might optimize system performance by designing a system so that the desired coupling is achieved with shorter evanescent resonant field tails at the source resonator and longer at the device resonator, so that the perturbed Q of the source in the presence of other objects is optimized (or vice versa if the perturbed Q of the device needs to be optimized).

[00244] Note that many common extraneous materials and objects such as people, animals, plants, building materials, and the like, may have low conductivities and therefore may have little impact on the wireless energy transfer scheme disclosed here. An important fact related to the magnetic resonator designs we describe is that their electric fields may be confined primarily within the resonator structure itself, so it should be possible to operate within the commonly accepted guidelines for human safety while providing wireless power exchange over mid range distances.

[00245] <u>Electromagnetic Resonators with Reduced Interactions</u>

[00246] One frequency range of interest for near-field wireless power transmission is between 10 kHz and 100 MHz. In this frequency range, a large variety of ordinary non-metallic materials, such as for example several types of wood and plastic may have relatively low conductivity, such that only small amounts of power may be dissipated inside them. In addition, materials with low loss tangents, $\tan\Delta$, where $\tan\Delta = \varepsilon'' / \varepsilon'$, and ε'' and ε' are the imaginary and real parts of the permittivity respectively, may also have only small amounts of power dissipated inside them. Metallic materials, such as copper, silver, gold, and the like, with relatively high conductivity, may also have little power dissipated in them, because electromagnetic fields are not able to significantly penetrate these materials, as discussed earlier. These very high and very low conductivity materials, and low loss tangent materials and objects may have a negligible impact on the losses of a magnetic resonator.

[00247] However, in the frequency range of interest, there are materials and objects such as some electronic circuits and some lower-conductivity metals, which may have moderate (in general inhomogeneous and anisotropic) conductivity, and/or moderate to high loss tangents, and which may have relatively high dissipative losses. Relatively larger amounts of power may be dissipated inside them. These materials and objects may dissipate enough energy to reduce $Q_{(p)}$ by non-trivial amounts, and may be referred to as "lossy objects".

[00248] One way to reduce the impact of lossy materials on the $Q_{(p)}$ of a resonator is to use high-conductivity materials to shape the resonator fields such that they avoid the lossy objects. The process of using high-conductivity materials to tailor electromagnetic fields so that they avoid lossy objects in their vicinity may be understood by visualizing high-conductivity materials as materials that deflect or reshape the fields. This picture is qualitatively correct as long as the thickness of the conductor is larger than the skin-depth because the boundary conditions for electromagnetic fields at the surface of a good conductor force the electric field to be nearly completely perpendicular to, and the magnetic field to be nearly completely tangential to, the conductor surface. Therefore, a perpendicular magnetic field or a tangential electric field will be "deflected away" from the conducting surface. Furthermore, even a tangential magnetic field or a perpendicular electric field may be forced to decrease in magnitude on one side and/or in particular locations of the conducting surface, depending on the relative position of the sources of the fields and the conductive surface.

[00249] As an example, Fig. 18 shows a finite element method (FEM) simulation of two high conductivity surfaces 1802 above and below a lossy dielectric material 1804 in an external, initially uniform, magnetic field of frequency $f = 6.78$ MHz. The system is azimuthally symmetric around the r=0 axis. In this simulation, the lossy dielectric material 1804 is sandwiched between two conductors 1802, shown as the white lines at approximately z = ±0.01m. In the absence of the conducting surfaces above and below the dielectric disk, the magnetic field (represented by the drawn magnetic field lines) would have remained essentially uniform (field lines straight and parallel with the z-axis), indicating that the magnetic field would have passed straight through the lossy dielectric material. In this case, power would have been dissipated in the lossy dielectric disk. In the presence of conducting surfaces, however, this simulation shows the magnetic field is reshaped. The magnetic field is forced to be tangential to surface of the conductor and so is deflected around those conducting surfaces 1802, minimizing the amount of power that may be dissipated in the lossy dielectric material 1804 behind or between the conducting surfaces. As used herein, an axis of electrical symmetry refers to any axis about which a fixed or time-varying electrical or magnetic field is substantially symmetric during an exchange of energy as disclosed herein.

[00250] A similar effect is observed even if only one conducting surface, above or below, the dielectric disk, is used. If the dielectric disk is thin, the fact that the electric field is essentially zero at the surface, and continuous and smooth close to it, means that the electric field is very low everywhere close to the surface (i.e. within the dielectric disk). A single surface implementation for deflecting resonator fields away from lossy objects may be preferred for applications where one is not allowed to cover both sides of the lossy material or object (e.g. an LCD screen). Note that even a very thin surface of conducting material, on the order of a few skin-depths, may be sufficient (the skin depth in pure copper at 6.78 MHz is ~20 μ m, and at 250 kHz is ~100 μ m) to significantly improve the $Q_{(p)}$ of a resonator in the presence of lossy materials.

[00251] Lossy extraneous materials and objects may be parts of an apparatus, in which a high-Q resonator is to be integrated. The dissipation of energy in these lossy materials and objects may be reduced by a number of techniques including:

- by positioning the lossy materials and objects away from the resonator, or, in special positions and orientations relative to the resonator.
- by using a high conductivity material or structure to partly or entirely cover lossy materials and objects in the vicinity of a resonator

- by placing a closed surface (such as a sheet or a mesh) of high-conductivity material around a lossy object to completely cover the lossy object and shape the resonator fields such that they avoid the lossy object.
- by placing a surface (such as a sheet or a mesh) of a high-conductivity material around only a portion of a lossy object, such as along the top, the bottom, along the side, and the like, of an object or material.
- by placing even a single surface (such as a sheet or a mesh) of high-conductivity material above or below or on one side of a lossy object to reduce the strength of the fields at the location of the lossy object.

[00252] Fig. 19 shows a capacitively-loaded loop inductor forming a magnetic resonator 102 and a disk-shaped surface of high-conductivity material 1802 that completely surrounds a lossy object 1804 placed inside the loop inductor. Note that some lossy objects may be components, such as electronic circuits, that may need to interact with, communicate with, or be connected to the outside environment and thus cannot be completely electromagnetically isolated. Partially covering a lossy material with high conductivity materials may still reduce extraneous losses while enabling the lossy material or object to function properly.

[00253] Fig. 20 shows a capacitively-loaded loop inductor that is used as the resonator 102 and a surface of high-conductivity material 1802, surrounding only a portion of a lossy object 1804, that is placed inside the inductor loop.

[00254] Extraneous losses may be reduced, but may not be completely eliminated, by placing a single surface of high-conductivity material above, below, on the side, and the like, of a lossy object or material. An example is shown in Fig. 21, where a capacitively-loaded loop inductor is used as the resonator 102 and a surface of high-conductivity material 1802 is placed inside the inductor loop under a lossy object 1804 to reduce the strength of the fields at the location of the lossy object. It may be preferable to cover only one side of a material or object because of considerations of cost, weight, assembly complications, air flow, visual access, physical access, and the like.

[00255] A single surface of high-conductivity material may be used to avoid objects that cannot or should not be covered from both sides (e.g. LCD or plasma screens). Such lossy objects may be avoided using optically transparent conductors. High-conductivity optically opaque materials may instead be placed on only a portion of the lossy object, instead of, or in addition to, optically transparent conductors. The adequacy of single-sided vs. multi-sided covering implementations, and the design trade-offs inherent therein may depend on the details of the wireless energy transfer scenario and the properties of the lossy materials and objects.

[00256] Below we describe an example using high-conductivity surfaces to improve the Q-insensitivity, $\Theta_{(p)}$, of an integrated magnetic resonator used in a wireless energy-transfer system. Fig. 22 shows a wireless projector 2200. The wireless projector may include a device resonator 102C, a projector 2202, a wireless network/video adapter 2204, and power conversion circuits 2208, arranged as shown. The device resonator 102C may include a three-turn conductor loop, arranged to enclose a surface, and a capacitor network 2210. The conductor loop may be designed so that the device resonator 102C has a high Q (e.g., >100) at its operating resonant frequency. Prior to integration in the completely wireless projector 2200, this device resonator 102C has a Q of approximately 477 at the designed operating resonant frequency of 6.78 MHz. Upon integration, and placing the wireless network/video adapter card 2204 in the center of the resonator loop inductor, the resonator $Q_{(integrated)}$ was decreased to approximately 347. At least some of the reduction from Q to $Q_{(integrated)}$ was attributed to losses in the perturbing wireless network/video adapter card. As described above, electromagnetic fields associated with the magnetic resonator 102C may induce currents in and on the wireless network/video adapter card 2204, which may be dissipated in resistive losses in the lossy materials that compose the card. We observed that $Q_{(integrated)}$ of the resonator may be impacted differently depending on the composition, position, and orientation, of objects and materials placed in its vicinity.

[00257] In a completely wireless projector example, covering the network/video adapter card with a thin copper pocket (a folded sheet of copper that covered the top and the bottom of the wireless network/video adapter card, but not the communication antenna) improved the $Q_{(integrated)}$ of the magnetic resonator to a $Q_{(integrated + copper\ pocket)}$ of approximately 444. In other words, most of the reduction in $Q_{(integrated)}$ due to the perturbation caused by the extraneous network/video adapter card could be eliminated using a copper pocket to deflect the resonator fields away from the lossy materials.

[00258] In another completely wireless projector example, covering the network/video adapter card with a single copper sheet placed beneath the card provided a $Q_{(integrated + copper\ sheet)}$ approximately equal to $Q_{(integrated + copper\ pocket)}$. In that example, the high perturbed Q of the system could be maintained with a single high-conductivity sheet used to deflect the resonator fields away from the lossy adapter card.

[00259] It may be advantageous to position or orient lossy materials or objects, which are part of an apparatus including a high-Q electromagnetic resonator, in places where the fields produced by the resonator are relatively weak, so that little or no power may be dissipated in these objects and so that the Q-insensitivity, $\Theta_{(p)}$, may be large. As was shown earlier, materials of different conductivity may respond differently to electric versus magnetic fields. Therefore, according to the conductivity of the extraneous object, the positioning technique may be specialized to one or the other field.

[00260] Fig. 23 shows the magnitude of the electric 2312 and magnetic fields 2314 along a line that contains the diameter of the circular loop inductor and the electric 2318 and magnetic fields 2320 along the axis of the loop inductor for a capacitively-loaded circular loop inductor of wire of radius 30 cm, resonant at 10 MHz. It can be seen that the amplitude of the resonant near-fields reach their maxima close to the wire and decay away from the loop, 2312 , 2314 . In the plane of the loop inductor 2318, 2320, the fields reach a local minimum at the center of the loop. Therefore, given the finite size of the apparatus, it may be that the fields are weakest at the extrema of the apparatus or it may be that the field magnitudes have local minima somewhere within the apparatus. This argument holds for any other type of electromagnetic resonator 102 and any type of apparatus. Examples are shown in Figs. 24a and 24b, where a capacitively-loaded inductor loop forms a magnetic resonator 102 and an extraneous lossy object 1804 is positioned where the electromagnetic fields have minimum magnitude.

[00261] In a demonstration example, a magnetic resonator was formed using a three-turn conductor loop, arranged to enclose a square surface (with rounded corners), and a capacitor network. The Q of the resonator was approximately 619 at the designed operating resonant frequency of 6.78 MHz. The perturbed Q of this resonator depended on the placement of the perturbing object, in this case a pocket projector, relative to the resonator. When the perturbing projector was located inside the inductor loop and at its center or on top of the inductor wire turns, $Q_{(projector)}$ was approximately 96, lower than when the perturbing projector was placed outside of the resonator, in which case $Q_{(projector)}$ was approximately 513. These measurements support the analysis that shows the fields inside the inductor loop may be larger than those outside it, so lossy objects placed inside such a loop inductor may yield lower perturbed *Q's* for the system than when the lossy object is placed outside the loop inductor. Depending on the resonator designs and the material composition and orientation of the lossy object, the arrangement shown in Fig. 24b may yield a higher Q-insensitivity, $\Theta_{(projector)}$, than the arrangement shown in Fig. 24a.

[00262] High-Q resonators may be integrated inside an apparatus. Extraneous materials and objects of high dielectric permittivity, magnetic permeability, or electric conductivity may be part of the apparatus into which a high-Q resonator is to be integrated. For these extraneous materials and objects in the vicinity of a high-Q electromagnetic resonator, depending on their size, position and orientation relative to the resonator, the resonator field-profile may be distorted and deviate significantly from the original unperturbed field-profile of the resonator. Such a distortion of the unperturbed fields of the resonator may significantly decrease the Q to a lower $Q_{(p)}$, even if the extraneous objects and materials are lossless.

[00263] It may be advantageous to position high-conductivity objects, which are part of an apparatus including a high-Q electromagnetic resonator, at orientations such that the surfaces of these objects are, as much as possible, perpendicular to the electric field lines produced by the unperturbed resonator and parallel to the magnetic field lines produced by the unperturbed resonator, thus distorting the resonant field profiles by the smallest amount possible. Other common objects that may be positioned perpendicular to the plane of a magnetic resonator loop include screens (LCD, plasma, etc), batteries, cases, connectors, radiative antennas, and the like. The Q-insensitivity, $\Theta_{(p)}$, of the resonator may be much larger than if the objects were positioned at a different orientation with respect to the resonator fields.

[00264] Lossy extraneous materials and objects, which are not part of the integrated apparatus including a high-Q resonator, may be located or brought in the vicinity of the resonator, for example, during the use of the apparatus. It may be advantageous in certain circumstances to use high conductivity materials to tailor the resonator fields so that they avoid the regions where lossy extraneous objects may be located or introduced to reduce power dissipation in these materials and objects and to increase Q-insensitivity, $\Theta_{(p)}$. An example is shown in Fig. 25, where a capacitively-loaded loop inductor and capacitor are used as the resonator 102 and a surface of high-conductivity material 1802 is placed above the inductor loop to reduce the magnitude of the fields in the region above the resonator, where lossy extraneous objects 1804 may be located or introduced.

[00265] Note that a high-conductivity surface brought in the vicinity of a resonator to reshape the fields may also lead to $Q_{(cond.\ surface)}<Q$. The reduction in the perturbed Q may be due to the dissipation of energy inside the lossy conductor or to the distortion of the unperturbed resonator field profiles associated with matching the field boundary conditions at the surface of the conductor. Therefore, while a high-conductivity surface may be used to reduce the extraneous losses due to dissipation inside an extraneous lossy object, in some cases, especially in some of those where this is achieved by significantly reshaping the electromagnetic fields, using such a high-conductivity surface so that the fields avoid the lossy object may result effectively in $Q_{(p\ +\ cond.\ surface)}<Q_{(p)}$ rather than the desired result $Q_{(p\ +\ cond.\ surface)}>Q_{(p)}$.

[00266] As described above, in the presence of loss inducing objects, the perturbed quality factor of a magnetic resonator may be improved if the electromagnetic fields associated with the magnetic resonator are reshaped to avoid the loss inducing objects. Another way to reshape the unperturbed resonator fields is to use high permeability materials to completely or partially enclose or cover the loss inducing objects, thereby reducing the interaction of the magnetic field with the loss inducing objects.

[00267] Magnetic field shielding has been described previously, for example in *Electrodynamics 3rd Ed.*, Jackson, pp. 201-203. There, a spherical shell of magnetically permeable material was shown to shield its interior from external magnetic fields. For example, if a shell of inner radius a, outer radius b, and relative permeability μ_r, is placed in an initially uniform magnetic field H_0, then the field inside the shell will have a constant magnitude, $9\mu_r H_0 \big/ \left[(2\mu_r+1)(\mu_r+2)-2(a/b)^3(\mu_r-1)^2\right]$, which tends to $9H_0 \big/ 2\mu_r\left(1-(a/b)^3\right)$ if $\mu_r>>1$. This result shows that an incident magnetic field (but not necessarily an incident electric field) may be greatly attenuated inside the shell, even if the shell is quite thin, provided the magnetic permeability is high enough. It may be advantageous in certain circumstances to use high permeability materials to partly or entirely cover lossy materials and objects so that they are avoided by the resonator magnetic fields and so that little or no power is dissipated in these materials and objects. In such an approach, the Q-insensitivity, $\Theta_{(p)}$, may be larger than if the materials and objects were not covered, possibly larger than 1.

[00268] It may be desirable to keep both the electric and magnetic fields away from loss inducing objects. As described above, one way to shape the fields in such a manner is to use high-conductivity surfaces to either completely or partially enclose or cover the loss inducing objects. A layer of magnetically permeable material, also referred to as magnetic material, (any material or meta-material having a non-trivial magnetic permeability), may be placed on or around the high-conductivity surfaces. The additional layer of magnetic material may present a lower reluctance path (compared to free space) for the deflected magnetic field to follow and may partially shield the electric conductor underneath it from the incident magnetic flux. This arrangement may reduce the losses due to induced currents in the high-conductivity surface. Under some circumstances the lower reluctance path presented by the magnetic material may improve the perturbed *Q* of the structure.

[00269] Fig. 26a shows an axially symmetric FEM simulation of a thin conducting 2604 (copper) disk (20 cm in diameter, 2 cm in height) exposed to an initially uniform, externally applied magnetic field (gray flux lines) along the z-axis. The axis of symmetry is at r=0. The magnetic streamlines shown originate at $z=-\infty$, where they are spaced from r=3 cm to r=10 cm in intervals of 1 cm. The axes scales are in meters. Imagine, for example, that this conducing cylinder encloses loss-inducing objects within an area circumscribed by a magnetic resonator in a wireless energy transfer system such as shown in Fig. 19.

[00270] This high-conductivity enclosure may increase the perturbing *Q* of the lossy objects and therefore the overall perturbed *Q* of the system, but the perturbed *Q* may still be less than the unperturbed *Q* because of induced losses in the conducting surface and changes to the profile of the electromagnetic fields. Decreases in the perturbed *Q* associated with the high-conductivity enclosure may be at least partially recovered by including a layer of magnetic material along the outer surface or surfaces of the high-conductivity enclosure. Fig. 26b shows an axially symmetric FEM simulation of the thin conducting 2604A (copper) disk (20 cm in diameter, 2 cm in height) from Fig. 26a, but with an additional layer of magnetic material placed directly on the outer surface of the high-conductivity enclosure. Note that the presence of the magnetic material may provide a lower reluctance path for the magnetic field, thereby at least partially shielding the underlying conductor and reducing losses due to induced eddy currents in the conductor.

[00271] Fig. 27 depicts a variation (in axi-symmetric view) to the system shown in Fig. 26 where not all of the lossy material 2708 may be covered by a high-conductivity surface 2706. In certain circumstances it may be useful to cover only one side of a material or object, such as due to considerations of cost, weight, assembly complications, air flow, visual access, physical access, and the like. In the exemplary arrangement shown in Fig. 27, only one surface of the lossy material 2708 is covered and the resonator inductor loop is placed on the opposite side of the high-conductivity surface.

[00272] Mathematical models were used to simulate a high-conductivity enclosure made of copper and shaped like a 20 cm diameter by 2 cm high cylindrical disk placed within an area circumscribed by a magnetic resonator whose inductive element was a single-turn wire loop with loop radius r=11 cm and wire radius a= 1 mm. Simulations for an applied 6.78 MHz electromagnetic field suggest that the perturbing quality factor of this high-conductivity enclosure, $\delta Q_{(enclosure)}$, is 1,870. When the high-conductivity enclosure was modified to include a 0.25 cm-thick layer of magnetic material with real relative permeability, $\mu_r' = 40$, and imaginary relative permeability, $\mu_r'' = 10^{-2}$, simulations suggest the perturbing quality factor is increased to $\delta Q_{(enclosure+magnetic\ material)}$=5,060.

[00273] The improvement in performance due to the addition of thin layers of magnetic material 2702 may be even more dramatic if the high-conductivity enclosure fills a larger portion of the area circumscribed by the resonator's loop inductor 2704. In the example above, if the radius of the inductor loop 2704 is reduced so that it is only 3 mm away from the surface of the high-conductivity enclosure, the perturbing quality factor may be improved from 670 (conducting enclosure only) to 2,730 (conducting enclosure with a thin layer of magnetic material) by the addition of a thin layer of magnetic material 2702around the outside of the enclosure.

[00274] The resonator structure may be designed to have highly confined electric fields, using shielding, or distributed capacitors, for example, which may yield high, even when the resonator is very close to materials that would typically induce loss.

[00275] **<u>Coupled Electromagnetic Resonators</u>**

[00276] The efficiency of energy transfer between two resonators may be determined by the strong-coupling figure-of-merit, $U = \kappa/\sqrt{\Gamma_s\Gamma_d} = \left(2\kappa/\sqrt{\omega_s\omega_d}\right)\sqrt{Q_sQ_d}$. In magnetic resonator implementations the coupling factor between the two resonators may be related to the inductance of the inductive elements in each of the resonators, L_1 and L_2, and the mutual inductance, M, between them by $\kappa_{12} = \omega M / 2\sqrt{L_1 L_2}$. Note that this expression assumes there is negligible coupling through electric-dipole coupling. For capacitively-loaded inductor loop resonators where the inductor loops are formed by circular conducting loops with N turns, separated by a distance D, and oriented as shown in Fig. 1(b), the mutual inductance is $M = \pi / 4 \cdot \mu_o N_1 N_2 (x_1 x_2)^2 / D^3$ where x_1, N_1 and x_2, N_2 are the characteristic size and number of turns of the conductor loop of the first and second resonators respectively. Note that this is a quasi-static result, and so assumes that the resonator's size is much smaller than the wavelength and the resonators' distance is much smaller than the wavelength, but also that their distance is at least a few times their size. For these circular resonators operated in the quasi-static limit and at mid-range distances, as described above, $k = 2\kappa / \sqrt{\omega_1 \omega_2} \sim \left(\sqrt{x_1 x_2} / D\right)^3$. Strong coupling (a large U) between resonators at mid-range distances may be established when the quality factors of the resonators are large enough to compensate for the small k at mid-range distances

[00277] For electromagnetic resonators, if the two resonators include conducting parts, the coupling mechanism may be that currents are induced on one resonator due to electric and magnetic fields generated from the other. The coupling factor may be proportional to the flux of the magnetic field produced from the high-Q inductive element in one resonator crossing a closed area of the high-Q inductive element of the second resonator.

[00278] **<u>Coupled Electromagnetic Resonators with Reduced Interactions</u>**

[00279] As described earlier, a high-conductivity material surface may be used to shape resonator fields such that they avoid lossy objects, *p*, in the vicinity of a resonator, thereby reducing the overall extraneous losses and maintaining a high Q-insensitivity $\Theta_{(p\,+\,cond.\,surface)}$ of the resonator. However, such a surface may also lead to a perturbed coupling factor, $\mathrm{k}_{(\mathrm{p\,+\,cond.\,surface})}$, between resonators that is smaller than the perturbed coupling factor, $k_{(p)}$ and depends on the size, position, and orientation of the high-conductivity material relative to the resonators. For example, if high-conductivity materials are placed in the plane and within the area circumscribed by the inductive element of at least one of the magnetic resonators in a wireless energy transfer system, some of the magnetic flux through the area of the resonator, mediating the coupling, may be blocked and *k* may be reduced.

[00280] Consider again the example of Fig. 19. In the absence of the high-conductivity disk enclosure, a certain amount of the external magnetic flux may cross the circumscribed area of the loop. In the presence of the high-conductivity disk enclosure, some of this magnetic flux may be deflected or blocked and may no longer cross the area of the loop, thus leading to a smaller perturbed coupling factor $k_{12(p\ +\ cond.\ surfaces)}$. However, because the deflected magnetic-field lines may follow the edges of the high-conductivity surfaces closely, the reduction in the flux through the loop circumscribing the disk may be less than the ratio of the areas of the face of the disk to the area of the loop.

[00281] One may use high-conductivity material structures, either alone, or combined with magnetic materials to optimize perturbed quality factors, perturbed coupling factors, or perturbed efficiencies.

[00282] Consider the example of Fig. 21. Let the lossy object have a size equal to the size of the capacitively-loaded inductor loop resonator, thus filling its area A 2102. A high-conductivity surface 1802 may be placed under the lossy object 1804. Let this be resonator 1 in a system of two coupled resonators 1 and 2, and let us consider how $U_{12(object\ +\ cond.\ surface)}$ scales compared to U_{12} as the area A_s 2104 of the conducting surface increases. Without the conducting surface 1802 below the lossy object 1804, the k-insensitivity, $\beta_{12(object)}$, may be approximately one, but the Q-insensitivity, $\Theta_{1(object)}$, may be small, so the U-insensitivity $\Xi_{12(object)}$ may be small.

[00283] Where the high-conductivity surface below the lossy object covers the entire area of the inductor loop resonator (A_s=A), $k_{12(object\ +\ cond.\ surface)}$ may approach zero, because little flux is allowed to cross the inductor loop, so $U_{12(object\ +\ cond.\ surface)}$ may approach zero. For intermediate sizes of the high-conductivity surface, the suppression of extrinsic losses and the associated Q-insensitivity, $\Theta_{1(object\ +\ cond.\ surface)}$, may be large enough compared to $\Theta_{1(object)}$, while the reduction in coupling may not be significant and the associated *k*-insensitivity, $\beta_{12(object\ +\ cond.\ surface)}$, may be not much smaller than $\beta_{12(object)}$, so that the overall $U_{12(object\ +\ cond.\ surface)}$ may be increased compared to $U_{12(object)}$. The optimal degree of avoiding of extraneous lossy objects via high-conductivity surfaces in a system of wireless energy transfer may depend on the details of the system configuration and the application.

[00284] We describe using high-conductivity materials to either completely or partially enclose or cover loss inducing objects in the vicinity of high-Q resonators as one potential method to achieve high perturbed *Q*'s for a system. However, using a good conductor alone to cover the objects may reduce the coupling of the resonators as described above, thereby reducing the efficiency of wireless power transfer. As the area of the conducting surface approaches the area of the magnetic resonator, for example, the perturbed coupling factor, $k_{(p)}$, may approach zero, making the use of the conducting surface incompatible with efficient wireless power transfer.

[00285] One approach to addressing the aforementioned problem is to place a layer of magnetic material around the high-conductivity materials because the additional layer of permeable material may present a lower reluctance path (compared to free space) for the deflected magnetic field to follow and may partially shield the electric conductor underneath it from incident magnetic flux. Under some circumstances the lower reluctance path presented by the magnetic material may improve the electromagnetic coupling of the resonator to other resonators. Decreases in the perturbed coupling factor associated with using conducting materials to tailor resonator fields so that they avoid lossy objects in and around high-Q magnetic resonators may be at least partially recovered by including a layer of magnetic material along the outer surface or surfaces of the conducting materials. The magnetic materials may increase the perturbed coupling factor relative to its initial unperturbed value.

[00286] Note that the simulation results in Fig. 26 show that an incident magnetic field may be deflected less by a layered magnetic material and conducting structure than by a conducting structure alone. If a magnetic resonator loop with a radius only slightly larger than that of the disks shown in Figs. 26(a) and 26(b) circumscribed the disks, it is clear that more flux lines would be captured in the case illustrated in Fig. 26(b) than in Fig. 26(a), and therefore $k_{(disk)}$ would be larger for the case illustrated in Fig. 26(b). Therefore, including a layer of magnetic material on the conducting material may improve the overall system performance. System analyses may be performed to determine whether these materials should be partially, totally, or minimally integrated into the resonator.

[00287] As described above, Fig. 27 depicts a layered conductor 2706 and magnetic material 2702 structure that may be appropriate for use when not all of a lossy material 2708 may be covered by a conductor and/or magnetic material structure. It was shown earlier that for a copper conductor disk with a 20 cm diameter and a 2 cm height, circumscribed by a resonator with an inductor loop radius of 11 cm and a wire radius a=1 mm, the calculated perturbing Q for the copper cylinder was 1,870. If the resonator and the conducting disk shell are placed in a uniform magnetic field (aligned along the axis of symmetry of the inductor loop), we calculate that the copper conductor has an associated coupling factor insensitivity of 0.34. For comparison, we model the same arrangement but include a 0.25 cm-thick layer of magnetic material with a real relative permeability, $\mu_r' = 40$, and an imaginary relative permeability, $\mu_r'' = 10^{-2}$. Using the same model and parameters described above, we find that the coupling factor insensitivity is improved to 0.64 by the addition of the magnetic material to the surface of the conductor.

[00288] Magnetic materials may be placed within the area circumscribed by the magnetic resonator to increase the coupling in wireless energy transfer systems. Consider a solid sphere of a magnetic material with relative permeability, μ_r, placed in an initially uniform magnetic field. In this example, the lower reluctance path offered by the magnetic material may cause the magnetic field to concentrate in the volume of the sphere. We find that the magnetic flux through the area circumscribed by the equator of the sphere is enhanced by a factor of $3\mu_r/(\mu_r + 2)$, by the addition of the magnetic material. If $\mu_r >> 1$, this enhancement factor may be close to 3.

[00289] One can also show that the dipole moment of a system comprising the magnetic sphere circumscribed by the inductive element in a magnetic resonator would have its magnetic dipole enhanced by the same factor. Thus, the magnetic sphere with high permeability practically triples the dipole magnetic coupling of the resonator. It is possible to keep most of this increase in coupling if we use a spherical shell of magnetic material with inner radius *a,* and outer radius *b,* even if this shell is on top of block or enclosure made from highly conducting materials. In this case, the enhancement in the flux through the equator is

$$\frac{3\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)}{\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)+2\left(1+\frac{1}{2}\left(\frac{a}{b}\right)^3\right)}.$$

For μ_r=1,000 and *(a/b)*=0.99, this enhancement factor is still 2.73, so it possible to significantly improve the coupling even with thin layers of magnetic material.

[00290] As described above, structures containing magnetic materials may be used to realize magnetic resonators. Fig. 16(a) shows a 3 dimensional model of a copper and magnetic material structure 1600 driven by a square loop of current around the choke point at its center. Fig. 16(b) shows the interaction, indicated by magnetic field streamlines , between two identical structures 1600A-B with the same properties as the one shown in Fig. 16(a). Because of symmetry, and to reduce computational complexity, only one half of the system is modeled. If we fix the relative orientation between the two objects and vary their center-to-center distance (the image shown is at a relative separation of 50 cm), we find that, at 300 kHz, the coupling efficiency varies from 87% to 55% as the separation between the structures varies from 30 cm to 60 cm. Each of the example structures shown 1600 A-B includes two 20 cm x 8 cm x 2cm parallelepipeds made of copper joined by a 4 cm x 4 cm x 2 cm block of magnetic material and entirely covered with a 2 mm layer of the same magnetic material (assumed to have μ_r=1,400+j5). Resistive losses in the driving loop are ignored. Each structure has a calculated *Q* of 815.

[00291] ELECTROMAGNETIC RESONATORS AND IMPEDANCE MATCHING

[00292] Impedance Matching Architectures for Low-Loss Inductive Elements

[00293] For purposes of the present discussion, an inductive element may be any coil or loop structure (the 'loop') of any conducting material, with or without a (gapped or ungapped) core made of magnetic material, which may also be coupled inductively or in any other contactless way to other systems. The element is inductive because its impedance, including both the impedance of the loop and the so-called 'reflected' impedances of any potentially coupled systems, has positive reactance, X, and resistance, *R*.

[00294] Consider an external circuit, such as a driving circuit or a driven load or a transmission line, to which an inductive element may be connected. The external circuit (e.g. a driving circuit) may be delivering power to the inductive element and the inductive element may be delivering power to the external circuit (e.g. a driven load). The efficiency and amount of power delivered between the inductive element and the external circuit at a desired frequency may depend on the impedance of the inductive element relative to the properties of the external circuit. Impedance-matching networks and external circuit control techniques may be used to regulate the power delivery between the external circuit and the inductive element, at a desired frequency, *f*.

[00295] The external circuit may be a driving circuit configured to form a amplifier of class A, B, C, D, DE, E, F and the like, and may deliver power at maximum efficiency (namely with minimum losses within the driving circuit) when it is driving a resonant network with specific impedance Z_o^*, where Z_o may be complex and * denotes complex conjugation. The external circuit may be a driven load configured to form a rectifier of class A, B, C, D, DE, E, F and the like, and may receive power at maximum efficiency (namely with minimum losses within the driven load) when it is driven by a resonant network with specific impedance Z_o^*, where Z_o may be complex. The external circuit may be a transmission line with characteristic impedance, Z_o, and may exchange power at maximum efficiency (namely with zero reflections) when connected to an impedance Z_o^*. We will call the characteristic impedance Z_o of an external circuit the complex conjugate of the impedance that may be connected to it for power exchange at maximum efficiency.

[00296] Typically the impedance of an inductive element, $R+jX$, may be much different from Z_o^*. For example, if the inductive element has low loss (a high X/R), its resistance, R, may be much lower than the real part of the characteristic impedance, Z_0, of the external circuit. Furthermore, an inductive element by itself may not be a resonant network. An impedance-matching network connected to an inductive element may typically create a resonant network, whose impedance may be regulated.

[00297] Therefore, an impedance-matching network may be designed to maximize the efficiency of the power delivered between the external circuit and the inductive element (including the reflected impedances of any coupled systems). The efficiency of delivered power may be maximized by matching the impedance of the combination of an impedance-matching network and an inductive element to the characteristic impedance of an external circuit (or transmission line) at the desired frequency.

[00298] An impedance-matching network may be designed to deliver a specified amount of power between the external circuit and the inductive element (including the reflected impedances of any coupled systems). The delivered power may be determined by adjusting the complex ratio of the impedance of the combination of the impedance-matching network and the inductive element to the impedance of the external circuit (or transmission line) at the desired frequency.

[00299] Impedance-matching networks connected to inductive elements may create magnetic resonators. For some applications, such as wireless power transmission using strongly-coupled magnetic resonators, a high Q may be desired for the resonators. Therefore, the inductive element may be chosen to have low losses (high X/R).

[00300] Since the matching circuit may typically include additional sources of loss inside the resonator, the components of the matching circuit may also be chosen to have low losses. Furthermore, in high-power applications and/or due to the high resonator Q, large currents may run in parts of the resonator circuit and large voltages may be present across some circuit elements within the resonator. Such currents and voltages may exceed the specified tolerances for particular circuit elements and may be too high for particular components to withstand. In some cases, it may be difficult to find or implement components, such as tunable capacitors for example, with size, cost and performance (loss and current/voltage-rating) specifications sufficient to realize high-Q and high-power resonator designs for certain applications. We disclose matching circuit designs, methods, implementations and techniques that may preserve the high Q for magnetic resonators, while reducing the component requirements for low loss and/or high current/voltage-rating.

[00301] Matching-circuit topologies may be designed that minimize the loss and current-rating requirements on some of the elements of the matching circuit. The topology of a circuit matching a low-loss inductive element to an impedance, Z_0, may be chosen so that some of its components lie outside the associated high-Q resonator by being in series with the external circuit. The requirements for low series loss or high current-ratings for these components may be reduced. Relieving the low series loss and/or high-current-rating requirement on a circuit element may be particularly useful when the element needs to be variable and/or to have a large voltage-rating and/or low parallel loss.

[00302] Matching-circuit topologies may be designed that minimize the voltage rating requirements on some of the elements of the matching circuit. The topology of a circuit matching a low-loss inductive element to an impedance, Z_0, may be chosen so that some of its components lie outside the associated high-Q resonator by being in parallel with Z_0. The requirements for low parallel loss or high voltage-rating for these components may be reduced. Relieving the low parallel loss and/or high-voltage requirement on a circuit element may be particularly useful when the element needs to be variable and/or to have a large current-rating and/or low series loss.

[00303] The topology of the circuit matching a low-loss inductive element to an external characteristic impedance, Z_0, may be chosen so that the field pattern of the associated resonant mode and thus its high Q are preserved upon coupling of the resonator to the external impedance. Otherwise inefficient coupling to the desired resonant mode may occur (potentially due to coupling to other undesired resonant modes), resulting in an effective lowering of the resonator Q.

[00304] For applications where the low-loss inductive element or the external circuit, may exhibit variations, the matching circuit may need to be adjusted dynamically to match the inductive element to the external circuit impedance, Z_0, at the desired frequency, f. Since there may typically be two tuning objectives, matching or controlling both the real and imaginary part of the impedance level, Z_0, at the desired frequency, f, there may be two variable elements in the matching circuit. For inductive elements, the matching circuit may need to include at least one variable capacitive element.

[00305] A low-loss inductive element may be matched by topologies using two variable capacitors, or two networks of variable capacitors. A variable capacitor may, for example, be a tunable butterfly-type capacitor having, e.g., a center terminal for connection to a ground or other lead of a power source or load, and at least one other terminal across which a capacitance of the tunable butterfly-type capacitor can be varied or tuned, or any other capacitor having a user-configurable, variable capacitance.

[00306] A low-loss inductive element may be matched by topologies using one, or a network of, variable capacitor(s) and one, or a network of, variable inductor(s).

[00307] A low-loss inductive element may be matched by topologies using one, or a network of, variable capacitor(s) and one, or a network of, variable mutual inductance(s), which transformer-couple the inductive element either to an external circuit or to other systems.

[00308] In some cases, it may be difficult to find or implement tunable lumped elements with size, cost and performance specifications sufficient to realize high-Q, high-power, and potentially high-speed, tunable resonator designs. The topology of the circuit matching a variable inductive element to an external circuit may be designed so that some of the variability is assigned to the external circuit by varying the frequency, amplitude, phase, waveform, duty cycle, and the like, of the drive signals applied to transistors, diodes, switches and the like, in the external circuit.

[00309] The variations in resistance, R, and inductance, L, of an inductive element at the resonant frequency may be only partially compensated or not compensated at all. Adequate system performance may thus be preserved by tolerances designed into other system components or specifications. Partial adjustments, realized using fewer tunable components or less capable tunable components, may be sufficient.

[00310] Matching-circuit architectures may be designed that achieve the desired variability of the impedance matching circuit under high-power conditions, while minimizing the voltage/current rating requirements on its tunable elements and achieving a finer (i.e. more precise, with higher resolution) overall tunability. The topology of the circuit matching a variable inductive element to an impedance, Z_0, may include appropriate combinations and placements of fixed and variable elements, so that the voltage/current requirements for the variable components may be reduced and the desired tuning range may be covered with finer tuning resolution. The voltage/current requirements may be reduced on components that are not variable.

[00311] The disclosed impedance matching architectures and techniques may be used to achieve the following:

- To maximize the power delivered to, or to minimize impedance mismatches between, the source low-loss inductive elements (and any other systems wirelessly coupled to them) from the power driving generators.
- To maximize the power delivered from, or to minimize impedance mismatches between, the device low-loss inductive elements (and any other systems wirelessly coupled to them) to the power driven loads.
- To deliver a controlled amount of power to, or to achieve a certain impedance relationship between, the source low-loss inductive elements (and any other systems wirelessly coupled to them) from the power driving generators.
- To deliver a controlled amount of power from, or to achieve a certain impedance relationship between, the device low-loss inductive elements (and any other systems wirelessly coupled to them) to the power driven loads.

[00312] TOPOLOGIES FOR PRESERVATION OF MODE PROFILE (HIGH-Q)

[00313] The resonator structure may be designed to be connected to the generator or the load wirelessly (indirectly) or with a hard-wired connection (directly).

[00314] Consider a general indirectly coupled matching topology such as that shown by the block diagram in Fig. 28(a). There, an inductive element 2802 , labeled as (R,L) and represented by the circuit symbol for an inductor, may be any of the inductive elements discussed in this disclosure or in the references provided herein, and where an impedance-matching circuit 2402 includes or consists of parts A and B. B may be the part of the matching circuit that connects the impedance 2804 , Z_0, to the rest of the circuit (the combination of A and the inductive element (A+(R,L)) via a wireless connection (an inductive or capacitive coupling mechanism).

[00315] The combination of A and the inductive element 2802 may form a resonator 102, which in isolation may support a high-Q resonator electromagnetic mode, with an associated current and charge distribution. The lack of a wired connection between the external circuit, Z_0 and B, and the resonator, A + (R,L), may ensure that the high-Q resonator electromagnetic mode and its current/charge distributions may take the form of its intrinsic (in-isolation) profile, so long as the degree of wireless coupling is not too large. That is, the electromagnetic mode, current/charge distributions, and thus the high-Q of the resonator may be automatically maintained using an indirectly coupled matching topology.

[00316] This matching topology may be referred to as indirectly coupled, or transformer-coupled, or inductively-coupled, in the case where inductive coupling is used between the external circuit and the inductor loop. This type of coupling scenario was used to couple the power supply to the source resonator and the device resonator to the light bulb in the demonstration of wireless energy transfer over mid-range distances described in the referenced *Science* article.

[00317] Next consider examples in which the inductive element may include the inductive element and any indirectly coupled systems. In this case, as disclosed above, and again because of the lack of a wired connection between the external circuit or the coupled systems and the resonator, the coupled systems may not, with good approximation for not-too-large degree of indirect coupling, affect the resonator electromagnetic mode profile and the current/charge distributions of the resonator. Therefore, an indirectly-coupled matching circuit may work equally well for any general inductive element as part of a resonator as well as for inductive elements wirelessly-coupled to other systems, as defined herein. Throughout this disclosure, the matching topologies we disclose refer to matching topologies for a general inductive element of this type, that is, where any additional systems may be indirectly coupled to the low-loss inductive element, and it is to be understood that those additional systems do not greatly affect the resonator electromagnetic mode profile and the current/charge distributions of the resonator.

[00318] Based on the argument above, in a wireless power transmission system of any number of coupled source resonators, device resonators and intermediate resonators the wireless magnetic (inductive) coupling between resonators does not affect the electromagnetic mode profile and the current/charge distributions of each one of the resonators. Therefore, when these resonators have a high (unloaded and unperturbed) Q, their (unloaded and unperturbed) Q may be preserved in the presence of the wireless coupling. (Note that the loaded Q of a resonator may be reduced in the presence of wireless coupling to another resonator, but we may be interested in preserving the unloaded Q, which relates only to loss mechanisms and not to coupling/loading mechanisms.)

[00319] Consider a matching topology such as is shown in Fig. 28(b). The capacitors shown in Fig. 28(b) may represent capacitor circuits or networks. The capacitors shown may be used to form the resonator 102 and to adjust the frequency and/or impedance of the source and device resonators. This resonator 102 may be directly coupled to an impedance, Z_0, using the ports labeled “terminal connections” 2808. Fig. 28(c) shows a generalized directly coupled matching topology, where the impedance-matching circuit 2602 includes or consists of parts A, B and C. Here, circuit elements in A, B and C may be considered part of the resonator 102 as well as part of the impedance matching 2402 (and frequency tuning) topology. B and C may be the parts of the matching circuit 2402 that connect the impedance Z_0 2804 (or the network terminals) to the rest of the circuit (A and the inductive element) via a single wire connection each. Note that B and C could be empty (short-circuits). If we disconnect or open circuit parts B and C (namely those single wire connections), then, the combination of A and the inductive element (R,L) may form the resonator.

[00320] The high-Q resonator electromagnetic mode may be such that the profile of the voltage distribution along the inductive element has nodes, namely positions where the voltage is zero. One node may be approximately at the center of the length of the inductive element, such as the center of the conductor used to form the inductive element, (with or without magnetic materials) and at least one other node may be within A. The voltage distribution may be approximately anti-symmetric along the inductive element with respect to its voltage node. A high Q may be maintained by designing the matching topology (A, B, C) and/or the terminal voltages (V1, V2) so that this high-Q resonator electromagnetic mode distribution may be approximately preserved on the inductive element. This high-Q resonator electromagnetic mode distribution may be approximately preserved on the inductive element by preserving the voltage node (approximately at the center) of the inductive element. Examples that achieve these design goals are provided herein.

[00321] A, B, and C may be arbitrary (namely not having any special symmetry), and V1 and V2 may be chosen so that the voltage across the inductive element is symmetric (voltage node at the center inductive). These results may be achieved using simple matching circuits but potentially complicated terminal voltages, because a topology-dependent common-mode signal (V1+V2)/2 may be required on both terminals.

[00322] Consider an 'axis' that connects all the voltage nodes of the resonator, where again one node is approximately at the center of the length of the inductive element and the others within A. (Note that the 'axis' is really a set of points (the voltage nodes) within the electric-circuit topology and may not necessarily correspond to a linear axis of the actual physical structure. The 'axis' may align with a physical axis in cases where the physical structure has symmetry.) Two points of the resonator are electrically symmetric with respect to the 'axis', if the impedances seen between each of the two points and a point on the 'axis', namely a voltage-node point of the resonator, are the same.

[00323] B and C may be the same (C=B), and the two terminals may be connected to any two points of the resonator (A + (R,L)) that are electrically symmetric with respect to the 'axis' defined above and driven with opposite voltages (V2=-V1) as shown in Fig. 28(d). The two electrically symmetric points of the resonator 102 may be two electrically symmetric points on the inductor loop. The two electrically symmetric points of the resonator may be two electrically symmetric points inside A. If the two electrically symmetric points, (to which each of the equal parts B and C is connected), are inside A, A may need to be designed so that these electrically-symmetric points are accessible as connection points within the circuit. This topology may be referred to as a 'balanced drive' topology. These balanced-drive examples may have the advantage that any common-mode signal that may be present on the ground line, due to perturbations at the external circuitry or the power network, for example, may be automatically rejected (and may not reach the resonator). In some balanced-drive examples, this topology may require more components than other topologies.

[00324] In other examples, C may be chosen to be a short-circuit and the corresponding terminal to be connected to ground (V=0) and to any point on the electric-symmetry (zero-voltage) 'axis' of the resonator, and B to be connected to any other point of the resonator not on the electric-symmetry 'axis', as shown in Fig. 28(e). The ground-connected point on the electric-symmetry 'axis' may be the voltage node on the inductive element, approximately at the center of its conductor length. The ground-connected point on the electric-symmetry 'axis' may be inside the circuit A. Where the ground-connected point on the electric-symmetry 'axis' is inside A, A may need to be designed to include one such point on the electrical-symmetric 'axis' that is electrically accessible, namely where connection is possible.

[00325] This topology may be referred to as an 'unbalanced drive' topology. The approximately anti-symmetric voltage distribution of the electromagnetic mode along the inductive element may be approximately preserved, even though the resonator may not be driven exactly symmetrically. The reason is that the high Q and the large associated R-vs.-Z_0 mismatch necessitate that a small current may run through B and ground, compared to the much larger current that may flow inside the resonator, (A+(R,L)). In this scenario, the perturbation on the resonator mode may be weak and the location of the voltage node may stay at approximately the center location of the inductive element. These unbalanced-drive examples may have the advantage that they may be achieved using simple matching circuits and that there is no restriction on the driving voltage at the V1 terminal. In some unbalanced-drive examples, additional designs may be required to reduce common-mode signals that may appear at the ground terminal.

[00326] The directly-coupled impedance-matching circuit, generally including or consisting of parts A, B and C, as shown in Fig. 28(c), may be designed so that the wires and components of the circuit do not perturb the electric and magnetic field profiles of the electromagnetic mode of the inductive element and/or the resonator and thus preserve the high resonator Q. The wires and metallic components of the circuit may be oriented to be perpendicular to the electric field lines of the electromagnetic mode. The wires and components of the circuit may be placed in regions where the electric and magnetic field of the electromagnetic mode are weak.

[00327] TOPOLOGIES FOR ALLEVIATING LOW-SERIES-LOSS AND HIGH-CURRENT-RATING REQUIREMENTS ON ELEMENTS

[00328] If the matching circuit used to match a small resistance, R, of a low-loss inductive element to a larger characteristic impedance, Z_0, of an external circuit may be considered lossless, then $I_{Z_o}^2 Z_o = I_R^2 R \leftrightarrow I_{Z_o} / I_R = \sqrt{R / Z_o}$ and the current flowing through the terminals is much smaller than the current flowing through the inductive element. Therefore, elements connected immediately in series with the terminals (such as in directly-coupled B, C (Fig. 28(c))) may not carry high currents. Then, even if the matching circuit has lossy elements, the resistive loss present in the elements in series with the terminals may not result in a significant reduction in the high-*Q* of the resonator. That is, resistive loss in those series elements may not significantly reduce the efficiency of power transmission from Z_0 to the inductive element or vice versa. Therefore, strict requirements for low-series-loss and/or high current-ratings may not be necessary for these components. In general, such reduced requirements may lead to a wider selection of components that may be designed into the high-*Q* and/or high-power impedance matching and resonator topologies. These reduced requirements may be especially helpful in expanding the variety of variable and/or high voltage and/or low-parallel-loss components that may be used in these high-Q and/or high-power impedance-matching circuits.

[00329] TOPOLOGIES FOR ALLEVIATING LOW-PARALLEL-LOSS AND HIGH-VOLTAGE-RATING REQUIREMENTS ON ELEMENTS

[00330] If, as above, the matching circuit used to match a small resistance, *R*, of a low-loss inductive element to a larger characteristic impedance, Z_0, of an external circuit is lossless, then using the previous analysis,

$$|V_{Z_o} / V_{load}| = |I_{Z_o} Z_o / I_R (R + jX)| \approx \sqrt{R / Z_o} \cdot Z_o / X = \sqrt{Z_o / R} / \left(X / R \right),$$

and, for a low-loss (high-*X/R*) inductive element, the voltage across the terminals may be typically much smaller than the voltage across the inductive element. Therefore, elements connected immediately in parallel to the terminals may not need to withstand high voltages. Then, even if the matching circuit has lossy elements, the resistive loss present in the elements in parallel with the terminals may not result in a significant reduction in the high-*Q* of the resonator. That is, resistive loss in those parallel elements may not significantly reduce the efficiency of power transmission from Z_0 to the inductive element or vice versa. Therefore, strict requirements for low-parallel-loss and/or high voltage-ratings may not be necessary for these components. In general, such reduced requirements may lead to a wider selection of components that may be designed into the high-*Q* and/or high-power impedance matching and resonator topologies. These reduced requirements may be especially helpful in expanding the variety of variable and/or high current and/or low-series-loss components that may be used in these high-Q and/or high-power impedance-matching and resonator circuits.

[00331] Note that the design principles above may reduce currents and voltages on various elements differently, as they variously suggest the use of networks in series with Z_0 (such as directly-coupled B, C) or the use of networks in parallel with Z_0. The preferred topology for a given application may depend on the availability of low-series-loss/high-current-rating or low-parallel-loss/high-voltage-rating elements.

[00332] COMBINATIONS OF FIXED AND VARIABLE ELEMENTS FOR ACHIEVING FINE TUNABILITY AND ALLEVIATING HIGH-RATING REQUIREMENTS ON VARIABLE ELEMENTS

[00333] **Circuit topologies**

[00334] Variable circuit elements with satisfactory low-loss and high-voltage or current ratings may be difficult or expensive to obtain. In this disclosure, we describe impedance-matching topologies that may incorporate combinations of fixed and variable elements, such that large voltages or currents may be assigned to fixed elements in the circuit, which may be more likely to have adequate voltage and current ratings, and alleviating the voltage and current rating requirements on the variable elements in the circuit.

[00335] Variable circuit elements may have tuning ranges larger than those required by a given impedance-matching application and, in those cases, fine tuning resolution may be difficult to obtain using only such large-range elements. In this disclosure, we describe impedance-matching topologies that incorporate combinations of both fixed and variable elements, such that finer tuning resolution may be accomplished with the same variable elements.

[00336] Therefore, topologies using combinations of both fixed and variable elements may bring two kinds of advantages simultaneously: reduced voltage across, or current through, sensitive tuning components in the circuit and finer tuning resolution. Note that the maximum achievable tuning range may be related to the maximum reduction in voltage across, or current through, the tunable components in the circuit designs.

[00337] **Element topologies**

[00338] A single variable circuit-element (as opposed to the network of elements discussed above) may be implemented by a topology using a combination of fixed and variable components, connected in series or in parallel, to achieve a reduction in the rating requirements of the variable components and a finer tuning resolution. This can be demonstrated mathematically by the fact that:

$$\text{If } x_{|total|} = x_{|fixed|} + x_{|\mathrm{var}iable|},$$
$$\text{then } \Delta x_{|total|} / x_{|total|} = \Delta x_{|\mathrm{variable}|} / (x_{|fixed|} + x_{|\mathrm{variable}|}),$$
$$\text{and } X_{\mathrm{variable}} / X_{total} = X_{\mathrm{variable}} / (X_{fixed} + X_{\mathrm{variable}}),$$

where $x_{|\mathrm{subscript}|}$ is any element value (e.g. capacitance, inductance), X is voltage or current, and the "+ sign" denotes the appropriate (series-addition or parallel-addition) combination of elements. Note that the subscript format for $x_{|\mathrm{subscript}|}$, is chosen to easily distinguish it from the radius of the area enclosed by a circular inductive element (e.g. x, x_1, etc.).

[00339] Furthermore, this principle may be used to implement a variable electric element of a certain type (e.g. a capacitance or inductance) by using a variable element of a different type, if the latter is combined appropriately with other fixed elements.

[00340] In conclusion, one may apply a topology optimization algorithm that decides on the required number, placement, type and values of fixed and variable elements with the required tunable range as an optimization constraint and the minimization of the currents and/or voltages on the variable elements as the optimization objective.

[00341] EXAMPLES

[00342] In the following schematics, we show different specific topology implementations for impedance matching to and resonator designs for a low-loss inductive element. In addition, we indicate for each topology: which of the principles described above are used, the equations giving the values of the variable elements that may be used to achieve the matching, and the range of the complex impedances that may be matched (using both inequalities and a Smith-chart description). For these examples, we assume that Z_0 is real, but an extension to a characteristic impedance with a non-zero imaginary part is straightforward, as it implies only a small adjustment in the required values of the components of the matching network. We will use the convention that the subscript, n, on a quantity implies normalization to (division by) Z_0.

[00343] Fig. 29 shows two examples of a transformer-coupled impedance-matching circuit, where the two tunable elements are a capacitor and the mutual inductance between two inductive elements. If we define respectively $X_2=\omega L_2$ for Fig. 29(a) and $X_2=\omega L_2-1/\omega C_2$ for Fig. 29(b), and $X \equiv \omega L$, then the required values of the tunable elements are:

$$\omega C_1 = \frac{1}{X + RX_{2n}}$$
$$\omega M = \sqrt{Z_o R(1 + X_{2n}^2)} .$$

For the topology of Fig. 29(b), an especially straightforward design may be to choose $X_2=0$. In that case, these topologies may match the impedances satisfying the inequalities:

$$R_n > 0 , \; X_n > 0 ,$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 29(c).

[00344] Given a well pre-chosen fixed M, one can also use the above matching topologies with a tunable C_2 instead.

[00345] Fig. 30 shows six examples (a)-(f) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and six examples (h)-(m) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 30(a),(b),(c),(h),(i),(j), a common-mode signal may be required at the two terminals to preserve the voltage node of the resonator at the center of the inductive element and thus the high *Q*. Note that these examples may be described as implementations of the general topology shown in Fig. 28(c). For the symmetric topologies of Figs. 30(d),(e),(f),(k),(l),(m), the two terminals may need to be driven anti-symmetrically (balanced drive) to preserve the voltage node of the resonator at the center of the inductive element and thus the high *Q*. Note that these examples may be described as implementations of the general topology shown in Fig. 28(d). It will be appreciated that a network of capacitors, as used herein, may in general refer to any circuit topology including one or more capacitors, including without limitation any of the circuits specifically disclosed herein using capacitors, or any other equivalent or different circuit structure(s), unless another meaning is explicitly provided or otherwise clear from the context.

[00346] Let us define respectively $Z=R+j\omega L$ for Figs. 30(a),(d),(h),(k), $Z=R+j\omega L+1/j\omega C_3$ for Figs. 30(b),(e),(i),(l), and $Z=(R+j\omega L)||(1/j\omega C_3)$ for Figs. 30(c),(f),(j),(m), where the symbol "||" means "the parallel combination of", and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, for Figs.30(a)-(f) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X - \sqrt{X^2 R_n - R^2(1-R_n)}}{X^2 + R^2},$$

$$\omega C_2 = \frac{R_n \omega C_1}{1 - X\omega C_1 - R_n},$$

and these topologies can match the impedances satisfying the inequalities:

$$R_n \leq 1,\ X_n \geq \sqrt{R_n(1-R_n)}$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 30(g). For Figs.30(h)-(m) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X + \sqrt{X^2 R_n - R^2(1-R_n)}}{X^2 + R^2},$$

$$\omega L_2 = -\frac{1 - X\omega C_1 - R_n}{R_n \omega C_1}.$$

[00347] Fig. 31 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 31(a),(b),(c),(e),(f),(g), the ground terminal is connected between two equal-value capacitors, $2C_1$, (namely on the axis of symmetry of the main resonator) to preserve the voltage node of the resonator at the center of the inductive element and thus the high *Q*. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00348] Let us define respectively $Z=R+j\omega L$ for Figs. 31(a),(e), $Z=R+j\omega L+1/j\omega C_3$ for Figs. 31(b),(f), and $Z=(R+j\omega L)||(1/j\omega C_3)$ for Fig. 31(c),(g), and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, for Figs.31(a)-(c) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X - \frac{1}{2}\sqrt{X^2 R_n - R^2(4 - R_n)}}{X^2 + R^2},$$

$$\omega C_2 = \frac{R_n \omega C_1}{1 - X\omega C_1 - \frac{R_n}{2}},$$

and these topologies can match the impedances satisfying the inequalities:

$$R_n \le 1, \quad X_n \ge \sqrt{\frac{R_n}{1 - R_n}(2 - R_n)}$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 31(d). For Figs.31(e)-(g) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X + \frac{1}{2}\sqrt{X^2 R_n - R^2(4 - R_n)}}{X^2 + R^2},$$

$$\omega L_2 = -\frac{1 - X\omega C_1 - \frac{R_n}{2}}{R_n \omega C_1}.$$

[00349] Fig. 32 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 32(a),(b),(c),(e),(f),(g), the ground terminal may be connected at the center of the inductive element to preserve the voltage node of the resonator at that point and thus the high *Q*. Note that these example may be described as implementations of the general topology shown in Fig. 28(e).

[00350] Let us define respectively Z=R+jωL for Fig. 32(a), Z=R+jωL+1/jωC_3 for Fig. 32(b), and Z=(R+jωL)||(1/jωC_3) for Fig. 32(c), and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, for Figs.32(a)-(c) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X - \sqrt{\dfrac{X^2 R_n - 2R^2(2-R_n)}{4-R_n}}}{X^2+R^2},$$
$$\omega C_2 = \frac{R_n \omega C_1}{1 - X\omega C_1 - \dfrac{R_n}{2} + \dfrac{R_n X \omega C_1}{2(1+k)}},$$

where k is defined by $M' = -kL'$, where L' is the inductance of each half of the inductor loop and M' is the mutual inductance between the two halves, and these topologies can match the impedances satisfying the inequalities:

$$R_n \leq 2, \quad X_n \geq \sqrt{2R_n(2-R_n)}$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 32(d). For Figs.32(e)-(g) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{X + \sqrt{\dfrac{X^2 R_n - 2R^2(2-R_n)}{4-R_n}}}{X^2+R^2},$$

[00351] In the circuits of Figs. 30, 31, 32, the capacitor, C_2, or the inductor, L_2, is (or the two capacitors, $2C_2$, or the two inductors, $L_2/2$, are) in series with the terminals and may not need to have very low series-loss or withstand a large current.

[00352] Fig. 33 shows six examples (a)-(f) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and six examples (h)-(m) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 33(a),(b),(c),(h),(i),(j), a common-mode signal may be required at the two terminals to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(c), where B and C are short-circuits and A is not balanced. For the symmetric topologies of Figs. 33(d),(e),(f),(k),(l),(m), the two terminals may need to be driven anti-symmetrically (balanced drive) to preserve the voltage node of the resonator at the center of the inductive element and thus the high *Q*. Note that these examples may be described as implementations of the general topology shown in Fig. 28(d), where B and C are short-circuits and A is balanced.

[00353] Let us define respectively Z=R+jωL for Figs. 33(a),(d),(h),(k), Z=R+jωL+1/jωC$_3$ for Figs. 33(b),(e),(i),(l), and Z=(R+jωL)||(1/jωC$_3$) for Figs. 33(c),(f),(j),(m), and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, for Figs.33(a)-(f) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{1}{X - Z_o\sqrt{R_n(1-R_n)}},$$

$$\omega C_2 = \frac{1}{Z_o}\sqrt{\frac{1}{R_n} - 1},$$

and these topologies can match the impedances satisfying the inequalities:

$$R_n \le 1, \quad X_n \ge \sqrt{R_n(1-R_n)}$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 33(g). For Figs.35(h)-(m) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{1}{X + Z_o\sqrt{R_n(1-R_n)}},$$

$$\omega L_2 = \frac{Z_o}{\sqrt{\frac{1}{R_n} - 1}}.$$

[00354] Fig. 34 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 34(a),(b),(c),(e),(f),(g), the ground terminal is connected between two equal-value capacitors, 2C$_2$, (namely on the axis of symmetry of the main resonator) to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00355] Let us define respectively Z=R+jωL for Fig. 34(a),(e), Z=R+jωL+1/jωC$_3$ for Fig. 34(b),(f), and Z=(R+jωL)||(1/jωC$_3$) for Fig. 34(c),(g), and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, for Figs.34(a)-(c) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{1}{X - Z_o\sqrt{\frac{1-R_n}{R_n}(2-R_n)}},$$

$$\omega C_2 = \frac{1}{2Z_o}\sqrt{\frac{1}{R_n}-1},$$

and these topologies can match the impedances satisfying the inequalities:

$$R_n \le 1,\ X_n \ge \sqrt{\frac{R_n}{1-R_n}(2-R_n)}$$

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 34(d). For Figs.34(e)-(g) the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{1}{X + Z_o\sqrt{\frac{1-R_n}{R_n}(2-R_n)}},$$

$$\omega L_2 = \frac{2Z_o}{\sqrt{\frac{1}{R_n}-1}}.$$

[00356] Fig. 35 shows three examples of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors. For the topologies of Figs. 35, the ground terminal may be connected at the center of the inductive element to preserve the voltage node of the resonator at that point and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00357] Let us define respectively Z=R+jωL for Fig. 35(a), Z=R+jωL+1/jωC$_3$ for Fig. 35(b), and Z=(R+jωL)||(1/jωC$_3$) for Fig. 35(c), and then $R \equiv \mathrm{Re}\{Z\}$, $X \equiv \mathrm{Im}\{Z\}$. Then, the required values of the tunable elements may be given by:

$$\omega C_1 = \frac{2}{X(1+a) - \sqrt{Z_o R(4-R_n)(1+a^2)}},$$
$$\omega C_2 = \frac{2}{X(1+a) + \sqrt{Z_o R(4-R_n)(1+a^2)}},$$

where $a = \frac{R}{2Z_o - R} \cdot \frac{k}{1+k}$ and k is defined by $M' = -kL'$, where L' is the inductance of each half of the inductive element and M' is the mutual inductance between the two halves. These topologies can match the impedances satisfying the inequalities:

$$R_n \le 2 \,\&\, \frac{2}{\gamma} \le R_n \le 4,$$
$$X_n \ge \sqrt{\frac{R_n(4-R_n)(2-R_n)}{2-\gamma R_n}},$$

where

$$\gamma = \frac{1-6k+k^2}{1+2k+k^2} \le 1$$

which are shown by the area enclosed by the bold lines on the three Smith charts shown in Fig. 35(d) for k=0, Fig. 35(e) for k=0.05, and Fig. 35(f) for k=1. Note that for 0<k<1 there are two disconnected regions of the Smith chart that this topology can match.

[00358] In the circuits of Figs. 33, 34, 35, the capacitor, C$_2$, or the inductor, L$_2$, is (or one of the two capacitors, 2C$_2$, or one of the two inductors, 2L$_2$, are) in parallel with the terminals and thus may not need to have a high voltage-rating. In the case of two capacitors, 2C$_2$, or two inductors, 2L$_2$, both may not need to have a high voltage-rating, since approximately the same current flows through them and thus they experience approximately the same voltage across them.

[00359] For the topologies of Figs. 30-35, where a capacitor, C$_3$, is used, the use of the capacitor, C$_3$, may lead to finer tuning of the frequency and the impedance. For the topologies of

Figs. 30-35, the use of the fixed capacitor, C_3, in series with the inductive element may ensure that a large percentage of the high inductive-element voltage will be across this fixed capacitor, C_3, thus potentially alleviating the voltage rating requirements for the other elements of the impedance matching circuit, some of which may be variable. Whether or not such topologies are preferred depends on the availability, cost and specifications of appropriate fixed and tunable components.

[00360] In all the above examples, a pair of equal-value variable capacitors without a common terminal may be implemented using ganged-type capacitors or groups or arrays of varactors or diodes biased and controlled to tune their values as an ensemble. A pair of equal-value variable capacitors with one common terminal can be implemented using a tunable butterfly-type capacitor or any other tunable or variable capacitor or group or array of varactors or diodes biased and controlled to tune their capacitance values as an ensemble.

[00361] Another criterion which may be considered upon the choice of the impedance matching network is the response of the network to different frequencies than the desired operating frequency. The signals generated in the external circuit, to which the inductive element is coupled, may not be monochromatic at the desired frequency but periodic with the desired frequency, as for example the driving signal of a switching amplifier or the reflected signal of a switching rectifier. In some such cases, it may be desirable to suppress the amount of higher-order harmonics that enter the inductive element (for example, to reduce radiation of these harmonics from this element). Then the choice of impedance matching network may be one that sufficiently suppresses the amount of such harmonics that enters the inductive element.

[00362] The impedance matching network may be such that the impedance seen by the external circuit at frequencies higher than the fundamental harmonic is high, when the external periodic signal is a signal that can be considered to behave as a voltage-source signal (such as the driving signal of a class-D amplifier with a series resonant load), so that little current flows through the inductive element at higher frequencies. Among the topologies of Figs. 30-35, those which use an inductor, L_2, may then be preferable, as this inductor presents a high impedance at high frequencies.

[00363] The impedance matching network may be such that the impedance seen by the external circuit at frequencies higher than the fundamental harmonic is low, when the external periodic signal is a signal that can be considered to behave as a current-source signal, so that little voltage is induced across the inductive element at higher frequencies. Among the topologies of Figs. 30-35, those which use a capacitor, C_2, are then preferable, as this capacitor presents a low impedance at high frequencies.

[00364] Fig. 36 shows four examples of a variable capacitance, using networks of one variable capacitor and the rest fixed capacitors. Using these network topologies, fine tunability of the total capacitance value may be achieved. Furthermore, the topologies of Figs. 36(a),(c),(d), may be used to reduce the voltage across the variable capacitor, since most of the voltage may be assigned across the fixed capacitors.

[00365] Fig. 37 shows two examples of a variable capacitance, using networks of one variable inductor and fixed capacitors. In particular, these networks may provide implementations for a variable reactance, and, at the frequency of interest, values for the variable inductor may be used such that each network corresponds to a net negative variable reactance, which may be effectively a variable capacitance.

[00366] Tunable elements such as tunable capacitors and tunable inductors may be mechanically-tunable, electrically-tunable, thermally-tunable and the like. The tunable elements may be variable capacitors or inductors, varactors, diodes, Schottky diodes, reverse-biased PN diodes, varactor arrays, diode arrays, Schottky diode arrays and the like. The diodes may be Si diodes, GaN diodes, SiC diodes, and the like. GaN and SiC diodes may be particularly attractive for high power applications. The tunable elements may be electrically switched capacitor banks, electrically-switched mechanically-tunable capacitor banks, electrically-switched varactor-array banks, electrically-switched transformer-coupled inductor banks, and the like. The tunable elements may be combinations of the elements listed above.

[00367] As described above, the efficiency of the power transmission between coupled high-Q magnetic resonators may be impacted by how closely matched the resonators are in resonant frequency and how well their impedances are matched to the power supplies and power consumers in the system. Because a variety of external factors including the relative position of extraneous objects or other resonators in the system, or the changing of those relative positions, may alter the resonant frequency and/or input impedance of a high-Q magnetic resonator, tunable impedance networks may be required to maintain sufficient levels of power transmission in various environments or operating scenarios.

[00368] The capacitance values of the capacitors shown may be adjusted to adjust the resonant frequency and/or the impedance of the magnetic resonator. The capacitors may be adjusted electrically, mechanically, thermally, or by any other known methods. They may be adjusted manually or automatically, such as in response to a feedback signal. They may be adjusted to achieve certain power transmission efficiencies or other operating characteristics between the power supply and the power consumer.

[00369] The inductance values of the inductors and inductive elements in the resonator may be adjusted to adjust the frequency and/or impedance of the magnetic resonator. The inductance may be adjusted using coupled circuits that include adjustable components such as tunable capacitors, inductors and switches. The inductance may be adjusted using transformer coupled tuning circuits. The inductance may be adjusted by switching in and out different sections of conductor in the inductive elements and/or using ferro-magnetic tuning and/or mu-tuning, and the like.

[00370] The resonant frequency of the resonators may be adjusted to or may be allowed to change to lower or higher frequencies. The input impedance of the resonator may be adjusted to or may be allowed to change to lower or higher impedance values. The amount of power delivered by the source and/or received by the devices may be adjusted to or may be allowed to change to lower or higher levels of power. The amount of power delivered to the source and/or received by the devices from the device resonator may be adjusted to or may be allowed to change to lower or higher levels of power. The resonator input impedances, resonant frequencies, and power levels may be adjusted depending on the power consumer or consumers in the system and depending on the objects or materials in the vicinity of the resonators. The resonator input impedances, frequencies, and power levels may be adjusted manually or automatically, and may be adjusted in response to feedback or control signals or algorithms.

[00371] Circuit elements may be connected directly to the resonator, that is, by physical electrical contact, for example to the ends of the conductor that forms the inductive element and/or the terminal connectors. The circuit elements may be soldered to, welded to, crimped to, glued to, pinched to, or closely position to the conductor or attached using a variety of electrical components, connectors or connection techniques. The power supplies and the power consumers may be connected to magnetic resonators directly or indirectly or inductively.

Electrical signals may be supplied to, or taken from, the resonators through the terminal connections.

[00372] It is to be understood by one of ordinary skill in the art that in real implementations of the principles described herein, there may be an associated tolerance, or acceptable variation, to the values of real components (capacitors, inductors, resistors and the like) from the values calculated via the herein stated equations, to the values of real signals (voltages, currents and the like) from the values suggested by symmetry or anti-symmetry or otherwise, and to the values of real geometric locations of points (such as the point of connection of the ground terminal close to the center of the inductive element or the 'axis' points and the like) from the locations suggested by symmetry or otherwise.

[00373] **<u>Examples</u>**

[00374] <u>SYSTEM BLOCK DIAGRAMS</u>

[00375] We disclose examples of high-Q resonators for wireless power transmission systems that may wirelessly power or charge devices at mid-range distances. High-Q resonator wireless power transmission systems also may wirelessly power or charge devices with magnetic resonators that are different in size, shape, composition, arrangement, and the like, from any source resonators in the system.

[00376] Fig. 1(a)(b) shows high level diagrams of two exemplary two-resonator systems. These exemplary systems each have a single source resonator 102S or 104S and a single device resonator 102D or 104D. Fig. 38 shows a high level block diagram of a system with a few more features highlighted. The wirelessly powered or charged device 2310 may include or consist of a device resonator 102D, device power and control circuitry 2304, and the like, along with the device 2308 or devices, to which either DC or AC or both AC and DC power is transferred. The energy or power source for a system may include the source power and control circuitry 2302, a source resonator 102S, and the like. The device 2308 or devices that receive power from the device resonator 102D and power and control circuitry 2304 may be any kind of device 2308 or devices as described previously. The device resonator 102D and circuitry 2304 delivers power to the device/devices 2308 that may be used to recharge the battery of the device/devices, power the device/devices directly, or both when in the vicinity of the source resonator 102S.

[00377] The source and device resonators may be separated by many meters or they may be very close to each other or they may be separated by any distance in between. The source and device resonators may be offset from each other laterally or axially. The source and device resonators may be directly aligned (no lateral offset), or they may be offset by meters, or anything in between. The source and device resonators may be oriented so that the surface areas enclosed by their inductive elements are approximately parallel to each other. The source and device resonators may be oriented so that the surface areas enclosed by their inductive elements are approximately perpendicular to each other, or they may be oriented for any relative angle (0 to 360 degrees) between them.

[00378] The source and device resonators may be free standing or they may be enclosed in an enclosure, container, sleeve or housing. These various enclosures may be composed of almost any kind of material. Low loss tangent materials such as Teflon, REXOLITE, styrene, and the like may be preferable for some applications. The source and device resonators may be integrated in the power supplies and power consumers. For example, the source and device resonators may be integrated into keyboards, computer mice, displays, cell phones, etc. so that they are not visible outside these devices. The source and device resonators may be separate from the power supplies and power consumers in the system and may be connected by a standard or custom wires, cables, connectors or plugs.

[00379] The source 102S may be powered from a number of DC or AC voltage, current or power sources including a USB port of a computer. The source 102S may be powered from the electric grid, from a wall plug, from a battery, from a power supply, from an engine, from a solar cell, from a generator, from another source resonator, and the like. The source power and control circuitry 2302 may include circuits and components to isolate the source electronics from the power source, so that any reflected power or signals are not coupled out through the source input terminals. The source power and control circuits 2302 may include power factor correction circuits and may be configured to monitor power usage for monitoring accounting, billing, control, and like functionalities.

[00380] The system may be operated bi-directionally. That is, energy or power that is generated or stored in a device resonator may be fed back to a power source including the electric grid, a battery, any kind of energy storage unit, and the like. The source power and control circuits may include power factor correction circuits and may be configured to monitor power usage for monitoring accounting, billing, control, and like functionalities for bi-directional energy flow. Wireless energy transfer systems may enable or promote vehicle-to-grid (V2G) applications.

[00381] The source and the device may have tuning capabilities that allow adjustment of operating points to compensate for changing environmental conditions, perturbations, and loading conditions that can affect the operation of the source and device resonators and the efficiency of the energy exchange. The tuning capability may also be used to multiplex power delivery to multiple devices, from multiple sources, to multiple systems, to multiple repeaters or relays, and the like. The tuning capability may be manually controlled, or automatically controlled and may be performed continuously, periodically, intermittently or at scheduled times or intervals.

[00382] The device resonator and the device power and control circuitry may be integrated into any portion of the device, such as a battery compartment, or a device cover or sleeve, or on a mother board, for example, and may be integrated alongside standard rechargeable batteries or other energy storage units. The device resonator may include a device field reshaper which may shield any combination of the device resonator elements and the device power and control electronics from the electromagnetic fields used for the power transfer and which may deflect the resonator fields away from the lossy device resonator elements as well as the device power and control electronics. A magnetic material and/or high-conductivity field reshaper may be used to increase the perturbed quality factor Q of the resonator and increase the perturbed coupling factor of the source and device resonators.

[00383] The source resonator and the source power and control circuitry may be integrated into any type of furniture, structure, mat, rug, picture frame (including digital picture frames, electronic frames), plug-in modules, electronic devices, vehicles, and the like. The source resonator may include a source field reshaper which may shield any combination of the source resonator elements and the source power and control electronics from the electromagnetic fields used for the power transfer and which may deflect the resonator fields away from the lossy source resonator elements as well as the source power and control electronics. A magnetic material and/or high-conductivity field reshaper may be used to increase the perturbed quality factor Q of the resonator and increase the perturbed coupling factor of the source and device resonators.

[00384] A block diagram of the subsystems in an example of a wirelessly powered device is shown in Fig. 39. The power and control circuitry may be designed to transform the alternating current power from the device resonator 102D and convert it to stable direct current power suitable for powering or charging a device. The power and control circuitry may be designed to transform an alternating current power at one frequency from the device resonator to alternating current power at a different frequency suitable for powering or charging a device. The power and control circuitry may include or consist of impedance matching circuitry 2402D, rectification circuitry 2404, voltage limiting circuitry (not shown), current limiting circuitry (not shown), AC-to-DC converter 2408 circuitry, DC-to-DC converter 2408 circuitry, DC-to-AC converter 2408 circuitry, AC-to-AC converter 2408 circuitry, battery charge control circuitry (not shown), and the like.

[00385] The impedance-matching 2402D network may be designed to maximize the power delivered between the device resonator 102D and the device power and control circuitry 2304 at the desired frequency. The impedance matching elements may be chosen and connected such that the high-Q of the resonators is preserved. Depending on the operating conditions, the impedance matching circuitry 2402D may be varied or tuned to control the power delivered from the source to the device, from the source to the device resonator, between the device resonator and the device power and control circuitry, and the like. The power, current and voltage signals may be monitored at any point in the device circuitry and feedback algorithms circuits, and techniques, may be used to control components to achieve desired signal levels and system operation. The feedback algorithms may be implemented using analog or digital circuit techniques and the circuits may include a microprocessor, a digital signal processor, a field programmable gate array processor and the like.

[00386] The third block of Fig. 39 shows a rectifier circuit 2404 that may rectify the AC voltage power from the device resonator into a DC voltage. In this configuration, the output of the rectifier 2404 may be the input to a voltage clamp circuit. The voltage clamp circuit (not shown) may limit the maximum voltage at the input to the DC-to-DC converter 2408D or DC-to-AC converter 2408D. In general, it may be desirable to use a DC-to-DC/AC converter with a large input voltage dynamic range so that large variations in device position and operation may be tolerated while adequate power is delivered to the device. For example, the voltage level at the output of the rectifier may fluctuate and reach high levels as the power input and load characteristics of the device change. As the device performs different tasks it may have varying power demands. The changing power demands can cause high voltages at the output of the rectifier as the load characteristics change. Likewise as the device and the device resonator are brought closer and further away from the source, the power delivered to the device resonator may vary and cause changes in the voltage levels at the output of the rectifier. A voltage clamp circuit may prevent the voltage output from the rectifier circuit from exceeding a predetermined value which is within the operating range of the DC-to-DC/AC converter. The voltage clamp circuitry may be used to extend the operating modes and ranges of a wireless energy transfer system.

[00387] The next block of the power and control circuitry of the device is the DC-to-DC converter 2408D that may produce a stable DC output voltage. The DC-to-DC converter may be a boost converter, buck converter, boost-buck converter, single ended primary inductance converter (SEPIC), or any other DC-DC topology that fits the requirements of the particular application. If the device requires AC power, a DC-to-AC converter may be substituted for the DC-to-DC converter, or the DC-to-DC converter may be followed by a DC-to-AC converter. If the device contains a rechargeable battery, the final block of the device power and control circuitry may be a battery charge control unit which may manage the charging and maintenance of the battery in battery powered devices.

[00388] The device power and control circuitry 2304 may contain a processor 2410D, such as a microcontroller, a digital signal processor, a field programmable gate array processor, a microprocessor, or any other type of processor. The processor may be used to read or detect the state or the operating point of the power and control circuitry and the device resonator. The processor may implement algorithms to interpret and adjust the operating point of the circuits, elements, components, subsystems and resonator. The processor may be used to adjust the impedance matching, the resonator, the DC to DC converters, the DC to AC converters, the battery charging unit, the rectifier, and the like of the wirelessly powered device.

[00389] The processor may have wireless or wired data communication links to other devices or sources and may transmit or receive data that can be used to adjust the operating point of the system. Any combination of power, voltage, and current signals at a single, or over a range of frequencies, may be monitored at any point in the device circuitry. These signals may be monitored using analog or digital or combined analog and digital techniques. These monitored signals may be used in feedback loops or may be reported to the user in a variety of known ways or they may be stored and retrieved at later times. These signals may be used to alert a user of system failures, to indicate performance, or to provide audio, visual, vibrational, and the like, feedback to a user of the system.

[00390] Fig. 40 shows components of source power and control circuitry 2302 of an exemplary wireless power transfer system configured to supply power to a single or multiple devices. The source power and control circuitry 2302 of the exemplary system may be powered from an AC voltage source 2502 such as a home electrical outlet, a DC voltage source such as a battery, a USB port of a computer, a solar cell, another wireless power source, and the like. The source power and control circuitry 2302 may drive the source resonator 102S with alternating current, such as with a frequency greater than 10 kHz and less than 100 MHz. The source power and control circuitry 2302 may drive the source resonator 102S with alternating current of frequency less than less than 10 GHz. The source power and control circuitry 2302 may include a DC-to-DC converter 2408S, an AC-to-DC converter 2408S, or both an AC-to-DC converter 2408S and a DC-to-DC 2408S converter, an oscillator 2508, a power amplifier 2504, an impedance matching network 2402S, and the like.

[00391] The source power and control circuitry 2302 may be powered from multiple AC-or-DC voltage sources 2502 and may contain AC-to-DC and DC-to-DC converters 2408S to provide necessary voltage levels for the circuit components as well as DC voltages for the power amplifiers that may be used to drive the source resonator. The DC voltages may be adjustable and may be used to control the output power level of the power amplifier. The source may contain power factor correction circuitry.

[00392] The oscillator 2508 output may be used as the input to a power amplifier 2504 that drives the source resonator 102S. The oscillator frequency may be tunable and the amplitude of the oscillator signal may be varied as one means to control the output power level from the power amplifier. The frequency, amplitude, phase, waveform, and duty cycle of the oscillator signal may be controlled by analog circuitry, by digital circuitry or by a combination of analog and digital circuitry. The control circuitry may include a processor 2410S, such as a microprocessor, a digital signal processor, a field programmable gate array processor, and the like.

[00393] The impedance matching blocks 2402 of the source and device resonators may be used to tune the power and control circuits and the source and device resonators. For example, tuning of these circuits may adjust for perturbation of the quality factor *Q* of the source or device resonators due to extraneous objects or changes in distance between the source and device in a system. Tuning of these circuits may also be used to sense the operating environment, control power flow to one or more devices, to control power to a wireless power network, to reduce power when unsafe or failure mode conditions are detected, and the like.

[00394] Any combination of power, voltage, and current signals may be monitored at any point in the source circuitry. These signals may be monitored using analog or digital or combined analog and digital techniques. These monitored signals may be used in feedback circuits or may be reported to the user in a variety of known ways or they may be stored and retrieved at later times. These signals may be used to alert a user to system failures, to alert a user to exceeded safety thresholds, to indicate performance, or to provide audio, visual, vibrational, and the like, feedback to a user of the system.

[00395] The source power and control circuitry may contain a processor. The processor may be used to read the state or the operating point of the power and control circuitry and the source resonator. The processor may implement algorithms to interpret and adjust the operating point of the circuits, elements, components, subsystems and resonator. The processor may be used to adjust the impedance matching, the resonator, the DC-to-DC converters, the AC-to-DC converters, the oscillator, the power amplifier of the source, and the like. The processor and adjustable components of the system may be used to implement frequency and/or time power delivery multiplexing schemes. The processor may have wireless or wired data communication links to devices and other sources and may transmit or receive data that can be used to adjust the operating point of the system.

[00396] Although detailed and specific designs are shown in these block diagrams, it should be clear to those skilled in the art that many different modifications and rearrangements of the components and building blocks are possible within the spirit of the exemplary system. The division of the circuitry was outlined for illustrative purposes and it should be clear to those skilled in the art that the components of each block may be further divided into smaller blocks or merged or shared. In equivalent examples the power and control circuitry may be composed of individual discrete components or larger integrated circuits. For example, the rectifier circuitry may be composed of discrete diodes, or use diodes integrated on a single chip. A multitude of other circuits and integrated devices can be substituted in the design depending on design criteria such as power or size or cost or application. The whole of the power and control circuitry or any portion of the source or device circuitry may be integrated into one chip.

[00397] The impedance matching network of the device and or source may include a capacitor or networks of capacitors, an inductor or networks of inductors, or any combination of capacitors, inductors, diodes, switches, resistors, and the like. The components of the impedance matching network may be adjustable and variable and may be controlled to affect the efficiency and operating point of the system. The impedance matching may be performed by controlling the connection point of the resonator, adjusting the permeability of a magnetic material, controlling a bias field, adjusting the frequency of excitation, and the like. The impedance matching may use or include any number or combination of varactors, varactor arrays, switched elements, capacitor banks, switched and tunable elements, reverse bias diodes, air gap capacitors, compression capacitors, BZT electrically tuned capacitors, MEMS-tunable capacitors, voltage variable dielectrics, transformer coupled tuning circuits, and the like. The variable components may be mechanically tuned, thermally tuned, electrically tuned, piezo-electrically tuned, and the like. Elements of the impedance matching may be silicon devices, gallium nitride devices, silicon carbide devices and the like. The elements may be chosen to withstand high currents, high voltages, high powers, or any combination of current, voltage and power. The elements may be chosen to be high-Q elements.

[00398] The matching and tuning calculations of the source may be performed on an external device through a USB port that powers the device. The device may be a computer a PDA or other computational platform.

[00399] A demonstration system used a source resonator, coupled to a device resonator, to wirelessly power/recharge multiple electronic consumer devices including, but not limited to, a laptop, a DVD player, a projector, a cell-phone, a display, a television, a projector, a digital picture frame, a light, a TV/DVD player, a portable music player, a circuit breaker, a hand-held tool, a personal digital assistant, an external battery charger, a mouse, a keyboard, a camera, an active load, and the like. A variety of devices may be powered simultaneously from a single device resonator. Device resonators may be operated simultaneously as source resonators.

The power supplied to a device resonator may pass through additional resonators before being delivered to its intended device resonator.

[00400] *Monitoring, Feedback and Control*

[00401] So-called port parameter measurement circuitry may measure or monitor certain power, voltage, and current, signals in the system and processors or control circuits may adjust certain settings or operating parameters based on those measurements. In addition to these port parameter measurements, the magnitude and phase of voltage and current signals, and the magnitude of the power signals, throughout the system may be accessed to measure or monitor the system performance. The measured signals referred to throughout this disclosure may be any combination of the port parameter signals, as well as voltage signals, current signals, power signals, and the like. These parameters may be measured using analog or digital signals, they may be sampled and processed, and they may be digitized or converted using a number of known analog and digital processing techniques. Measured or monitored signals may be used in feedback circuits or systems to control the operation of the resonators and/or the system. In general, we refer to these monitored or measured signals as reference signals, or port parameter measurements or signals, although they are sometimes also referred to as error signals, monitor signals, feedback signals, and the like. We will refer to the signals that are used to control circuit elements such as the voltages used to drive voltage controlled capacitors as the control signals.

[00402] In some cases the circuit elements may be adjusted to achieve a specified or predetermined impedance value for the source and device resonators. In other cases the impedance may be adjusted to achieve a desired impedance value for the source and device resonators when the device resonator is connected to a power consumer or consumers. In other cases the impedance may be adjusted to mitigate changes in the resonant frequency, or impedance or power level changes owing to movement of the source and/or device resonators, or changes in the environment (such as the movement of interacting materials or objects) in the vicinity of the resonators. In other cases the impedance of the source and device resonators may be adjusted to different impedance values.

[00403] The coupled resonators may be made of different materials and may include different circuits, components and structural designs or they may be the same. The coupled resonators may include performance monitoring and measurement circuitry, signal processing and control circuitry or a combination of measurement and control circuitry. Some or all of the high-*Q* magnetic resonators may include tunable impedance circuits. Some or all of the high-*Q* magnetic resonators may include automatically controlled tunable impedance circuits.

[00404] Fig. 41 shows a magnetic resonator with port parameter measurement circuitry 3802 configured to measure certain parameters of the resonator. The port parameter measurement circuitry may measure the input impedance of the structure, or the reflected power. Port parameter measurement circuits may be included in the source and/or device resonator designs and may be used to measure two port circuit parameters such as S-parameters (scattering parameters), Z-parameters (impedance parameters), Y-parameters (admittance parameters), T-parameters (transmission parameters), H-parameters (hybrid parameters), ABCD-parameters (chain, cascade or transmission parameters), and the like. These parameters may be used to describe the electrical behavior of linear electrical networks when various types of signals are applied.

[00405] Different parameters may be used to characterize the electrical network under different operating or coupling scenarios. For example, S-parameters may be used to measure matched and unmatched loads. In addition, the magnitude and phase of voltage and current signals within the magnetic resonators and/or within the sources and devices themselves may be monitored at a variety of points to yield system performance information. This information may be presented to users of the system via a user interface such as a light, a read-out, a beep, a noise, a vibration or the like, or it may be presented as a digital signal or it may be provided to a processor in the system and used in the automatic control of the system. This information may be logged, stored, or may be used by higher level monitoring and control systems.

[00406] Fig. 42 shows a circuit diagram of a magnetic resonator where the tunable impedance network may be realized with voltage controlled capacitors 3902 or capacitor networks. Such an implementation may be adjusted, tuned or controlled by electrical circuits and/or computer processors, such as a programmable voltage source 3908, and the like. For example, the voltage controlled capacitors may be adjusted in response to data acquired by the port parameter measurement circuitry 3802 and processed by a measurement analysis and control algorithm subsystem 3904. Reference signals may be derived from the port parameter measurement circuitry or other monitoring circuitry designed to measure the degree of deviation from a desired system operating point. The measured reference signals may include voltage, current, complex-impedance, reflection coefficient, power levels and the like, at one or several points in the system and at a single frequency or at multiple frequencies.

[00407] The reference signals may be fed to measurement analysis and control algorithm subsystem modules that may generate control signals to change the values of various components in a tunable impedance matching network. The control signals may vary the resonant frequency and/or the input impedance of the magnetic resonator, or the power level supplied by the source, or the power level drawn by the device, to achieve the desired power exchange between power supplies/generators and power drains/loads.

[00408] Adjustment algorithms may be used to adjust the frequency and/or impedance of the magnetic resonators. The algorithms may take in reference signals related to the degree of deviation from a desired operating point for the system and output correction or control signals related to that deviation that control variable or tunable elements of the system to bring the system back towards the desired operating point or points. The reference signals for the magnetic resonators may be acquired while the resonators are exchanging power in a wireless power transmission system, or they may be switched out of the circuit during system operation. Corrections to the system may be applied or performed continuously, periodically, upon a threshold crossing, digitally, using analog methods, and the like.

[00409] Fig. 43 shows an end-to-end wireless power transmission system. Both the source and the device may include port measurement circuitry 3802 and a processor 2410. The box labeled “coupler/switch” 4002 indicates that the port measurement circuitry 3802 may be connected to the resonator 102 by a directional coupler or a switch, enabling the measurement, adjustment and control of the source and device resonators to take place in conjunction with, or separate from, the power transfer functionality.

[00410] The port parameter measurement and/or processing circuitry may reside with some, any, or all resonators in a system. The port parameter measurement circuitry may utilize portions of the power transmission signal or may utilize excitation signals over a range of frequencies to measure the source/device resonator response (i.e. transmission and reflection between any two ports in the system), and may contain amplitude and/or phase information. Such measurements may be achieved with a swept single frequency signal or a multi-frequency signal. The signals used to measure and monitor the resonators and the wireless power transmission system may be generated by a processor or processors and standard input/output

(I/O) circuitry including digital to analog converters (DACs), analog to digital converters (ADCs), amplifiers, signal generation chips, passive components and the like. Measurements may be achieved using test equipment such as a network analyzer or using customized circuitry. The measured reference signals may be digitized by ADCs and processed using customized algorithms running on a computer, a microprocessor, a DSP chip, an ASIC, and the like. The measured reference signals may be processed in an analog control loop.

[00411] The measurement circuitry may measure any set of two port parameters such as S-parameters, Y-parameters, Z-parameters, H-parameters, G-parameters, T-parameters, ABCD-parameters, and the like. Measurement circuitry may be used to characterize current and voltage signals at various points in the drive and resonator circuitry, the impedance and/or admittance of the source and device resonators at opposite ends of the system, i.e. looking into the source resonator matching network ("port 1" in Fig. 43) towards the device and vice versa.

[00412] The device may measure relevant signals and/or port parameters, interpret the measurement data, and adjust its matching network to optimize the impedance looking into the coupled system independently of the actions of the source. The source may measure relevant port parameters, interpret the measurement data, and adjust its matching network to optimize the impedance looking into the coupled system independently of the actions of the device.

[00413] Fig. 43 shows a block diagram of a source and device in a wireless power transmission system. The system may be configured to execute a control algorithm that actively adjusts the tuning/matching networks in either of or both the source and device resonators to optimize performance in the coupled system. Port measurement circuitry 3802S may measure signals in the source and communicate those signals to a processor 2410. A processor 2410 may use the measured signals in a performance optimization or stabilization algorithm and generate control signals based on the outputs of those algorithms. Control signals may be applied to variable circuit elements in the tuning/impedance matching circuits 2402S to adjust the source's operating characteristics, such as power in the resonator and coupling to devices. Control signals may be applied to the power supply or generator to turn the supply on or off, to increase or decrease the power level, to modulate the supply signal and the like.

[00414] The power exchanged between sources and devices may depend on a variety of factors. These factors may include the effective impedance of the sources and devices, the Q's of the sources and devices, the resonant frequencies of the sources and devices, the distances between sources and devices, the interaction of materials and objects in the vicinity of sources and devices and the like. The port measurement circuitry and processing algorithms may work in concert to adjust the resonator parameters to maximize power transfer, to hold the power transfer constant, to controllably adjust the power transfer, and the like, under both dynamic and steady state operating conditions.

[00415] Some, all or none of the sources and devices in a system implementation may include port measurement circuitry 3802S and processing 2410 capabilities. Fig. 44 shows an end-to-end wireless power transmission system in which only the source 102S contains port measurement circuitry 3802 and a processor 2410S. In this case, the device resonator 102D operating characteristics may be fixed or may be adjusted by analog control circuitry and without the need for control signals generated by a processor.

[00416] Fig. 45 shows an end-to-end wireless power transmission system. Both the source and the device may include port measurement circuitry 3802 but in the system of Fig. 45, only the source contains a processor 2410S. The source and device may be in communication with each other and the adjustment of certain system parameters may be in response to control signals that have been wirelessly communicated, such as though wireless communications circuitry 4202, between the source and the device. The wireless communication channel 4204 may be separate from the wireless power transfer channel 4208, or it may be the same. That is, the resonators 102 used for power exchange may also be used to exchange information. In some cases, information may be exchanged by modulating a component a source or device circuit and sensing that change with port parameter or other monitoring equipment.

[00417] Implementations where only the source contains a processor 2410 may be beneficial for multi-device systems where the source can handle all of the tuning and adjustment "decisions" and simply communicate the control signals back to the device(s). This implementation may make the device smaller and cheaper because it may eliminate the need for, or reduce the required functionality of, a processor in the device. A portion of or an entire data set from each port measurement at each device may be sent back to the source microprocessor for analysis, and the control instructions may be sent back to the devices. These communications may be wireless communications.

[00418] Fig. 46 shows an end-to-end wireless power transmission system. In this example, only the source contains port measurement circuitry 3802 and a processor 2410S. The source and device may be in communication, such as via wireless communication circuitry 4202, with each other and the adjustment of certain system parameters may be in response to control signals that have been wirelessly communicated between the source and the device.

[00419] Fig. 47 shows coupled electromagnetic resonators 102 whose frequency and impedance may be automatically adjusted using a processor or a computer. Resonant frequency tuning and continuous impedance adjustment of the source and device resonators may be implemented with reverse biased diodes, Schottky diodes and/or varactor elements contained within the capacitor networks shown as C1, C2, and C3 in Fig. 47. The circuit topology that was built and demonstrated and is described here is exemplary and is not meant to limit the discussion of automatic system tuning and control in any way. Other circuit topologies could be utilized with the measurement and control architectures discussed in this disclosure.

[00420] Device and source resonator impedances and resonant frequencies may be measured with a network analyzer 4402A-B, or by other means described above, and implemented with a controller, such as with Lab View 4404. The measurement circuitry or equipment may output data to a computer or a processor that implements feedback algorithms and dynamically adjusts the frequencies and impedances via a programmable DC voltage source.

[00421] In one arrangement, the reverse biased diodes (Schottky, semiconductor junction, and the like) used to realize the tunable capacitance drew very little DC current and could be reverse biased by amplifiers having large series output resistances. This implementation may enable DC control signals to be applied directly to the controllable circuit elements in the resonator circuit while maintaining a very high-Q in the magnetic resonator.

[00422] C2 biasing signals may be isolated from C1 and/or C3 biasing signals with a DC blocking capacitor as shown in Fig. 47, if the required DC biasing voltages are different. The output of the biasing amplifiers may be bypassed to circuit ground to isolate RF voltages from the biasing amplifiers, and to keep non-fundamental RF voltages from being injected into the resonator. The reverse bias voltages for some of the capacitors may instead be applied through the inductive element in the resonator itself, because the inductive element acts as a short circuit at DC.

[00423] The port parameter measurement circuitry may exchange signals with a processor (including any required ADCs and DACs) as part of a feedback or control system that is used to automatically adjust the resonant frequency, input impedance, energy stored or captured by the resonator or power delivered by a source or to a device load. The processor may also send control signals to tuning or adjustment circuitry in or attached to the magnetic resonator.

[00424] When utilizing varactors or diodes as tunable capacitors, it may be beneficial to place fixed capacitors in parallel and in series with the tunable capacitors operating at high reverse bias voltages in the tuning/matching circuits. This arrangement may yield improvements in circuit and system stability and in power handling capability by optimizing the operating voltages on the tunable capacitors.

[00425] Varactors or other reverse biased diodes may be used as a voltage controlled capacitor. Arrays of varactors may be used when higher voltage compliance or different capacitance is required than that of a single varactor component. Varactors may be arranged in an N by M array connected serially and in parallel and treated as a single two terminal component with different characteristics than the individual varactors in the array. For example, an N by N array of equal varactors where components in each row are connected in parallel and components in each column are connected in series may be used as a two terminal device with the same capacitance as any single varactor in the array but with a voltage compliance that is N times that of a single varactor in the array. Depending on the variability and differences of parameters of the individual varactors in the array additional biasing circuits composed of resistors, inductors, and the like may be needed. A schematic of a four by four array of unbiased varactors 4502 that may be suitable for magnetic resonator applications is shown in Fig. 48.

[00426] Further improvements in system performance may be realized by careful selection of the fixed value capacitor(s) that are placed in parallel and/or in series with the tunable (varactor/diode/capacitor) elements. Multiple fixed capacitors that are switched in or out of the circuit may be able to compensate for changes in resonator Q's, impedances, resonant frequencies, power levels, coupling strengths, and the like, that might be encountered in test, development and operational wireless power transfer systems. Switched capacitor banks and other switched element banks may be used to assure the convergence to the operating frequencies and impedance values required by the system design.

[00427] An exemplary control algorithm for isolated and coupled magnetic resonators may be described for the circuit and system elements shown in Fig. 47. One control algorithm first adjusts each of the source and device resonator loops “in isolation”, that is, with the other resonators in the system “shorted out” or “removed” from the system. For practical purposes, a resonator can be “shorted out” by making it resonant at a much lower frequency such as by maximizing the value of C1 and/or C3. This step effectively reduces the coupling between the resonators, thereby effectively reducing the system to a single resonator at a particular frequency and impedance.

[00428] Tuning a magnetic resonator in isolation includes varying the tunable elements in the tuning and matching circuits until the values measured by the port parameter measurement circuitry are at their predetermined, calculated or measured relative values. The desired values for the quantities measured by the port parameter measurement circuitry may be chosen based on the desired matching impedance, frequency, strong coupling parameter, and the like. For the exemplary algorithms disclosed below, the port parameter measurement circuitry measures S-parameters over a range of frequencies. The range of frequencies used to characterize the resonators may be a compromise between the system performance information obtained and computation/measurement speed. For the algorithms described below the frequency range may be approximately +/- 20% of the operating resonant frequency.

[00429] Each isolated resonator may be tuned as follows. First, short out the resonator not being adjusted. Next minimize C1, C2, and C3, in the resonator that is being characterized and adjusted. In most cases there will be fixed circuit elements in parallel with C1, C2, and C3, so this step does not reduce the capacitance values to zero. Next, start increasing C2 until the resonator impedance is matched to the “target” real impedance at any frequency in the range of measurement frequencies described above. The initial “target” impedance may be less than the expected operating impedance for the coupled system.

[00430] C2 may be adjusted until the initial “target” impedance is realized for a frequency in the measurement range. Then C1 and/or C3 may be adjusted until the loop is resonant at the desired operating frequency.

[00431] Each resonator may be adjusted according to the above algorithm. After tuning each resonator in isolation, a second feedback algorithm may be applied to optimize the resonant frequencies and/or input impedances for wirelessly transferring power in the coupled system.

[00432] The required adjustments to C1 and/or C2 and/or C3 in each resonator in the coupled system may be determined by measuring and processing the values of the real and imaginary parts of the input impedance from either and/or both "port(s)" shown in Fig. 43. For coupled resonators, changing the input impedance of one resonator may change the input impedance of the other resonator. Control and tracking algorithms may adjust one port to a desired operating point based on measurements at that port, and then adjust the other port based on measurements at that other port. These steps may be repeated until both sides converge to the desired operating point.

[00433] S-parameters may be measured at both the source and device ports and the following series of measurements and adjustments may be made. In the description that follows, Z_0 is an input impedance and may be the target impedance. In some cases Z_0 is 50 ohms or is near 50 ohms. Z_1 and Z_2 are intermediate impedance values that may be the same value as Z_0 or may be different than Z_0. Re{value} means the real part of a value and Im{value} means the imaginary part of a value.

[00434] An algorithm that may be used to adjust the input impedance and resonant frequency of two coupled resonators is set forth below:

1) Adjust each resonator "in isolation" as described above.

2) Adjust source C1/C3 until, at ω_o, Re{S11} = (Z_1 +/- ε_{Re}) as follows:

- If Re{S11 @ ω_o } > ($Z_1 + \varepsilon_{Re}$), decrease C1/C3. If Re{S11 @ ω_o } < (Zo - ε_{Re}), increase C1/C3.

3) Adjust source C2 until, at ω_o, Im{S11} = (+/- ε_{Im}) as follows:

- If Im{S11 @ ω_o} > ε_{Im}, decrease C2. If Im{S11 @ ω_o} < - ε_{Im} , increase C2.

4) Adjust device C1/C3 until, at ω_0, Re{S22} = (Z_2 +/- ε_{Re}) as follows:

- If Re{S22 @ ω_o} > ($Z_2 + \varepsilon_{Re}$), decrease C1/C3. If Re{S22 @ ω_o} < (Zo - ε_{Re}), increase C1/C3.

5) Adjust device C2 until, at ω_o, Im{S22} = 0 as follows:

- If Im{S22 @ ω_o} > ε_{Im}, decrease C2. If Im{S22 @ ω_o} < -ε_{Im} , increase C2.

[00435] We have achieved a working system by repeating steps 1-4 until both (Re{S11}, Im{S11}) and (Re{S22}, Im{S22}) converge to ((Z_0 +/- ε_{Re}), (+/- ε_{Im})) at ω_o, where Z_0 is the desired matching impedance and ω_o is the desired operating frequency. Here, ε_{Im} represents the maximum deviation of the imaginary part, at ω_o, from the desired value of 0, and ε_{Re} represents the maximum deviation of the real part from the desired value of Z_0. It is understood that ε_{Im} and ε_{Re} can be adjusted to increase or decrease the number of steps to convergence at the potential cost of system performance (efficiency). It is also understood that steps 1-4 can be performed in a variety of sequences and a variety of ways other than that outlined above (i.e. first adjust the source imaginary part, then the source real part; or first adjust the device real part, then the device imaginary part, etc.) The intermediate impedances Z_1 and Z_2 may be adjusted during steps 1-4 to reduce the number of steps required for convergence. The desire or target impedance value may be complex, and may vary in time or under different operating scenarios.

[00436] Steps 1-4 may be performed in any order, in any combination and any number of times. Having described the above algorithm, variations to the steps or the described implementation may be apparent to one of ordinary skill in the art. The algorithm outlined above may be implemented with any equivalent linear network port parameter measurements (i.e., Z-parameters, Y-parameters, T-parameters, H-parameters, ABCD-parameters, etc.) or other monitor signals described above, in the same way that impedance or admittance can be alternatively used to analyze a linear circuit to derive the same result.

[00437] The resonators may need to be retuned owing to changes in the “loaded” resistances, Rs and Rd, caused by changes in the mutual inductance M (coupling) between the source and device resonators. Changes in the inductances, Ls and Ld, of the inductive elements themselves may be caused by the influence of external objects, as discussed earlier, and may also require compensation. Such variations may be mitigated by the adjustment algorithm described above.

[00438] A directional coupler or a switch may be used to connect the port parameter measurement circuitry to the source resonator and tuning/adjustment circuitry. The port parameter measurement circuitry may measure properties of the magnetic resonator while it is exchanging power in a wireless power transmission system, or it may be switched out of the circuit during system operation. The port parameter measurement circuitry may measure the parameters and the processor may control certain tunable elements of the magnetic resonator at start-up, or at certain intervals, or in response to changes in certain system operating parameters.

[00439] A wireless power transmission system may include circuitry to vary or tune the impedance and/or resonant frequency of source and device resonators. Note that while tuning circuitry is shown in both the source and device resonators, the circuitry may instead be included in only the source or the device resonators, or the circuitry may be included in only some of the source and/or device resonators. Note too that while we may refer to the circuitry as "tuning" the impedance and or resonant frequency of the resonators, this tuning operation simply means that various electrical parameters such as the inductance or capacitance of the structure are being varied. In some cases, these parameters may be varied to achieve a specific predetermined value, in other cases they may be varied in response to a control algorithm or to stabilize a target performance value that is changing. In some cases, the parameters are varied as a function of temperature, of other sources or devices in the area, of the environment, at the like.

[00440] **Applications**

[00441] For each listed application, it will be understood by one of ordinary skill-in-the-art that there are a variety of ways that the resonator structures used to enable wireless power transmission may be connected or integrated with the objects that are supplying or being powered. The resonator may be physically separate from the source and device objects. The resonator may supply or remove power from an object using traditional inductive techniques or through direct electrical connection, with a wire or cable for example. The electrical connection may be from the resonator output to the AC or DC power input port on the object. The electrical connection may be from the output power port of an object to the resonator input.

[00442] FIG. 49 shows a source resonator 4904 that is physically separated from a power supply and a device resonator 4902 that is physically separated from the device 4900, in this illustration a laptop computer. Power may be supplied to the source resonator, and power may be taken from the device resonator directly, by an electrical connection. One of ordinary skill in the art will understand from the materials incorporated by reference that the shape, size, material composition, arrangement, position and orientation of the resonators above are provided by way of non-limiting example, and that a wide variation in any and all of these parameters could be supported by the disclosed technology for a variety of applications.

[00443] Continuing with the example of the laptop, and without limitation, the device resonator may be physically connected to the device it is powering or charging. For example, as shown in FIG. 50a and FIG. 50b, the device resonator 5002 may be (a) integrated into the housing of the device 5000 or (b) it may be attached by an adapter. The resonator 5002 may (FIG. 50b-d) or may not (FIG. 50a) be visible on the device. The resonator may be affixed to the device, integrated into the device, plugged into the device, and the like.

[00444] The source resonator may be physically connected to the source supplying the power to the system. As described above for the devices and device resonators, there are a variety of ways the resonators may be attached to, connected to or integrated with the power supply. One of ordinary skill in the art will understand that there are a variety of ways the resonators may be integrated in the wireless power transmission system, and that the sources and devices may utilize similar or different integration techniques.

[00445] Continuing again with the example of the laptop computer, and without limitation, the laptop computer may be powered, charged or recharged by a wireless power transmission system. A source resonator may be used to supply wireless power and a device resonator may be used to capture the wireless power. A device resonator 5002 may be integrated into the edge of the screen (display) as illustrated in FIG. 50d, and/or into the base of the laptop as illustrated in FIG. 50c. The source resonator 5002 may be integrated into the base of the laptop and the device resonator may be integrated into the edge of the screen. The resonators may also or instead be affixed to the power source and/or the laptop. The source and device resonators may also or instead be physically separated from the power supply and the laptop and may be electrically connected by a cable. The source and device resonators may also or instead be physically separated from the power supply and the laptop and may be electrically coupled using a traditional inductive technique. One of ordinary skill in the art will understand that, while the preceding examples relate to wireless power transmission to a laptop, that the methods and systems disclosed for this application may be suitably adapted for use with other electrical or electronic devices. In general, the source resonator may be external to the source and supplying power to a device resonator that in turn supplies power the device, or the source resonator may be connected to the source and supplying power to a device resonator that in turn supplies power to a portion of the device, or the source resonator may internal to the source and supplying power to a device resonator that in turn supplies power to a portion of the device, as well as any combination of these.

[00446] In some systems, the source, or source resonator may be movable or active and may track, follow, or attach to the source or source resonator. For a movable device it may be preferable to maintain alignment between the source resonator and the device resonator to maximize power transfer efficiency. As a device moves a source or a source resonator may track the position of the device or device resonator and adjust its position to ensure optimum or improved alignment. The device tracking by the source may be automatic. A source may include sensors for determining the position of the device and means for adjusting its position, such as by actuators, motors, magnets, and the like. The source may sense the position of the device by measuring power efficiency, magnetic fields, signals generated by the device, optical recognition, and the like. In some embodiments the source may partially attach to the device. A source and device may include magnets which attach the source and device together. A magnetic attachment may be functional through a supporting structure such as a table. The magnetic attachment will attach the source through the supporting structure making a freely movable source to follow the device as it moves. For example, continuing with the laptop example, a source mounted on a freely movable structure may be mounted under a supporting structure such as a table surface, dock, box, and the like. A laptop, with a magnetic attachment placed on top of the table surface will attract the source below the supporting structure and result in proper alignment. Furthermore, as the laptop with the device resonator is moved, or slid on top of the supporting structure, the freely movable source and source resonator may follow the device resonator of the laptop due to the magnetic attraction between the source and the device without requiring active movement mechanisms. In some embodiments, a combination of active and passive movement mechanisms may be used, such that for example, move the source into initial alignment with the device whereupon magnetic attachment means ensures that the source may passively follow the device as it moves.

[00447] A system or method disclosed herein may provide power to an electrical or electronics device, such as, and not limited to, phones, cell phones, cordless phones, smart phones, PDAs, audio devices, music players, MP3 players, radios, portable radios and players, wireless headphones, wireless headsets, computers, laptop computers, wireless keyboards, wireless mouse, televisions, displays, flat screen displays, computer displays, displays embedded in furniture, digital picture frames, electronic books, (e.g. the Kindle, e-ink books, magazines, and the like), remote control units (also referred to as controllers, game controllers, commanders, clickers, and the like, and used for the remote control of a plurality of electronics devices, such as televisions, video games, displays, computers, audio visual equipment, lights, and the like), lighting devices, cooling devices, air circulation devices, purification devices, personal hearing aids, power tools, security systems, alarms, bells, flashing lights, sirens, sensors, loudspeakers, electronic locks, electronic keypads, light switches, other electrical switches, and the like. Here the term electronic lock is used to indicate a door lock which operates electronically (e.g. with electronic combo-key, magnetic card, RFID card, and the like) which is placed on a door instead of a mechanical key-lock. Such locks are often battery operated, risking the possibility that the lock might stop working when a battery dies, leaving the user locked-out. This may be avoided where the battery is either charged or completely replaced by a wireless power transmission implementation as described herein.

[00448] Here, the term light switch (or other electrical switch) is meant to indicate any switch (e.g. on a wall of a room) in one part of the room that turns on/off a device (e.g. light fixture at the center of the ceiling) in another part of the room. To install such a switch by direct connection, one would have to run a wire all the way from the device to the switch. Once such a switch is installed at a particular spot, it may be very difficult to move. Alternately, one can envision a 'wireless switch', where "wireless" means the switching (on/off) commands are communicated wirelessly, but such a switch has traditionally required a battery for operation. In general, having too many battery operated switches around a house may be impractical, because those many batteries will need to be replaced periodically. So, a wirelessly communicating switch may be more convenient, provided it is also wirelessly powered. For example, there already exist communications wireless door-bells that are battery powered, but where one still has to replace the battery in them periodically. The remote doorbell button may be made to be completely wireless, where there may be no need to ever replace the battery again. Note that here, the term 'cordless' or 'wireless' or 'communications wireless' is used to indicate that there is a cordless or wireless communications facility between the device and another electrical component, such as the base station for a cordless phone, the computer for a wireless keyboard, and the like. One skilled in the art will recognize that any electrical or electronics device may include a wireless communications facility, and that the systems and methods described herein may be used to add wireless power transmission to the device. As described herein, power to the electrical or electronics device may be delivered from an external or internal source resonator, and to the device or portion of the device. Wireless power transmission may significantly reduce the need to charge and/or replace batteries for devices that enter the near vicinity of the source resonator and thereby may reduce the downtime, cost and disposal issues often associated with batteries.

[00449] The systems and methods described herein may provide power to lights without the need for either wired power or batteries. That is, the systems and methods described herein may provide power to lights without wired connection to any power source, and provide the energy to the light non-radiatively across mid-range distances, such as across a distance of a quarter of a meter, one meter, three meters, and the like. A ‘light’ as used herein may refer to the light source itself, such as an incandescent light bulb, florescent light bulb lamps, Halogen lamps, gas discharge lamps, fluorescent lamps, neon lamps, high-intensity discharge lamps, sodium vapor lamps, Mercury-vapor lamps, electroluminescent lamps, light emitting diodes (LED) lamps, and the like; the light as part of a light fixture, such as a table lamp, a floor lamp, a ceiling lamp, track lighting, recessed light fixtures, and the like; light fixtures integrated with other functions, such as a light/ceiling fan fixture, and illuminated picture frame, and the like. As such, the systems and methods described herein may reduce the complexity for installing a light, such as by minimizing the installation of electrical wiring, and allowing the user to place or mount the light with minimal regard to sources of wired power. For instance, a light may be placed anywhere in the vicinity of a source resonator, where the source resonator may be mounted in a plurality of different places with respect to the location of the light, such as on the floor of the room above, (e.g. as in the case of a ceiling light and especially when the room above is the attic); on the wall of the next room, on the ceiling of the room below, (e.g. as in the case of a floor lamp); in a component within the room or in the infrastructure of the room as described herein; and the like. For example, a light/ceiling fan combination is often installed in a master bedroom, and the master bedroom often has the attic above it. In this instance a user may more easily install the light/ceiling fan combination in the master bedroom, such as by simply mounting the light/ceiling fan combination to the ceiling, and placing a source coil (plugged into the house wired AC power) in the attic above the mounted fixture. In another example, the light may be an external light, such as a flood light or security light, and the source resonator mounted inside the structure. This way of installing lighting may be particularly beneficial to users who rent their homes, because now they may be able to mount lights and such other electrical components without the need to install new electrical wiring. The control for the light may also be communicated by near-field communications as described herein, or by traditional wireless communications methods.

[00450] The systems and methods described herein may provide power from a source resonator to a device resonator that is either embedded into the device component, or outside the device component, such that the device component may be a traditional electrical component or fixture. For instance, a ceiling lamp may be designed or retrofitted with a device resonator integrated into the fixture, or the ceiling lamp may be a traditional wired fixture, and plugged into a separate electrical facility equipped with the device resonator. In an example, the electrical facility may be a wireless junction box designed to have a device resonator for receiving wireless power, say from a source resonator placed on the floor of the room above (e.g. the attic), and which contains a number of traditional outlets that are powered from the device resonator. The wireless junction box, mounted on the ceiling, may now provide power to traditional wired electrical components on the ceiling (e.g. a ceiling light, track lighting, a ceiling fan). Thus, the ceiling lamp may now be mounted to the ceiling without the need to run wires through the infrastructure of the building. This type of device resonator to traditional outlet junction box may be used in a plurality of applications, including being designed for the interior or exterior of a building, to be made portable, made for a vehicle, and the like. Wireless power may be transferred through common building materials, such as wood, wall board, insulation, glass. brick, stone, concrete, and the like. The benefits of reduced installation cost, re-configurability, and increased application flexibility may provide the user significant benefits over traditional wired installations. The device resonator for a traditional outlet junction box may include a plurality of electrical components for facilitating the transfer of power from the device resonator to the traditional outlets, such as power source electronics which convert the specific frequencies needed to implement efficient power transfer to line voltage, power capture electronics which may convert high frequency AC to usable voltage and frequencies (AC and/or DC), controls which synchronize the capture device and the power output and which ensure consistent, safe, and maximally efficient power transfer, and the like.

[00451] The systems and methods described herein may provide advantages to lights or electrical components that operate in environments that are wet, harsh, controlled, and the like, such has outside and exposed to the rain, in a pool/sauna/shower, in a maritime application, in hermetically sealed components, in an explosive-proof room, on outside signage, a harsh industrial environment in a volatile environment (e.g. from volatile vapors or airborne organics, such as in a grain silo or bakery) , and the like. For example, a light mounted under the water level of a pool is normally difficult to wire up, and is required to be water-sealed despite the need for external wires. But a pool light using the principles disclosed herein may more easily be made water sealed, as there may be no external wires needed. In another example, an explosion proof room, such as containing volatile vapors, may not only need to be hermetically sealed, but may need to have all electrical contacts (that could create a spark) sealed. Again, the principles disclosed herein may provide a convenient way to supply sealed electrical components for such applications.

[00452] The systems and methods disclosed herein may provide power to game controller applications, such as to a remote handheld game controller. These game controllers may have been traditionally powered solely by batteries, where the game controller’s use and power profile caused frequent changing of the battery, battery pack, rechargeable batteries, and the like, that may not have been ideal for the consistent use to the game controller, such as during extended game play. A device resonator may be placed into the game controller, and a source resonator, connected to a power source, may be placed in the vicinity. Further, the device resonator in the game controller may provide power directly to the game controller electronics without a battery; provide power to a battery, battery pack, rechargeable battery, and the like, which then provides power to the game controller electronics; and the like. The game controller may utilize multiple battery packs, where each battery pack is equipped with a device resonator, and thus may be constantly recharging while in the vicinity of the source resonator, whether plugged into the game controller or not. The source resonator may be resident in a main game controller facility for the game, where the main game controller facility and source resonator are supplied power from AC ‘house’ power; resident in an extension facility form AC power, such as in a source resonator integrated into an ‘extension cord’; resident in a game chair, which is at least one of plugged into the wall AC, plugged into the main game controller facility, powered by a battery pack in the game chair; and the like. The source resonator may be placed and implemented in any of the configurations described herein.

[00453] The systems and methods disclosed herein may integrate device resonators into battery packs, such as battery packs that are interchangeable with other battery packs. For instance, some portable devices may use up electrical energy at a high rate such that a user may need to have multiple interchangeable battery packs on hand for use, or the user may operate the device out of range of a source resonator and need additional battery packs to continue operation, such as for power tools, portable lights, remote control vehicles, and the like. The use of the principles disclosed herein may not only provide a way for device resonator enabled battery packs to be recharged while in use and in range, but also for the recharging of battery packs not currently in use and placed in range of a source resonator. In this way, battery packs may always be ready to use when a user runs down the charge of a battery pack being used. For example, a user may be working with a wireless power tool, where the current requirements may be greater than can be realized through direct powering from a source resonator. In this case, despite the fact that the systems and methods described herein may be providing charging power to the in-use battery pack while in range, the battery pack may still run down, as the power usage may have exceeded the recharge rate. Further, the user may simply be moving in and out of range, or be completely out of range while using the device. However, the user may have placed additional battery packs in the vicinity of the source resonator, which have been recharged while not in use, and are now charged sufficiently for use. In another example, the user may be working with the power tool away from the vicinity of the source resonator, but leave the supplemental battery packs to charge in the vicinity of the source resonator, such as in a room with a portable source resonator or extension cord source resonator, in the user's vehicle, in user's tool box, and the like. In this way, the user may not have to worry about taking the time to, and/or remembering to plug in their battery packs for future use. The user may only have to change out the used battery pack for the charged battery pack and place the used one in the vicinity of the source resonator for recharging. Device resonators may be built into enclosures with known battery form factors and footprints and may replace traditional chemical batteries in known devices and applications. For example, device resonators may be built into enclosures with mechanical dimensions equivalent to AA batteries, AAA batteries, D batteries, 9V batteries, laptop batteries, cell phone batteries, and the like. The enclosures may include a smaller "button battery" in addition to the device resonator to store charge and provide extended operation, either in terms of time or distance. Other energy storage devices in addition to or instead of button batteries may be integrated with the device resonators and any associated power conversion circuitry. These new energy packs may provide similar voltage and current levels as provided by traditional batteries, but may be composed of device resonators, power conversion electronics, a small battery, and the like. These new energy packs may last longer than traditional batteries because they may be more easily recharged and may be recharging constantly when they are located in a wireless power zone. In addition, such energy packs may be lighter than traditional batteries, may be safer to use and store, may operate over wider temperature and humidity ranges, may be less harmful to the environment when thrown away, and the like. As described herein, these energy packs may last beyond the life of the product when used in wireless power zones as described herein.

[00454] The systems and methods described herein may be used to power visual displays, such as in the case of the laptop screen, but more generally to include the great variety and diversity of displays utilized in today's electrical and electronics components, such as in televisions, computer monitors, desktop monitors, laptop displays, digital photo frames, electronic books, mobile device displays (e.g. on phones, PDAs, games, navigation devices, DVD players), and the like. Displays that may be powered through one or more of the wireless power transmission systems described herein may also include embedded displays, such as embedded in electronic components (e.g. audio equipment, home appliances, automotive displays, entertainment devices, cash registers, remote controls), in furniture, in building infrastructure, in a vehicle, on the surface of an object (e.g. on the surface of a vehicle, building, clothing, signs, transportation), and the like. Displays may be very small with tiny resonant devices, such as in a smart card as described herein, or very large, such as in an advertisement sign. Displays powered using the principles disclosed herein may also be any one of a plurality of imaging technologies, such as liquid crystal display (LCD), thin film transistor LCD, passive LCD, cathode ray tube (CRT), plasma display, projector display (e.g. LCD, DLP, LCOS), surface-conduction electron-emitter display (SED), organic light-emitting diode (OLED), and the like. Source coil configurations may include attaching to a primary power source, such as building power, vehicle power, from a wireless extension cord as described herein, and the like; attached to component power, such as the base of an electrical component (e.g. the base of a computer, a cable box for a TV); an intermediate relay source coil; and the like. For example, hanging a digital display on the wall may be very appealing, such as in the case of a digital photo frame that receives its information signals wirelessly or through a portable memory device, but the need for an unsightly power cord may make it aesthetically unpleasant. However, with a device coil embedded in the digital photo frame, such as wrapped within the frame portion, may allow the digital photo frame to be hung with no wires at all. The source resonator may then be placed in the vicinity of the digital photo frame, such as in the next room on the other side of the wall, plugged directly into a traditional power outlet, from a wireless extension cord as described herein, from a central source resonator for the room, and the like.

[00455] The systems and methods described herein may provide wireless power transmission between different portions of an electronics facility. Continuing with the example of the laptop computer, and without limitation, the screen of the laptop computer may require power from the base of the laptop. In this instance, the electrical power has been traditionally routed via direct electrical connection from the base of the laptop to the screen over a hinged portion of the laptop between the screen and the base. When a wired connection is utilized, the wired connection may tend to wear out and break, the design functionality of the laptop computer may be limited by the required direct electrical connection, the design aesthetics of the laptop computer may be limited by the required direct electrical connection, and the like. However, a wireless connection may be made between the base and the screen. In this instance, the device resonator may be placed in the screen portion to power the display, and the base may be either powered by a second device resonator, by traditional wired connections, by a hybrid of resonator-battery- direct electrical connection, and the like. This may not only improve the reliability of the power connection due to the removal of the physical wired connection, but may also allow designers to improve the functional and/or aesthetic design of the hinge portion of the laptop in light of the absence of physical wires associated with the hinge. Again, the laptop computer has been used here to illustrate how the principles disclosed herein may improve the design of an electric or electronic device, and should not be taken as limiting in any way. For instance, many other electrical devices with separated physical portions could benefit from the systems and methods described herein, such as a refrigerator with electrical functions on the door, including an ice maker, a sensor system, a light, and the like; a robot with movable portions, separated by joints; a car's power system and a component in the car's door; and the like. The ability to provide power to a device via a device resonator from an external source resonator, or to a portion of the device via a device resonator from either external or internal source resonators, will be recognized by someone skilled in the art to be widely applicable across the range of electric and electronic devices.

[00456] The systems and methods disclosed herein may provide for a sharing of electrical power between devices, such as between charged devices and uncharged devices. For instance a charged up device or appliance may act like a source and send a predetermined amount of energy, dialed in amount of energy, requested and approved amount of energy, and the like, to a nearby device or appliance. For example, a user may have a cell phone and a digital camera that are both capable of transmitting and receiving power through embedded source and device resonators, and one of the devices, say the cell phone, is found to be low on charge. The user may then transfer charge from the digital camera to the cell phone. The source and device resonators in these devices may utilize the same physical resonator for both transmission and reception, utilize separate source and device resonators, one device may be designed to receive and transmit while the other is designed to receive only, one device may be designed to transmit only and the other to receive only, and the like.

[00457] To prevent complete draining the battery of a device it may have a setting allowing a user to specify how much of the power resource the receiving device is entitled to. It may be useful, for example, to put a limit on the amount of power available to external devices and to have the ability to shut down power transmission when battery power falls below a threshold.

[00458] The systems and methods described herein may provide wireless power transfer to a nearby electrical or electronics component in association with an electrical facility, where the source resonator is in the electrical facility and the device resonator is in the electronics component. The source resonator may also be connected to, plugged into, attached to the electrical facility, such as through a universal interface (e.g. a USB interface, PC card interface), supplemental electrical outlet, universal attachment point, and the like, of the electrical facility. For example, the source resonator may be inside the structure of a computer on a desk, or be integrated into some object, pad, and the like, that is connected to the computer, such as into one of the computer’s USB interfaces. In the example of the source resonator embedded in the object, pad, and the like, and powered through a USB interface, the source resonator may then be easily added to a user’s desktop without the need for being integrated into any other electronics device, thus conveniently providing a wireless energy zone around which a plurality of electric and/or electronics devices may be powered. The electrical facility may be a computer, a light fixture, a dedicated source resonator electrical facility, and the like, and the nearby components may be computer peripherals, surrounding electronics components, infrastructure devices, and the like, such as computer keyboards, computer mouse, fax machine, printer, speaker system, cell phone, audio device, intercom, music player, PDA, lights, electric pencil sharpener, fan, digital picture frame, calculator, electronic games, and the like. For example, a computer system may be the electrical facility with an integrated source resonator that utilizes a 'wireless keyboard' and 'wireless mouse', where the use of the term wireless here is meant to indicate that there is wireless communication facility between each device and the computer, and where each device must still contain a separate battery power source. As a result, batteries would need to be replaced periodically, and in a large company, may result in a substantial burden for support personnel for replacement of batteries, cost of batteries, and proper disposal of batteries. Alternatively, the systems and methods described herein may provide wireless power transmission from the main body of the computer to each of these peripheral devices, including not only power to the keyboard and mouse, but to other peripheral components such as a fax, printer, speaker system, and the like, as described herein. A source resonator integrated into the electrical facility may provide wireless power transmission to a plurality of peripheral devices, user devices, and the like, such that there is a significant reduction in the need to charge and/or replace batteries for devices in the near vicinity of the source resonator integrated electrical facility. The electrical facility may also provide tuning or auto-tuning software, algorithms, facilities, and the like, for adjusting the power transfer parameters between the electrical facility and the wirelessly powered device. For example, the electrical facility may be a computer on a user's desktop, and the source resonator may be either integrated into the computer or plugged into the computer (e.g. through a USB connection), where the computer provides a facility for providing the tuning algorithm (e.g. through a software program running on the computer).

[00459] The systems and methods disclosed herein may provide wireless power transfer to a nearby electrical or electronics component in association with a facility infrastructure component, where the source resonator is in, or mounted on, the facility infrastructure component and the device resonator is in the electronics component. For instance, the facility infrastructure component may be a piece of furniture, a fixed wall, a movable wall or partition, the ceiling, the floor, and the source resonator attached or integrated into a table or desk (e.g. just below/above the surface, on the side, integrated into a table top or table leg), a mat placed on the floor (e.g. below a desk, placed on a desk), a mat on the garage floor (e.g. to charge the car and/or devices in the car), in a parking lot/garage (e.g. on a post near where the car is parked), a television (e.g. for charging a remote control), a computer monitor (e.g. to power/charge a wireless keyboard, wireless mouse, cell phone), a chair (e.g. for powering electric blankets, medical devices, personal health monitors), a painting, office furniture, common household appliances, and the like. For example, the facility infrastructure component may be a lighting fixture in an office cubical, where the source resonator and light within the lighting fixture are both directly connected to the facility's wired electrical power. However, with the source resonator now provided in the lighting fixture, there would be no need to have any additional wired connections for those nearby electrical or electronics components that are connected to, or integrated with, a device resonator. In addition, there may be a reduced need for the replacement of batteries for devices with device resonators, as described herein.

[00460] The use of the systems and methods described herein to supply power to electrical and electronic devices from a central location, such as from a source resonator in an electrical facility, from a facility infrastructure component and the like, may minimize the electrical wiring infrastructure of the surrounding work area. For example, in an enterprise office space there are typically a great number of electrical and electronic devices that need to be powered by wired connections. With utilization of the systems and methods described herein, much of this wiring may be eliminated, saving the enterprise the cost of installation, decreasing the physical limitations associated with office walls having electrical wiring, minimizing the need for power outlets and power strips, and the like. The systems and methods described herein may save money for the enterprise through a reduction in electrical infrastructure associated with installation, re-installation (e.g., reconfiguring office space), maintenance, and the like. In another example, the principles disclosed herein may allow the wireless placement of an electrical outlet in the middle of a room. Here, the source could be placed on the ceiling of a basement below the location on the floor above where one desires to put an outlet. The device resonator could be placed on the floor of the room right above it. Installing a new lighting fixture (or any other electric device for that matter, e.g. camera, sensor, etc., in the center of the ceiling may now be substantially easier for the same reason).

[00461] In another example, the systems and methods described herein may provide power "through" walls. For instance, suppose one has an electric outlet in one room (e.g. on a wall), but one would like to have an outlet in the next room, but without the need to call an electrician, or drill through a wall, or drag a wire around the wall, or the like. Then one might put a source resonator on the wall in one room, and a device resonator outlet/pickup on the other side of the wall. This may power a flat-screen TV or stereo system or the like (e.g. one may not want to have an ugly wire climbing up the wall in the living room, but doesn't mind having a similar wire going up the wall in the next room, e.g. storage room or closet, or a room with furniture that blocks view of wires running along the wall). The systems and methods described herein may be used to transfer power from an indoor source to various electric devices outside of homes or buildings without requiring holes to be drilled through, or conduits installed in, these outside walls. In this case, devices could be wirelessly powered outside the building without the aesthetic or structural damage or risks associated with drilling holes through walls and siding. In addition, the systems and methods described herein may provide for a placement sensor to assist in placing an interior source resonator for an exterior device resonator equipped electrical component. For example, a home owner may place a security light on the outside of their home which includes a wireless device resonator, and now needs to adequately or optimally position the source resonator inside the home. A placement sensor acting between the source and device resonators may better enable that placement by indicating when placement is good, or to a degree of good, such as in a visual indication, an audio indication, a display indication, and the like. In another example, and in a similar way, the systems and methods described herein may provide for the installation of equipment on the roof of a home or building, such as radio transmitters and receivers, solar panels and the like. In the case of the solar panel, the source resonator may be associated with the panel, and power may be wirelessly transferred to a distribution panel inside the building without the need for drilling through the roof. The systems and methods described herein may allow for the mounting of electric or electrical components across the walls of vehicles (such as through the roof) without the need to drill holes, such as for automobiles, water craft, planes, trains, and the like. In this way, the vehicle's walls may be left intact without holes being drilled, thus maintaining the value of the vehicle, maintaining watertightness, eliminating the need to route wires, and the like. For example, mounting a siren or light to the roof of a police car decreases the future resale of the car, but with the systems and methods described herein, any light, horn, siren, and the like, may be attached to the roof without the need to drill a hole.

[00462] The systems and methods described herein may be used for wireless transfer of power from solar photovoltaic (PV) panels. PV panels with wireless power transfer capability may have several benefits including simpler installation, more flexible, reliable, and weatherproof design. Wireless power transfer may be used to transfer power from the PV panels to a device, house, vehicle, and the like. Solar PV panels may have a wireless source resonator allowing the PV panel to directly power a device that is enabled to receive the wireless power. For example, a solar PV panel may be mounted directly onto the roof of a vehicle, building, and the like. The energy captured by the PV panel may be wirelessly transferred directly to devices inside the vehicle or under the roof of a building. Devices that have resonators can wirelessly receive power from the PV panel. Wireless power transfer from PV panels may be used to transfer energy to a resonator that is coupled to the wired electrical system of a house, vehicle, and the like allowing traditional power distribution and powering of conventional devices without requiring any direct contact between the exterior PV panels and the internal electrical system.

[00463] With wireless power transfer significantly simpler installation of rooftop PV panels is possible because power may be transmitted wirelessly from the panel to a capture resonator in the house, eliminating all outside wiring, connectors, and conduits, and any holes through the roof or walls of the structure. Wireless power transfer used with solar cells may have a benefit in that it can reduced roof danger since it eliminates the need for electricians to work on the roof to interconnect panels, strings, and junction boxes. Installation of solar panels integrated with wireless power transfer may require less skilled labor since fewer electrical contacts need to be made. Less site specific design may be required with wireless power transfer since the technology gives the installer the ability to individually optimize and position each solar PV panel, significantly reducing the need for expensive engineering and panel layout services. There may not be need to carefully balance the solar load on every panel and no need for specialized DC wiring layout and interconnections.

[00464] For rooftop or on-wall installations of PV panels, the capture resonator may be mounted on the underside of the roof, inside the wall, or in any other easily accessible inside space within a foot or two of the solar PV panel. A diagram showing a possible general rooftop PV panel installation is shown in Figure 51. Various PV solar collectors may be mounted in top of a roof with wireless power capture coils mounted inside the building under the roof. The resonator coils in the PV panels can transfer their energy wirelessly through the roof to the wireless capture coils. The captured energy from the PV cells may be collected and coupled to the electrical system of the house to power electric and electronic devices or coupled to the power grid when more power than needed is generated. Energy is captured from the PV cells without requiring holes or wires that penetrate the roof or the walls of the building. Each PV panel may have a resonator that is coupled to a corresponding resonator on the interior of the vehicle or building. Multiple panels may utilize wireless power transfer between each other to transfer or collect power to one or a couple of designated panels that are coupled to resonators on the interior of the vehicle of house. Panels may have wireless power resonators on their sides or in their perimeter that can couple to resonators located in other like panels allowing transfer of power from panel to panel. An additional bus or connection structure may be provided that wirelessly couples the power from multiple panels on the exterior of a building or vehicle and transfers power to one or a more resonators on the interior of building or vehicle.

[00465] For example, as shown in Fig. 51, a source resonator 5102 may be coupled to a PV cell 5100 mounted on top of roof 5104 of a building. A corresponding capture resonator 5106 is placed inside the building. The solar energy captured by the PV cells can then be transferred between the source resonators 5102 outside to the device resonators 5106 inside the building without having direct holes and connections through the building.

[00466] Each solar PV panel with wireless power transfer may have its own inverter, significantly improving the economics of these solar systems by individually optimizing the power production efficiency of each panel, supporting a mix of panel sizes and types in a single installation, including single panel “pay-as-you-grow” system expansions. Reduction of installation costs may make a single panel economical for installation. Eliminating the need for panel string designs and careful positioning and orienting of multiple panels, and eliminating a single point of failure for the system.

[00467] Wireless power transfer in PV solar panels may enable more solar deployment scenarios because the weather-sealed solar PV panels eliminate the need to drill holes for wiring through sealed surfaces such as car roofs and ship decks, and eliminate the requirement that the panels be installed in fixed locations. With wireless power transfer, PV panels may be deployed temporarily, and then moved or removed, without leaving behind permanent alterations to the surrounding structures. They may be placed out in a yard on sunny days, and moved around to follow the sun, or brought inside for cleaning or storage, for example. For backyard or mobile solar PV applications, an extension cord with a wireless energy capture device may be thrown on the ground or placed near the solar unit. The capture extension cord can be completely sealed from the elements and electrically isolated, so that it may be used in any indoor or outdoor environment.

[00468] With wireless power transfer no wires or external connections may be necessary and the PV solar panels can be completely weather sealed. Significantly improved reliability and lifetime of electrical components in the solar PV power generation and transmission circuitry can be expected since the weather-sealed enclosures can protect components from UV radiation, humidity, weather, and the like. With wireless power transfer and weather-sealed enclosures it may be possible to use less expensive components since they will no longer be directly exposed to external factors and weather elements and it may reduce the cost of PV panels.

[00469] Power transfer between the PV panels and the capture resonators inside a building or a vehicle may be bidirectional. Energy may be transmitted from the house grid to the PV panels to provide power when the panels do not have enough energy to perform certain tasks such. Reverse power flow can be used to melt snow from the panels, or power motors that will position the panels in a more favorable positions with respect to the sun energy. Once the snow is melted or the panels are repositioned and the PV panels can generate their own energy the direction of power transfer can be returned to normal delivering power from the PV panels to buildings, vehicles, or devices.

[00470] PV panels with wireless power transfer may include auto-tuning on installation to ensure maximum and efficient power transfer to the wireless collector. Variations in roofing materials or variations in distances between the PV panels and the wireless power collector in different installations may affect the performance or perturb the properties of the resonators of the wireless power transfer. To reduce the installation complexity the wireless power transfer components may include a tuning capability to automatically adjust their operating point to compensate for any effects due to materials or distance. Frequency, impedance, capacitance, inductance, duty cycle, voltage levels and the like may be adjusted to ensure efficient and safe power transfer

[00471] The systems and methods described herein may be used to provide a wireless power zone on a temporary basis or in extension of traditional electrical outlets to wireless power zones, such as through the use of a wireless power extension cord. For example, a wireless power extension cord may be configured as a plug for connecting into a traditional power outlet, a long wire such as in a traditional power extension cord, and a resonant source coil on the other end (e.g. in place of, or in addition to, the traditional socket end of the extension The wireless extension cord may also be configured where there are source resonators at a plurality of locations along the wireless extension cord. This configuration may then replace any traditional extension cord where there are wireless power configured devices, such as providing wireless power to a location where there is no convenient power outlet (e.g. a location in the living room where there’s no outlet), for temporary wireless power where there is no wired power infrastructure (e.g. a construction site), out into the yard where there are no outlets (e.g. for parties or for yard grooming equipment that is wirelessly powered to decrease the chances of cutting the traditional electrical cord), and the like. The wireless extension cord may also be used as a drop within a wall or structure to provide wireless power zones within the vicinity of the drop. For example, a wireless extension cord could be run within a wall of a new or renovated room to provide wireless power zones without the need for the installation of traditional electrical wiring and outlets.

[00472] The systems and methods described herein may be utilized to provide power between moving parts or rotating assemblies of a vehicle, a robot, a mechanical device, a wind turbine, or any other type of rotating device or structure with moving parts such as robot arms, construction vehicles, movable platforms and the like. Traditionally, power in such systems may have been provided by slip rings or by rotary joints for example. Using wireless power transfer as described herein, the design simplicity, reliability and longevity of these devices may be significantly improved because power can be transferred over a range of distances without any physical connections or contact points that may wear down or out with time. In particular, the preferred coaxial and parallel alignment of the source and device coils may provide wireless power transmission that is not severely modulated by the relative rotational motion of the two coils.

[00473] The systems and methods described herein may be utilized to extend power needs beyond the reach of a single source resonator by providing a series of source-device-source-device resonators. For instance, suppose an existing detached garage has no electrical power and the owner now wants to install a new power service. However, the owner may not want to run wires all over the garage, or have to break into the walls to wire electrical outlets throughout the structure. In this instance, the owner may elect to connect a source resonator to the new power service, enabling wireless power to be supplied to device resonator outlets throughout the back of the garage. The owner may then install a device-source 'relay' to supply wireless power to device resonator outlets in the front of the garage. That is, the power relay may now receive wireless power from the primary source resonator, and then supply available power to a second source resonator to supply power to a second set of device resonators in the front of the garage. This configuration may be repeated again and again to extend the effective range of the supplied wireless power.

[00474] Multiple resonators may be used to extend power needs around an energy blocking material. For instance, it may be desirable to integrate a source resonator into a computer or computer monitor such that the resonator may power devices placed around and especially in front of the monitor or computer such as keyboards, computer mice, telephones , and the like. Due to aesthetics, space constraints, and the like an energy source that may be used for the source resonator may only be located or connected to in the back of the monitor or computer. In many designs of computer or monitors metal components and metal containing circuits are used in the design and packaging which may limit and prevent power transfer from source resonator in the back of the monitor or computer to the front of the monitor or computer. An additional repeater resonator may be integrated into the base or pedestal of the monitor or computer that couples to the source resonator in the back of the monitor or computer and allows power transfer to the space in front of the monitor or computer. The intermediate resonator integrated into the base or pedestal of the monitor or computer does not require an additional power source, it captures power from the source resonator and transfers power to the front around the blocking or power shielding metal components of the monitor or computer.

[00475] The systems and methods described herein may be built-into, placed on, hung from, embedded into, integrated into, and the like, the structural portions of a space, such as a vehicle, office, home, room, building, outdoor structure, road infrastructure, and the like. For instance, one or more sources may be built into, placed on, hung from, embedded or integrated into a wall, a ceiling or ceiling panel, a floor, a divider, a doorway, a stairwell, a compartment, a road surface, a sidewalk, a ramp, a fence, an exterior structure, and the like. One or more sources may be built into an entity within or around a structure, for instance a bed, a desk, a chair, a rug, a mirror, a clock, a display, a television, an electronic device, a counter, a table, a piece of furniture, a piece of artwork, an enclosure, a compartment, a ceiling panel, a floor or door panel, a dashboard, a trunk, a wheel well, a post, a beam, a support or any like entity. For example, a source resonator may be integrated into the dashboard of a user's car so that any device that is equipped with or connected to a device resonator may be supplied with power from the dashboard source resonator. In this way, devices brought into or integrated into the car may be constantly charged or powered while in the car.

[00476] The systems and methods described herein may provide power through the walls of vehicles, such as boats, cars, trucks, busses, trains, planes, satellites and the like. For instance, a user may not want to drill through the wall of the vehicle in order to provide power to an electric device on the outside of the vehicle. A source resonator may be placed inside the vehicle and a device resonator may be placed outside the vehicle (e.g. on the opposite side of a window, wall or structure). In this way the user may achieve greater flexibility in optimizing the placement, positioning and attachment of the external device to the vehicle, (such as without regard to supplying or routing electrical connections to the device). In addition, with the electrical power supplied wirelessly, the external device may be sealed such that it is water tight, making it safe if the electric device is exposed to weather (e.g. rain), or even submerged under water. Similar techniques may be employed in a variety of applications, such as in charging or powering hybrid vehicles, navigation and communications equipment, construction equipment, remote controlled or robotic equipment and the like, where electrical risks exist because of exposed conductors. The systems and methods described herein may provide power through the walls of vacuum chambers or other enclosed spaces such as those used in semiconductor growth and processing, material coating systems, aquariums, hazardous materials handling systems and the like. Power may be provided to translation stages, robotic arms, rotating stages, manipulation and collection devices, cleaning devices and the like.

[00477] The systems and methods described herein may provide wireless power to a kitchen environment, such as to counter-top appliances, including mixers, coffee makers, toasters, toaster ovens, grills, griddles, electric skillets, electric pots, electric woks, waffle makers, blenders, food processors, crock pots, warming trays, induction cooktops, lights, computers, displays, and the like. This technology may improve the mobility and/or positioning flexibility of devices, reduce the number of power cords stored on and strewn across the counter-top, improve the washability of the devices, and the like. For example, an electric skillet may traditionally have separate portions, such as one that is submersible for washing and one that is not submersible because it includes an external electrical connection (e.g. a cord or a socket for a removable cord). However, with a device resonator integrated into the unit, all electrical connections may be sealed, and so the entire device may now be submersed for cleaning. In addition, the absence of an external cord may eliminate the need for an available electrical wall outlet, and there is no longer a need for a power cord to be placed across the counter or for the location of the electric griddle to be limited to the location of an available electrical wall outlet.

[00478] The systems and methods described herein may provide continuous power/charging to devices equipped with a device resonator because the device doesn’t leave the proximity of a source resonator, such as fixed electrical devices, personal computers, intercom systems, security systems, household robots, lighting, remote control units, televisions, cordless phones, and the like. For example, a household robot (e.g. ROOMBA) could be powered/charged via wireless power, and thus work arbitrarily long without recharging. In this way, the power supply design for the household robot may be changed to take advantage of this continuous source of wireless power, such as to design the robot to only use power from the source resonator without the need for batteries, use power from the source resonator to recharge the robot’s batteries, use the power from the source resonator to trickle charge the robot’s batteries, use the power from the source resonator to charge a capacitive energy storage unit, and the like. Similar optimizations of the power supplies and power circuits may be enabled, designed, and realized, for any and all of the devices disclosed herein.

[00479] The systems and methods described herein may be able to provide wireless power to electrically heated blankets, heating pads/patches, and the like. These electrically heated devices may find a variety of indoor and outdoor uses. For example, hand and foot warmers supplied to outdoor workers such as guards, policemen, construction workers and the like might be remotely powered from a source resonator associated with or built into a nearby vehicle, building, utility pole, traffic light, portable power unit, and the like.

[00480] The systems and methods described herein may be used to power a portable information device that contains a device resonator and that may be powered up when the information device is near an information source containing a source resonator. For instance, the information device may be a card (e.g. credit card, smart card, electronic card, and the like) carried in a user's pocket, wallet, purse, vehicle, bike, and the like. The portable information device may be powered up when it is in the vicinity of an information source that then transmits information to the portable information device that may contain electronic logic, electronic processors, memory, a display, an LCD display, LEDs, RFID tags, and the like. For example, the portable information device may be a credit card with a display that "turns on" when it is near an information source, and provide the user with some information such as, “You just received a coupon for 50% off your next Coca Cola purchase”. The information device may store information such as coupon or discount information that could be used on subsequent purchases. The portable information device may be programmed by the user to contain tasks, calendar appointments, to-do lists, alarms and reminders, and the like. The information device may receive up-to-date price information and inform the user of the location and price of previously selected or identified items.

[00481] The systems and methods described herein may provide wireless power transmission to directly power or recharge the batteries in sensors, such as environmental sensors, security sensors, agriculture sensors, appliance sensors, food spoilage sensors, power sensors, and the like, which may be mounted internal to a structure, external to a structure, buried underground, installed in walls, and the like. For example, this capability may replace the need to dig out old sensors to physically replace the battery, or to bury a new sensor because the old sensor is out of power and no longer operational. These sensors may be charged up periodically through the use of a portable sensor source resonator charging unit. For instance, a truck carrying a source resonator equipped power source, say providing ~kW of power, may provide enough power to a ~mW sensor in a few minutes to extend the duration of operation of the sensor for more than a year. Sensors may also be directly powered, such as powering sensors that are in places where it is difficult to connect to them with a wire but they are still within the vicinity of a source resonator, such as devices outside of a house (security camera), on the other side of a wall, on an electric lock on a door, and the like. In another example, sensors that may need to be otherwise supplied with a wired power connection may be powered through the systems and methods described herein. For example, a ground fault interrupter breaker combines residual current and over-current protection in one device for installation into a service panel. However, the sensor traditionally has to be independently wired for power, and this may complicate the installation. However, with the systems and methods described herein the sensor may be powered with a device resonator, where a single source resonator is provided within the service panel, thus simplifying the installation and wiring configuration within the service panel. In addition, the single source resonator may power device resonators mounted on either side of the source resonator mounted within the service panel, throughout the service panel, to additional nearby service panels, and the like. The systems and methods described herein may be employed to provide wireless power to any electrical component associated with electrical panels, electrical rooms, power distribution and the like, such as in electric switchboards, distribution boards, circuit breakers, transformers, backup batteries, fire alarm control panels, and the like. Through the use of the systems and methods described herein, it may be easier to install, maintain, and modify electrical distribution and protection components and system installations.

[00482] In another example, sensors that are powered by batteries may run continuously, without the need to change the batteries, because wireless power may be supplied to periodically or continuously recharge or trickle charge the battery. In such applications, even low levels of power may adequately recharge or maintain the charge in batteries, significantly extending their lifetime and usefulness. In some cases, the battery life may be extended to be longer than the lifetime of the device it is powering, making it essentially a battery that “lasts forever”.

[00483] The systems and methods described herein may be used for charging implanted medical device batteries, such as in an artificial heart, pacemaker, heart pump, insulin pump, implanted coils for nerve or acupressure/acupuncture point stimulation, and the like. For instance, it may not be convenient or safe to have wires sticking out of a patient because the wires may be a constant source of possible infection and may generally be very unpleasant for the patient. The systems and methods described herein may also be used to charge or power medical devices in or on a patient from an external source, such as from a bed or a hospital wall or ceiling with a source resonator. Such medical devices may be easier to attach, read, use and monitor the patient. The systems and methods described herein may ease the need for attaching wires to the patient and the patient's bed or bedside, making it more convenient for the patient to move around and get up out of bed without the risk of inadvertently disconnecting a medical device. This may, for example, be usefully employed with patients that have multiple sensors monitoring them, such as for measuring pulse, blood pressure, glucose, and the like. For medical and monitoring devices that utilize batteries, the batteries may need to be replaced quite often, perhaps multiple times a week. This may present risks associated with people forgetting to replace batteries, not noticing that the devices or monitors are not working because the batteries have died, infection associated with improper cleaning of the battery covers and compartments, and the like.

[00484] The systems and methods described herein may reduce the risk and complexity of medical device implantation procedures. Today many implantable medical devices such as ventricular assist devices, pacemakers, defibrillators and the like, require surgical implantation due to their device form factor, which is heavily influenced by the volume and shape of the long-life battery that is integrated in the device. In one aspect, there is described herein a non-invasive method of recharging the batteries so that the battery size may be dramatically reduced, and the entire device may be implanted, such as via a catheter. A catheter implantable device may include an integrated capture or device coil. A catheter implantable capture or device coil may be designed so that it may be wired internally, such as after implantation. The capture or device coil may be deployed via a catheter as a rolled up flexible coil (e.g. rolled up like two scrolls, easily unrolled internally with a simple spreader mechanism). The power source coil may be worn in a vest or article of clothing that is tailored to fit in such a way that places the source in proper position, may be placed in a chair cushion or bed cushion, may be integrated into a bed or piece of furniture, and the like.

[00485] The systems and methods described herein may enable patients to have a 'sensor vest', sensor patch, and the like, that may include at least one of a plurality of medical sensors and a device resonator that may be powered or charged when it is in the vicinity of a source resonator. Traditionally, this type of medical monitoring facility may have required batteries, thus making the vest, patch, and the like, heavy, and potentially impractical. But using the principles disclosed herein, no batteries (or a lighter rechargeable battery) may be required, thus making such a device more convenient and practical, especially in the case where such a medical device could be held in place without straps, such as by adhesive, in the absence of batteries or with substantially lighter batteries. A medical facility may be able to read the sensor data remotely with the aim of anticipating (e.g. a few minutes ahead of) a stroke, a heart-attack, or the like. When the vest is used by a person in a location remote from the medical facility, such as in their home, the vest may then be integrated with a cell-phone or communications device to call an ambulance in case of an accident or a medical event. The systems and methods described herein may be of particular value in the instance when the vest is to be used by an elderly person, where traditional non-wireless recharging practices (e.g. replacing batteries, plugging in at night, and the like) may not be followed as required. The systems and methods described herein may also be used for charging devices that are used by or that aid handicapped or disabled people who may have difficulty replacing or recharging batteries, or reliably supplying power to devices they enjoy or rely on.

[00486] The systems and methods described herein may be used for the charging and powering of artificial limbs. Artificial limbs have become very capable in terms of replacing the functionality of original limbs, such as arms, legs, hands and feet. However, an electrically powered artificial limb may require substantial power, (such as 10-20W) which may translate into a substantial battery. In that case, the amputee may be left with a choice between a light battery that doesn't last very long, and a heavy battery that lasts much longer, but is more difficult to 'carry' around. The systems and methods described herein may enable the artificial limb to be powered with a device resonator, where the source resonator is either carried by the user and attached to a part of the body that may more easily support the weight (such as on a belt around the waist, for example) or located in an external location where the user will spend an adequate amount of time to keep the device charged or powered, such as at their desk, in their car, in their bed, and the like.

[00487] The systems and methods described herein may be used for charging and powering of electrically powered exo-skeletons, such as those used in industrial and military applications, and for elderly/weak/sick people. An electrically powered exo-skeleton may provide up to a 10-to-20 times increase in "strength" to a person, enabling the person to perform physically strenuous tasks repeatedly without much fatigue. However, exo-skeletons may require more than 100W of power under certain use scenarios, so battery powered operation may be limited to 30 minutes or less. The delivery of wireless power as described herein may provide a user of an exo-skeleton with a continuous supply of power both for powering the structural movements of the exo-skeleton and for powering various monitors and sensors distributed throughout the structure. For instance, an exo-skeleton with an embedded device resonator(s) may be supplied with power from a local source resonator. For an industrial exo-skeleton, the source resonator may be placed in the walls of the facility. For a military exo-skeleton, the source resonator may be carried by an armored vehicle. For an exo-skeleton employed to assist a caretaker of the elderly, the source resonator(s) may be installed or placed in or the room(s) of a person's home.

[00488] The systems and methods described herein may be used for the powering/charging of portable medical equipment, such as oxygen systems, ventilators, defibrillators, medication pumps, monitors, and equipment in ambulances or mobile medical units, and the like. Being able to transport a patient from an accident scene to the hospital, or to move patients in their beds to other rooms or areas, and bring all the equipment that is attached with them and have it powered the whole time offers great benefits to the patients' health and eventual well-being. Certainly one can understand the risks and problems caused by medical devices that stop working because their battery dies or because they must be unplugged while a patient is transported or moved in any way. For example, an emergency medical team on the scene of an automotive accident might need to utilize portable medical equipment in the emergency care of patients in the field. Such portable medical equipment must be properly maintained so that there is sufficient battery life to power the equipment for the duration of the emergency. However, it is too often the case that the equipment is not properly maintained so that batteries are not fully charged and in some cases, necessary equipment is not available to the first responders. The systems and methods described herein may provide for wireless power to portable medical equipment (and associated sensor inputs on the patient) in such a way that the charging and maintaining of batteries and power packs is provided automatically and without human intervention. Such a system also benefits from the improved mobility of a patient unencumbered by a variety of power cords attached to the many medical monitors and devices used in their treatment.

[00489] The systems and methods described herein may be used to for the powering/charging of personal hearing aids. Personal hearing aids need to be small and light to fit into or around the ear of a person. The size and weight restrictions limit the size of batteries that can be used. Likewise, the size and weight restrictions of the device make battery replacement difficult due to the delicacy of the components. The dimensions of the devices and hygiene concerns make it difficult to integrate additional charging ports to allow recharging of the batteries. The systems and methods described herein may be integrated into the hearing aid and may reduce the size of the necessary batteries which may allow even smaller hearing aids. Using the principles disclosed herein, the batteries of the hearing aid may be recharged without requiring external connections or charging ports. Charging and device circuitry and a small rechargeable battery may be integrated into a form factor of a conventional hearing aid battery allowing retrofit into existing hearing aids. The hearing aid may be recharged while it is used and worn by a person. The energy source may be integrated into a pad or a cup allowing recharging when the hearing is placed on such a structure. The charging source may be integrated into a hearing aid dryer box allowing wireless recharging while the hearing aid is drying or being sterilized. The source and device resonator may be used to also heat the device reducing or eliminating the need for an additional heating element. Portable charging cases powered by batteries or AC adaptors may be used as storage and charging stations.

[00490] The source resonator for the medical systems described above may be in the main body of some or all of the medical equipment, with device resonators on the patient's sensors and devices; the source resonator may be in the ambulance with device resonators on the patient's sensors and the main body of some or all of the equipment; a primary source resonator may be in the ambulance for transferring wireless power to a device resonator on the medical equipment while the medical equipment is in the ambulance and a second source resonator is in the main body of the medical equipment and a second device resonator on the patient sensors when the equipment is away from the ambulance; and the like. The systems and methods described herein may significantly improve the ease with which medical personnel are able to transport patients from one location to another, where power wires and the need to replace or manually charge associated batteries may now be reduced.

[00491] The systems and methods described herein may be used for the charging of devices inside a military vehicle or facility, such as a tank, armored carrier, mobile shelter, and the like. For instance, when soldiers come back into a vehicle after "action" or a mission, they may typically start charging their electronic devices. If their electronic devices were equipped with device resonators, and there was a source resonator inside the vehicle, (e.g. integrated in the seats or on the ceiling of the vehicle), their devices would start charging immediately. In fact, the same vehicle could provide power to soldiers/robots (e.g. packbot from iRobot) standing outside or walking beside the vehicle. This capability may be useful in minimizing accidental battery-swapping with someone else (this may be a significant issue, as soldiers tend to trust only their own batteries); in enabling quicker exits from a vehicle under attack; in powering or charging laptops or other electronic devices inside a tank, as too many wires inside the tank may present a hazard in terms of reduced ability to move around fast in case of "trouble" and/or decreased visibility; and the like. The systems and methods described herein may provide a significant improvement in association with powering portable power equipment in a military environment.

[00492] The systems and methods described herein may provide wireless powering or charging capabilities to mobile vehicles such as golf carts or other types of carts, all-terrain vehicles, electric bikes, scooters, cars, mowers, bobcats and other vehicles typically used for construction and landscaping and the like. The systems and methods described herein may provide wireless powering or charging capabilities to miniature mobile vehicles, such as mini-helicopters, airborne drones, remote control planes, remote control boats, remote controlled or robotic rovers, remote controlled or robotic lawn mowers or equipment, bomb detection robots, and the like. For instance, mini-helicopter flying above a military vehicle to increase its field of view can fly for a few minutes on standard batteries. If these mini-helicopters were fitted with a device resonator, and the control vehicle had a source resonator, the mini-helicopter might be able to fly indefinitely. The systems and methods described herein may provide an effective alternative to recharging or replacing the batteries for use in miniature mobile vehicles. In addition, the systems and methods described herein may provide power/charging to even smaller devices, such as microelectromechanical systems (MEMS), nano-robots, nano devices, and the like. In addition, the systems and methods described herein may be implemented by installing a source device in a mobile vehicle or flying device to enable it to serve as an in-field or in-flight re-charger, that may position itself autonomously in proximity to a mobile vehicle that is equipped with a device resonator.

[00493] The systems and methods described herein may be used to provide power networks for temporary facilities, such as military camps, oil drilling setups, remote filming locations, and the like, where electrical power is required, such as for power generators, and where power cables are typically run around the temporary facility. There are many instances when it is necessary to set up temporary facilities that require power. The systems and methods described herein may enable a more efficient way to rapidly set up and tear down these facilities, and may reduce the number of wires that must be run throughout the faculties to supply power. For instance, when Special Forces move into an area, they may erect tents and drag many wires around the camp to provide the required electricity. Instead, the systems and methods described herein may enable an army vehicle, outfitted with a power supply and a source resonator, to park in the center of the camp, and provide all the power to nearby tents where the device resonator may be integrated into the tents, or some other piece of equipment associated with each tent or area. A series of source-device-source-device resonators may be used to extend the power to tents that are farther away. That is, the tents closest to the vehicle could then provide power to tents behind them. The systems and methods described herein may provide a significant improvement to the efficiency with which temporary installations may be set up and torn down, thus improving the mobility of the associated facility.

[00494] The systems and methods described herein may be used in vehicles, such as for replacing wires, installing new equipment, powering devices brought into the vehicle, charging the battery of a vehicle (e.g. for a traditional gas powered engine, for a hybrid car, for an electric car, and the like), powering devices mounted to the interior or exterior of the vehicle, powering devices in the vicinity of the vehicle, and the like. For example, the systems and methods described herein may be used to replace wires such as those are used to power lights, fans and sensors distributed throughout a vehicle. As an example, a typical car may have 50kg of wires associated with it, and the use of the systems and methods described herein may enable the elimination of a substantial amount of this wiring. The performance of larger and more weight sensitive vehicles such as airplanes or satellites could benefit greatly from having the number of cables that must be run throughout the vehicle reduced. The systems and methods described herein may allow the accommodation of removable or supplemental portions of a vehicle with electric and electrical devices without the need for electrical harnessing. For example, a motorcycle may have removable side boxes that act as a temporary trunk space for when the cyclist is going on a long trip. These side boxes may have exterior lights, interior lights, sensors, auto equipment, and the like, and if not for being equipped with the systems and methods described herein might require electrical connections and harnessing.

[00495] An in-vehicle wireless power transmission system may charge or power one or more mobile devices used in a car: mobile phone handset, Bluetooth headset, blue tooth hands free speaker phone, GPS, MP3 player, wireless audio transceiver for streaming MP3 audio through car stereo via FM, Bluetooth, and the like. The in vehicle wireless power source may utilize source resonators that are arranged in any of several possible configurations including charging pad on dash, charging pad otherwise mounted on floor, or between seat and center console, charging "cup" or receptacle that fits in cup holder or on dash, and the like.

[00496] The wireless power transmission source may utilize a rechargeable battery system such that said supply battery gets charged whenever the vehicle power is on such that when the vehicle is turned off the wireless supply can draw power from the supply battery and can continue to wirelessly charge or power mobile devices that are still in the car.

[00497] The plug-in electric cars, hybrid cars, and the like, of the future need to be charged, and the user may need to plug in to an electrical supply when they get home or to a charging station. Based on a single over-night recharging, the user may be able to drive up to 50 miles the next day. Therefore, in the instance of a hybrid car, if a person drives less than 50 miles on most days, they will be driving mostly on electricity. However, it would be beneficial if they didn't have to remember to plug in the car at night. That is, it would be nice to simply drive into a garage, and have the car take care of its own charging. To this end, a source resonator may be built into the garage floor and/or garage side-wall, and the device resonator may be built into the bottom (or side) of the car. Even a few kW transfer may be sufficient to recharge the car over-night. The in-vehicle device resonator may measure magnetic field properties to provide feedback to assist in vehicle (or any similar device) alignment to a stationary resonating source. The vehicle may use this positional feedback to automatically position itself to achieve optimum alignment, thus optimum power transmission efficiency. Another method may be to use the positional feedback to help the human operator to properly position the vehicle or device, such as by making LED's light up, providing noises, and the like when it is well positioned. In such cases where the amount of power being transmitted could present a safety hazard to a person or animal that intrudes into the active field volume, the source or receiver device may be equipped with an active light curtain or some other external device capable of sensing intrusion into the active field volume, and capable of shutting off the source device and alert a human operator. In addition, the source device may be equipped with self-sensing capability such that it may detect that its expected power transmission rate has been interrupted by an intruding element, and in such case shut off the source device and alert a human operator. Physical or mechanical structures such as hinged doors or inflatable bladder shields may be incorporated as a physical barrier to prevent unwanted intrusions. Sensors such as optical, magnetic, capacitive, inductive, and the like may also be used to detect foreign structures or interference between the source and device resonators. The shape of the source resonator may be shaped such to prevent water or debris accumulation. The source resonator may be placed in a cone shaped enclosure or may have an enclosure with an angled top to allow water and debris to roll off. The source of the system may use battery power of the vehicle or its own battery power to transmit its presence to the source to initiate power transmission.

[00498] The source resonator may be mounted on an embedded or hanging post, on a wall, on a stand, and the like for coupling to a device resonator mounted on the bumper, hood, body panel, and the like, of an electric vehicle. The source resonator may be enclosed or embedded into a flexible enclosure such as a pillow, a pad, a bellows, a spring loaded enclosure and the like so that the electric vehicle may make contact with the structure containing the source coil without damaging the car in any way. The structure containing the source may prevent objects from getting between the source and device resonators. Because the wireless power transfer may be relatively insensitive to misalignments between the source and device coils, a variety of flexible source structures and parking procedures may be appropriate for this application.

[00499] The systems and methods described herein may be used to trickle charge batteries of electric, hybrid or combustion engine vehicles. Vehicles may require small amounts of power to maintain or replenish battery power. The power may be transferred wirelessly from a source to a device resonator that may be incorporated into the front grill, roof, bottom, or other parts of the vehicle. The device resonator may be designed to fit into a shape of a logo on the front of a vehicle or around the grill as not to obstruct air flow through the radiator. The device or source resonator may have additional modes of operation that allow the resonator to be used as a heating element which can be used to melt of snow or ice from the vehicle.

[00500] An electric vehicle or hybrid vehicle may require multiple device resonators, such as to increase the ease with which the vehicle may come in proximity with a source resonator for charging (i.e. the greater the number and varied position of device resonators are, the greater the chances that the vehicle can pull in and interface with a diversity of charging stations), to increase the amount of power that can be delivered in a period of time (e.g. additional device resonators may be required to keep the local heating due to charging currents to acceptable levels), to aid in automatic parking/docking the vehicle with the charging station, and the like. For example, the vehicle may have multiple resonators (or a single resonator) with a feedback system that provides guidance to either the driver or an automated parking/docking facility in the parking of the vehicle for optimized charging conditions (i.e., the optimum positioning of the vehicle's device resonator to the charging station's source resonator may provide greater power transfer efficiency). An automated parking/docking facility may allow for the automatic parking of the vehicle based on how well the vehicle is coupled.

[00501] The power transmission system may be used to power devices and peripherals of a vehicle. Power to peripherals may be provided while a vehicle is charging, or while not charging, or power may be delivered to conventional vehicles that do not need charging. For example, power may be transferred wirelessly to conventional non-electric cars to power air conditioning, refrigeration units, heaters, lights, and the like while parked to avoid running the engine which may be important to avoid exhaust build up in garage parking lots or loading docks. Power may for example be wirelessly transferred to a bus while it is parked to allow powering of lights, peripherals, passenger devices, and the like avoiding the use of onboard engines or power sources. Power may be wirelessly transferred to an airplane while parked on the tarmac or in a hanger to power instrumentation, climate control, de-icing equipment, and the like without having to use onboard engines or power sources.

[00502] Wireless power transmission on vehicles may be used to enable the concept of Vehicle to Grid (V2G). Vehicle to grid is based on utilizing electric vehicles and plug-in hybrid electric vehicles (PHEV) as distributed energy storage devices, charged at night when the electric grid is underutilized, and available to discharge back into the grid during episodes of peak demand that occur during the day. The wireless power transmission system on a vehicle and the respective infrastructure may be implemented in such a way as to enable bidirectional energy flow—so that energy can flow back into the grid from the vehicle—without requiring a plug in connection. Vast fleets of vehicles, parked at factories, offices, parking lots, can be viewed as "peaking power capacity" by the smart grid. Wireless power transmission on vehicles can make such a V2G vision a reality. By simplifying the process of connecting a vehicle to the grid, (i.e. by simply parking it in a wireless charging enabled parking spot), it becomes much more likely that a certain number of vehicles will be "dispatchable" when the grid needs to tap their power. Without wireless charging, electric and PHEV owners will likely charge their vehicles at home, and park them at work in conventional parking spots. Who will want to plug their vehicle in at work, if they do not need charging? With wireless charging systems capable of handling 3 kW, 100,000 vehicles can provide 300 Megawatts back to the grid—using energy generated the night before by cost effective base load generating capacity. It is the streamlined ergonomics of the cordless self charging PHEV and electric vehicles that make it a viable V2G energy source.

[00503] The systems and methods described herein may be used to power sensors on the vehicle, such as sensors in tires to measure air-pressure, or to run peripheral devices in the vehicle, such as cell phones, GPS devices, navigation devices, game players, audio or video players, DVD players, wireless routers, communications equipment, anti-theft devices, radar devices, and the like. For example, source resonators described herein may be built into the main compartment of the car in order to supply power to a variety of devices located both inside and outside of the main compartment of the car. Where the vehicle is a motorcycle or the like, devices described herein may be integrated into the body of the motorcycle, such as under the seat, and device resonators may be provided in a user's helmet, such as for communications, entertainment, signaling, and the like, or device resonators may be provided in the user's jacket, such as for displaying signals to other drivers for safety, and the like.

[00504] The systems and methods described herein may be used in conjunction with transportation infrastructure, such as roads, trains, planes, shipping, and the like. For example, source resonators may be built into roads, parking lots, rail-lines, and the like. Source resonators may be built into traffic lights, signs, and the like. For example, with source resonators embedded into a road, and device resonators built into vehicles, the vehicles may be provided power as they drive along the road or as they are parked in lots or on the side of the road. The systems and methods described herein may provide an effective way for electrical systems in vehicles to be powered and/or charged while the vehicle traverses a road network, or a portion of a road network. In this way, the systems and methods described herein may contribute to the powering/charging of autonomous vehicles, automatic guided vehicles, and the like. The systems and methods described herein may provide power to vehicles in places where they typically idle or stop, such as in the vicinity of traffic lights or signs, on highway ramps, or in parking lots.

[00505] The systems and methods described herein may be used in an industrial environment, such as inside a factory for powering machinery, powering/charging robots, powering and/or charging wireless sensors on robot arms, powering/charging tools and the like. For example, using the systems and methods described herein to supply power to devices on the arms of robots may help eliminate direct wire connections across the joints of the robot arm. In this way, the wearing out of such direct wire connections may be reduced, and the reliability of the robot increased. In this case, the device resonator may be out on the arm of the robot, and the source resonator may be at the base of the robot, in a central location near the robot, integrated into the industrial facility in which the robot is providing service, and the like. The use of the systems and methods described herein may help eliminate wiring otherwise associated with power distribution within the industrial facility, and thus benefit the overall reliability of the facility.

[00506] The systems and methods described herein may be used for underground applications, such as drilling, mining, digging, and the like. For example, electrical components and sensors associated with drilling or excavation may utilize the systems and methods described herein to eliminate cabling associated with a digging mechanism, a drilling bit, and the like, thus eliminating or minimizing cabling near the excavation point. In another example, the systems and methods described herein may be used to provide power to excavation equipment in a mining application where the power requirements for the equipment may be high and the distances large, but where there are no people to be subjected to the associated required fields. For instance, the excavation area may have device resonator powered digging equipment that has high power requirements and may be digging relatively far from the source resonator. As a result the source resonator may need to provide high field intensities to satisfy these requirements, but personnel are far enough away to be outside these high intensity fields. This high power, no personnel, scenario may be applicable to a plurality of industrial applications.

[00507] The systems and methods described herein may also use the near-field non-radiative resonant scheme for information transfer rather than, or in addition to, power transfer. For instance, information being transferred by near-field non-radiative resonance techniques may not be susceptible to eavesdropping and so may provide an increased level of security compared to traditional wireless communication schemes. In addition, information being transferred by near-field non-radiative resonance techniques may not interfere with the EM radiative spectrum and so may not be a source of EM interference, thereby allowing communications in an extended frequency range and well within the limits set by any regulatory bodies. Communication services may be provided between remote, inaccessible or hard-to-reach places such as between remote sensors, between sections of a device or vehicle, in tunnels, caves and wells (e.g. oil wells, other drill sites) and between underwater or underground devices, and the like. Communications services may be provided in places where magnetic fields experience less loss than electric fields.

[00508] The systems and methods described herein may enable the simultaneous transmission of power and communication signals between sources and devices in wireless power transmission systems, or it may enable the transmission of power and communication signals during different time periods or at different frequencies. The performance characteristics of the resonator may be controllably varied to preferentially support or limit the efficiency or range of either energy or information transfer. The performance characteristics of the resonators may be controlled to improve the security by reducing the range of information transfer, for example. The performance characteristics of the resonators may be varied continuously, periodically, or according to a predetermined, computed or automatically adjusted algorithm. For example, the power and information transfer enabled by the systems and methods described herein may be provided in a time multiplexed or frequency multiplexed manner. A source and device may signal each other by tuning, changing, varying, dithering, and the like, the resonator impedance which may affect the reflected impedance of other resonators that can be detected. The information transferred as described herein may include information regarding device identification, device power requirements, handshaking protocols, and the like.

[00509] The source and device may sense, transmit, process and utilize position and location information on any other sources and/or devices in a power network. The source and device may capture or use information such as elevation, tilt, latitude and longitude, and the like from a variety of sensors and sources that may be built into the source and device or may be part of a component the source or device connect. The positioning and orientation information may include sources such as global positioning sensors (GPS), compasses, accelerometers, pressure sensors, atmospheric barometric sensors, positioning systems which use Wi-Fi or cellular network signals, and the like. The source and device may use the position and location information to find nearby wireless power transmission sources. A source may broadcast or communicate with a central station or database identifying its location. A device may obtain the source location information from the central station or database or from the local broadcast and guide a user or an operator to the source with the aid of visual, vibrational, or auditory signals. Sources and devices may be nodes in a power network, in a communications network, in a sensor network, in a navigational network, and the like or in kind of combined functionality network.

[00510] The position and location information may also be used to optimize or coordinate power delivery. Additional information about the relative position of a source and a device may be used to optimize magnetic field direction and resonator alignment. The orientation of a device and a source which may be obtained from accelerometers and magnetic sensors, and the like, for example, may be used to identify the orientation of resonators and the most favorable direction of a magnetic field such that the magnetic flux is not blocked by the device circuitry. With such information a source with the most favorable orientation, or a combination of sources, may be used. Likewise, position and orientation information may be used to move or provide feedback to a user or operator of a device to place a device in a favorable orientation or location to maximize power transmission efficiency, minimize losses, and the like.

[00511] The source and device may include power metering and measuring circuitry and capability. The power metering may be used to track how much power was delivered to a device or how much power was transferred by a source. The power metering and power usage information may be used in fee based power delivery arrangements for billing purposes. Power metering may be also be used to enable power delivery policies to ensure power is distributed to multiple devices according to specific criteria. For example, the power metering may be used to categorize devices based on the amount of power they received and priority in power delivery may be given to those having received the least power. Power metering may be used to provide tiered delivery services such as “guaranteed power” and “best effort power” which may be billed at separate rates. Power metering may be used to institute and enforce hierarchical power delivery structures and may enable priority devices to demand and receive- more power under certain circumstances or use scenarios.

[00512] Power metering may be used to optimize power delivery efficiency and minimize absorption and radiation losses. Information related to the power received by devices may be used by a source in conjunction with information about the power output of the source to identify unfavorable operating environments or frequencies. For example, a source may compare the amount of power which was received by the devices and the amount of power which it transmitted to determine if the transmission losses may be unusually or unacceptably large. Large transmission losses may be due to an unauthorized device receiving power from the source and the source and other devices may initiate frequency hopping of the resonance frequency or other defensive measures to prevent or deter unauthorized use. Large transmission losses may be due to absorption losses for example, and the device and source may tune to alternate resonance frequencies to minimize such losses. Large transmission losses may also indicate the presence of unwanted or unknown objects or materials and the source may turn down or off its power level until the unwanted or unknown object is removed or identified, at which point the source may resume powering remote devices.

[00513] The source and device may include authentication capability. Authentication may be used to ensure that only compatible sources and devices are able to transmit and receive power. Authentication may be used to ensure that only authentic devices that are of a specific manufacturer and not clones or devices and sources from other manufacturers, or only devices that are part of a specific subscription or plan, are able to receive power from a source. Authentication may be based on cryptographic request and respond protocols or it may be based on the unique signatures of perturbations of specific devices allowing them to be used and authenticated based on properties similar to physically unclonable functions. Authentication may be performed locally between each source and device with local communication or it may be used with third person authentication methods where the source and device authenticate with communications to a central authority. Authentication protocols may use position information to alert a local source or sources of a genuine device.

[00514] The source and device may use frequency hopping techniques to prevent unauthorized use of a wireless power source. The source may continuously adjust or change the resonant frequency of power delivery. The changes in frequency may be performed in a pseudorandom or predetermined manner that is known, reproducible, or communicated to authorized device but difficult to predict. The rate of frequency hopping and the number of various frequencies used may be large and frequent enough to ensure that unauthorized use is difficult or impractical. Frequency hopping may be implemented by tuning the impedance network, tuning any of the driving circuits, using a plurality of resonators tuned or tunable to multiple resonant frequencies, and the like.

[00515] The source may have a user notification capability to show the status of the source as to whether it is coupled to a device resonator and transmitting power, if it is in standby mode, or if the source resonator is detuned or perturbed by an external object. The notification capability may include visual, auditory, and vibrational methods. The notification may be as simple as three color lights, one for each state, and optionally a speaker to provide notification in case of an error in operation. Alternatively, the notification capability may involve an interactive display that shows the status of the source and optionally provides instructions on how to fix or solve any errors or problems identified.

[00516] As another example, wireless power transfer may be used to improve the safety of electronic explosive detonators. Explosive devices are detonated with an electronic detonator, electric detonator, or shock tube detonator. The electronic detonator utilizes stored electrical energy (usually in a capacitor) to activate the igniter charge, with a low energy trigger signal transmitted conductively or by radio. The electric detonator utilizes a high energy conductive trigger signal to provide both the signal and the energy required to activate the igniter charge. A shock tube sends a controlled explosion through a hollow tube coated with explosive from the generator to the igniter charge. There are safety issues associated with the electric and electronic detonators, as there are cases of stray electromagnetic energy causing unintended activation. Wireless power transfer via sharply resonant magnetic coupling can improve the safety of such systems.

[00517] Using the wireless power transfer methods disclosed herein, one can build an electronic detonation system that has no locally stored energy, thus reducing the risk of unintended activation. A wireless power source can be placed in proximity (within a few meters) of the detonator. The detonator can be equipped with a resonant capture coil. The activation energy can be transferred when the wireless power source has been triggered. The triggering of the wireless power source can be initiated by any number of mechanisms: radio, magnetic near field radio, conductive signaling, ultrasonics, laser light. Wireless power transfer based on resonant magnetic coupling also has the benefit of being able to transfer power through materials such as rock, soil, concrete, water, and other dense materials. The use of very high Q coils as receivers and sources, having very narrow band response and sharply tuned to proprietary frequencies, further ensure that the detonator circuits cannot capture stray EMI and activate unintentionally.

[00518] The resonator of a wirelessly powered device may be external, or outside of the device, and wired to the battery of the device. The battery of the device may be modified to include appropriate rectification and control circuitry to receive the alternating currents of the device resonator. This can enable configurations with larger external coils, such as might be built into a battery door of a keyboard or mouse, or digital still camera, or even larger coils that are attached to the device but wired back to the battery/converter with ribbon cable. The battery door can be modified to provide interconnection from the external coil to the battery/converter (which will need an exposed contact that can touch the battery door contacts.

[00519] **Stranded Printed Circuit Board Traces**

[00520] As described in previous sections, high-Q inductive elements in magnetic resonators may be formed from litz wire conductors. Litz wires are bundles of thinner, insulated wires woven together in specially designed patterns so that the thinner individual wires do not occupy the same radial position within the larger bundle over any significant length. The weave pattern and the use of multiple smaller diameter wires effectively increases the skin depth and decreases the AC resistance of the wire over a range of frequencies.

[00521] High-Q inductive elements in magnetic resonators may also be formed from printed circuit board (PCB) traces. Printed circuit board traces may have a variety of attractive features including accurate reproducibility, easy integration, and cost effective mass-production. In this section, we disclose low AC resistance stranded PCB traces, comprising multiple narrower insulated traces, potentially distributed over multiple board layers, that do not maintain fixed positions within the weave pattern, and that may be fabricated using standard fabrication techniques. The AC resistance of these stranded traces may be determined by the number, the size, and the relative spacing of the narrower individual traces in the designed weave pattern, as well as by the number of board layers on which the weave patterns are printed and interconnected. Individual trace insulation may be provided by air, by circuit board materials, by coatings, by flexible sheets, by cured materials, and the like.

[00522] In embodiments, stranded trace weave patterns for PCB fabrication may be designed to be easily reproducible and scalable, as well as to achieve high individual trace densities. The achievable trace density may be determined by the narrowness of the individual traces, by the geometry of the weave pattern, and by the need to incorporate other, potentially larger structures or features, such as "vias" for example, in the weave pattern. In embodiments, methods and designs that place all the vias or through-holes used to connect individual traces between multiple layers of a PCB may be preferably placed on the outer perimeters of the multi-trace weave pattern. The outer location of the vias enables easy scaling and replication of the pattern as well as tight and uniform individual trace placement and density since the normally larger feature sized vias are not used within the weave pattern itself, potentially disrupting the uniformity of the pattern and the density of the weave.

[00523] As used in the description of this section, the term 'stranded trace' means a conductor formed from a group of multiple smaller or narrower individual traces, trace segments, or wires. In this section we describe techniques for routing individual traces on a multilayer PCB to form stranded traces that have a lower AC resistance than a solid conductor trace of equivalent size would have.

[00524] The braiding of the individual traces on the layered PCB board may be accomplished by routing each individual trace of a stranded trace in a specific pattern such that it undulates across and through the various layers of the PCB. The weave pattern of the individual traces may be designed so that all the individual traces in a stranded trace have substantially the same impedance. That is, an alternating current applied to the stranded trace will flow in substantially equal amounts in each of the individual traces. Because the current may be distributed uniformly across the strands, the AC resistance may be reduced. Note that the stranded conductor may be optimally designed for minimized resistance for specific AC frequencies. In embodiments, system trade-offs such as number and size of individual traces, numbers of layers of the PCB, connection complexities, board space, and the like, may be considered to determine the optimum weave pattern and design.

[00525] In this section we may discuss examples which utilize a layered PCB board with a specific number of layers. The specific number of layers in an example is used to clarify the methods and designs and should not be considered as limiting. The methods and designs can be extended and scaled to PCBs with more or fewer layers.

[00526] In this section we may discuss and describe examples which refer to specific layered PCB technologies or implementations. All of the techniques, methods, algorithms, and implementations described herein may be generic and may be applicable to a wide range of layered printed circuit board technologies and implementations including flex circuit boards and the like.

[00527] The method of routing individual traces to form a stranded trace comprises routing individual traces or segments of traces on different layers of a PCB and varying the relative location of each individual trace or segment within the resulting stranded trace. Each individual trace of a stranded trace may alter its position on each PCB layer, or the individual trace may alternate between two or more positions within a pattern on different PCB layers. It may be preferable that each individual trace of a stranded trace undulate through all the various layers of the layered PCB.

[00528] In layered PCB technologies, traces may be routed through to different conductor or PCB layers with vias or through-holes. The dimensions of the vias may be larger than the possible minimum dimensions of the individual traces, the minimum spacing between individual traces, or the skin depth of AC currents at the frequencies of interest. In embodiments, the designed weave patterns and routing methods may be realized by placing the vias on the outside edges or the exterior of the stranded traces or weave patterns. In embodiments, it may be possible to pack the individual traces as closely as feasible given the fabrication constraints on the individual traces and trace spacing and still achieve AC resistance values suitable for high-Q inductive elements.

[00529] The methods and designs for forming stranded traces on a PCB may comprise a specific routing of individual conductor traces on each layer and specific routing between each layer of the PCB.

[00530] The routing methods and designs may be illustrated and described with an example shown in Figure 52 which demonstrates some of the main characteristics of the methods and designs. Figure 52 depicts an exemplary weave pattern for individual traces that may be formed on each layer of a four layer printed circuit board. Connecting the individual traces across the four layers of the board may form a stranded trace comprising seven individual traces. These seven individual traces may be arranged in the pattern shown and may be repeated to the desired length of the stranded trace. The individual traces on each layer are depicted by the black lines in Figure 52(a) and the vias are represented by the black dots on either side of the traces. Figure 52(a) depicts the individual layers of conductors side by side for clarity. In a PCB, the four layers are stacked, one on top of the other, and separated by the insulator layers of the PCB. The vias on the sides of the stranded conductor may be shared through (or across) all of the layers. For this exemplary embodiment, the first bottom via **5201** in Figure 52 is the same via when the layers are stacked on top of one another. The two numbers next to each via represent the layers with individual traces that are connected by that via. For example, the first bottom via **5201**, which is labeled as 4-1 connects the individual trace segments on the fourth conducting layer and the first conducting layer that are connected to that via.

[00531] Figure 52(b) shows an isometric three dimensional view of the pattern from Figure 52(a). Individual traces on each layer are depicted with black lines and the connections made by the vias between the layers are depicted with dashed and dotted lines. The four layers of patterns in this example are stacked on top one another. The spacing and scale of the layers, as well as the separation between individual traces on each layer have been exaggerated to improve the clarity of the figure. The vias connect individual trace segments between two layers. In this example, all individual trace segments from each layer traverse the width of the stranded trace and are routed with the vias to an adjacent layer.

[00532] A stranded trace may be flanked by rows of vias on both sides of the weave pattern. On each PCB layer, the individual traces may traverse the width of the effective stranded trace. Each individual trace segment may be routed from a via on one side of the stranded trace to a via on the other side of the stranded trace. On each PCB layer, each routed individual trace may be routed from a via that connects that individual trace to an individual trace on another PCB layer. The individual traces may be routed in a manner such that they traverse the width of the effective stranded trace and also traverse a distance with respect to the axis of the stranded trace. The axis of the stranded trace is the virtual line that runs along the length of the stranded trace and is parallel to the rows of vias that flank the stranded trace. The axis of an exemplary stranded trace is illustrated in Figure 52(a) with an arrow **5203.**

[00533] In embodiments, each individual trace may be routed in effectively a substantially diagonal direction with respect to the axis of the stranded trace. In each conducting layer of the PCB, the individual traces may be routed in substantially the same direction. In the exemplary embodiment of Figure 52(a), and 52(b), all the individual traces of

Layer 1 may be routed in a substantially diagonal direction from the vias on one side of the stranded trace to the vias on the other side. At the vias, the individual traces may be routed to another layer of the PCB. All of the individual traces from a layer may be routed to another layer, with a similar, different, translated, reversed and the like, weave pattern at the vias. On the next layer, the individual traces may again be routed, for example, in a substantially diagonal pattern, from the vias on one side of the stranded trace to the vias on the other side of the stranded trace and so on to other layers. This pattern may continue until the individual traces have traversed all or some of the conducting layers of the PCB, whereupon the individual traces may return to the starting conducing layer or an intermediate conducting layer. The individual traces may undulate in such a manner for any number of cycles, depending on the weave pattern, the number of conducting layers in the PCB, the desired length of the stranded trace, and the like. In embodiments, the end points of the stranded traces may be designed to reside of the top and/or bottom layers of the PCBs so they are accessible for easy connection to other circuit elements or conductors.

[00534] In embodiments, on each sequential conductor layer, individual traces may be routed in a substantially diagonal direction with respect to the axis of the stranded trace. In embodiments, on each subsequent conductor layer, individual conductor traces may be routed in a substantially orthogonal direction to that of the previous conductor layer. This pattern can be seen in Figure 52(a) and Figure 52(b). The individual traces in Layer 1 are routed in a substantially diagonal direction traversing the stranded trace from left to right in the Figure. In the subsequent layer, Layer 2, the individual traces are routed in a substantially diagonal direction that is substantially orthogonal to the conductor traces of Layer 1, and are routed from right to left of the stranded trace.

[00535] The routing or path of one individual conductor trace through the various conductor layers may be more easily distinguishable in Figure 53(a) , where the path of one of the individual traces is highlighted by a dotted black line. Starting with the bottom via **5201**, that connects Layer 4 and Layer 1, the individual trace is routed from the left side of the stranded trace to a via on the right side that connects Layer 1 and Layer 2. In this exemplary embodiment, all the individual traces on Layer 1 are routed from vias that connect Layer 4 and Layer 1 and a via that connects Layer 1 and Layer 2. The individual trace is routed to Layer 2 by the via and routed right to left in Layer 2 to a via that connects Layers 2 and 3. On Layer 2 the individual trace is routed to a via that connects Layers 3 and 4. On Layer 4 the individual trace is routed to a via that connects Layers 4 and 1, bringing the individual trace back to the first layer. The pattern can be repeated as many times as required for a specific length of the stranded trace.

[00536] An isometric view of the routing or path of one individual conductor trace through the conductor layers of one example embodiment is depicted in Figure 53(b). The path of one of the individual traces is highlighted by a thick black line. The individual trace traverses the width of the stranded trace on each layer from one via on one side of the stranded trace to a via on the other side of the stranded trace. The individual trace is routed to other layers by the vias. After traversing all of the four layers the individual trace returns to the starting layer and the pattern continues.

[00537] While the example routing patterns shown in Figure 52 and Figure 53 feature 90 degree angles in the individual traces that form the weave pattern, and is based on a rectilinear routing pattern for the individual traces, various other weave and routing patterns may be used. In exemplary embodiments, other weave and routing patterns may yield individual trace patterns that may be along substantially diagonal directions with respect to the axis of the stranded trace. For example, the individual traces may bend at shallower angles (such as 45 degrees) to help reduce the gap between traces. In some embodiments, it may be advantageous to make each individual trace a slanted straight line connected directly between two vias. In other embodiments, various curves of the individual traces may be used when the stranded trace does not follow a straight line path along the circuit board, but turns or loops in a direction, for example. Several alternative exemplary diagonal weave and routing patterns for individual traces are shown in Figure 54, but many other patterns can be derived. In some applications some of the diagonal routing methods may be preferable. For example, for the routing shown in Figure 54(a), the individual traces are straight lines which may be preferable because it may result in the shortest overall conductor length while maintaining consistent spacing between adjacent individual traces. In embodiments, the weave pattern may differ between some or all of the conductor layers in a PCB. For the exemplary stranded trace shown in Figure 52, the weave pattern on the even layers differs from the weave pattern on the odd layers. In the exemplary stranded trace shown in Figure 52 the individual traces are routed a distance of four vias in the direction of the axis of the stranded trace in the odd layers while only a distance of three vias in the even layers.

[00538] As exemplified in Figure 52, the scheme of the present invention concentrates the vias on either side of the array or group of individual traces. Thus, the vias (which may have larger minimum feature sizes than traces and gaps between traces) do not take up space within or between the individual traces. This arrangement of the vias may lead to a higher overall density of traces and therefore to a lower AC resistance per cross-sectional area.

[00539] The exemplary routed structures described above can be generalized for stranded traces that comprise a various number of conducting layers of a layered PCB as well as various numbers of individual traces. The general characteristics of the routing method may be characterized by an integer N, representing the number of conductor layers, and an integer M, representing the number of individual conductor traces that make up the stranded trace.

[00540] For the designs and methods disclosed here, it may be preferable to have an even number of conductor layers. For some specific weave and routing patterns vias that connect traces on two layers may be used. A stranded trace with N conductor layers should have N types of vias connecting the different layers if each via connects only two layers. Each type of via is distinguished or differentiated by the layers that it connects. If each via connects only two layers, for an individual conductor to traverse all of the N layers of a PCB board, there should be N types of vias in the stranded trace. Preferably, there may be $N/2$ types of vias on either side of the stranded trace, arranged in a fixed repeating order. In the exemplary pattern shown in Figure 52, of the four types of vias, two types of vias, those that connect Layers 4 and 1 and Layers 2 and 3 are located only on one side of the stranded trace while the other two types of vias, those that connect Layers 1 and 2 and Layers 3 and 4 are located on the other side of the stranded trace. On each layer, an individual trace may preferably be routed in a substantially diagonal direction with respect to the axis of the stranded trace such that it has a displacement of a distance equivalent to at least $N/2$ vias. All individual conducting traces on a layer may have the same displacement in the axis of the stranded trace.

[00541] The number of individual traces that make make-up a stranded trace may be at least partially determined by the total displacement, sometimes characterized by the number of vias that are passed by, that an individual trace makes after traveling through all the conductor layers of a PCB. If the displacement, after all the layers have been traversed, is D vias, then the stranded trace may be comprised of up to $D/(N/2)$ individual traces. This relationship can be seen in the example in Figure 53. The individual trace represented by the dotted line is displaced a distance equivalent to14 vias along the axis of the stranded trace after traversing through all of the conductor layers. Since the example had $N=4$ layers, the total number of individual conductors that make up the stranded conductor is $M=14/2=7$.

[00542] A stranded trace can be optimized by considering the number of individual traces included in the strand. The larger the number of individual traces, the longer each individual trace spends on any one layer which may reduce the effectiveness of the weaving pattern on reducing skin/proximity effects.

[00543] If the number of individual traces and the number of conductor layers are chosen appropriately, it may be possible to ensure that each individual trace will be displaced the same distance in each layer along the axis of the stranded conductor. A sufficient condition for this to occur is to choose $M(N/2)$ such that it is divisible by N and to choose M such that $(M/2)\mathrm{mod}(N/2)$ and $N/2$ are co-prime where "*mod*" is the modulo operation.

[00544] Figure 55 shows another example of a partial pattern of weaved individual traces of the proposed methods. The Figure depicts the individual traces of the first layer of a ten layer stranded trace design. The ten layer stranded trace consists of 136 separate conductors. The parameters of the stranded trace may allow complete symmetry in all ten layers of the stranded conductor. Each conductor layer pattern may be a translated mirror image of the previous layer. That is, the pattern of traces on odd-numbered layers may be the same pattern as the first layer translated in such a way that the ends of the individual trace segments are connected to the correct vias. The patterns for the even-numbered layers can be recovered by reflection symmetry and similar translations for this example.

[00545] Figure 56 is a cross-sectional view representing the conducting layers of a multi-layered PCB. The individual trace segments on each layer (not visible), and therefore the currents they conduct, may flow primarily into the page but they have an additional sideways displacement along each layer, as indicated by the horizontal arrows in the figure. This horizontal displacement enables each trace to move from one side of the weave pattern on a given layer to the opposite side of the weave pattern. Once an individual trace segment reaches the edge of the weave pattern on a particular layer, it is connected by a via (indicated by vertical arrows) to another trace segment on the next layer of the board and makes its way back across the weave pattern in the opposite direction. This pattern repeats itself so that each individual trace spends an approximately equal amount of time at each position along the cross-section of the weave pattern. Alternatively, the individual traces may be routed between the layers in a non-sequential manner. Any permutation of the order of layers may be used. It may be preferable that each individual trace follow the same order or permutation of layers in a strand of traces. Note that the pattern may be continued by connecting trace segments on the bottom layer to trace segments on the top layer, or by routing the traces up and down following the alternate permutations described above.

[00546] Preferably, the cross-sectional dimensions of the individual traces that make up the stranded trace on a PCB are small enough (preferably smaller than one skin-depth $\delta = \sqrt{2 / \omega\mu_r\mu_0\sigma}$) that they render the losses induced by one individual trace or segment on its neighbors small compared to the losses of an isolated individual trace or segment (which for an individual trace smaller than a skin-depth will be close to the direct current (DC) losses). The braiding of the strands helps to ensure that all the strands may have substantially the same impedance, so that if the same voltage is applied across the bundled strands (i.e., the strands are driven in parallel), the strands may individually conduct substantially the same current. Because the AC current may be distributed uniformly across the strands, the AC resistance may be minimized further.

[00547] As an illustration of the above, finite element analysis simulations were performed on stranded traces made of individual copper traces of square cross-section, driven at 250kHz. The simulations were performed on stranded traces that have varying aspect ratios as well different dimensions of the individual conductors. The cross sections of the stranded traces, showing the cross-section of the individual traces in gray are shown in Figure 58. At this frequency, the skin depth of pure copper is ~131μm. If we arrange individual traces that are 152 μm x 152 μm in cross-section **5801** (a little larger than one skin depth) into a square array of 8 layers such that the gap between nearest traces both along and between the layers is 76 μm as in Figure 58(a), we find that the resistance per meter of a stranded trace conductor braided similarly to the pattern in Figure 52 may be 18.7 mΩ/m, which is 64% higher than the DC resistance per length of this structure ,11.4 mΩ/m. By contrast, the resistance per length of this structure if the traces are not braided, or all parallel to the axis of the stranded trace is 31.2 mΩ/m, nearly 3 times the DC value.

[00548] If we make the individual traces of the stranded trace 76 μm x 76 μm in cross section **5802** and arrange them into a square array of 16 layers such that the gap between traces is 38μm as in Figure 58(b) (the overall cross-section being thus essentially unchanged from the previous example), we find that the AC resistance of a braided structure may be 13.2 mΩ/m, about 16% higher than the DC value.

[00549] In the case where the cross-sectional dimensions of the traces cannot be made much smaller than the skin-depth (e.g., because of limitations in manufacturing), the proximity losses may be reduced by increasing the aspect ratio of the individual traces. The aspect ratio in this context is the effective width of the stranded conductor on a single trace divided by the thickness of the stack of conducting and insulating layers that make up the stranded trace. In some cases, the thickness of the stranded trace is given roughly by the thickness of the PCB. Simulations show that if the aspect ratio of the strand of 152 μm x 152 μm traces described above is changed so that there are twice as many trace segments on each layer, but half as many layers as depicted in Figure 58(c), the AC resistance at 250 kHz may be reduced from 18.7mΩ/m to 16.0mΩ/m. For the structure with 76 μm x 76 μm traces, again keeping the number of individual conductors the same, but reducing the thickness of the structure by a factor of two as depicted in Figure 58(d) lowers the AC resistance from 13.2mΩ/m to 12.6mΩ/m. The DC resistance per length in both cases is 11.4mΩ/m. In embodiments, the preferable aspect ratio of the stranded trace may be application dependent. In embodiments, a variety of factors may be considered in determining the best weave patterns for specific high-Q inductive element designs.

[00550] A benefit of the proposed approach is that the vias used in the stranded traces may perforate the board completely. That is, there is no need for partial vias or buried vias. Using vias that perforate the board completely may simplify the manufacturing process. For example, several boards can be stacked together and perforated at the same time. Partial vias, or vias that go through only a few consecutive layers of a PCB typically require perforation prior to assembly of the individual layers. Likewise, buried vias, or vias that connect or go through some internal layers of a PCB require perforation and preparation prior to assembly of the outer layers of the PCB during manufacturing.

[00551] Another benefit of the methods and designs described herein is that the location of vias at the outer edges of the weave pattern may allow for smaller separations between multi-turn or higher density stranded trace patterns. When two stranded traces run near each other on a PCB, or when a single stranded trace is shaped, patterned, folded, turned, and/or routed so that different sections of the stranded trace run near each other on the PCB, the separation between these traces may be reduced by reusing or interspacing the nearby vias. For example, Figure 57 shows the top layer of a PCB with two stranded traces **5701, 5702** that share the same row of vias wherein, for clarity, the vias of the right stranded trace **5702** are depicted as white filled circles while the vias of the left stranded trace **5701** are depicted as black circles. The vias **5703** between the two stranded traces **5701, 5702,** are all in the same row and there is substantially no spacing between the two stranded traces. With the use of buried or blind vias, which individually do not traverse or go through the whole thickness or all the layers of a PCB may be stacked on top of each other and the density of the routing of the individual conductor traces can be further increased since the spacing between the vias may not need to be increased to accommodate the vias of an adjacent stranded trace.

[00552] It will be clear to those skilled in the art that many changes and modifications can be made to the examples shown within the spirit of the invention. For example, although through vias which perforate the PCB may be used with the methods, blind vias or buried vias may also be used. It may be possible to have more than one via stacked on top of another, and one via location may be used to connect more than two sets of conductor layers together which may be used to increase the density of the conductor traces in the stranded trace. Likewise, although examples use vias that connected only two board (conductor) layers together, the routing method may be modified such that each conductor trace is routed on multiple layers simultaneously. Other modification in the spirit of the proposed methods may include routing individual conductor traces from one via to multiple vias, routing from multiple vias to one via on each layer, using multiple conductor traces to route from one via to another on each conductor layer, or any combination thereof.

[00553] In some embodiments it may be beneficial to misalign the conductor traces between the layers to ensure that the traces all present substantially the same impedance.

[00554] The stranded traces may be useful in a large diverse set of applications and may serve as a substitute in any application that typically used traditional braided litz wire. The stranded trace may be routed in a loop or loops of various shapes and dimensions to create a coil that may be used in magnetic field power transfer systems such as traditional induction based power transfer systems or near-field magnetic resonance power transfer systems. In some embodiments and applications where the stranded trace may be used as part of a resonator, the trace dimensions, aspect ratio, routing pattern, and the like may be chosen and optimized to maximize the Q of the resonator. In embodiments, the resonant frequency of the high-Q resonator may be chosen to take advantage of specific weave patterns and/or stranded trace designs.

[00555] In embodiments, the PCB stranded trace loops may be routed such that a core of magnetic material may be placed in the middle of the loop to create a cored loop. The PCB may have a number of cutouts, channels, pockets, mounts, or holes to accommodate a core.

[00556] In embodiments, the PCB of the stranded trace may further be used to carry and integrate other electronics or electronic components. Electronics to power or drive a resonator formed by the stranded trace may be located on the same PCB as the traces.

[00557] <u>Adjustable Source Size</u>

[00558] The efficiency of wireless power transfer methods decreases with the separation distance between a source and a device. The efficiency of wireless power transfer at certain separations between the source and device resonators may be improved with a source that has an adjustable size. The inventors have discovered that the efficiency of wireless power transfer at fixed separations can be optimized by adjusting the relative size of the source and device resonators. For a fixed size and geometry of a device resonator, a source resonator may be sized to optimize the efficiency of wireless power transfer at a certain separations, positions, and/or orientations. When the source and device resonators are close to each other, power transfer efficiency may be optimized when the characteristic sizes or the effective sizes of the resonators are similar. At larger separations, the power transfer efficiency may be optimized by increasing the effective size of the source resonator relative to the device resonator. The source may be configured to change or adjust the source resonator size as a device moves closer or further away from the source, so as to optimize the power transfer efficiency or to achieve a certain desired power transfer efficiency.

[00559] In examples in this section we may describe wireless power transfer systems and methods for which only the source has an adjustable size. It is to be understood that the device may also be of an adjustable size and achieve many of the same benefits. In some systems both the source and the device may be of an adjustable size, or in other systems only the source, or only the device may be of an adjustable size. Systems with only the source being of an adjustable size may be more practical in certain situations. In many practical designs the device size may be fixed or constrained, such as by the physical dimensions of the device into which the device resonator must be integrated, by cost, by weight, and the like, making an adjustable size device resonator impractical or more difficult to implement. It should be apparent to those skilled in the art, however, that the techniques described herein can be used in systems with an adjustable size device, an adjustable size source, or both.

[00560] In this section we may refer to the "effective size" of the resonator rather than the "physical size" of the resonator. The physical size of the resonator may be quantified by the characteristic size of the resonator (the radius of the smallest circle than encompasses an effectively 2-D resonator, for example). The effective size refers to the size or extent of the surface area circumscribed by the current-carrying inductive element in the resonator structure. If the inductive element comprises a series of concentric loops with decreasing radii, connected to each other by a collection of switches, for example, the physical size of the resonator may be given by the radius of the largest loop in the structure, while the effective size of the resonator will be determined by the radius of the largest loop that is "switched into" the inductor and is carrying current.

[00561] In some embodiments, the effective size of the resonator may be smaller than the physical size of the resonator, for example, when a small part of the conductor comprising the resonator is energized. Likewise, the effective size of the resonator may be larger than the physical size of the resonator. For example, as described below in one of the embodiments of the invention, when multiple individual resonators with given physical sizes are arranged to create a resonator array, grid, multi-element pattern, and the like, the effective size of the resonator array may be larger than the physical size of any of the individual resonators.

[00562] The relationship between wireless power transfer efficiency and source-device resonator separation is shown in Figure 59(a). The plot in Figure 59(a) shows the wireless power transfer efficiency for the configuration shown in Figure 59(b) where the source **5902** and device **5901** capacitively loaded conductor loop resonators are on axis **5903** (centered) and parallel to each other. The plot is shown for a fixed size 5 cm by 5 cm device resonator **5901** and three different size source resonators **5902**, 5 cm x 5 cm, 10 cm x 10 cm and 20 cm x 20 cm for a range of separation distances **5906**. Note that the efficiency of wireless power transfer at different separations may depend on the relative sizes of the source and device resonators. That is, the size of the source resonator that results in the most efficient wireless power transfer may be different for different separations between the source and the device resonators. For the configuration captured by the plot in Figure 59(a), for example, at smaller separations the efficiency is highest when the source and device resonators are sized to be substantially equal. For larger separations, the efficiency of wireless power transfer is highest when the source resonator is substantially larger than the device resonator.

[00563] The inventors have discovered that for wireless power transfer systems in which the separation between the source and device resonators changes, there may be a benefit to a source that can be configured to have various effective resonator sizes. As a device is brought closer to or further away from the source, the source resonator may change its effective resonator size to optimize the power transfer efficiency or to operate in a range of desired transfer efficiencies. Such adjustment of the effective resonator size may be manual or automatic and may be part of the overall system control, tracking, operating, stabilization and optimization architectures.

[00564] A wireless power transfer system with an adjustable source size may also be beneficial when all devices that are to be powered by the source do not have similarly sized device resonators. At a fixed separation between a source and a device, devices with two different sizes of device resonators may realize maximum transfer efficiency for different sized source resonators. Then, depending on the charging protocols and the device power requirements and hierarchies, the source may alter its size to preferentially charge or power one of the devices, a class of devices, all of the devices, and the like.

[00565] Furthermore, an additional benefit from an adjustable size source may be obtained when a single source may be required to simultaneously power multiple devices. As more devices require power, the spatial location or the area circumscribed by the source resonator or the active area of the source resonator may need to change. For example, if multiple devices are positioned in an area but are separated from each other, the source may need to be enlarged in order to energize the larger area that includes all the multiple devices. As the number of devices requiring power changes, or their spatial distribution and locations change with respect to the source, an adjustable size source may change its size to change the characteristics and the spatial distribution of the magnetic fields around the source. For example, when a source is required to transfer power to a single device, a relatively smaller source size with the appropriate spatial distribution of the magnetic field may be used to achieve the desired wireless power transfer efficiency. When the source is required to transfer power to multiple devices, a larger source size or a source with a different spatial distribution of the magnetic field may be beneficial since the devices may be in multiple locations around the source. As the number of devices that require power changes, or their distributions or power requirements change, an adjustable size source may change its size to adjust, maximize, optimize, exceed, or meet its operating parameters and specifications.

[00566] Another possible benefit of an adjustable source size may be in reducing power transfer inefficiencies associated with uncertainty or variability of the location of a device with respect to the source. For example, a device with a certain lateral displacement relative to the source may experience reduced power transfer efficiencies. The plot in Figure 60(a) shows the wireless power transfer efficiency for the configuration shown in Figure 60(b) where the source **6002** and device **6001** capacitively loaded conductor loop resonators are parallel to each other but have a lateral offset **6008** between their center axes **6006, 6005**. The plot in Figure 60(a) shows power transfer efficiency for a 5 cm x 5 cm device resonator **6001** separated from a parallel oriented 5 cm x 5 cm source resonator **6002** (bold line) or a 20 cm x 20 cm source resonator **6002** (dotted line) by 2 cm **6008**. Note that at a lateral offset **6007** of approximately 5 cm from the 5 cm x 5 cm source resonator (from the center of the device resonator to the center of the source resonator), there is a “dead spot” in the power transfer efficiency. That is, the transfer efficiency is minimized or approaches zero at a particular source-device offset. The dashed line in Figure 60(a) shows that the wireless power transfer efficiency for the same device at the same separation and same lateral offset but with the source size adjusted to 20 cm by 20 cm may be greater than 90%. The adjustment of the source size from 5 cm x 5 cm to 20 cm x 20 cm moves the location of the “dead spot” from a lateral offset of approximately 5 cm to a lateral offset of greater than 10 cm. In this example, adjusting the source size increases the wireless power transfer efficiency from almost zero to greater than 90%. Note that the 20 cm x 20 cm source is less efficient transferring power to the 5 cm x 5 cm device resonator when the two resonators are on axis, or centered, or are laterally offset by less than approximately 2 to 3 cm. In embodiments, a change in source size may be used to move the location of a charging or powering dead spot, or transfer efficiency minimum, allowing greater positioning flexibility for and/or higher coupling efficiency to, a device.

[00567] In some embodiments, a source with an adjustable size may be implemented as a bank of resonators of various sizes that are selectively driven by a power source or by power and control circuitry. Based on predetermined requirements, calculated requirements, from information from a monitoring, sensing or feedback signal, communication, and the like, an appropriately sized source resonator may be driven by a power source and/or by power and control circuitry and that size may be adjusted as the requirements or distances between the source and the device resonators change. A possible arrangement of a bank of differently sized resonators is shown in Figure 61 which depicts a bank of three differently sized resonators. In the example of Figure 61, the three resonators **6101, 6102, 6103** are arranged concentrically and coupled to power and control circuitry **6104**. The bank of resonators may have other configurations and arrangements. The different resonators may be placed side by side as in Figure 62, arranged in an array, and the like.

[00568] Each resonator in a multi-size resonator bank may have its own power and control circuitry, or they each may be switched in and selectively connected to one or more power and control circuits by switches, relays, transistors, and the like. In some systems, each of the resonators may be coupled to power and control circuitry inductively. In other systems, each of the resonators may be coupled to power and control circuitry through additional networks of electronic components. A three resonator configuration with additional circuitry **6201, 6202, 6203** is shown in Figure 62. In some systems, the additional circuitry **6201, 6202, 6203** may be used for impedance matching between each of the resonators **6101, 6102, 6103** and the power and control circuitry **6204.** In some systems it may be advantageous to make each of the resonators and its respective additional circuitry have the same effective impedance as seen from the power and control circuitry. It some embodiments the effective impedance of each resonator and additional impedance matching network may be matched to the characteristic impedance of the power source or the power and control circuitry. The same effective impedance for all of the resonators may make switching between resonators in a resonator bank easier, more efficient, or quicker and may require less tuning or tunable components in the power and control circuitry.

[00569] In some embodiments of the system with a bank of multi-sized resonators, the additional circuitry **6201, 6202, 6203** may also include additional transistors, switches, relays, and the like, which disable, deactivate, or detune a resonator when not driven or powered by the power and control circuitry. In some embodiments of the system, not all of the resonators in a resonator bank of a source may be powered or driven simultaneously. It such embodiments of the system, it may be desirable to disable, or detune the non-active resonators to reduce energy losses in power transfer due to energy absorption by the unpowered resonators of the source. The unpowered resonators of the source may be deactivated or detuned from the resonant frequency of the other resonators by open circuiting, disrupting, grounding, or cutting the conductor of the resonator. Transistors, switches, relays and the like may be used to selectively open or close electrical paths in the conductor part of a resonator. An unpowered resonator may be likewise detuned or deactivated by removing or adding capacitance or inductance to the resonator with switches, transistors, relays, and the like. In some embodiments, the natural state of individual resonators may be to be detuned from the system operating frequency and to use signals or power from the drive signal to appropriately tune the resonator as it is activated in the bank.

[00570] In some embodiments of a system of a source with a bank of multi-sized resonators, multiple resonators may be driven by one or more power and control circuits simultaneously. In some embodiments of the system powered resonators may be driven out of phase to extend or direct the wireless power transfer. Constructive and destructive interference between the oscillating magnetic fields of multiple resonators driven in-phase or out of phase or at any relativephase or phases may be used to create specific “hotspots” or areas of concentrated magnetic energy. In embodiments, the position of these hotspots may be variable and may be moved around to achieve the desired wireless power transfer efficiencies to devices that are moving around or to address devices at different locations, orientations, and the like. In embodiments, the multi-sized source resonator may be adjusted to implement a power distribution and/or sharing algorithm and/or protocol.

[00571] In some embodiments of a bank of multi-sized resonators, the resonators may all have substantially similar parameters and characteristics despite the differences in their size. For example, the resonators may all have similar impedance, resonant frequency, quality factor, wire gauge, winding spacing, number of turns, power levels, and the like. The properties and characteristics of the resonators may be within 20% of their values.

[00572] In other embodiments of a bank of multi-sized resonators, the resonators may have non-identical parameters and characteristics tailored or optimized for the size of each resonator. For example, in some embodiments the number of turns of a conductor for the larger resonator may be less than for the smallest resonator. Likewise, since the larger resonator may be intended for powering devices that are at a distance from the resonator, the unloaded impedance of the large resonator may be different than that of the small resonator that is intended for powering devices that are closer to the resonator to compensate for the differences in effective loading on the respective resonators due to the differences in separation. In other embodiments, the resonators may have different or variable Q's, they may have different shapes and thicknesses, they may be composed of different inductive and capacitive elements and different conducting materials. In embodiments, the variable source may be custom designed for a specific application.

[00573] In other embodiments, a source with an adjustable size may be realized as an array or grid of similarly sized resonators. Power and control circuitry of the array may selectively drive one or more resonators to change the effective size of the resonator. For example, a possible configuration of a grid of resonators is shown in Figure 63. A grid of similarly sized resonators **6301** may be arranged in a grid and coupled to one or more power and control circuits (not shown). Each of the resonators **6301** of the array can be individually powered or any number of the resonators may be powered simultaneously. In the array, the effective size of the resonator may be changed by controlling the number, location, and driving characteristics (e.g. drive signal phase, phase offset, amplitude, and the like) of the powered resonators. For example, for the array of resonators in Figure 63, the effective size of the resonator may be controlled by changing which individual resonators of the array are powered. The resonator may power only one of the resonators resulting in an effective resonator size **6304** which is equal to the size of one of the individual resonators. Alternatively, four of the individual resonators in the upper left portion of the array may be energized simultaneously creating an effective resonator size **6303** that may be approximately twice the size of each of the individual resonators. All of the resonators may also be energized simultaneously resulting in an effective resonator size **6302** that may be approximately three (3) times larger than the physical size each of the individual resonators.

[00574] In embodiments, the size of the array of individual resonators may be scaled to any size. In larger embodiments it may be impractical to have power and control circuitry for every individual resonator due to cost, wiring constraints, and the like. A switching bar of a cross-switch may be used to connect any of the individual resonators to as few power and control circuits as needed.

[00575] In embodiments of the array of individual resonators, the pattern of the individual energized resonators may be modified or optimized. The shape of the effective resonator may be rectangular, triangular, square, circular, or any arbitrary shape.

[00576] In embodiments of arrays of resonators, which resonators get energized may depend on the separation or distance, the lateral offset, the orientation, and the like, between the device resonator and the source resonator. The number of resonators that may be driven may, for example, depend on the distance and/or the orientation between the device resonators and the source resonators, the number of device resonators, their various power requirements, and the like. The location of the energized resonators in the array or grid may be determined according to the lateral position of the device with respect to the source. For example, in a large array of smaller individual resonators that may cover a floor of a room or a surface of a desk, the number of energized resonators may change as the distance between the device and the floor or desk changes. Likewise, as the device is moved around a room or a desk the location of the energized resonators in the array may change.

[00577] In another embodiment, an adjustable size source resonator may be realized with an array of multi-sized resonators. Several small equally sized resonators may be arranged to make a small assembly of small resonators. The small array may be surrounded by a larger sized resonator to make a larger assembly. The larger assembly may itself be arranged in an array forming a yet larger array with an even larger resonator that may surround the larger array which itself may be arranged in an array, and so on. In this arrangement, the source resonator comprises resonators of various physical sizes distributed throughout the array. An example diagram of an arrangement of resonators is shown in Figure 64. Smaller resonators **6401** may be arranged in two by two arrays and surrounded by another resonator with a larger physical size **6402,** forming an assembly of resonators**.** That assembly of resonators may be arranged in a two by two array and surrounded by a resonator with an even larger physical size **6403**. The pattern can be repeated to make a larger array. The number of times each resonator or assembly of resonators is repeated may be configured and optimized and may or may not be symmetric. In the example of Figure 64, each resonator and assembly may be repeated in a two by two array, but any other dimension of array may be suitable. Note that the arrays may be circular, square, rectangular, triangular, diamond shaped, and the like, or any combination of shapes and sizes. The use of multi-sized resonators in an array may have a benefit in that it may not require that multiple resonators be energized to result in a larger effective resonator. This feature may simplify the power and control circuitry of the source.

[00578] In embodiments, an adjustable source size may also be realized using planar or cored resonator structures that have a core of magnetic material wrapped with a capacitively loaded conductor, examples of which are shown in Figures 11, 12, and 13 and described herein. In one embodiment, as depicted in Figure 65(a), an adjustable source may be realized with a core of magnetic material **6501** and a plurality of conductors **6502, 6503**, and **6504** wrapped around the core such that the loops of the different conductors do not overlap. The effective size of the resonator may be changed or adjusted by energizing a different number of the conductors. A larger effective resonator may be realized when several adjacent conductors are driven or energized simultaneously.

[00579] Another embodiment of an adjustable size source with a cored resonator is shown in Figure 65(b) where a core of magnetic material **6505** is wrapped with a plurality of overlapping conductors **6506, 6507, 6508.** The conductors may be wrapped such that each extends a different distance across the magnetic core **6505.** For example, for the resonator in Figure 65(b), conductor **6508** covers the shortest distance or part of the core **6505** while conductors **6507** and **6506** each cover a longer distance. The effective size of the resonator may be adjusted by energizing a different conductor, with the smallest effective size occurring when the conductor that covers the smallest distance of the magnetic core is energized and the largest effective size when the conductor covering the largest distance of the core is energized. Each of the conductors may be wrapped to achieve similar inductances, impedances, capacitances, and the like. The conductors may all be the same length with the covering distance modified by changing the density or spacing between the multiple loops of a conductor. In some embodiments, each conductor may be wrapped with equal spacing thereby requiring conductors of different lengths for each winding. In other embodiments the number of conductors and the wrapping of each conductor may be further optimized with non constant or varying wrapping spacing, gauge, size, and the like.

[00580] Another embodiment of an adjustable size source with a cored resonator is shown in Figure 65(c) where multiple magnetic cores **6509, 6510, 6511** are gapped, or not touching, and wrapped with a plurality of conductors **6512, 6513, 6514.** Each of the magnetic cores **6509, 6510, 6511** is separated with a gap **6515, 6516** and a conductor is wrapped around each magnetic core, extending past the gap and around the adjacent magnetic core. Conductors that do not span a gap between two magnetic cores, such as the conductor **6513** in Figure 65(c), may be used in some embodiments. The effective size of the resonator may be adjusted by simultaneously energizing a different number of the conductors wrapped around the core. The conductors that are wrapped around the gaps between the magnetic cores may be energized guiding the magnetic field from one core to another extending the effective size of the resonator.

[00581] As those skilled in the art will appreciate, the methods and designs depicted in Figure 65 may be extended to planar resonators and magnetic cores having various shapes and protrusions which may enable adjustable size resonators with a variable size in multiple dimensions. For example, multiple resonators may be wrapped around the extensions of the core shaped as in Figure 13, enabling an adjustable size resonator that has a variable size in two or more dimensions.

[00582] In embodiments an adjustable size source resonator may comprise control and feedback systems, circuits, algorithms, and architectures for determining the most effective source size for a configuration of devices or objects in the environment. The control and feedback systems may use a variety of sensors, communication channels, measurements, and the like for determining the most efficient source size. In embodiments data from sensors, measurement circuitry, communication channels and the like may be processed by a variety of algorithms that select the appropriate source size.

[00583] In embodiments the source and device may comprise a wireless communication channel such as Bluetooth, WiFi, near-field communication, or modulation of the magnetic field which may be used to communicate information allowing selection of the most appropriate or most efficient source size. The device, for example, may communicate received power, current, or voltage to the source, which may be used by the source to determine the efficiency of power transfer. The device may communicate its position or relative position which may be used to calculate the separation distance between the source and device and used to determine the appropriate size of the source.

[00584] In embodiments the source may measure parameters of the resonator or the characteristics of the power transfer to determine the appropriate source size. The source may employ any number of electric or electronic sensors to determine parameters of various resonators or various configurations of source resonators of the source. The source may monitor the impedance, resistance, resonant frequency, the magnitude and phase of currents and voltages, and the like, of each configuration, resonator, or size of the source. These parameters, or changes in these parameters, may be used by the source to determine the most effective source size. For example, a configuration of the source which exhibits the largest impedance difference between its unloaded state and present state may be the most appropriate or the most efficient for the state of the system.

[00585] The operating parameters and the size of the source may be changed continuously, periodically, or on demand, such as in response to a request by the device or by an operator of the system. A device may request or prompt the source to seek the most appropriate source size during specific time intervals, or when the power or voltage at the device drops below a threshold value.

[00586] Figure 66 depicts a possible way a wireless power transfer system may use an adjustable source size **6604** comprising two different sized resonators **6601, 6605** during operation in several configurations and orientations of the device resonator **6602** in one possible system embodiment. When a device with a small resonator **6602** is aligned and in close proximity, the source **6604** may energize the smaller resonator **6605** as shown in Figure 66(a). When a device with a small resonator **6602** is aligned and positioned further away, the source **6604** may energize the larger resonator **6601** as shown in Figure 66(b). When a device with a small resonator **6602** is misaligned, the source **6604** may energize the larger resonator **6602** as shown in Figure 66(c). Finally, when a device with a large resonator **6602** is present, the source **6604** may energize the larger resonator **6601** as shown in Figure 66(d) to maximize the power transfer efficiency.

[00587] In embodiments an algorithm for determining the appropriate source size may be executed on a processor, gate array, or ASIC that is part of the source, connected to the source, or is in communication with the source. In embodiments, the algorithm may sequentially energize all, or a subset of possible source configurations or sizes, measure operating characteristics of the configurations and choose the source size with the most desirable characteristics.

[00588] Wireless Power Transfer with Immersed Resonators

[00589] In embodiments, wireless power transfer systems may be designed to operate when one, two or more resonators are immersed in liquids, slurries, mud, ice, salt solutions, and the like, embedded in materials or surrounded by materials that may be lossy, and/or electrically conducting. In embodiments, power may be transferred wirelessly between one or more resonators that are under water, underground, in streams, in pavement, in cement, in slurries, in mud, in mixtures of materials, in pools of any type of liquid or viscous materials, in wells such as water wells, gas wells, oil wells and the like.

[00590] In embodiments, the source and/or device resonators of the wireless power transfer systems may be designed to reduce the magnitude of the electric field in or at lossy or conducting materials or objects that may be in the regions surrounding the resonators, especially those materials and regions nearest to the resonator, so as to achieve a desirable perturbed Q. In embodiments, enclosures with certain dimensions and positions relative to the conducting loops and electrical components of magnetic resonators may be used to improve the perturbed Q relative to an enclosure-free implementation. Such enclosures may support higher perturbed Q resonators in immersed resonator applications by providing spacing between locations where the electric field strength is relatively high and where the lossy or conducting materials may be located. For example, in applications where the resonator may be immersed in water, salt water, oil, gas, or other lossy materials, it may be beneficial to package a magnetic resonator to ensure a minimum separation distance between the lossy materials and the electrical components of the resonator.

[00591] The packaging, structure, materials, and the like of the resonator may be designed to provide a spacing or “keep away” zone from the conducting loops in the magnetic resonator. In some embodiments the keep away zone may be less than a millimeter around the resonator. In other embodiments the keep away zone may be less than 1 cm or less than 10 cm around the resonator. In embodiments the size of the keep away zone may depend on the levels of power transferred, the lossiness of the surrounding material, operating frequency of the resonator, size of the resonator, and the like. In embodiments, the size of the keep away zone may be restricted by physical constraints of the application and the keep away zone may be designed such that the perturbed Q of the resonator due to the lossy material outside of the keep away zone is at least 50% of the unperturbed Q of the resonator. In embodiments, the keep away zone may be designed such that the perturbed Q of the resonator is greater than 1% of the unperturbed Q.

[00592] In embodiments the keep away zone around the resonator may be provided by packaging that surrounds the resonator and may also surround the power and control circuitry of the resonator. Preferably the packaging may be constructed from non-lossy materials such as certain plastics, composites, plastic composites, Teflon, Rexolite, ABS, ceramics, stone, and the like. The resonator and circuitry may be encased in such packaging or the packaging may provide an outer barrier with another non-lossy material filling the keep away zone within the packaging. Alternatively, the keep-away zone inside the packaging may comprise vacuum, air, gas, sand, and the like. In embodiments the keep away zone may be provided by the components of the resonator or the circuitry. In embodiments the elements of the resonators and circuitry may provide a sufficient keep away zone for some applications, or the components of a resonator may be chosen to naturally provide for a large enough keep away zone. For example, in some applications the electrical insulation on a conductor of a resonator may provide a suitable keep away zone and may not require additional separation. Diagrams of a resonator **6704** with packaging **6702** providing a keep away **6710** zone around the resonator are shown in Figure 67. A resonator **6704** may be completely surrounded by an enclosure **6702** that provides separation and a keep away zone as shown in Figure 67(a). In other embodiments the packaging **6702** may surround and follow the shape of the resonator **6704** to provide a keep away zone around the inside and outside edges of a resonator as shown in Figure 67(b).

[00593] In an exemplary embodiment, depicted in Figure 68, a 15 cm x 15 cm x 5 mm slab of magnetic material **6804** excited at 100kHz by 10 **6806** turns of conductors evenly spaced by 1 cm wound along one of the longer dimensions and immersed in a medium **6808** with resistivity $\rho = 0.2\ \Omega$-m was modeled in a finite element analysis to show the effect of adding a keep away zone. When there was no keep away zone, the perturbing Q due to the lossy medium was 66. With the addition of a keep away zone **6802** shaped like a parallelepiped extending 1 cm from each face of the magnetic material, the perturbing Q was raised to 86. When the shortest distance between the magnetic material **6804** and the edge of the keep away zone **6802** was increased to 2.5 cm, the perturbing Q was calculated to be 119, and when this distance was increased to 10 cm, the perturbing Q improved to 318.

[00594] In embodiments the keep away zone may not provide for a uniform keep away zone around the resonator but may be non uniform and may be larger or thicker in areas of the resonator that may have larger external electrical fields which may be near the capacitors or near the conductor windings or near the corners of the resonator, for example. This may be illustrated by extending the example above, and exploiting the fact that the electric field may be largest along the directions transversing the magnetic moment of the structure. As depicted in Figure 69, if the keep away zone along the magnetic moment of the resonator is reduced from 10 cm to 1 cm while the keep away zone along all other directions is kept at 10 cm, the perturbing Q is reduced from 318 to 255, while the volume occupied by the resonator and the keep away zone **6802** is reduced by more than 51% compared to the case where the keep away zone was 10 cm all around the resonator.

[00595] In embodiments, the resonant frequencies of the wireless power transfer system may be chosen to improve the perturbed Q of the system. For example, even though the intrinsic Q of an exemplary resonator may improve at higher frequencies, the perturbed Q may decrease at higher frequencies. Therefore, in exemplary embodiments, it may be preferable to choose operating frequencies that are lower than the frequency corresponding to the maximized intrinsic Q. In embodiments, the operating frequency may be chosen to be two to ten times lower than the optimum-Q frequency. In other embodiments, the operating frequency may be chosen to be 10 to 100 times lower than the optimum-Q frequency. In yet other embodiments, the operating frequency may be chosen to be one hundred to ten thousand times lower than the optimum-Q frequency. In embodiments, the operating frequency may be between 100 kHz and 500 kHz. In other embodiments, the operating frequency may be chosen to be between 10 kHz and 100 kHz. In yet other embodiments, the operating frequency may be between 500 kHz and 30 MHz.

[00596] In an exemplary embodiment, a capacitively-loaded conducting loop resonator with a loop radius of 15 cm, a resonant frequency of 100 kHz, and surrounded by a fluid with resistivity $\rho = 30\ \Omega$-m was modeled to show the impact of resonator and enclosure design on perturbed Q. The modeled embodiment is shown in Figure 67(a). The capacitively-loaded conducting loop **6704** is enclosed in a box **6702** filled with air **6708**. The spacing between the outer edge of the conducting loop or coil **6704** in Figure 67(a) and the outer edge of the enclosure **6702** is the keep away zone. This spacing **6708** may be filled with air, it may be filled by the enclosure material itself, and/or it may be filled by preferably non-lossy materials such as plastic, composites, plastic composites, ceramics, stone, air, gas, sand, and the like. In embodiments, the loss tangent for the enclosure material may be low enough that it does not perturb the Q of the resonator. In embodiments, the loss tangent of the material may be low enough that it improves the perturbed Q of the enclosed resonator relative to the perturbed Q when the resonator is immersed directly in surrounding materials.

[00597] For the exemplary system shown in Figure 67(a), the intrinsic Q of the resonators increased as the number of turns of the resonator coil increased. However, the perturbed Q of the resonators decreased as the number of turns increased. The perturbed Q could be increased by increasing the size of the keep out zone **6710** between the edges of the coil **6704** and the edges of the enclosure **6702**. In this exemplary embodiment, the perturbed Q of the 4-turn resonator was improved by more than a factor of two (2), for keep out zones larger than 1 cm, and approached its intrinsic Q when the spacing exceeded approximately 2.5 cm. Therefore, enclosures with keep out zones greater than 1 cm may enable efficient wireless power transfer even when the source and device resonators are immersed in or may be in the vicinity of lossy materials.

[00598] Some applications for wireless power transfer where at least one of the resonators is immersed in some material other than air may be currently enabled using directly wired solutions. For example, electrical wires may run along the bottom of a pond, through building materials, down a well shaft, through the hull of a boat, and the like. However, these wires, and the connectors that may be used to provide electrical continuity across different segments of the wiring may be prone to failure and may be expensive and/or difficult to replace when they do fail. In addition, they may be difficult or impossible to install because of positional and rotational uncertainties in the installation process and because that process may compromise the integrity of the structures that support the resonators. Wireless power transfer may be advantageous in these applications because it may accommodate gaps between the energy sources and the energy consuming devices or connections, thereby eliminating the need for wiring or electrical connectors in places where such wiring or connectors may be stressed, dangerous, or failure prone.

[00599] Figure 70 shows an exemplary embodiment of a wireless power transfer system for an underwater sensor application. In this example, a wireless power source **7008** is housed in an annular housing **7004** that surrounds tubing **7002** that may house the wiring used to supply power from a remote generator to the source as well as being used to guide the source resonator **7008** to the general vicinity of the underwater sensor **7010**. This tubing **7002** may be made from a variety of materials including steel, plastic, rubber, metal, and the like and may contain a variety of electronic components, strength members, tubes, valves, conduits and the like. The source **7008** may be used to wirelessly transfer power to a device resonator **7012** that may be coupled to a sensor **7010**. In embodiments, multiple sensors may be arranged at different locations and depths and the wireless power source **7008** may be flexibly positioned to address multiple sensors simultaneously or one at a time.

[00600] Figure 71 shows two exemplary embodiments of capacitively-loaded conducting loop source resonators, one comprising magnetic materials (Figure 71(b)), situated in a rotationally symmetric enclosure **7004**. In the embodiment shown in Figure 71(b), the resonators may have dipole moments that are aligned either parallel to the tubing, defined here as the z-axis (i.e. resonator **7104)**, or parallel to the x-axis or y-axis (i.e. resonator **7104** and **7110** respectively**)** depending on the orientation of the conductor loop **7106** that is wrapped around the core of magnetic material **7108**. In this exemplary embodiment, the highest energy transfer efficiency may be realized when the similarly-sized source and device resonators have z-directed dipole moments and the resonators are aligned. However, for this dipole orientation, the efficiency may vary through zero at relatively small translational misalignments of these resonators, as shown in Figure 72, before recovering and falling off with larger offsets. If both resonators are y-directed, the maximum coupling efficiency may not be as high as for the z-oriented dipoles, but the transfer efficiency only goes to zero when the resonators are relatively far apart. A resonator that comprises orthogonally wrapped capacitively-loaded conducting loops, and can be modeled as having both z-directed and y-directed dipoles as shown in Figure 12, may yield the highest transfer efficiencies over a range of operating scenarios. In embodiments, the orthogonal loops may be used simultaneously, or a selector or switch may be used to select between y-directed and z-directed dipole resonators to achieve the optimum performance. Note that different system considerations may impact which type of resonator is comprised by the source resonator and the device resonator.

[00601] When the source or device resonators are installed, positioned or activated, there may be uncertainty in the offset and rotation of the source resonators relative to the device resonators. Exemplary positional and rotational uncertainties are depicted in Figure 73(a) and 73(b). Source **7008** and device **7012** resonators may have rotational misalignment as shown in Figure 73(a) or lateral or vertical misalignment as shown in Figure 73(b). For single resonator designs, misalignment of resonators may decrease the efficiency of power transfer. In embodiments, the source and device resonator sizes and materials and the alignment of their dipole moments relative to their physical dimensions may be chosen to maximize the range of positional and rotational misalignments over which sufficiently efficient energy transfer may be realized.

[00602] In other embodiments, the potential reduced efficiency associated with positional and rotational uncertainty may be unacceptable. In those embodiments, a number of source resonators may be incorporated in a housing, increasing the probability that at least one of those source resonators is located close enough to the device resonator to yield adequate performance. Exemplary implementations of such a source array are shown in Figure 71. Multiple resonators may be arranged in a circular fashion in an annular housing **7004** such that a resonator is located every several degrees around the housing such that regardless of the rotational uncertainty at least one source and device may have partial alignment. In addition multiple circular arrangements of resonators may be combined to increase the vertical height of the resonator array. An increase in vertical length of a source may increase the system's ability to tolerate vertical misalignments (along the z axis). In embodiments, the outer radius of the annular housing may be increased to increase the system's ability to tolerate horizontal misalignments (along the y-axis). Note that a variety of source resonator designs and array patterns may be used to implement this concept. The array patterns that are shown here are not meant to be limiting in any way. An array may comprise capacitively loaded loop resonators (Figure 71(a)). An array may comprise planar resonators. In some embodiments planar resonators comprising a conductor wrapped around a core of magnetic material may be used. In an array of planar resonators the conductors of some resonators may be wrapped in orthogonal directions for different resonators as depicted in Figure 71(b).

[00603] In addition, the enclosure housing the resonators may be any shape and size and may be application specific. In some applications, the enclosures may be shaped as cubes, rectangular boxes, bulbs, balls, cylinders, sheets, and the like, and may be hollow, solid, or may comprise different materials in their centers. In embodiments, the primary housing and array design considerations may be housing strength, size, appearance, steerability, controllability, water, wind or earth resistance, and the like.

[00604] In embodiments, the multiple source resonators may be connected via switches so that after the source resonator array is installed or positioned, only one, or a few of the source resonators may be energized to achieve wireless power transfer. The system monitoring and control capabilities discussed herein may be used to determine which source resonators may be energized and included in the wireless power transfer system. In embodiments, the Q of the unused resonators may be spoiled or reduced to minimize interactions between these resonators and the energized resonators. The resonator Q's may be altered by remotely controllable switches, fuses, connections, and the like.

[00605] Note that the designs described above for source resonators may also be for device resonators.

[00606] In embodiments, a variety of resonator designs for wireless power transfer may be selected. In an exemplary well drilling application, the source and device resonators may comprise capacitively-loaded conducting loops with air cores or with cores that comprise magnetic materials, as shown in Figure 68. The resonators may include conducting surfaces to redirect and/or guide the resonator fields to reduce the impact of steel or metallic tubing, structures, instruments, casings, and the like. The conducting surfaces and magnetic materials may be shaped to follow the form of certain well structures, such as being bowed outward to conform to the circular tubing and casings that may run up the center of the well. In embodiments, the surface of the magnetic material closest to structures made of metal or steel may comprise a layer of a higher conductivity material so as to reduce losses due to eddy currents on lossier structures. The shapes and sizes of the conducting materials may be the same as for the magnetic materials, or they may be different. In embodiments, conducting layers may conform to the surface of the magnetic materials or to the inside surfaces of an enclosure or to a feature that has been built into the enclosure. In embodiments, conducting layers may be attached to magnetic materials or separate from them. In embodiments, field shaping may be used to direct resonator fields away for lossy materials or structures and/or to direct or guide resonator fields towards other resonators in the power transfer system. In embodiments, capacitively-loaded conducting loops wrapped around magnetic materials such as shown in

Figures 11-14 and Figure16 may be selected for transferring power from a main borehole in a well to a lateral borehole.

[00607] Note that a wireless transfer system for immersed resonator applications may comprise any combination of resonators, enclosures, arrays, electronics, monitoring and control methods as described herein. In embodiments, device resonators may also be installed in arrays, with a subset of the available resonators selected for the wireless power transfer system.

[00608] While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law.

[00609] All documents referenced herein are hereby incorporated by reference.

CLAIMS

What is claimed is:

1. A wireless power transfer system comprising:

   at least one source magnetic resonator comprising a capacitively-loaded conducting loop coupled to a power source and configured to generate an oscillating magnetic field; and

   at least one device magnetic resonator, distal from said source resonators, comprising a capacitively-loaded conducting loop configured to convert said oscillating magnetic fields into electrical energy;

   wherein at least one said resonator has a keep-out zone around the resonator that surrounds the resonator with a layer of non-lossy material.

2. The system of claim 1, wherein the keep-out zone extends at a symmetric distance around the resonator.

3. The system of claim 1, wherein the keep-out zone extends at a asymmetric distance around the resonator.

4. The system of claim 3, wherein the keep-out zone is largest around regions of the resonator where the electric fields are the largest.

5. The system of claim 1, wherein the smallest keep-out zone exceeds 0.25 mm.

6. The system of claim 1, wherein the smallest keep-out zone exceeds 1 cm.

7. The system of claim 1, wherein the smallest keep-out zone exceeds 10 cm.

8. The system of claim 1, wherein the smallest keep-out zone is approximately 1.0% of the characteristic size of the resonator.

9. The system of claim 1, wherein the smallest keep-out zone is approximately 0.1% of the characteristic size of the resonator.

10. The system of claim 1, wherein the magnetic resonator further comprises a magnetic material.

11. The system of claim 1, wherein at least one magnetic resonator has an intrinsic Q greater than 100.

12. The system of claim 10, wherein at least one magnetic resonator is immersed in water.

13. The system of claim 10, wherein at least one magnetic resonator is immersed in oil.

14. The system of claim 10, wherein at least one magnetic resonator is immersed in earthen materials.

15. The system of claim 10, wherein at least one magnetic resonator is located in a well.

16. The system of claim 10, wherein at least one magnetic resonator is located inside a living creature.

17. A method for wireless power transfer comprising:

energizing at least one source magnetic resonator comprising a capacitively-loaded conducting loop to generate an oscillating magnetic field; and

providing at least one device magnetic resonator, distal from said source resonators, comprising a capacitively-loaded conducting loop configured to convert said oscillating magnetic fields into electrical energy;

maintaining a keep-out zone around at least one resonator to maintain a separation distance between the resonator and lossy material of the environment.

18. The method of claim 17, wherein the keep-out zone extends at a symmetric distance around the resonator.

19. The method of claim 17, wherein the keep-out zone extends at an asymmetric distance around the resonator.

20. The method of claim 17, wherein the smallest keep out zone exceeds 0.25 mm.

21. The method of claim 17, wherein the smallest keep out zone exceeds 1 cm.

22. The method of claim 17, wherein the smallest keep out zone exceeds 10 cm.

23. The method of claim 17, wherein the smallest keep out zone is approximately 1.0% of the characteristic size of the resonator.

24. The method of claim 17, wherein the smallest keep out zone is approximately 0.1% of the characteristic size of the resonator.

25. The method of claim 17, wherein the magnetic resonator further comprises a magnetic material.

26. The method of claim 17, wherein at least one magnetic resonator has an intrinsic Q greater than 100.

27. The method of claim 26, wherein at least one magnetic resonator is immersed in water.

28. The method of claim 26, wherein at least one magnetic resonator is immersed in oil.

29. The method of claim 26, wherein at least one magnetic resonator is immersed in earthen materials.

30. The method of claim 26, wherein at least one magnetic resonator is located in a well.

31. The method of claim 26, wherein at least one magnetic resonator is located inside a living creature.

32. A source for wireless power transfer in a shaft comprising

a capacitively-loaded conducting loop wrapped around a core of magnetic material and coupled to a power source and configured to generate an oscillating magnetic field;

wherein the conducting loops are oriented to be coaxial with length of the shaft.

33. The source of claim 32, further comprising a plurality of capacitively-loaded conducting loops wrapped around cores of magnetic material arranged around the diameter of the shaft.

Fig. 1

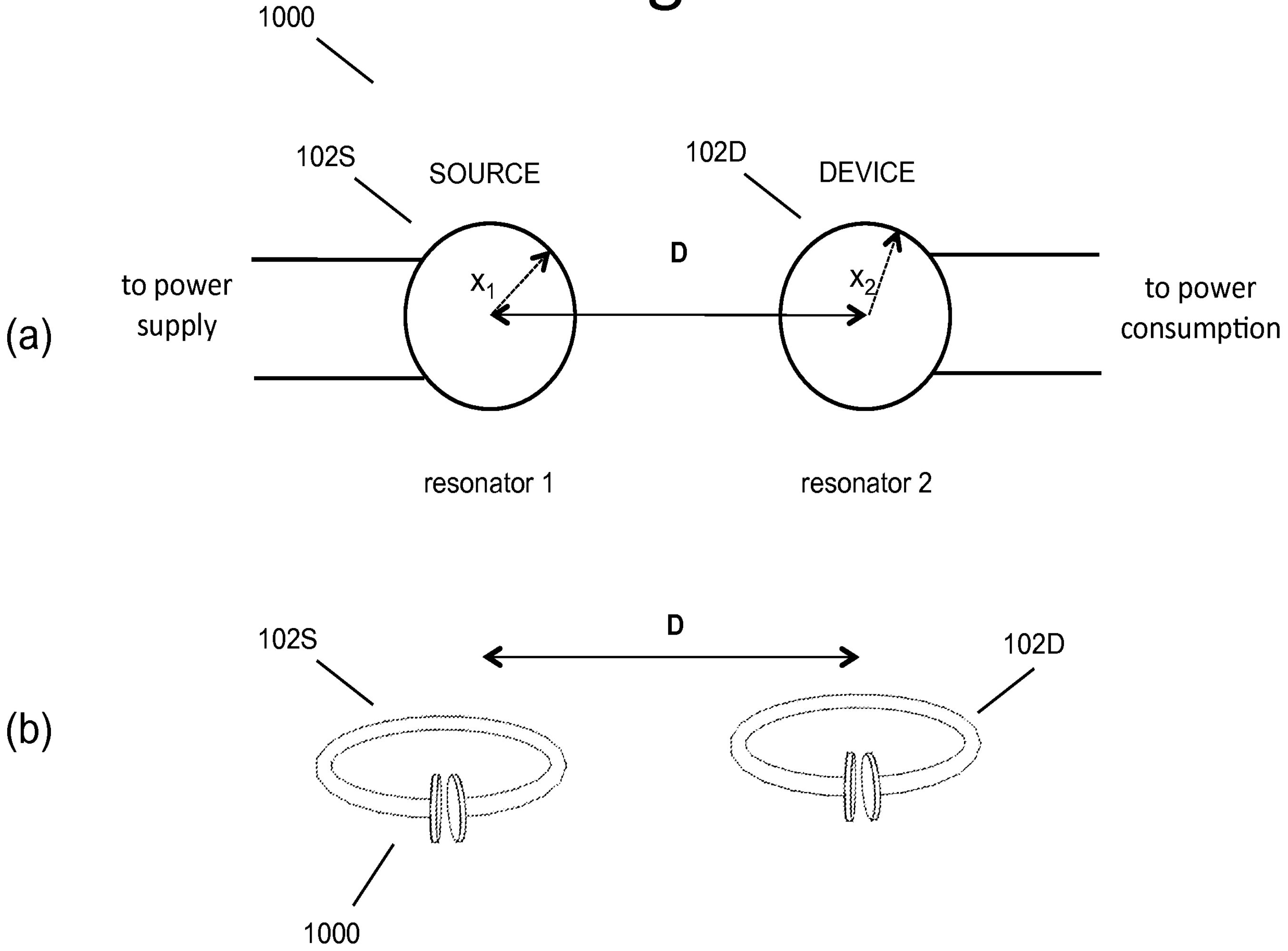

1000
102S
SOURCE
102D
DEVICE
D
(a)
to power
supply
x_1
x_2
to power
consumption
resonator 1
resonator 2
(b)
102S
D
102D
1000

Fig. 2

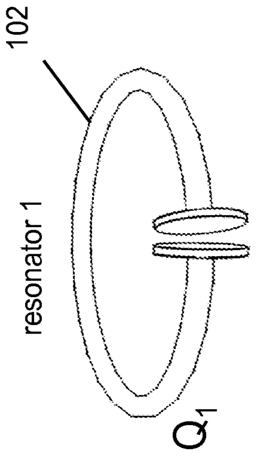


Fig. 3

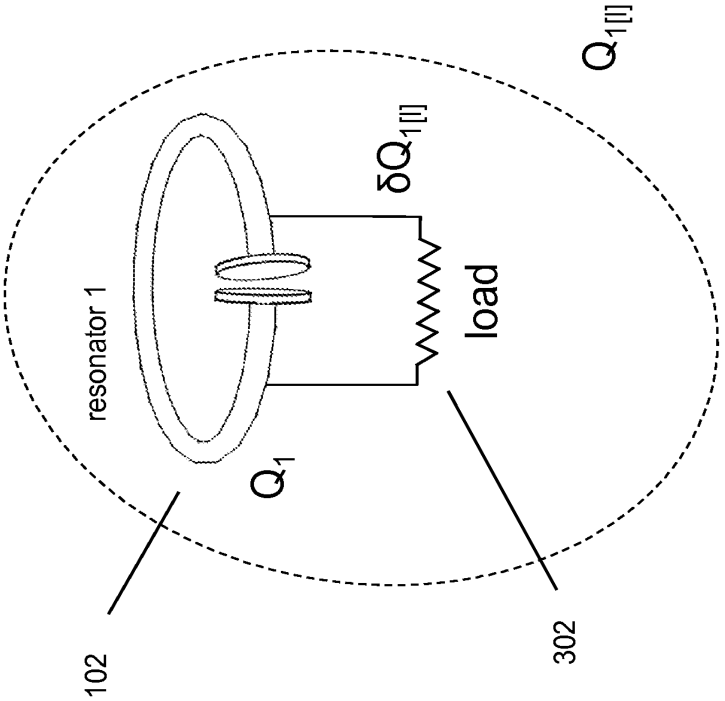


Fig. 4

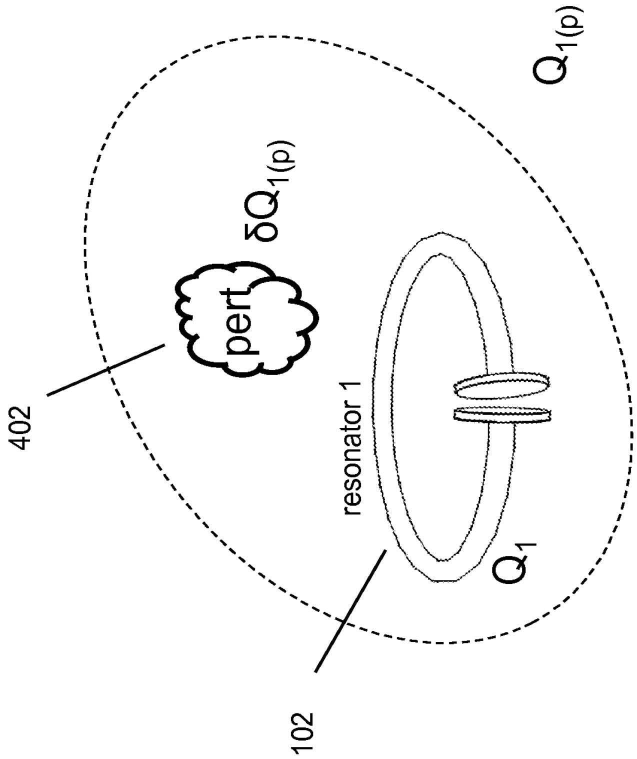


Fig. 5

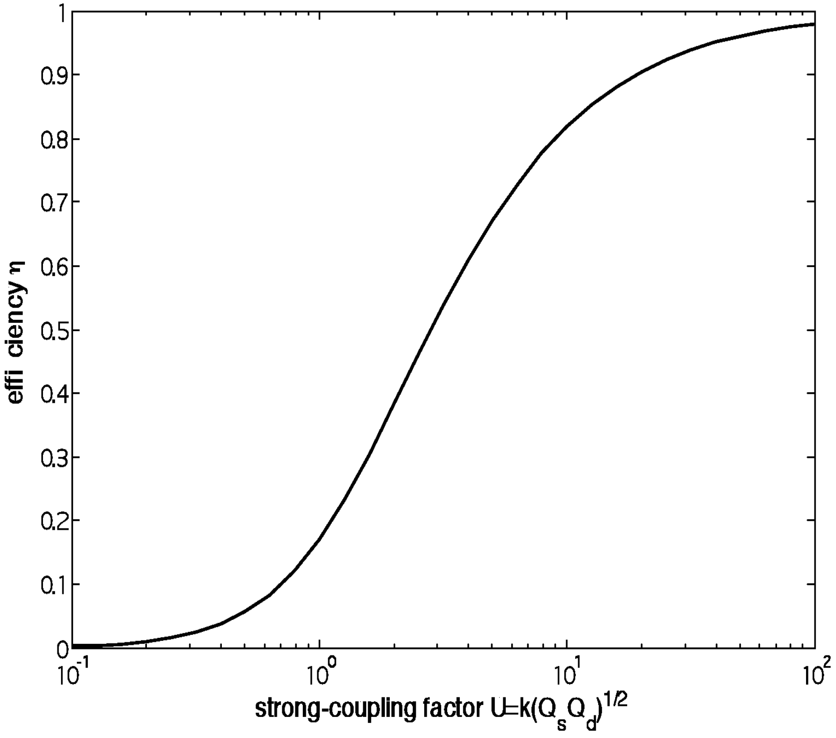

effi ciency η
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-1}
10^{0}
10^{1}
10^{2}
strong-coupling factor $U=k(Q_sQ_d)^{1/2}$

Fig. 6

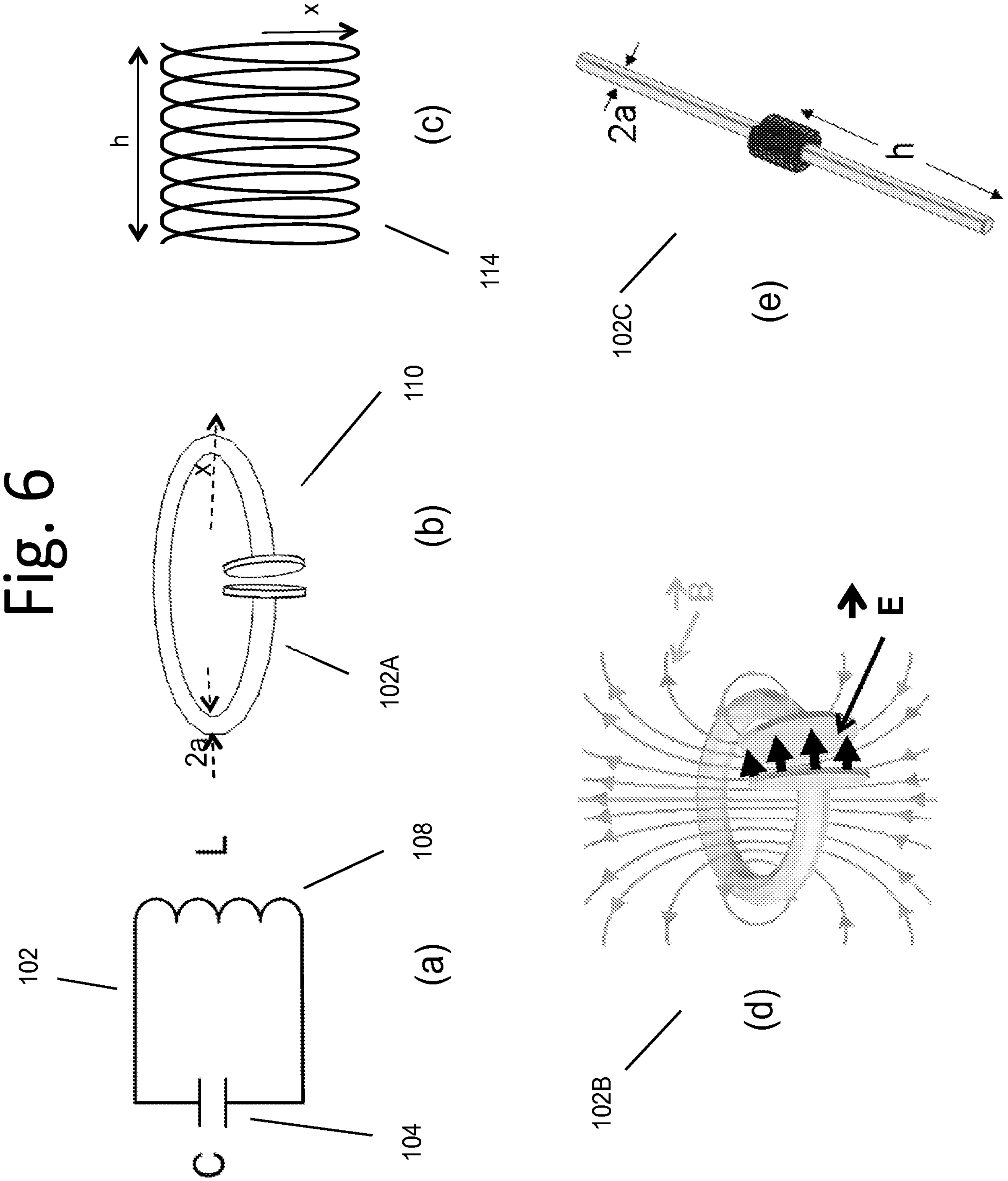


Fig. 7

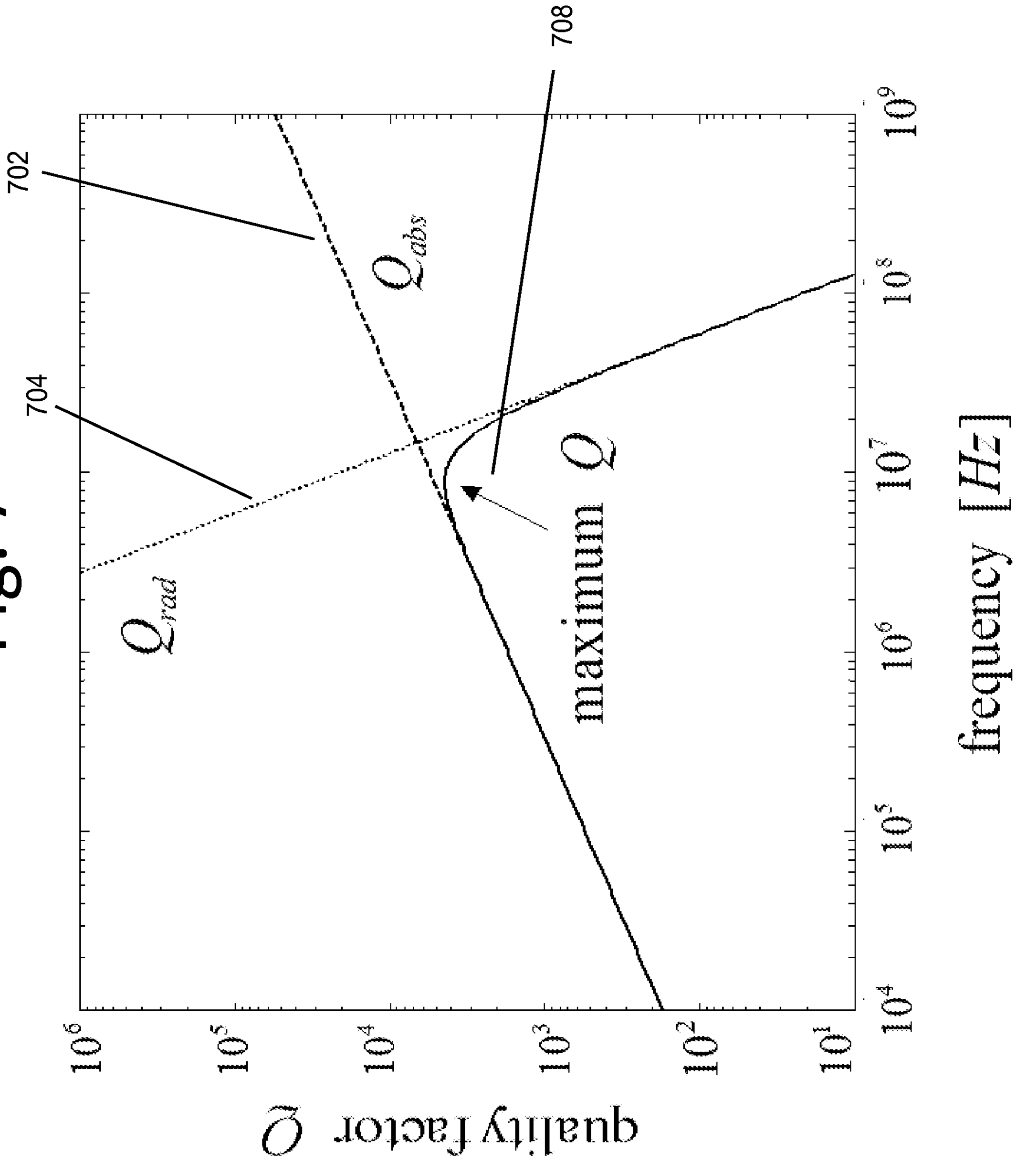
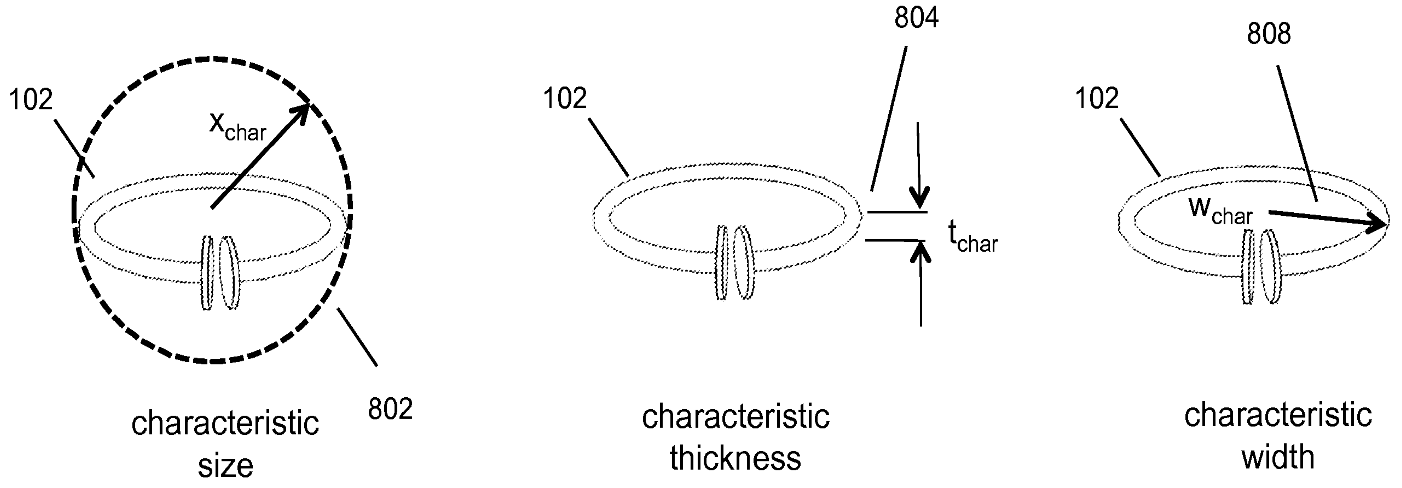

702
704
708
Q_{abs}
Q_{rad}
maximum Q
frequency $[Hz]$
quality factor Q
10^4
10^5
10^6
10^7
10^8
10^9
10^6
10^5
10^4
10^3
10^2
10^1

Fig. 8



characteristic size

characteristic thickness

characteristic width

Fig. 9

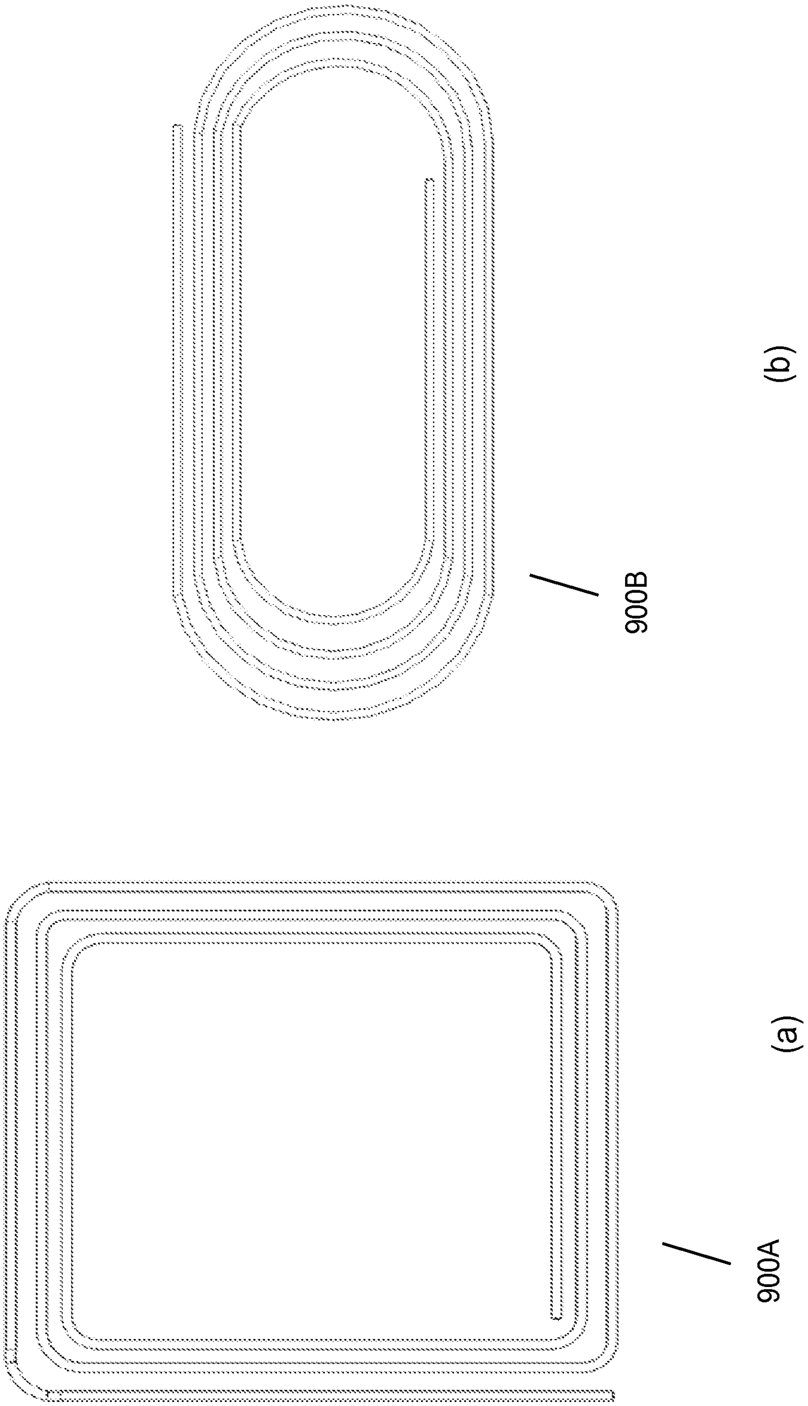


Fig. 10

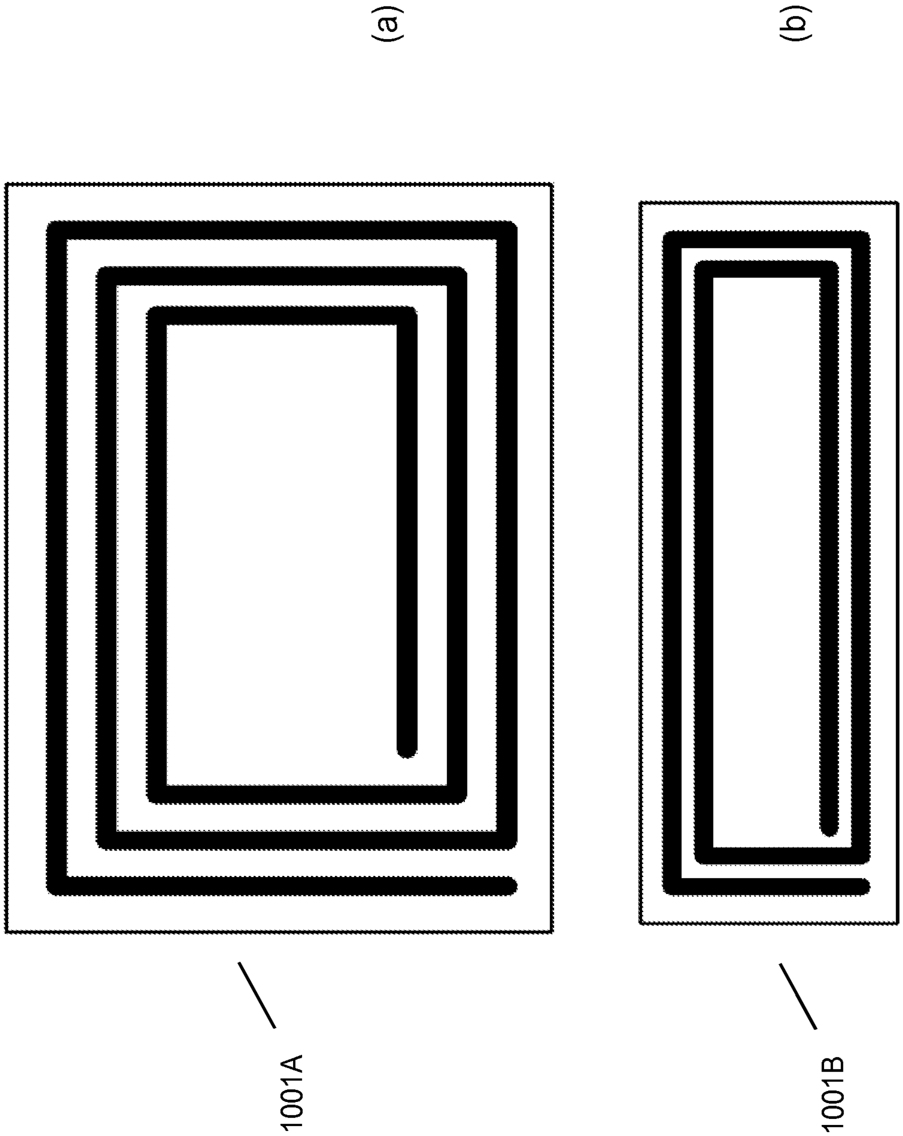
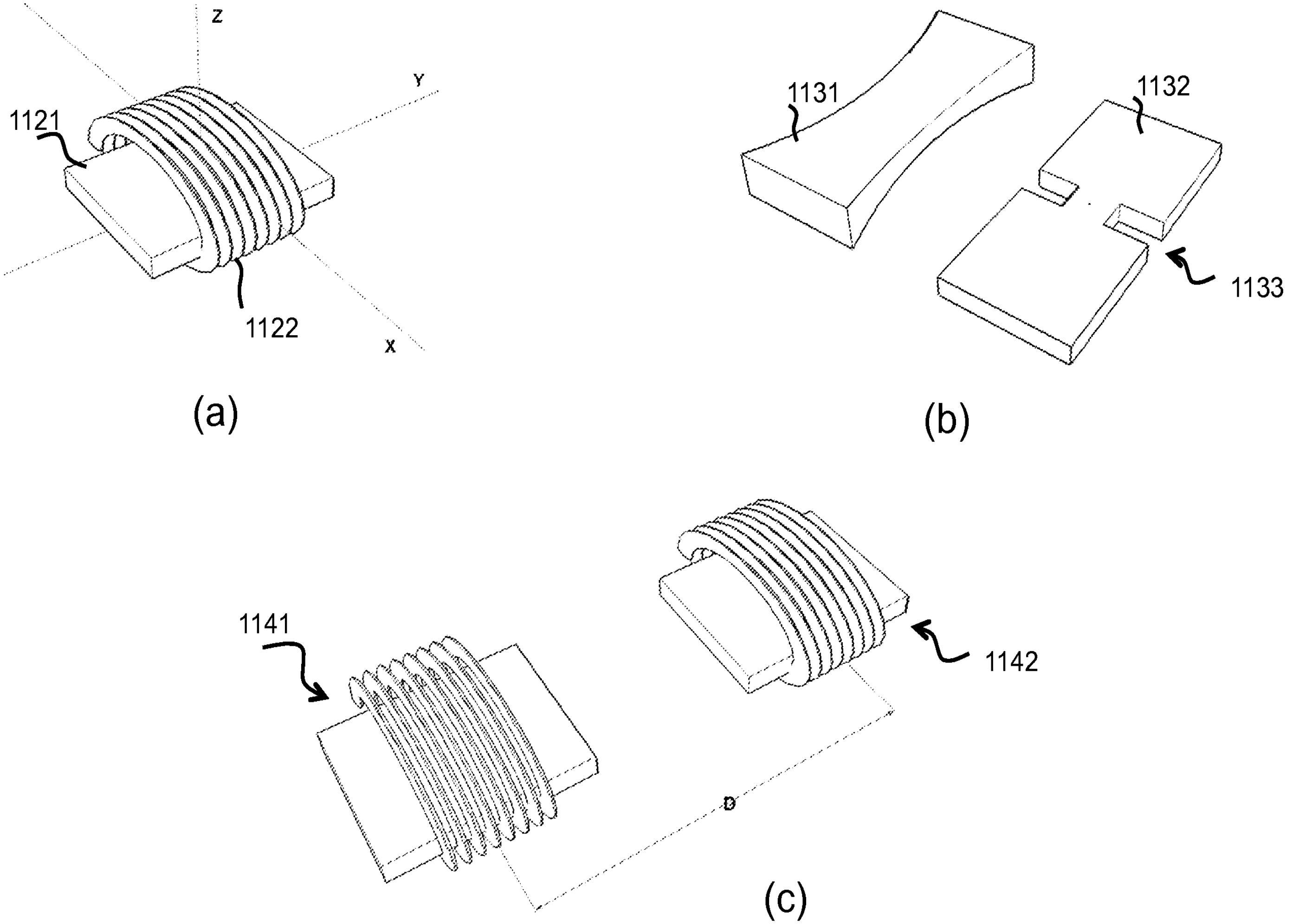


Fig. 11



(a)

(b)

(c)

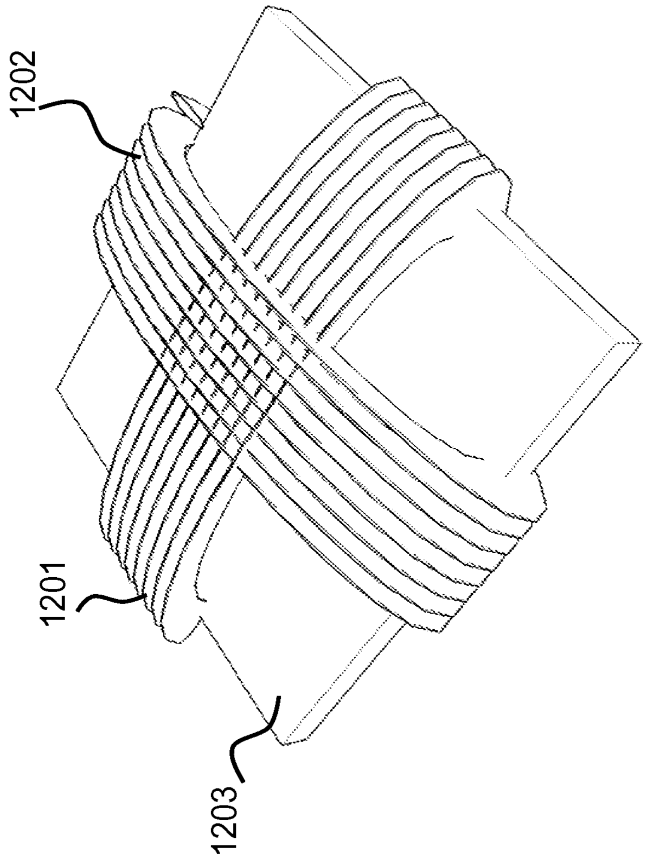


Fig. 12

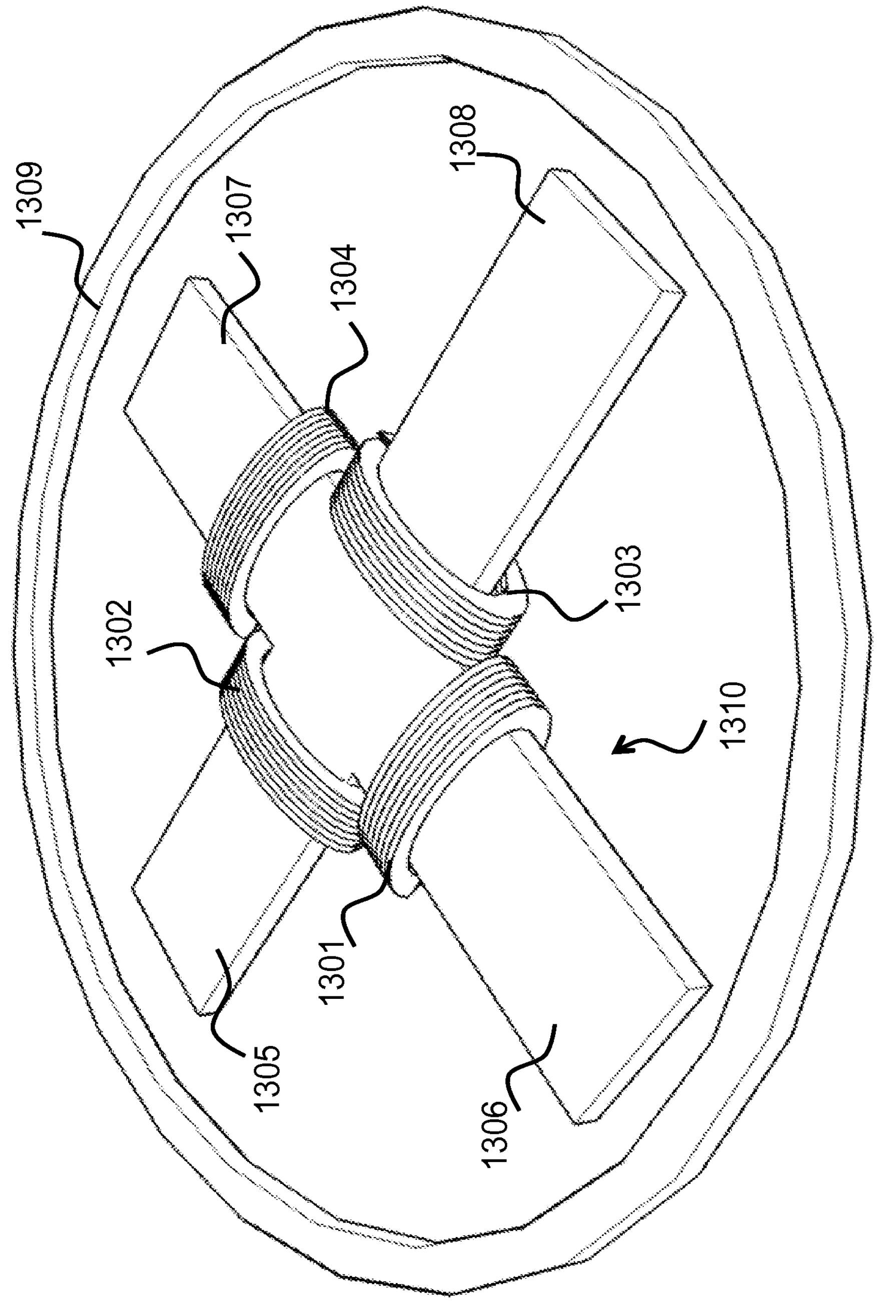


Fig. 13

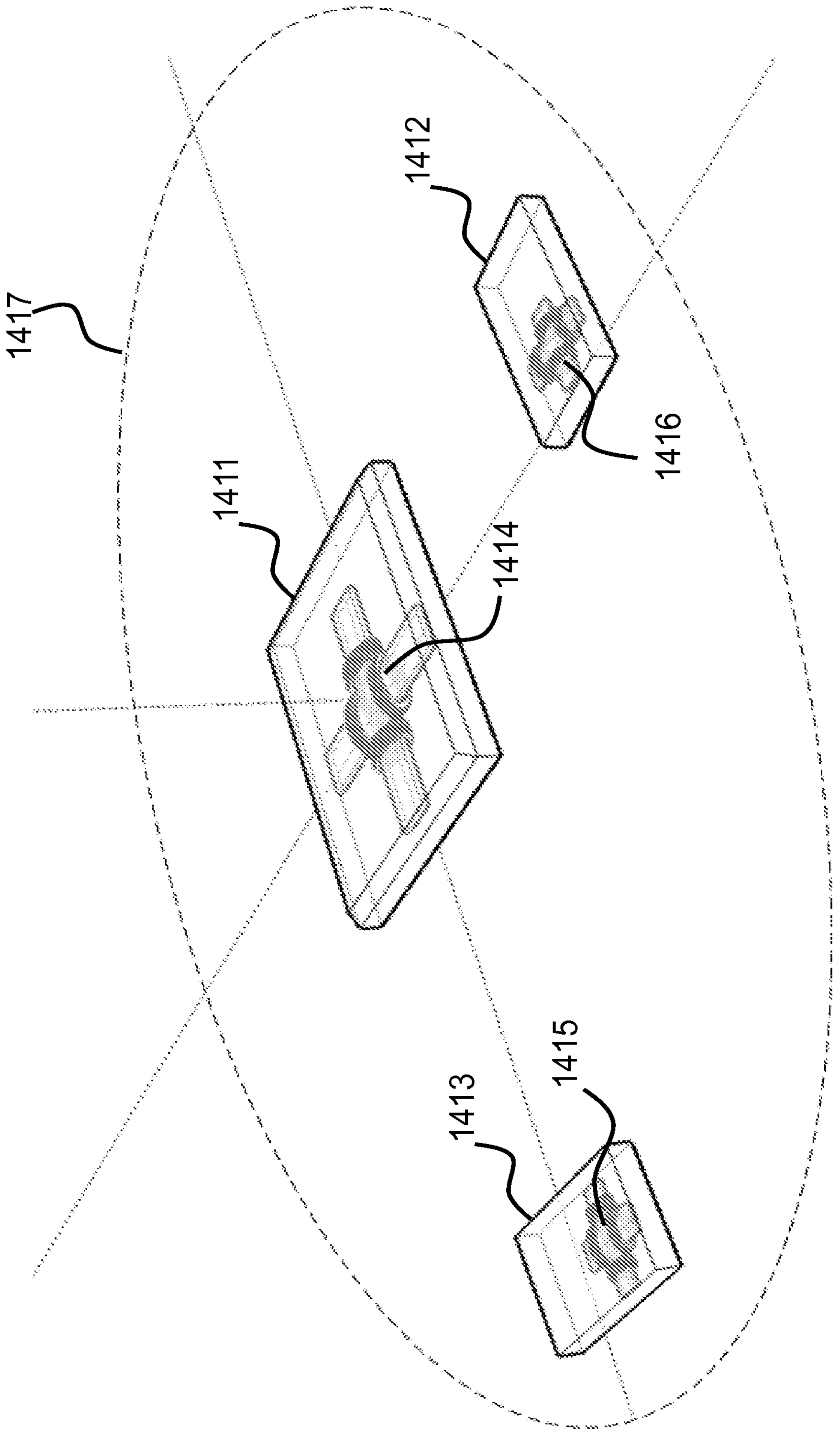


Fig. 14

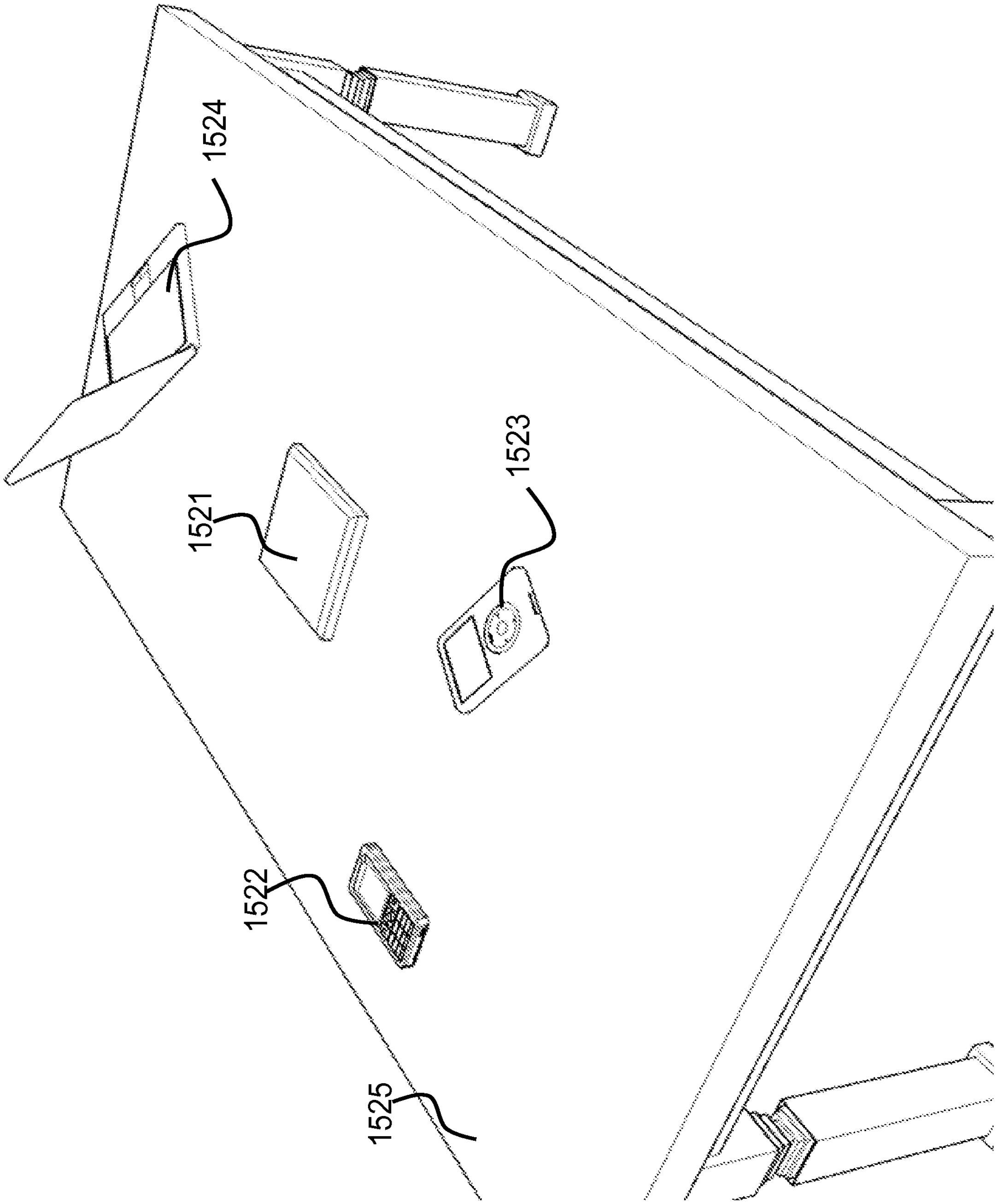
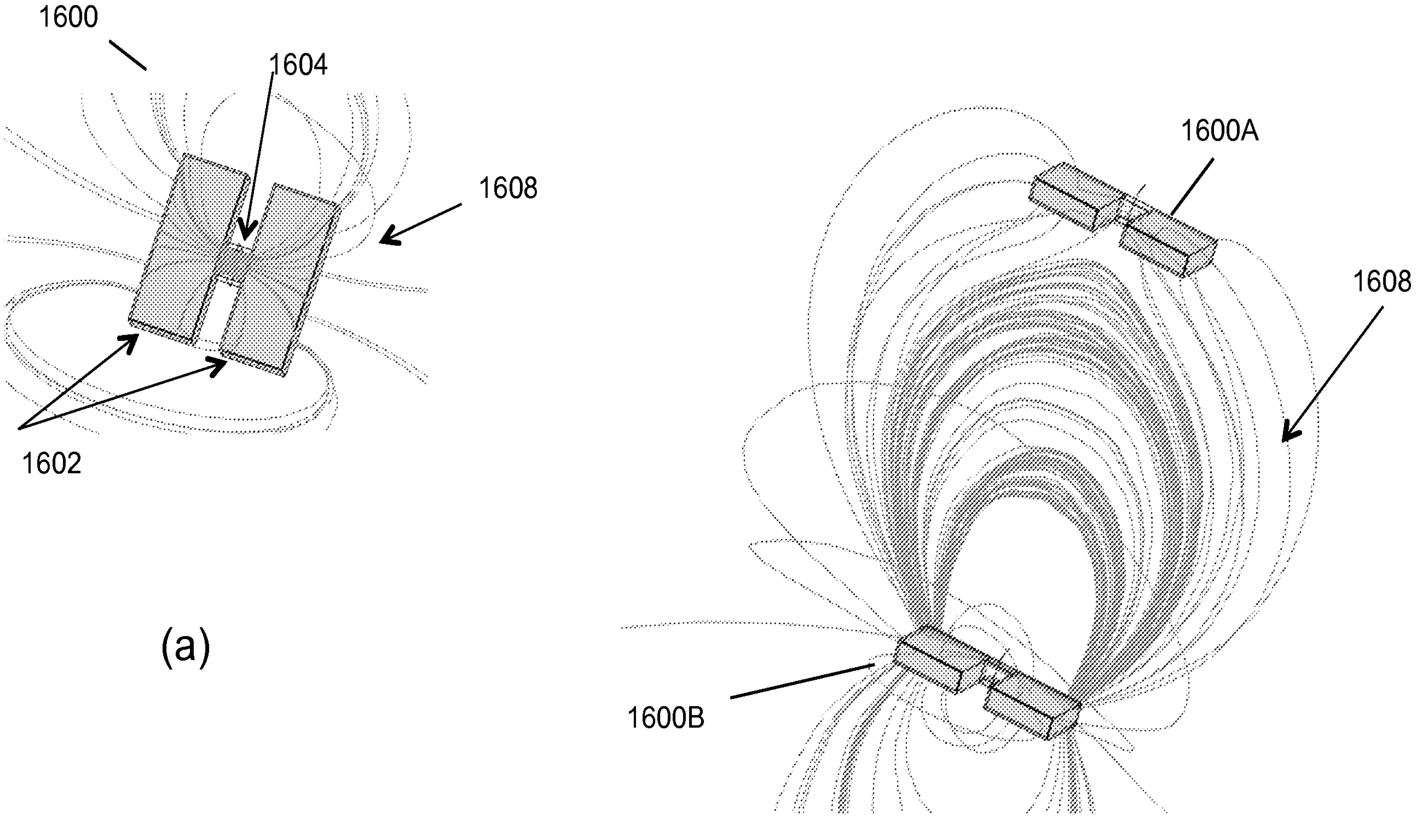


Fig. 15

Fig. 16



(a)

(b)

Fig. 17

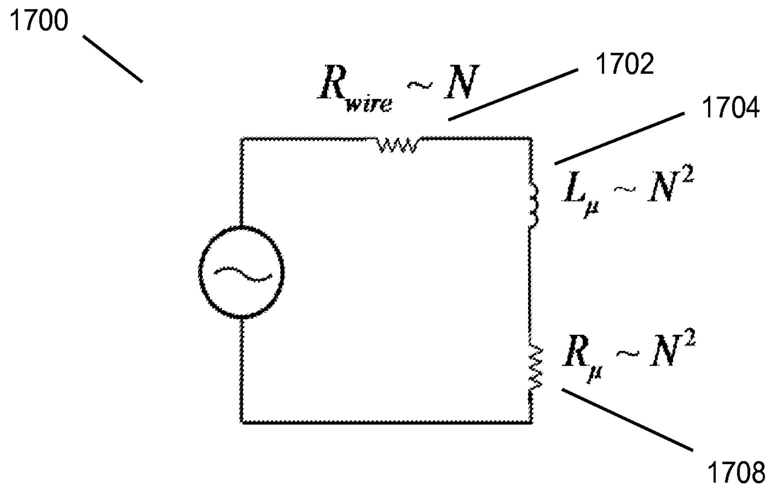
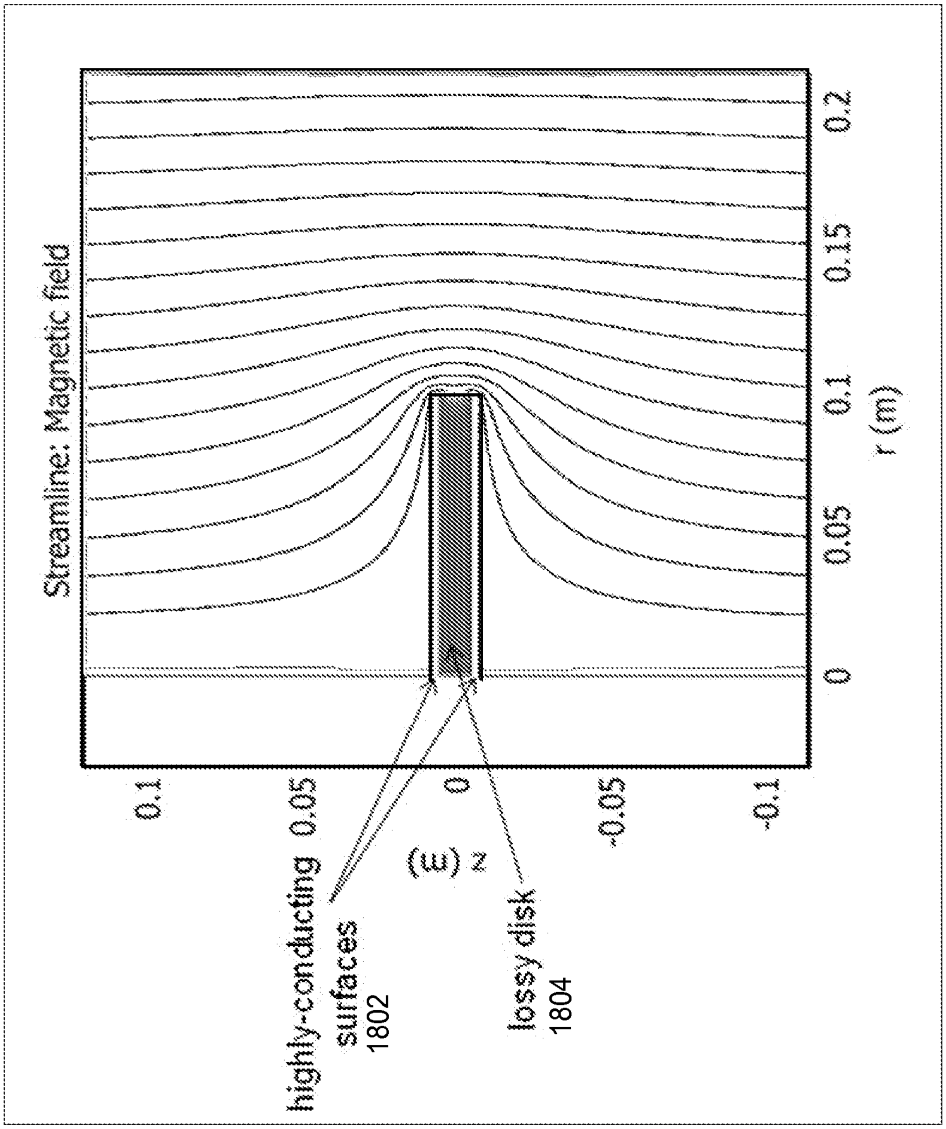


Fig. 18


Streamline: Magnetic field
0.1
0.05
0
-0.05
-0.1
z (m)
0
0.05
0.1
0.15
0.2
r (m)
highly-conducting surfaces 1802
lossy disk 1804

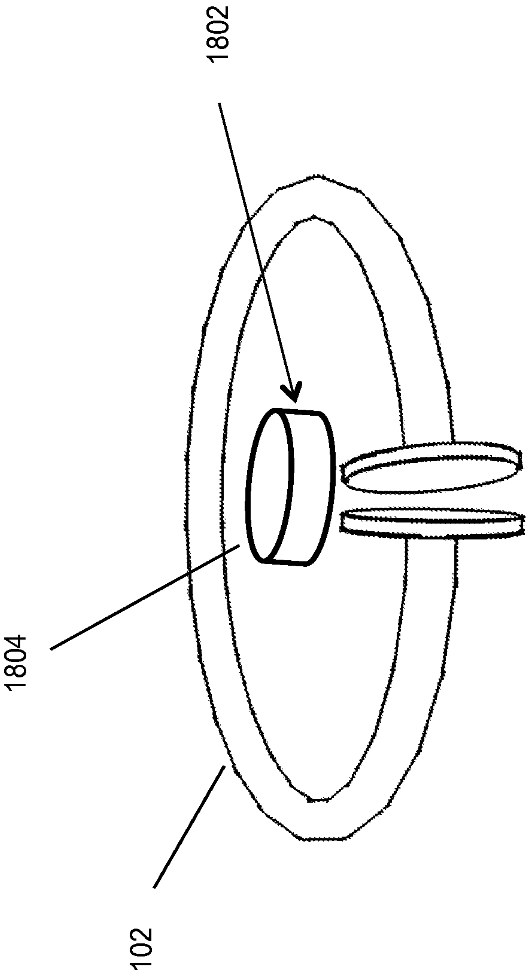


Fig. 19

Fig. 20

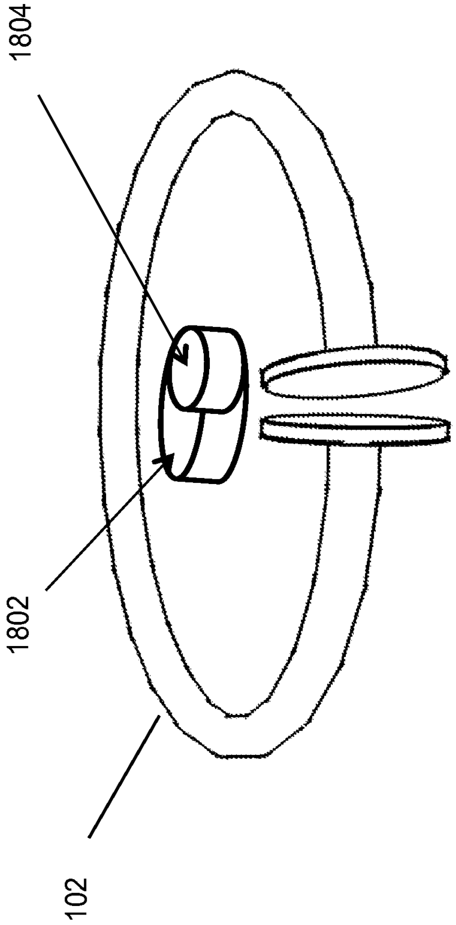


Fig. 21

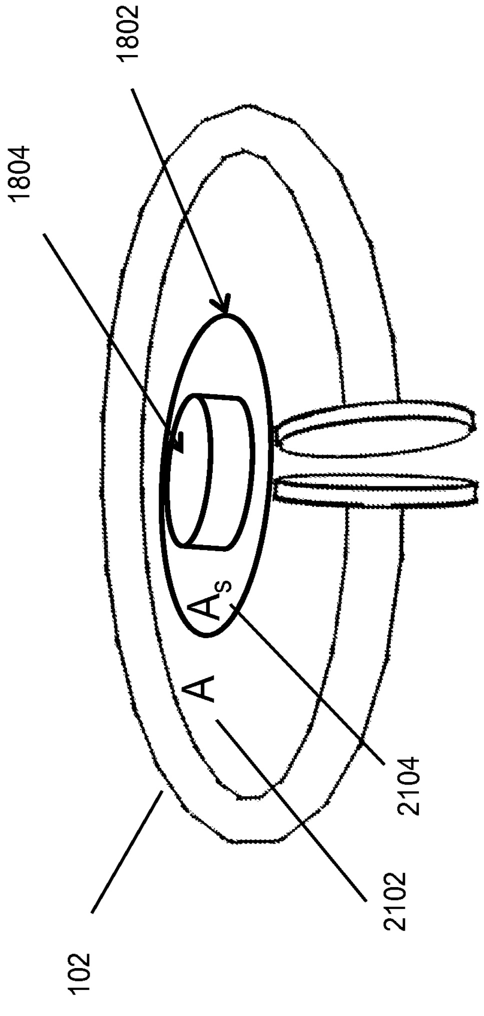


Fig. 22

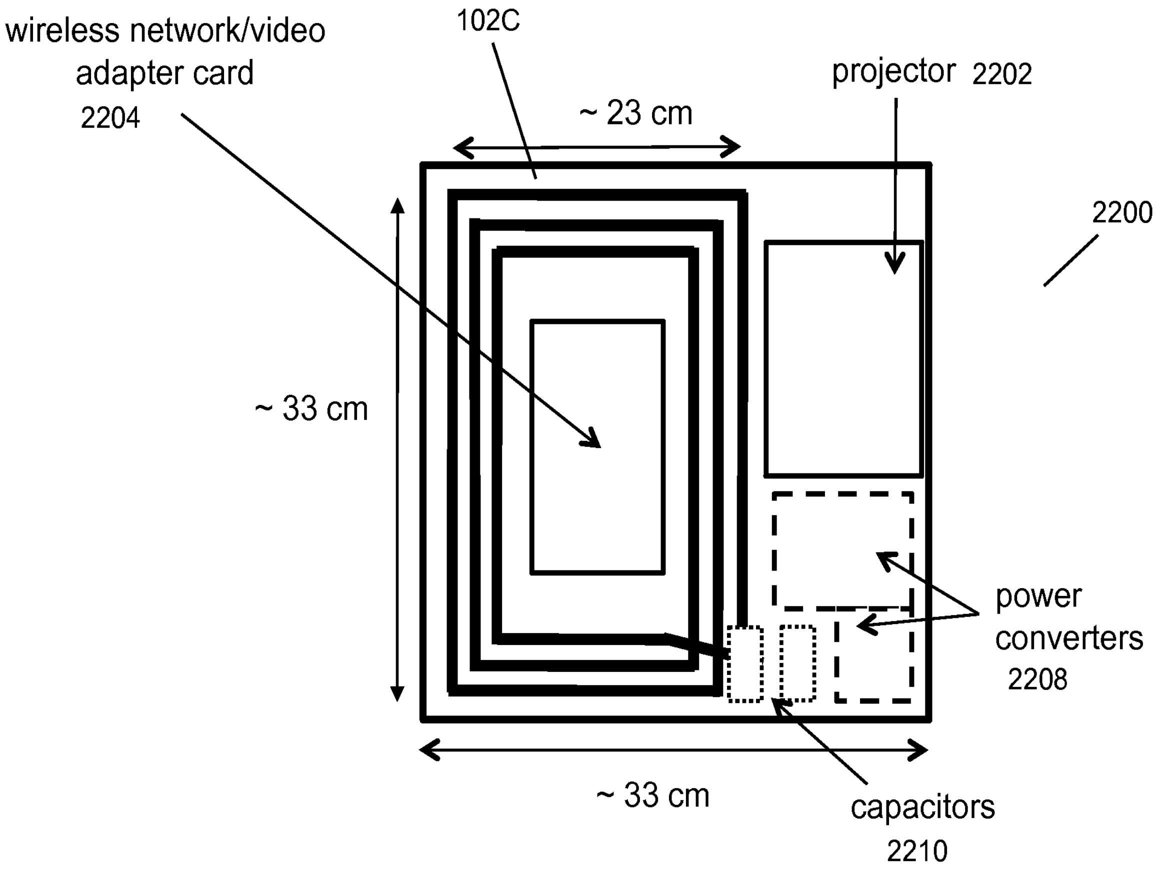

wireless network/video
adapter card
2204
102C
~ 23 cm
projector 2202
2200
~ 33 cm
power
converters
2208
~ 33 cm
capacitors
2210

Fig. 23

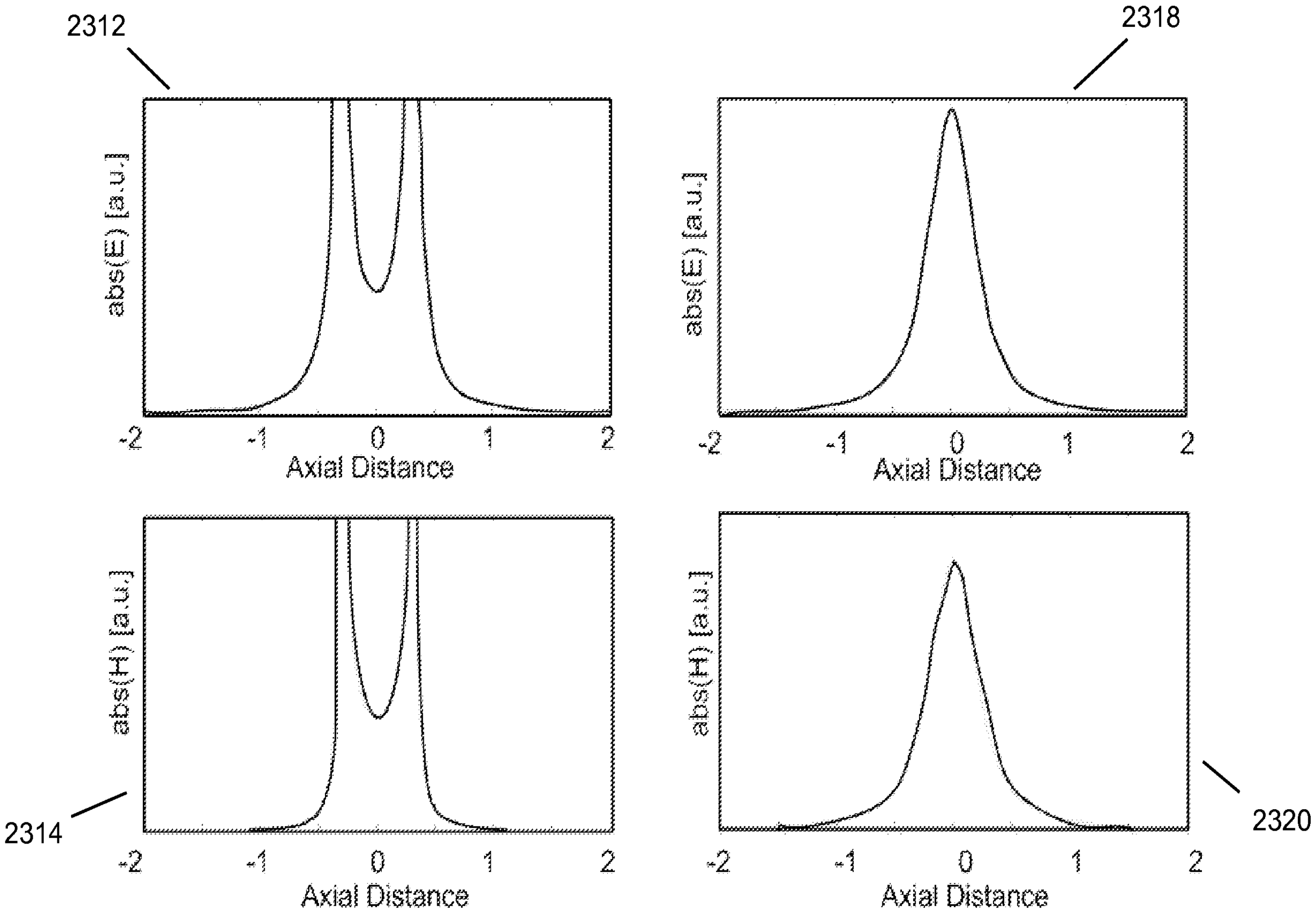
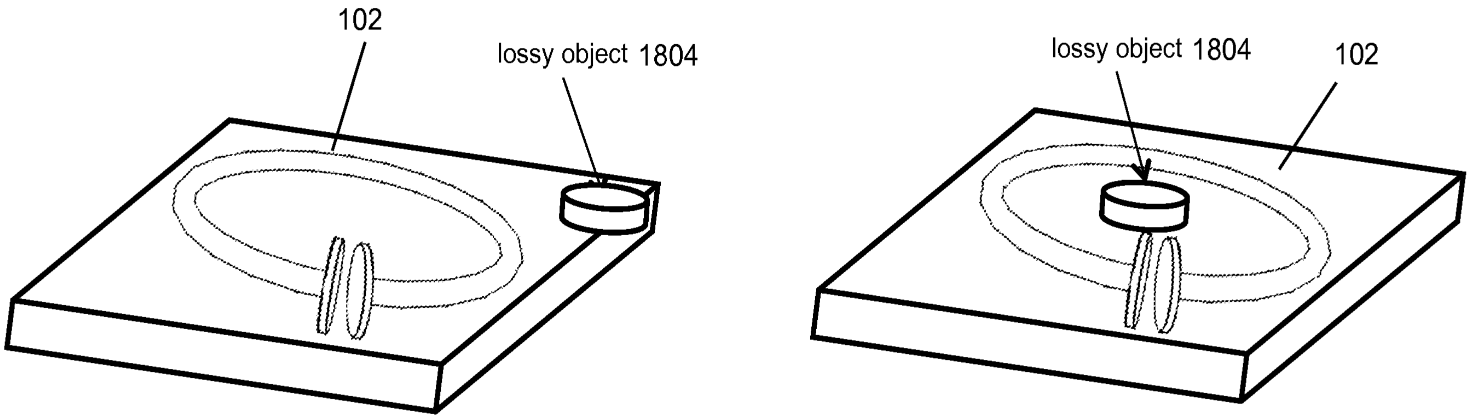

2312
2318
abs(E) [a.u.]
abs(E) [a.u.]
-2
-1
0
1
2
Axial Distance
-2
-1
0
1
2
Axial Distance
abs(H) [a.u.]
abs(H) [a.u.]
2314
2320
-2
-1
0
1
2
Axial Distance
-2
-1
0
1
2
Axial Distance

Fig. 24



(a)

(b)

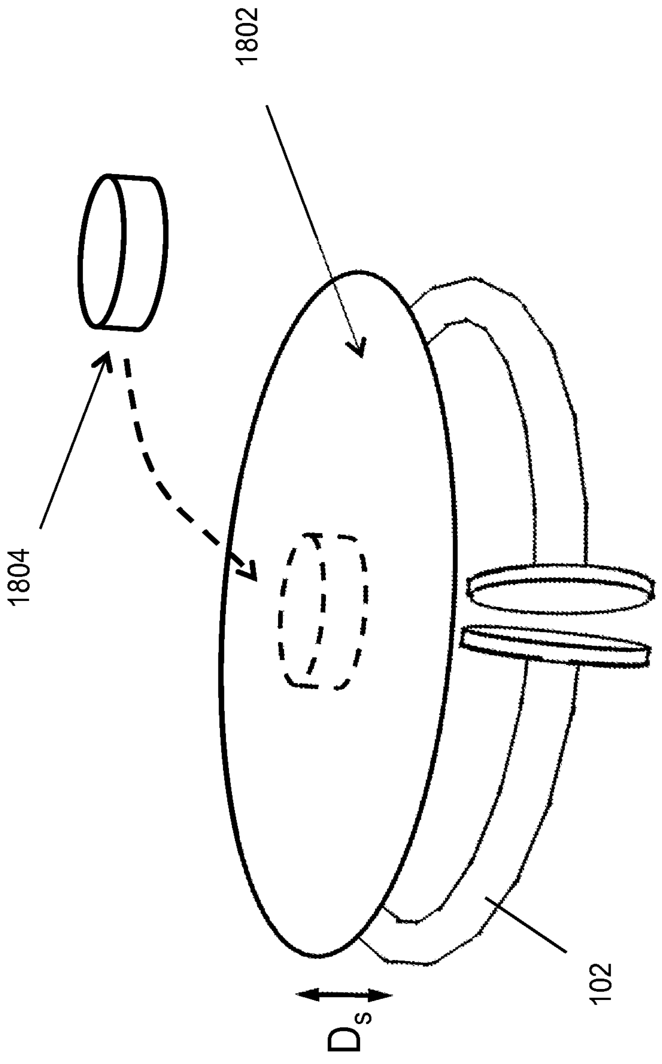
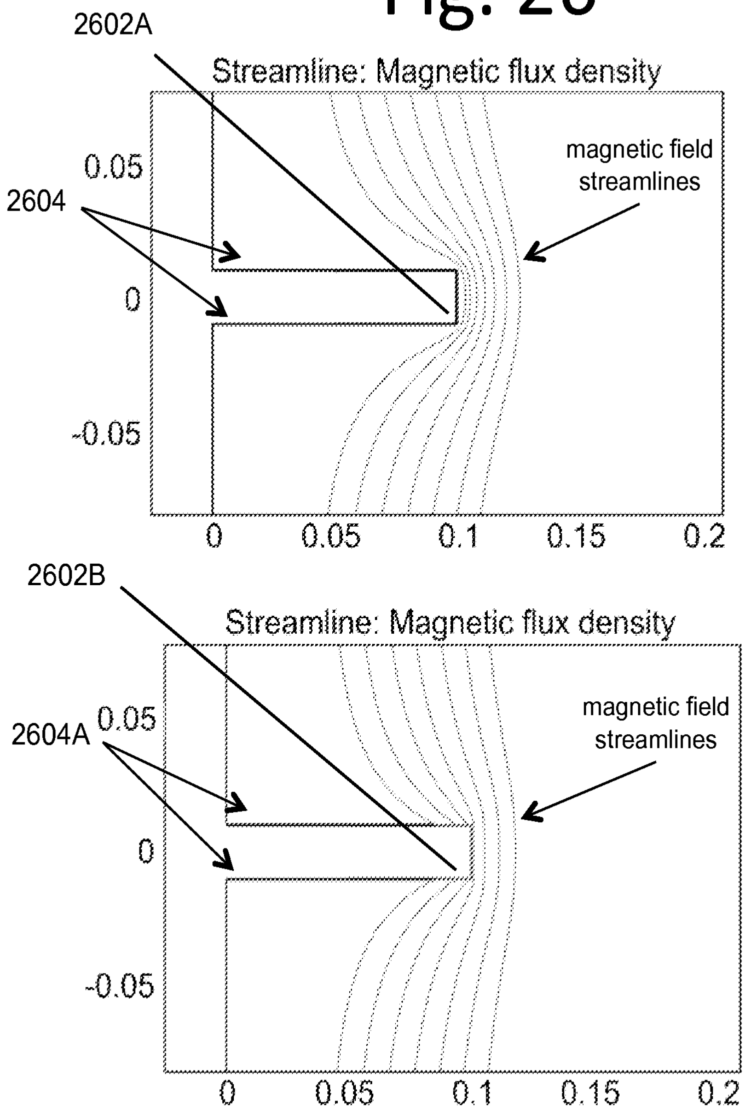


Fig. 25

Fig. 26


2602A
Streamline: Magnetic flux density
0.05
0
-0.05
0
0.05
0.1
0.15
0.2
2604
magnetic field
streamlines
2602B
Streamline: Magnetic flux density
2604A
0.05
0
-0.05
0
0.05
0.1
0.15
0.2
magnetic field
streamlines

(a)

(b)

Fig. 27

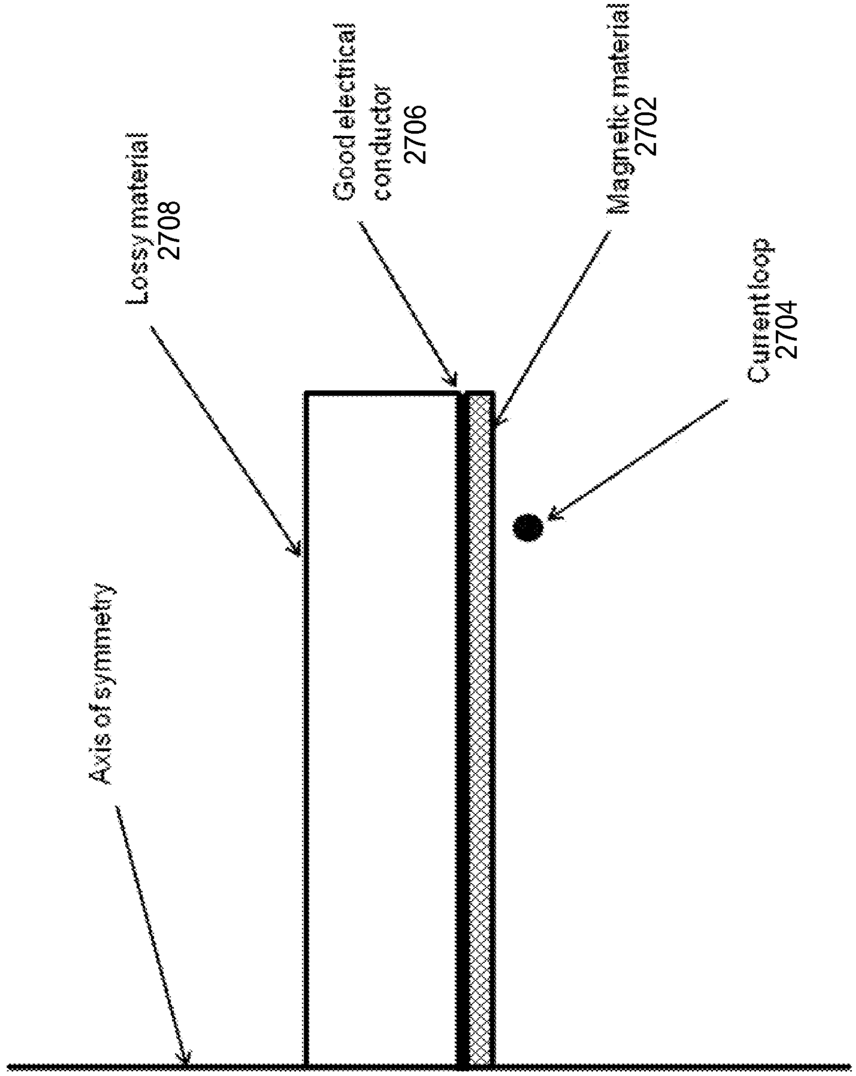

Lossy material
2708
Good electrical
conductor
2706
Magnetic material
2702
Current loop
2704
Axis of symmetry

Fig. 28

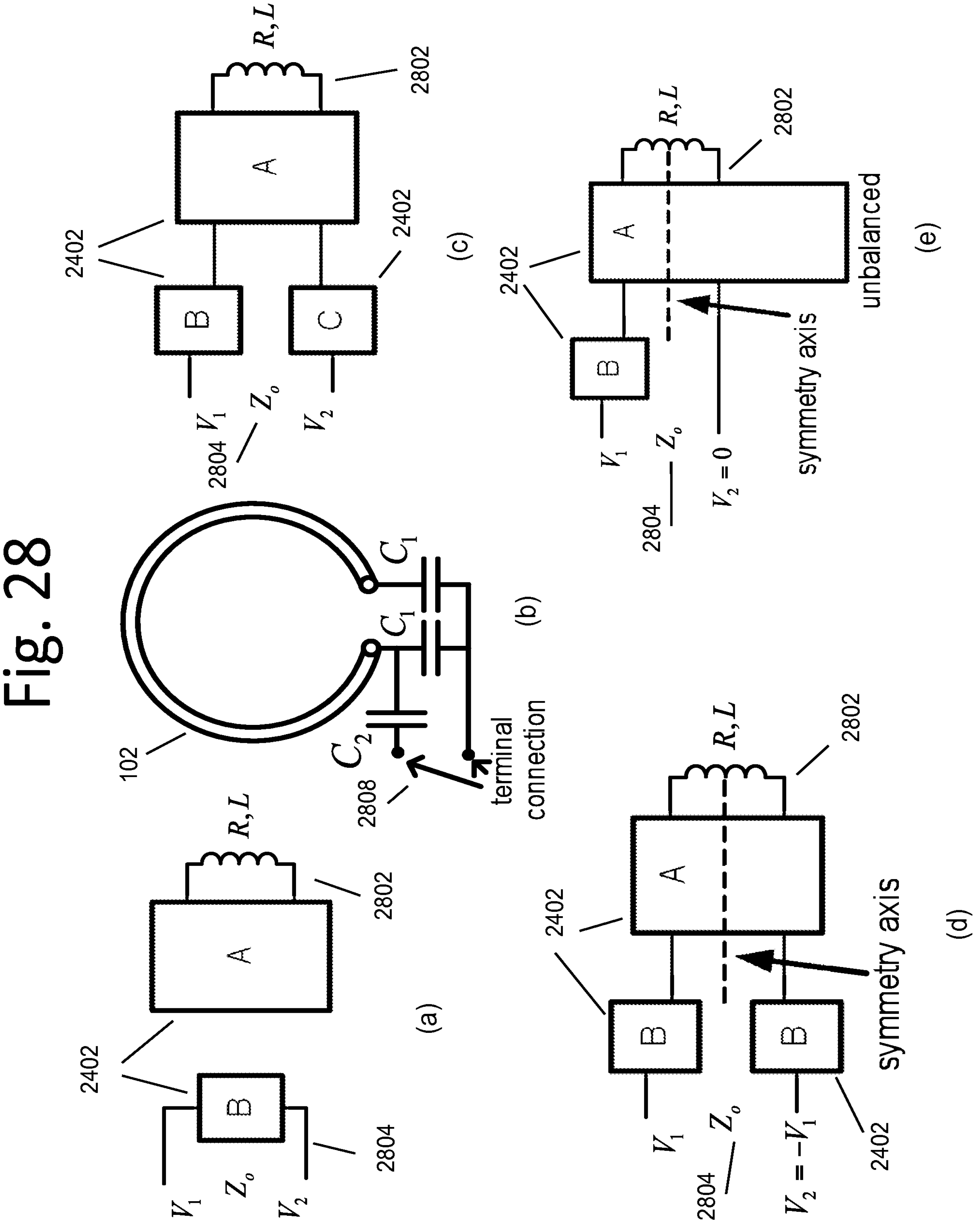

2402
A
R, L
2802
B
V_1
Z_o
V_2
2804
(a)
102
C_1
C_1
C_2
2808
terminal connection
(b)
2402
A
R, L
2802
B
C
2402
V_1
Z_o
V_2
2804
(c)
2402
A
R, L
2802
B
B
symmetry axis
V_1
Z_o
$V_2 = -V_1$
2804
2402
(d)
2402
A
R, L
2802
B
symmetry axis
unbalanced
V_1
Z_o
$V_2 = 0$
2804
(e)

Fig. 29

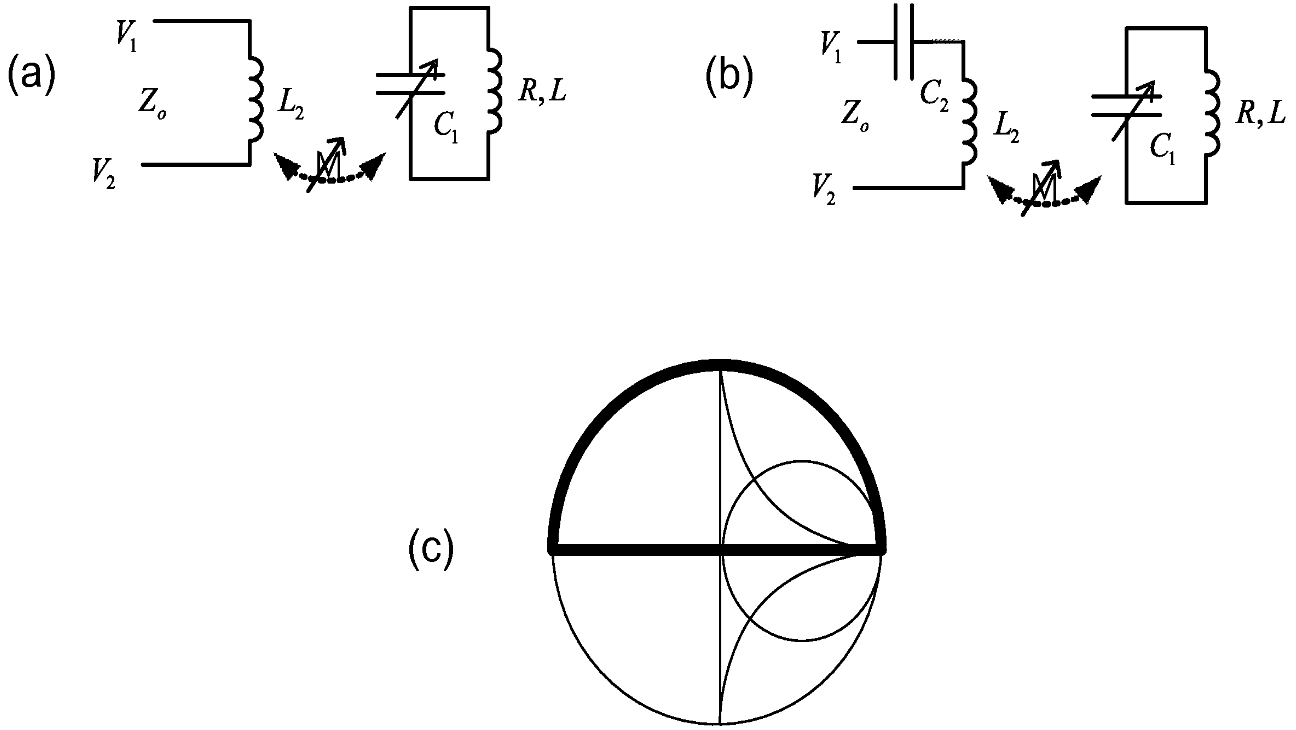


Fig. 30

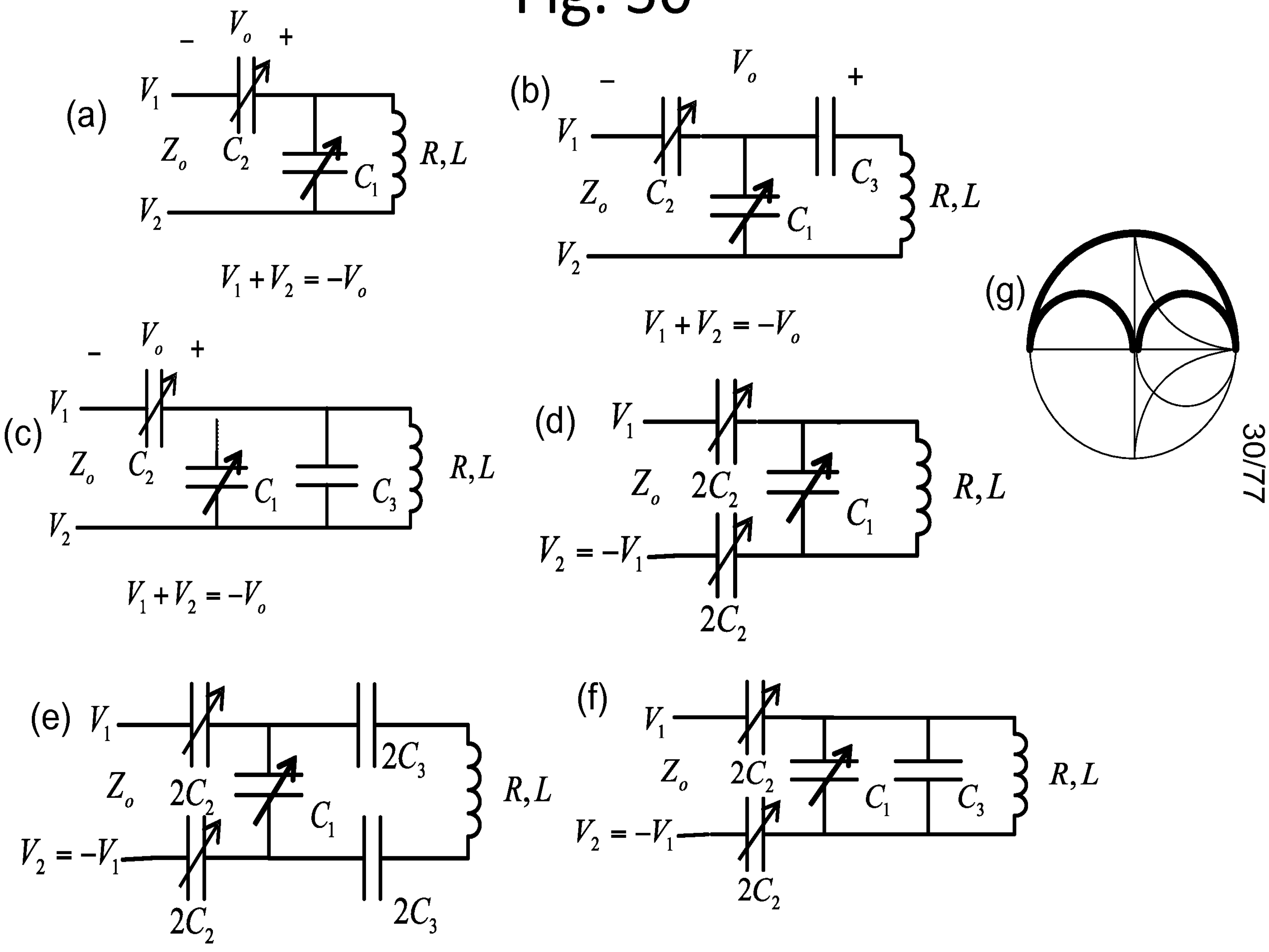

(a)
V_o
–
+
V_1
Z_o
C_2
C_1
R,L
V_2
$V_1 + V_2 = -V_o$
(b)
V_o
–
+
V_1
Z_o
C_2
C_1
C_3
R,L
V_2
$V_1 + V_2 = -V_o$
(g)
(c)
V_o
–
+
V_1
Z_o
C_2
C_1
C_3
R,L
V_2
$V_1 + V_2 = -V_o$
(d)
V_1
Z_o
$2C_2$
C_1
R,L
$V_2 = -V_1$
$2C_2$
(e)
V_1
Z_o
$2C_2$
$2C_3$
C_1
R,L
$V_2 = -V_1$
$2C_2$
$2C_3$
(f)
V_1
Z_o
$2C_2$
C_1
C_3
R,L
$V_2 = -V_1$
$2C_2$

Fig. 30

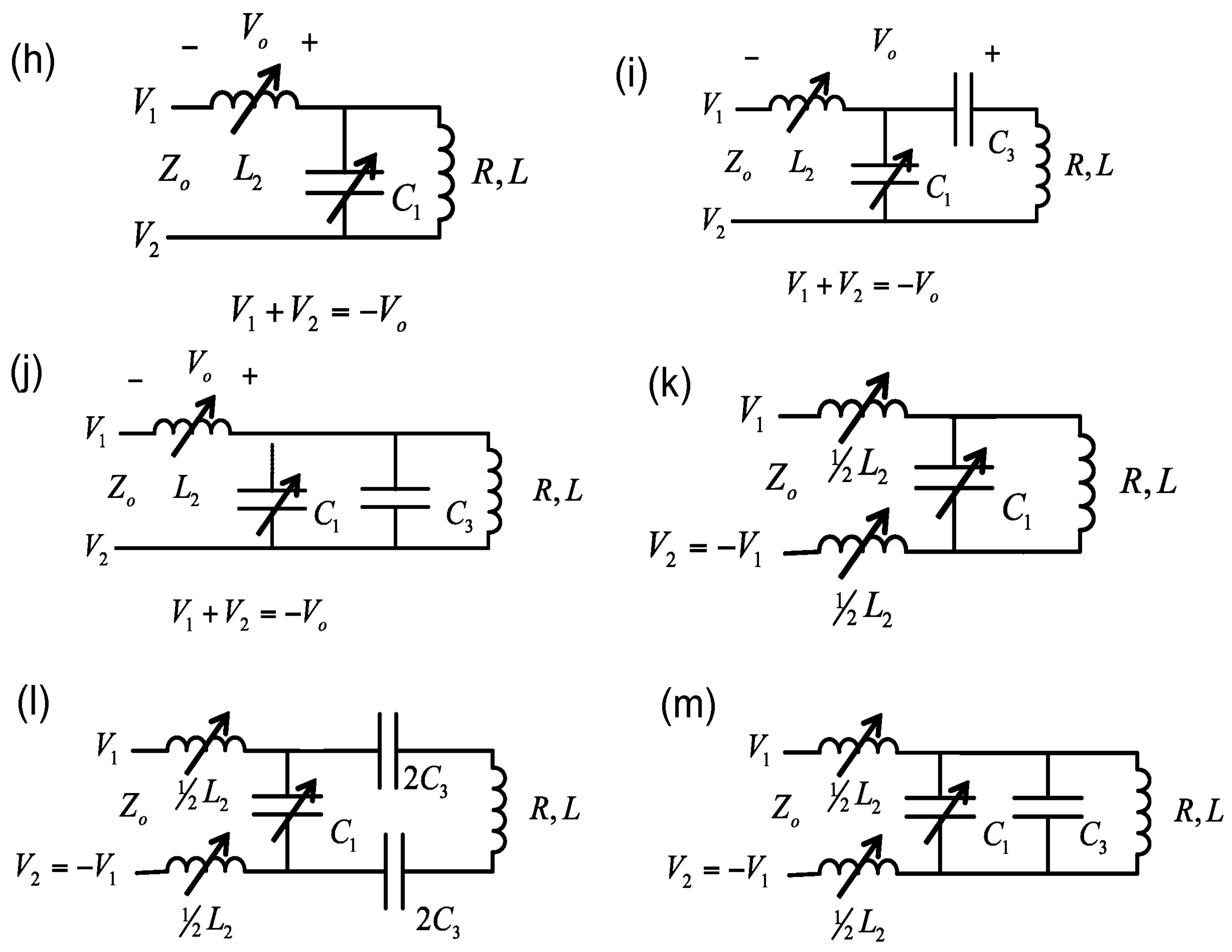

(h)
–
V_o
+
V_1
Z_o
L_2
C_1
R,L
V_2
$V_1 + V_2 = -V_o$
(i)
–
V_o
+
V_1
Z_o
L_2
C_1
C_3
R,L
V_2
$V_1 + V_2 = -V_o$
(j)
–
V_o
+
V_1
Z_o
L_2
C_1
C_3
R,L
V_2
$V_1 + V_2 = -V_o$
(k)
V_1
Z_o
$\frac{1}{2}L_2$
C_1
R,L
$V_2 = -V_1$
$\frac{1}{2}L_2$
(l)
V_1
Z_o
$\frac{1}{2}L_2$
C_1
$2C_3$
R,L
$V_2 = -V_1$
$\frac{1}{2}L_2$
$2C_3$
(m)
V_1
Z_o
$\frac{1}{2}L_2$
C_1
C_3
R,L
$V_2 = -V_1$
$\frac{1}{2}L_2$

Fig. 31

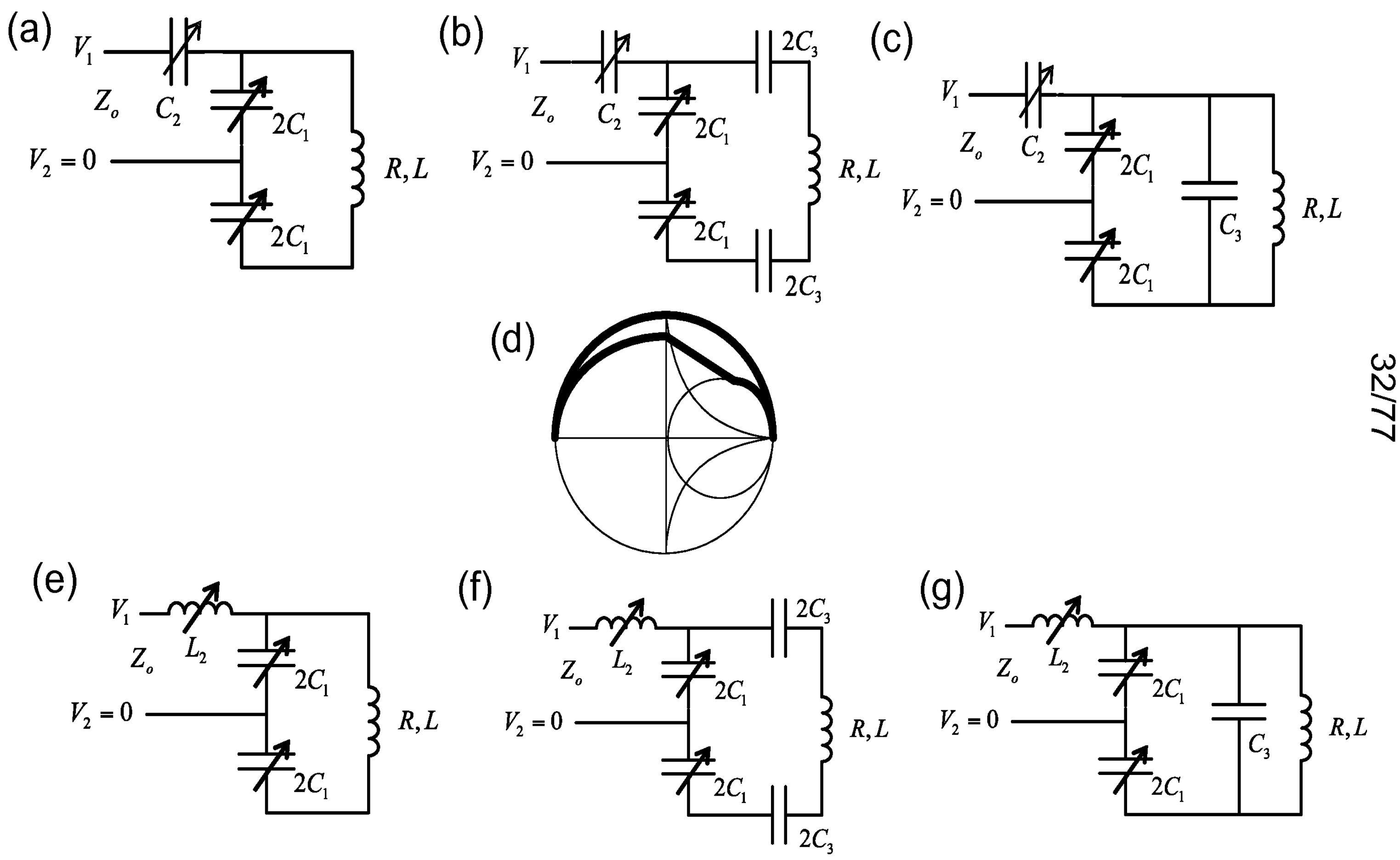

(a)
V_1
Z_o
C_2
$2C_1$
$V_2 = 0$
$2C_1$
R,L
(b)
V_1
Z_o
C_2
$2C_3$
$2C_1$
$V_2 = 0$
$2C_1$
R,L
$2C_3$
(c)
V_1
Z_o
C_2
$2C_1$
$V_2 = 0$
$2C_1$
C_3
R,L
(d)
(e)
V_1
Z_o
L_2
$2C_1$
$V_2 = 0$
$2C_1$
R,L
(f)
V_1
Z_o
L_2
$2C_3$
$2C_1$
$V_2 = 0$
$2C_1$
R,L
$2C_3$
(g)
V_1
Z_o
L_2
$2C_1$
$V_2 = 0$
$2C_1$
C_3
R,L

Fig. 32

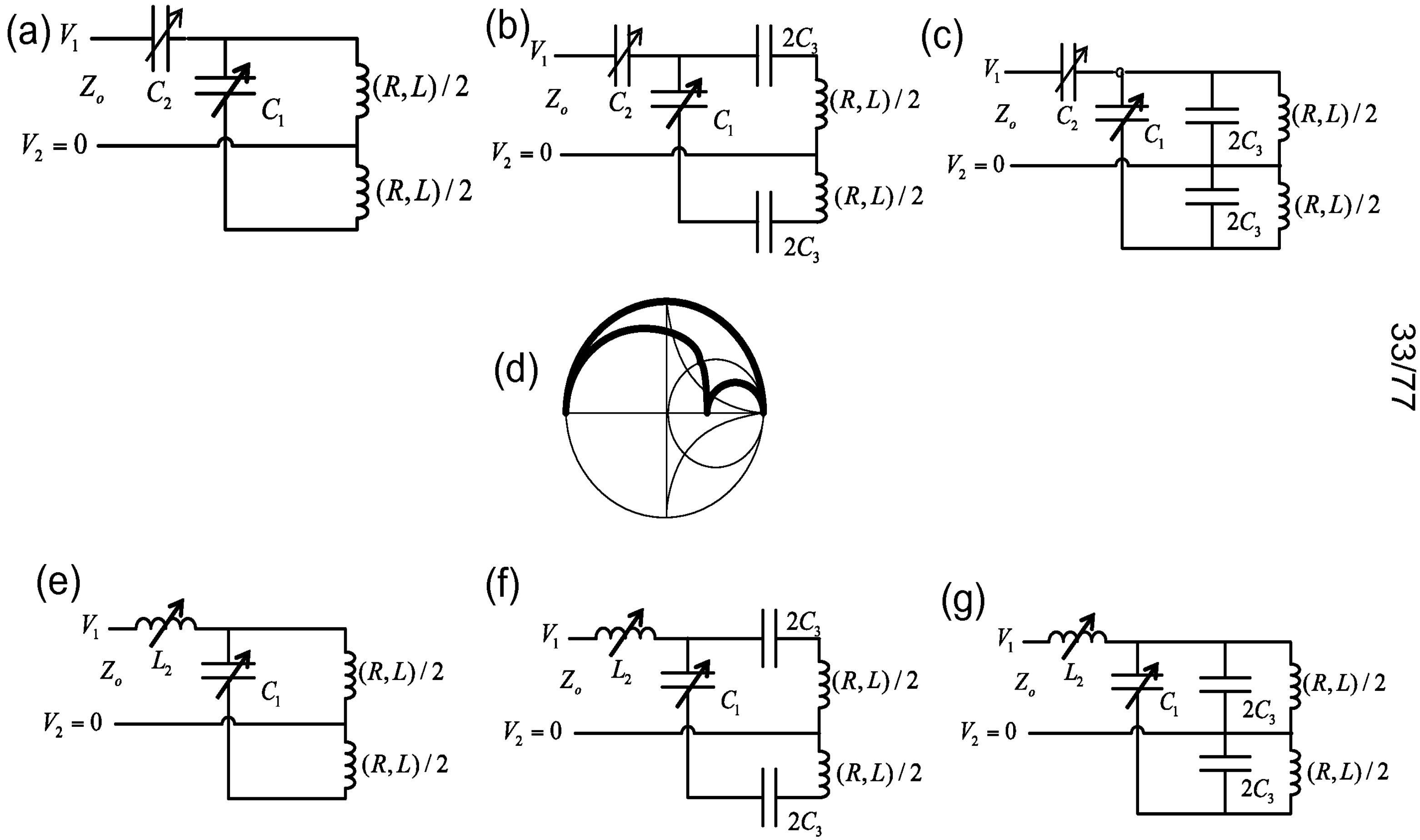

(a)
V_1
Z_o
C_2
C_1
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
(b)
V_1
Z_o
C_2
C_1
$2C_3$
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
$2C_3$
(c)
V_1
Z_o
C_2
C_1
$2C_3$
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
$2C_3$
(d)
(e)
V_1
Z_o
L_2
C_1
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
(f)
V_1
Z_o
L_2
C_1
$2C_3$
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
$2C_3$
(g)
V_1
Z_o
L_2
C_1
$2C_3$
$V_2 = 0$
$(R,L)/2$
$(R,L)/2$
$2C_3$

Fig. 33

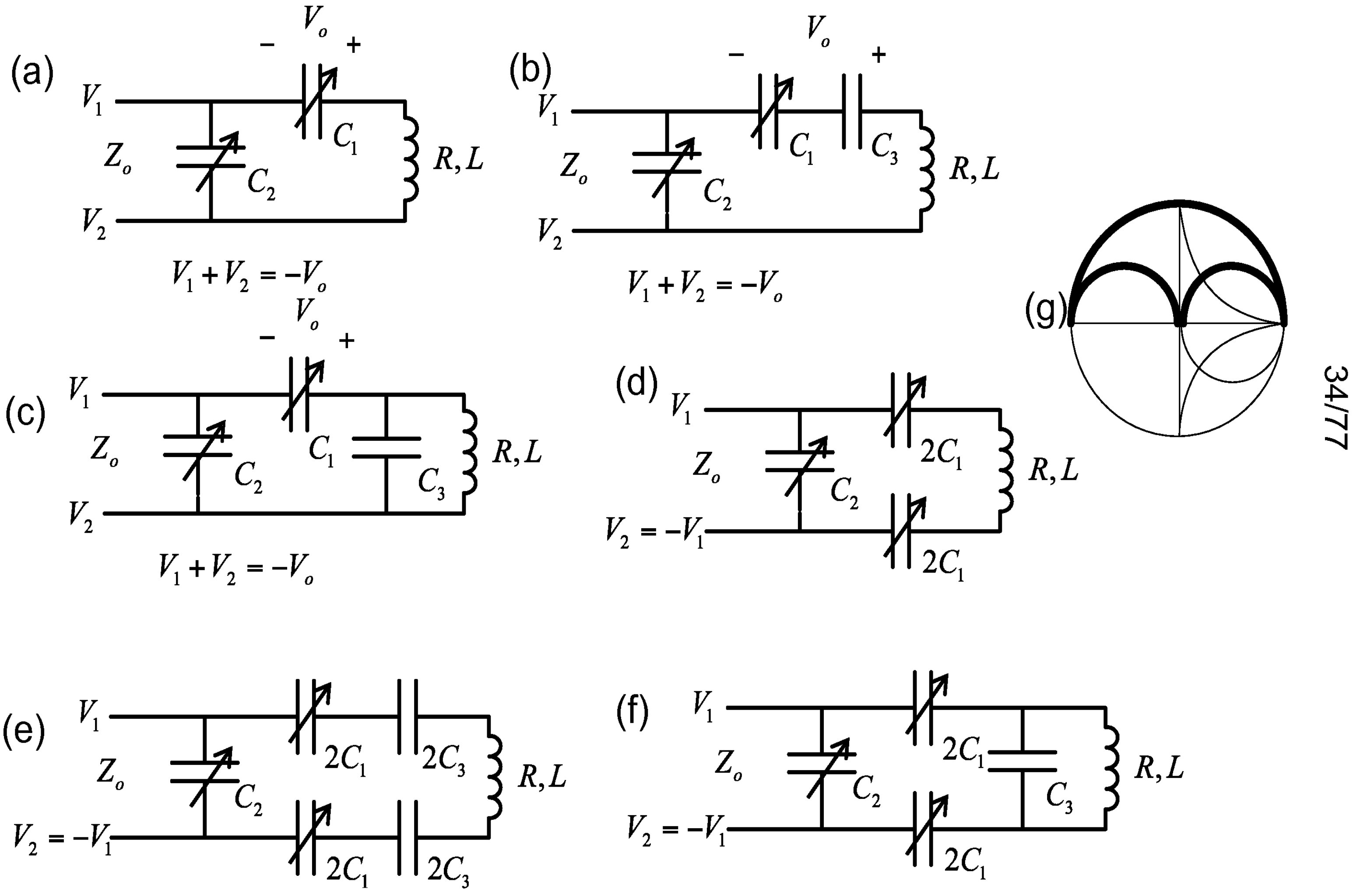

(a)
V_1
Z_o
V_2
V_o
–
+
C_1
C_2
R,L
$V_1 + V_2 = -V_o$
(b)
V_1
Z_o
V_2
V_o
–
+
C_1
C_3
C_2
R,L
$V_1 + V_2 = -V_o$
(c)
V_1
Z_o
V_2
V_o
–
+
C_1
C_2
C_3
R,L
$V_1 + V_2 = -V_o$
(d)
V_1
Z_o
$V_2 = -V_1$
$2C_1$
C_2
$2C_1$
R,L
(e)
V_1
Z_o
$V_2 = -V_1$
$2C_1$
$2C_3$
C_2
$2C_1$
$2C_3$
R,L
(f)
V_1
Z_o
$V_2 = -V_1$
$2C_1$
C_2
C_3
$2C_1$
R,L
(g)

Fig. 33

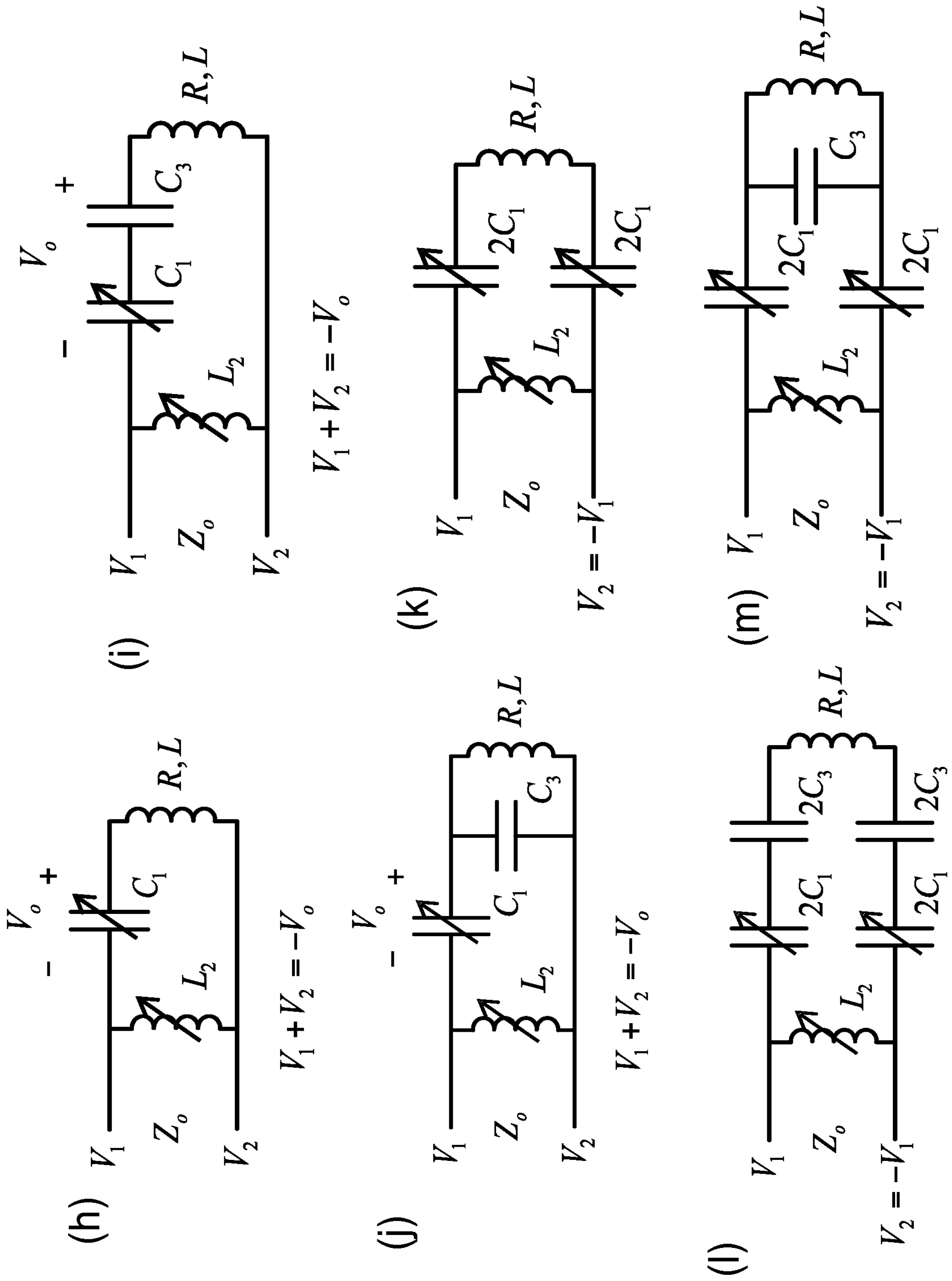

(h)
V_1
Z_o
V_2
L_2
C_1
V_o
-
+
R, L
$V_1 + V_2 = -V_o$
(i)
V_1
Z_o
V_2
L_2
C_1
C_3
V_o
-
+
R, L
$V_1 + V_2 = -V_o$
(j)
V_1
Z_o
V_2
L_2
C_1
C_3
V_o
-
+
R, L
$V_1 + V_2 = -V_o$
(k)
V_1
Z_o
$V_2 = -V_1$
L_2
$2C_1$
$2C_1$
R, L
(l)
V_1
Z_o
$V_2 = -V_1$
L_2
$2C_1$
$2C_1$
$2C_3$
$2C_3$
R, L
(m)
V_1
Z_o
$V_2 = -V_1$
L_2
$2C_1$
$2C_1$
C_3
R, L

Fig. 34

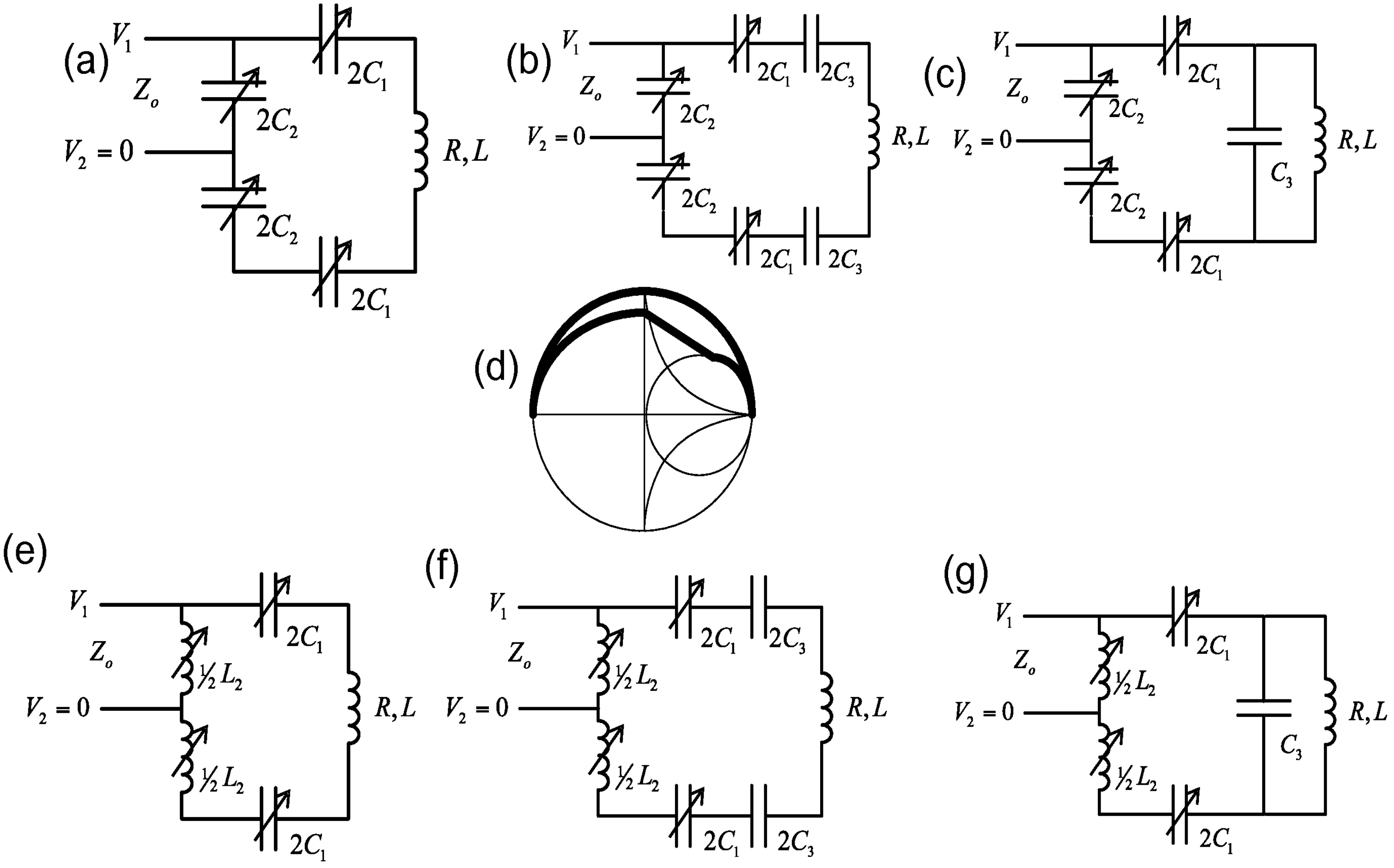

(a)
V_1
Z_o
$V_2 = 0$
$2C_2$
$2C_2$
$2C_1$
$2C_1$
R,L
(b)
V_1
Z_o
$V_2 = 0$
$2C_2$
$2C_2$
$2C_1$
$2C_3$
$2C_1$
$2C_3$
R,L
(c)
V_1
Z_o
$V_2 = 0$
$2C_2$
$2C_2$
$2C_1$
$2C_1$
C_3
R,L
(d)
(e)
V_1
Z_o
$V_2 = 0$
$½L_2$
$½L_2$
$2C_1$
$2C_1$
R,L
(f)
V_1
Z_o
$V_2 = 0$
$½L_2$
$½L_2$
$2C_1$
$2C_3$
$2C_1$
$2C_3$
R,L
(g)
V_1
Z_o
$V_2 = 0$
$½L_2$
$½L_2$
$2C_1$
$2C_1$
C_3
R,L

Fig. 35

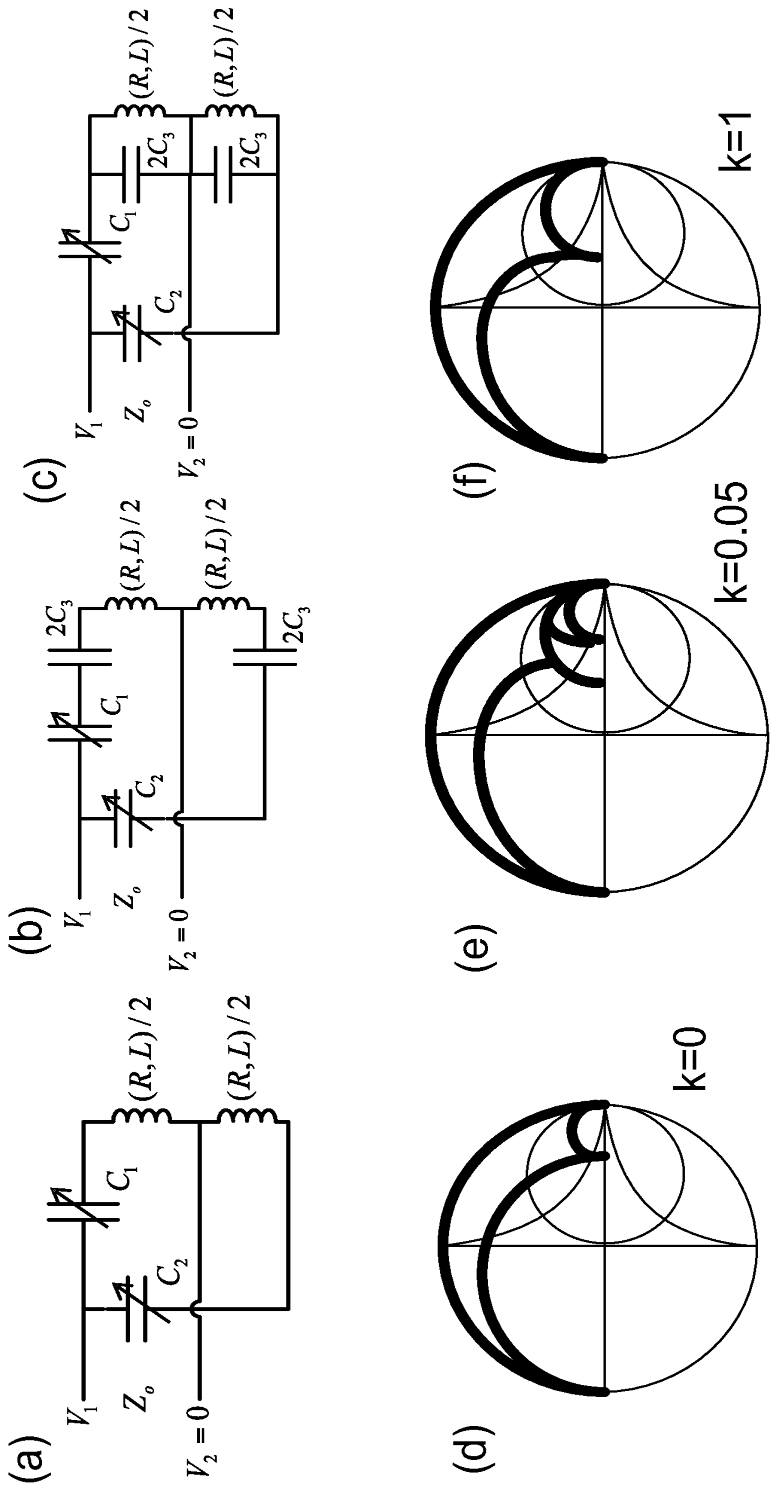

(a)
V_1
Z_o
$V_2 = 0$
C_1
C_2
$(R,L)/2$
$(R,L)/2$
(b)
V_1
Z_o
$V_2 = 0$
C_1
C_2
$2C_3$
$2C_3$
$(R,L)/2$
$(R,L)/2$
(c)
V_1
Z_o
$V_2 = 0$
C_1
C_2
$2C_3$
$2C_3$
$(R,L)/2$
$(R,L)/2$
(d)
k=0
(e)
k=0.05
(f)
k=1

Fig. 36

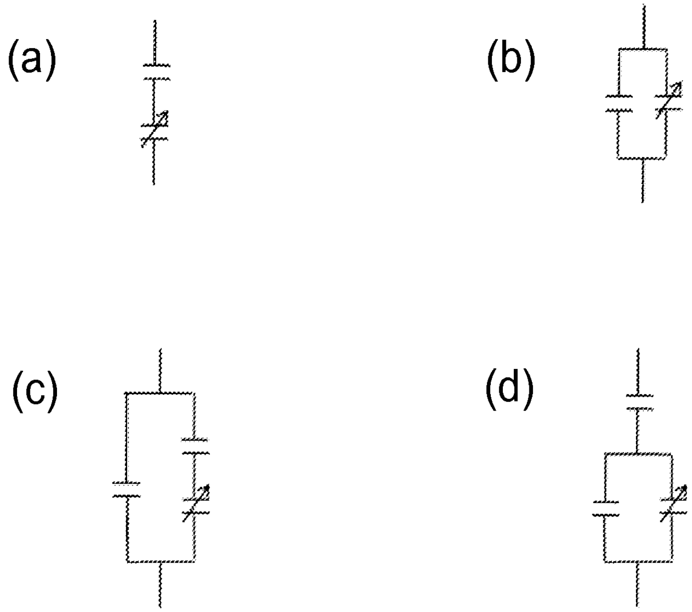


Fig. 37

Fig. 38

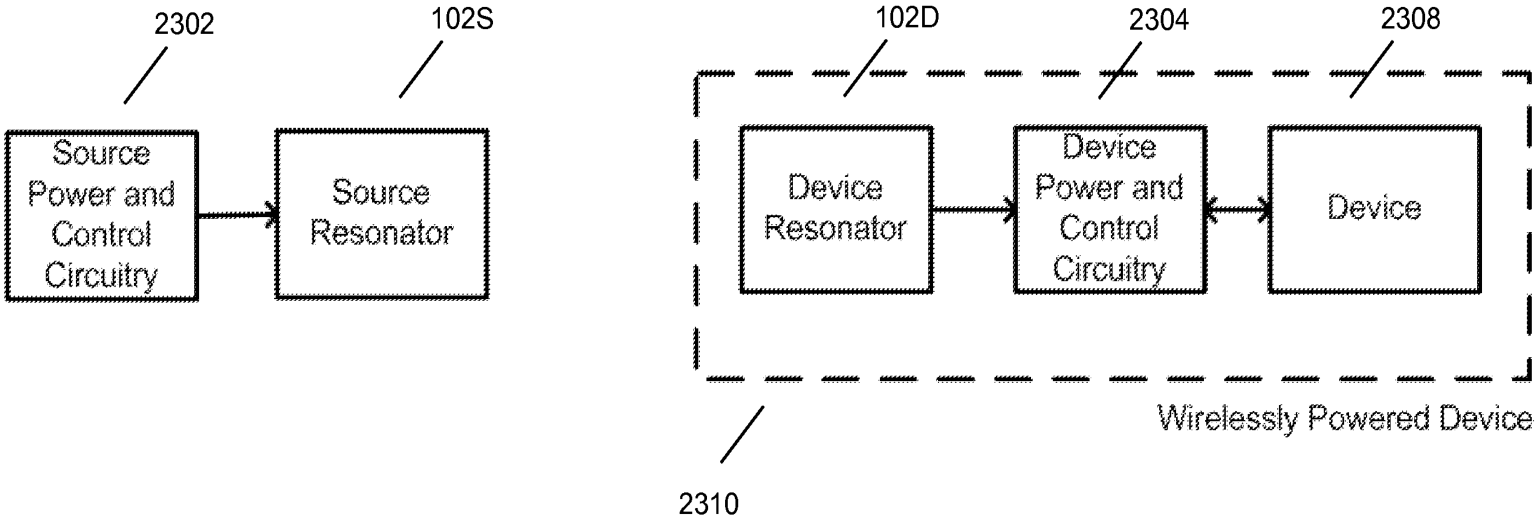

2302
102S
Source Power and Control Circuitry
Source Resonator
102D
2304
2308
Device Resonator
Device Power and Control Circuitry
Device
Wirelessly Powered Device
2310

Fig. 39

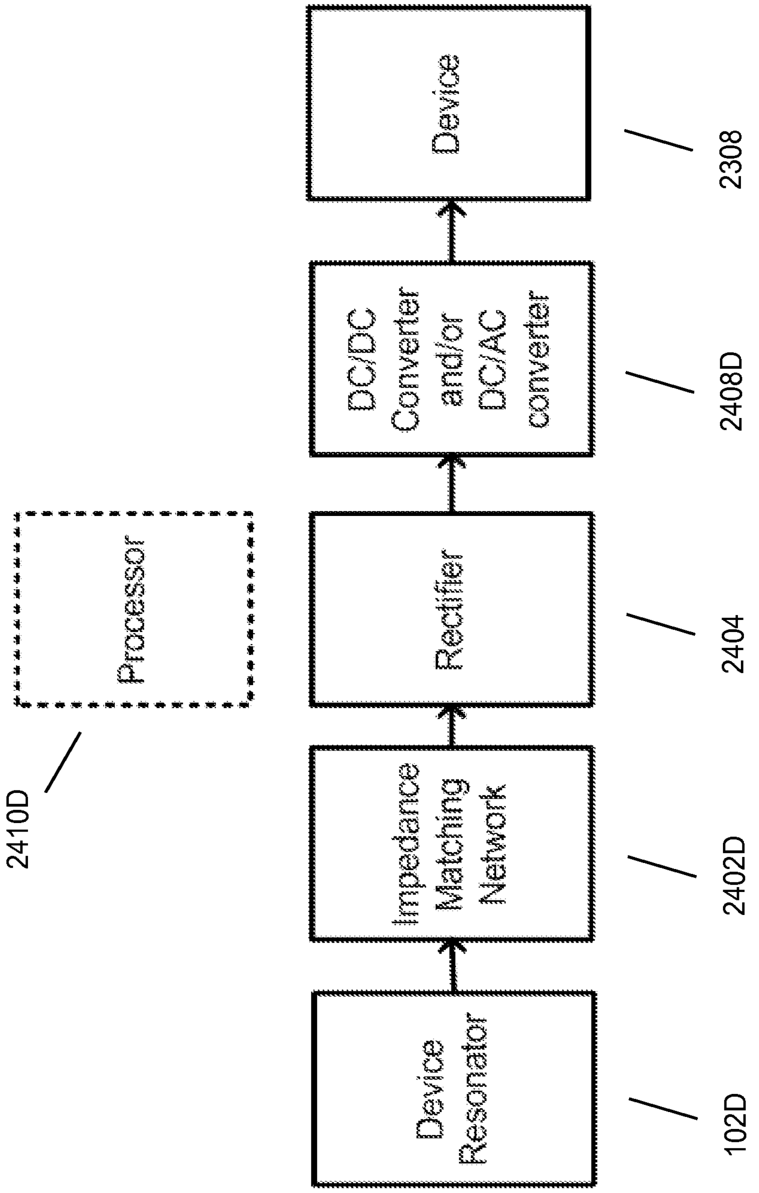

Device Resonator
102D
Impedance Matching Network
2402D
Rectifier
2404
DC/DC Converter and/or DC/AC converter
2408D
Device
2308
Processor
2410D

Fig. 40

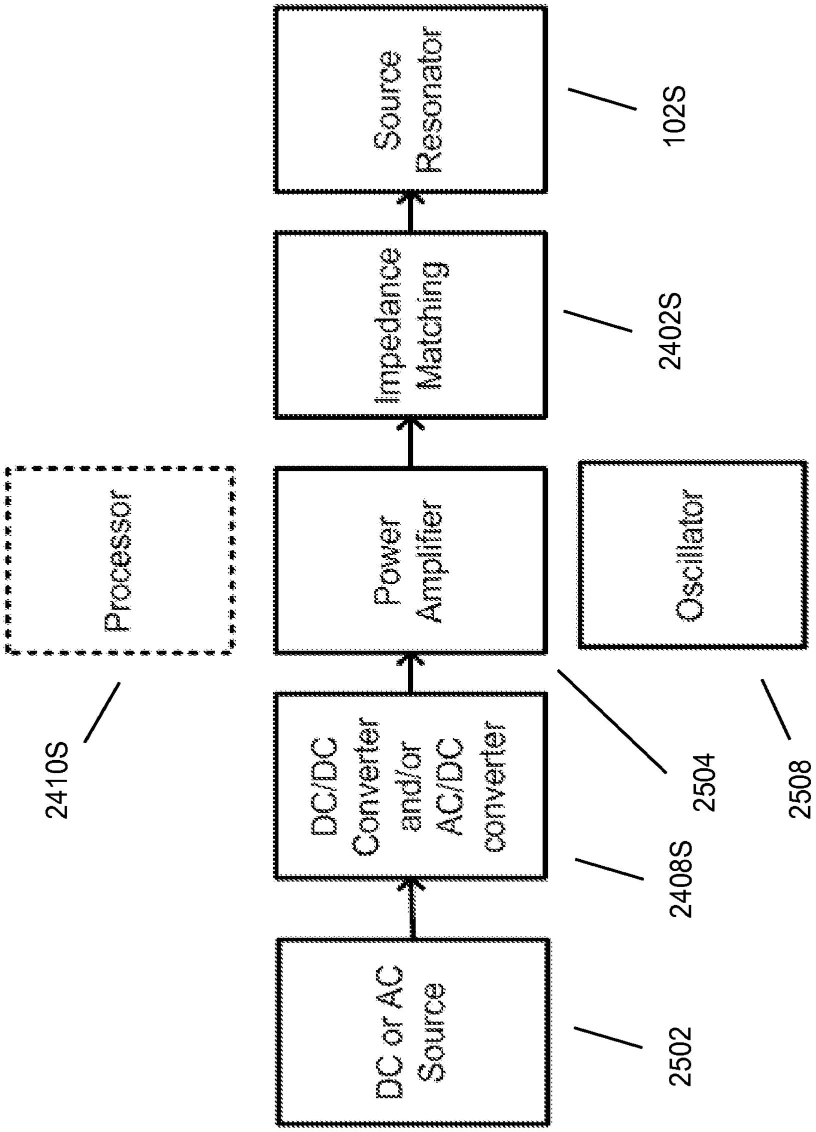

DC or AC Source
2502
DC/DC Converter and/or AC/DC converter
2408S
Power Amplifier
2504
Impedance Matching
2402S
Source Resonator
102S
Processor
2410S
Oscillator
2508

Fig. 41

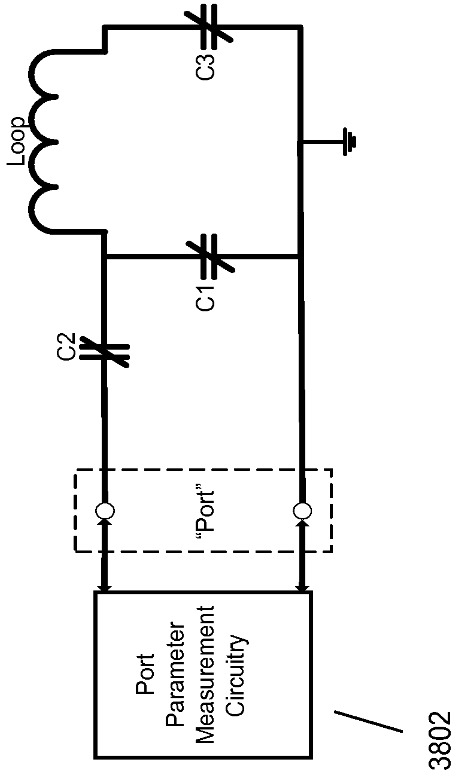

Loop
C3
C1
C2
"Port"
Port Parameter Measurement Circuitry
3802

Fig. 42

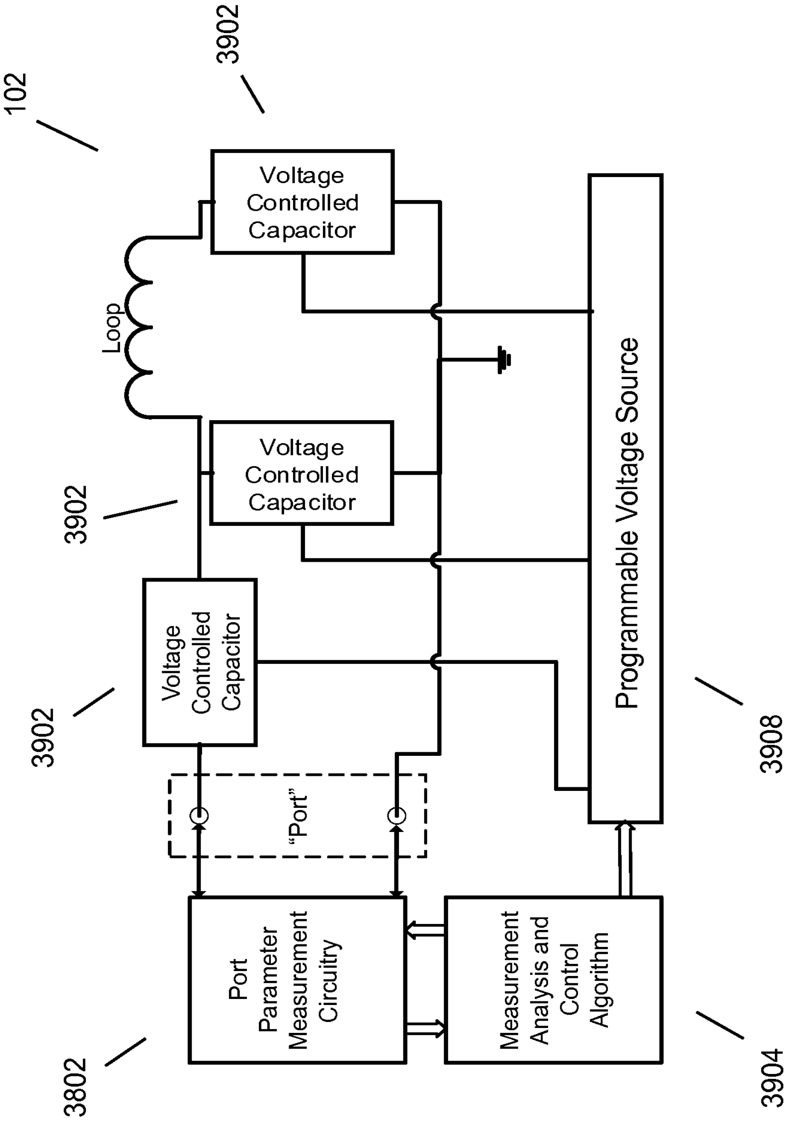

102
3902
Voltage Controlled Capacitor
Loop
Voltage Controlled Capacitor
3902
Voltage Controlled Capacitor
3902
Programmable Voltage Source
3908
"Port"
Port Parameter Measurement Circuitry
Measurement Analysis and Control Algorithm
3802
3904

Fig. 43

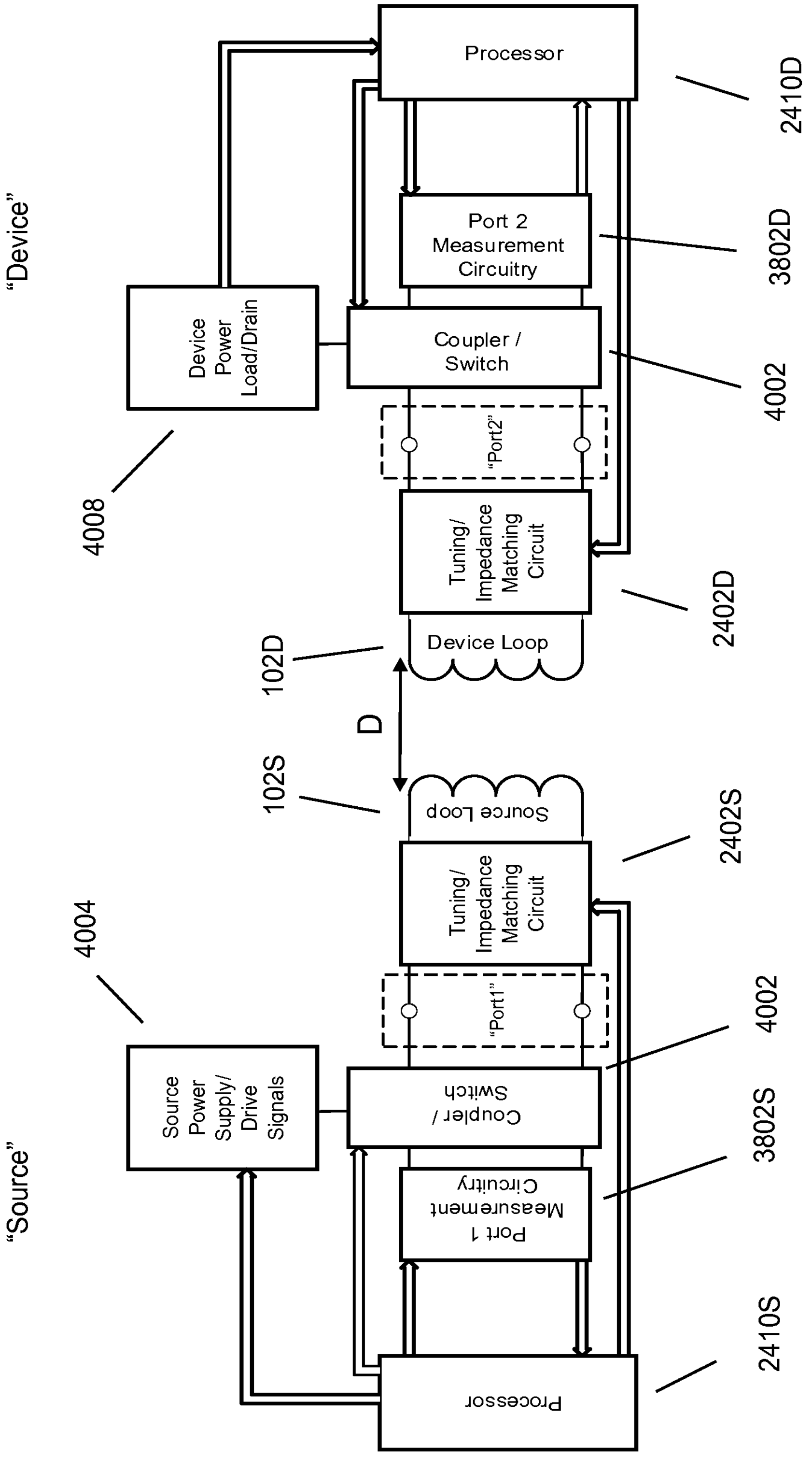

"Device"
Processor
2410D
Port 2 Measurement Circuitry
3802D
Coupler / Switch
4002
Device Power Load/Drain
4008
"Port2"
Tuning/ Impedance Matching Circuit
2402D
Device Loop
102D
D
102S
Source Loop
2402S
Tuning/ Impedance Matching Circuit
4004
Source Power Supply/ Drive Signals
"Port1"
4002
Coupler / Switch
3802S
Port 1 Measurement Circuitry
"Source"
Processor
2410S

Fig. 44

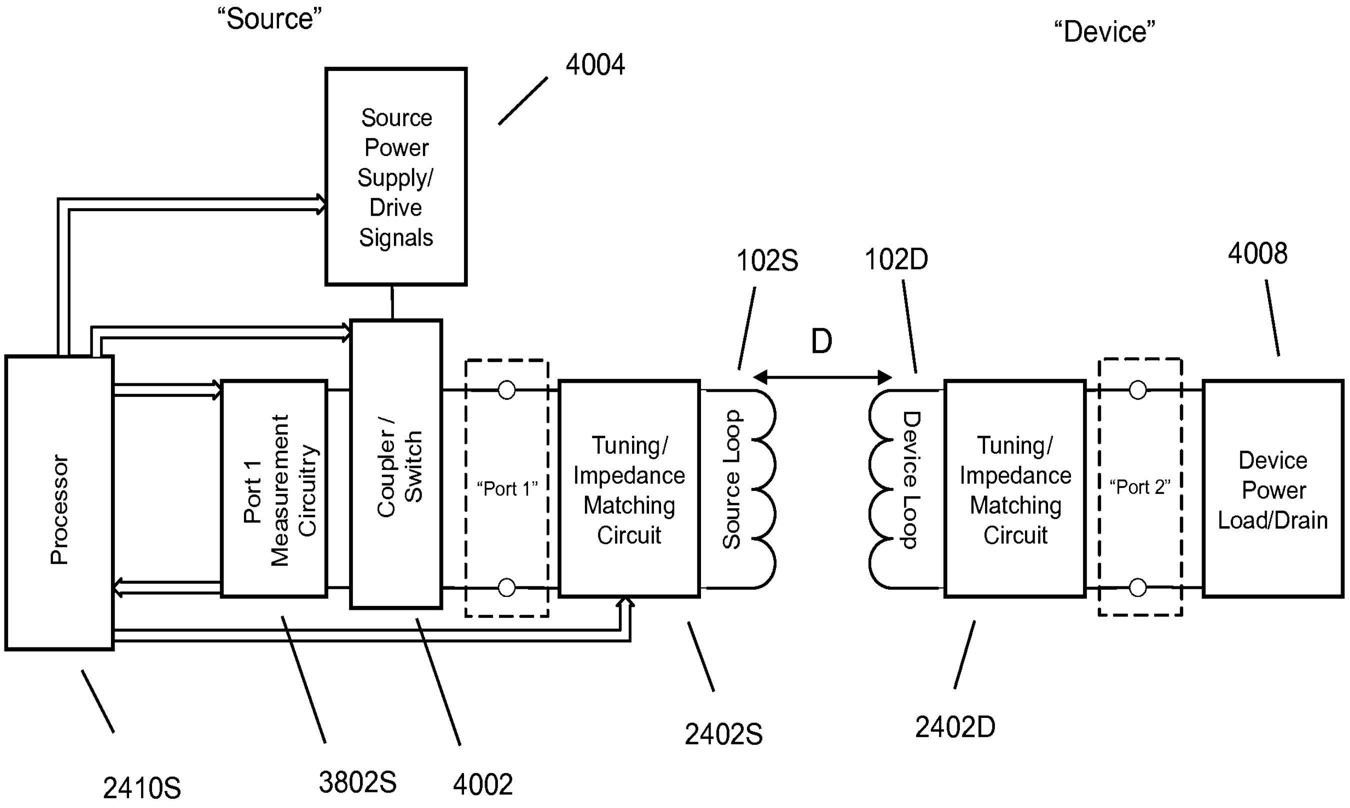

"Source"
"Device"
4004
Source Power Supply/ Drive Signals
102S
102D
4008
D
Processor
Port 1 Measurement Circuitry
Coupler / Switch
"Port 1"
Tuning/ Impedance Matching Circuit
Source Loop
Device Loop
Tuning/ Impedance Matching Circuit
"Port 2"
Device Power Load/Drain
2410S
3802S
4002
2402S
2402D

Fig. 45

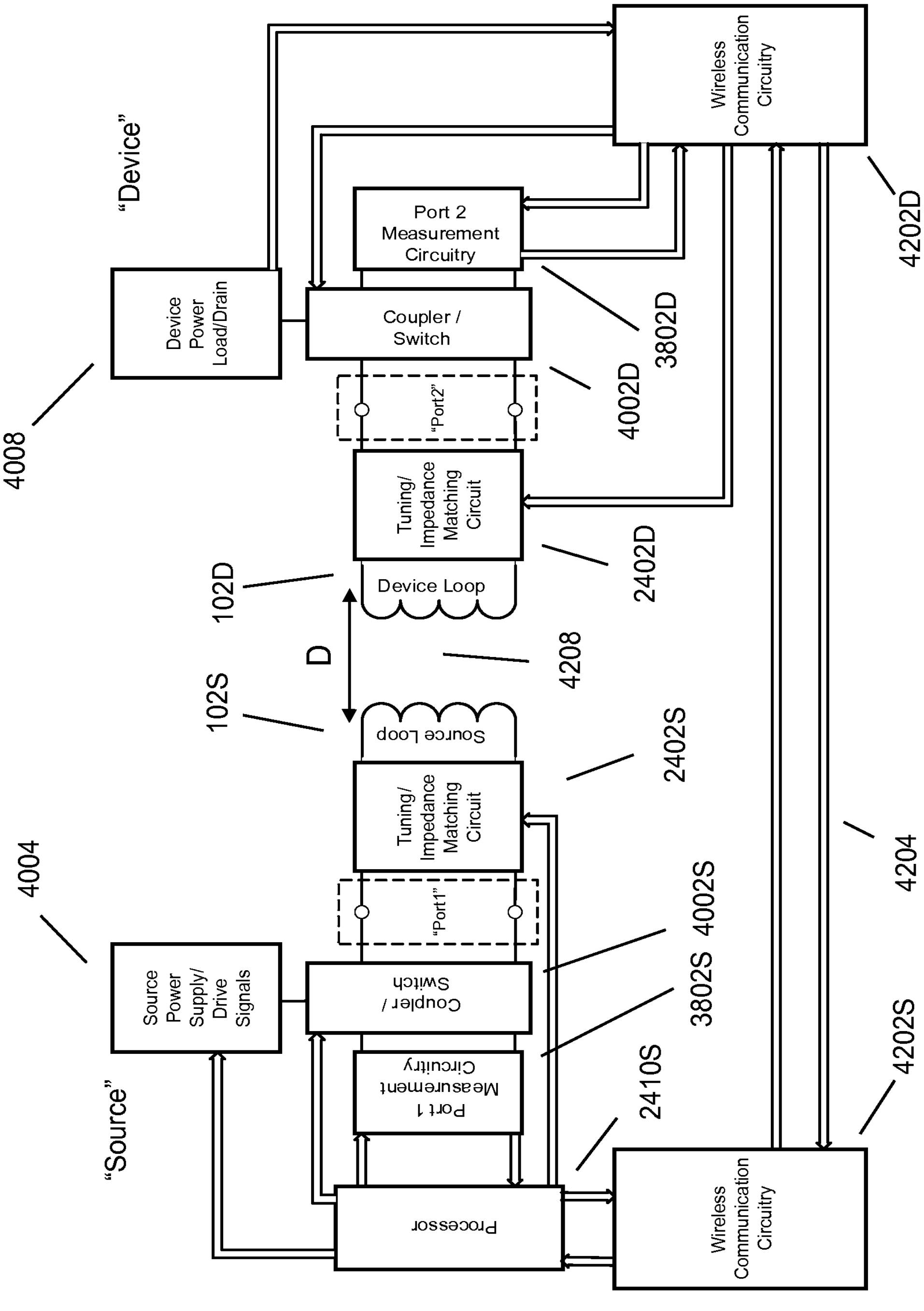

"Device"
"Source"
Wireless Communication Circuitry
Wireless Communication Circuitry
Port 2 Measurement Circuitry
Device Power Load/Drain
Coupler / Switch
"Port2"
Tuning/ Impedance Matching Circuit
Device Loop
D
Source Loop
Tuning/ Impedance Matching Circuit
"Port1"
Source Power Supply/ Drive Signals
Coupler / Switch
Port 1 Measurement Circuitry
Processor
4008
4004
102D
102S
4208
3802D
4002D
2402D
2402S
4202D
4204
3802S
4002S
2410S
4202S

Fig. 46

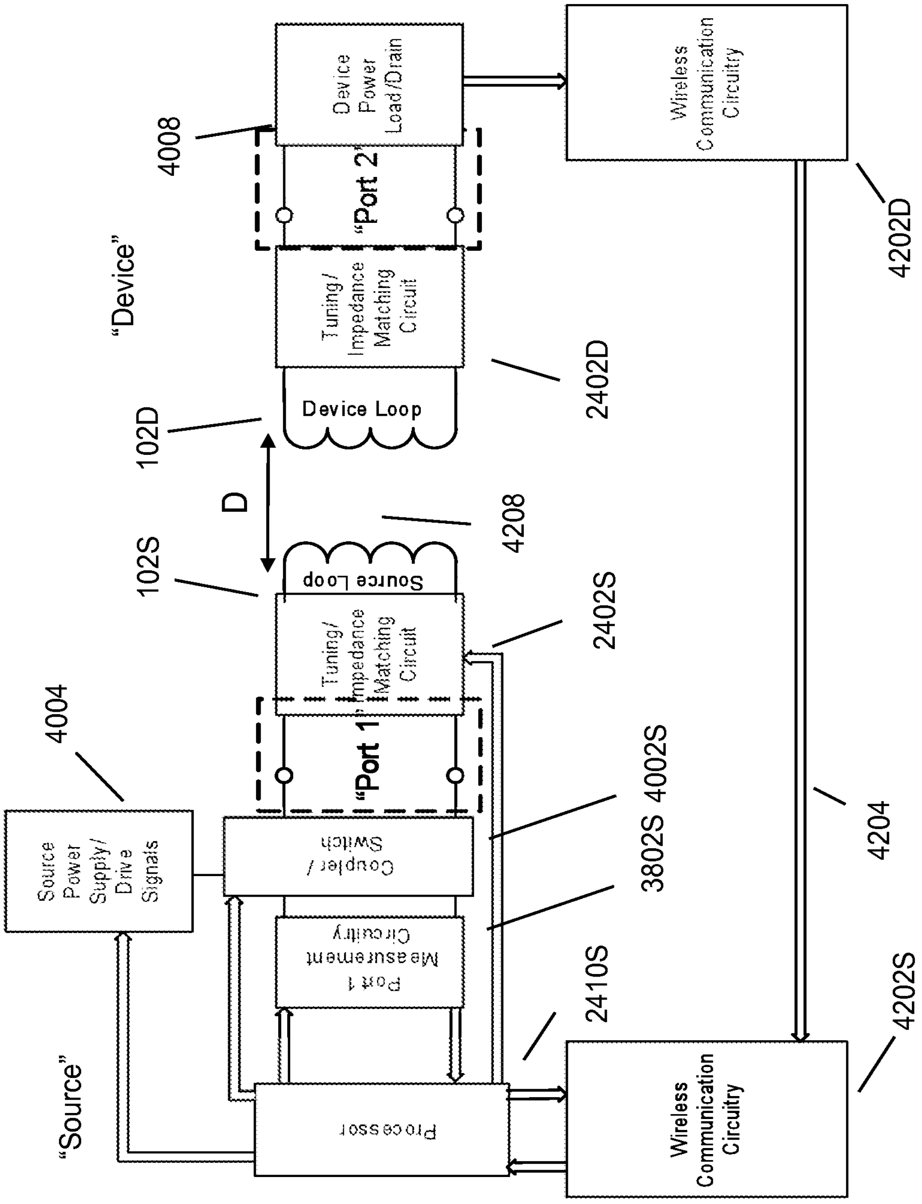

"Device"
4008
Device Power Load/Drain
Wireless Communication Circuitry
"Port 2"
4202D
Tuning/ Impedance Matching Circuit
2402D
Device Loop
102D
D
4208
102S
Source Loop
Tuning/ Impedance Matching Circuit
2402S
4004
"Port 1"
3802S 4002S
Source Power Supply/ Drive Signals
Coupler / Switch
Port 1 Measurement Circuitry
4204
2410S
4202S
"Source"
Processor
Wireless Communication Circuitry

Fig. 47

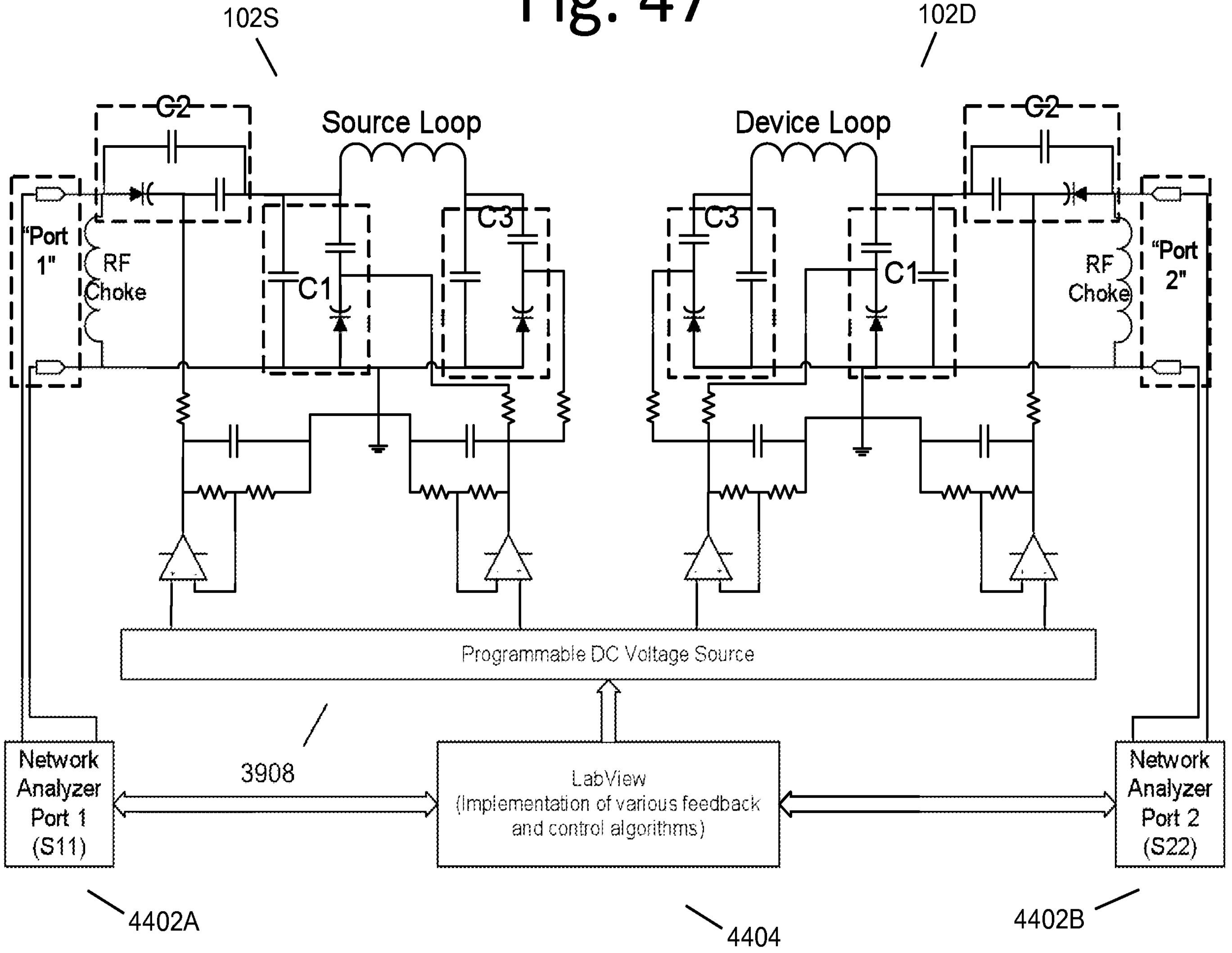

102S
102D
G2
Source Loop
Device Loop
G2
"Port 1"
RF Choke
C1
C3
C3
C1
RF Choke
"Port 2"
Programmable DC Voltage Source
3908
Network Analyzer Port 1 (S11)
LabView (Implementation of various feedback and control algorithms)
Network Analyzer Port 2 (S22)
4402A
4404
4402B

Fig. 48

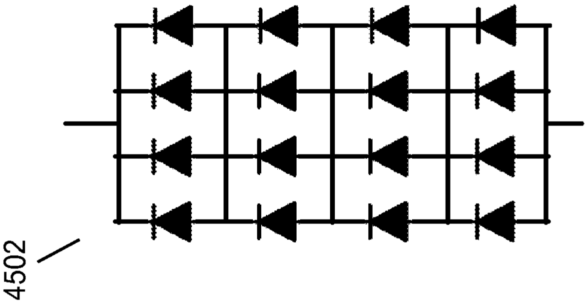


Fig. 49

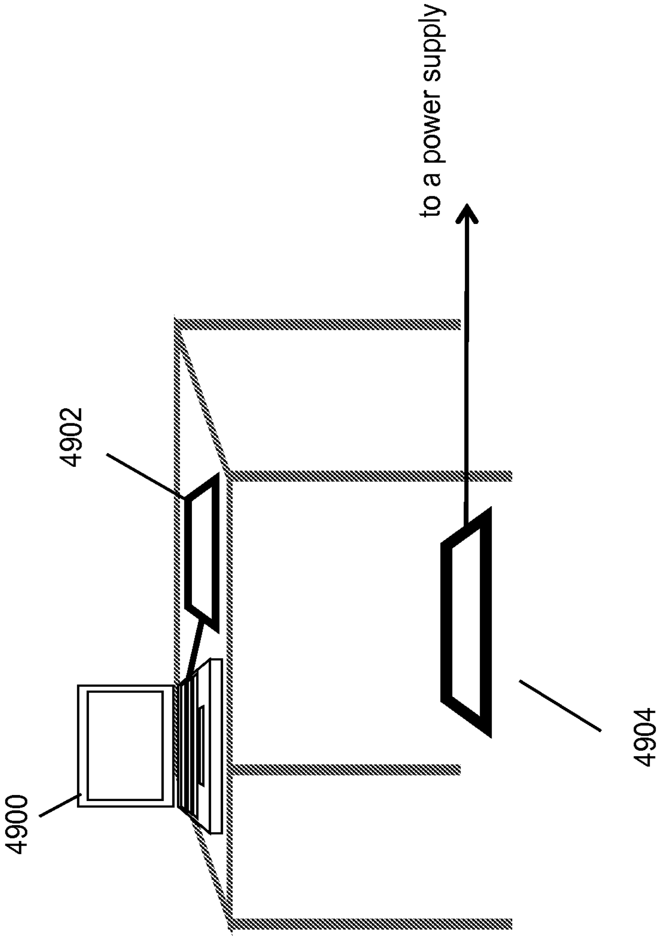


Fig. 50

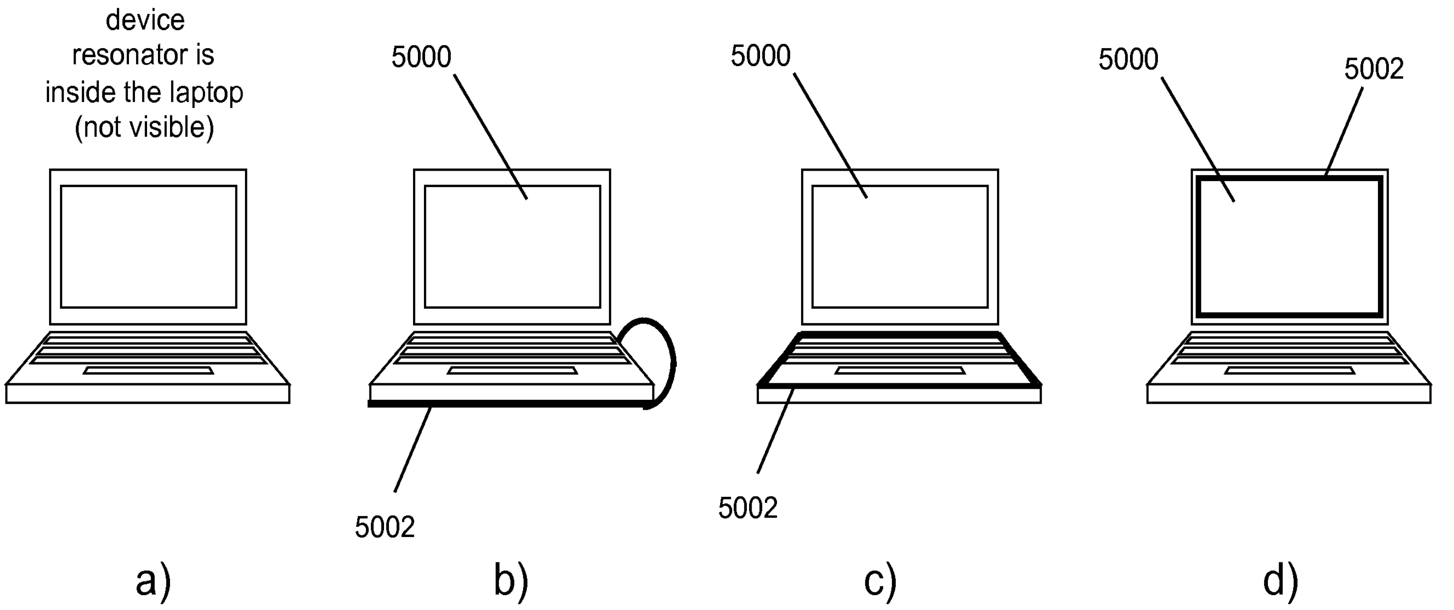
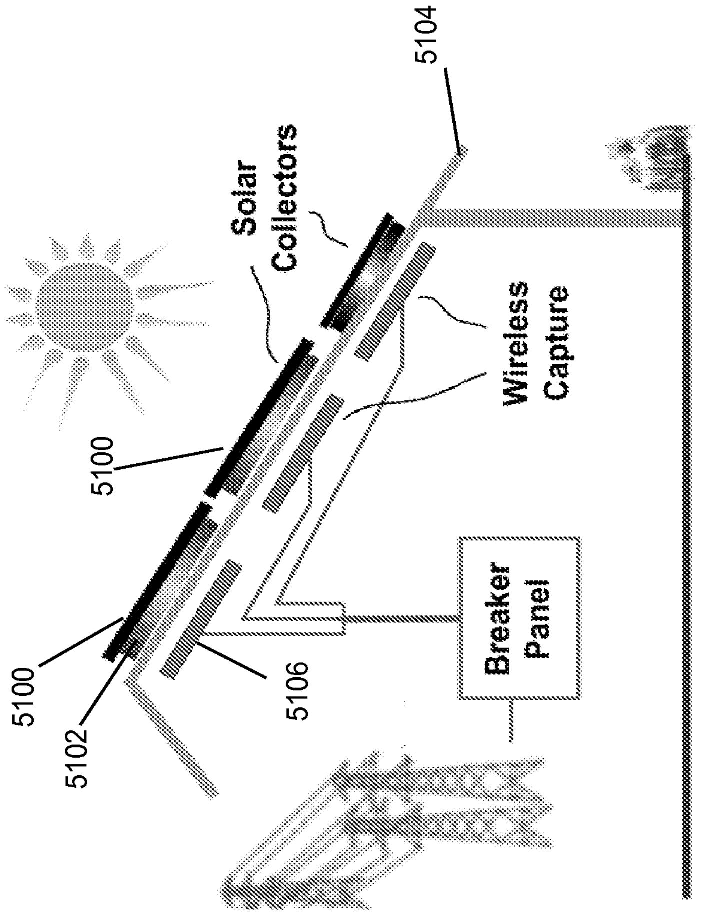

device
resonator is
inside the laptop
(not visible)
5000
5002
5000
5002
5000
5002
a)
b)
c)
d)

Fig. 51


5104
Solar Collectors
Wireless Capture
5100
5100
5102
5106
Breaker Panel

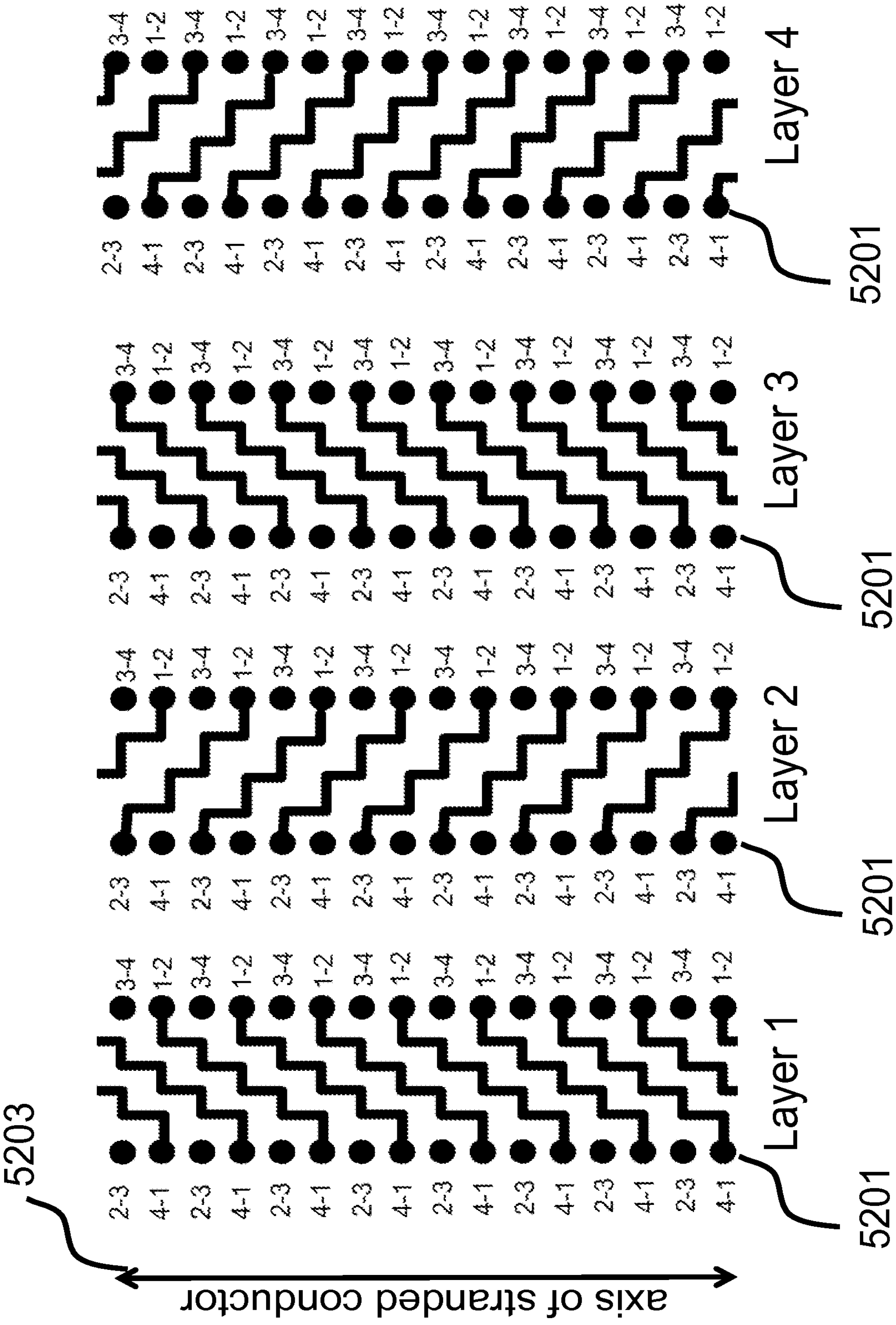

Layer 1
Layer 2
Layer 3
Layer 4
2-3
4-1
3-4
1-2
5201
5203
axis of stranded conductor

Fig. 52a

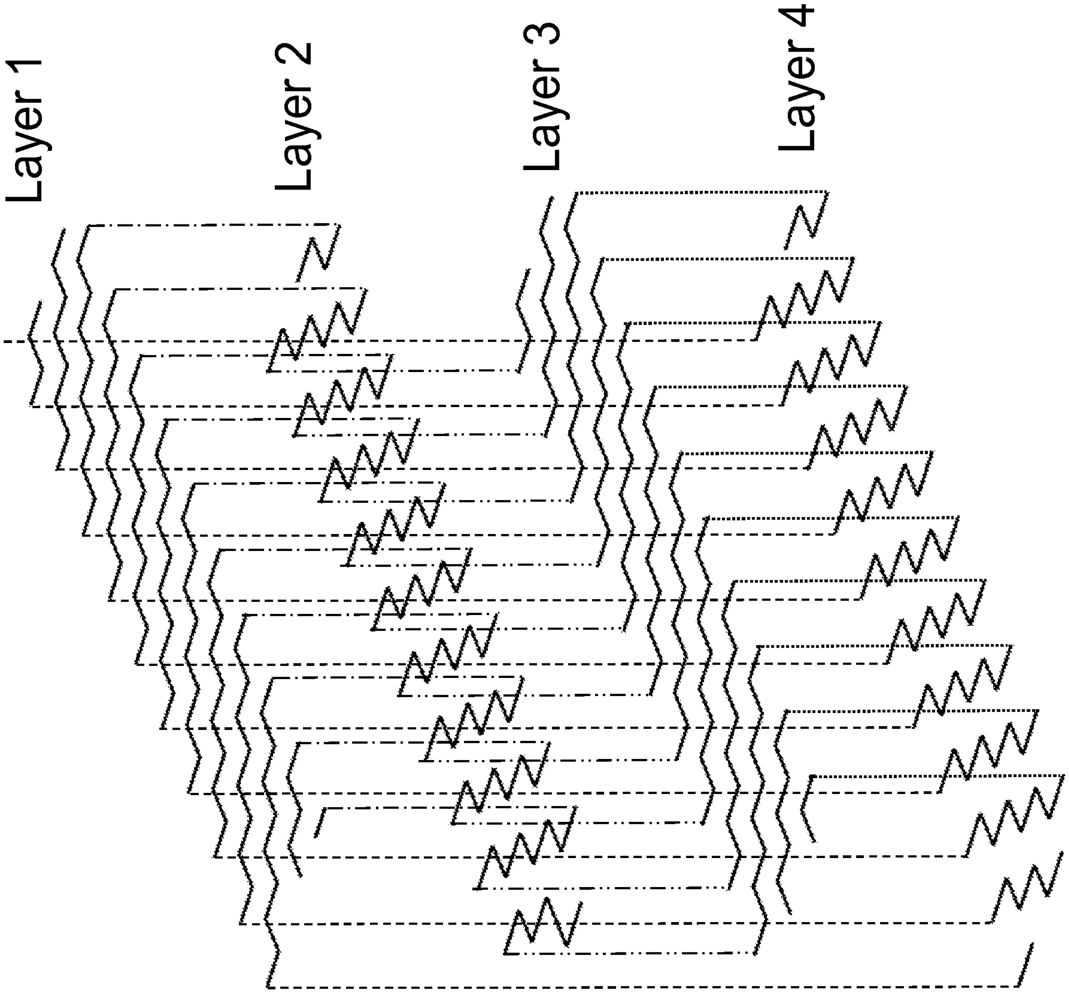
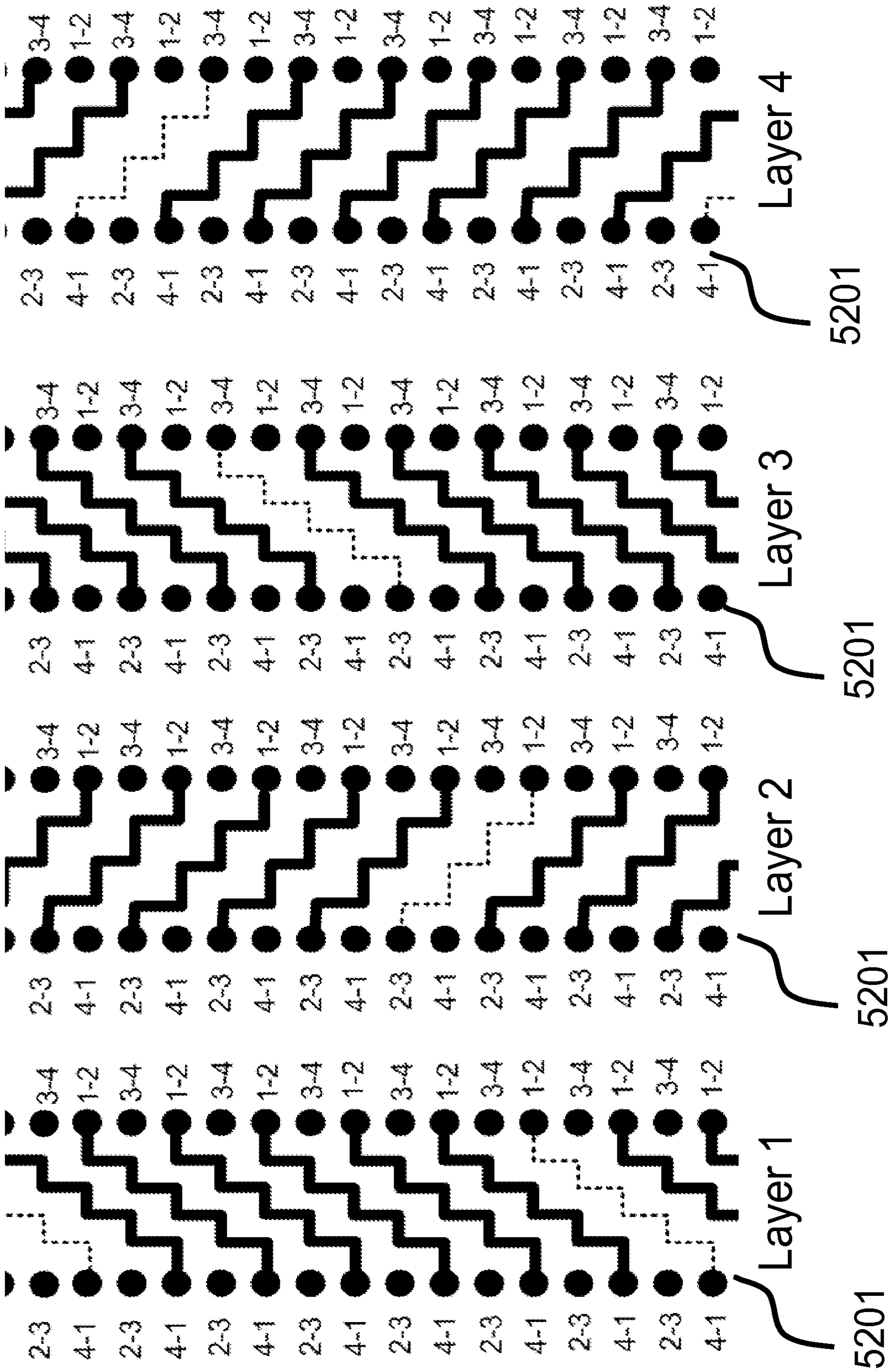


Fig. 52b

Fig. 53a



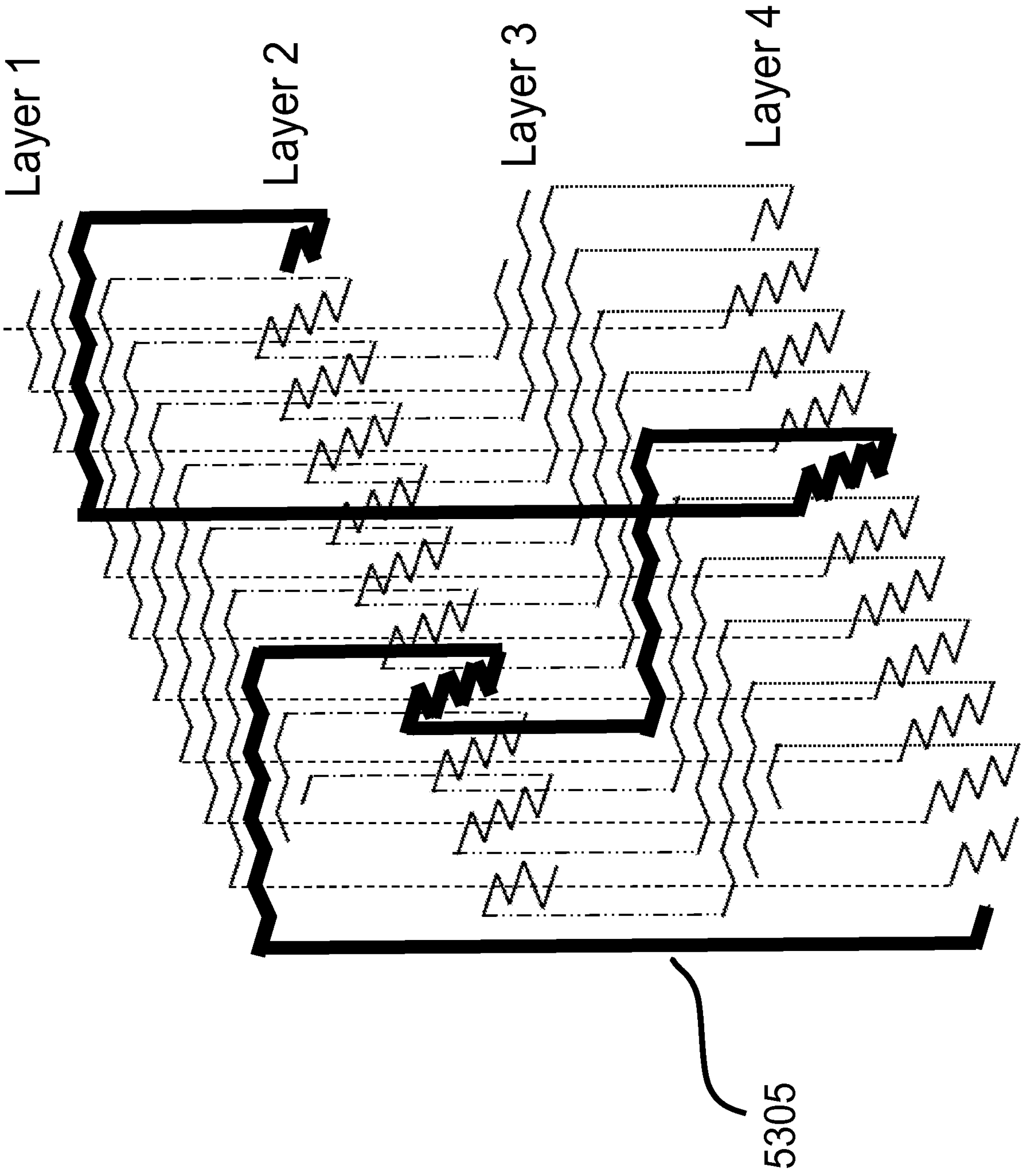
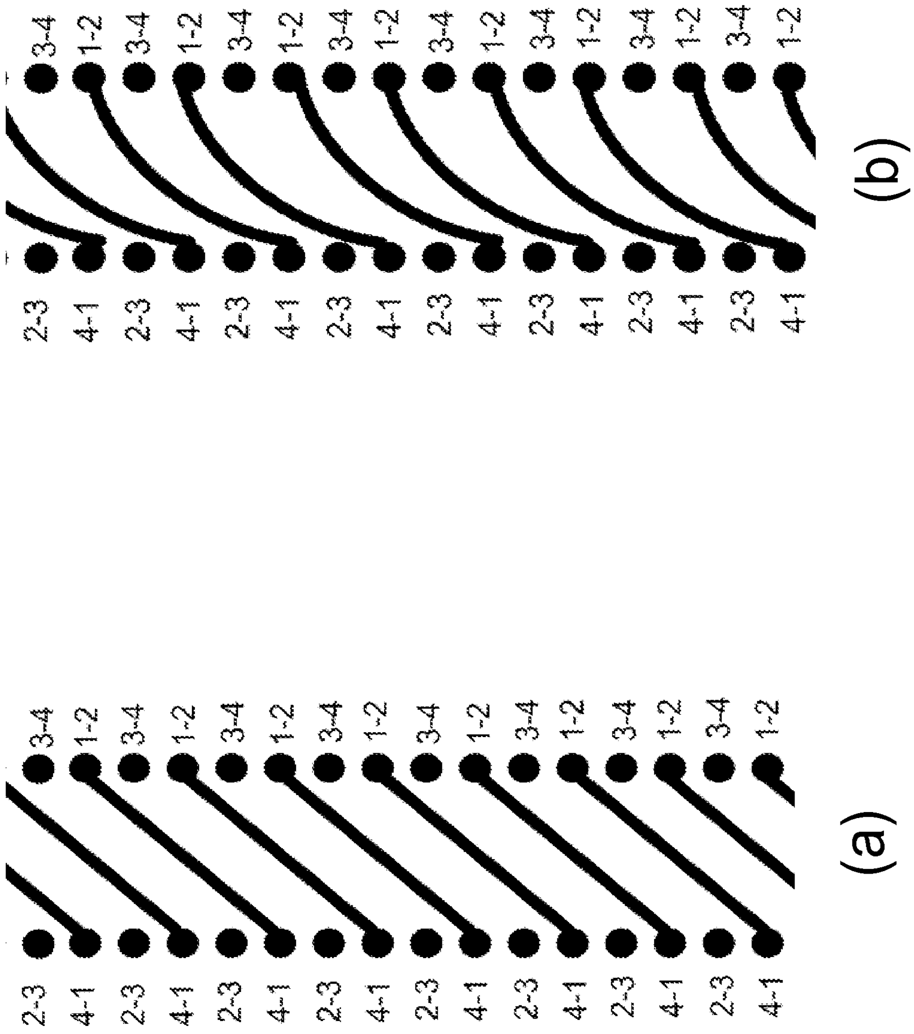


Fig. 53b

Fig. 54


3-4
1-2
3-4
1-2
3-4
1-2
3-4
1-2
3-4
1-2
3-4
1-2
3-4
1-2
3-4
1-2
2-3
4-1
2-3
4-1
2-3
4-1
2-3
4-1
2-3
4-1
2-3
4-1
2-3
4-1
2-3
4-1

(b)

(a)

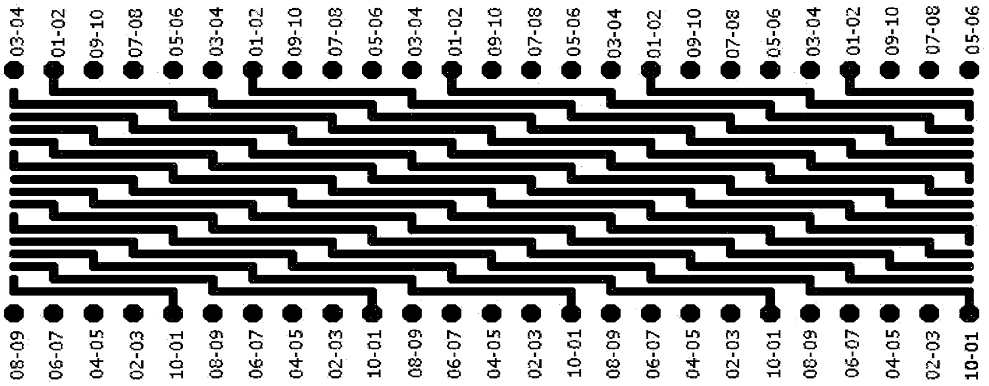

03-04
01-02
09-10
07-08
05-06
03-04
01-02
09-10
07-08
05-06
03-04
01-02
09-10
07-08
05-06
03-04
01-02
09-10
07-08
05-06
03-04
01-02
09-10
07-08
05-06
08-09
06-07
04-05
02-03
10-01
08-09
06-07
04-05
02-03
10-01
08-09
06-07
04-05
02-03
10-01
08-09
06-07
04-05
02-03
10-01
08-09
06-07
04-05
02-03
10-01

Fig. 55

Fig. 56

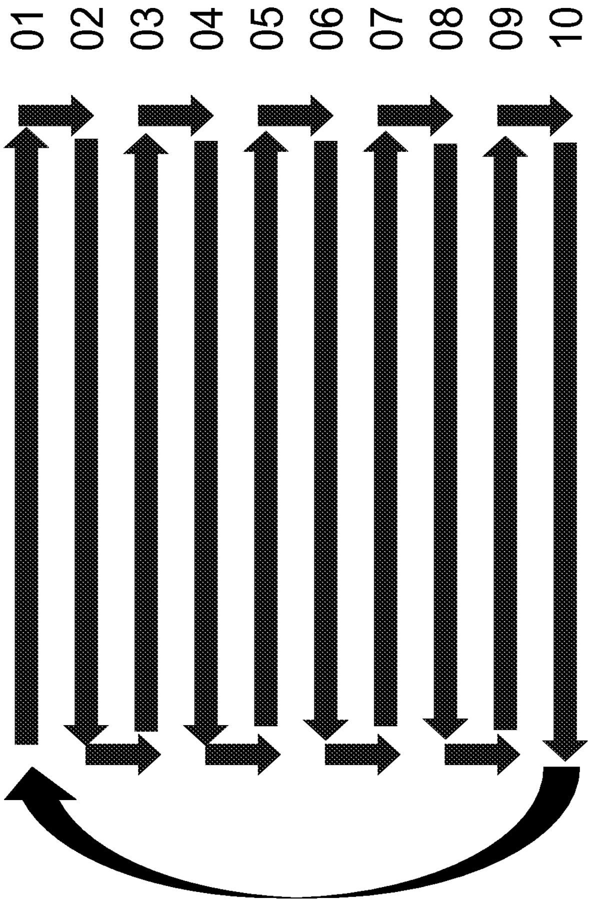


Fig. 57

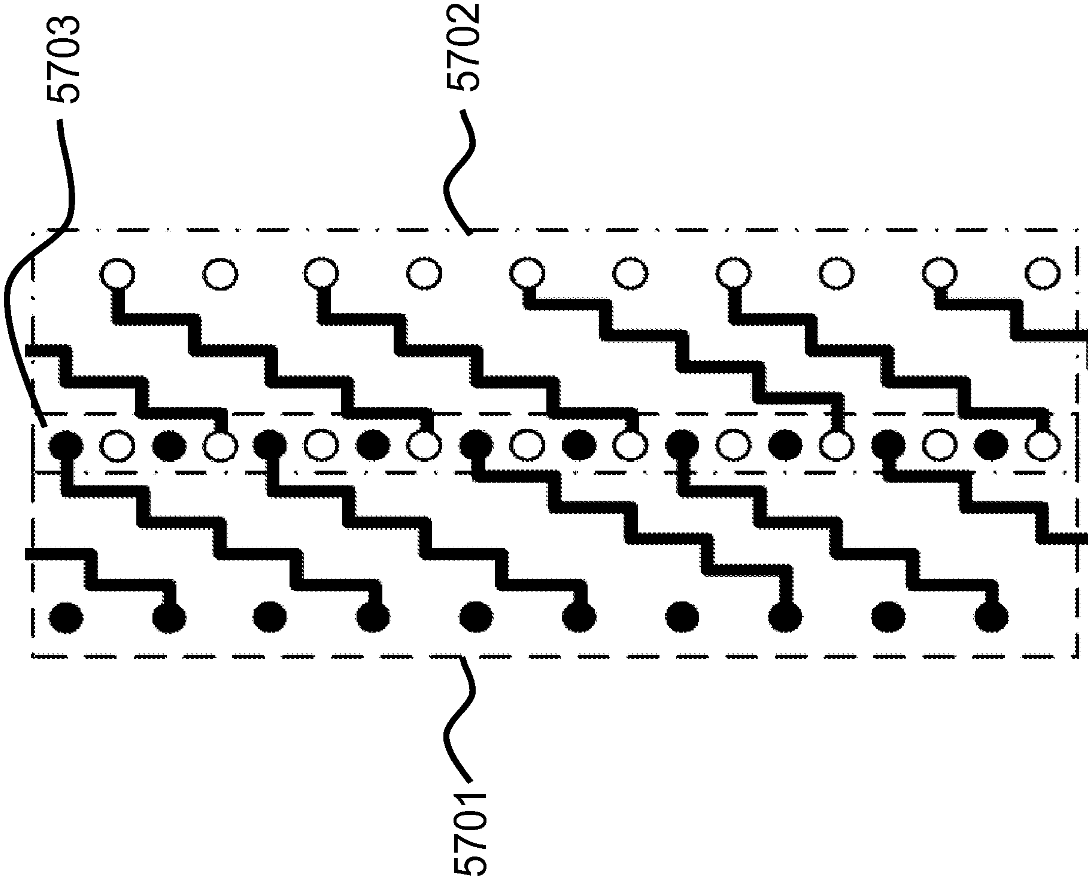


Fig. 58

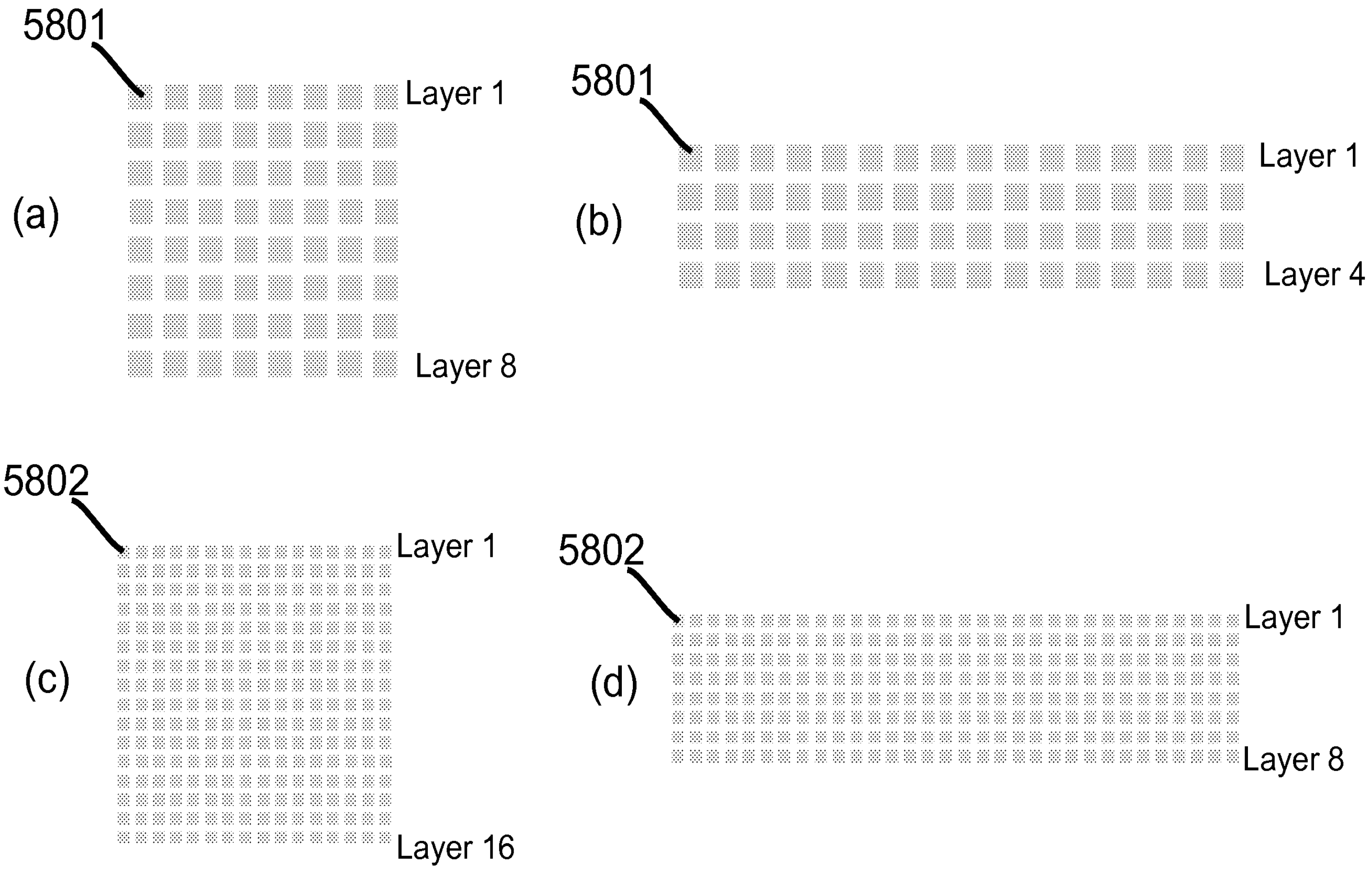
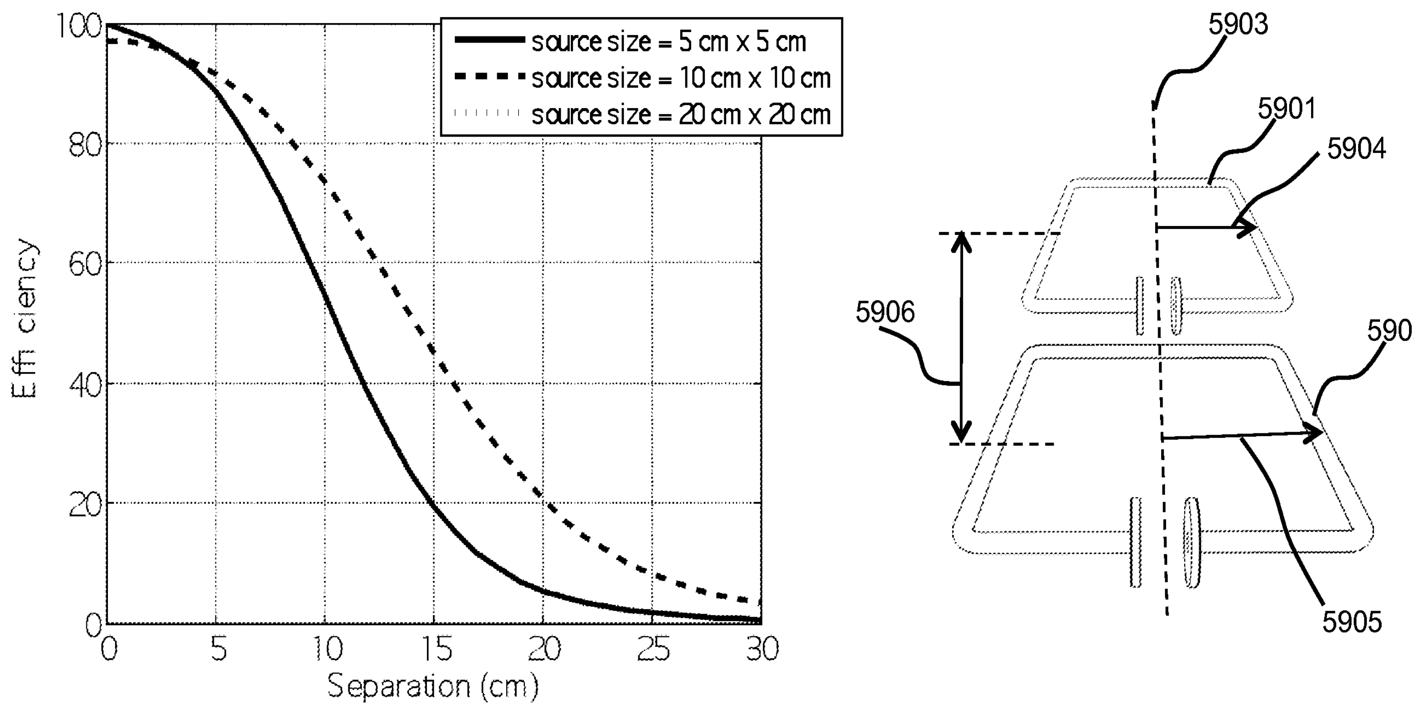

5801
Layer 1
(a)
Layer 8
5801
Layer 1
(b)
Layer 4
5802
Layer 1
(c)
Layer 16
5802
Layer 1
(d)
Layer 8

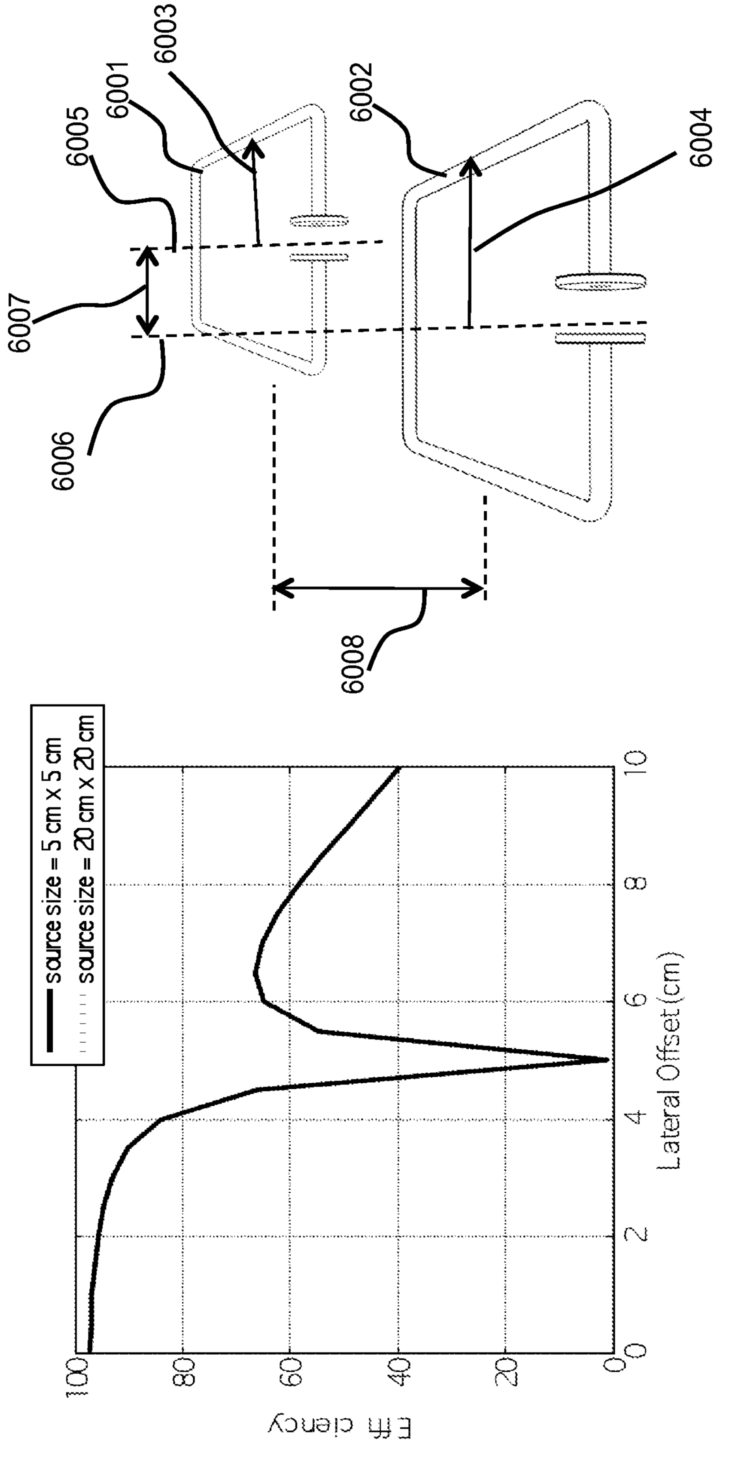
Fig. 59


100
80
60
40
20
0
Effi ciency
0
5
10
15
20
25
30
Separation (cm)
source size = 5 cm x 5 cm
source size = 10 cm x 10 cm
source size = 20 cm x 20 cm
5903
5901
5904
5906
5902
5905

(a)

(b)

Fig. 60


source size = 5 cm x 5 cm
source size = 20 cm x 20 cm
Efficiency
100
80
60
40
20
0
0
2
4
6
8
10
Lateral Offset (cm)
6001
6002
6003
6004
6005
6006
6007
6008

(a)

(b)

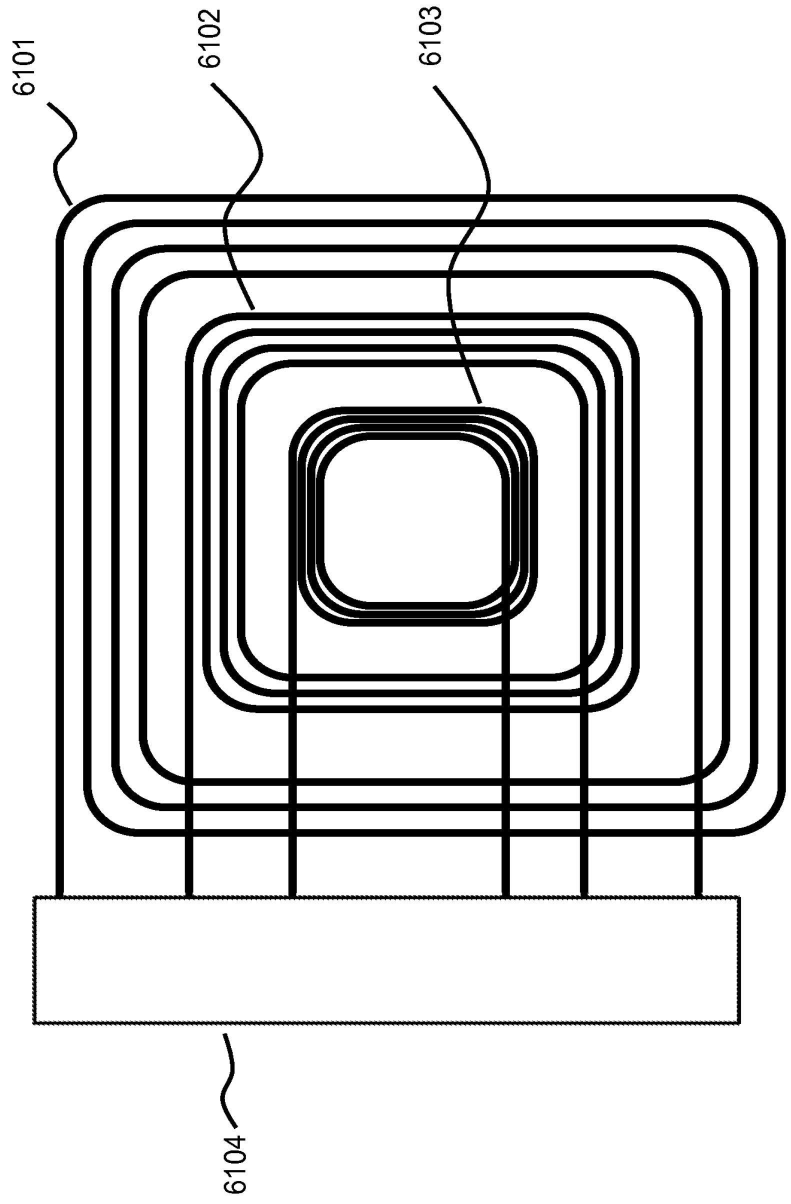


Fig. 61

Fig. 62

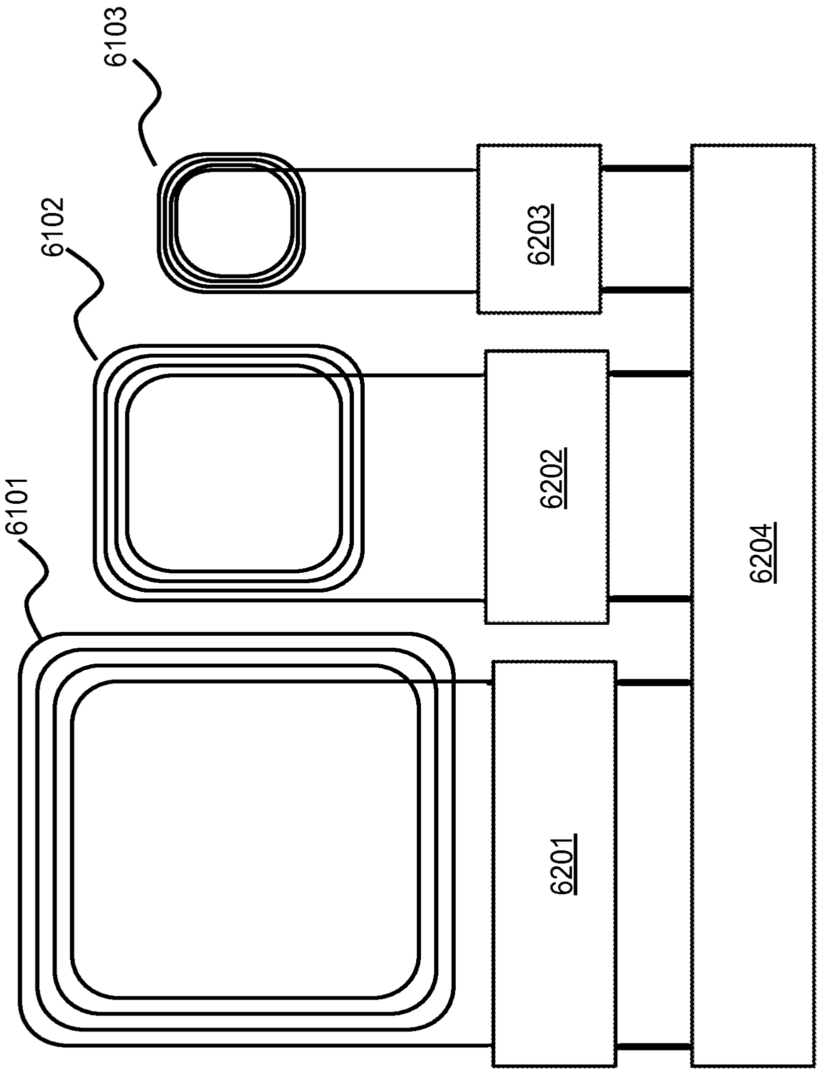


Fig. 63

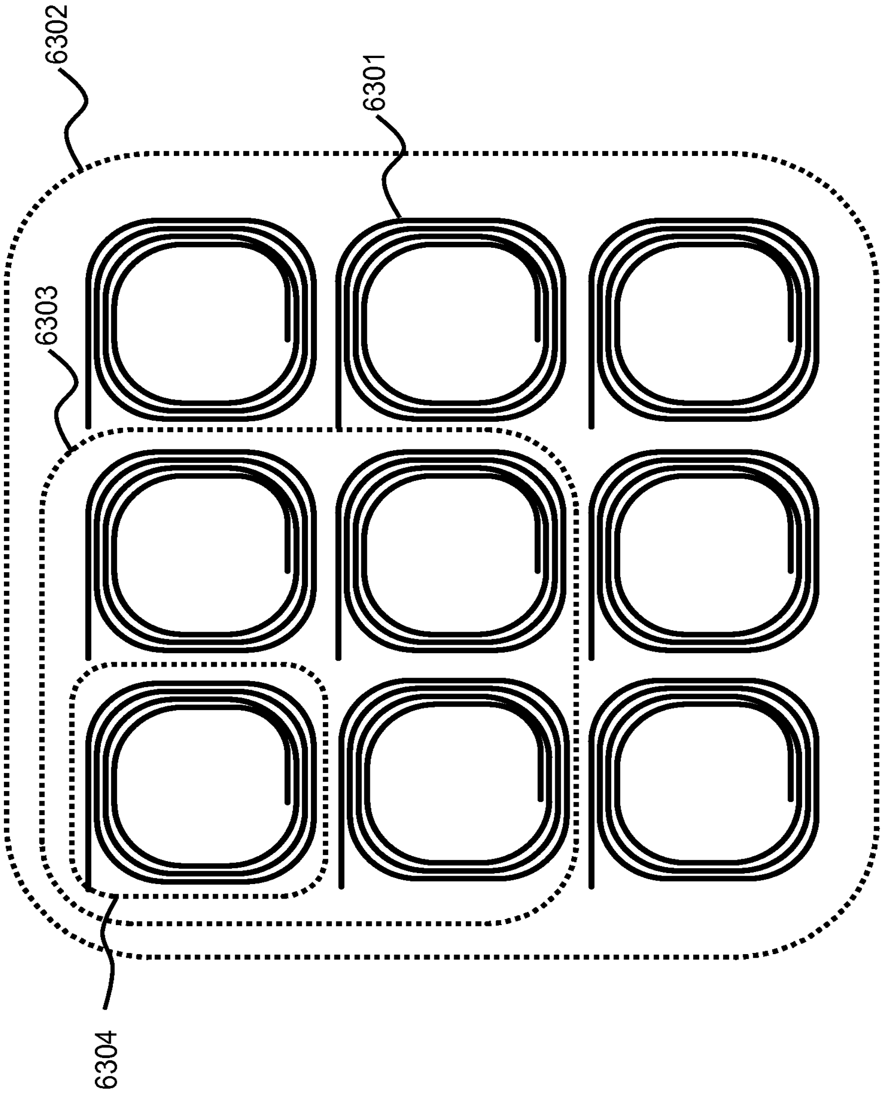


Fig. 64

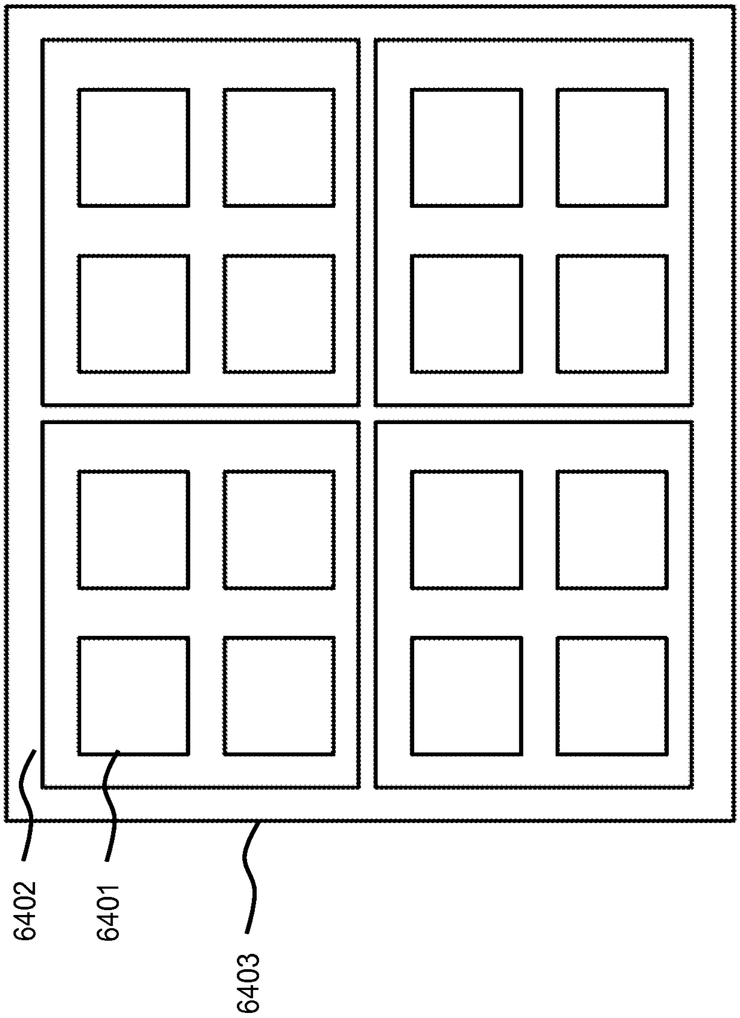


Fig. 65

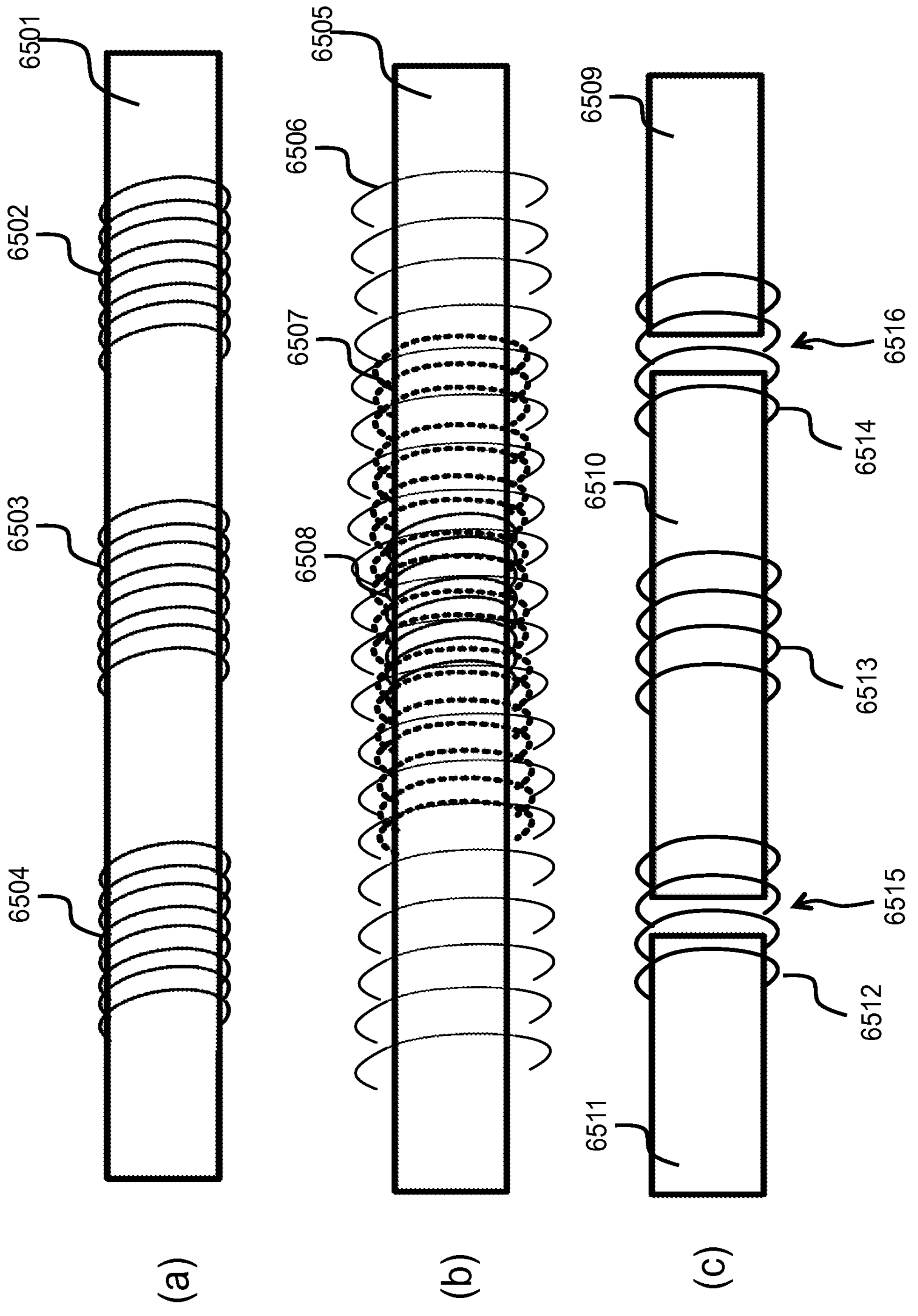

6501
6502
6503
6504
(a)
6505
6506
6507
6508
(b)
6509
6510
6511
6512
6513
6514
6515
6516
(c)

Fig. 66

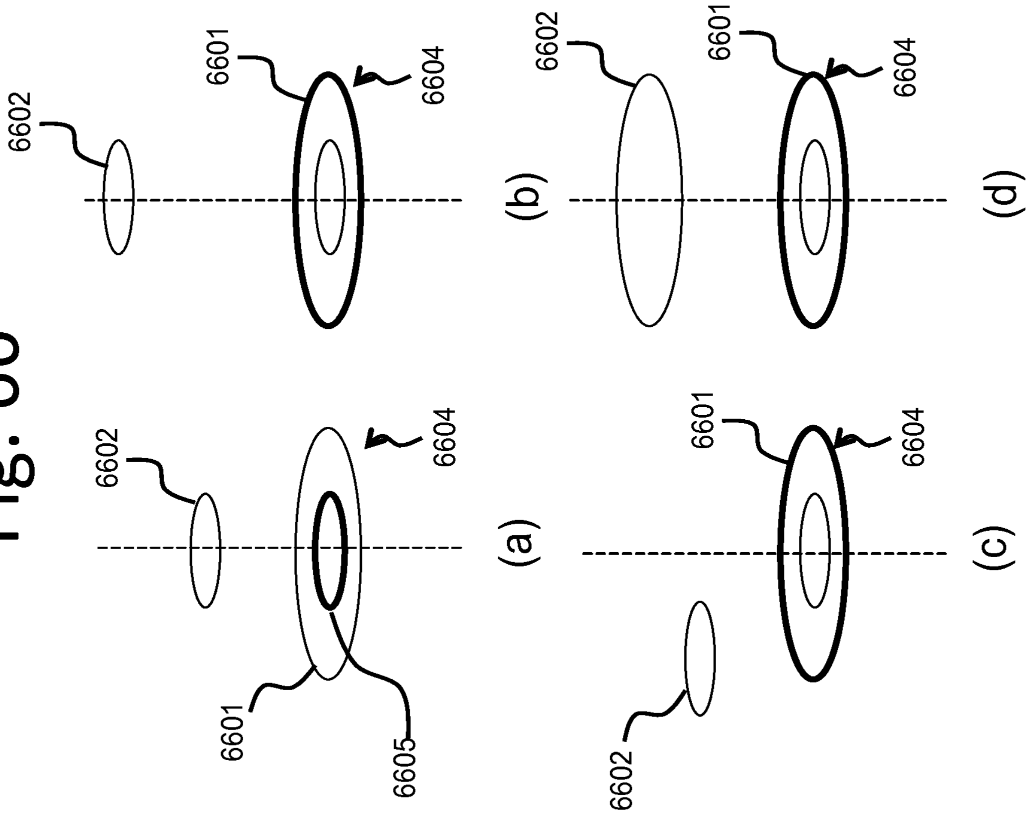

6602
6601
6604
(b)
6602
6601
6604
(d)
6602
6604
(a)
6601
6605
6601
6604
(c)
6602

Fig. 67

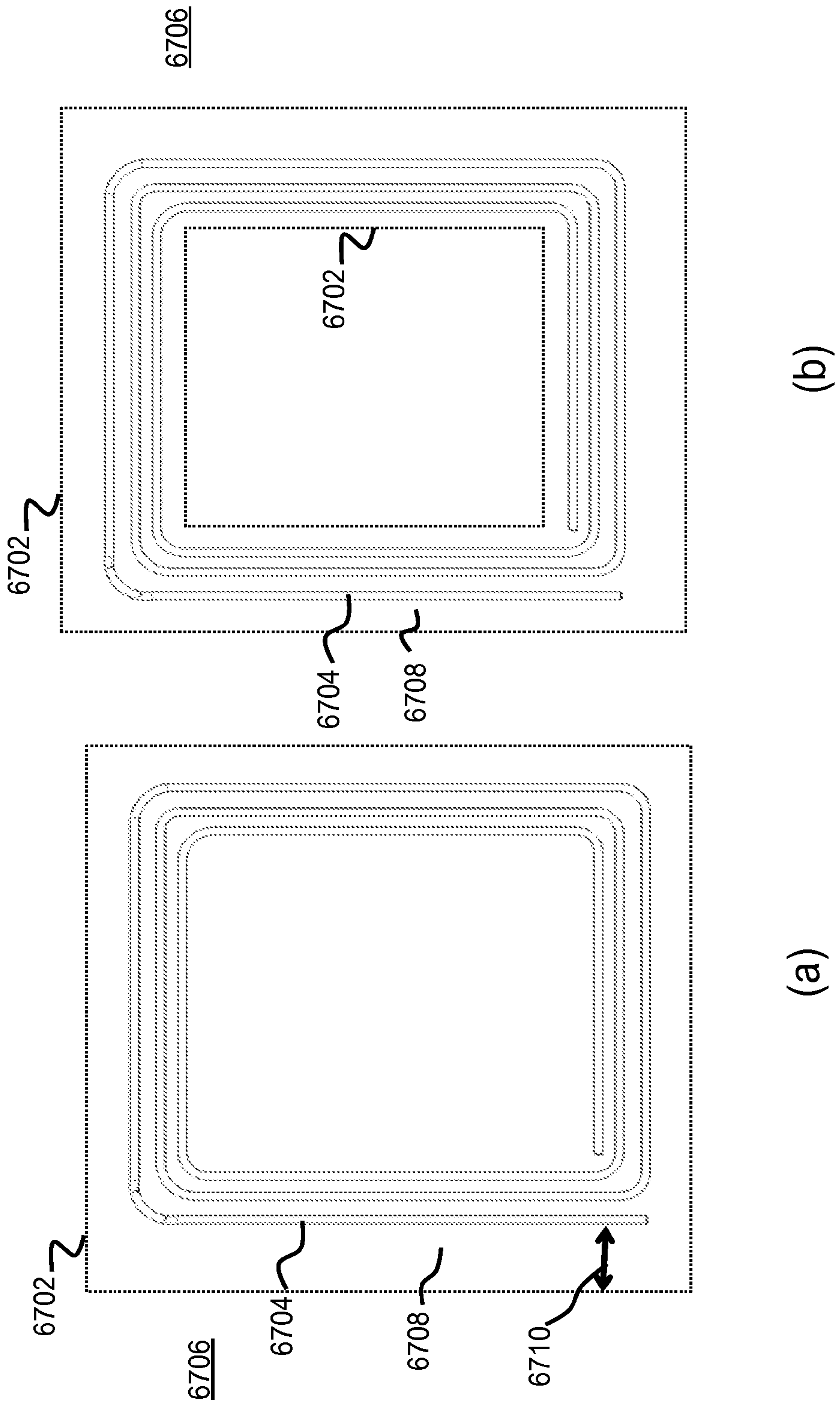


Fig. 68

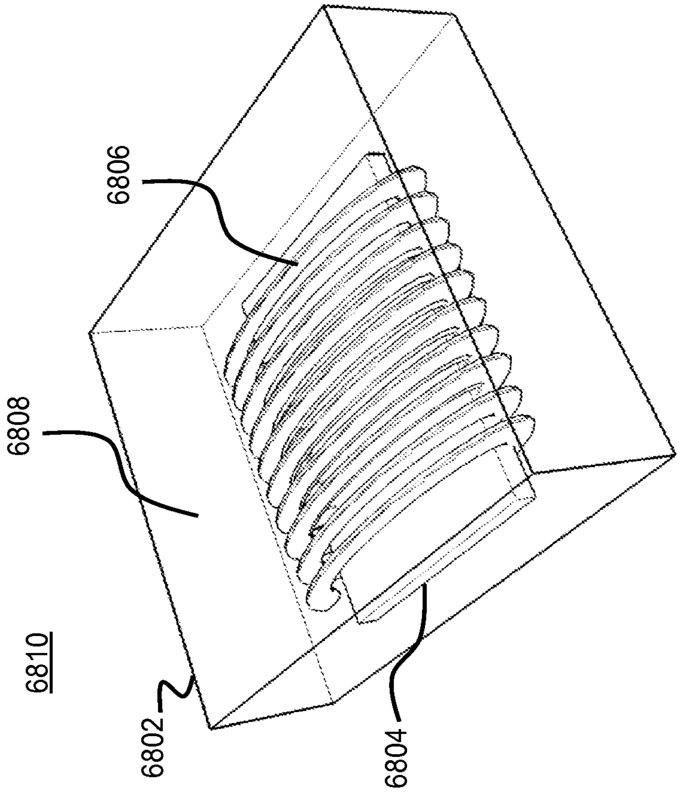


Fig. 69

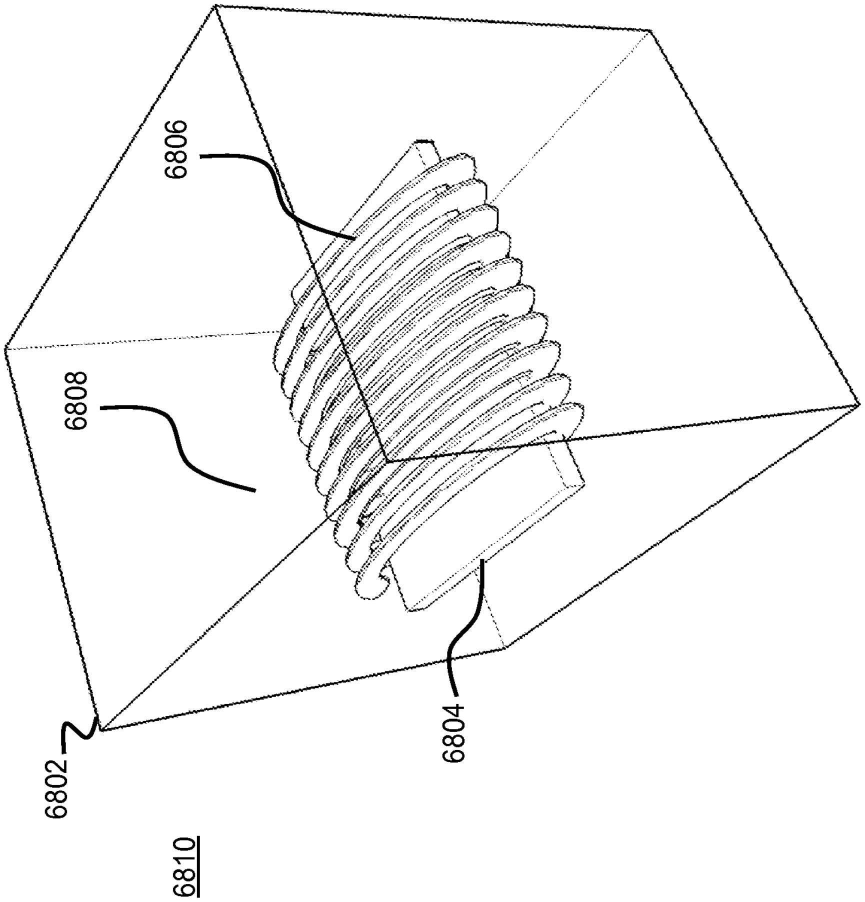


Fig. 70

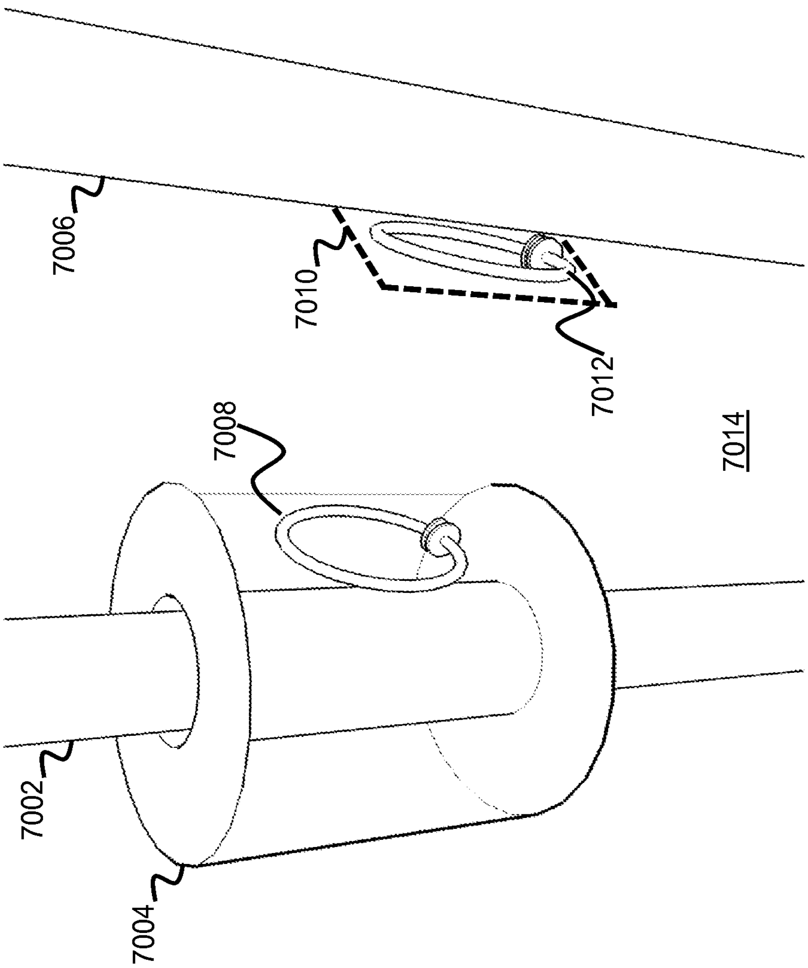
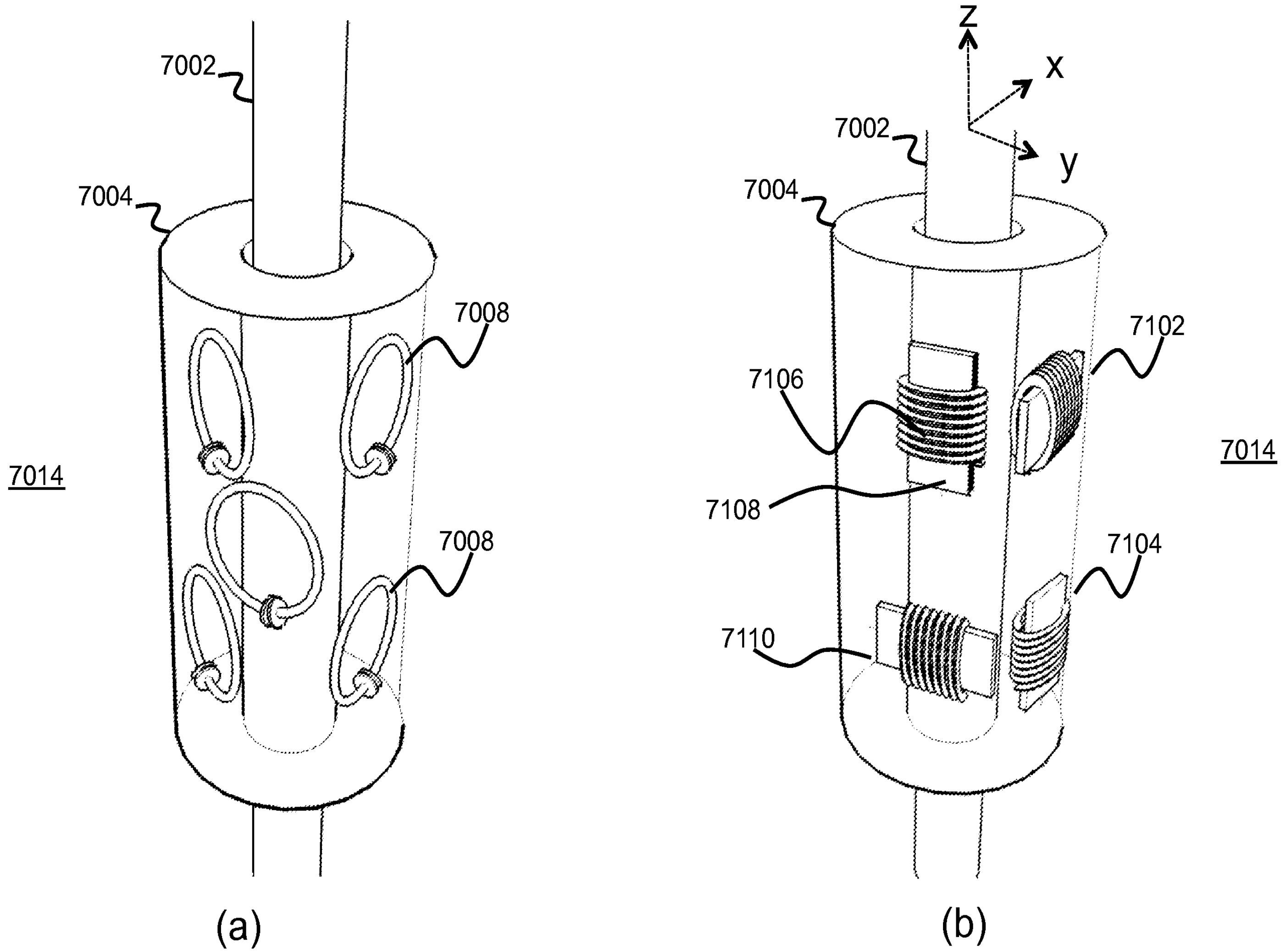


Fig. 71


7002
7004
7008
7008
7014
z
x
y
7002
7004
7102
7106
7108
7104
7110
7014

(a)

(b)

Fig. 72

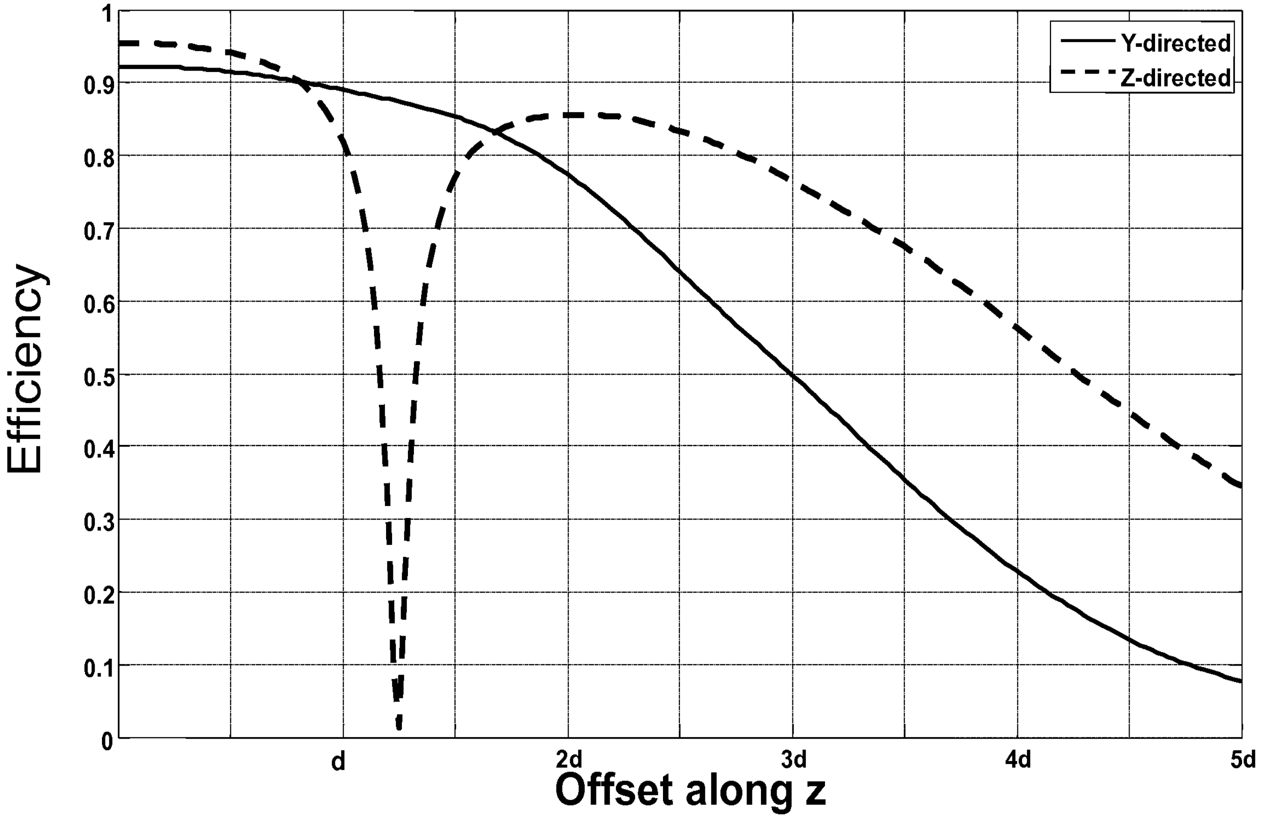
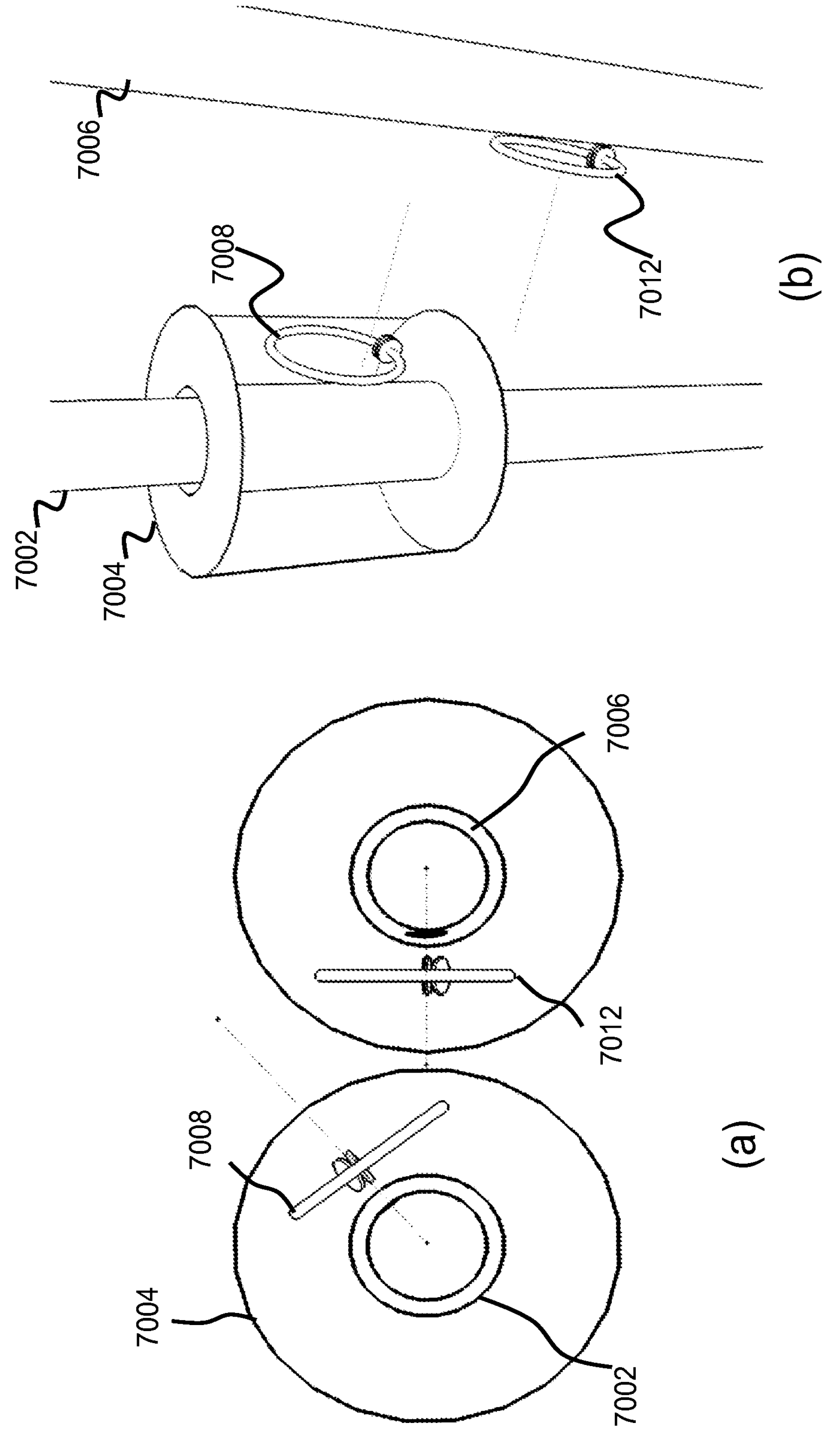

Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
d
2d
3d
4d
5d
Offset along z
Y-directed
Z-directed

Fig. 73



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/24199

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01F 27/42 (2010.01)
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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, EPAB, JPAB); Google Patent; Google Scholar: Search Terms: wireless power transmission coil magnetic field capacitive coupling dielectric ring electric conductive wire loop wireless resonant ferromagnetic medium contact-less power frequency amplitude

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2007/0222542 A1 (Joannopoulos) 27 September 2007 (27.09.2007), entire document, especially; para. [0001] through [0045], Fig. 1-6B	1-11, 16-26, 31 --- 12-15, 27-30
X --- Y	US 2008/0012569 A1 (Hall et al.) 17 January 2008 (17.01.2008), entire document, especially; para. [0034] through [0055], Fig. 1-14	32, 33 --- 14, 15, 29, 30
Y	US 2008/0030415 A1 (Homan et al.) 07 February 2008 (07.02.2008), para. [0005], [0042] through [0073], Fig. 9, 10	12, 13, 27, 28
A	US 2008/0278264 A1 (Karalis et al.) 13 November 2008 (13.11.2008), entire document	1 - 33
A	US 2009/0015075 A1 (Cook et al.) 15 January 2009 (15.01.2009), entire document	1 - 33

☐ Further documents are listed in the continuation of Box C. ☐

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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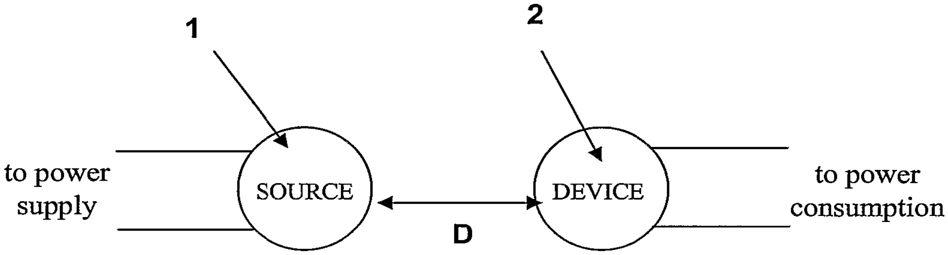
(54) Title: WIRELESS NON-RADIATIVE ENERGY TRANSFER



(57) Abstract: The electromagnetic energy transfer device includes a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. A second resonator structure is positioned distal from the first resonator structure, and supplies useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Non-radiative energy transfer between the first resonator structure and the second resonator structure is mediated through coupling of their resonant-field evanescent tails.

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WIRELESS NON-RADIATIVE ENERGY TRANSFER

PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/698,442 filed July 12, 2005, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

The invention relates to the field of oscillatory resonant electromagnetic modes, and in particular to oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer.

In the early days of electromagnetism, before the electrical-wire grid was deployed, serious interest and effort was devoted towards the development of schemes to transport energy over long distances wirelessly, without any carrier medium. These efforts appear to have met with little, if any, success. Radiative modes of omni-directional antennas, which work very well for information transfer, are not suitable for such energy transfer, because a vast majority of energy is wasted into free space. Directed radiation modes, using lasers or highly-directional antennas, can be efficiently used for energy transfer, even for long distances (transfer distance $L_{TRANS} \gg L_{DEV}$, where L_{DEV} is the characteristic size of the device), but require existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects.

Rapid development of autonomous electronics of recent years (e.g. laptops, cell-phones, house-hold robots, that all typically rely on chemical energy storage) justifies revisiting investigation of this issue. Today, the existing electrical-wire grid carries energy *almost* everywhere; even a medium-range wireless non-radiative energy transfer would be quite useful. One scheme currently used for some important applications relies on induction, but it is restricted to very close-range ($L_{TRANS} \ll L_{DEV}$) energy transfers.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided an electromagnetic energy transfer device. The electromagnetic energy transfer device includes a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. A second resonator structure is positioned distal from the first resonator structure, and supplies useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Non-radiative energy transfer between the first resonator structure and the second resonator structure is mediated through coupling of their resonant-field evanescent tails.

According to another aspect of the invention, there is provided a method of transferring electromagnetic energy. The method includes providing a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. Also, the method includes a second resonator structure being positioned distal from the first resonator structure, and supplying useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Furthermore, the method includes transferring non-radiative energy between the first resonator structure and the second resonator structure through coupling of their resonant-field evanescent tails.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram illustrating an exemplary embodiment of the invention;

FIG. 2A is a numerical FDTD result for a high-index disk cavity of radius r along with the electric field; FIG. 2B a numerical FDTD result for a medium-distance coupling between two resonant disk cavities: initially, all the energy is in one cavity (left panel); after some time both cavities are equally excited (right panel).

FIG. 3 is schematic diagram demonstrating two capacitively-loaded conducting-wire loops;

FIGs. 4A-4B are numerical FDTD results for reduction in radiation-Q of the resonant disk cavity due to scattering from extraneous objects;

FIG. 5 is a numerical FDTD result for medium-distance coupling between two resonant disk cavities in the presence of extraneous objects; and

FIGs. 6A-6B are graphs demonstrating efficiencies of converting the supplied power into useful work (η_w), radiation and ohmic loss at the device (η_d), and the source (η_s), and dissipation inside a human (η_h), as a function of the coupling-to- κ/Γ_d ; in panel (a) Γ_w is chosen so as to minimize the energy stored in the device, while in panel (b) Γ_w is chosen so as to maximize the efficiency η_w for each κ/Γ_d .

DETAILED DESCRIPTION OF THE INVENTION

In contrast to the currently existing schemes, the invention provides the feasibility of using long-lived oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer. The basis of this technique is that two same-frequency resonant objects tend to couple, while interacting weakly with other off-resonant environmental objects. The purpose of the invention is to quantify this mechanism using specific examples, namely quantitatively address the following questions: up to which distances can such a scheme be efficient and how sensitive is it to external perturbations. Detailed theoretical and numerical analysis show that a mid-range ($L_{TRANS} \approx few{*}L_{DEV}$) wireless energy-exchange can actually be achieved, while suffering only modest transfer and dissipation of energy into other off-resonant objects.

The omnidirectional but stationary (non-lossy) nature of the near field makes this mechanism suitable for mobile wireless receivers. It could therefore have a variety of possible applications including for example, placing a source connected to the wired electricity network on the ceiling of a factory room, while devices, such as robots, vehicles, computers, or similar, are roaming freely within the room. Other possible applications include electric-engine buses, RFIDs, and perhaps even nano-robots.

The range and rate of the inventive wireless energy-transfer scheme are the first subjects of examination, without considering yet energy drainage from the system for use into work. An appropriate analytical framework for modeling the exchange of energy between resonant objects is a weak-coupling approach called "coupled-mode theory". FIG. 1 is a schematic diagram illustrating a general description of the invention. The invention uses a source and device to perform energy transferring. Both the source 1 and device 2 are resonator structures, and are separated a distance D from each other. In this arrangement, the electromagnetic field of the system of source 1 and device 2 is approximated by $\mathbf{F}(\mathbf{r},t) \approx a_1(t)\mathbf{F}_1(\mathbf{r})+a_2(t)\mathbf{F}_2(\mathbf{r})$, where $\mathbf{F}_{1,2}(\mathbf{r})=[\mathbf{E}_{1,2}(\mathbf{r})\ \mathbf{H}_{1,2}(\mathbf{r})]$ are the eigenmodes of source 1 and device 2 alone, and then the field amplitudes $a_1(t)$ and $a_2(t)$ can be shown to satisfy the "coupled-mode theory":

$$\begin{aligned}\frac{da_1}{dt} &= -i(\omega_1 - i\Gamma_1)a_1 + i\kappa_{11}a_1 + i\kappa_{12}a_2 \\ \frac{da_2}{dt} &= -i(\omega_2 - i\Gamma_2)a_2 + i\kappa_{22}a_2 + i\kappa_{21}a_1\end{aligned}, \qquad (1)$$

where $\omega_{1,2}$ are the individual eigen-frequencies, $\Gamma_{1,2}$ are the resonance widths due to the objects' intrinsic (absorption, radiation etc.) losses, $\kappa_{12,21}$ are the coupling coefficients, and $\kappa_{11,22}$ model the shift in the *complex* frequency of each object due to the presence of the other.

The approach of Eq. 1 has been shown, on numerous occasions, to provide an excellent description of resonant phenomena for objects of similar complex eigen-frequencies (namely $|\omega_1-\omega_2| \ll |\kappa_{12,21}|$ and $\Gamma_1 \approx \Gamma_2$), whose resonances are reasonably well defined (namely $\Gamma_{1,2}$&$\mathrm{Im}\{\kappa_{11,22}\}\ll|\kappa_{12,21}|$) and in the weak coupling limit (namely $|\kappa_{12,21}|\ll\omega_{1,2}$). Coincidentally, these requirements also enable optimal operation for energy transfer. Also, Eq. (1) show that the energy exchange can be nearly perfect at exact resonance ($\omega_1=\omega_2$ and $\Gamma_1=\Gamma_2$), and that the losses are minimal when the "coupling-time" is much shorter than all "loss-times". Therefore, the invention requires resonant modes of high $Q=\omega/(2\Gamma)$ for low intrinsic-loss rates $\Gamma_{1,2}$, and with evanescent tails significantly longer than the characteristic sizes L_1 and L_2 of the two objects for strong coupling rate $|\kappa_{12,21}|$ over large distances D, where D is the closest distance between the two objects. This is a regime of operation that has *not* been studied extensively, since one usually prefers short tails, to minimize interference with nearby devices.

Objects of nearly infinite extent, such as dielectric waveguides, can support guided modes whose evanescent tails are decaying exponentially in the direction away from the object, slowly if tuned close to cutoff, and can have nearly infinite Q. To implement the inventive energy-transfer scheme, such geometries might be suitable for certain applications, but usually finite objects, namely ones that are topologically surrounded everywhere by air, are more appropriate.

Unfortunately, objects of finite extent cannot support electromagnetic states that are exponentially decaying in *all* directions in air, since in free space: $\vec{k}^2=\omega^2/c^2$. Because of this, one can show that they cannot support states of infinite Q. However, very long-lived (so-called "high-Q") states can be found, whose tails display the needed exponential-like decay away from the resonant object over long enough distances before they turn oscillatory (radiative). The limiting surface, where this change in the field behavior happens, is called the "radiation caustic", and, for the wireless energy-transfer scheme to be based on the near field rather than the far/radiation field, the distance between the coupled objects must be such that one lies within the radiation caustic of the other.

The invention is very general and *any* type of resonant structure satisfying the above requirements can be used for its implementation. As examples and for definiteness, one can choose to work with two well-known, but quite different electromagnetic resonant systems: dielectric disks and capacitively-loaded conducting-wire loops. Even without optimization, and despite their simplicity, both will be shown to exhibit fairly good performance. Their difference lies mostly in the frequency range of applicability due to practical considerations, for example, in the optical regime dielectrics prevail, since conductive materials are highly lossy.

Consider a 2D dielectric disk cavity of radius r and permittivity ε surrounded by air that supports high-Q whispering-gallery modes, as shown in FIG. 2A. Such a cavity is studied using both analytical modeling, such as separation of variables in cylindrical coordinates and application of boundary conditions, and detailed numerical finite-difference-time-domain (FDTD) simulations with a resolution of $30pts/r$. Note that the physics of the 3D case should not be significantly different, while the analytical complexity and numerical requirements would be immensely increased. The results of the two methods for the complex eigen-frequencies and the field patterns of the so-called "leaky" eigenmodes are in an excellent agreement with each other for a variety of geometries and parameters of interest.

The radial modal decay length, which determines the coupling strength $\kappa \equiv |\kappa_{21}| = |\kappa_{12}|$, is on the order of the wavelength, therefore, for near-field coupling to take place between cavities whose distance is much larger than their size, one needs subwavelength-sized resonant objects ($r \ll \lambda$). High-radiation-Q and long-tailed subwavelength resonances can be achieved, when the dielectric permittivity ε is as large as practically possible and the azimuthal field variations (of principal number m) are slow (namely m is small).

One such TE-polarized dielectric-cavity mode, which has the favorable characteristics $Q_{rad}=1992$ and $\lambda / r = 20$ using $\varepsilon = 147.7$ and $m = 2$, is shown in FIG. 2A, and will be the "test" cavity 18 for all subsequent calculations for this class of resonant objects. Another example of a suitable cavity has $Q_{rad}=9100$ and $\lambda / r = 10$ using $\varepsilon = 65.61$ and $m = 3$. These values of ε might at first seem unrealistically large. However, not only are there in the microwave regime (appropriate for meter-range coupling applications) many materials that have both reasonably high enough dielectric constants and low losses, for example, Titania: $\varepsilon \approx 96$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-3}$; Barium tetratitanate: $\varepsilon \approx 37$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-4}$; Lithium tantalite: $\varepsilon \approx 40$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-4}$; etc.), but also ε could instead signify the effective index of other known subwavelength ($\lambda/r \gg 1$) surface-wave systems, such as surface-plasmon modes on surfaces of metal-like (negative-ε) materials or metallodielectric photonic crystals.

With regards to material absorption, typical loss tangents in the microwave (e.g. those listed for the materials above) suggest that $Q_{abs} \sim \varepsilon/Im\{\varepsilon\} \sim 10000$. Combining the effects of radiation and absorption, the above analysis implies that for a properly designed resonant device-object d a value of $Q_d \sim 2000$ should be achievable. Note though, that the resonant source s will in practice often be immobile, and the restrictions on its allowed geometry and size will typically be much less stringent than the restrictions on the design of the device; therefore, it is reasonable to assume that the radiative losses can be designed to be negligible allowing for Q_s~10000, limited only by absorption.

To calculate now the achievable rate of energy transfer, one can place two of the cavities 20, 22 at distance D between their centers, as shown in FIG. 2B. The normal modes of the combined system are then an even and an odd superposition of the initial modes and their frequencies are split by the coupling coefficient κ, which we want to calculate. Analytically, coupled-mode theory gives for dielectric objects $\kappa_{12} = \omega_2/2 \cdot \int d^3r E_1^*(r) E_2(r) \varepsilon_1(r) \Big/ \int d^3r \left|E_1(r)\right|^2 \varepsilon(r)$, where $\varepsilon_{1,2}(\mathbf{r})$ denote the dielectric functions of only object 1 alone or 2 alone excluding the background dielectric (free space) and $\varepsilon(\mathbf{r})$ the dielectric function of the entire space with both objects present. Numerically, one can find κ using FDTD simulations either by exciting one of the cavities and calculating the energy-transfer time to the other or by determining the split normal-mode frequencies. For the "test" disk cavity the radius r_C of the radiation caustic is $r_C \approx 11r$, and for non-radiative coupling $D < r_C$, therefore here one can choose $D/r=10, 7, 5, 3$. Then, for the mode of FIG. 3, which is odd with respect to the line that connects the two cavities, the analytical predictions are $\omega/2\kappa=1602, 771, 298, 48$, while the numerical predictions are $\omega/2\kappa=1717, 770, 298, 47$ respectively, so the two methods agree well. The radiation fields of the two initial cavity modes interfere constructively or destructively depending on their relative phases and amplitudes, leading to increased or decreased net radiation loss respectively, therefore for any cavity distance the even and odd normal modes have Qs that are one larger and one smaller than the initial single-cavity $Q=1992$ (a phenomenon not captured by coupled-mode theory), but in a way that the average Γ is always approximately $\Gamma \approx \omega/2Q$. Therefore, the corresponding coupling-to-loss ratios are $\kappa/\Gamma=1.16, 2.59, 6.68, 42.49$, and although they do not fall in the ideal operating regime $\kappa/\Gamma \gg 1$, the achieved values are still large enough to be useful for applications.

Consider a loop 10 or 12 of N coils of radius r of conducting wire with circular cross-section of radius a surrounded by air, as shown in FIG. 3. This wire has inductance $L = \mu_o N^2 r\left[\ln(8r/a) - 2\right]$, where μ_o is the magnetic permeability of free space, so connecting it to a capacitance C will make the loop resonant at frequency $\omega = 1/\sqrt{LC}$. The nature of the resonance lies in the periodic exchange of energy from the electric field inside the capacitor due to the voltage across it to the magnetic field in free space due to the current in the wire. Losses in this resonant system consist of ohmic loss inside the wire and radiative loss into free space.

For non-radiative coupling one should use the near-field region, whose extent is set roughly by the wavelength λ, therefore the preferable operating regime is that where the loop is small ($r \ll \lambda$). In this limit, the resistances associated with the two loss channels are respectively $R_{ohm} = \sqrt{\mu_o \rho \omega / 2} \cdot Nr / a$ and $R_{rad} = \pi / 6 \cdot \eta_o N^2 (\omega r / c)^4$, where ρ is the resistivity of the wire material and $\eta_o \approx 120\pi\ \Omega$ is the impedance of free space. The quality factor of such a resonance is then $Q = \omega L / (R_{ohm} + R_{rad})$ and is highest for some frequency determined by the system parameters: at lower frequencies it is dominated by ohmic loss and at higher frequencies by radiation.

To get a rough estimate in the microwave, one can use one coil ($N=1$) of copper ($\rho=1.69 \cdot 10^{-8}\Omega m$) wire and then for $r=1cm$ and $a=1mm$, appropriate for example for a cell phone, the quality factor peaks to $Q=1225$ at $f=380MHz$, for $r=30cm$ and $a=2mm$ for a laptop or a household robot $Q=1103$ at $f=17MHz$, while for $r=1m$ and $a=4mm$ (that could be a source loop on a room ceiling) $Q=1315$ at $f=5MHz$. So in general, expected quality factors are $Q \approx 1000\text{-}1500$ at $\lambda/r \approx 50\text{-}80$, namely suitable for near-field coupling.

The rate for energy transfer between two loops 10 and 12 at distance D between their centers, as shown in FIG. 3, is given by $\kappa_{12} = \omega M / 2\sqrt{L_1 L_2}$, where M is the mutual inductance of the two loops 10 and 12. In the limit $r \ll D \ll \lambda$ one can use the quasi-static result $M = \pi / 4 \cdot \mu_o N_1 N_2 (r_1 r_2)^2 / D^3$, which means that $\omega / 2\kappa \sim \left(D / \sqrt{r_1 r_2}\right)^3$. For example, by choosing again $D/r=10, 8, 6$ one can get for two loops of $r=1cm$, same as used before, that $\omega/2\kappa=3033, 1553, 655$ respectively, for the $r=30cm$ that $\omega/2\kappa=7131, 3651, 1540$, and for the $r=1m$ that $\omega/2\kappa=6481, 3318, 1400$. The corresponding coupling-to-loss ratios peak at the frequency where peaks the single-loop Q and are $\kappa/\Gamma=0.4, 0.79, 1.97$ and $0.15, 0.3, 0.72$ and $0.2, 0.4, 0.94$ for the three loop-kinds and distances. An example of dissimilar loops is that of a $r=1m$ (source on the ceiling) loop and a $r=30cm$ (household robot on the floor) loop at a distance $D=3m$ (room height) apart, for which $\kappa / \sqrt{\Gamma_1 \Gamma_2} = 0.88$ peaks at $f=6.4MHz$, in between the peaks of the individual Q's. Again, these values are not in the optimal regime $\kappa/\Gamma \gg 1$, but will be shown to be sufficient.

It is important to appreciate the difference between this inductive scheme and the already used close-range inductive schemes for energy transfer in that those schemes are *non-resonant*. Using coupled-mode theory it is easy to show that, keeping the geometry and the energy stored at the source fixed, the presently proposed resonant-coupling inductive mechanism allows for Q approximately 1000 times more power delivered for work at the device than the traditional non-resonant mechanism, and this is why mid-range energy transfer is now possible. Capacitively-loaded conductive loops are actually being widely used as resonant antennas (for example in cell phones), but those operate in the far-field regime with $r/\lambda \sim 1$, and the radiation Q's are intentionally designed to be small to make the antenna efficient, so they are not appropriate for energy transfer.

Clearly, the success of the inventive resonance-based wireless energy-transfer scheme depends strongly on the robustness of the objects' resonances. Therefore, their sensitivity to the near presence of random non-resonant extraneous objects is another aspect of the proposed scheme that requires analysis. The interaction of an extraneous object with a resonant object can be obtained by a modification of the coupled-mode-theory model in Eq. (1), since the extraneous object either does not have a well-defined resonance or is far-off-resonance, the energy exchange between the resonant and extraneous objects is minimal, so the term κ_{12} in Eq. (1) can be dropped. The appropriate analytical model for the field amplitude in the resonant object $a_1(t)$ becomes:

$$\frac{da_1}{dt} = -i\left(\omega_1 - i\Gamma_1\right)a_1 + i\kappa_{11}a_1 \qquad (2)$$

Namely, the effect of the extraneous object is just a perturbation on the resonance of the resonant object and it is twofold: First, it shifts its resonant frequency through the real part of κ_{11} thus detuning it from other resonant objects. This is a problem that can be fixed rather easily by applying a feedback mechanism to every device that corrects its frequency, such as through small changes in geometry, and matches it to that of the source. Second, it forces the resonant object to lose modal energy due to scattering into radiation from the extraneous object through the induced polarization or currents in it, and due to material absorption in the extraneous object through the imaginary part of κ_{11}. This reduction in Q can be a detrimental effect to the functionality of the energy-transfer scheme, because it cannot be remedied, so its magnitude must be quantified.

In the first example of resonant objects that have been considered, the class of dielectric disks, small, low-index, low-material-loss or far-away stray objects will induce small scattering and absorption. To examine realistic cases that are more dangerous for reduction in Q, one can therefore place the "test" dielectric disk cavity 40 close to: a) another off-resonance object 42, such as a human being, of large $Re\{\varepsilon\}=49$ and $Im\{\varepsilon\}=16$ and of same size but different shape, as shown in FIG. 4A; and b) a roughened surface 46, such as a wall, of large extent but of small $Re\{\varepsilon\}=2.5$ and $Im\{\varepsilon\}=0.05$, as shown in FIG. 4B.

Analytically, for objects that interact with a small perturbation the reduced value of radiation-Q due to scattering could be estimated using the polarization

$\int d^3r\left|P_{X1}(r)\right|^2 \propto \int d^3r\left|E_1(r)\cdot\mathrm{Re}\{\varepsilon_X(r)\}\right|^2$ induced by the resonant cavity 1 inside the extraneous object X=42 or roughened surface X=46. Since in the examined cases either the refractive index or the size of the extraneous objects is large, these first-order perturbation-theory results would not be accurate enough, thus one can only rely on numerical FDTD simulations. The absorption-*Q* inside these objects can be estimated through $\mathrm{Im}\{\kappa_{11}\}=\omega_1/2\cdot\int d^3r\left|E_1(r)\right|^2\mathrm{Im}\{\varepsilon_X(r)\}\Big/\int d^3r\left|E_1(r)\right|^2\varepsilon(r)$.

Using these methods, for distances *D/r=10, 7, 5, 3* between the cavity and extraneous-object centers one can find that $Q_{rad}=1992$ is respectively reduced to $Q_{rad}=1988,\ 1258,\ 702,\ 226$, and that the absorption rate inside the object is $Q_{abs}=312530,\ 86980,\ 21864,\ 1662$, namely the resonance of the cavity is not detrimentally disturbed from high-index and/or high-loss extraneous objects, unless the (possibly mobile) object comes *very* close to the cavity. For distances *D/r=10, 7, 5, 3, 0* of the cavity to the roughened surface we find respectively $Q_{rad}=2101,\ 2257,\ 1760,\ 1110,\ 572$, and $Q_{abs}>4000$, namely the influence on the initial resonant mode is acceptably low, even in the extreme case when the cavity is embedded on the surface. Note that a close proximity of metallic objects could also significantly scatter the resonant field, but one can assume for simplicity that such objects are not present.

Imagine now a combined system where a resonant source-object *s* is used to wirelessly transfer energy to a resonant device-object *d* but there is an off-resonance extraneous-object *e* present. One can see that the strength of all extrinsic loss mechanisms from *e* is determined by $|\mathbf{E}_s(\mathbf{r}_e)|^2$, by the square of the *small* amplitude of the tails of the resonant source, evaluated at the position $\mathbf{r}_e$ of the extraneous object. In contrast, the coefficient of resonant coupling of energy from the source to the device is determined by the *same-order* tail amplitude $|\mathbf{E}_s(\mathbf{r}_d)|$, evaluated at the position $\mathbf{r}_d$ of the device, but this time it is not squared! Therefore, for equal distances of the source to the device and to the extraneous object, the coupling time for energy exchange with the device is much shorter than the time needed for the losses inside the extraneous object to accumulate, especially if the amplitude of the resonant field has an exponential-like decay away from the source. One could actually optimize the performance by designing the system so that the desired coupling is achieved with smaller tails at the source and longer at the device, so that interference to the source from the other objects is minimal.

The above concepts can be verified in the case of dielectric disk cavities by a simulation that combines FIGs. 2A-2B and 4A-4B, namely that of two (source-device) "test" cavities 50 placed *10r* apart, in the presence of a same-size extraneous object 52 of $\varepsilon=49$ between them, and at a distance *5r* from a large roughened surface 56 of $\varepsilon=2.5$, as shown in FIG. 5. Then, the original values of $Q=1992$, $\omega/2\kappa=1717$ (and thus $\kappa/\Gamma=1.16$) deteriorate to $Q=765$, $\omega/2\kappa=965$ (and thus $\kappa/\Gamma=0.79$). This change is acceptably small, considering the extent of the considered external perturbation, and, since the system design has not been optimized, the final value of coupling-to-loss ratio is promising that this scheme can be useful for energy transfer.

In the second example of resonant objects being considered, the conducting-wire loops, the influence of extraneous objects on the resonances is nearly absent. The reason for this is that, in the quasi-static regime of operation ($r \ll \lambda$) that is being considered, the near field in the air region surrounding the loop is predominantly magnetic, since the electric field is localized inside the capacitor. Therefore, extraneous objects that could interact with this field and act as a perturbation to the resonance are those having significant magnetic properties (magnetic permeability $Re\{\mu\}>1$ or magnetic loss $Im\{\mu\}>0$). Since almost all common materials are non-magnetic, they respond to magnetic fields in the same way as free space, and thus will not disturb the resonance of a conducting-wire loop. The only perturbation that is expected to affect these resonances is a close proximity of large metallic structures.

An extremely important implication of the above fact relates to safety considerations for human beings. Humans are also non-magnetic and can sustain strong magnetic fields without undergoing any risk. This is clearly an advantage of this class of resonant systems for many real-world applications. On the other hand, dielectric systems of high (effective) index have the advantages that their efficiencies seem to be higher, judging from the larger achieved values of κ/Γ, and that they are also applicable to much smaller length-scales, as mentioned before.

Consider now again the combined system of resonant source s and device d in the presence of a human h and a wall, and now let us study the efficiency of this resonance-based energy-transfer scheme, when energy is being drained from the device for use into operational work. One can use the parameters found before: for dielectric disks, absorption-dominated loss at the source $Q_s \sim 10^4$, radiation-dominated loss at the device $Q_d \sim 10^3$ (which includes scattering from the human and the wall), absorption of the source- and device-energy at the human $Q_{s\text{-}h}$, $Q_{d\text{-}h} \sim 10^4\text{-}10^5$ depending on his/her not-very-close distance from the objects, and negligible absorption loss in the wall; for conducting-wire loops, $Q_s \sim Q_d \sim 10^3$, and perturbations from the human and the wall are negligible. With corresponding loss-rates $\Gamma=\omega/2Q$, distance-dependent coupling κ, and the rate at which working power is extracted Γ_w, the coupled-mode-theory equation for the device field-amplitude is

$$\frac{da_d}{dt} = -i\left(\omega - i\Gamma_d\right)a_d + i\kappa a_s - \Gamma_{d-h}a_d - \Gamma_w a_d . \qquad (3)$$

Different temporal schemes can be used to extract power from the device and their efficiencies exhibit different dependence on the combined system parameters. Here, one can assume steady state, such that the field amplitude inside the source is maintained constant, namely $a_s(t)=A_s e^{-i\omega t}$, so then the field amplitude inside the device is $a_d(t)=A_d e^{-i\omega t}$ with $A_d=i\kappa/(\Gamma_d+\Gamma_{d\text{-}h}+\Gamma_w)A_s$. Therefore, the power lost at the source is $P_s=2\Gamma_s|A_s|^2$, at the device it is $P_d=2\Gamma_d|A_d|^2$, the power absorbed at the human is $P_h=2\Gamma_{s\text{-}h}|A_s|^2+2\Gamma_{d\text{-}h}|A_d|^2$, and the useful extracted power is $P_w=2\Gamma_w|A_d|^2$. From energy conservation, the total power entering the system is $P_{total}= P_s+P_d+P_h+P_w$. Denote the total loss-rates $\Gamma_s^{tot}=\Gamma_s+\Gamma_{s-h}$ and $\Gamma_d^{tot}=\Gamma_d+\Gamma_{d-h}$. Depending on the targeted application, the work-drainage rate should be chosen either $\Gamma_w=\Gamma_d^{tot}$ to minimize the required energy stored in the resonant objects or $\Gamma_w=\Gamma_d^{tot}\sqrt{1+\kappa^2/\Gamma_s^{tot}\Gamma_d^{tot}}>\Gamma_d^{tot}$ such that the ratio of useful-to-lost powers , namely the efficiency $\eta_w=P_w/P_{total}$, is maximized for some value of κ. The efficiencies η for the two different choices are shown in FIGs. 6A and 6B respectively, as a function of the κ/Γ_d figure-of-merit which in turn depends on the source-device distance.

FIGs. 6A-6B show that for the system of dielectric disks and the choice of optimized efficiency, the efficiency can be large, e.g., at least 40%. The dissipation of energy inside the human is small enough, less than 5%, for values $\kappa/\Gamma_d>1$ and $Q_h>10^5$, namely for medium-range source-device distances ($D_d/r<10$) and most human-source/device distances ($D_h/r>8$). For example, for $D_d/r=10$ and $D_h/r=8$, if $10W$ must be delivered to the load, then, from FIG. 6B, $\sim 0.4W$ will be dissipated inside the human, $\sim 4W$ will be absorbed inside the source, and $\sim 2.6W$ will be radiated to free space. For the system of conducting-wire loops, the achieved efficiency is smaller, ~20% for $\kappa/\Gamma_d\approx 1$, but the significant advantage is that there is no dissipation of energy inside the human, as explained earlier.

Even better performance should be achievable through optimization of the resonant object designs. Also, by exploiting the earlier mentioned interference effects between the radiation fields of the coupled objects, such as continuous-wave operation at the frequency of the normal mode that has the larger radiation-Q, one could further improve the overall system functionality. Thus the inventive wireless energy-transfer scheme is promising for many modern applications. Although all considerations have been for a static geometry, all the results can be applied directly for the dynamic geometries of mobile objects, since the energy-transfer time $\kappa^{-1} \sim 1\mu s$, which is much shorter than any timescale associated with motions of macroscopic objects.

The invention provides a resonance-based scheme for mid-range wireless non-radiative energy transfer. Analyses of very simple implementation geometries provide encouraging performance characteristics for the potential applicability of the proposed mechanism. For example, in the macroscopic world, this scheme could be used to deliver power to robots and/or computers in a factory room, or electric buses on a highway (source-cavity would in this case be a "pipe" running above the highway). In the microscopic world, where much smaller wavelengths would be used and smaller powers are needed, one could use it to implement optical inter-connects for CMOS electronics or else to transfer energy to autonomous nano-objects, without worrying much about the relative alignment between the sources and the devices; energy-transfer distance could be even longer compared to the objects' size, since $Im\{\varepsilon(\omega)\}$ of dielectric materials can be much lower at the required optical frequencies than it is at microwave frequencies.

As a venue of future scientific research, different material systems should be investigated for enhanced performance or different range of applicability. For example, it might be possible to significantly improve performance by exploring plasmonic systems. These systems can often have spatial variations of fields on their surface that are much shorter than the free-space wavelength, and it is precisely this feature that enables the required decoupling of the scales: the resonant object can be significantly smaller than the exponential-like tails of its field. Furthermore, one should also investigate using acoustic resonances for applications in which source and device are connected via a common condensed-matter object.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

CLAIMS

1. A method of transferring energy comprising:

providing a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1, and

providing a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2

wherein the two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2,

transferring energy non-radiatively between said first resonator structure and said second resonator structure, said energy transfer being mediated through coupling of their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator being denoted by κ,

wherein non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, wherein c is the propagation speed of radiation in the surrounding medium.

2. The method of claim 1, wherein said method comprising said resonators with $Q_1>100$, and $Q_2>100$, and $\kappa/\text{sqrt}(\Gamma_1*\Gamma_2)>0.2,0.5,1,2,5$, and $D/L_2>1,2,3,5$.

3. The method of claim 1, wherein said method comprising said resonators with $Q_1>200$, and $Q_2>200$, and $\kappa/\text{sqrt}(\Gamma_1*\Gamma_2)>0.2,0.5,1,2,5$, and $D/L_2>1,2,3,5$.

4. The method of claim1, said method comprising said resonators with $Q_1>500$, and $Q_2>500$, and $\kappa/\text{sqrt}(\Gamma_1*\Gamma_2)>0.2,0.5,1,2,5$, and $D/L_2>1,2,3,5$.

5. The method of claim 1, said method comprising said resonators with $Q_1>1000$, and $Q_2>1000$, and $\kappa/\text{sqrt}(\Gamma_1*\Gamma_2)>0.2,0.5,1,2,5$, and $D/L_2>1,2,3,5$.

6. An energy transfer device comprising:

a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1, and

a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2,

wherein the two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2, wherein non-radiative energy transfer between said first resonator structure and said second resonator structure is mediated through coupling of their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator is denoted by κ,

wherein non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, wherein c is the propagation speed of radiation in the surrounding medium.

7. The energy transfer device of claim 6, said method comprising said resonators with $Q_1>200$, and $Q_2>200$, and $\kappa/\mathrm{sqrt}(\Gamma_1*\Gamma_2)>0.2,0.5,1,2,5$, and $D/L_2>1,2,3,5$.

8. The energy transfer device of claim 7, wherein said resonant field in said device is electromagnetic.

9. The energy transfer device of claim 8 and said first resonator structure comprises a dielectric sphere, where the characteristic size L_1 is the radius of the sphere.

10. The energy transfer device of claim 8, and said first resonator structure comprises a metallic sphere, where the characteristic size L_1 is the radius of the sphere.

11. The energy transfer device of claim 8, and said first resonator structure comprises a metallodielectric sphere, where the characteristic size L_1 is the radius of the sphere.

12. The energy transfer device of claim 8, and said first resonator structure comprises a plasmonic sphere, where the characteristic size L_1 is the radius of the sphere.

13. The energy transfer device of claim 8, and said first resonator structure comprises a polaritonic sphere, where the characteristic size L_1 is the radius of the sphere.

14. The energy transfer device of claim 8, and said first resonator structure comprises a capacitively-loaded conducting-wire loop, where the characteristic size L_1 is the radius of the loop.

15. The energy transfer device of claim 8, and said second resonator structure comprises a dielectric sphere, where the characteristic size L_2 is the radius of the sphere.

16. The energy transfer device of claim 8, and said second resonator structure comprises a metallic sphere where the characteristic size L_2 is the radius of the sphere.

17. The energy transfer device of claim 8, and said second resonator structure comprises a metallodielectric sphere where the characteristic size L_2 is the radius of the sphere.

18. The energy transfer device of claim 8, and said second resonator structure comprises a plasmonic sphere where the characteristic size L_2 is the radius of the sphere.

19. The energy transfer device of claim 8, and said second resonator structure comprises a polaritonic sphere where the characteristic size L_2 is the radius of the sphere.

20. The energy transfer device of claim 8, and said second resonator structure comprises a capacitively-loaded conducting-wire loop where the characteristic size L_2 is the radius of the loop.

21. The energy transfer device of claim 7, wherein said resonant field in said device is acoustic.

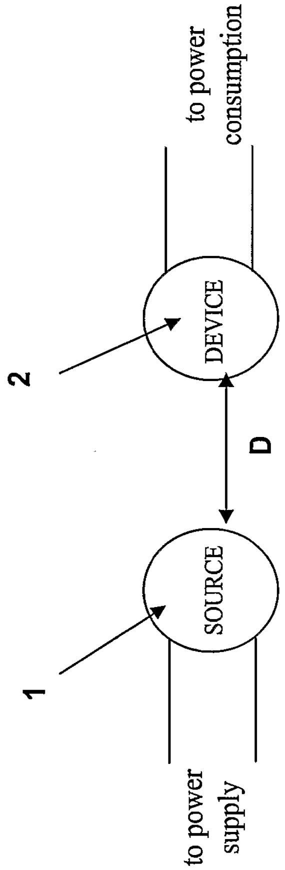
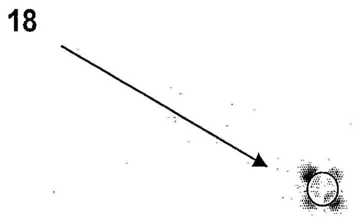


FIG. 1



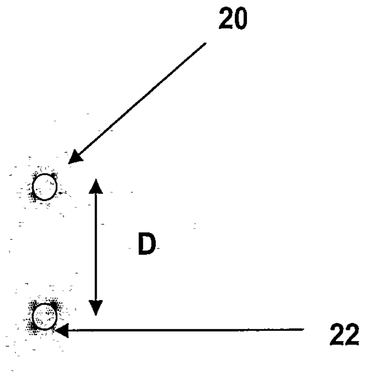


FIG 2A

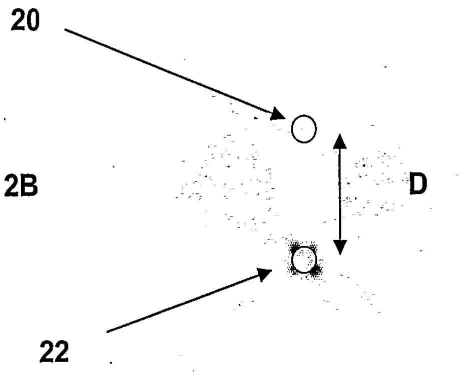


FIG. 2B

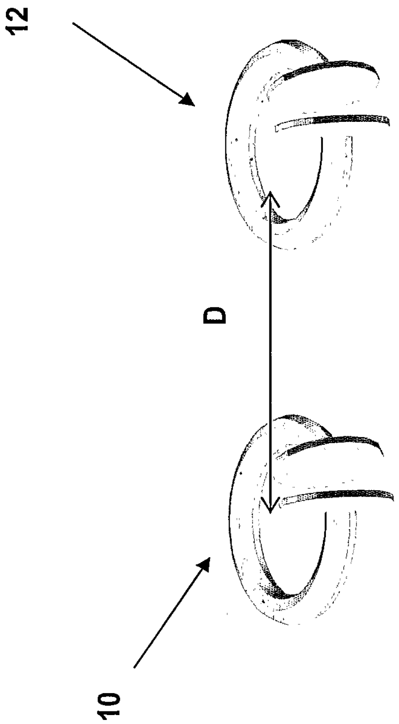


FIG. 3

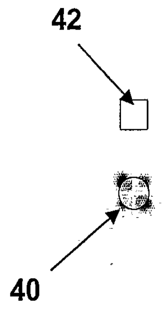


FIG. 4A

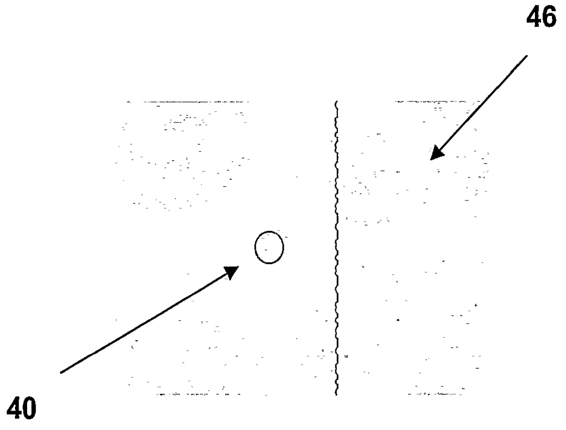


FIG. 4B

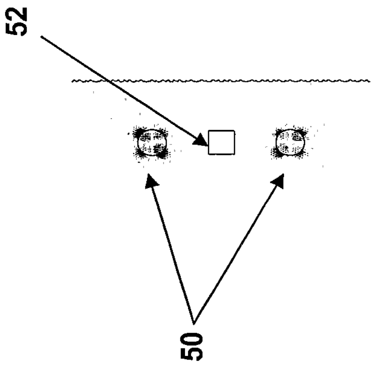


FIG. 5

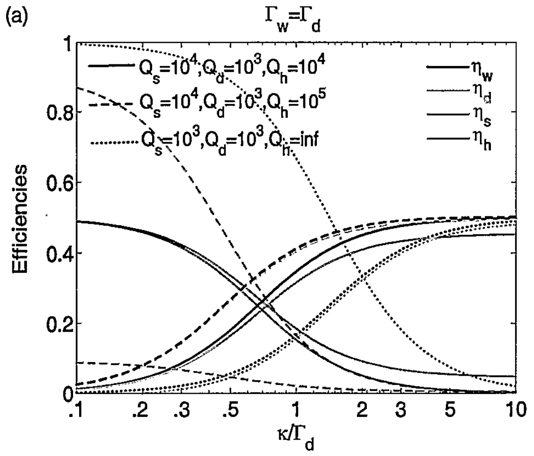

(a)
$\Gamma_w=\Gamma_d$
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^5$
$Q_s=10^3, Q_d=10^3, Q_h=$inf
η_w
η_d
η_s
η_h
Efficiencies
1
0.8
0.6
0.4
0.2
0
.1
.2
.3
.5
1
2
3
5
10
κ/Γ_d

FIG. 6A

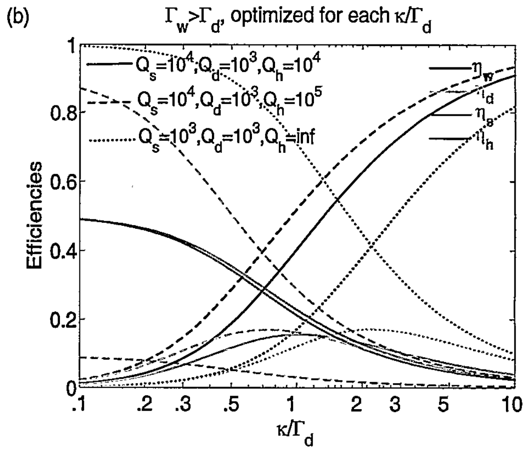

(b)
$\Gamma_w>\Gamma_d$, optimized for each κ/Γ_d
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^5$
$Q_s=10^3, Q_d=10^3, Q_h=$inf
η_w
η_d
η_s
η_h
Efficiencies
1
0.8
0.6
0.4
0.2
0
.1
.2
.3
.5
1
2
3
5
10
κ/Γ_d

FIG. 6B

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(75) Inventors/Applicants *(for US only)*: **JOANNOPOULOS, John, D.** [US/US]; 64 Douglas Road, Belmont, MA 02478 (US). **KARALIS, Arsteidis** [GR/US]; 70 Pacific Street, Apt. #907, Cambridge, MA 02139 (US). **SOLJACIC, Marin** [HU/US]; 67 Fairfax Street, Somerville, MA 02744 (US).

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Published:
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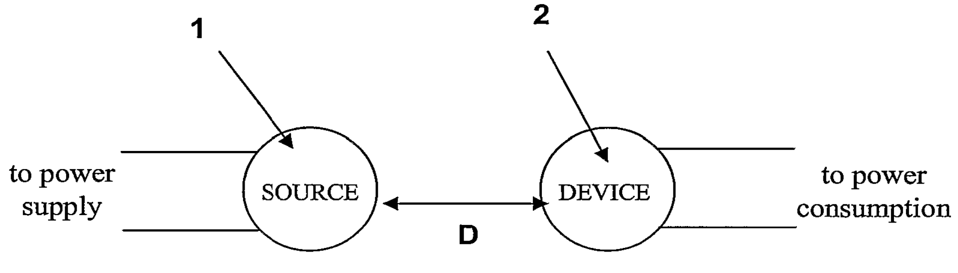
(54) Title: WIRELESS NON-RADIATIVE ENERGY TRANSFER



(57) Abstract: The electromagnetic energy transfer device includes a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. A second resonator structure is positioned distal from the first resonator structure, and supplies useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Non-radiative energy transfer between the first resonator structure and the second resonator structure is mediated through coupling of their resonant-field evanescent tails.

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/026480

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02J17/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 335 477 A (AUCKLAND UNISERVICES LIMITED) 13 August 2003 (2003-08-13) abstract paragraphs [0002], [0007], [0016], [0022], [0028] - [0030], [0064], [0086], [0088], [0100], [0109] figures 2,4	1-21
X	US 2 133 494 A (H.F.WATERS) 18 October 1938 (1938-10-18) figures 1,3,5 column 2, line 9 - line 52 column 6, line 1 - line 11	1-21

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search 11 December 2007	Date of mailing of the international search report 21/12/2007
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Lund, Michael

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INTERNATIONAL SEARCH REPORT

International application No
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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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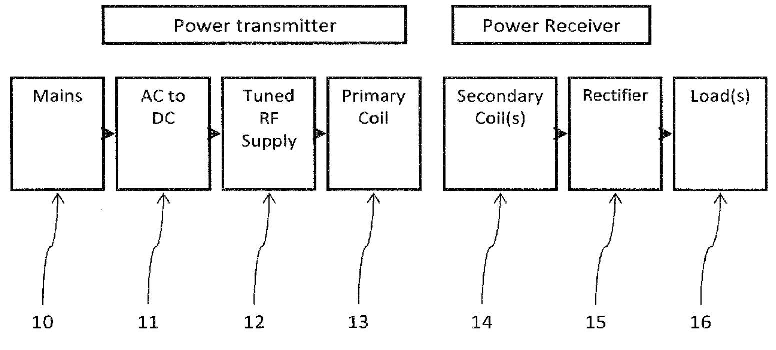


FIG. 1

(57) Abstract: Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enable a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

DESCRIPTION

METHOD AND APPARATUS FOR CONTACTLESS POWER TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/059,663, filed June 6, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

In recent years, inductive charging technology has become a leading candidate to eliminate power cables. Inductive power systems and other contactless power systems typically use one or more transmitters to send power to one or more receivers. Electronic devices with contactless power receivers can be powered or charged by being positioned in close proximity to a contactless power transmitter. Such systems have been designed and implemented.

Contemporary contactless power systems are make use of switch-mode inverters, such as the Class, D, DE, E, E^{-1}, F, F^{-1}, EF, EF2, EF3, Phi. The switch-mode inverter converts DC voltage that is provided by a DC voltage source to into a high frequency signal that enables efficient coupling of one or more primary coils to one or more secondary coils. The secondary coils are ultimately connected to one more loads. In the case of a contactless power transfer system the load of an inverter is typically a portable electronic device or some other load device with a variable power requirement. In many instances the load has an input impedance that is variable. The load can use energy or it can be designed to store energy. The load can comprise a voltage regulator and / or a power management system for regulating and relaying the power to an energy consuming or energy storing element. The impedance of the load helps determine the loading condition.

A typical switch-mode inverter comprises an active device, a supply network, and a load network with output terminals for connecting to a load.

The active device is typically a transistor and operates as a switch. The switch alternates between a conductive and non-conductive state. A control signal from a gate drive or clock can be used to operate the switch. The switch is connected to a supply network and a load network. The switching of the active devices helps form an AC signal at the output of the load network.

The supply network relays power from a source the DC voltage source to a terminal of the active device. The DC voltage source can have an output voltage that is variable. The supply network can be a simple inductor and typically comprises passive components. In some cases it may comprise an active device or variable elements for active reconfiguration of the supply network. A reconfiguration of the supply network can be performed depending on the load conditions in order to optimize efficiency or regulate the power which is delivered from the source.

The load network relays power to the load device from a terminal of the active device and supply network. The load network typically comprises passive components. In some cases it may contain an active device or variable for active reconfiguration of the load network. A reconfiguration of the load network may be performed depending on the load conditions in order to optimize efficiency and / or regulate the power delivered to the load.

The load network includes one or more primary coils for inductively coupling to one or more secondary coils. Because of size mismatches and restrictions on the use of bulky core materials, the coupling between the primary and secondary coils can be weak thereby reducing efficiency, power delivery, or both.

In order to compensate for weak coupling between primary and secondary coils, typical inductive charge systems typically operate at frequencies greater than 50kHz. At these higher operating frequencies soft-switching inverters, such as the Class E, E^{-1}, are preferred because they are more efficient than hard-switching inverters. High efficiency is preferable for environmental and regulatory reasons as well as practical reasons such as minimizing heat dissipation.

Soft-switching describes a mode of operation where an active device, such as a transistor, will switch when either the voltage or current across the transistor is zero. Soft-switching eliminates losses that normally occur with hard switching due to switch capacitance and the overlap of voltage and current in the switch. For example, in the case of zero voltage switching, the voltage across a transistor to swings to zero before the device turns on and current flows. Likewise, at turn-off, the voltage differential across the active device swings to zero before it is driven to a non-conductive state.

A practical system is preferably capable of matching the power supplied to the power demanded by a load device. This is important because many load devices have variable power requirements. If the power delivered does not match power required, the excess energy can be dissipated as heat. A load device can have an input impedance that is variable because of a power requirement that is variable (see Figure 5 for a graph of resistance versus changing time for a typical cell phone battery). The input impedance of the load device can change by an order of magnitude. The input impedance of a voltage regulator connected to a portable electronic device can change by two orders of magnitude. The variable impedance of a load device makes the implementation of contactless power system difficult.

The following two characteristics of soft-switched inverters found in typical contactless power system make the adaptation to a load device with a variable impedance challenging: 1. Most switch-mode inverters have high efficiency over a narrow range of impedances. As an example, a class E inverter typically operates under, high-efficiency soft-switched conditions over a factor of two in load impedance (see Figure 3) (Raab, 1978). (see Figure 2 for a graph of efficiency versus normalized resistance for typical switch-mode inverters); 2. The output power vs. load impedance relationship of a switch-mode inverter is different than the output power vs. load impedance relationship of a DC supply (See figure 4 for a graph of power delivery vs. load resistance for a DC supply and an inverter). Because of this, a load device's pre-existing power management control system can fail to appropriately regulate the power delivered to the load device which can lead to component failure.

Due to the above described characteristics a contactless power system is likely to encounter one or more of the following problems: 1) over-voltage and/or under-voltage conditions throughout the circuit; 2) excess or inadequate power delivery to individual loads 3) power oscillations; 4) heat problems; and 5) low efficiency.

Notably, a class D inverter architecture does not share the unfavorable characteristics and resulting problems of the other soft-switched inverters. Class D inverters are optimized for driving an impedance looking into the load network that has zero-phase angle (ZPA), and works for positive phase angles. Zero phase angle operation can be maintained by eliminating the reactance in a circuit of by using a combination of control functionalities, including, but not limited to, frequency, and tank circuit control (see Figures 7 and 8). A contactless power system with other soft-switched inverter architectures would be expected to make use of similar control functionality because of their sensitivity to the input impedance of the load(s). (Laouamer, R., *et al.*, " A multi-resonant converter for non-contact charging with electromagnetic coupling," in *Proc. 23rd International Conference on Electronics, Control and Instrumentation,* Nov 1997, Vol. 2, pp. 792 – 797; Abe, H., *et al.,* "A non-contact charger using a resonant converter with parallel capacitor of the secondary coil," in *Proc. Applied Power Electronics Conference and Exposition,* 15-19 Feb 1998, Vol. 1, pp. 136 – 141; Joung, G. B. *et al.*, "An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transfor*mer," IEEE Transactions on Power*

Electronics, Vol. 13, pp. 1013 – 1022 Nov 1998; Lu, Y., *et al.*, "Gapped air-cored power converter for intelligent clothing power transfer," in *Proc. 7th International Conference on Power Electronics and Drive Systems,* 27-30 Nov. 2007, pp. 1578 – 1584; Jang, Y., *et al.*, "A contactless electrical energy transmission system for portable-telephone battery chargers," *IEEE Transactions on Industrial Electronics*, Vol. 3, pp. 520 – 527, June 2003; Wang, C., *et al.*, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer system," *IEEE Transactions on Industrial Electronics*, Vol. 51, pp. 148 – 157, Feb. 2004; Wang, C., *et al.*, "Investigating an LCL load resonant inverter for inductive power transfer applications," *IEEE Transactions on Power Electronics*, Vol. 19, pp. 995 – 1002, July 2004; Wang, C., *et al.*, "Design consideration for a contactless electric vehicle battery charger," *IEEE Transactions on Industrial Electronics*, Vol. 52, pp. 1308 – 1314, Oct. 2005) Control functionality adds to the cost and complexity of a system and detracts from the commercial viability.

To enable better control functionality and to ensure proper operation of the system, communication systems between the power supply and the load have been proposed (see Figures 6 and 9). Such communication systems also add undesirable cost to the system.

The previously described control functionality has been implemented in both contactless power transmitters and contactless power receivers. Control functionality in the receiver has been considered of particular importance when multiple loads require power from the same transmitter. To support multiple loads, it has been proposed that receiver units incorporate mechanisms such as, but not limited to, variable inductance and duty cycling. These mechanisms allow multiple loads to receive power from the same source by giving load devices a mechanism to protect themselves from over-voltage and/or current conditions (Figure 6). These mechanisms are of high importance because loads without such mechanisms will continue to receive power even when they no longer require power. The power will be dissipated as heat in the load device. Contemporary batteries will not charge at temperatures over 50°C. These systems also add undesirable cost to the system.

SUMMARY OF THE INVENTION

Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enables a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

Embodiments of the impedance transformation network enables the contactless power system to avoid one or more of the four common problems described above, without any feedback, communication, and/or control functionality. The pre-existing power and battery charge management circuitry for a load, which may include a voltage regulator, can regulate the power output of a contactless power system under normal modes of operation. In accordance with embodiments of the invention, contactless power systems can be combined with very simple controls to improve the performance of the system. In this preferred mode of operation, a contactless power system can predictably and reliably deliver power to a load across a wide range of load impedances.

Embodiments of the invention provide one or more of, and a preferred embodiment of the invention provides each of, the following four functions:

1) Reactance shifting and phase angle control: a reactance is added to the resistance looking from the switch-mode supply through the load network. The reactance is shifted such that the phase angle looking from the switch-mode inverter into the load network is within a range that provides substantially soft-switching operation of the active device either when connected to or disconnected from one or more loads. Embodiments of the invention use the phase angle to control the power delivered by the inverter. Such embodiments can take advantage of the correlation between phase angle and load resistance. Changes in load resistance are transformed into a shift in the phase angle looking into the impedance transformation network. The output power response is more pronounced with respect to phase than with respect to load resistance (see Figure 12). This enables the invention to match power delivery and more closely mimic the response of a traditional DC supply (see Figure 13). In this method of operation, the contactless power system can deliver the necessary amount of power to the load. The soft-switching operation of the active device is preferably maintained for all load impedances.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is inductive, then the impedance transformation network is configured such that the impedance of the phase angle looking from the active device into the load network is positively correlated with the effective resistance of the load(s). If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases. If the effective resistance of the load decreases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network decreases. In a specific embodiment the reference phase angle is 40 degrees or greater, and in another 45 degrees or greater. In further embodiments, increases in load resistance can increase the phase angle up to 85 degrees.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is capacitive, than the impedance transformation network can be configured such that impedance of the phase angle looking from the active device into the load network is negatively correlated with the effective resistance requirement of the load. If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network decreases. If the effective resistance of the load decreases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases.

The effective resistance is a combination of the resistances of the loads looking from the terminals of the secondary coils toward the load. The loads can be seen as in series or parallel. The loads can be seen as the series or parallel combination of the inverse of the individual load resistances. In the generalized form, the effective load resistance of any close proximity contactless power system via magnetic induction that incorporates m primary coils and n secondary coils can be described by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{IM}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

Typically, the power requirement of the device is negatively correlated with load resistance. As the resistance of the load increases the power required by the load decreases.

2) Resistance isolation: the resistance looking from the switch-mode supply through the load network can be minimally affected by changes in load resistance (see Figure 10);

Embodiments of the invention can isolate the switch-mode supply from changes in load resistance in order to improve the predictability and stability of the output power. The isolation from changes can be accomplished by the implementation one or more filter networks such that the range of resistances presented by load appear much narrower at the output terminals of a switch-mode inverter. The switch-mode supply should see a resistance such that it is in a high efficiency mode of operation (see Figure 2).

3) Frequency filtering: a filter removes extra harmonics, effectively "cleaning" the power signal before it enters the primary or secondary coil. In one embodiment this frequency filter incorporates an inductor and a capacitor with a "low Q" value. In another embodiment this frequency filter incorporates an inductor and a capacitor, the filter being considered to have a high Q value.

4) Coupling: at least one primary coil in the load network is inductively coupled to one or more secondary coils of the same load network. The primary coils can be configured in a spiral configuration and maybe designed with a variable pitch in order to create an even

magnetic field distribution. The primary coils can be arranged in an array pattern with each coil in the array wound with an irregular shape so that the array has a substantially even magnetic field distribution. The secondary coils can be coupled to the primary coil in any position or orientation. The secondary coil can be adapted to attach to a load. In a preferred embodiment the secondary coil is adapted to attach to a portable electronic device. In specific embodiments, both the primary coil and the secondary coil are the same size to maximize coupling. In this example, and other specific embodiments, the receiver coil is significantly smaller than the primary coil, in order to allow the user to place the device in any orientation. It is desirable for the secondary coil to be much smaller than the primary coil, but the efficiency and power transfer capabilities start to degrade significantly if the receiver is too small, due to poor coupling. In this example the secondary is wound along a single path with minimal spacing between turns in order to minimize the occupied volume and ease integration.

The voltage and current characteristics of the primary coil and the secondary coil can be described using the following equations [7][12]:

$$V_1 = M_{11}\frac{dI_1}{dt} + M_{12}\frac{dI_2}{dt} \quad (1)$$

$$V_2 = M_{21}\frac{dI_1}{dt} + M_{22}\frac{dI_2}{dt} \quad (2)$$

$$M_{12} = k\sqrt{M_{11}M_{22}} \quad (3)$$

Where

V_1 is the voltage at the transmitting coil

I_1 is the current at the transmitting coil

V_2 is the voltage at the receiving coil

I_2 is the current at the receiving coil

M_{11} is the self inductance of the transmitting coil

M_{22} is the self inductance of the receiving coil

$M_{12} = M_{21}$ is the mutual inductance of the two coils

k is the coupling coefficient between the two coils

By Ohm's law:

$$\begin{aligned} Z_{tx} &= R_{tx} + jX_{tx} \\ &= \frac{V_1}{I_1} \end{aligned} \tag{4}$$

$$\begin{aligned} Z_{rx} &= R_{rx} + jX_{rx} \\ &= \frac{V_2}{I_2} \end{aligned} \tag{5}$$

Solving equations (1-3)

$$\begin{aligned} Z_{tx} = &\frac{\omega^2 M_{12}^2 R_{rx}}{R_{rx}^2 + \left(\omega M_{22} + X_{rx}\right)^2} \\ &+ j\left(\omega M_{11} - \frac{\omega^2 M_{12}^2 \left(\omega M_{22} + X_{rx}\right)}{R_{rx}^2 + \left(\omega M_{22} + X_{rx}\right)^2}\right) \end{aligned} \tag{6}$$

The above equations neglect any 2nd order effects such as skin depth and proximity effects. A more in-depth analysis accounting for the above effects can be utilized. In an embodiment, litz wires can be used to mitigate such effects to the extent that they do not create significant discrepancies.

By using the combination of resistance isolation and phase angle control, a reliable, stable transmitter can power a variable load. First, the inverter preferably will not fail or overheat when the secondary coil is removed from the primary coil. Although a load detection scheme can be used to turn off the transmitter and reduce unloaded power losses, it can still be desirable for the unloaded power consumption to be sufficiently low. Since the coil voltage is unique to each load resistance as shown in Figure 49, load detection and status can be easily acquired. To avoid false detection, the load detection and status can be verified by analyzing the supply current via a current sense resistor. Limiting unloaded power loss can be achieved by ensuring the unloaded transmitting load network has effective impedance similar to a high load resistance case (high impedance with large phase angle). From the schematic of the class E circuit in Figure 44, it can be deduced that most of the power lost is due to the primary coil and inductor parasitic resistances as they are in the path of power transfer. Therefore, one way to reduce the unloaded power loss is to use an inductor with lower parasitic resistance.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other objects, features, and advantages of the present invention, as well as the invention itself, will be more fully understood from the following description of various embodiments, when read together with the accompanying drawings.

Figure 1 shows a typical contactless power system that uses an inverter to drive a primary coil that may couple to one or more secondary coils and loads.

Figure 2 shows the operating efficiency versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 3 shows the power in (Pi) and power out (Po) versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 4 shows the power delivered to a variable load resistance from two different sources: a tuned switch-mode inverter supply and a fixed voltage DC supply, illustrating that power delivered to the load across a range of impedances is very different depending on the source, and that the range of output power can be much smaller with switch-mode inverters.

Figure 5 shows the load resistance of a Motorola Razr during the charge cycle, illustrating that during the charge cycle, the resistance can change by greater than one order of magnitude.

Figure 6 shows a block diagram of a typical prior art contactless power system, including commonly proposed and implemented communication and control functionality.

Figure 7 shows a logic diagram, which is continued in Figure 8, of a typical prior art contactless power system, including commonly proposed and implemented control functionality.

Figure 8 shows a continuation of the logic diagram of Figure 7.

Figure 9 shows a block diagram of a typical prior art wireless power system with communication capability.

Figure 10 shows the correlation between load resistance and the resistance looking from the inverter in accordance with an embodiment of the subject method, where the load resistance is transformed such that the resistance seen by the switch-mode supply is relatively constant, and in particular, the resistance from the supply is seen as between 2 and 6 ohms while the resistance of the load is varied from 5-500 ohms.

Figure 11 shows the operating efficiency and power output of a class E inverter that is driving a fixed resistance with a phase angle ranging from -90 to 90 degrees, where the operating region for an embodiment of the invention is indicated.

Figures 12A and 12B show the power output of a class E inverter in response to variable load resistance and variable phase, respectively, showing a calculation of output range and compares them against each other.

Figure 13 shows the power delivered to a variable load resistance from three different sources: an inverter, a fixed voltage DC supply, and a switch-mode inverter operating in accordance with an embodiment of the invention.

Figure 14 shows the decoupling, or degradation of coupling efficiency between the load and the transmitter for various filter networks.

Figure 15 shows a block diagram of a system in accordance with an embodiment of the subject invention, where the block diagram shows the direction of power flow and the various networks that can be used.

Figure 16 shows a typical load resistance vs. time plot as seen from the input of a rectifier feeding into a device.

Figure 17 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 18 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention .

Figure 19 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 20 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 21 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 22 shows the actual power delivery and efficiency of a system that is operating in accordance with a preferred embodiment of the invention.

Figures 23A-23C show the actual power delivery and efficiency for another system in accordance with the invention. The experimental results are from a 12V supply system. Efficiency peaks at main power delivery band, which is approximately 25-100Ω load resistance, are shown. Power delivery drops rapidly after 100Ω, when the system goes into low load condition or trickle charge condition. Although the efficiency at high load resistance is poor, the absolute power loss is kept at about 1.75W, while power delivery continues to drop. This power loss is distributed in the system and little or no heat issues are observed (especially at the receiver) during the low load operation.

Figure 24 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in the non-preferred mode of operation.

Figure 25 shows the actual power delivery and efficiency of a system that is operating in the non- preferred mode of operation.

Figures 26A-26B show the instantaneous peak power loss for hard switching topologies, known in the art, as they are compared to soft-switching topologies, known in the art, where Figure 26A shows a “hard switching” topology power loss waveform for a bridge MOSFET (320 W/div) showing high instantaneous peak power loss during each switching cycle, and Figure 26B shows a “soft switching” topology power supply with the same rating as that in Figure 26A.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different C_{tx}.

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where $C_{shunt} = 19nF$.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

DETAILED DISCLOSURE

Contactless power systems typically use high frequency power electronics to deliver power to one or more loads. Figure 1 shows the fundamental components of many contactless power systems. A contactless power supply generally draws its power from the electrical grid through a standard wall outlet **10**. The power from the wall is typically AC so it is generally converted to DC voltage by an AC to DC converter 11. In order to shrink the size of components it is desirable to work at a high frequency, so the DC voltage is switched by an inverter **12**. The high frequency signal, such as a high frequency voltage signal or high frequency current signal, is fed into one or more primary coils **13**. The high frequency signal may pass through one or more filters before it feeds in to the primary **13**. The primary coil **13** couples with one or more secondary coils **14**. The secondary coil **14** will receive the high frequency power signal and will feed that into a rectifier **15**, which will then output power to the load **16**. One or more filter networks may be present between the secondary coil **14**, rectifier **15**, and load **16**. Voltage regulation and battery charge management circuitry may be considered part of load **16**.

The incorporation of a switch-mode inverter can make it difficult to deliver the correct amount of power to the load or loads. This is partially attributable to the limited range of load resistances that enable high-efficiency operation. Figure 2 shows the high efficiency operating range **20** of an inverter as it compares to the operating range **21** of a typical battery operated device. The operating range of resistances of the battery operated device is substantially wider than the high efficiency operating range or the inverter. Figure 3 shows the relation of input power **34** and output power **33** of an inverter across a range of resistances. The lost power can be calculated by subtracting output power **33** from input power **34**. The power loss is significant outside the high efficiency operating region **31**.

Switch-mode inverters are difficult to implement in contactless power systems with variable loads because the output power response relative to load resistance is very different than a DC supply's output power response relative to load resistance. Figure 3 shows output power **33** increasing with load resistance until it reaches a center value and decreases again. This is different than a typical constant-voltage DC supply whose power delivery follows the relationship P=V^2/R. The difference is illustrated in Figure 4 where we can see that the power delivery from a DC supply **41** will decrease rapidly with an increase in load resistance. By contrast, the output power from an inverter **42** will increase with load resistance and will later drop as load resistance continues to increase. The drop in power delivery **42** is markedly slower than the drop in power delivery **41**. Although Figure 4 shows the curve for one example of a tuned switch-mode inverter supply, other tuned inverters can have different curves.

Portable electronic devices display a wide range of input resistances. Figure 5 shows the effective resistance **51** looking into a Motorola Razr during the charge cycle. Figure 5 shows the wide dynamic range of the load **52**, and in this case it is greater than one order of magnitude.

The aforementioned challenges of efficiency and power delivery can be overcome by implementing a variety of communications and controls. Figure 6 shows a contactless charging system that is an elaboration of the basic components and systems show in Figure 1. The grayed blocks are components that are found in a basic contactless power system. The white boxes are components that enhance the performance of a typical contactless power system. It show a transmitter control **60** which can alter the phase, duty cycle, frequency, tank circuit impedance, or rail voltage depending on loading conditions. There is a detection circuit **61** that draws information from various parts of the circuit and feeds that information back into the controller **60**. It show contactless communication links **62** on both the transmitter side **66** and receiver side **67**. The communication link can work in conjunction with the detection mechanisms **61** to help the controller **60** make the most appropriate adjustments to the system. The receiver side **67** also has a controller **63** which can adjust the resonant frequency, duty cycle **65**, or perform other functionality to regulate power being delivered to the load. A front end regulator **64** is added to provide an additional level of protection to the load.

With a system such as the one in Figure 6 in place, designers can implement control logic such as that shown in Figure 7 and Figure 8 taken from a prior art system. We can see from Figure 8 **433**, **434**, **436**, **438**, **440**, **442** some of the logic functionality that designers have built into contemporary contactless power systems. We can see from **432** that this system includes memory in order to achieve the desired functionality. Figure 9 shows another prior art system that uses a communication mechanism **91** on the receiver and a communication mechanism **90** on the transmitter. The communication, logic, and use of memory add additional cost to the system and require a large number of sensing points to be considered.

In order to stay within the high-efficiency operating region **20** and to match the power delivery of DC supply **41** several steps can be taken. Figure 10 shows the resistance seen by the switch-mode supply **100** as it compares to actual load resistance. From **100**, we can see that the resistance appears to vary from 2 to 6 ohms over a range from 5 to 500 ohms. This enables the switch-mode supply to stay in the high efficiency region **20** shown in Figure 2, regardless of load resistance.

Compressing the resistance will not solve the problem of improper power delivery. Figure 2 shows that if we keep the resistance in a narrowband, power output changes minimally. In fact, the compression would exacerbate the power delivery discrepancy shown in Figure 4 where we see that power output response to load resistance from a switch-mode supply **42** does not match the power output response to load resistance from a constant voltage, DC supply. If too much power is delivered, the device may be destroyed, if too little is delivered it may not function.

In order to address the challenge, the phase angle of the load can be affected in order to affect the power output of the switch-mode supply, in accordance with embodiments of the invention. Figure 11 shows, for class E inverters, that an increase or decrease in phase correlates with an increase or decrease in output power. Input power **111** and output power **110** matched closely for a phase angle in the range of about +45 to +80 degrees. Even though efficiency **112** drops considerably as the phase angle approaches +90 degrees, the absolute power lost remains low. The use of phase angle control enables a +/-70% usable range of output power **113** with very low absolute power loss.

Embodiments of the invention use phase angle control to power a battery operated device. Conventional voltage regulators increase the resistance so that the power output of a DC supply is reduced **41**. Figures 12A-12B show, for class E inverters, the difference between using traditional resistance controlled output power vs. using phase controlled output power in accordance with embodiments of the invention. Referring to Figure 12A, in a resistance controlled scheme, input power **122** matches power out **123** for a very small dynamic range **125** of output power. This shows that varying the resistance is an ineffective way of controlling output power. The usable range of power levels for a resistance controlled scheme is only about +/- 9% **125** of the center value. Outside of this range the high absolute losses are high and can create harmful heat and wear and tear on components. Referring to Figure 12B, in a phase controlled scheme, input power **121** matches power out **120** for a much wider dynamic range of output power **124**. This shows that varying the phase dramatically increases the output power range. The usable range of power levels is +/- 70% **124** of the center value. Even though resistance may drop over this range, the absolute power losses are relatively low in this band **124**. Efficiency can be low, but total dissipated power is very low. The low absolute power loss avoids the problem of overheating and device damage.

By combining the resistance compression and the phase control, the contactless system can achieve a power output response to load resistance that is very similar to that of a conventional DC supply. Figure 13 shows the power output response of a DC supply **130**, an inverter **131**, and an inverter in accordance with an embodiment of the subject method of operation **132**. The output power in response to load resistance of the inverter in accordance with the embodiment of the subject method of operation **132** is much closer to the output power a device should expect from a constant voltage DC supply **130**.

An additional challenge to designing and implementing a contactless power system is that multiple loads may draw power from a single source. This is problematic when different devices have different power requirements. For instance, a fully discharged cell phone may require 10-15 times the power of a fully charged cell phone. Embodiments of the subject method of operation can provide a mechanism to protect individual devices from damage if the power output exceeds the device requirement. Loads that no longer require power can be decoupled from the primary coil. De-coupling can include degradation in coupling efficiency so that the load is effectively isolated from the transmitter. This can be accomplished by using pre-existing voltage regulator behavior. As a voltage regulator increases the effective input resistance, coupling efficiency drops and vice-versa.

Figure 14 shows the decoupling effect for various receiver circuits. A parallel capacitor can be selected to tune the decoupling point, which is the point when efficiency of receiver is at 50%. For this case, the decoupling point for 100nF capacitor is at 700Ω, whereas the decoupling point for 150nF capacitor is at 320Ω. We can see that for various configurations **141**,**142**, **143** the rate of decoupling occurs at varying rates. **143** shows a curve that is a good fit for a single device charger that can regulate power output from the transmitter. **141** shows a curve that is good fit for a multi-device charger where individual loads may need to be isolated from the source. Although not shown in Figure 14, when the capacitor valve is changed the power received is also changed.

In order to accomplish this method of operation without any communication and control functionality, other than the pre-existing control found in today's voltage regulators, embodiments of the subject system can use a series of carefully tuned transformation networks that transform, compress, and shift the impedance of the load. Through these filter networks the resistance can be compressed, the phase angle manipulated, and the loads allowed to decouple from the primary.

Example 1:

A high power, high-efficiency contactless power transfer system using the impedance transformation network and has been designed and fabricated using the subject impedance transformation network. The contactless transfer system requires minimal control to achieve the desired power delivery profile across a wide range of load resistances, while maintaining high efficiency to which helps to prevent overheating of components. This embodiment of the subject system includes more than one active device with independent gate drive to control power delivery. The system is able to achieve power delivery of 295W to a load of 50Ω with a DC voltage of 121.5V and current of 2.43A. The input current was current-limited at 3.25A. The system efficiency at maximum power output is 75.7%. The system operates at a minimum of 77% efficiency across load resistances ranging from 60Ω to 140Ω which corresponds to a high output power state. The system can be scaled to achieve higher output power if the current limit is removed. Higher efficiency and better power delivery can be achieved by using components with lower parasitic resistance.

The DC source voltage is the 600W CSI12005S power supply by Circuit Specialists, Inc rated at 120V at 5A. The active devices are transistors, specifically the transistors are part IRFP21N60L from International Rectifier.

A pair of coils was fabricated using 16 AWG magnet wire for the set-up. The primary coil is 21cm by 21cm with 10 turns with variable spacing between turns while the secondary coil is 13cm by 13cm with 5 turns wound along the same path. Figure 57 shows the primary coil embedded in plastic with the secondary coil placed on top. The primary and secondary coils are separated by a gap of 10mm. The primary coil is designed with the appropriate spacing between the turns to achieve only 5% power variation of the received power at all different locations. In this example, the coupling is approximately constant regardless of the receiver position provided that the entire secondary coil is within the outer perimeter of the primary coil. The self inductance of the primary coil is 31.95μH with a parasitic resistance of 0.32Ω and secondary coil is 12.52μH with a parasitic resistance of 0.2Ω. Mutual inductance between the coils is 7.454uH with a coupling coefficient of 0.373. The measurements were taken using the HP4192A LF Impedance Analyzer.

In order to reduce losses through parasitic resistance, low loss Polypropylene capacitors are used. In order to strike a balance between size and efficiency, 1140-101K-RC by Bourns Jw Miller is selected to be L_{out}. Since most of the losses of the transmitter are from the parasitic resistance of L_{out}, a larger and more efficient inductor can be replaced, if space permits. The fabricated dual channel driver with a dimension of 10cm x 8.5cm is shown in Figure 56. There are a lot of empty spaces; therefore its size can be further reduced. L_{out} takes up a significant amount of space due to the requirement for low parasitic resistance so as to maintain sufficiently high efficiency and power delivery.

Peak drain voltage is only 460V, which is approximately 25% lower than the rated voltage of the transistor used. Figure 58 shows the efficiency and power delivery of the 120V system with respect to load resistance. The power delivery of the system can be scaled by varying the supply voltage as long as the DC power supply driving system is able to provide sufficient power and the drain voltage across the transistor stays within its breakdown voltage.

The efficiency of the single channel is approximately 10-15% lower for the same load resistance because the current is flowing through a single L_{out} inductor instead of a pair of them, which means the parasitic resistance is doubled, thus resulting in a low system and transmitter efficiency as shown in Figure 63 and Figure 64, respectively. However, when the system goes into light load mode or trickle charge mode, it would be desirable to go into the single channel mode. It can be seen from Figure 65 that the system efficiency is approximately 15% higher than the dual channel mode for delivering the same amount of power below 10W. Instead of operating at high load resistance for a dual channel mode resulting in high receiver DC voltage as shown in Figure 67, it is possible to achieve similar power delivery at much lower load resistance for a single channel mode resulting in lower receiver DC voltage as lower load resistance would result in higher system efficiency. In addition, a typical buck regulator has higher DC-DC efficiency when the input voltage is lower. Therefore, a load resistance detection scheme can be used to determine the switch over point from dual channel to single channel. It can be seen from Figure 62 that a power delivery of 10W occurs at 500Ω load resistance of the dual channel mode making it a good switch over point. It can be concluded that a 500Ω load resistance would translate to an approximate primary coil RMS voltage of 20V for the dual channel mode as shown in Figure 66. Likewise, if the power requirement for the single channel mode is too high, it can be switched to dual channel mode. It can be inferred from Figure 62 that the switch over point would be approximately 75Ω, which translates to a RMS coil voltage of 22V from Figure 65. The coil voltage can be read using an ADC where the DC voltage at the input of the ADC can be transformed from the coil voltage by rectification and stepping down using a potential divider.

In a specific embodiment, for size and efficiency considerations, capacitors can be used for the network. This is because resistors dissipate power and a low loss inductor would be large in size. Alternative embodiments can incorporate resistors and inductors. Although, a multi-element transformation network might achieve a more appropriate response, for simplicity and low components count, an embodiment of the system uses a single-element transformation network. Four topologies are shown in Figures 42 and 43.

A series capacitor only introduces a negative reactance and does not change the real part of the impedance. A parallel capacitor affects both the real and imaginary part of the impedance. For simplicity, the receiver input impedance can be modeled using a variable resistor load such that equation (7) illustrates the transformation performed by the parallel capacitor.

$$Z_{rx} = \frac{R}{1+\omega^2C^2R^2} - j\frac{\omega CR^2}{1+\omega^2C^2R^2} \qquad (7)$$

Equation (7) shows that the resistance is "compressed" non-linearly by a factor of $1/(1+\omega^2C^2R^2)$. Thus, the effective resistance decreases with increasing load resistance. At high load resistance, the transformed resistance is small. Therefore, a significant part of the power received is dissipated across the secondary coil as heat. This phenomenon is actually desirable if the receiver is in a state that requires very little power or during trickle charge. Therefore, it has a "decoupling" effect regulating the power delivery with increasing load resistance. However, this should preferably occur only when the transmitter is designed to use limited power at this state of operation as heating would become an issue if too much power is being dissipated across the secondary coil. By using a parallel capacitor, a reactive term can be introduced. The reactive term decreases nonlinearly from null with increasing load resistance with an asymptote of $-1/\omega C$, which can be useful in compensating the secondary coil inductance.

From equation (6) it can be observed that the resistance looking into the transmitter coil can be reduced significantly with the increase of resistance looking from the receiver coil into the receiver. Due to loose coupling between the coils, the resistance looking into the primary coil can be further reduced as the mutual inductance can be relatively low. If the total resistance looking into the primary coil is comparable to the parasitic resistance of the primary coil, limited power is transmitted to the receiver as most of the power would be dissipated across the primary coil as heat. Therefore, it would be preferred for a power transmission via loosely coupled coils to have a parallel capacitor on the secondary coil. By substituting equation (7) into equation (6),

$$Z_{tx} = \left(\frac{\omega^2 M_{12}^2 \left(\frac{R}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) + j \left(\omega M_{11} - \frac{\omega^2 M_{12}^2 \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) \quad (8)$$

For the transmitter transformation network, a series or parallel topology can be used. However, to maintain an ideal efficiency above 95%, the allowable variation of load resistance of an ideal class E inverter can be kept within +55% and -37% [F. H. Raab, "Effects of circuit variations on the class E tuned power amplifier," *IEEE Journal of Solid-State Circuits*, vol. 13, pp. 239 – 247, Apr 1978.]. Therefore, if the variation of resistance with respect to load resistance looking into the transmitter is too large, it can be preferable to use a parallel capacitor instead of a series capacitor. A capacitor value can be selected that ensures that the transmitter would not suffer immediate failure when there is no secondary coil as well as having an increasing reactance trend with increasing load resistance. Having an increasing reactance trend with increasing load resistance can ensure the preferred power delivery trend.

Figure 15 shows an example configuration of a system that can work in this mode of operation in accordance with an embodiment of the subject invention. Other circuit configurations can also be utilized to work in this mode of operation in accordance with the subject invention. The grayed boxes, which include an AC/DC converter **150**, switch-mode inverter **151**, primary coil **154**, secondary coil **156**, rectifier stage **158**, regulator stage **159**, and load **1500**, are components of a typical contactless power system, for example, as shown in Figure 1. In order to achieve the method of operation in accordance with the subject invention, this system uses four transformation networks, including receiver-side impedance transformation network **157**, coupling network **155**, transmitter-side impedance transformation network **153**, phase shift network **152**. Measuring the impedance at probe points looking into the rectifier stage **1503**, receiver-side impedance transformation network **1504**, primary coil **1505**, transmitter-side impedance transformation network **1506**, and phase shift network **1507**, facilitate a better understanding of the operation.

Figure 16 shows a simulated load resistance vs. time **160** measured looking into the rectifier stage from probe **1503**. The swing from 0-500 ohms is well outside usable operating range of an inverter **20** and **31**, shown in Figure 2 and Figure 3, respectively. It would be desirable to compress the resistance into a useable operating range **20**, **31**. At this stage there is no reactive component which is introduced by the impedance transformation network **157** in order to use the phase angle method of power control in accordance with embodiments of the invention.

Figure 17 shows the transformed load resistance **170** looking into the receiver-side impedance transformation stage from probe **1504**. The objective of this stage is to achieve the decoupling effect shown in Figure 14. This decoupling effect is automatic decoupling where the degradation of coupling efficiency between the contactless power transmitter and the load(s) effectively decouples the receiver from the transmitter. Figure 17 also shows the reactive component **171** introduced by the impedance transformation network **157**. The introduction of the reactive component **171** compresses the resistance looking into the receiver in order to stay within the useable operating range of the inverter identified in Figure 2. Additional reactive components will be further added on the transmitter side for implementing the phase-angle method of control in accordance with the invention. At this stage the reactive component **171** decreases with respect to load resistances, which means that phase angle is decreasing with respect to load resistance. From Figure 11, we can see that the working range **114** requires an increase in phase angle for inductive load, to reduce power output. Impedance transformation networks **153** on the transmitter side can compensate from the phase angle introduced by the impedance transformation network **157**.

Figure 18 shows the impedance transformation that is the result of the coupling network **155** and is measured looking into the primary coil **154** from probe **1505**. The objective is to maximize the real part **170** shown in Figure 17, which has been compressed to the point where parasitic losses would become less dominant. Increasing the resistance can improve the efficiency of the circuit. The real part **180** is much greater at this stage and has been increased to maximize power delivery through to the secondary coil **156** and minimize the losses from other parasitic upstream stages closer to the wall outlet, or AC/DC **150**. The negative aspect, however, is that magnitude change of the real component **180** is too large when compared to the working region of a switch-mode supply **20**and **31,** shown in Figure 2 and Figure 3, respectively. This can be corrected by the upstream transformation networks, such as impedance transformation network **153**. The reactive component **181** still trends downward with load resistance and can also be corrected by upstream transformation networks.

Figure 19 shows the impedance transformation that is the result of impedance transformation network **153** and is measured looking into the impedance transformation network **153** from probe **1506**. The objective is to compress the real component **180** such that it falls within the operating range **20**and **31**, defined in Figure 2 and Figure 3, respectively. The second objective is to transform the reactive component **181** such that the increase in load resistance increases the reactive component and phase angle. The real part **190** is compressed back within the operating range of a switch-mode inverter **20** and **31**. The reactive part **191** has been corrected such that it trends upward with increasing load resistance. This corresponds to an increasing phase angle and decreased power delivery as load resistance increases. The reactive part **191** is negative at this stage and this would correspond to a negative phase angle. From Figure 11, it can be seen, for a class E inverter, that a negative phase angle corresponds with poor efficiency and high actual power losses. The same is true for class D and Phi inverters. The trend is undesirable at this stage because an increase in phase angle on the negative slope of **110** would increase power output. The reactive component can be shifted by phase shift network **152**, for example, so that is falls within the working region **114**.

Figure 20 shows the impedance transformation that is the result of the phase shift network **152** and is measured looking into the phase shift network **152** from probe **1507**. The objective is to keep the real part **190** in the operating range of the switch-mode inverter and shift the reactive part **191** into the operating range of the switch-mode inverter. The real part **200** is within the operating range of resistances of a switch-mode inverter **20** and **31**, from Figure 2 and Figure 3, respectively. The reactive part **201** now falls in the correct operating region **114** shown in Figure 11. Confirmation that the phase angle and trend are correct can be shown by converting **200** and **201** into a phase angle plot, as shown in Figure 21. The phase angle **210** is within the operating region **114** and increases with respect to load resistance. The phase angle **210** has a dip at very low impedances and in specific embodiments the initial dip in phase can be avoided.

Figure 22 shows actual experimental data taken from the system shown in Figure 15. After the 30 Ohm inflection point **220**, power output decreases with load impedance and the system achieves high operating efficiency. Because a typical portable electronic device will operate at impedances greater than 30 ohms when the supply voltage is sufficiently high, this is an example of a preferred power delivery vs. load resistance vs. efficiency plot.

Example 2:

A primary coil parallel capacitor value in a specific embodiment can meet two constraints.

Figure 24 offers a contrast to the preferred phase angle vs. load resistance trend shown in Figure 21. The reference phase angle is approximately 80 degrees and decreases with load resistance. The phase angle **240** decreases with load resistance.

Figure 25 shows the result of this mode of operation when there are no communication and control mechanisms in place. The power output increases with load resistance, which is exactly opposite the response of a fixed voltage DC supply **130** which is shown in Figure 13.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figures 31-40 show a variety of ways that the components of various embodiments of the subject invention can be located, for example proximate the transmitter coil, proximate the receiver coil, or separate from both.

Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figures 42-83 show various components and systems or subsystems that can be utilized with various embodiments of the invention, and/or data corresponding to various embodiments of the invention.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different $C_{tx.}$

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where $C_{shunt} = 19nF$.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

Specific embodiments pertain to a method and a circuit for inductive power transfer, incorporating an impedance transformation network, where the impedance transformation network has an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, where the reactive network includes a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, where when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load. A real part of the impedance looking into the impedance transformation network through the input port can be in a range between a minimum real part and a maximum real part. The maximum real part can be less than or equal to one order of magnitude greater than the minimum real part. Further embodiments can incorporate at least one additional input port, at least one additional output port, at least one additional primary coil, and/or at least one additional secondary coil. The output port can be adapted for coupling to at least two loads.

In an embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load. In another embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load. In a specific embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{IM}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

The reactive network can have at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. The at least one shunt network with a negative reactance can have a capacitor. The active device can have a transistor. In a specific embodiment, active device includes a switching component that operates substantially as a switch; and a capacitance in parallel with the switching component. The input port can be coupled to a voltage source or input port can be coupled to a current source. A supply network can be connected between the input port and a voltage source, where the supply network includes at least one inductor. The supply network connected between the input port and a voltage source can be configured to reject harmonics not intended to reach the load. In specific embodiments, the supply network connected between the input port and a voltage source can include elements of the supply network, load network, and the active device so as to represent at least one class D inverter or variant, at least one class DE inverter or variant, at least one class E inverter or variant, at least one class E^{-1} inverter or variant at least one class F inverter or variant, at least one class F^{-1} inverter or variant, at least one class EF^{-1} inverter or variant, or at least one class Phi inverter or variant.

The signal from the active device can be an AC signal and/or a periodic signal. When the active device is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Regarding this range, in specific embodiments switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device can occur when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

In another embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs. Regarding this range, in specific embodiments, switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1. In a further specific embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs. Such switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1, when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5, and/or when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs. Switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port can be within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port. A supply network can be connected between the input port and a voltage source, where the supply network is configured to reject harmonics not intended to reach the load. At least one load having a time-dependent impedance connected to the output port. In another embodiment, the system can be adapted least one load having a time dependent non-negative real resistance can be connected to the output port. In a specific embodiment where the phase angle of the impedance looking into the impedance transformation network through the input port is inductive, the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

In an embodiment with a shunt network connected between the first terminal of the secondary coil and the second terminal of the secondary coil, where the shunt network has a negative reactance, the shunt network can be configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance. In specific embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, or the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms. In a further specific embodiment, the at least one shunt network has a negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance. In a further specific embodiment, the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, where the reactive network further utilizes at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, the at least one additional shunt network having a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

The reactive network can further include at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

The reactive network can include at least one reactive component connected to the primary coil, where the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port can be within a range such that substantially zero-voltage switching of the active device occurs. In specific embodiments, the impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, where the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance. In various embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, and the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

The at least one filter network having a positive reactance can be connected in series with the primary coil, where a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

The impedance transformation network can be configured to couple to two active devices via a single input port. The input port can have at least two input ports for coupling to at least two active devices.

A rectifier can be positioned between the impedance transformation network and the load.

The primary coil can be connected in series with at least one reactive component and the secondary coil can be connected in series with at least one additional reactive component. In another embodiment, the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. In yet another embodiment, at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component. In further embodiments, at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

The primary coil can be a single primary coil inductively coupled to at least two secondary coils. In another embodiment, at least two primary coils are inductively coupled to the secondary coils. In various other embodiments, m primary coils are inductively coupled to n secondary coils, where m>1 and n>1.

A specific embodiment relates to a circuit for inductive power transfer having an impedance transformation network, incorporating an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, wherein the reactive network has a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, such that when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

Another embodiment pertains to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network has an input port for coupling to a active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, and a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, and at least one inductor, such that when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

Another embodiment relates to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network includes an input port for coupling to an one active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, at least one inductor, such that when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment pertains to a circuit for inductive power transfer, having a secondary side impedance transformation network, where the secondary side impedance transformation network incorporates at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the output port and coupled to the secondary coil, where the reactive network incorporates at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment is directed to a circuit for inductive power transfer, having a secondary side impedance transformation network, wherein the secondary side impedance transformation network has at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network includes at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

An embodiment of the invention is directed to an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a first impedance transformation network (FITN), where the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil; a secondary coil, where the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN; a primary coil, where the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil; a second impedance transformation network (SITN), where the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil; a phase shifting network, where the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter; a tuned switch-mode inverter, where the tuned switch-mode inverter is interconnected with the phase shifting network; and a power source, where the power source is interconnected with the tuned switch-mode inverter. In this embodiment, the load can have a load resistance that can range from 0 to 500 ohms.

An embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected between the secondary coil and the rectifier stage, such that power output to the load decreases as the impedance of the load increases.

Another embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, where the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected between the secondary coil and the rectifier stage, such that power output to the load is adjusted as the phase angle of the load changes.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

1. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load.

2. The circuit according to claim 1, wherein a real part of the impedance looking into the impedance transformation network through the input port is in a range between a minimum real part and a maximum real part.

3. The circuit according to claim 2, wherein the maximum real part is less than or equal to one order of magnitude greater than the minimum real part.

4. The circuit according to claim 1, further comprising at least one additional input port.

5. The circuit according to claim 1, further comprising at least one additional output port.

6. The circuit according to claim 1, further comprising at least one additional primary coil.

7. The circuit according to claim 1, further comprising at least one additional secondary coil.

8. The circuit according to claim 1, wherein the output port is for coupling to at least two loads.

9. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load.

10. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load.

11. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^I)^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^I \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

12. The circuit according to claim 1, wherein the reactive network further comprises at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

13. The circuit according to claim 12, wherein the at least one shunt network with a negative reactance comprises a capacitor.

14. The circuit according to claim 1, wherein the active device comprises a transistor.

15. The circuit according to claim 1 wherein the active device comprises:

a switching component that operates substantially as a switch; and
a capacitance in parallel with the switching component.

16. The circuit according to claim 1 wherein the input port is coupled to a voltage source.

17. The circuit according to claim 1, wherein the input port is coupled to a current source.

18. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network comprises at least one inductor.

19. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

20. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class D inverter or variant.

21. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class DE inverter or variant.

22. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E inverter or variant.

23. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E^{-1} inverter or variant.

24. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F inverter or variant.

25. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F^{-1} inverter or variant.

26. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class EF^{-1} inverter or variant.

27. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class Phi inverter or variant.

28. The circuit according to claim 1, wherein the signal is an AC signal.

29. The circuit according to claim 1, wherein the signal is a periodic signal.

30. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

31. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

32. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

33. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

34. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

35. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

36. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

37. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

38. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs.

39. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1.

40. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5.

41. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

42. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

43. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

44. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

45. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

46. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

47. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

48. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

49. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

50. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

51. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

52. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

53. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

54. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

55. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

56. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

57. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

58. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

59. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

60. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

61. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

62. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

63. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

64. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

65. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

66. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port is within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port.

67. The circuit according to any of claims 27 – 31, comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

68. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time-dependent impedance.

69. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time dependent non-negative real resistance.

70. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is inductive.

71. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

72. The circuit according to claim 12, wherein the shunt network is configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance.

73. The circuit according to claim 72, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

74. The circuit according to claim 72, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

75. The circuit according to claim 72, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

76. The circuit according to claim 72, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

77. The circuit according to claim 12, wherein the at least one shunt network has a negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance.

78. The circuit according to claim 12, wherein the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

79. The circuit according to claim 1, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

80. The circuit according to claim 78, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

81. The circuit according to claim 1, wherein the reactive network comprises at least one reactive component connected to the primary coil, wherein the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port is within a range such that substantially zero-voltage switching of the active device occurs.

82. The circuit according to claim 1, wherein impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance.

83. The circuit according to claim 82, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

84. The circuit according to claim 82, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

85. The circuit according to claim 82, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

86. The circuit according to claim 82, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

87. The circuit according to claim 1, wherein at least one filter network having a positive reactance is connected in series with the primary coil, wherein a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

88. The circuit according to claim 1, wherein the impedance transformation network is configured to couple to two active devices via a single input port.

89. The circuit according to claim 1, wherein the input port comprises at least two input ports for coupling to at least two active devices.

90. The circuit according to claim 1, wherein the load is resistive.

91. The circuit according to claim 1, wherein the load is reactive.

92. The circuit according to claim 1, wherein the load comprises resistive and reactive components.

93. The circuit according to claim 1, wherein a rectifier is positioned between the impedance transformation network and the load.

94. The circuit according to claim 93, wherein the load comprises a portable electronic device.

95. The circuit according to claim 94, wherein the load comprises:
a voltage regulator;
a power management system; and
a battery.

96. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and the secondary coil is connected in series with at least one additional reactive component.

97. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

98. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component.

99. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

100. The circuit according to claim 1, wherein the primary coil is a single primary coil inductively coupled to at least two secondary coils.

101. The circuit according to claim 1, wherein the at least two primary coils are inductively coupled to the secondary coils.

102. The circuit according to claim 1, wherein m primary coils are inductively coupled to n secondary coils, where m>1 and n>1.

103. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

104. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to a active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

105. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to an one active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

106. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the output port and coupled to the secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

107. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

108. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a first impedance transformation network (FITN), wherein the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil;

a secondary coil, wherein the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN;

a primary coil, wherein the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil;

a second impedance transformation network (SITN), wherein the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil;

a phase shifting network, wherein the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter;

a tuned switch-mode inverter, wherein the tuned switch-mode inverter is interconnected with the phase shifting network; and

a power source, wherein the power source is interconnected with the tuned switch-mode inverter.

109. The apparatus according to claim 108, wherein the load has a load resistance that can range from 0 to 500 ohms.

110. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load decreases as the impedance of the load increases.

111. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load is adjusted as the phase angle of the load changes.

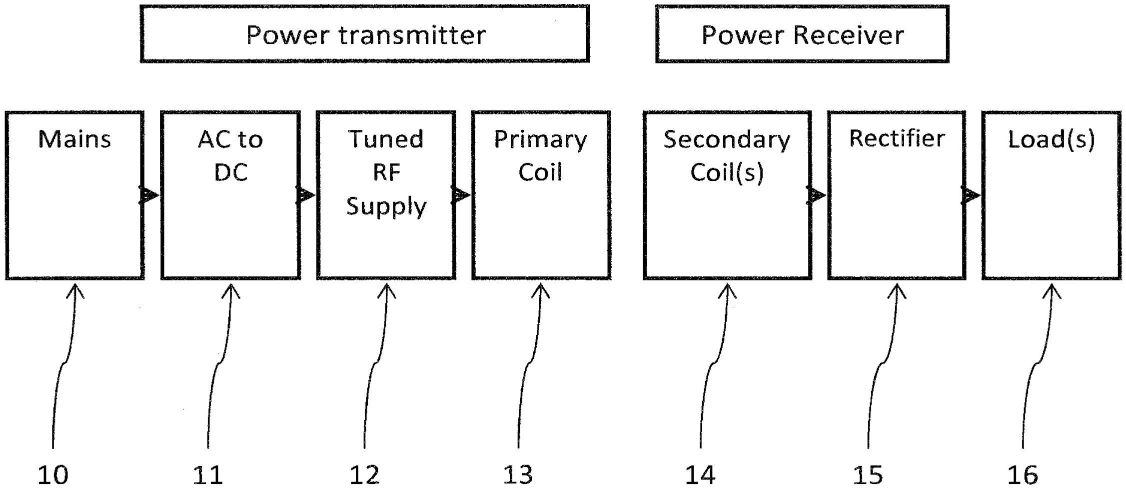

Power transmitter
Power Receiver
Mains
AC to DC
Tuned RF Supply
Primary Coil
Secondary Coil(s)
Rectifier
Load(s)
10
11
12
13
14
15
16

FIG. 1

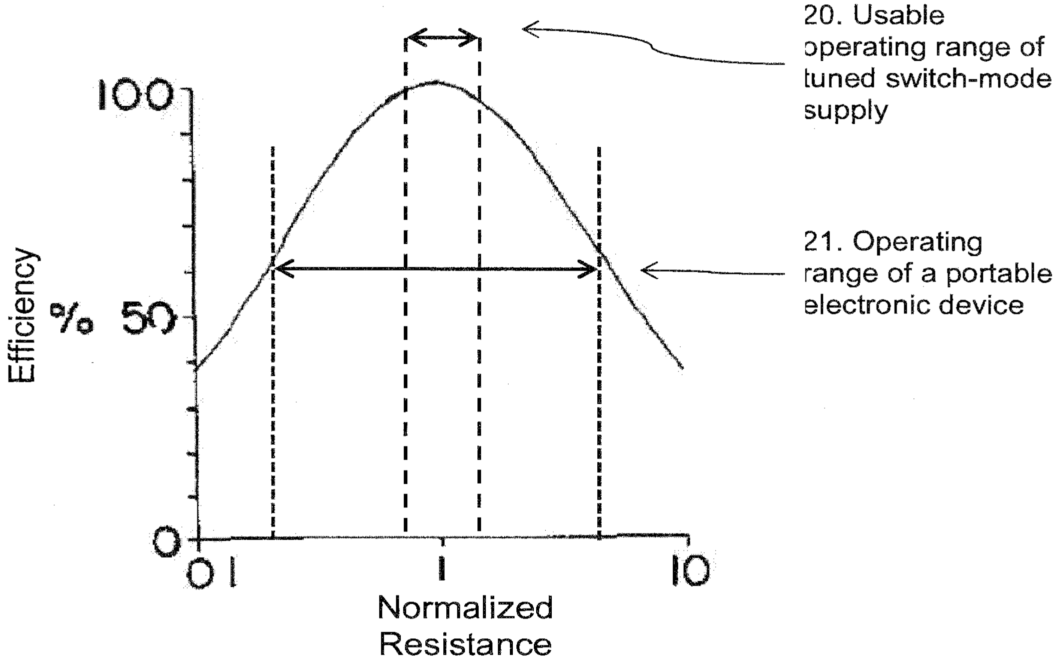

20. Usable operating range of tuned switch-mode supply
21. Operating range of a portable electronic device
100
% 50
0
Efficiency
0.1
1
10
Normalized Resistance

FIG. 2

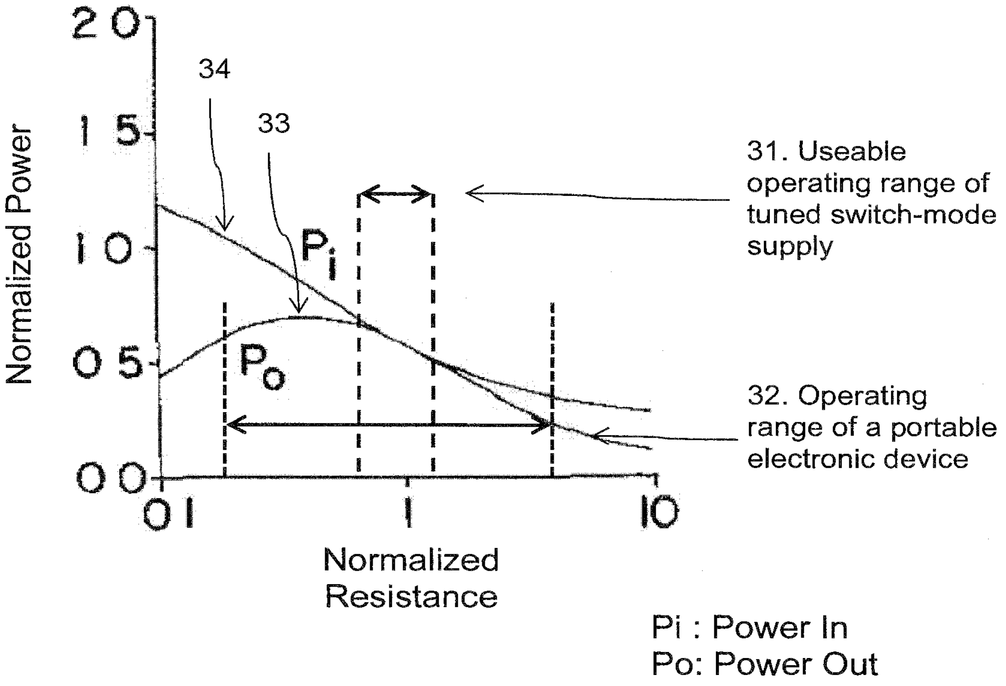

2 0
1 5
1 0
0 5
0 0
Normalized Power
34
33
Pi
Po
31. Useable operating range of tuned switch-mode supply
32. Operating range of a portable electronic device
0 1
1
10
Normalized Resistance
Pi : Power In
Po: Power Out

FIG. 3

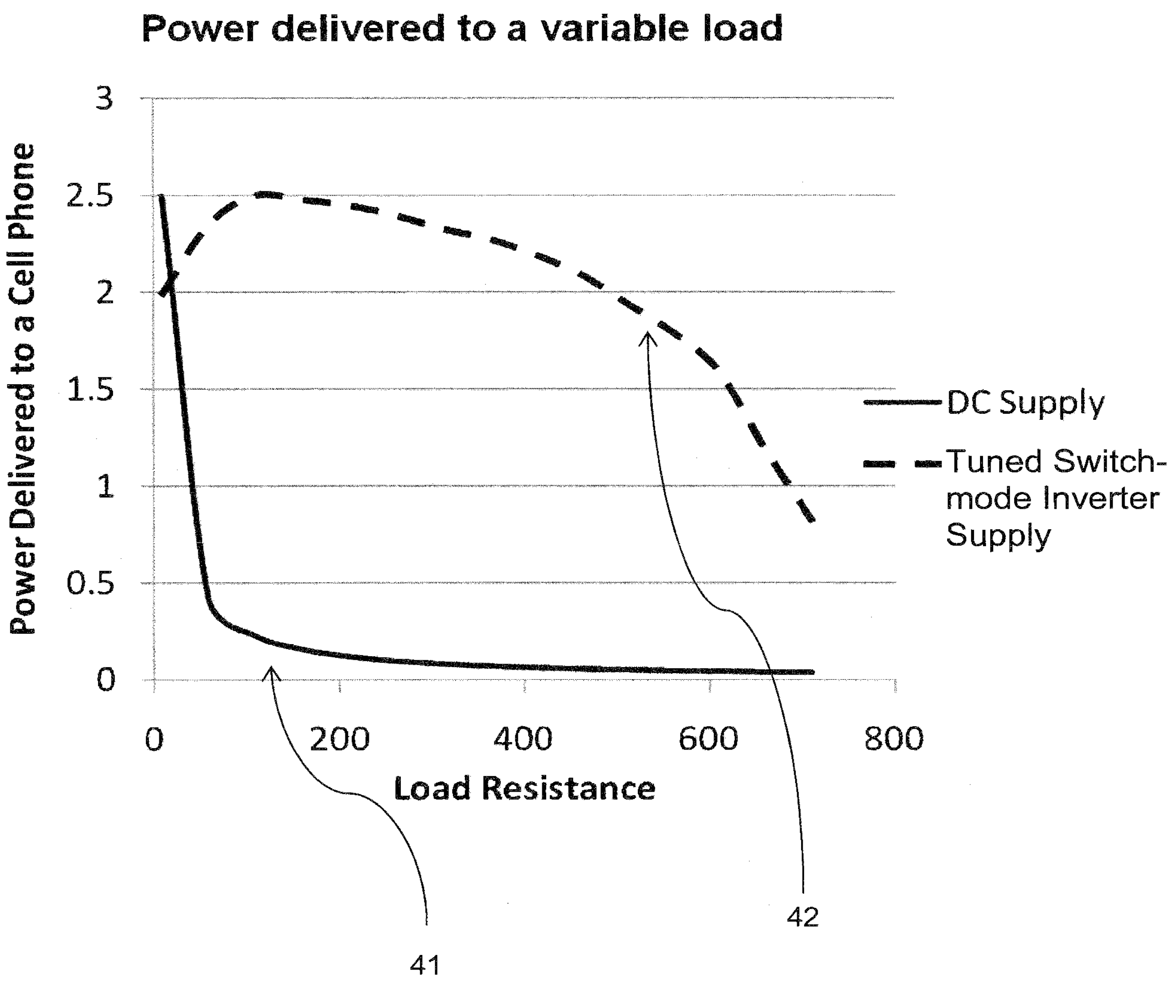

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
41
42

FIG. 4

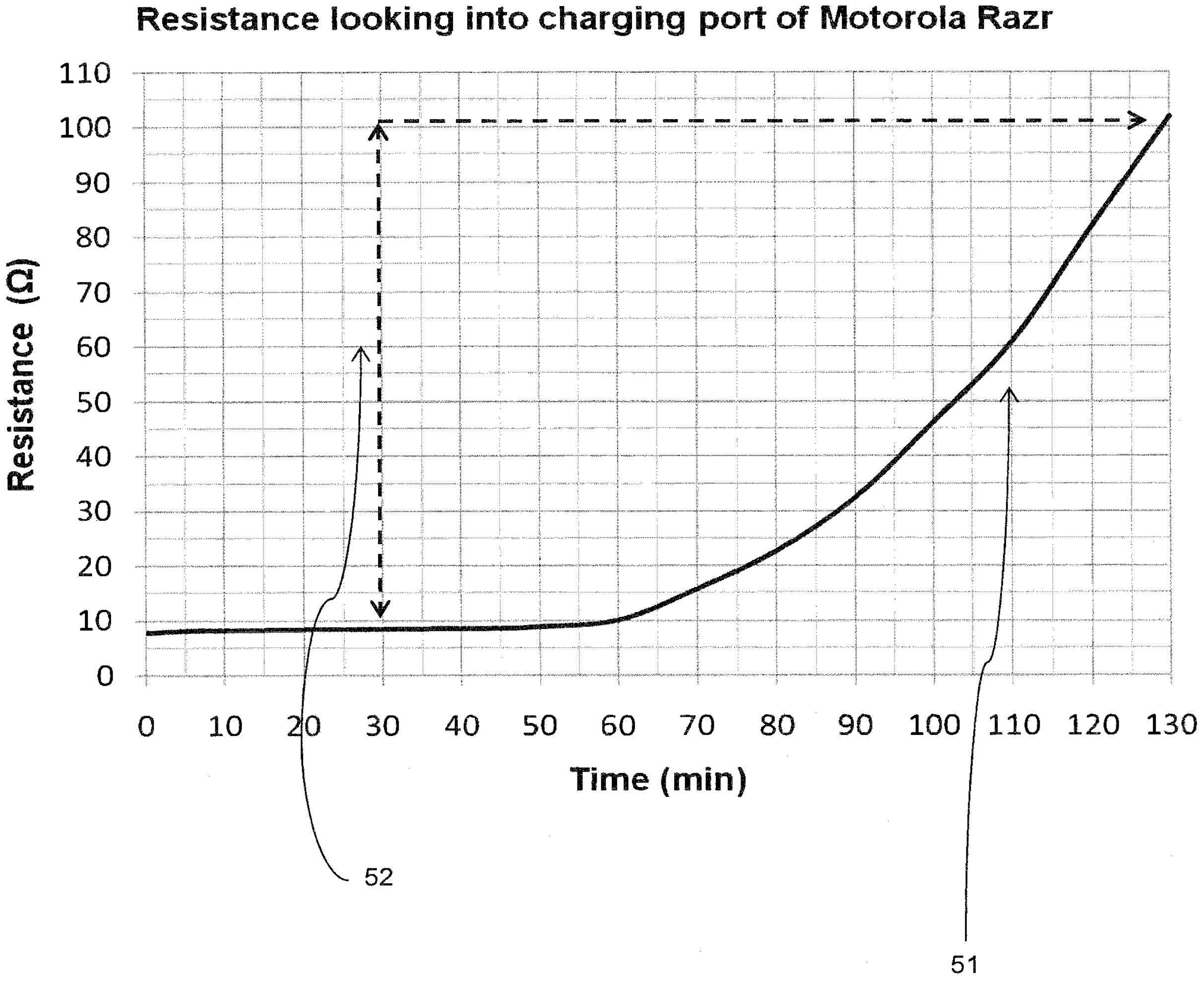

Resistance looking into charging port of Motorola Razr
Resistance (Ω)
0
10
20
30
40
50
60
70
80
90
100
110
Time (min)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
52
51

FIG. 5

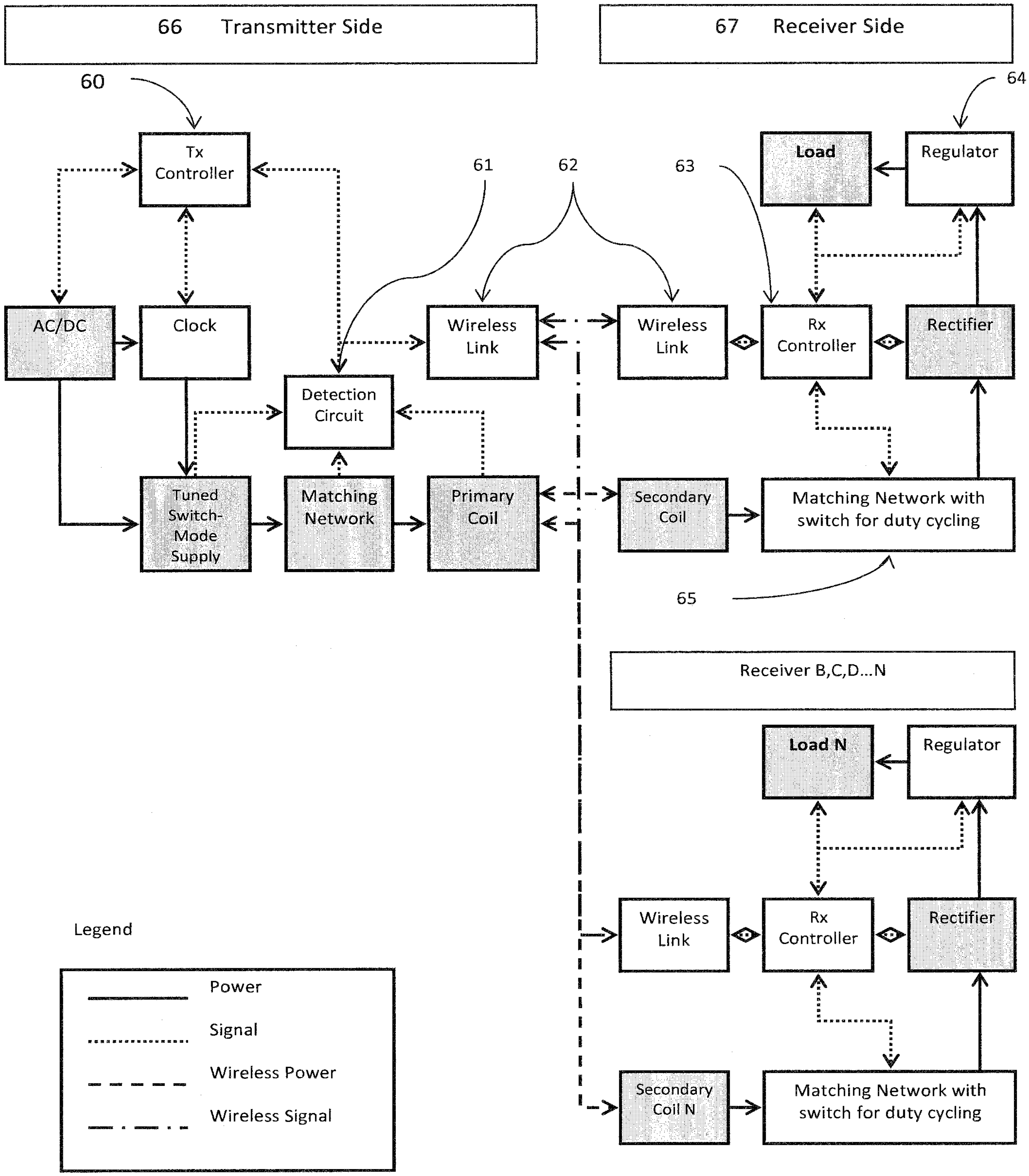
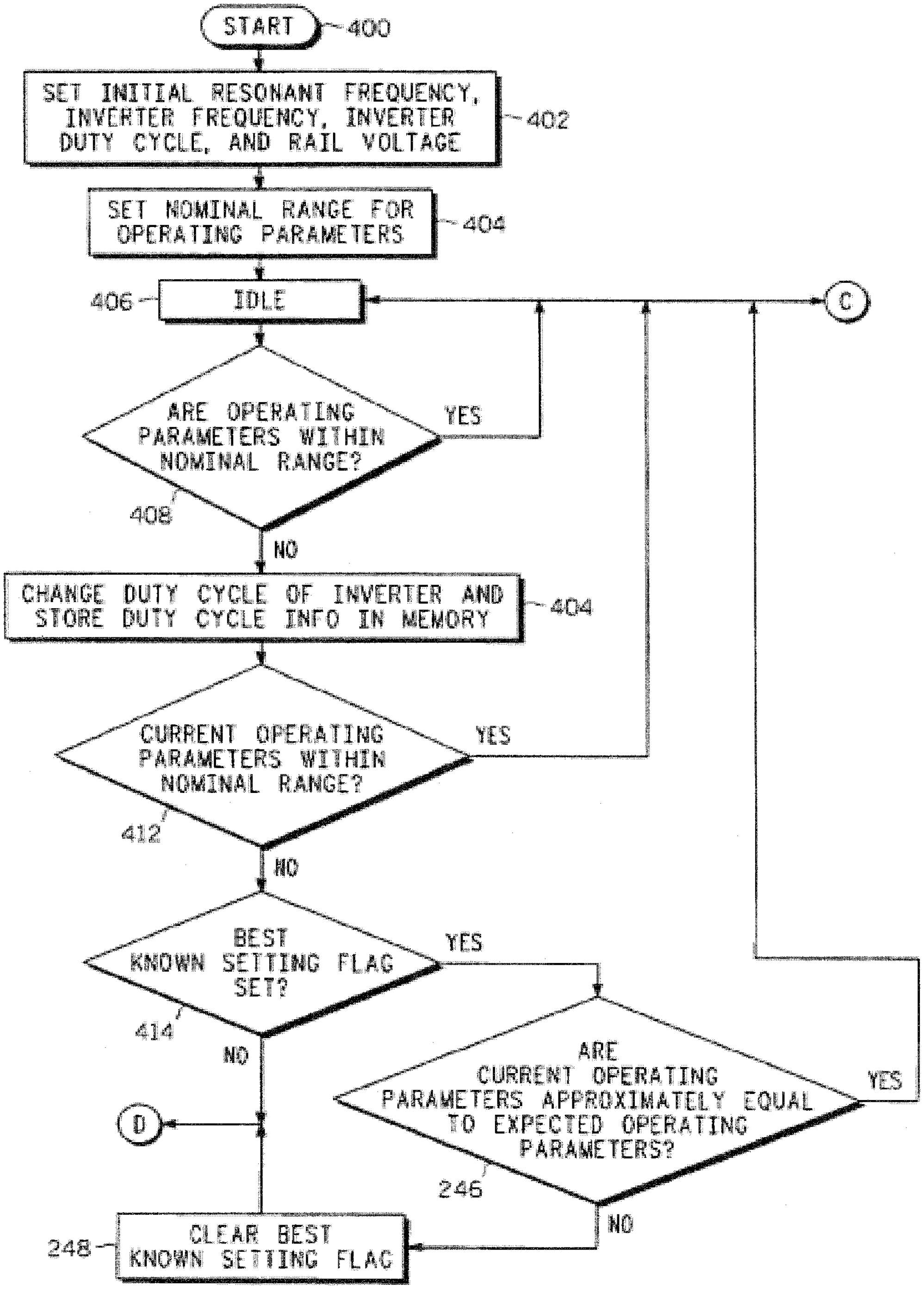
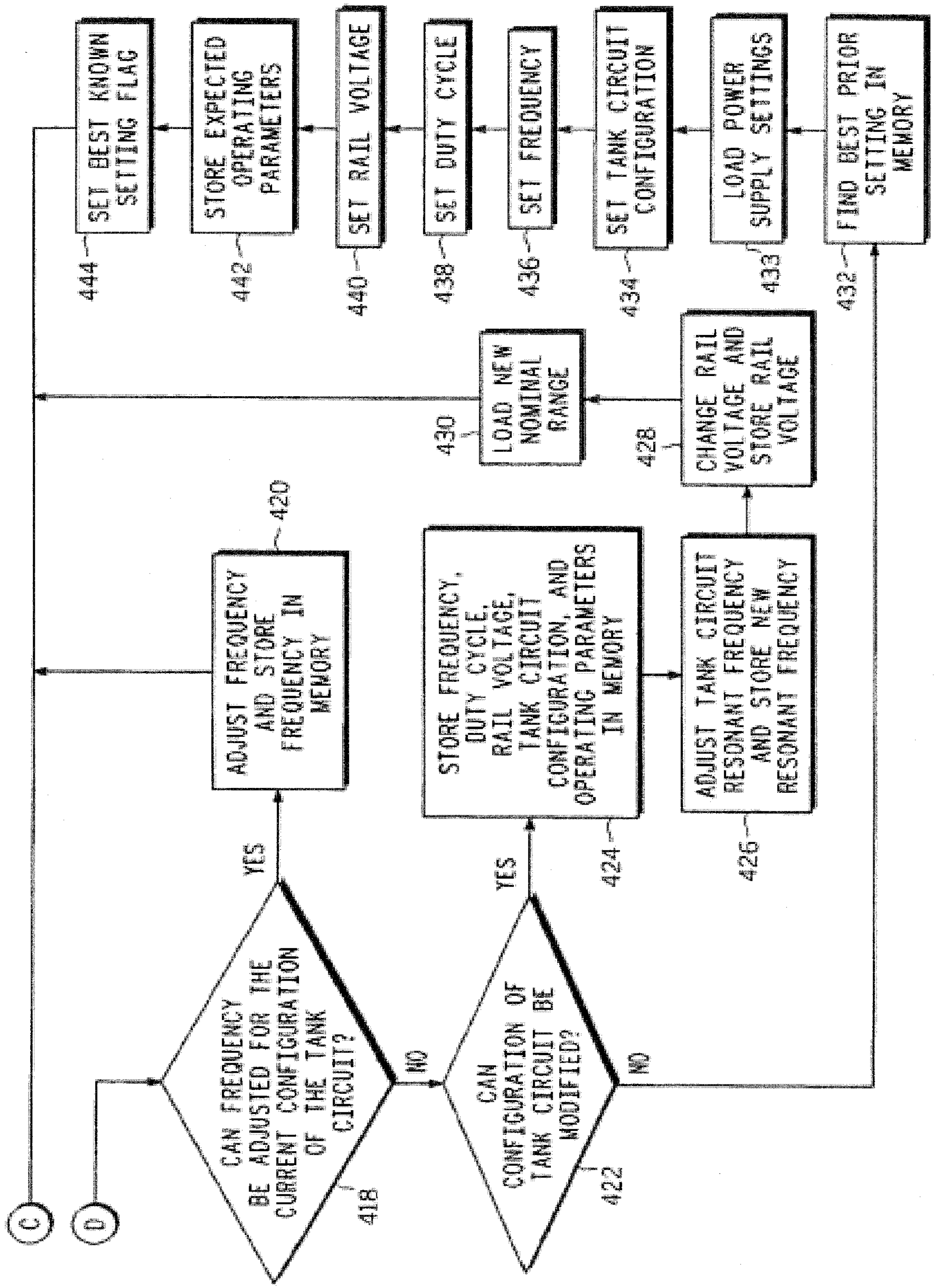

66 Transmitter Side
67 Receiver Side
60
64
Tx Controller
61
62
63
Load
Regulator
AC/DC
Clock
Wireless Link
Wireless Link
Rx Controller
Rectifier
Detection Circuit
Tuned Switch-Mode Supply
Matching Network
Primary Coil
Secondary Coil
Matching Network with switch for duty cycling
65
Receiver B,C,D...N
Load N
Regulator
Wireless Link
Rx Controller
Rectifier
Secondary Coil N
Matching Network with switch for duty cycling
Legend
Power
Signal
Wireless Power
Wireless Signal

FIG. 6



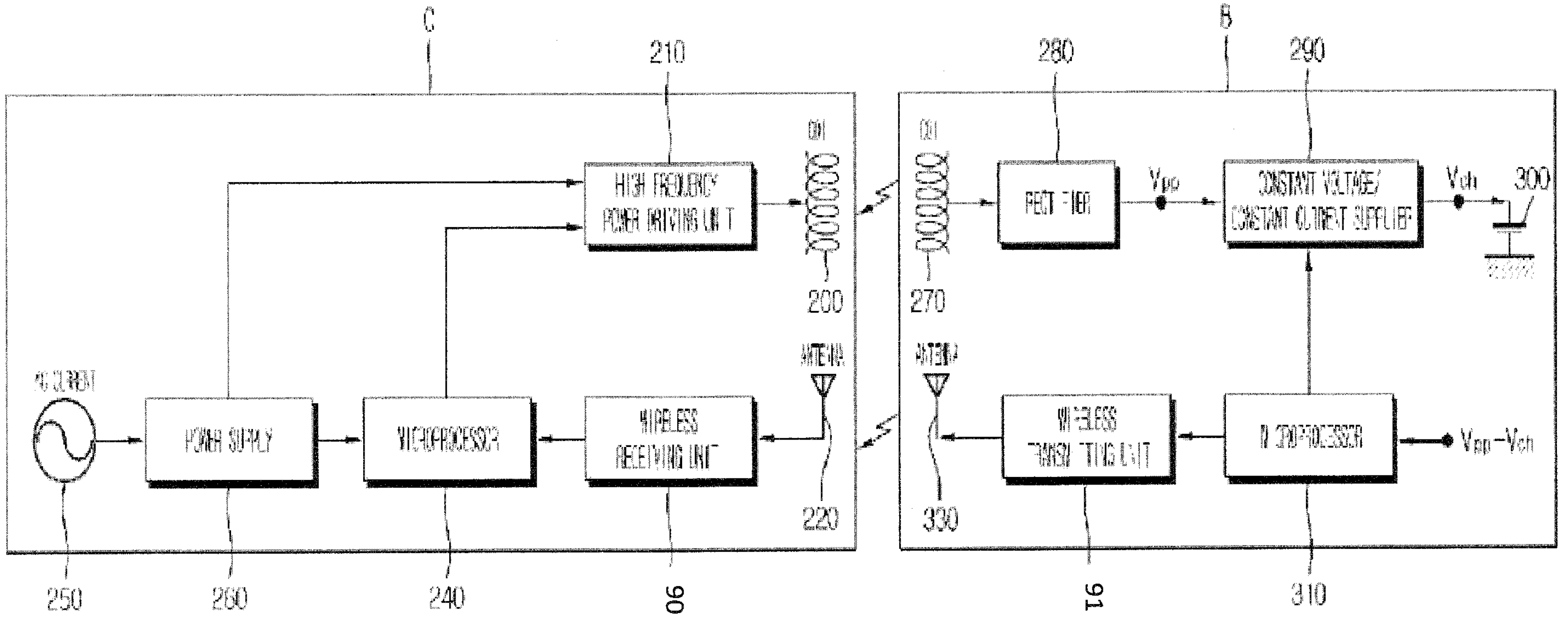
(PRIOR ART)

FIG. 7



(PRIOR ART)

FIG. 8



(PRIOR ART)

FIG. 9

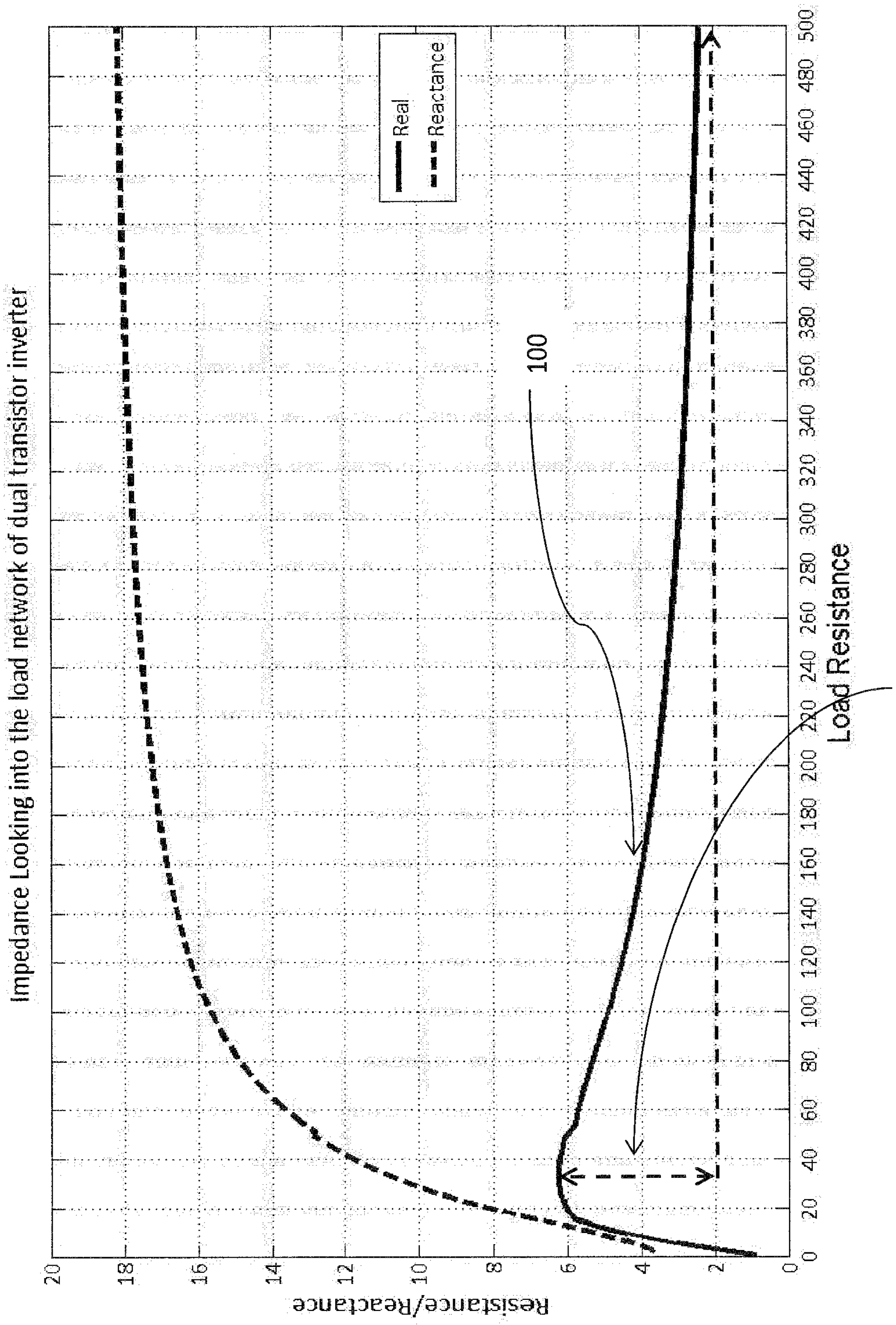
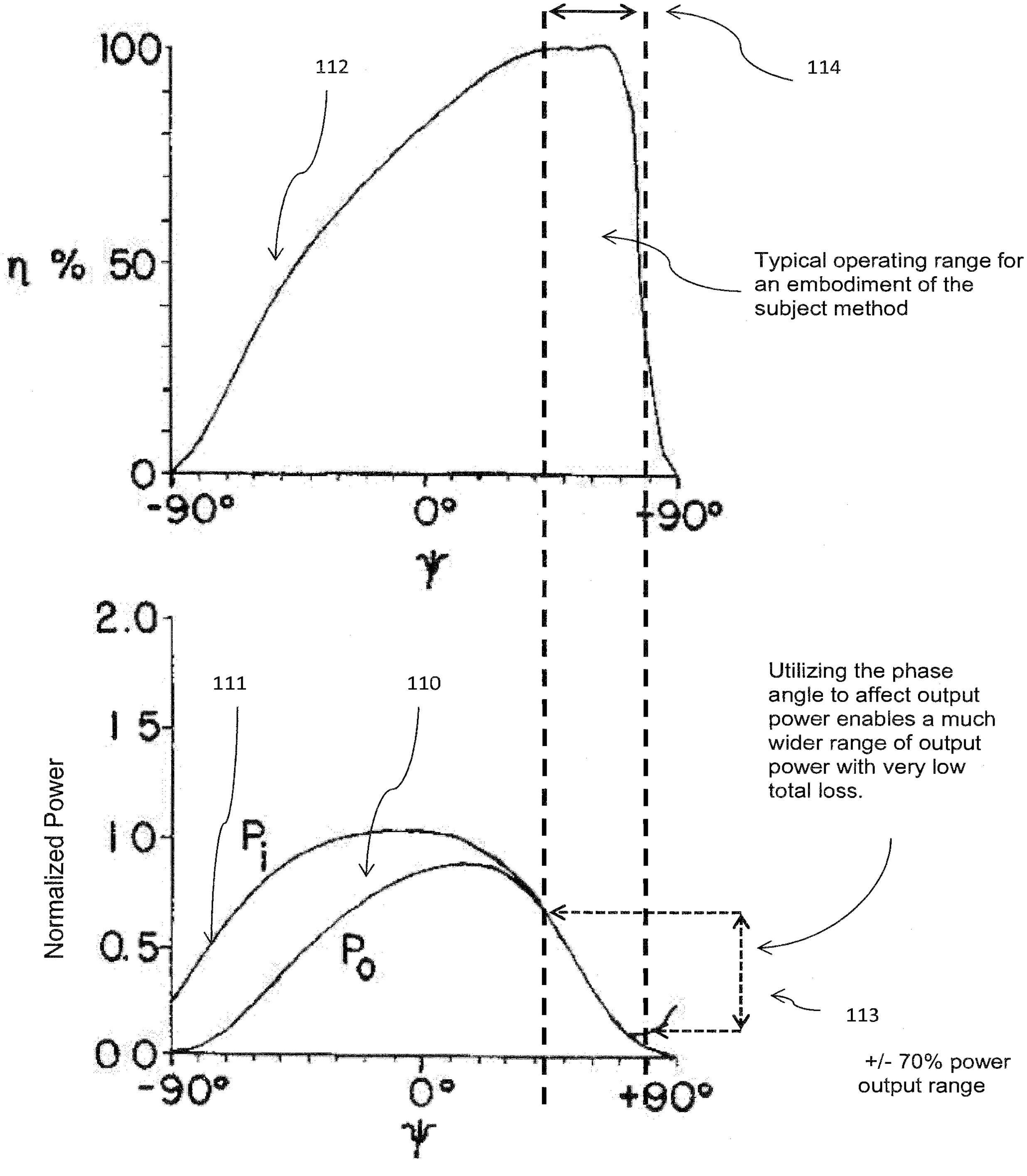

Impedance Looking into the load network of dual transistor inverter
Resistance/Reactance
Load Resistance
Real
Reactance
100
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 10



Typical operating range for an embodiment of the subject method

Utilizing the phase angle to affect output power enables a much wider range of output power with very low total loss.

+/- 70% power output range

FIG. 11

127 Resistance controlled power delivery

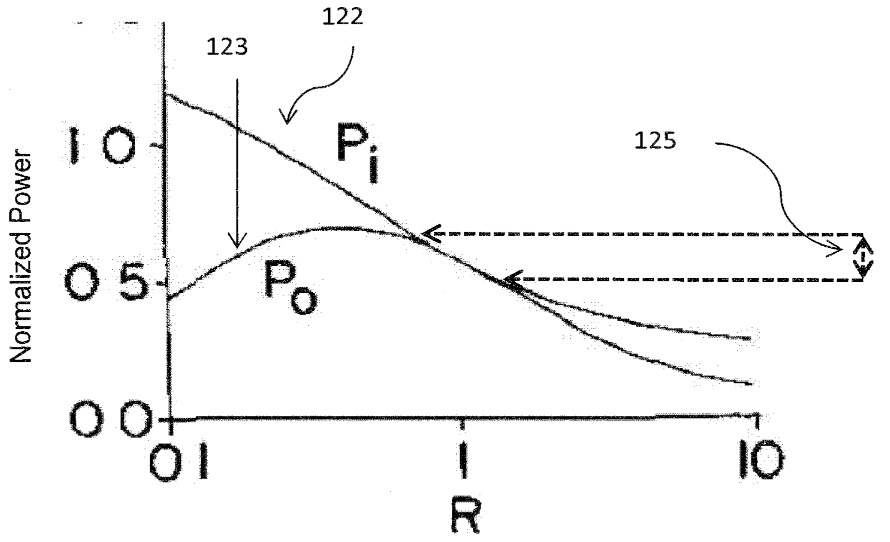


FIG. 12A

126 Phase controlled power delivery

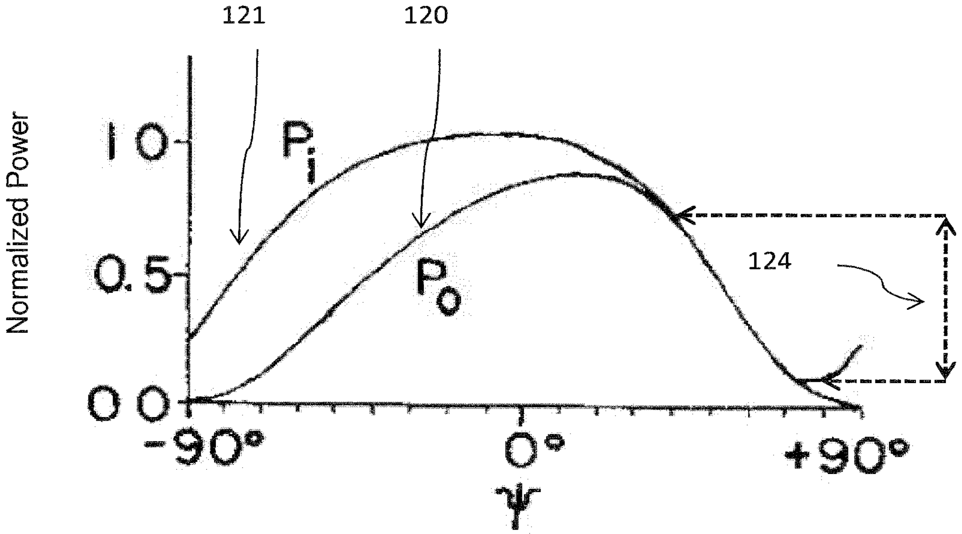


FIG. 12B

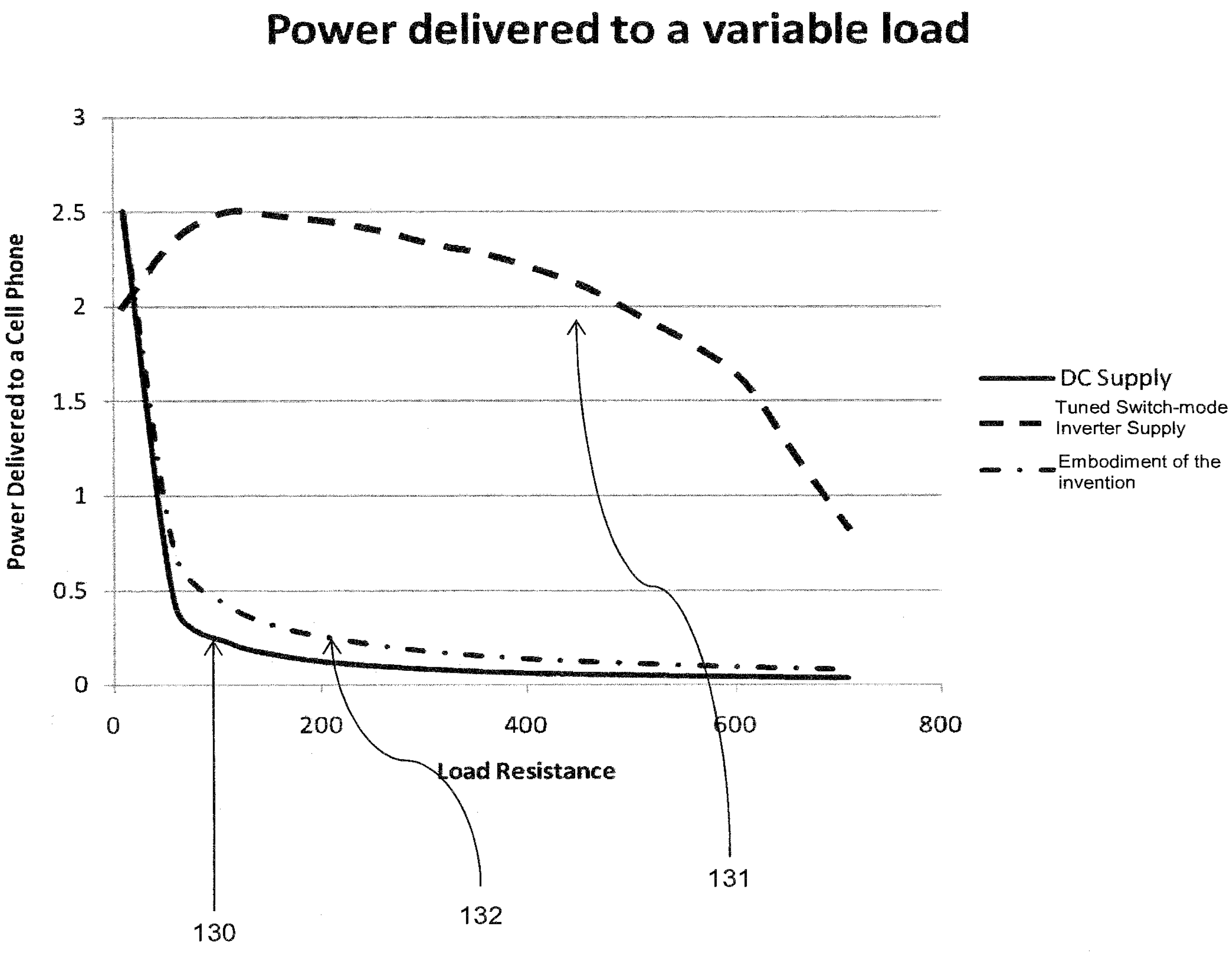

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
Embodiment of the invention
130
132
131

FIG. 13

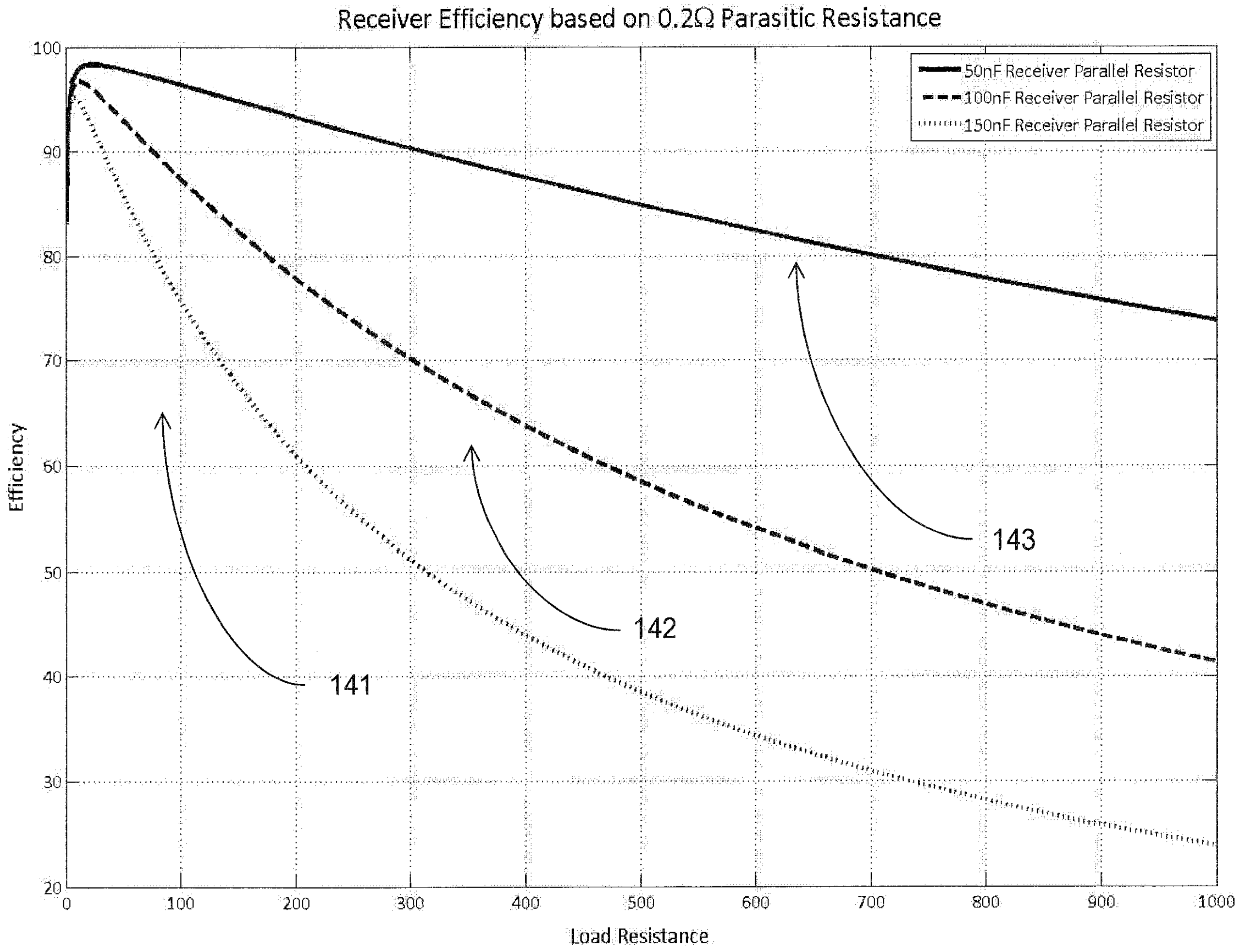

Receiver Efficiency based on 0.2Ω Parasitic Resistance
50nF Receiver Parallel Resistor
100nF Receiver Parallel Resistor
150nF Receiver Parallel Resistor
Efficiency
100
90
80
70
60
50
40
30
20
0
100
200
300
400
500
600
700
800
900
1000
Load Resistance
141
142
143

FIG. 14

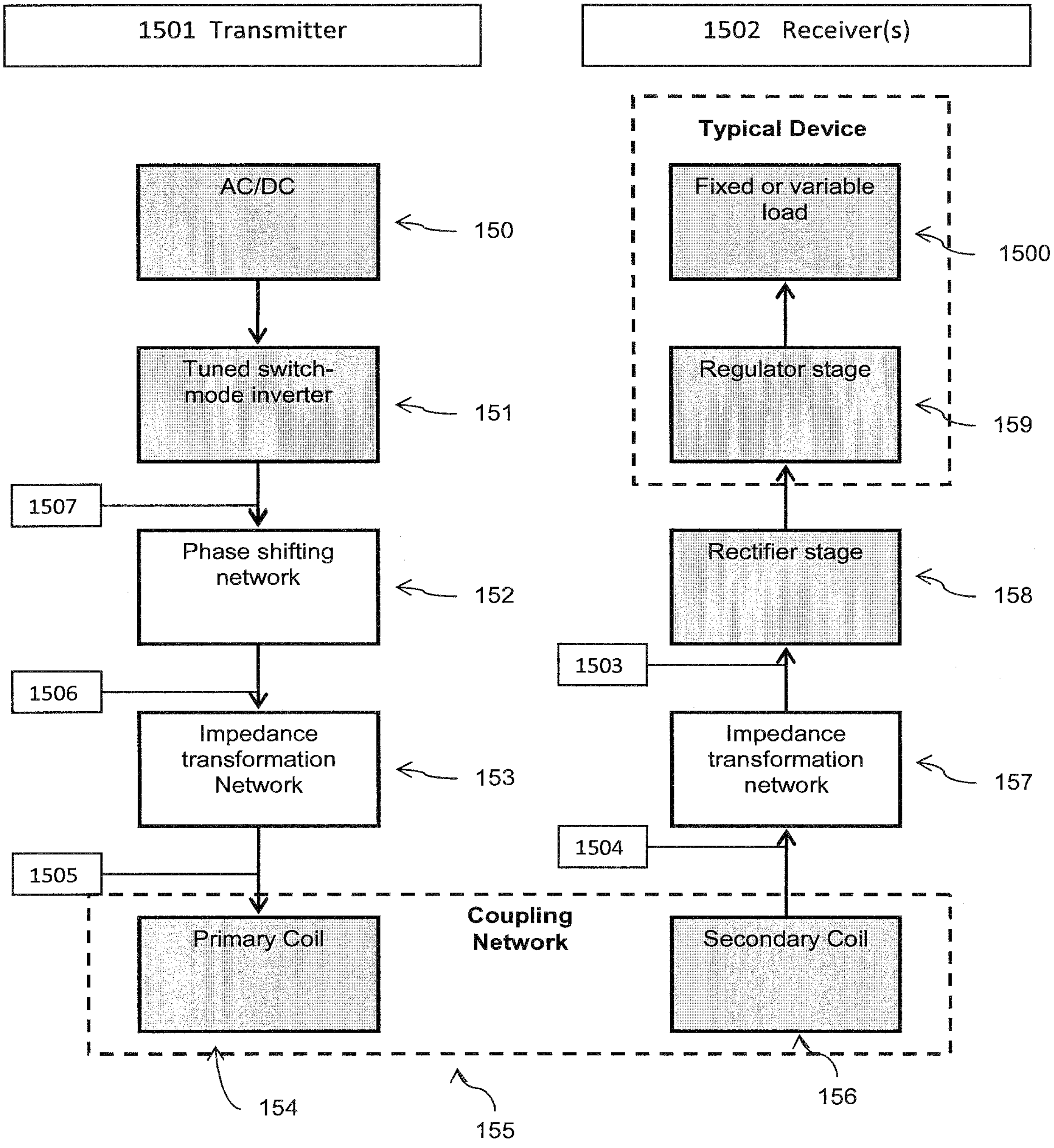

1501 Transmitter
1502 Receiver(s)
Typical Device
AC/DC
150
Fixed or variable load
1500
Tuned switch-mode inverter
151
Regulator stage
159
1507
Phase shifting network
152
Rectifier stage
158
1503
1506
Impedance transformation Network
153
Impedance transformation network
157
1504
1505
Coupling Network
Primary Coil
Secondary Coil
154
155
156

FIG. 15

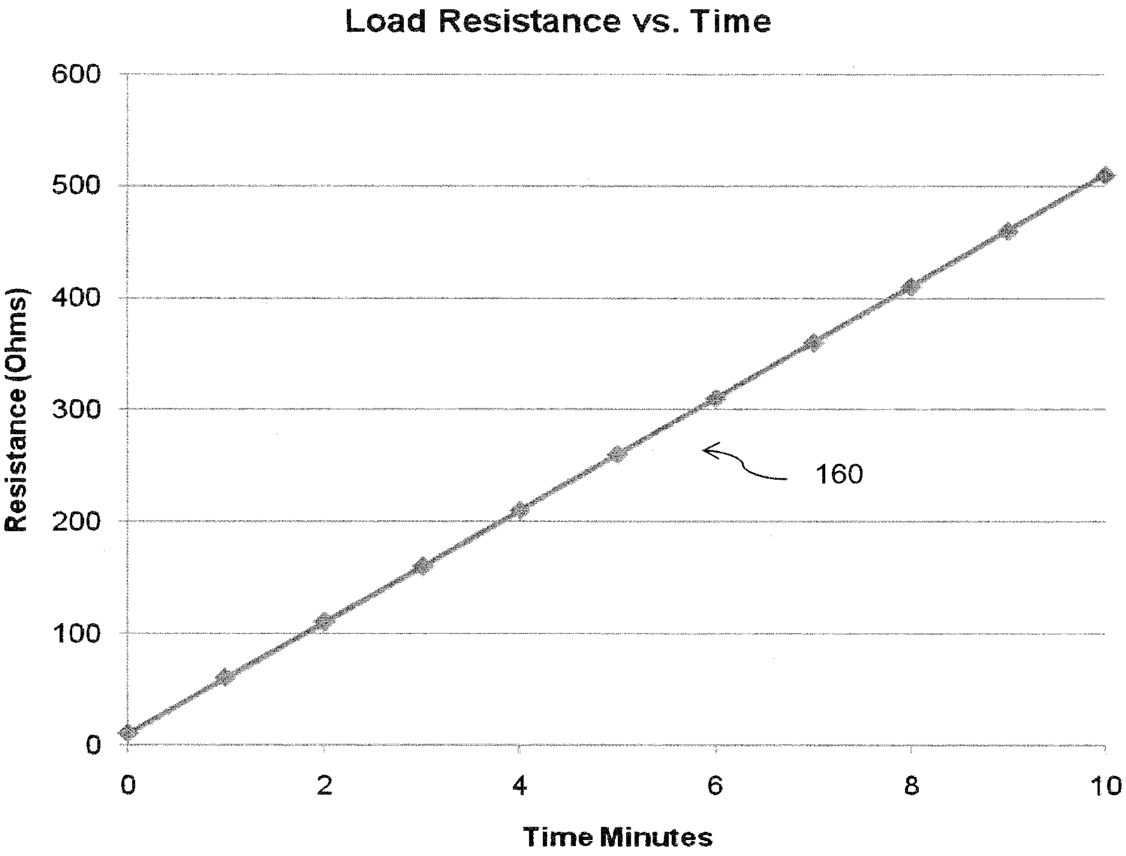

Load Resistance vs. Time
Resistance (Ohms)
600
500
400
300
200
100
0
0
2
4
6
8
10
Time Minutes
160

FIG. 16

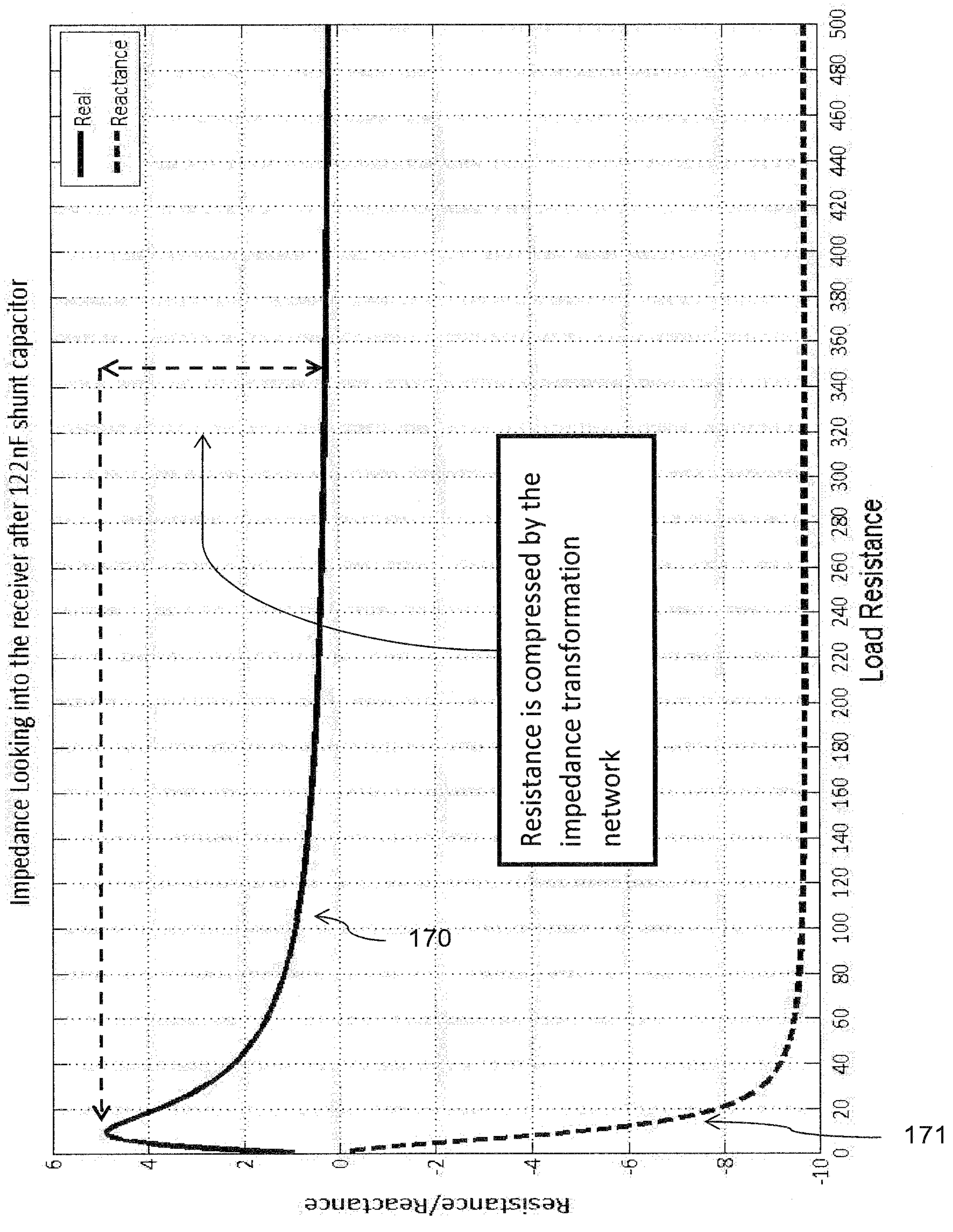

Impedance Looking into the receiver after 122nF shunt capacitor
Real
Reactance
Resistance is compressed by the impedance transformation network
170
171
Resistance/Reactance
6
4
2
0
-2
-4
-6
-8
-10
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 17

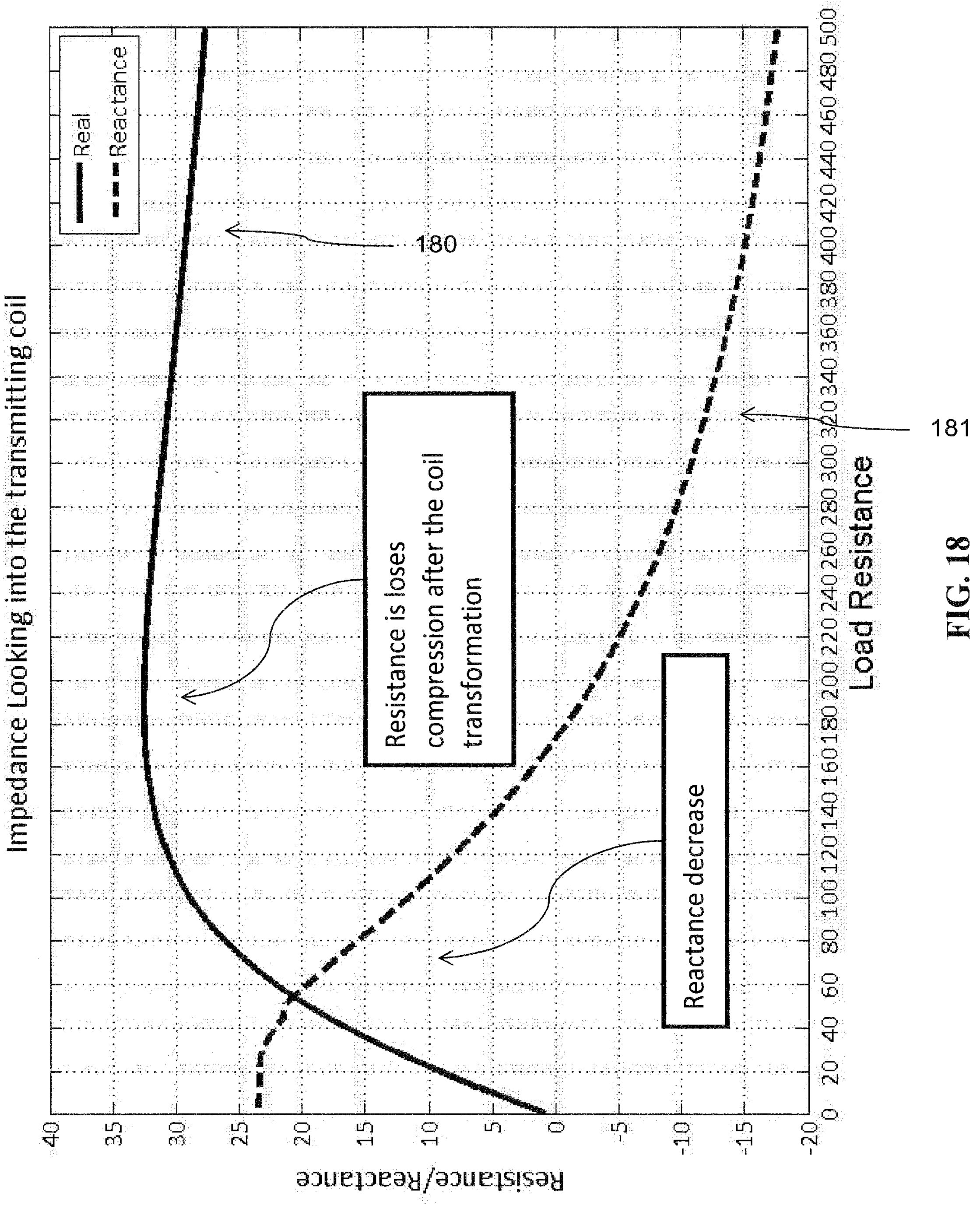

Impedance Looking into the transmitting coil
Real
Reactance
180
181
Resistance is loses compression after the coil transformation
Reactance decrease
Resistance/Reactance
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 18

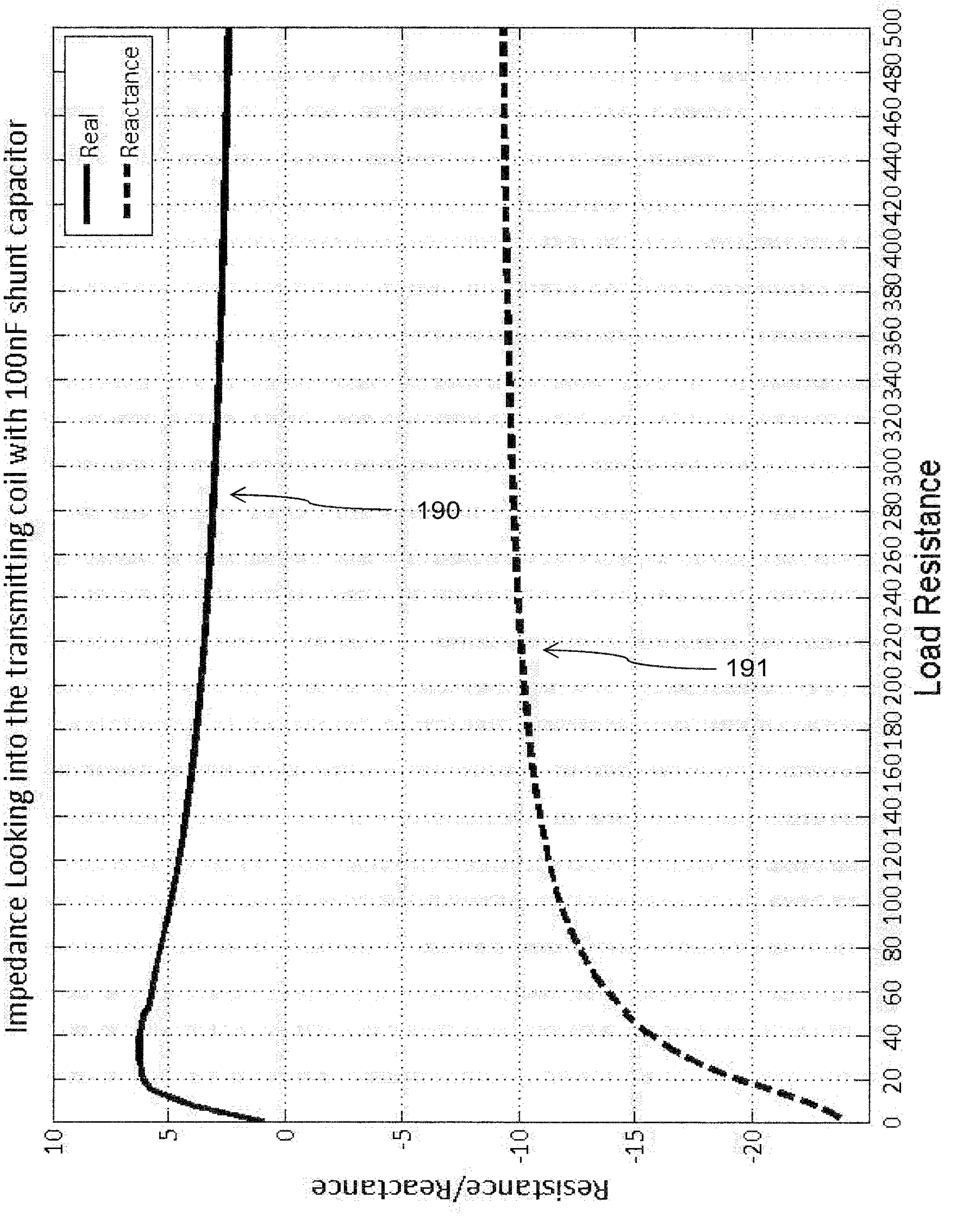

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
10
5
0
-5
-10
-15
-20
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
190
191

FIG. 19

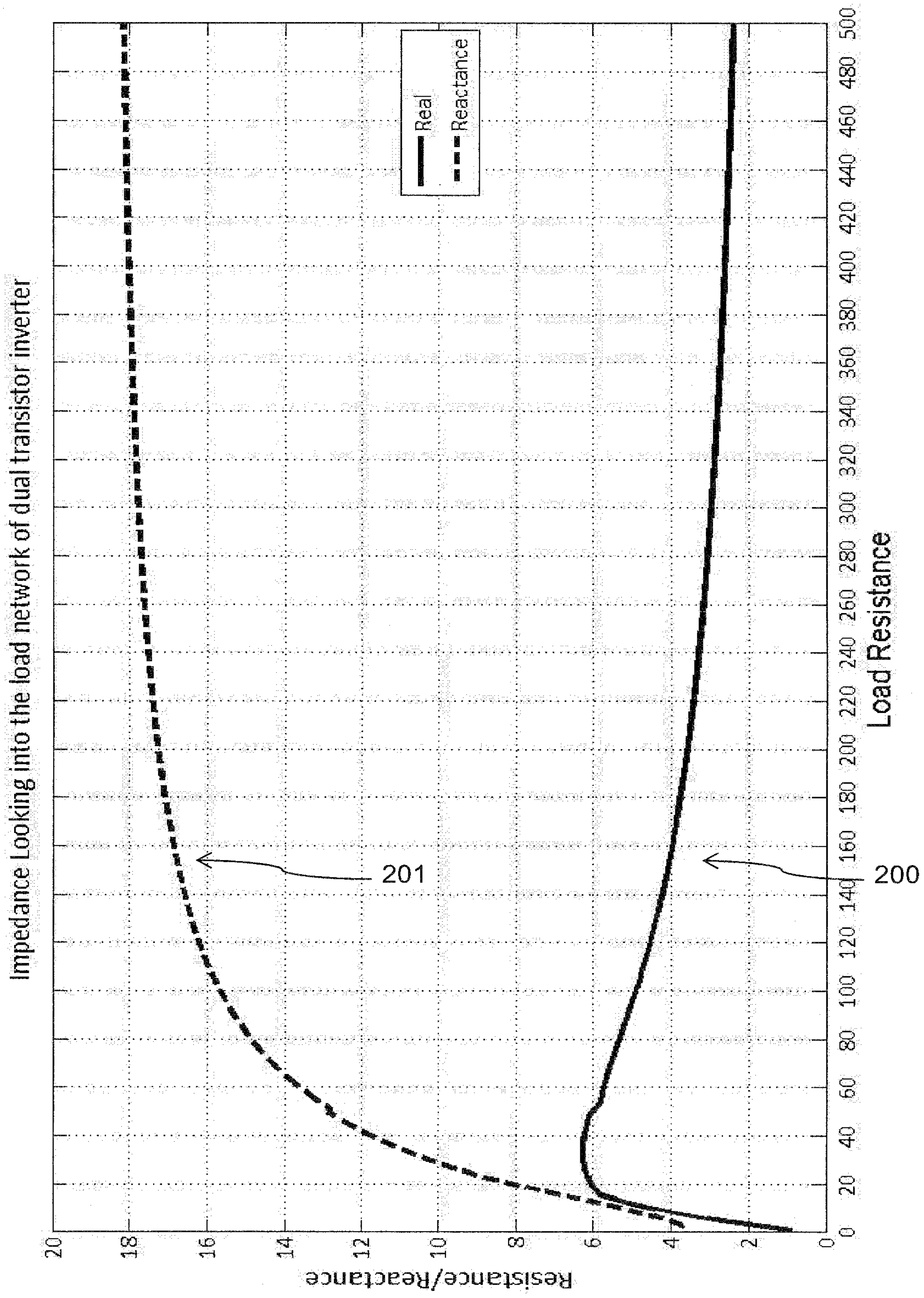

Impedance Looking into the load network of dual transistor inverter
Resistance/Reactance
20
18
16
14
12
10
8
6
4
2
0
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
Real
Reactance
201
200

FIG. 20

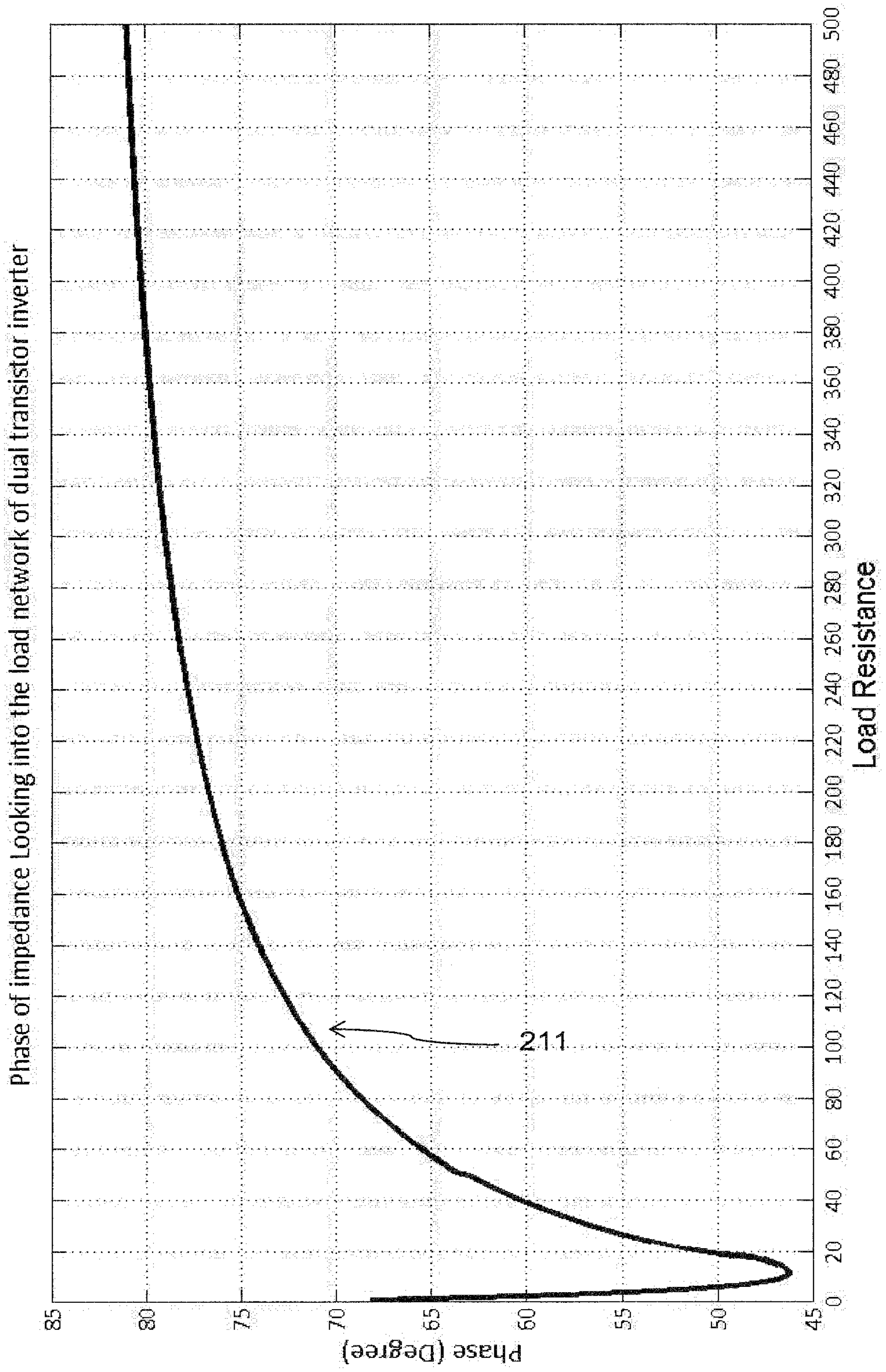

Phase of impedance Looking into the load network of dual transistor inverter
Phase (Degree)
85
80
75
70
65
60
55
50
45
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
211

FIG. 21

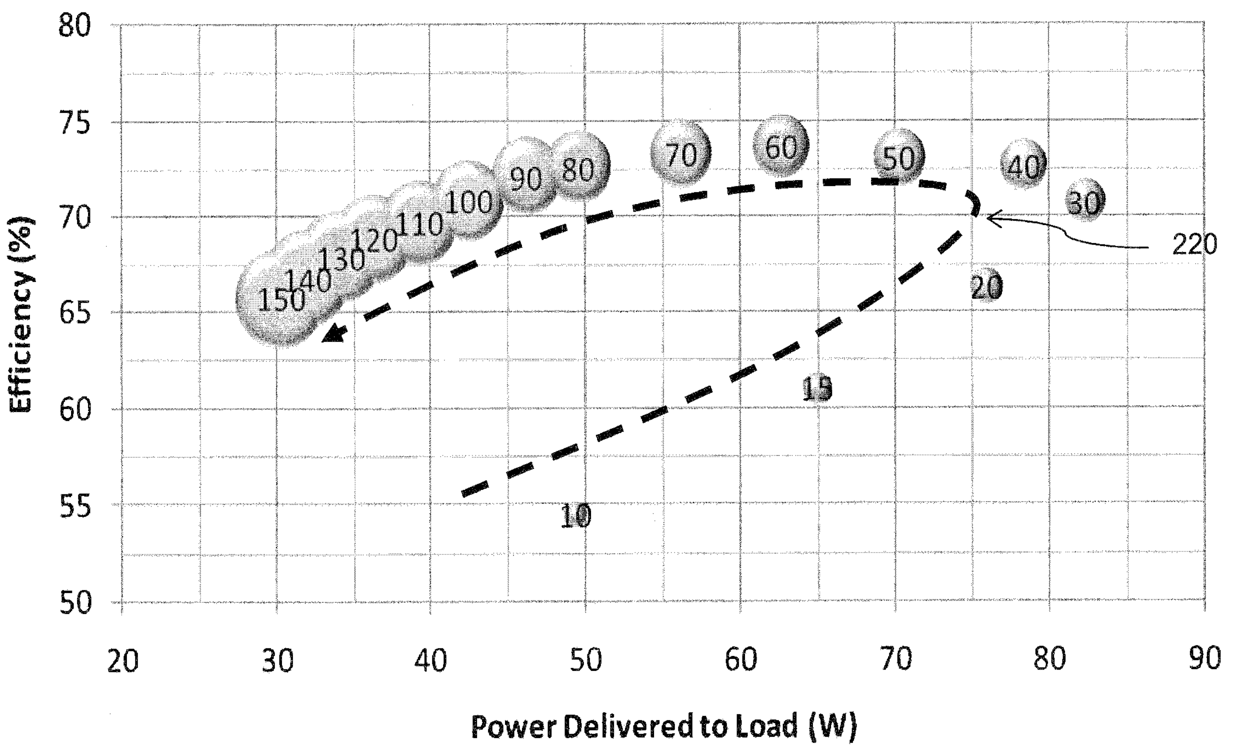

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
20
30
40
50
60
70
80
90
150
140
130
120
110
100
90
80
70
60
50
40
30
20
15
10
220

FIG. 22

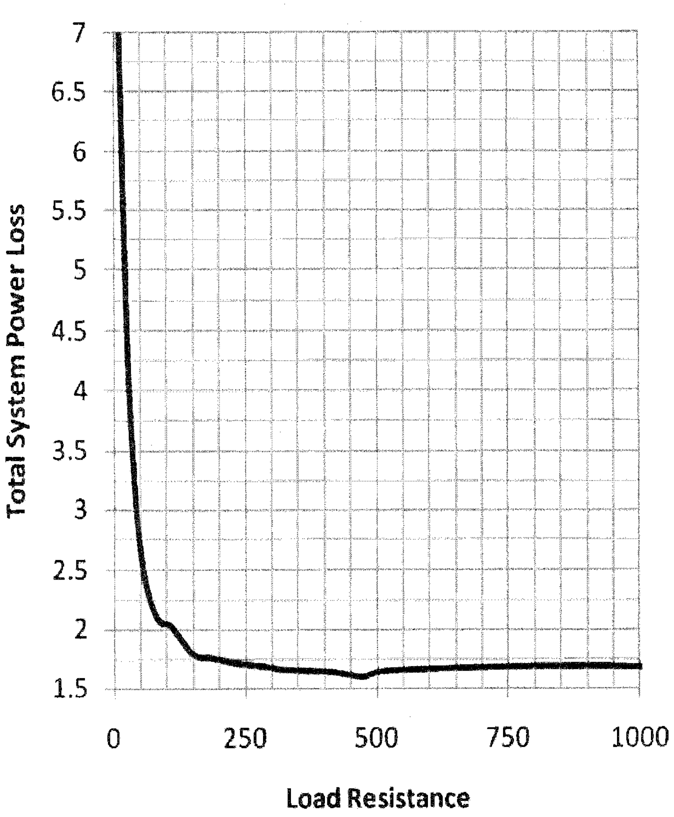


FIG. 23A

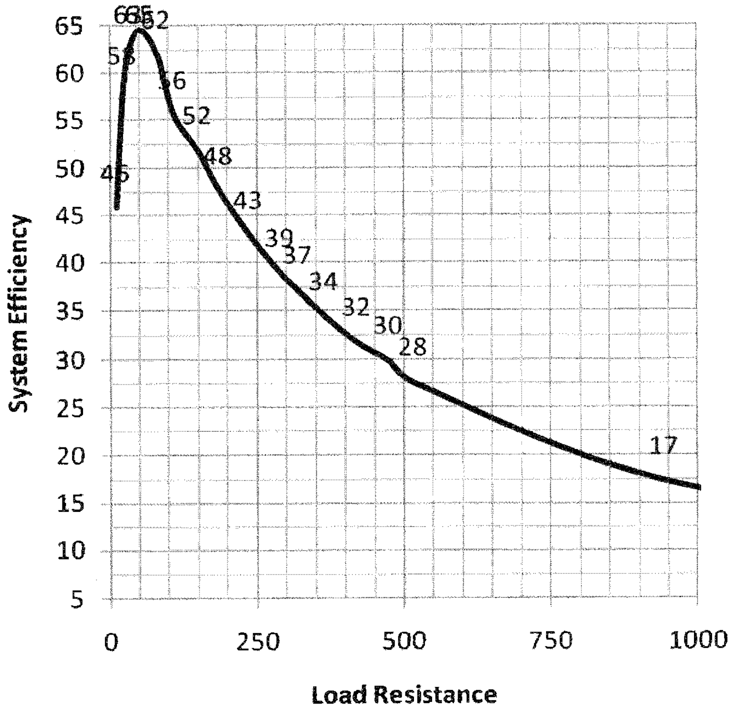


FIG. 23B

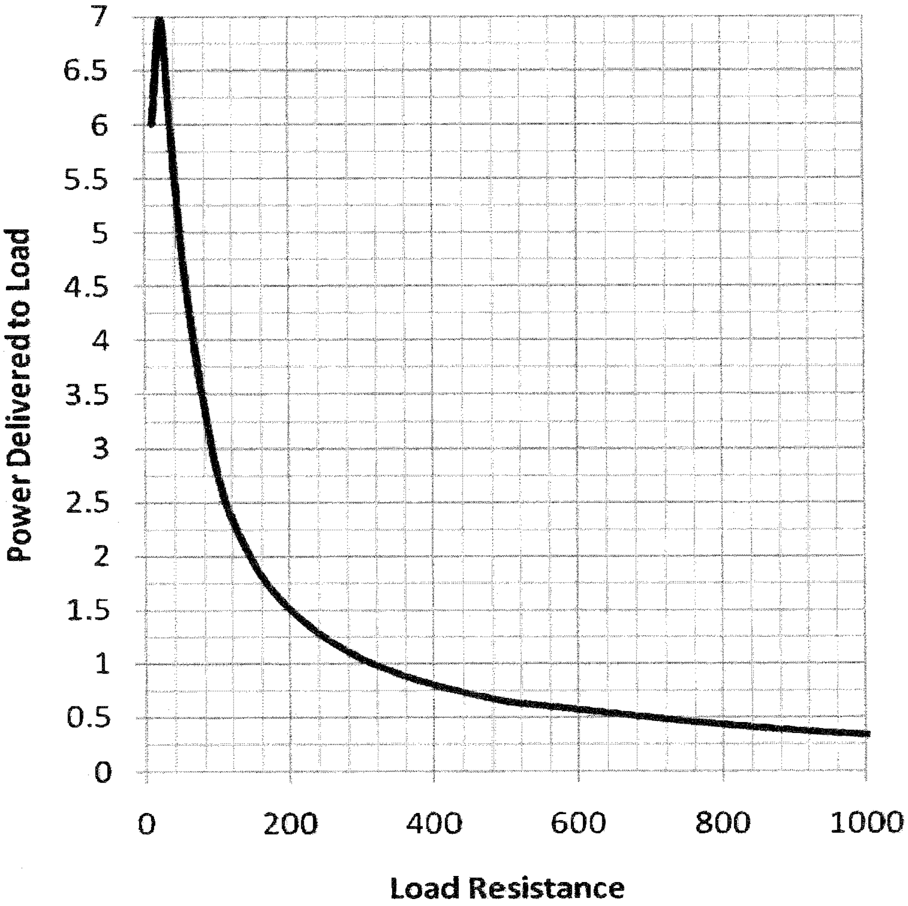

Power Delivered to Load
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
Load Resistance

FIG. 23C

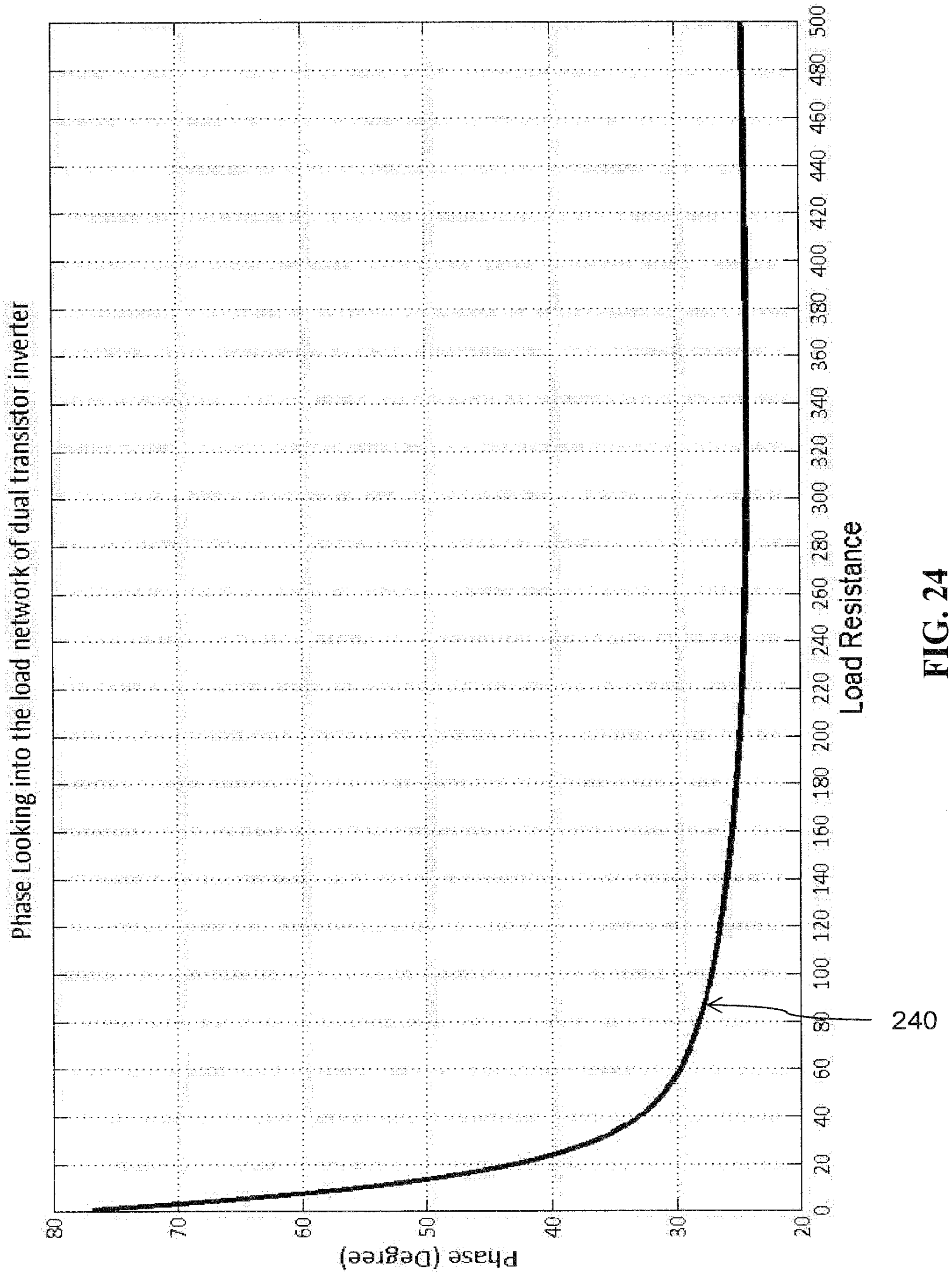

Phase Looking into the load network of dual transistor inverter
Phase (Degree)
80
70
60
50
40
30
20
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
240

FIG. 24

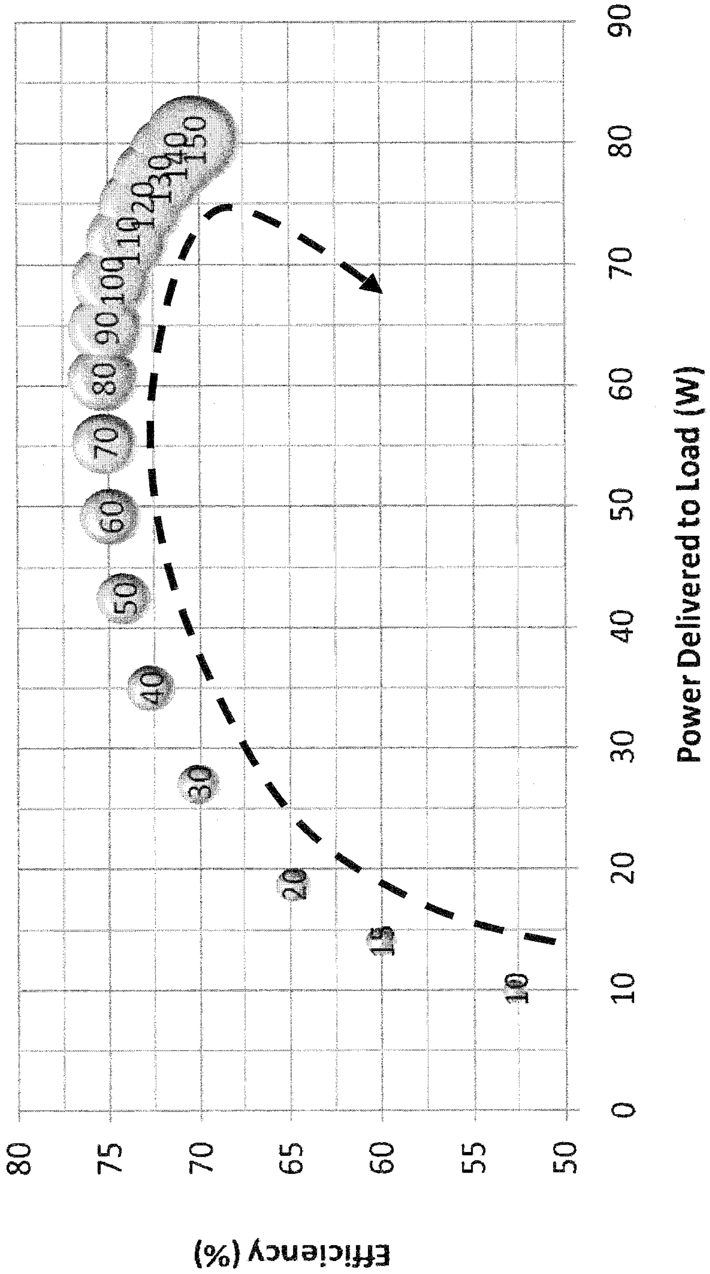

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
0
10
20
30
40
50
60
70
80
90
10
15
20
30
40
50
60
70
80
90
100
110
120
130
140
150

FIG. 25

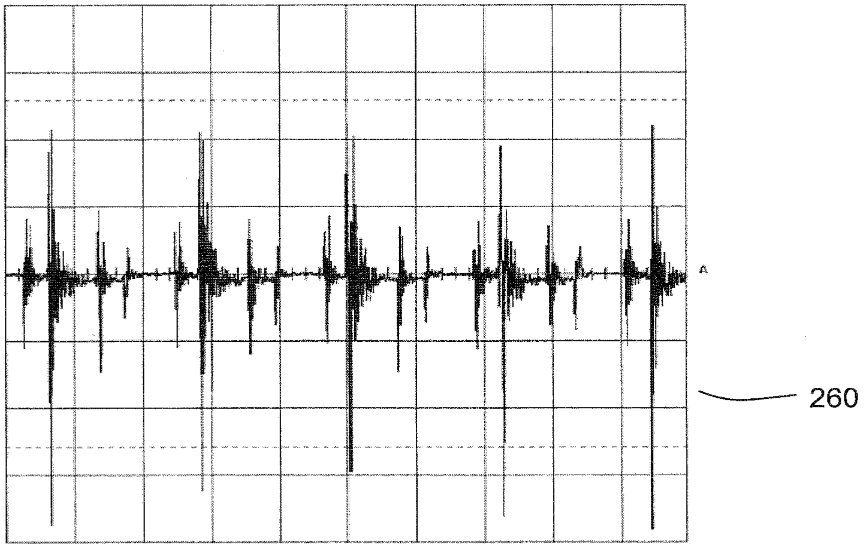


FIG. 26A

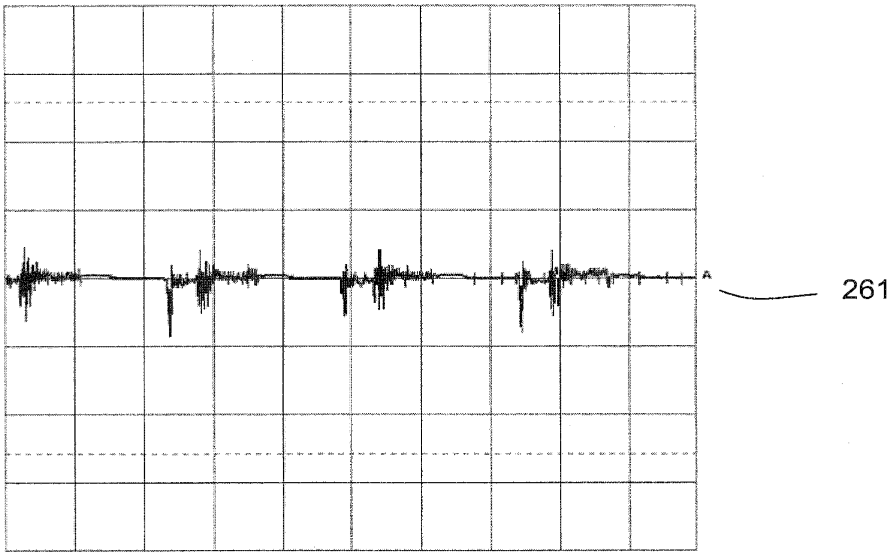


FIG. 26B

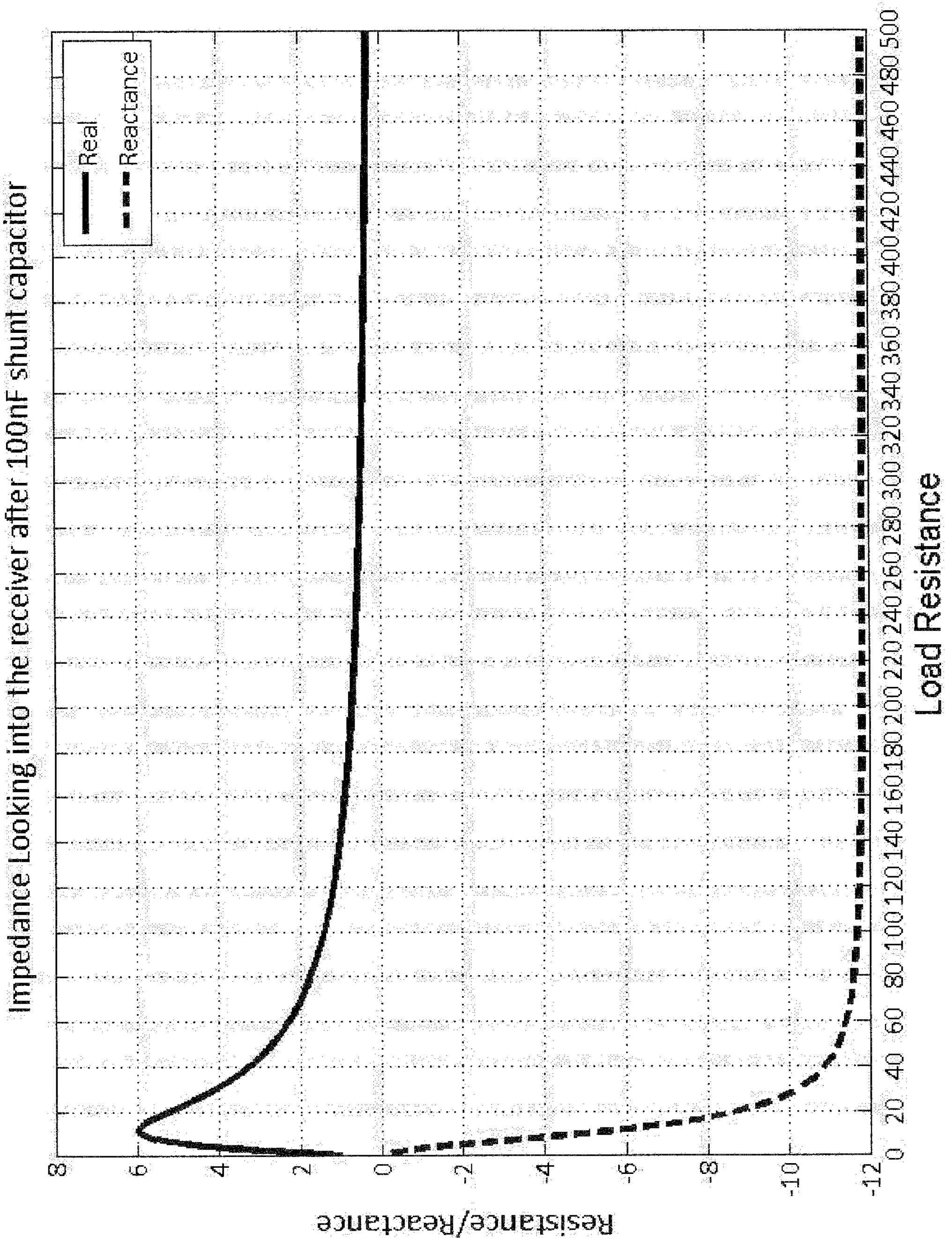

Impedance Looking into the receiver after 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
8
6
4
2
0
-2
-4
-6
-8
-10
-12
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 27

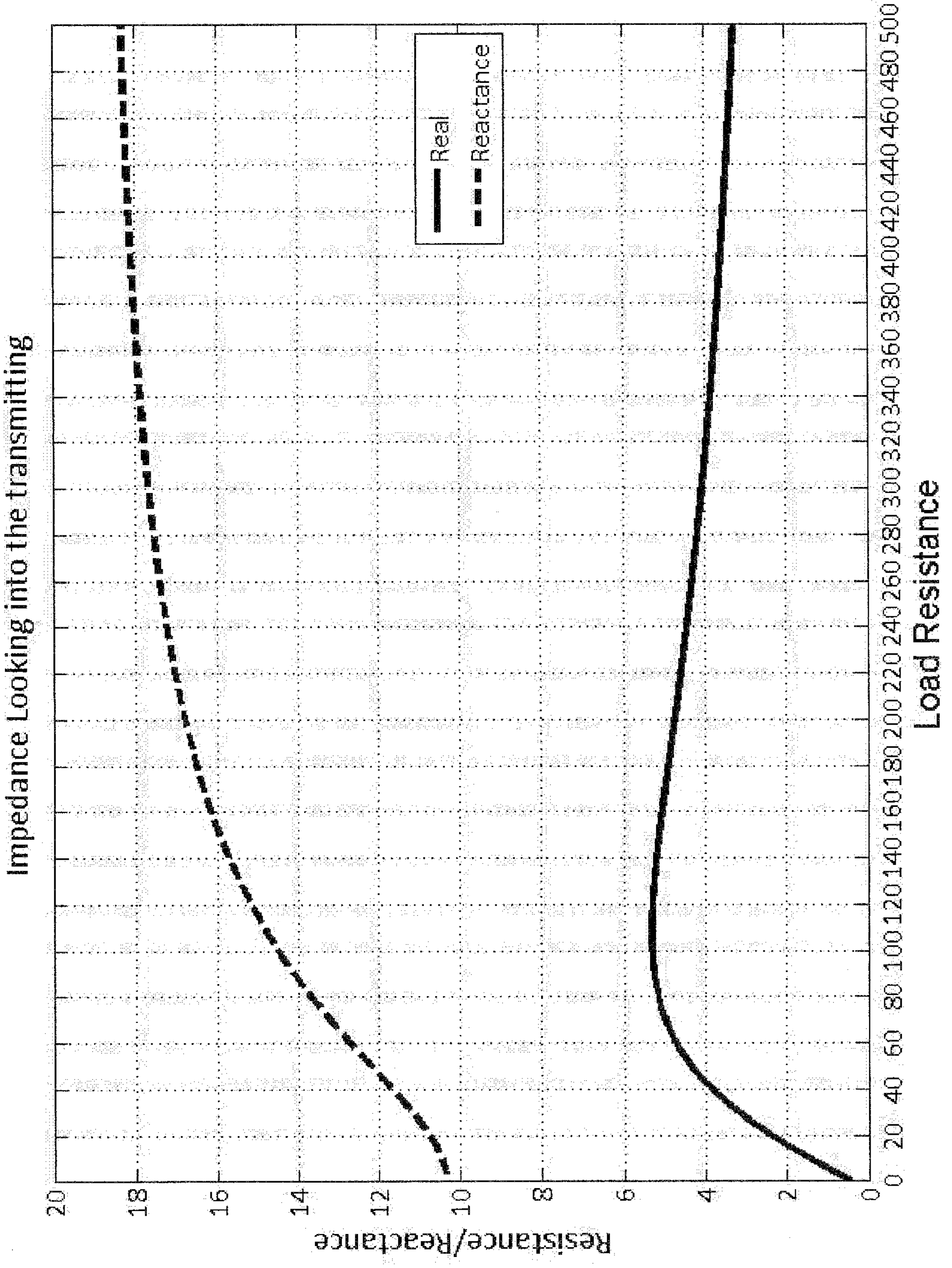

Impedance Looking into the transmitting
Resistance/Reactance
20
18
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
Load Resistance
Real
Reactance

FIG. 28

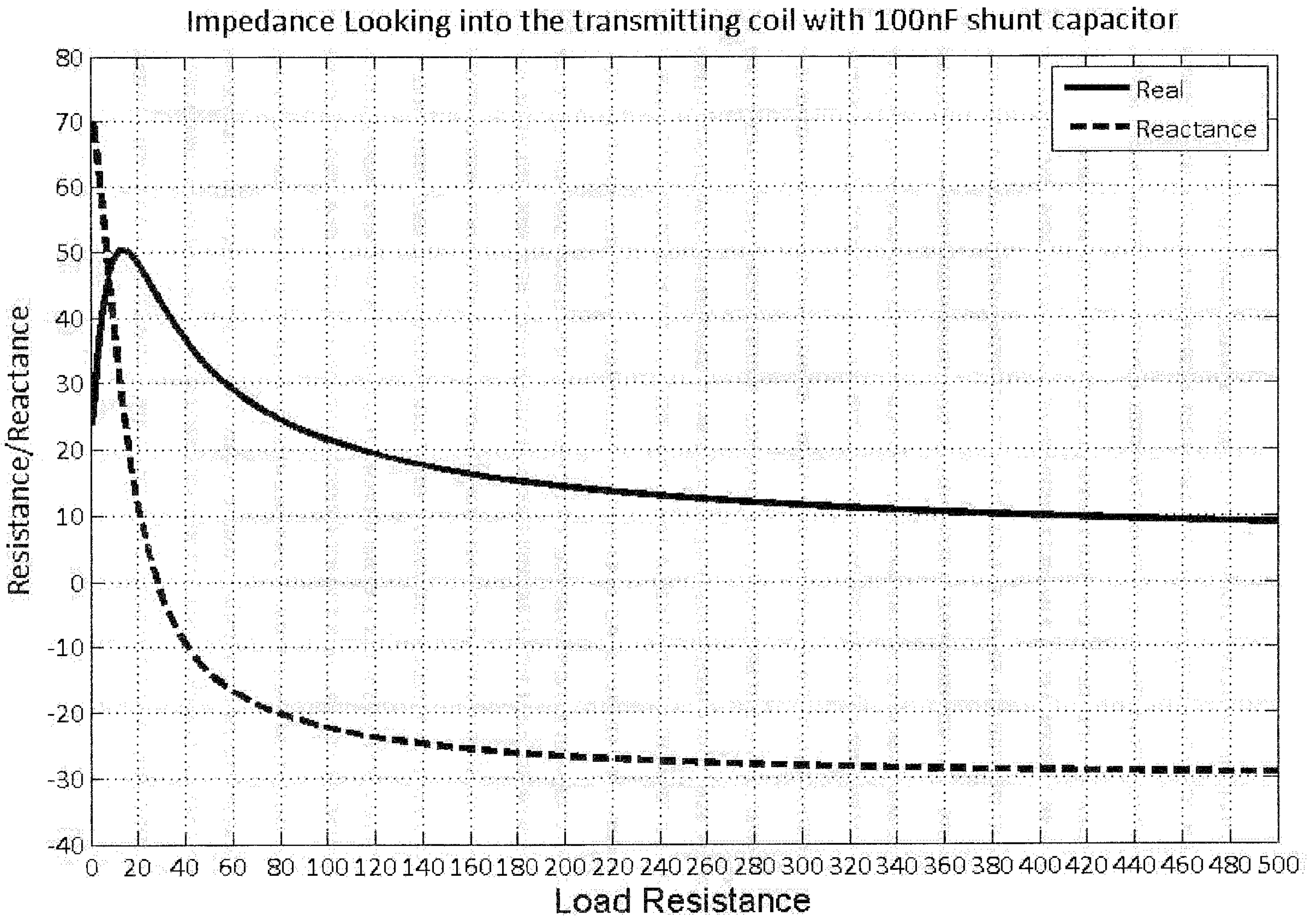

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
Load Resistance

FIG. 29

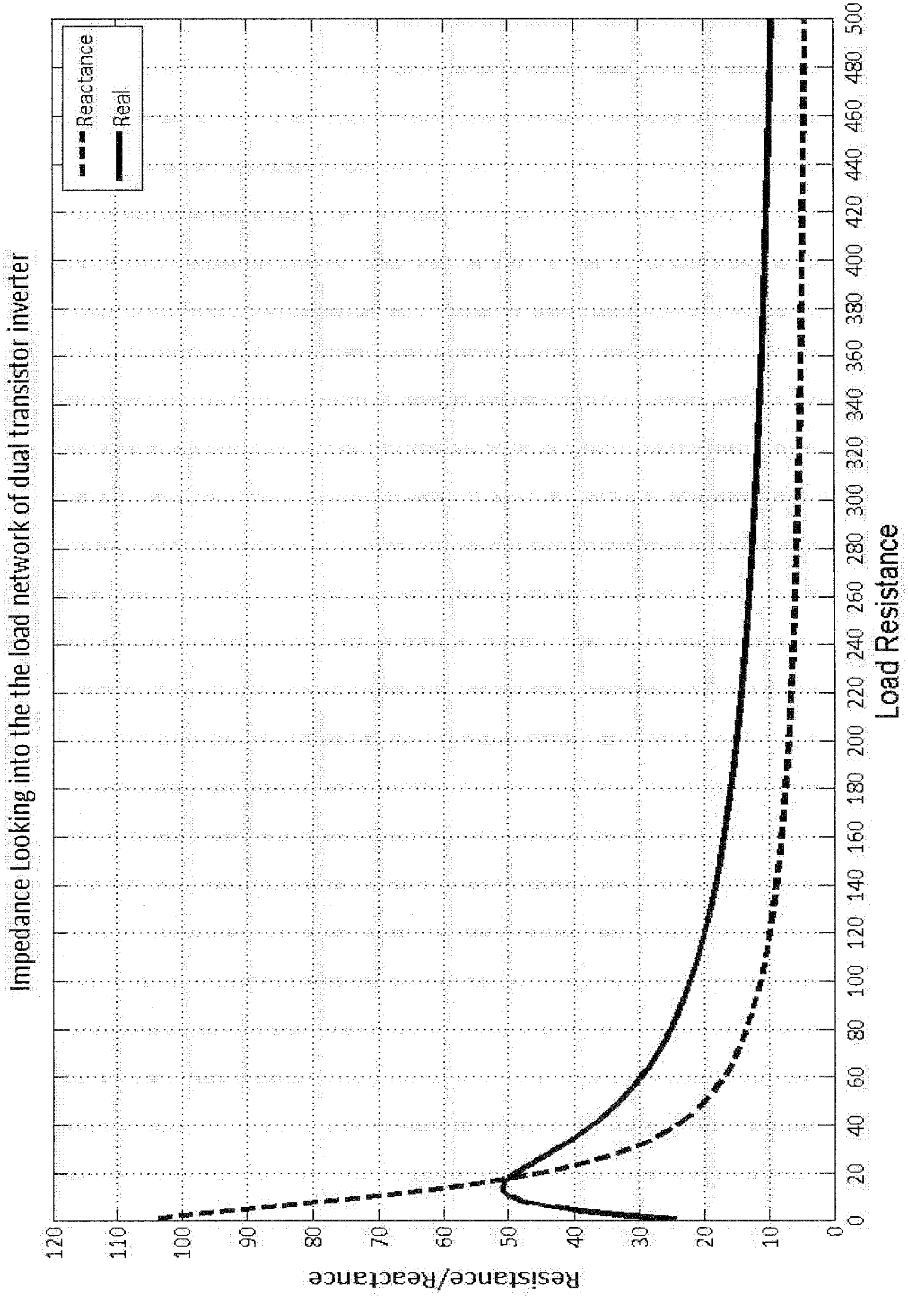

Impedance Looking into the the load network of dual transistor inverter
Reactance
Real
Resistance/Reactance
120
110
100
90
80
70
60
50
40
30
20
10
0
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 30

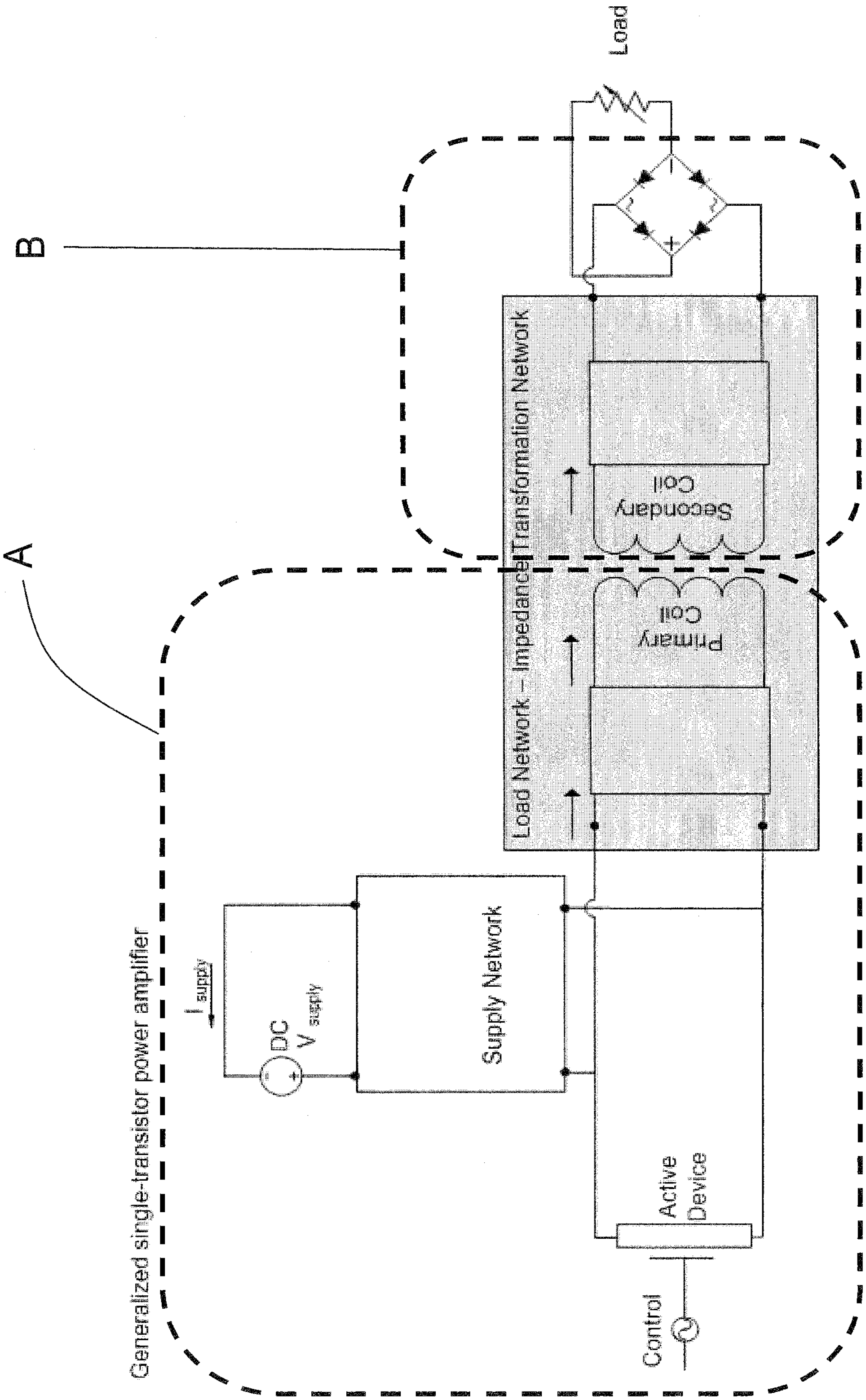

Generalized single-transistor power amplifier
A
B
Load
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Supply Network
DC
V_{supply}
I_{supply}
Active Device
Control

FIG. 31

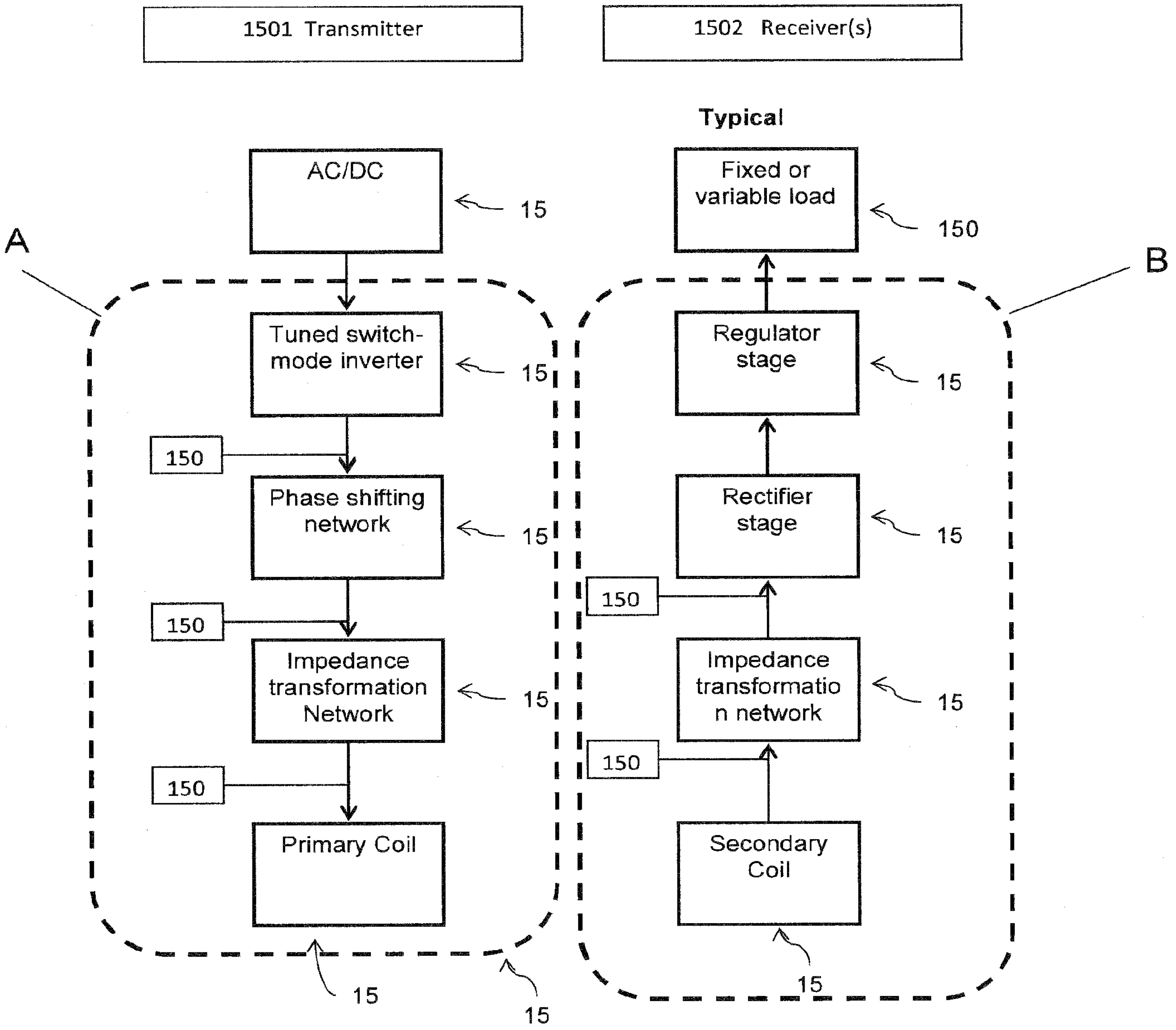

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
A
Tuned switch-mode inverter
15
150
Phase shifting network
15
150
Impedance transformation Network
15
150
Primary Coil
15
15
Fixed or variable load
150
B
Regulator stage
15
Rectifier stage
15
150
Impedance transformatio n network
15
150
Secondary Coil
15

FIG. 32

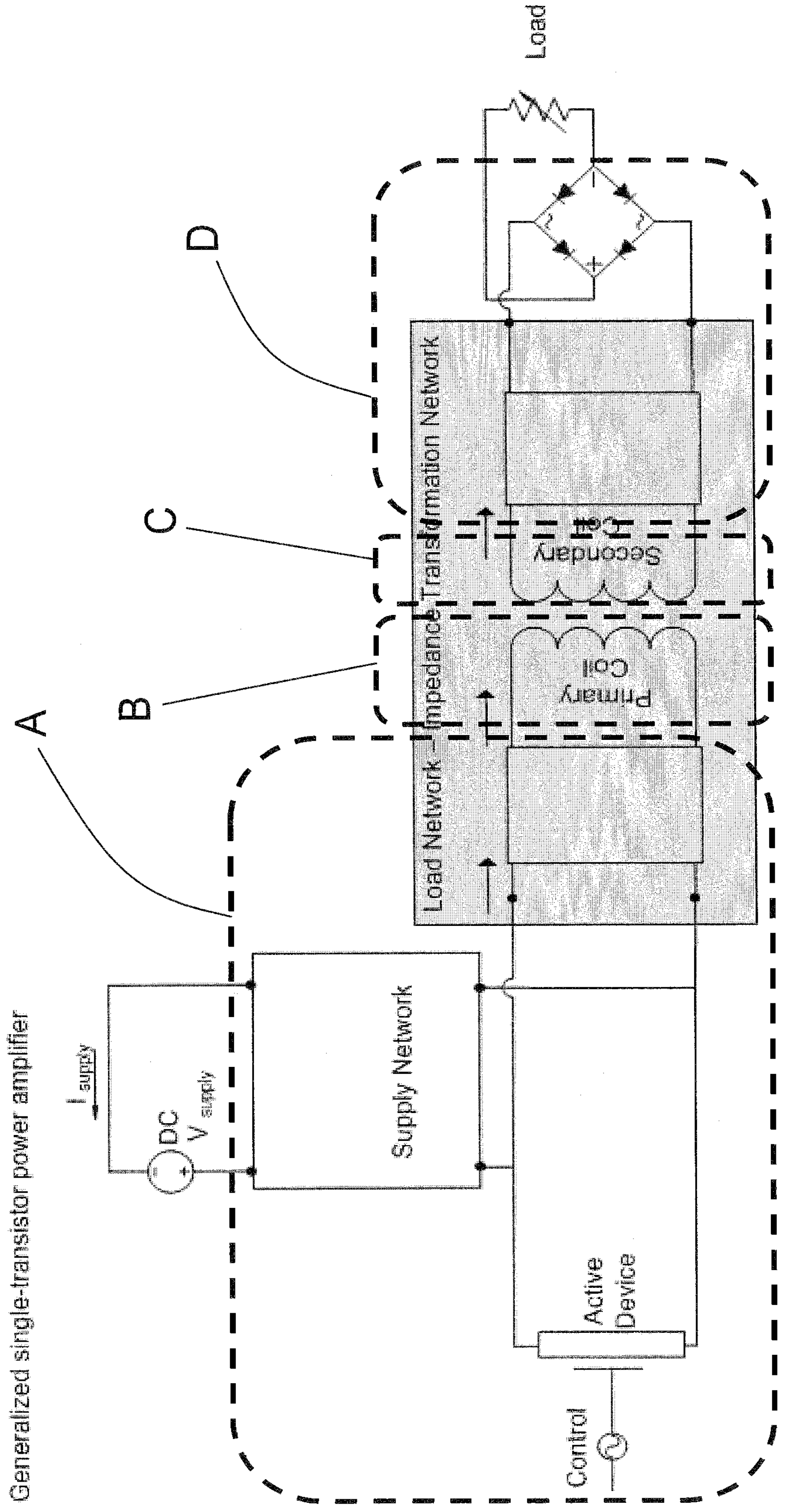

Generalized single-transistor power amplifier
A
B
C
D
I_{supply}
DC
V_{supply}
Supply Network
Active Device
Control
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load

FIG. 33

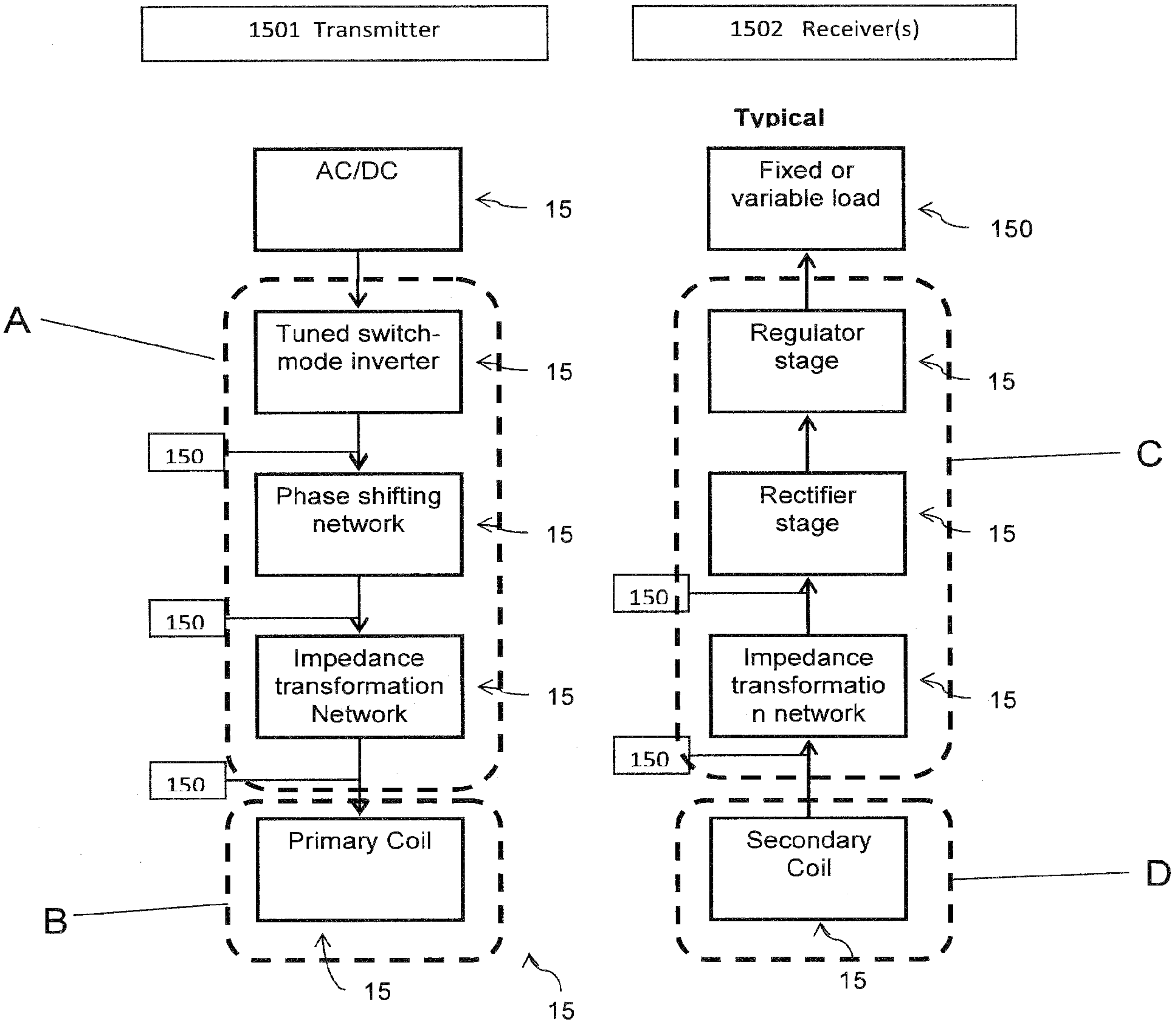

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Fixed or variable load
150
A
Tuned switch-mode inverter
15
Regulator stage
15
150
C
Phase shifting network
15
Rectifier stage
15
150
150
Impedance transformation Network
15
Impedance transformatio n network
15
150
150
Primary Coil
Secondary Coil
B
D
15
15
15

FIG. 34

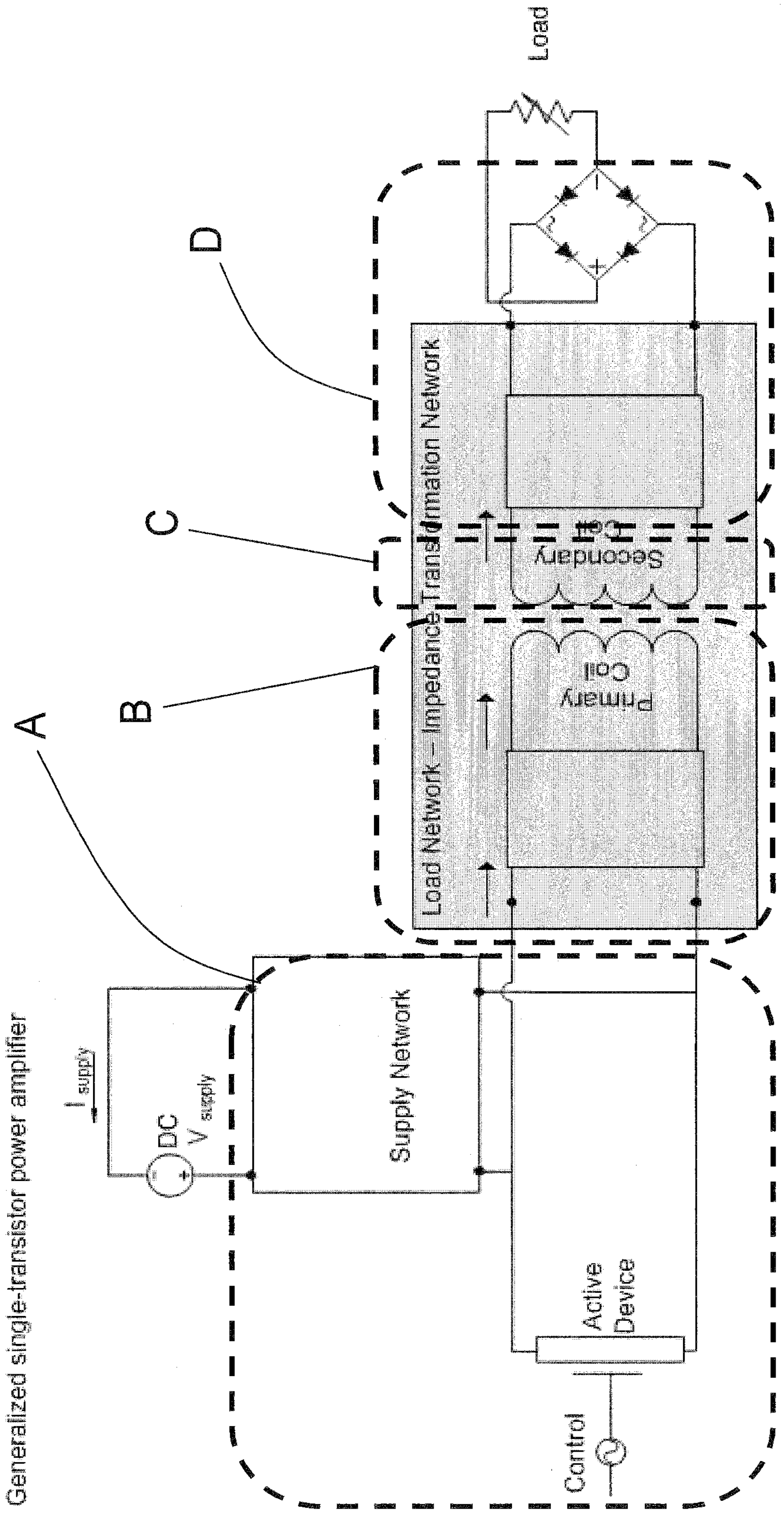

Generalized single-transistor power amplifier
I_{supply}
DC
V_{supply}
Supply Network
Active Device
Control
A
B
C
D
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load

FIG. 35

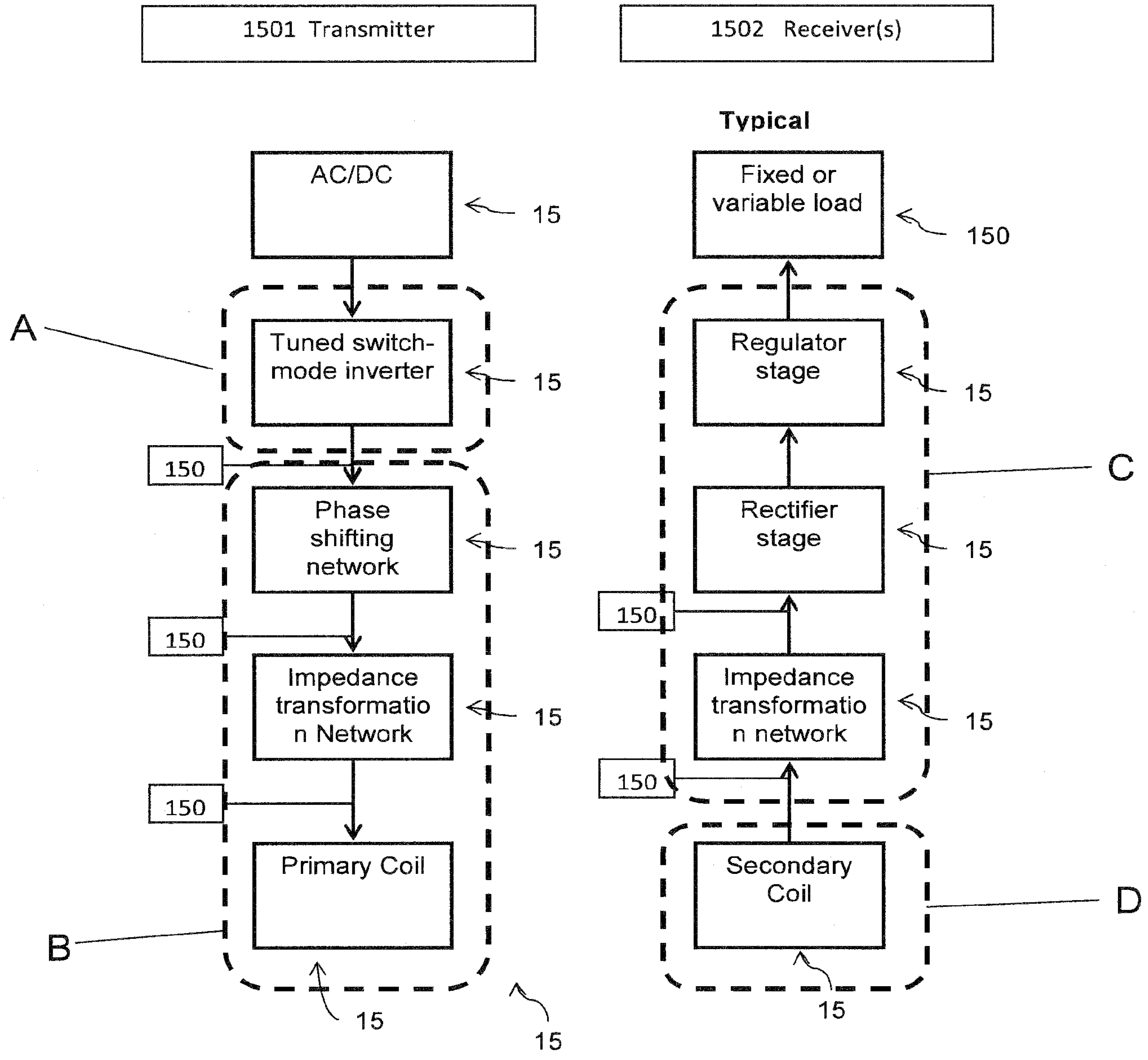

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Fixed or variable load
150
A
Tuned switch-mode inverter
15
Regulator stage
15
C
150
Phase shifting network
15
Rectifier stage
15
150
150
Impedance transformation Network
15
Impedance transformation network
15
150
150
Primary Coil
Secondary Coil
D
B
15
15
15

FIG. 36

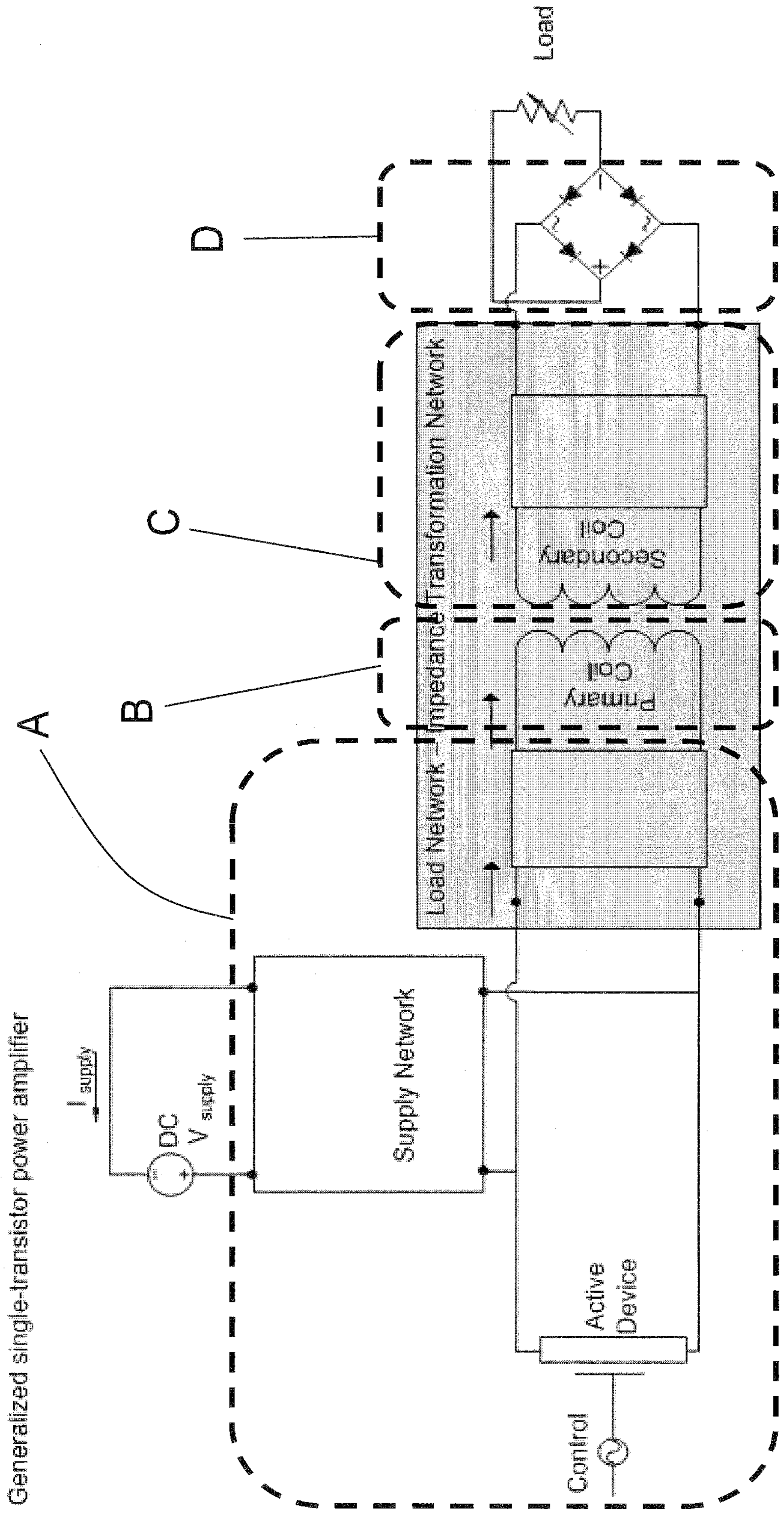

Generalized single-transistor power amplifier
I_{supply}
DC
V_{supply}
Supply Network
Active Device
Control
A
B
C
D
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load

FIG. 37

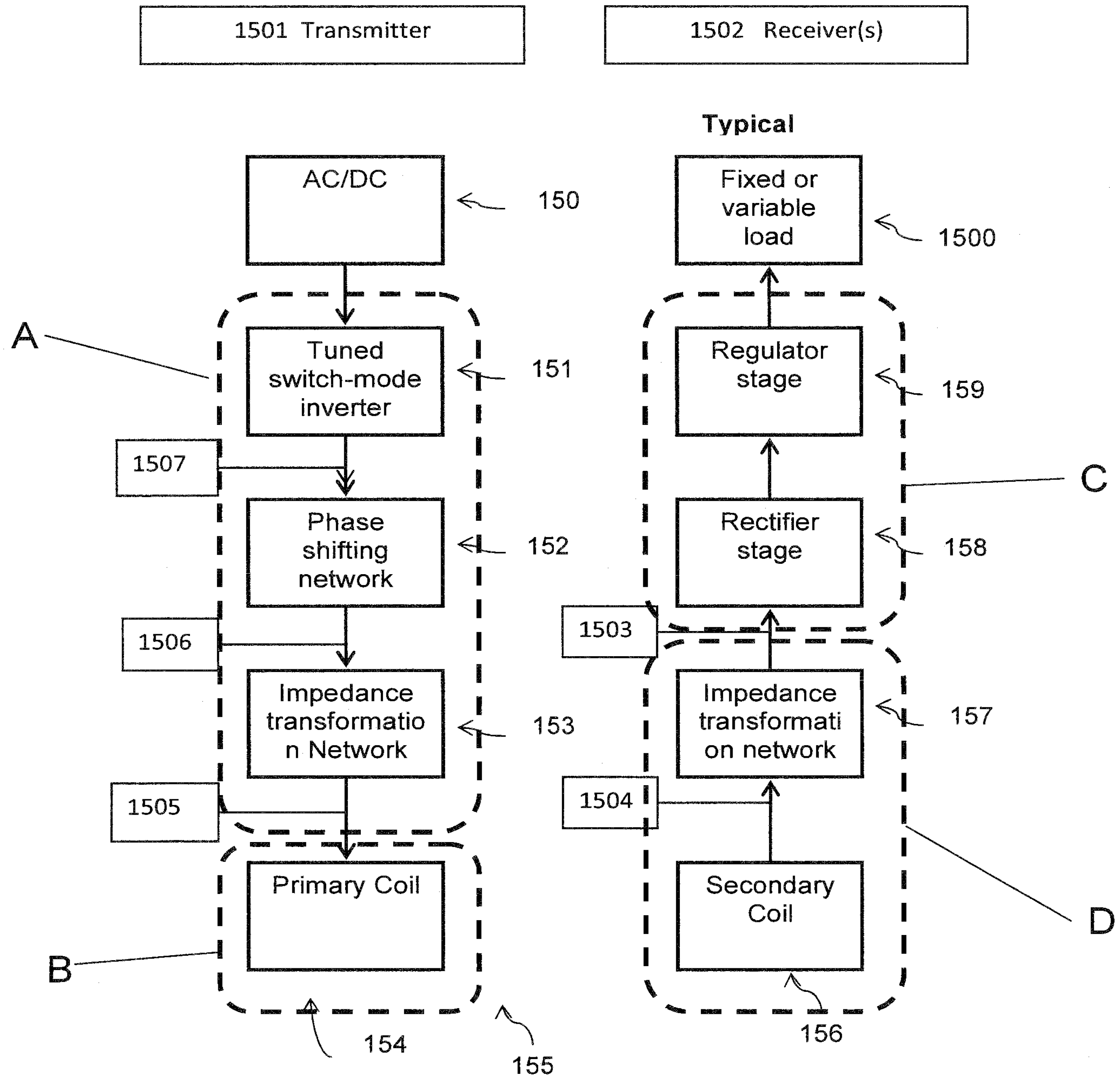

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1506
1503
Impedance transformation Network
153
Impedance transformation network
157
1505
1504
Primary Coil
Secondary Coil
D
B
154
156
155

FIG. 38

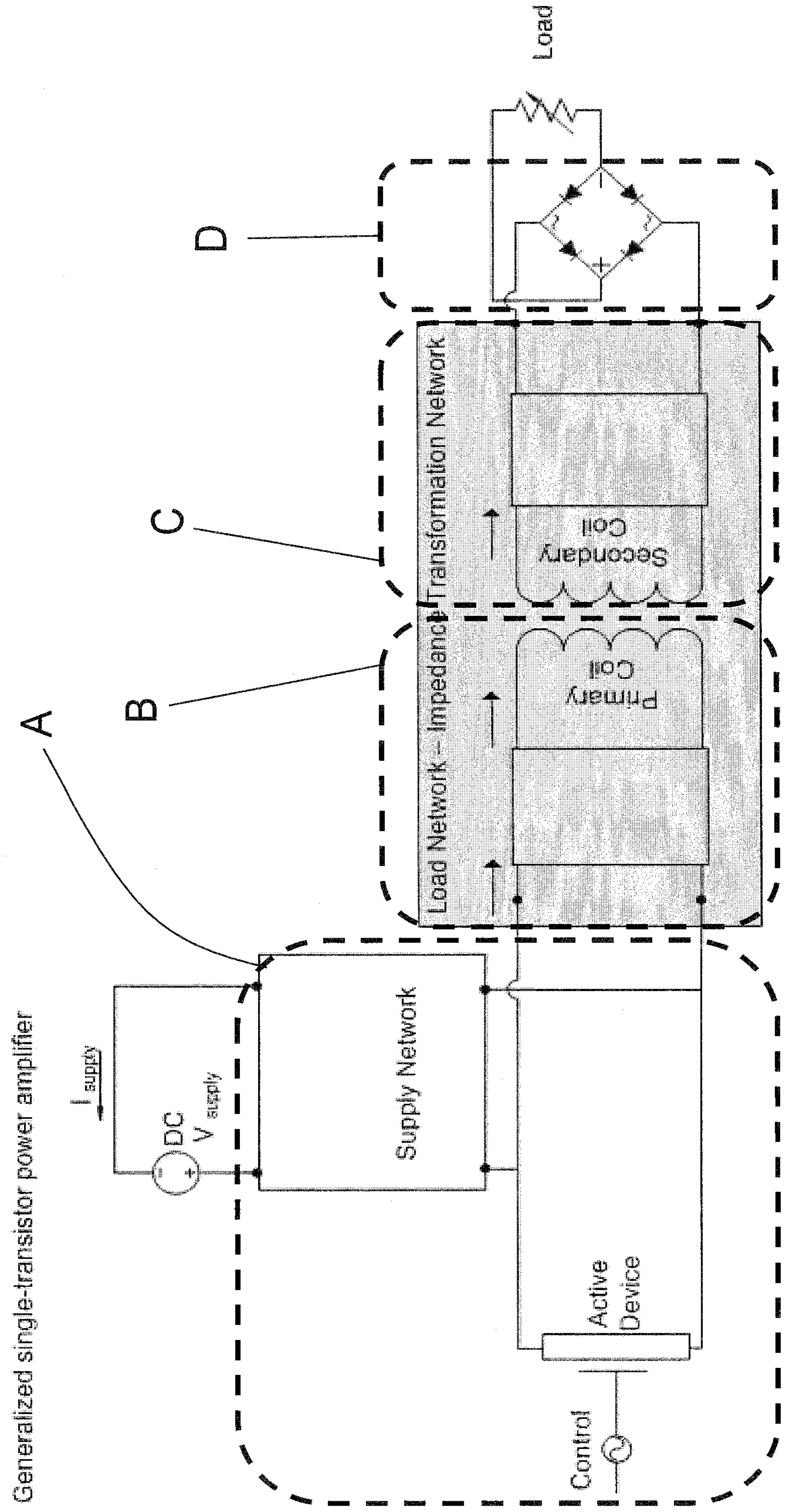

Generalized single-transistor power amplifier
DC
V_{supply}
I_{supply}
Supply Network
Active Device
Control
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load
A
B
C
D

FIG. 39

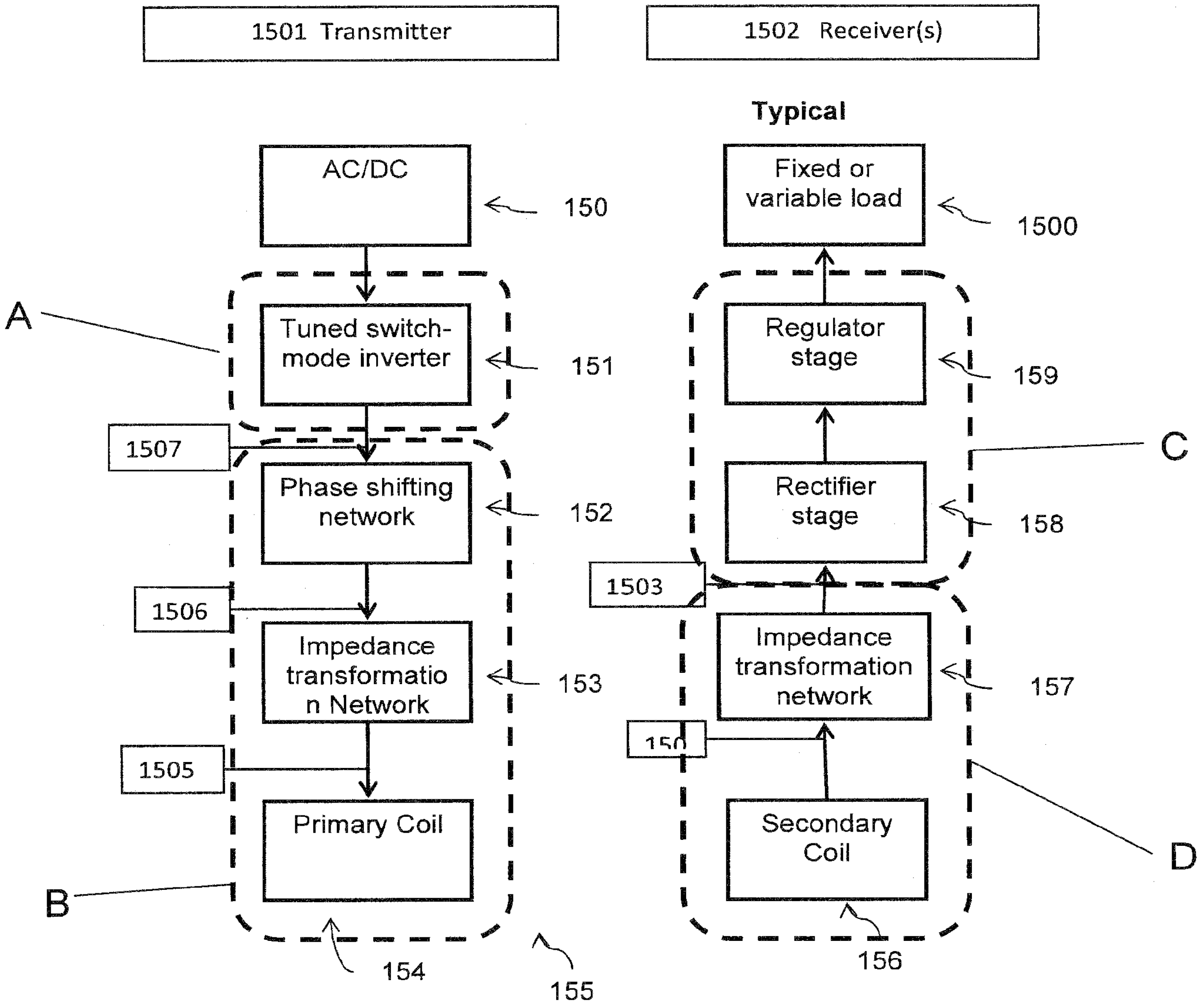

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1503
1506
Impedance transformation Network
153
Impedance transformation network
157
150
1505
Primary Coil
Secondary Coil
B
D
154
155
156

FIG. 40

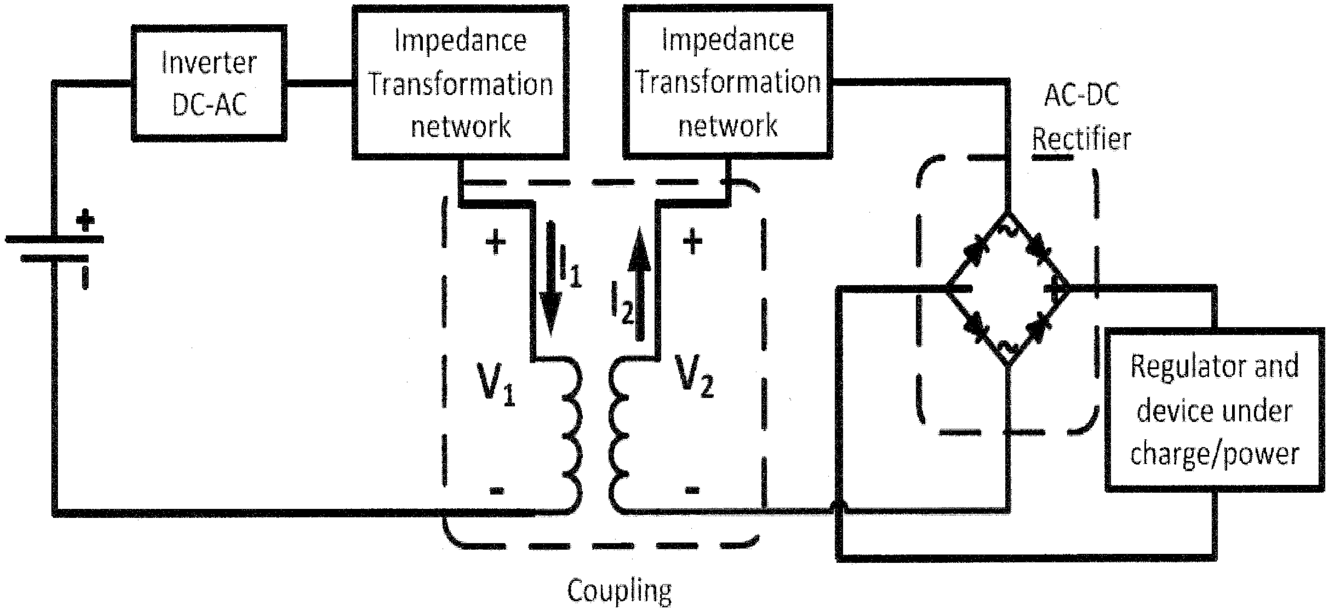

Inverter
DC-AC
Impedance
Transformation
network
Impedance
Transformation
network
AC-DC
Rectifier
+
-
+
I_1
I_2
+
V_1
V_2
-
-
Regulator and
device under
charge/power
Coupling

FIG. 41

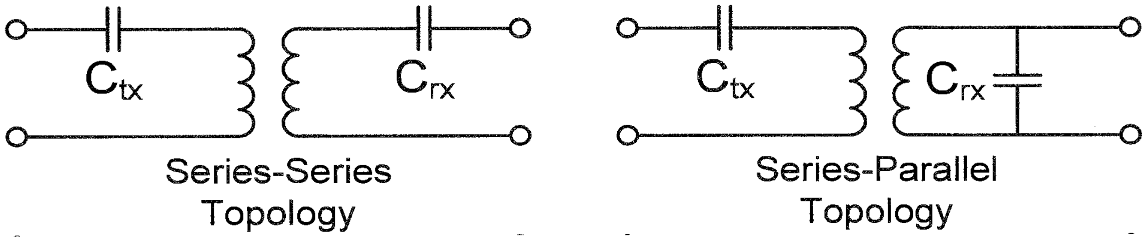

Ctx
Crx
Series-Series Topology
Ctx
Crx
Series-Parallel Topology

FIG. 42

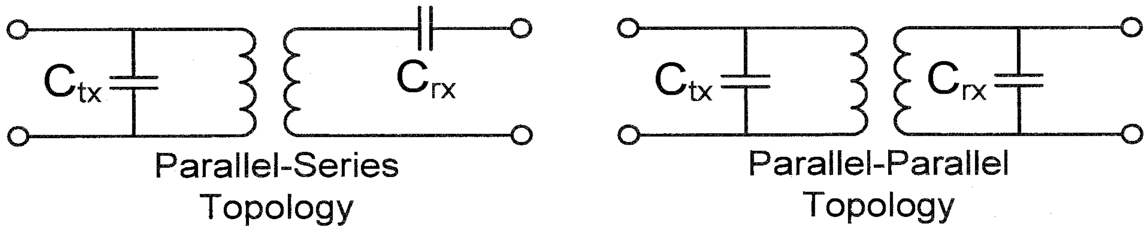

Ctx
Crx
Parallel-Series Topology
Ctx
Crx
Parallel-Parallel Topology

FIG. 43

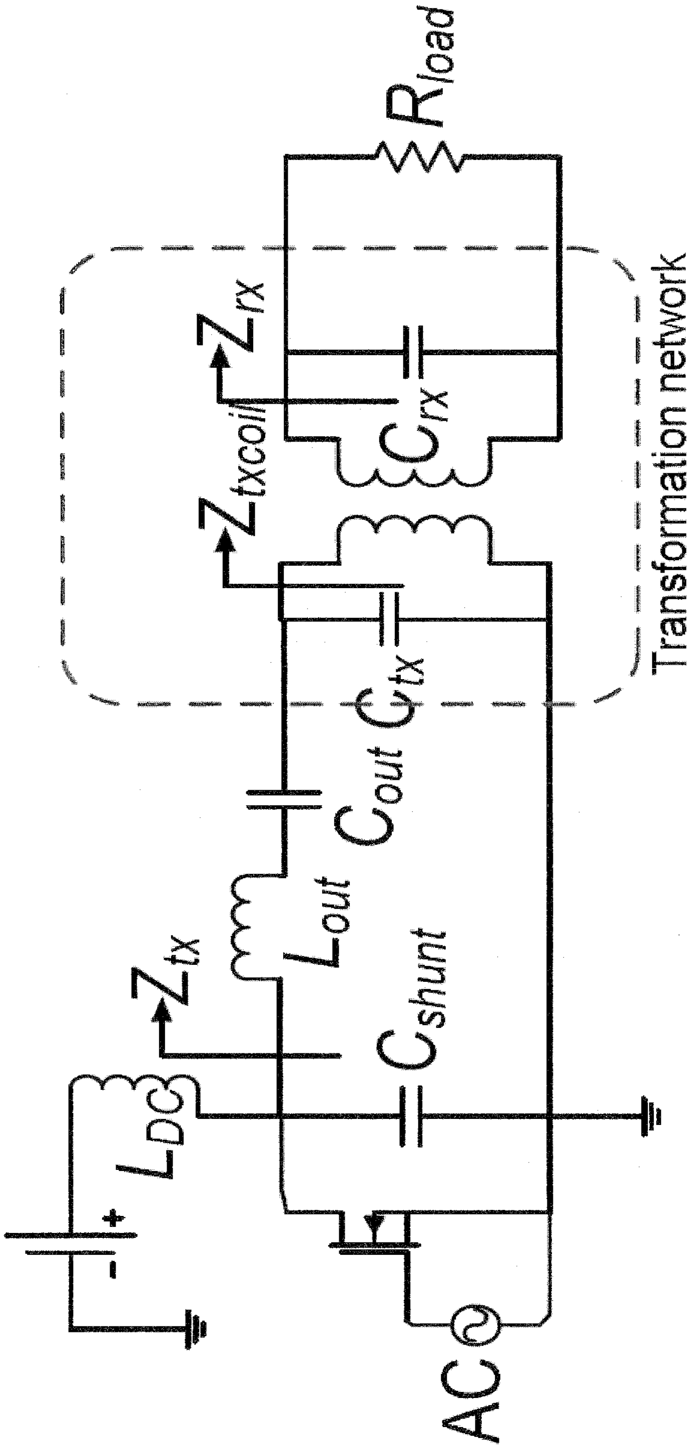

R_{load}
Z_{rx}
Z_{txcoil}
C_{rx}
Transformation network
C_{tx}
C_{out}
L_{out}
Z_{tx}
C_{shunt}
L_{DC}
+
-
AC

FIG. 44

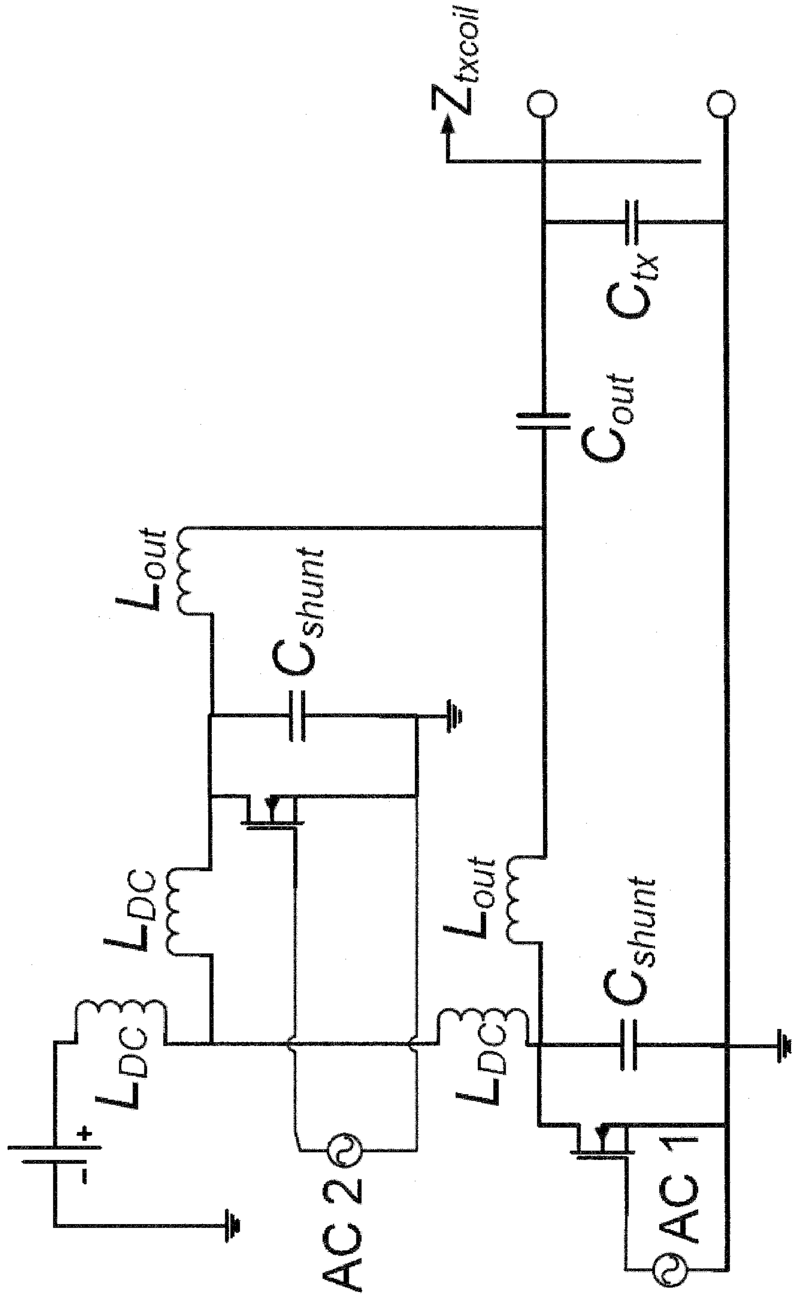


FIG. 45

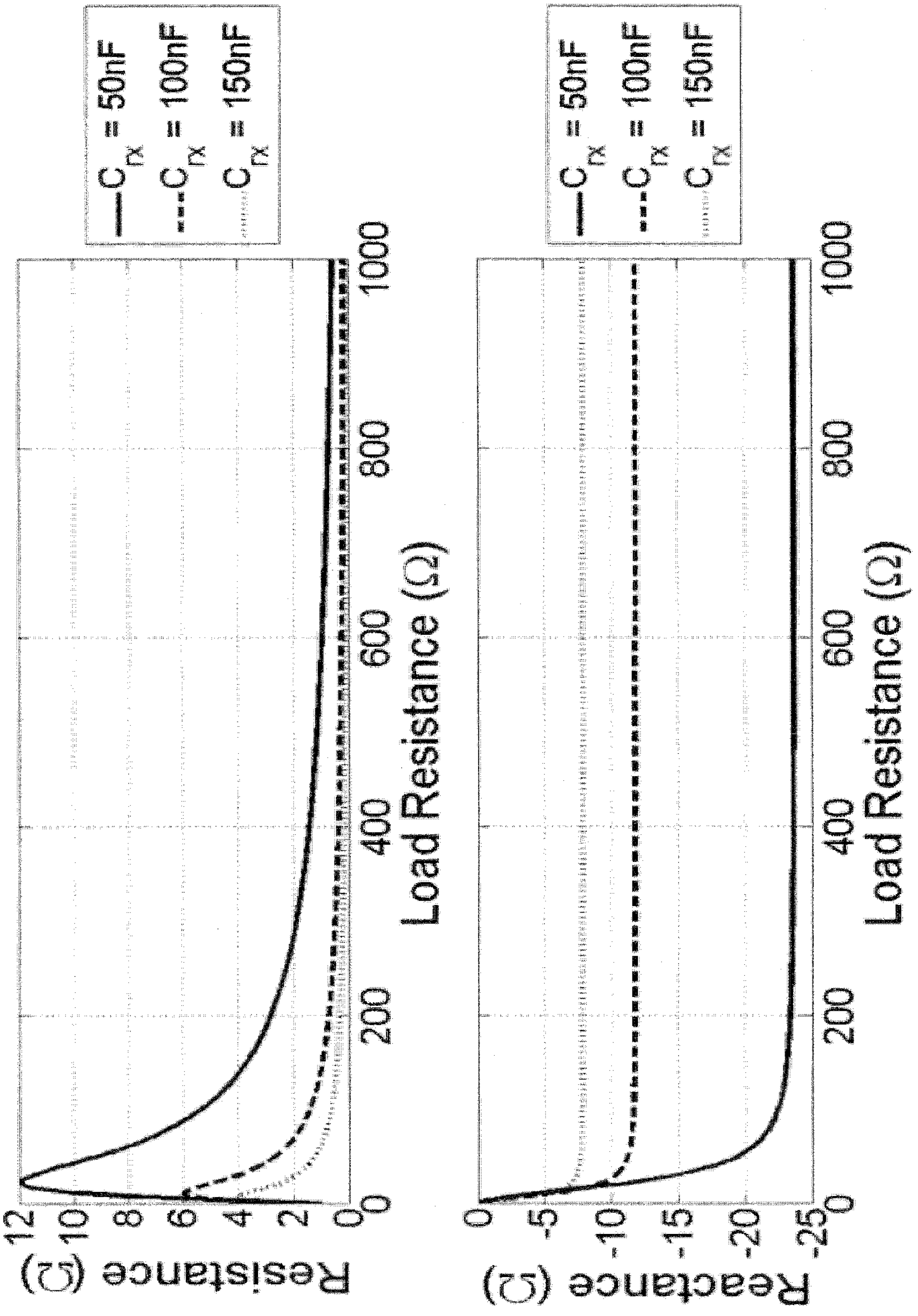

Resistance (Ω)
12
10
8
6
4
2
0
0
200
400
600
800
1000
Load Resistance (Ω)
C_{rx} = 50nF
C_{rx} = 100nF
C_{rx} = 150nF
Reactance (Ω)
0
-5
-10
-15
-20
-25
0
200
400
600
800
1000
Load Resistance (Ω)
C_{rx} = 50nF
C_{rx} = 100nF
C_{rx} = 150nF

FIG. 46

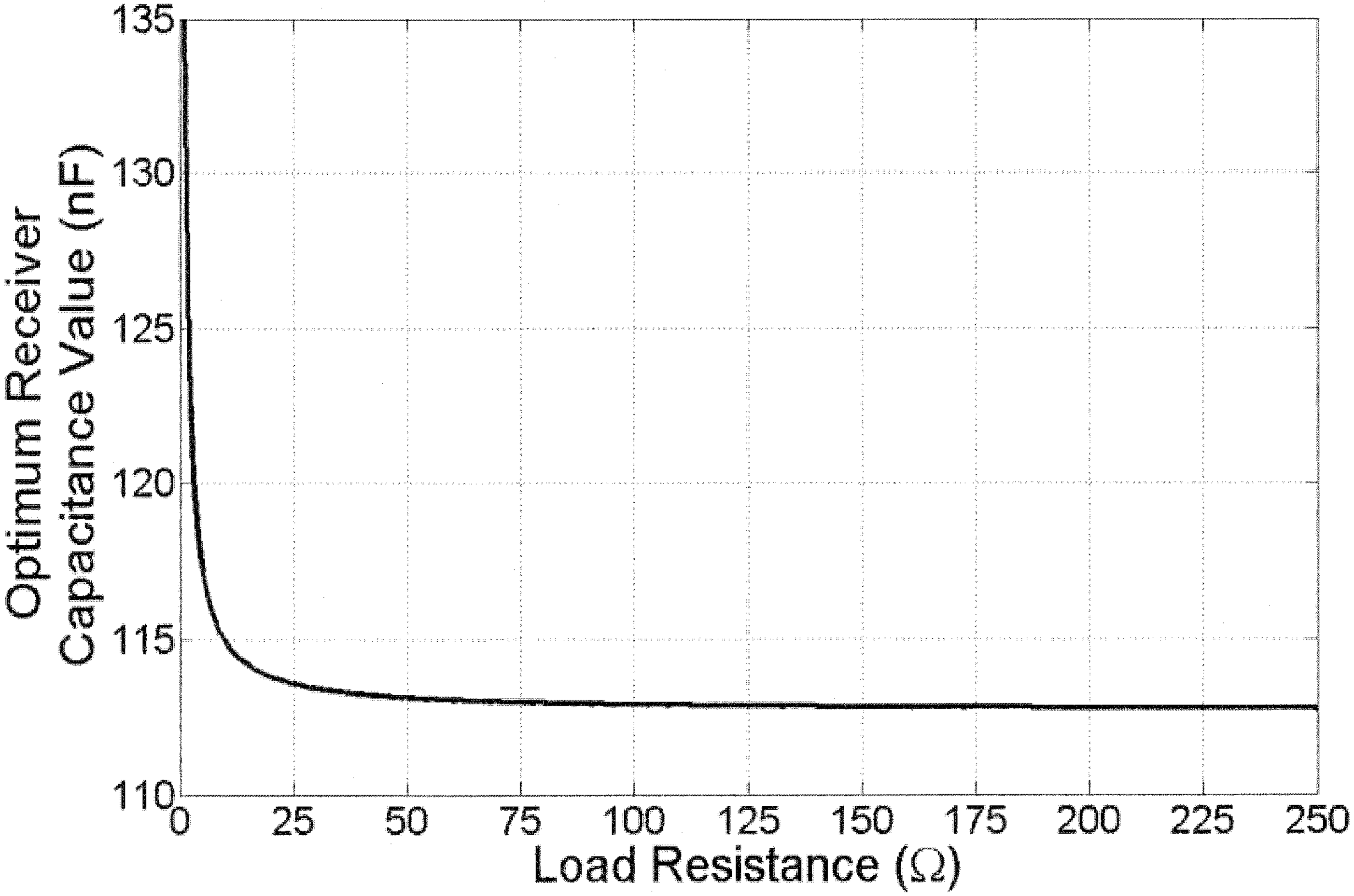

135
130
125
120
115
110
0
25
50
75
100
125
150
175
200
225
250
Optimum Receiver Capacitance Value (nF)
Load Resistance (Ω)

FIG. 47

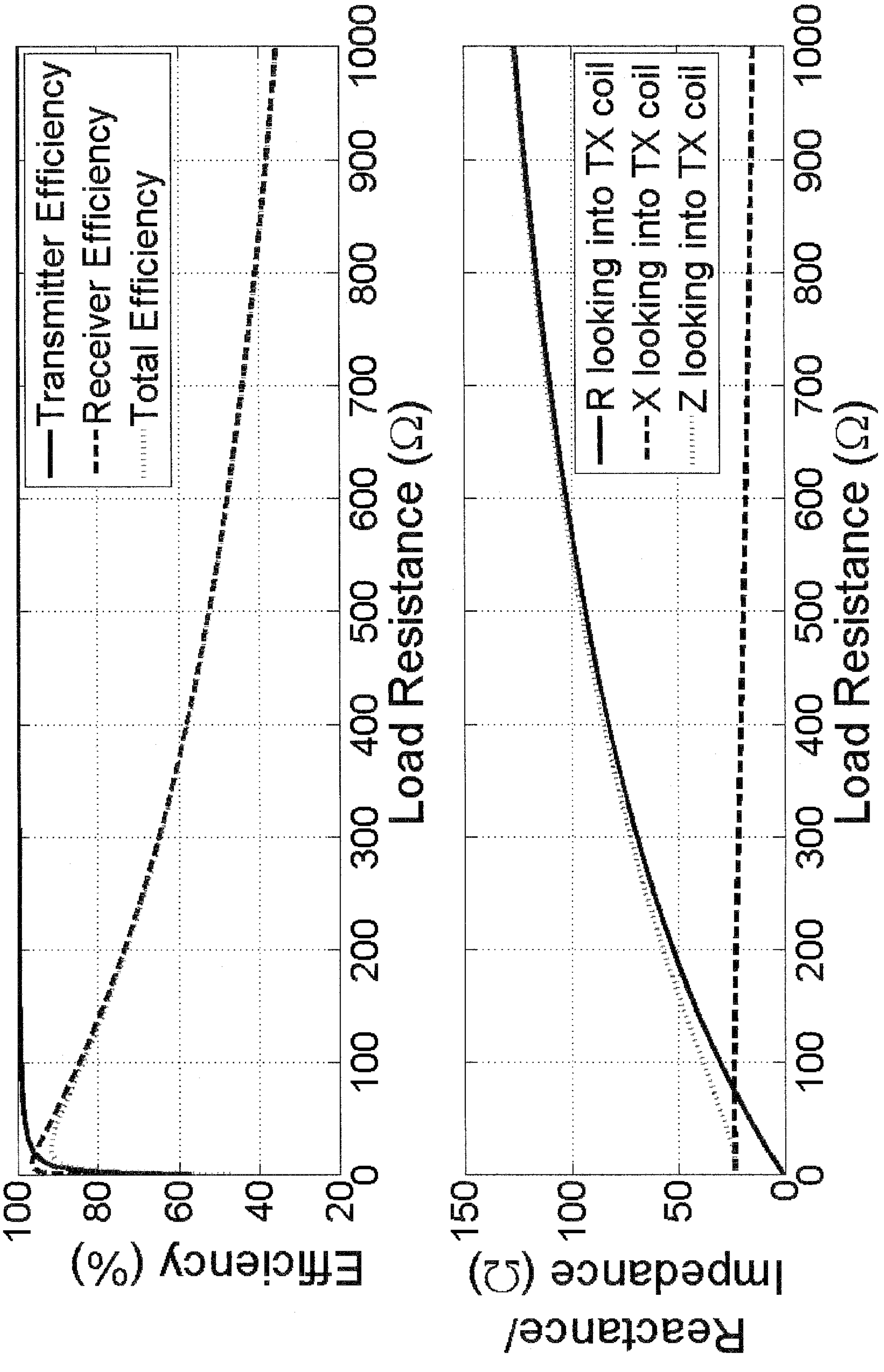

Transmitter Efficiency
Receiver Efficiency
Total Efficiency
Efficiency (%)
100
80
60
40
20
0
100
200
300
400
500
600
700
800
900
1000
Load Resistance (Ω)
R looking into TX coil
X looking into TX coil
Z looking into TX coil
Reactance/ Impedance (Ω)
150
100
50
0
Load Resistance (Ω)

FIG. 48A

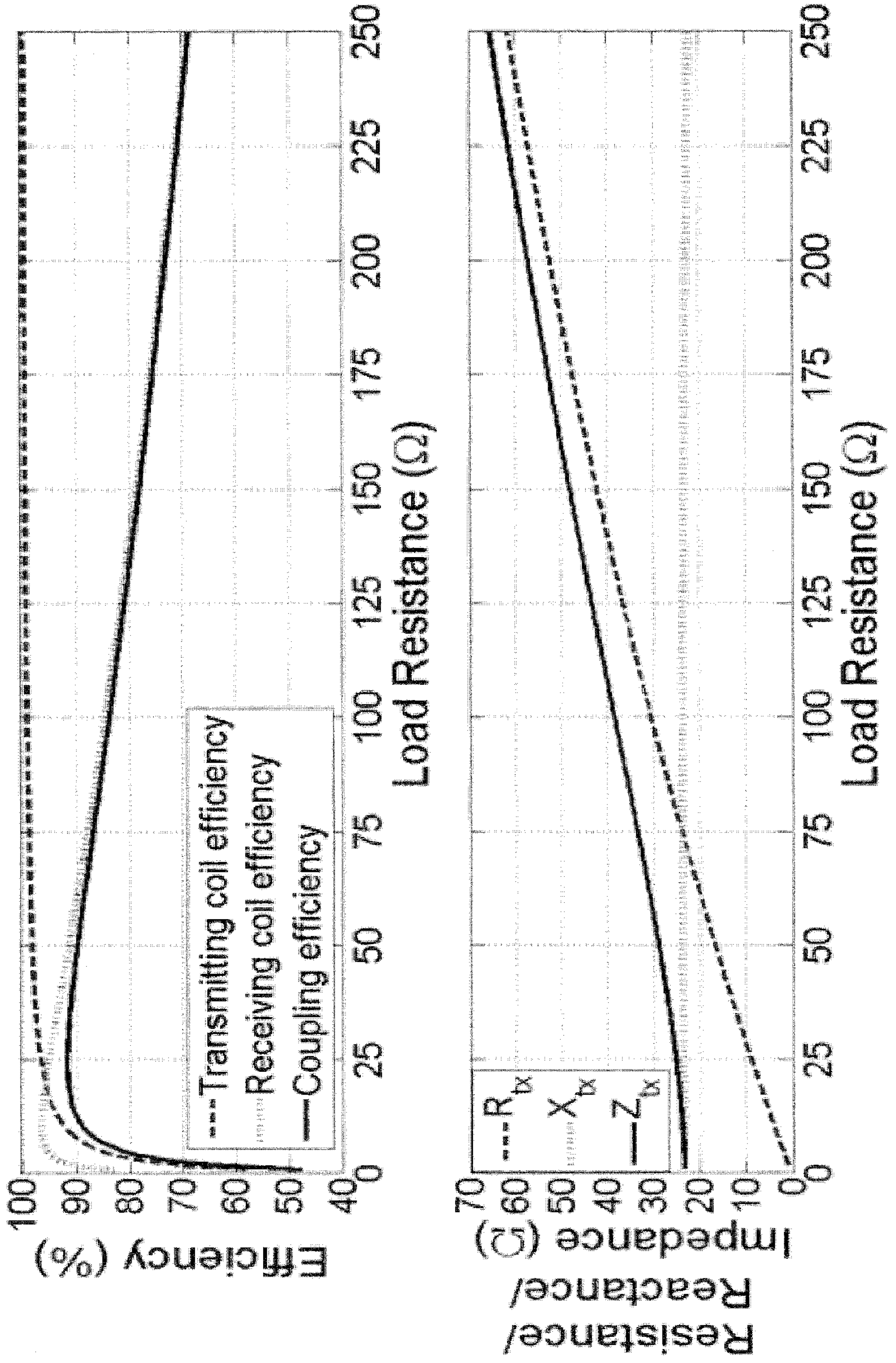

Efficiency (%)
100
90
80
70
60
50
40
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)
Transmitting coil efficiency
Receiving coil efficiency
Coupling efficiency
Resistance/
Reactance/
Impedance (Ω)
70
60
50
40
30
20
10
0
R_{tx}
X_{tx}
Z_{tx}

FIG. 48B

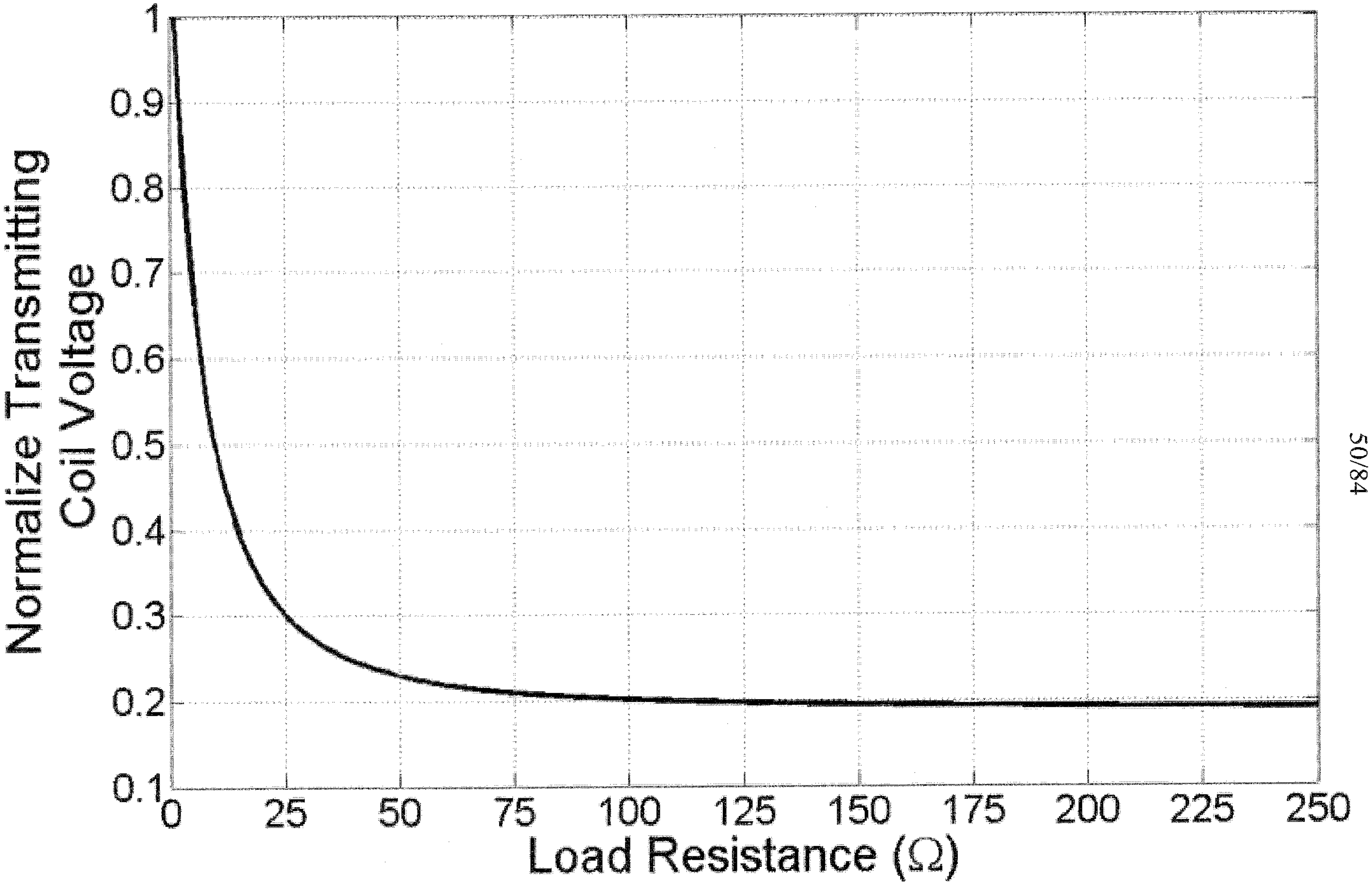

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Normalize Transmitting Coil Voltage
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 49

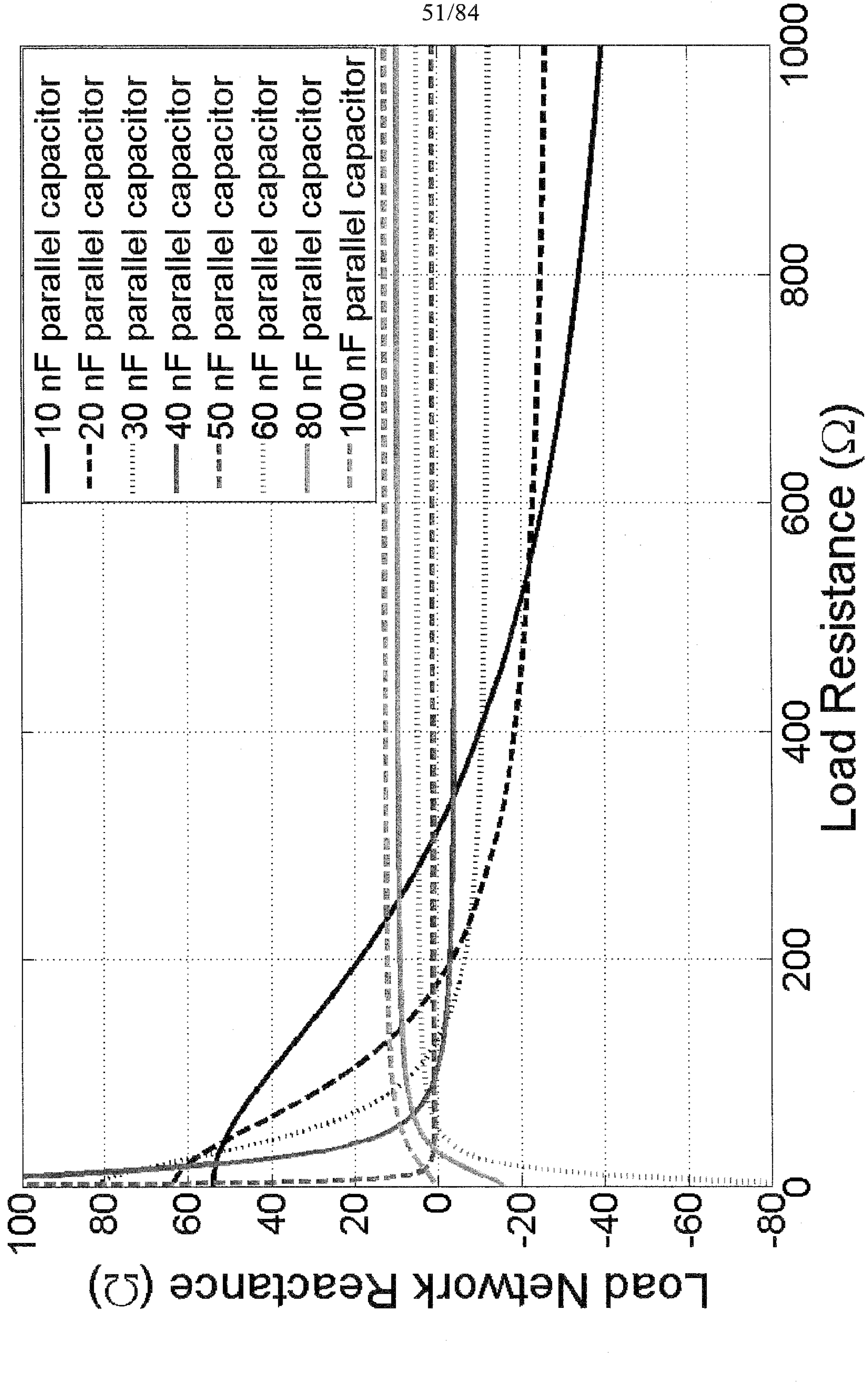

10 nF parallel capacitor
20 nF parallel capacitor
30 nF parallel capacitor
40 nF parallel capacitor
50 nF parallel capacitor
60 nF parallel capacitor
80 nF parallel capacitor
100 nF parallel capacitor
Load Network Reactance (Ω)
100
80
60
40
20
0
-20
-40
-60
-80
0
200
400
600
800
1000
Load Resistance (Ω)

FIG. 50

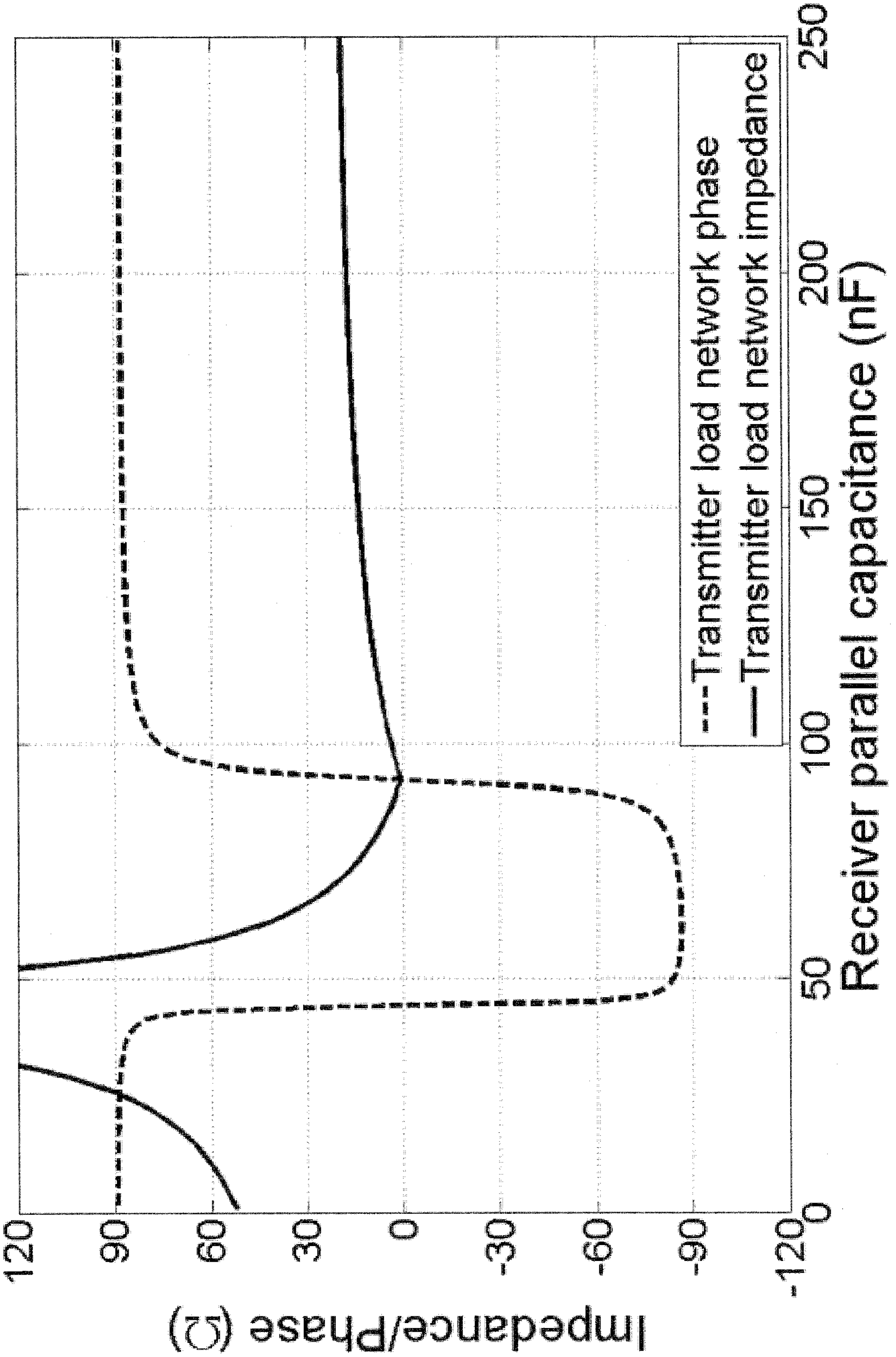

Impedance/Phase (Ω)
120
90
60
30
0
-30
-60
-90
-120
0
50
100
150
200
250
Receiver parallel capacitance (nF)
---Transmitter load network phase
—Transmitter load network impedance

FIG. 51

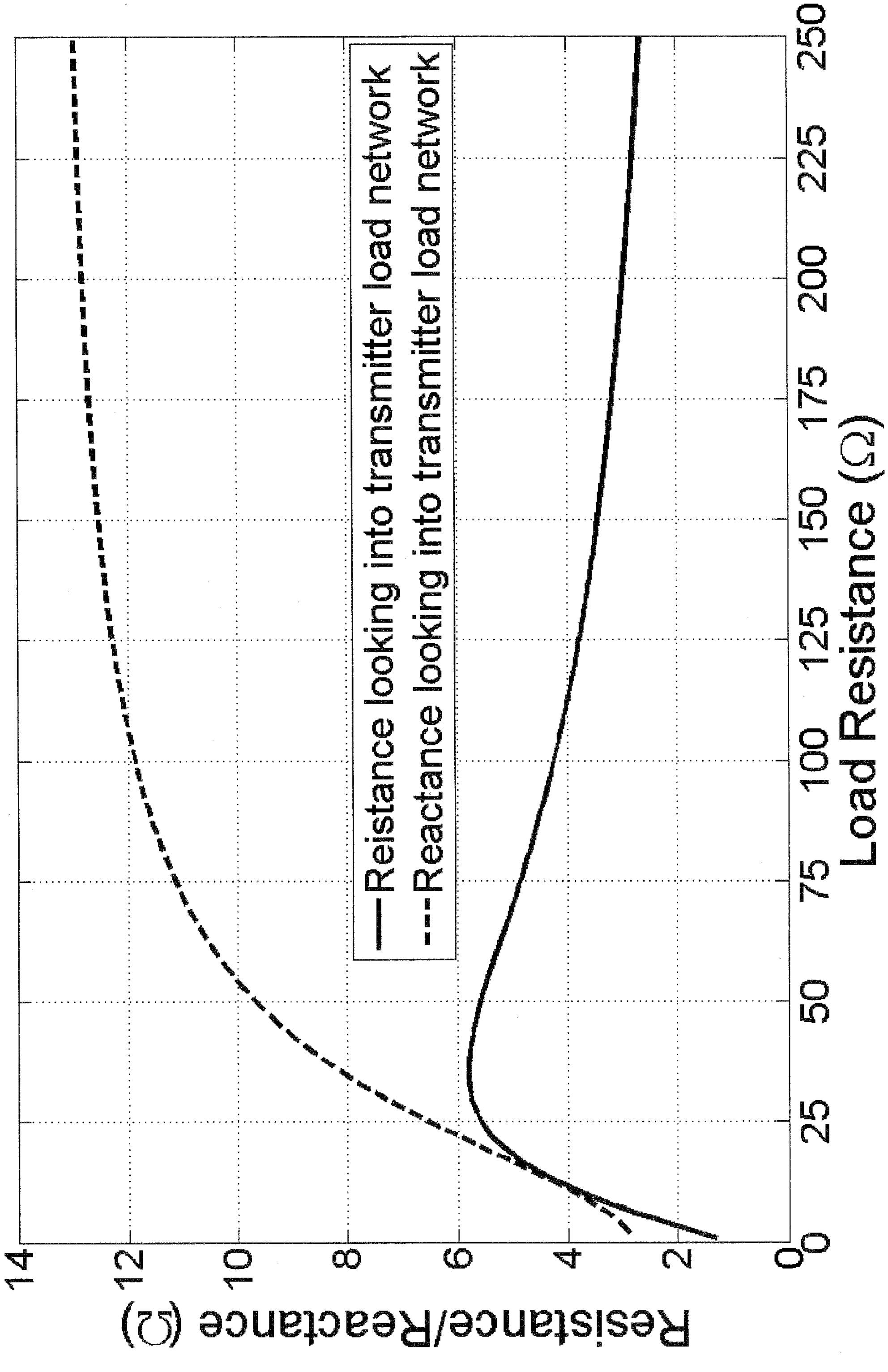

Resistance/Reactance (Ω)
14
12
10
8
6
4
2
0
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)
—Reistance looking into transmitter load network
---Reactance looking into transmitter load network

FIG. 52

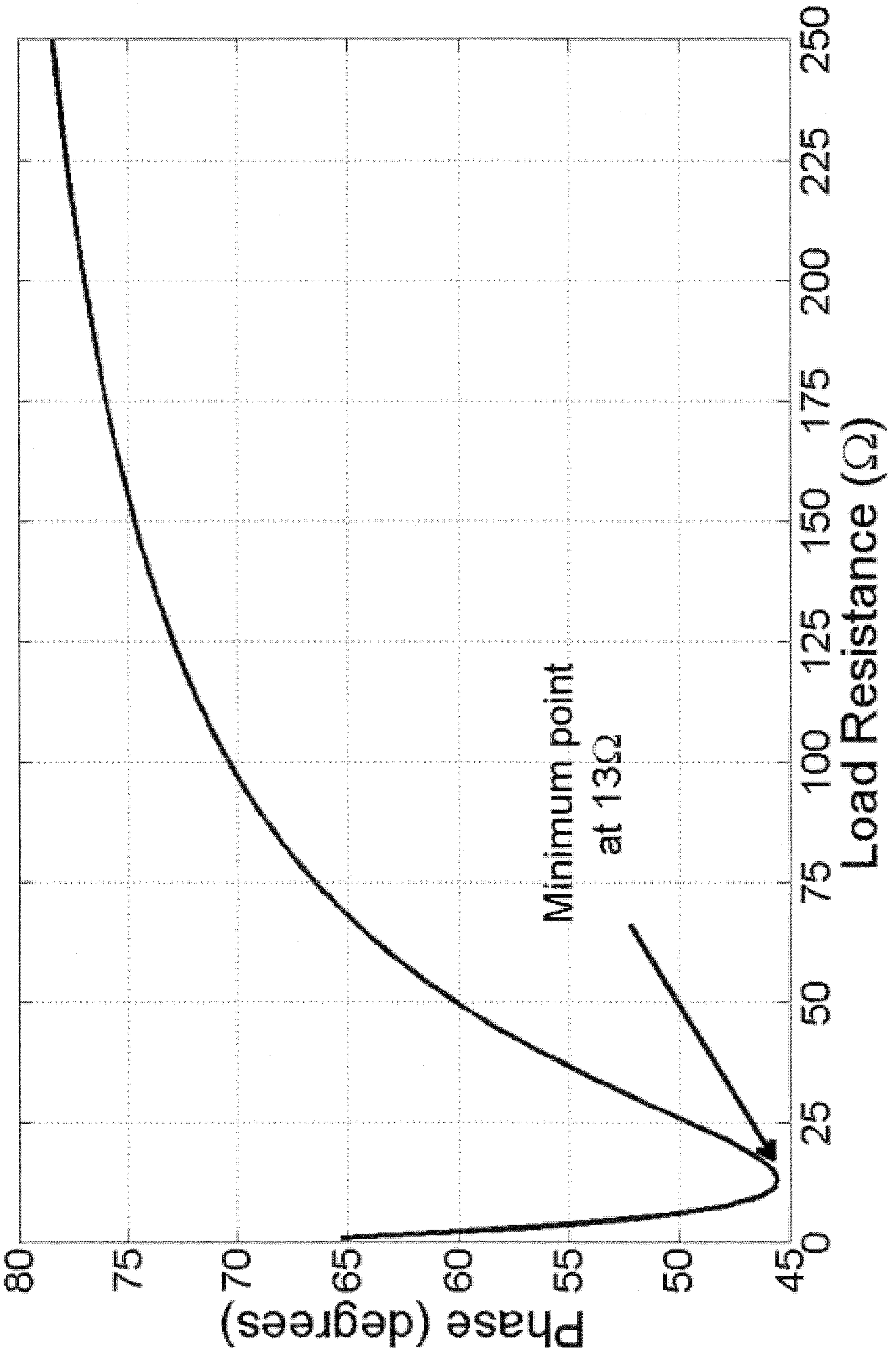

Phase (degrees)
80
75
70
65
60
55
50
45
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)
Minimum point
at 13Ω

FIG. 53

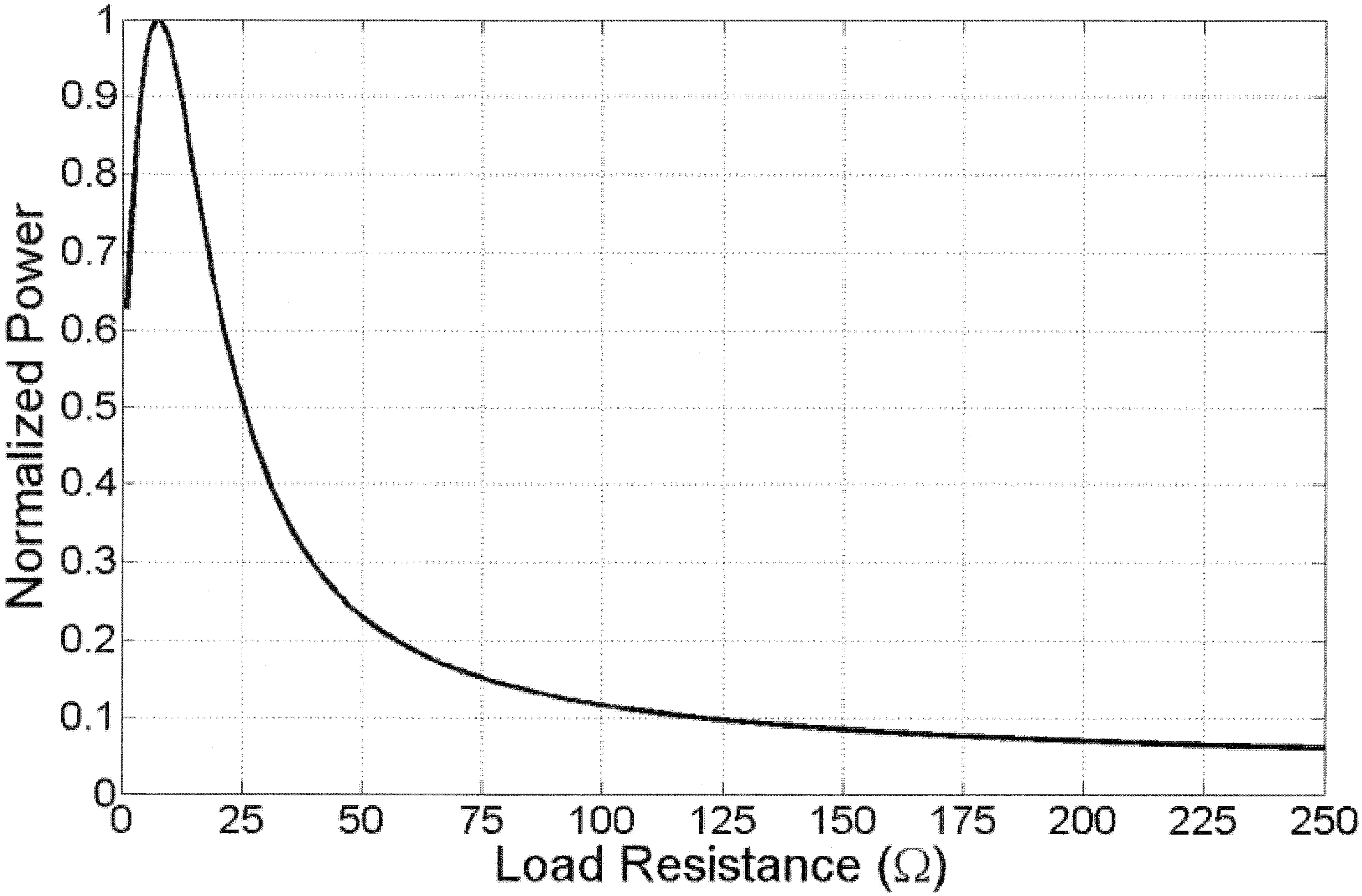

Normalized Power
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 54

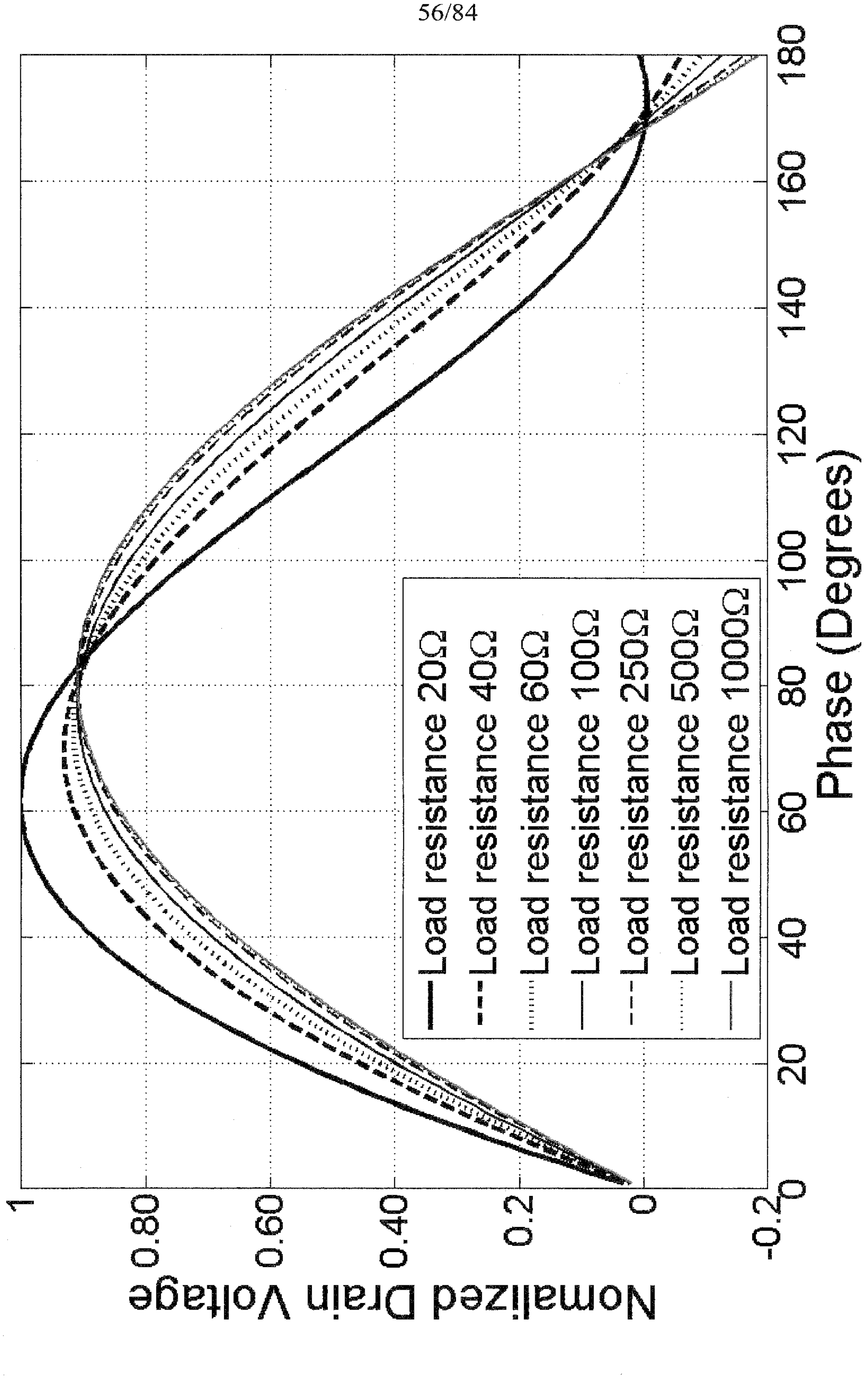
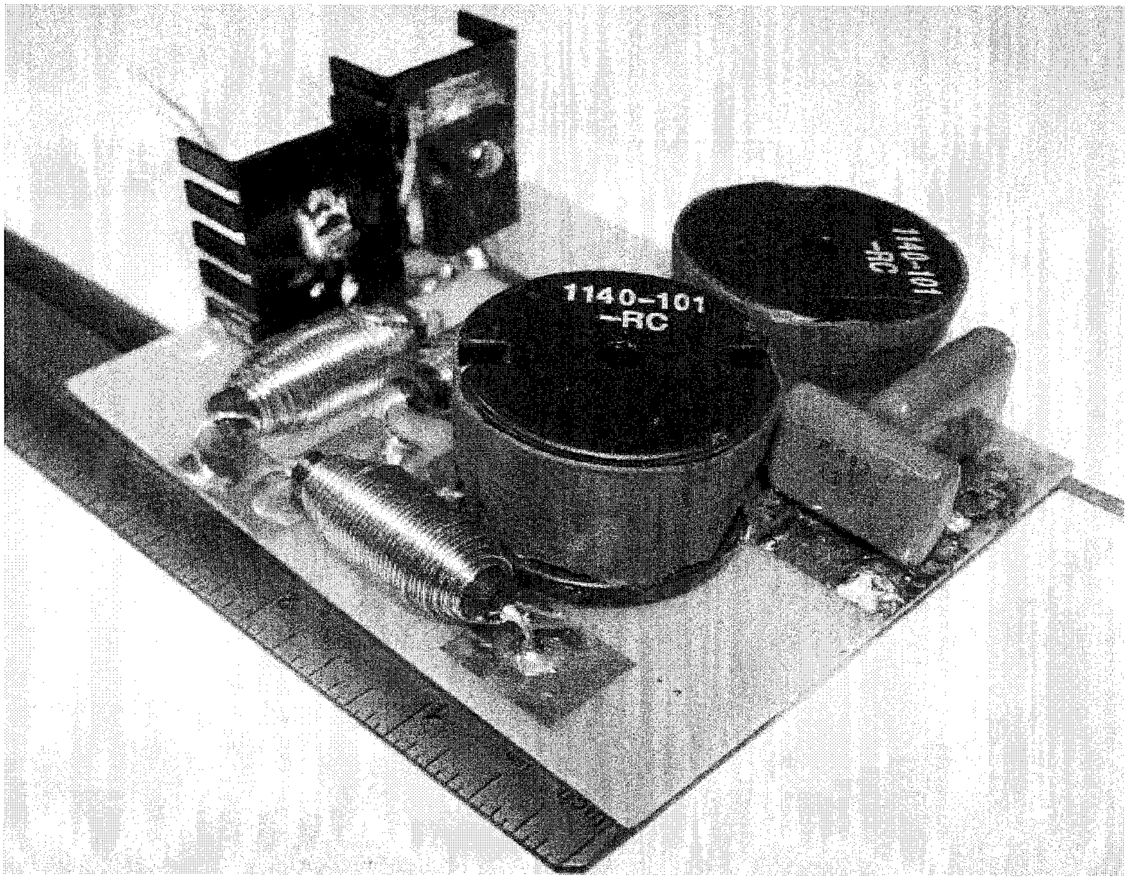

Nomalized Drain Voltage
1
0.80
0.60
0.40
0.2
0
-0.2
0
20
40
60
80
100
120
140
160
180
Phase (Degrees)
Load resistance 20Ω
Load resistance 40Ω
Load resistance 60Ω
Load resistance 100Ω
Load resistance 250Ω
Load resistance 500Ω
Load resistance 1000Ω

FIG. 55


1140-101
-RC
1140-101
-RC

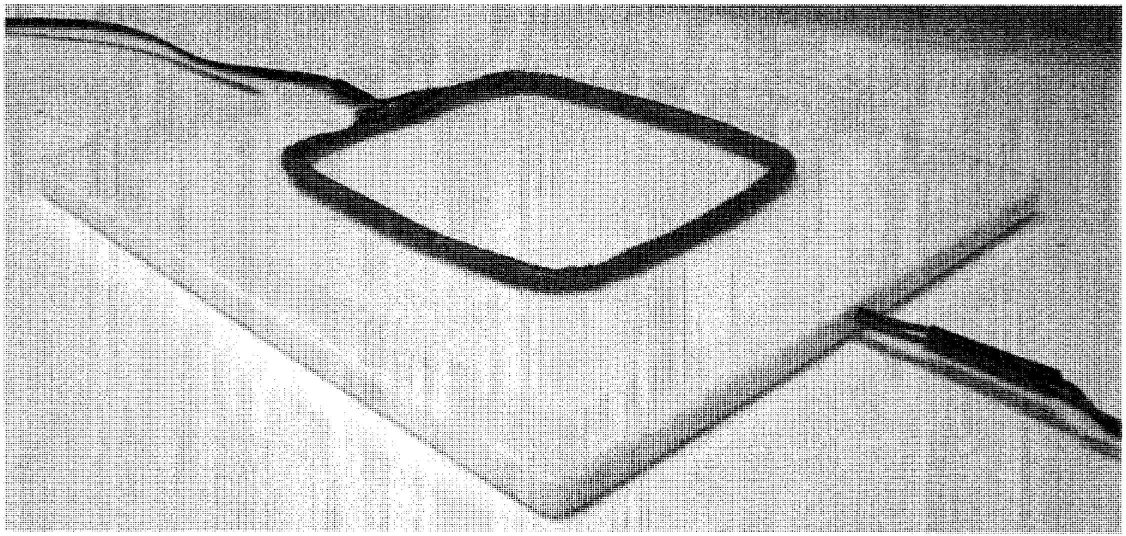


FIG. 57

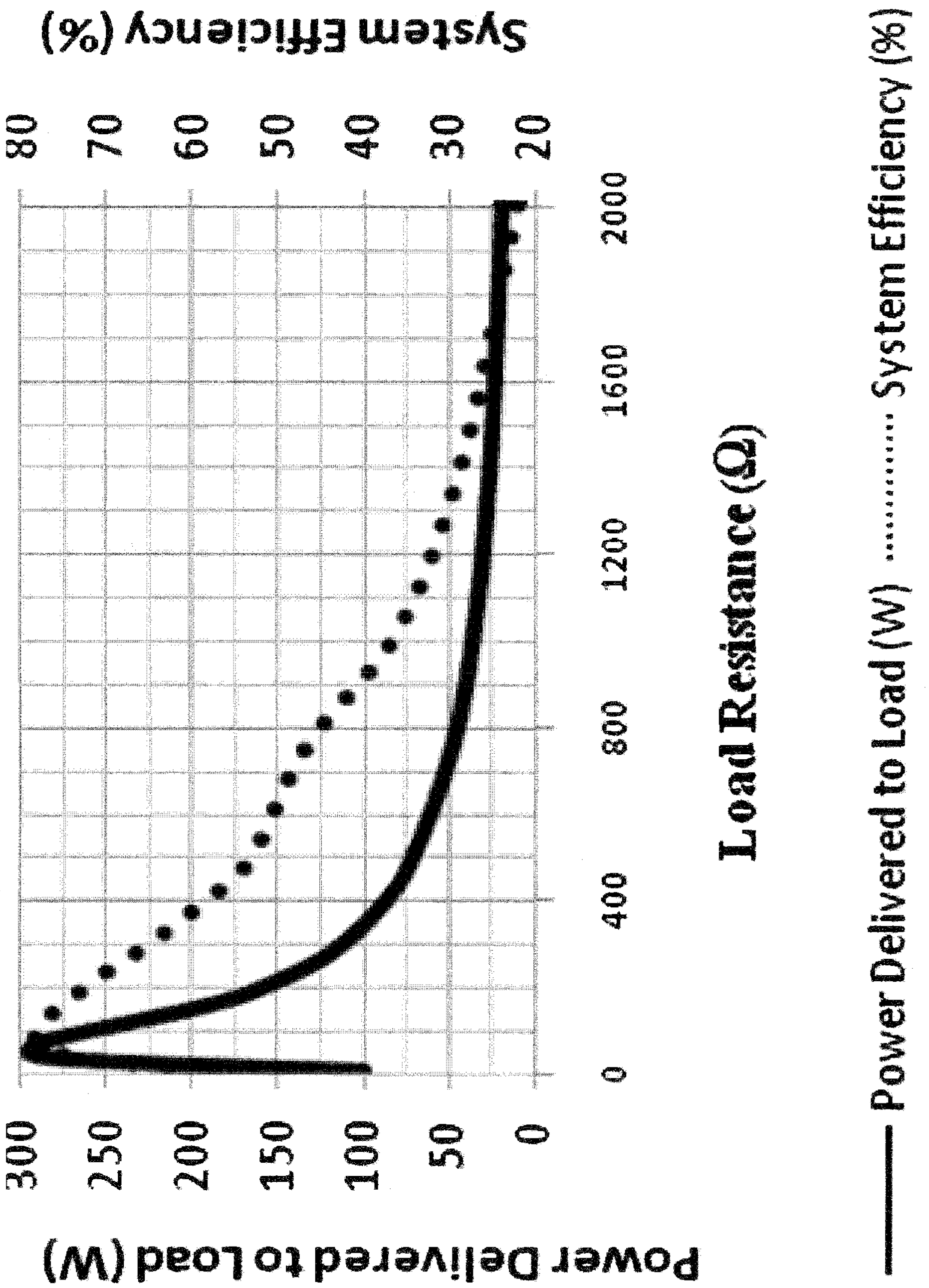

System Efficiency (%)
80
70
60
50
40
30
20
Power Delivered to Load (W)
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
Load Resistance (Ω)
—— Power Delivered to Load (W) ………… System Efficiency (%)

FIG. 58

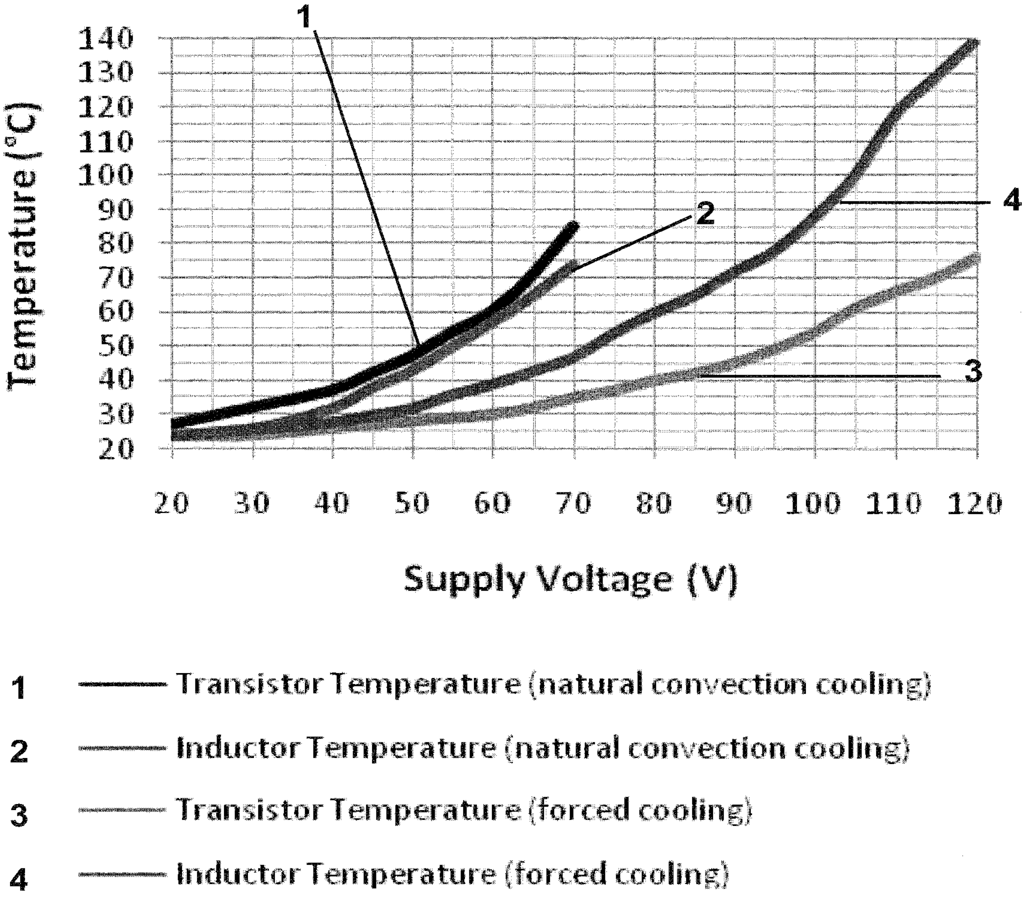

1
2
3
4
140
130
120
110
100
90
80
70
60
50
40
30
20
Temperature (°C)
20 30 40 50 60 70 80 90 100 110 120
Supply Voltage (V)
1 Transistor Temperature (natural convection cooling)
2 Inductor Temperature (natural convection cooling)
3 Transistor Temperature (forced cooling)
4 Inductor Temperature (forced cooling)

FIG. 59

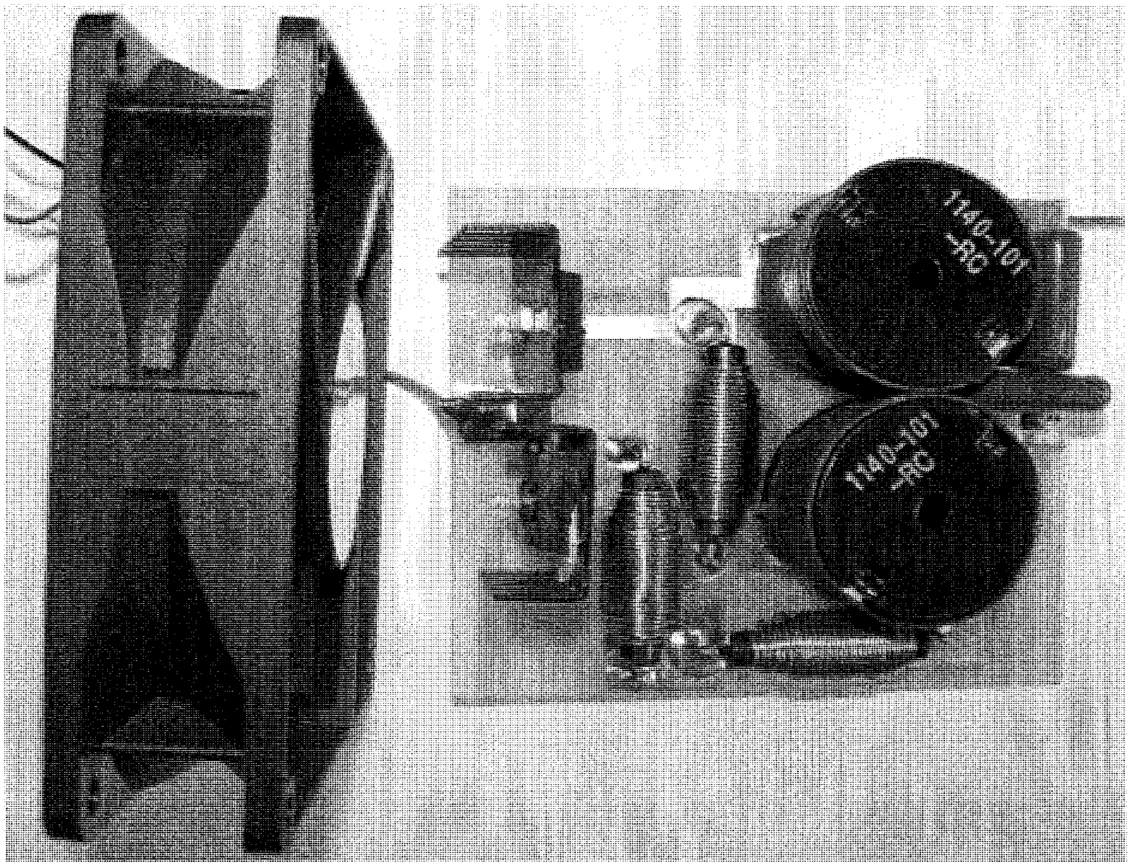
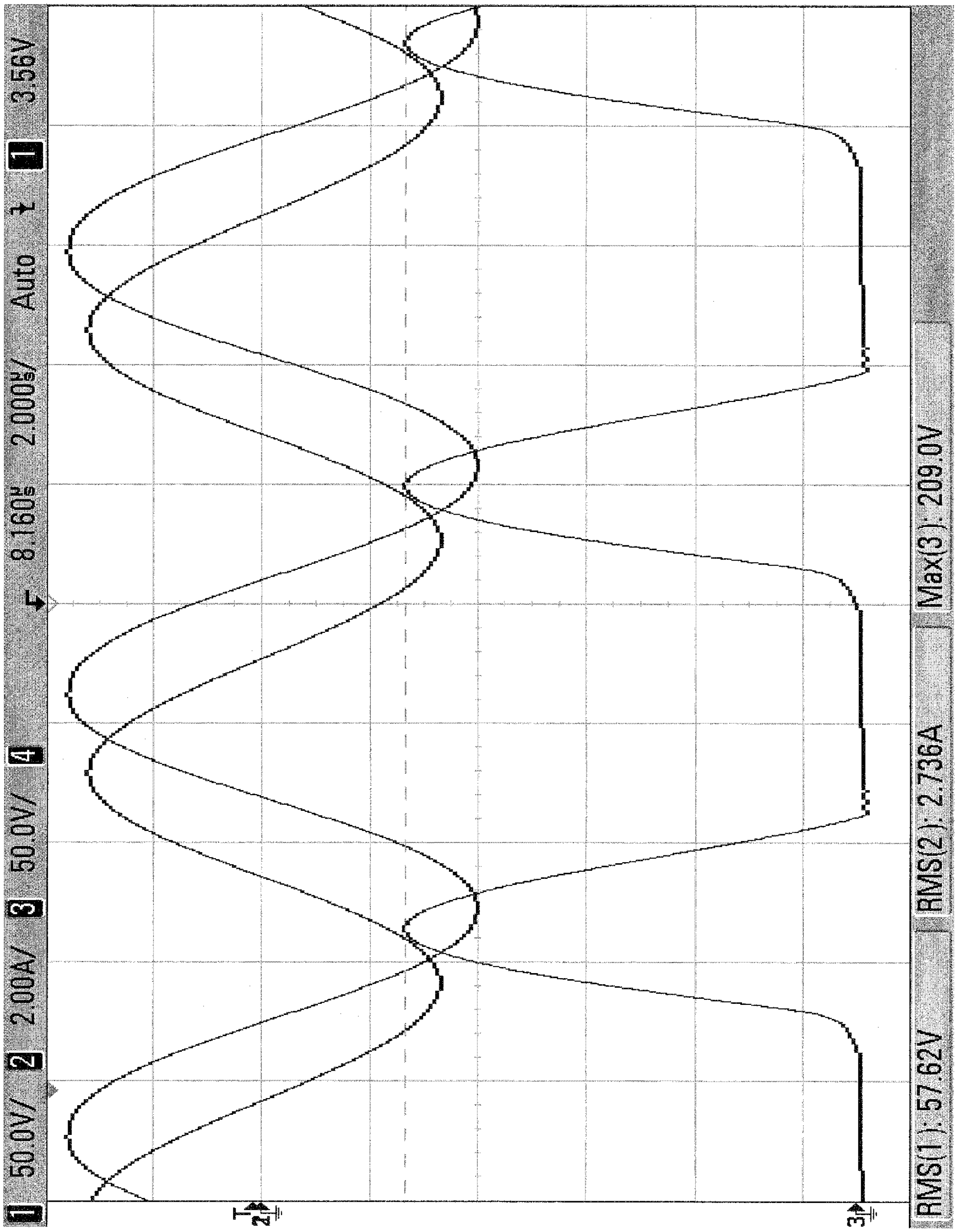


FIG. 60



RMS(1): 57.62V
RMS(2): 2.736A
Max(3): 209.0V

FIG. 61

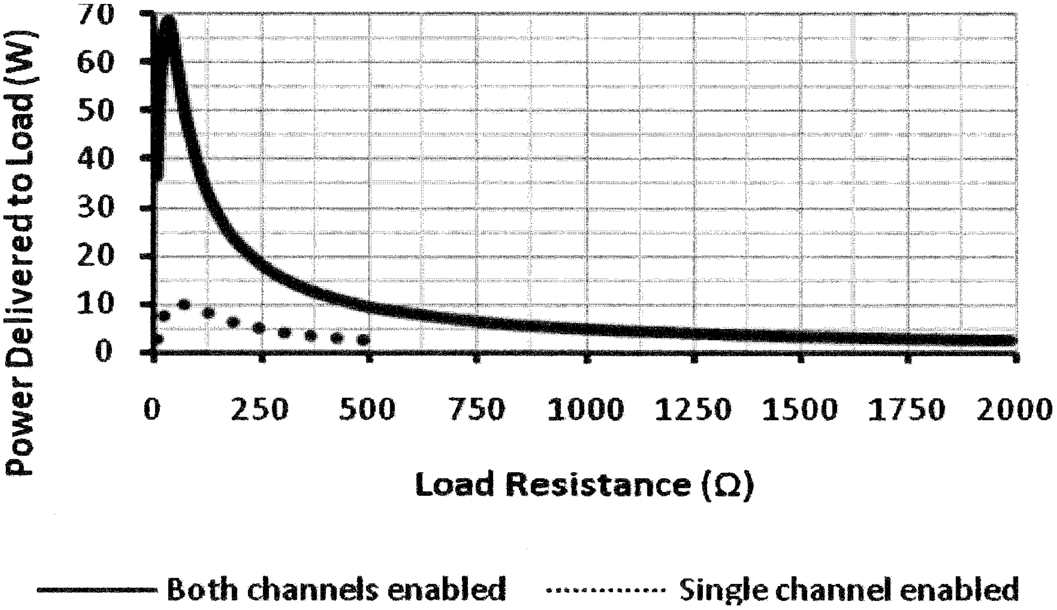


FIG. 62A

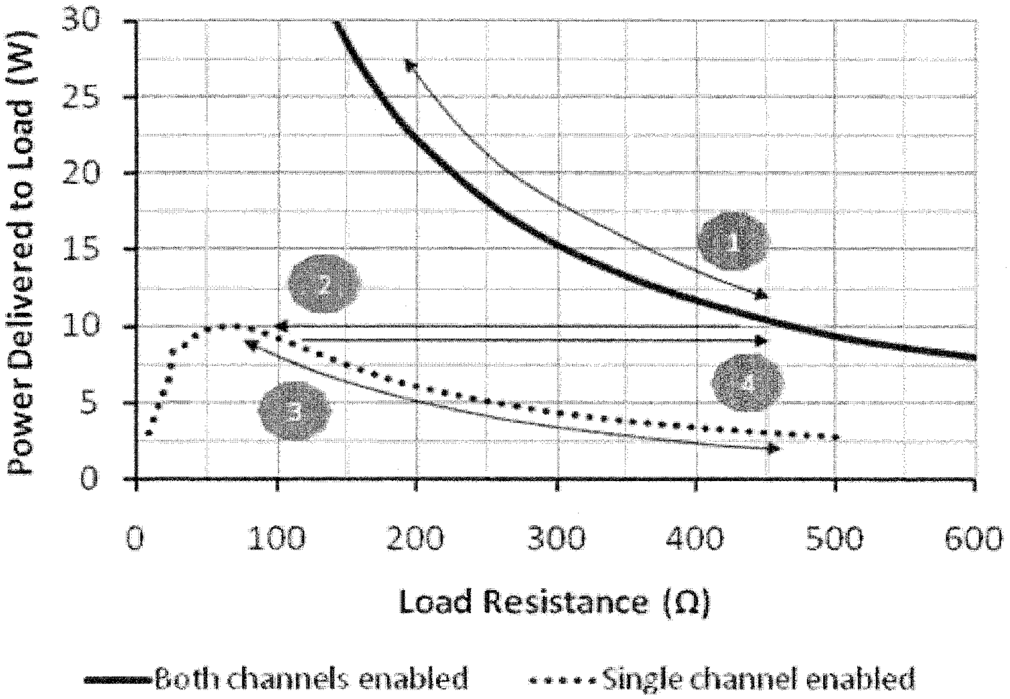


FIG. 62B

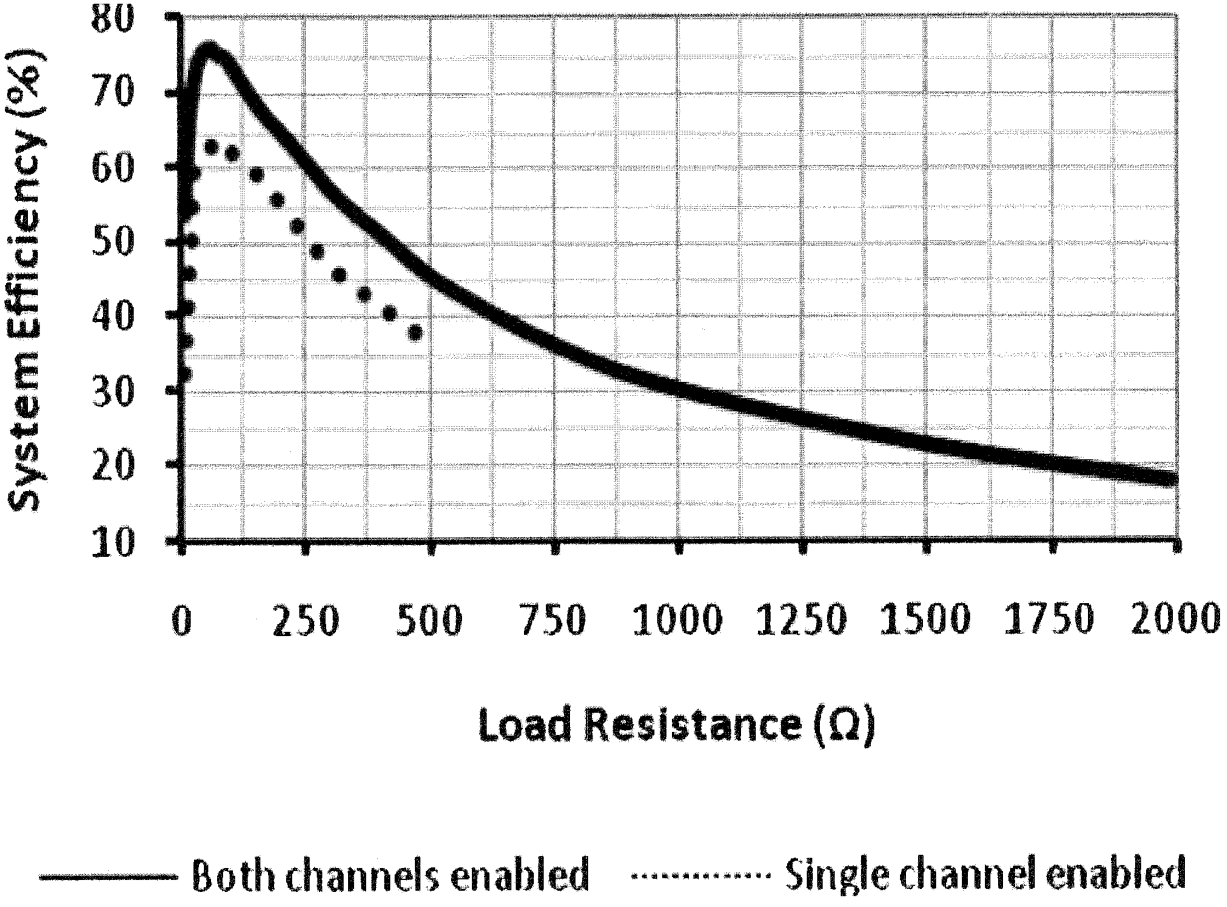

System Efficiency (%)
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 63

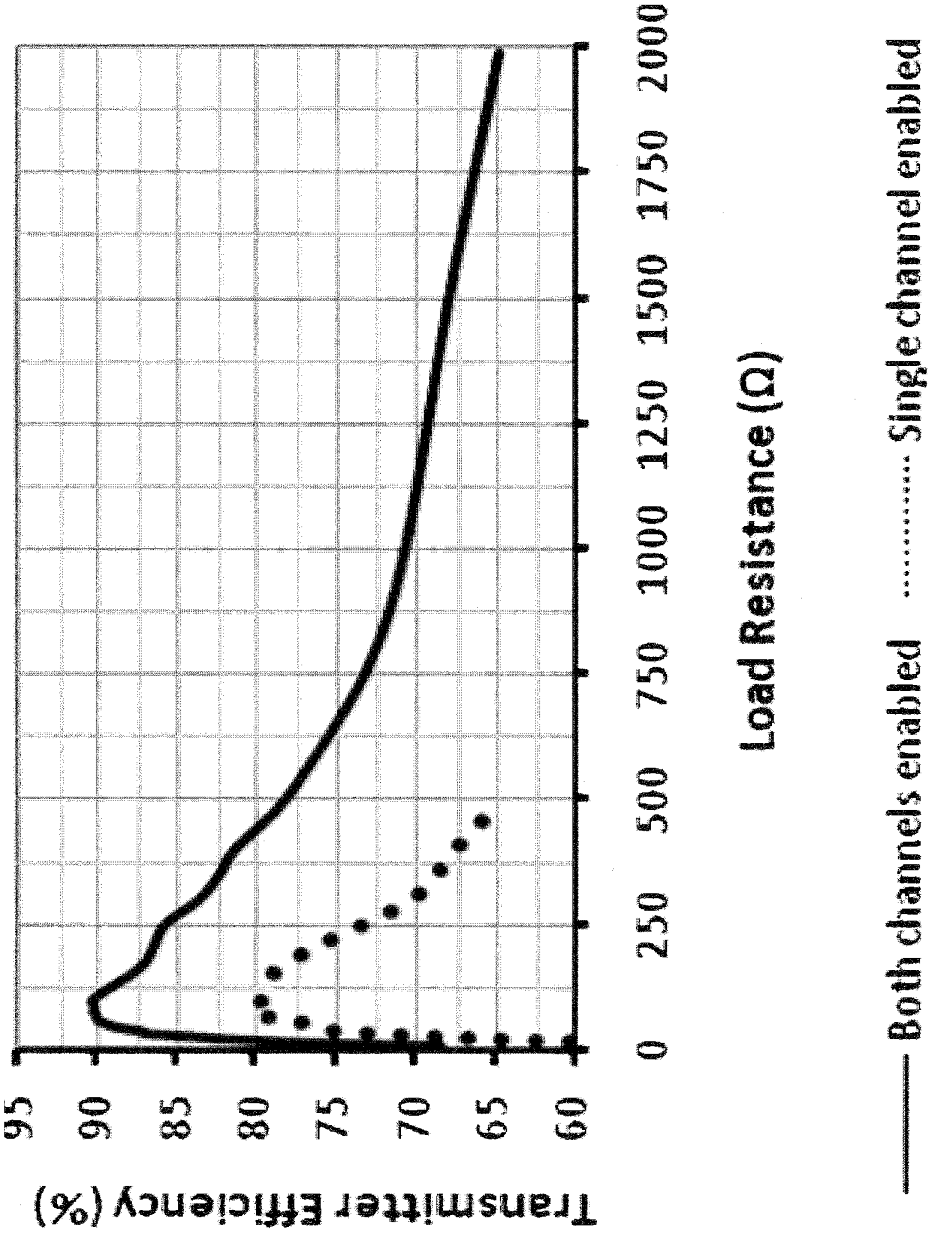

Transmitter Efficiency (%)
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 64

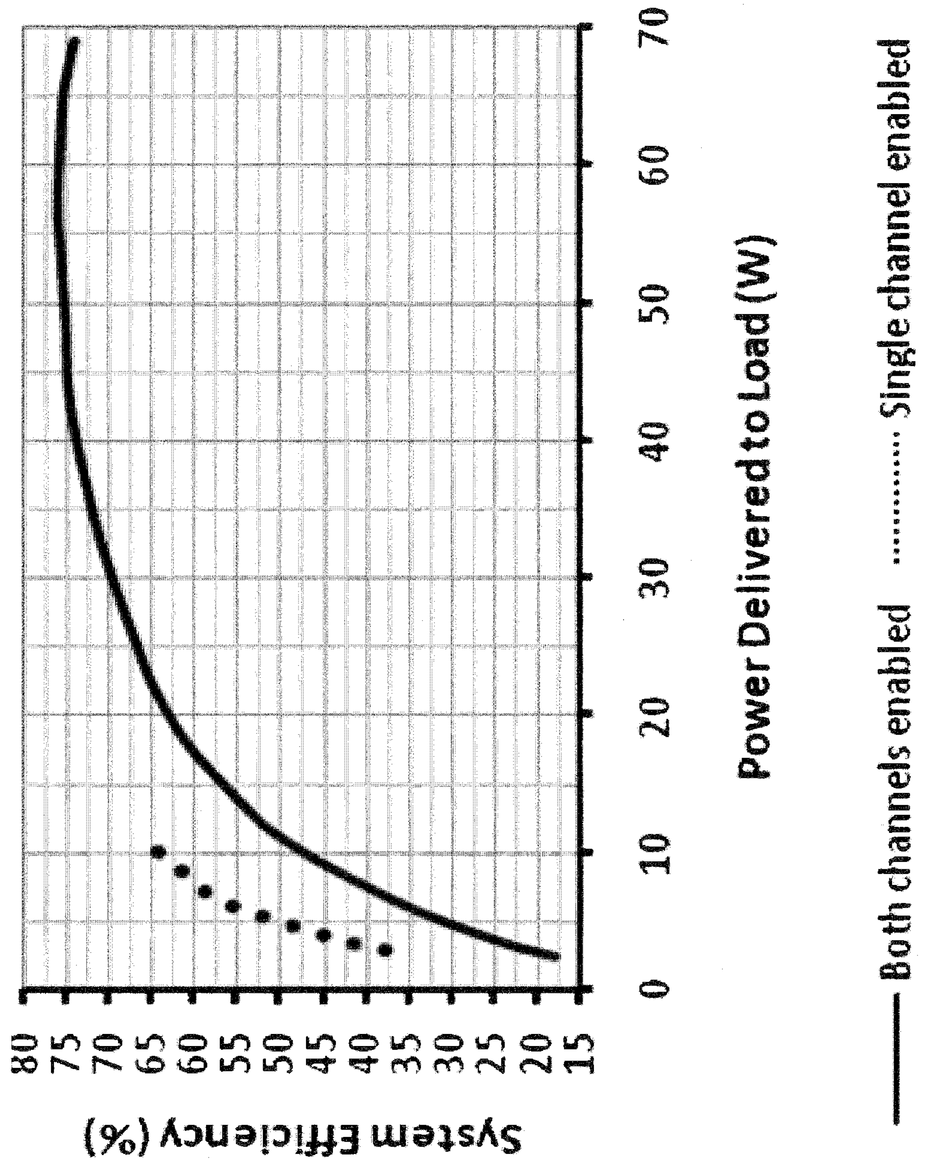

System Efficiency (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
0
10
20
30
40
50
60
70
Power Delivered to Load (W)
Both channels enabled
Single channel enabled

FIG. 65

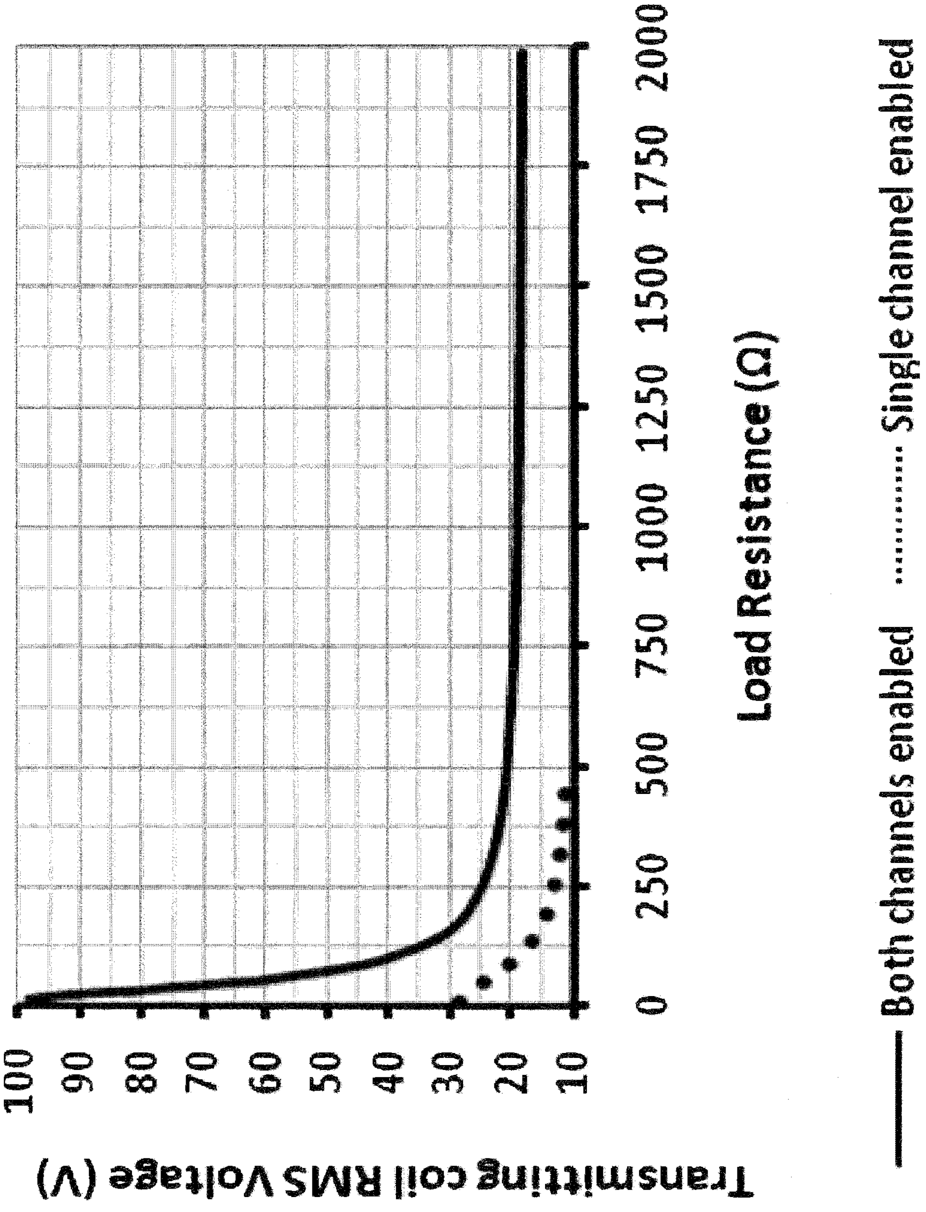

Transmitting coil RMS Voltage (V)
100
90
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 66

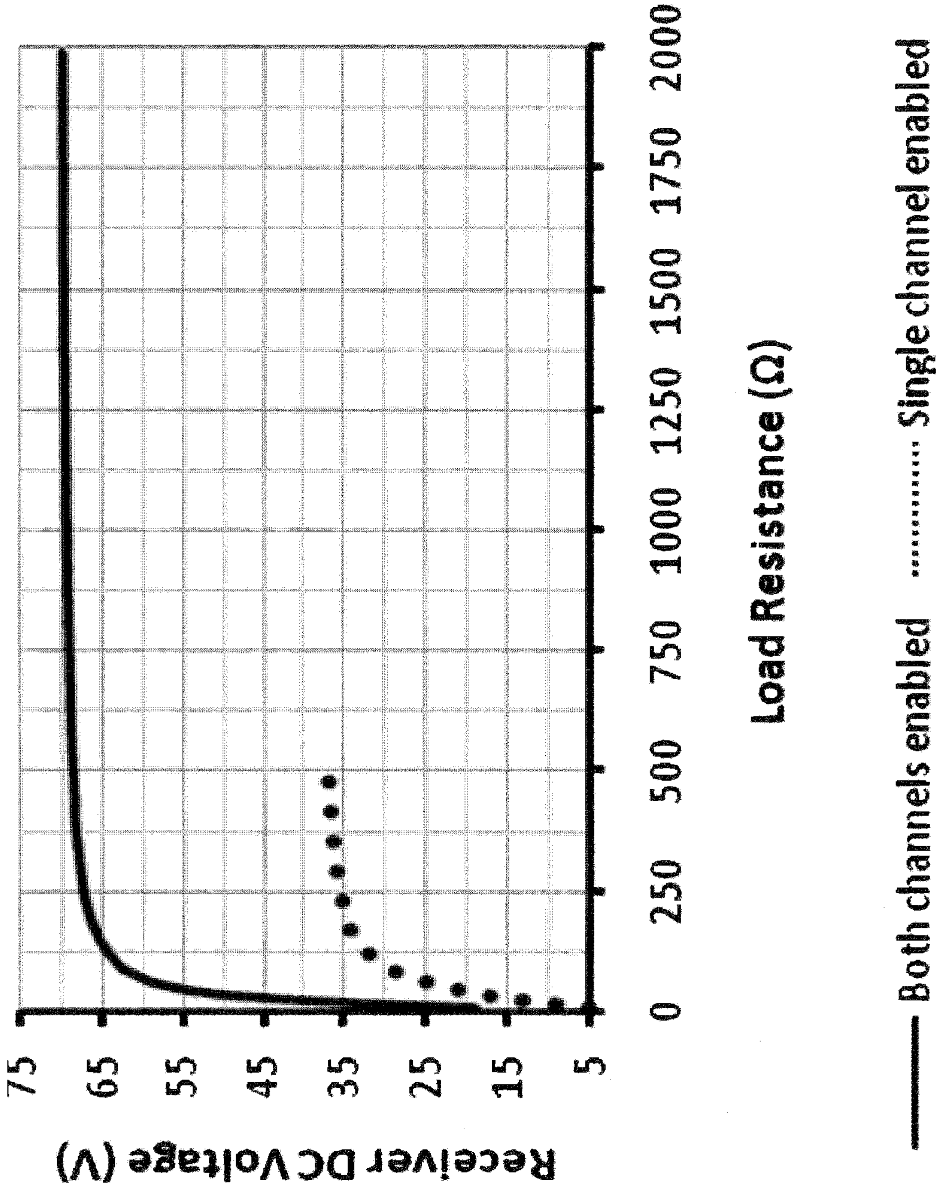

Receiver DC Voltage (V)
75
65
55
45
35
25
15
5
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 67

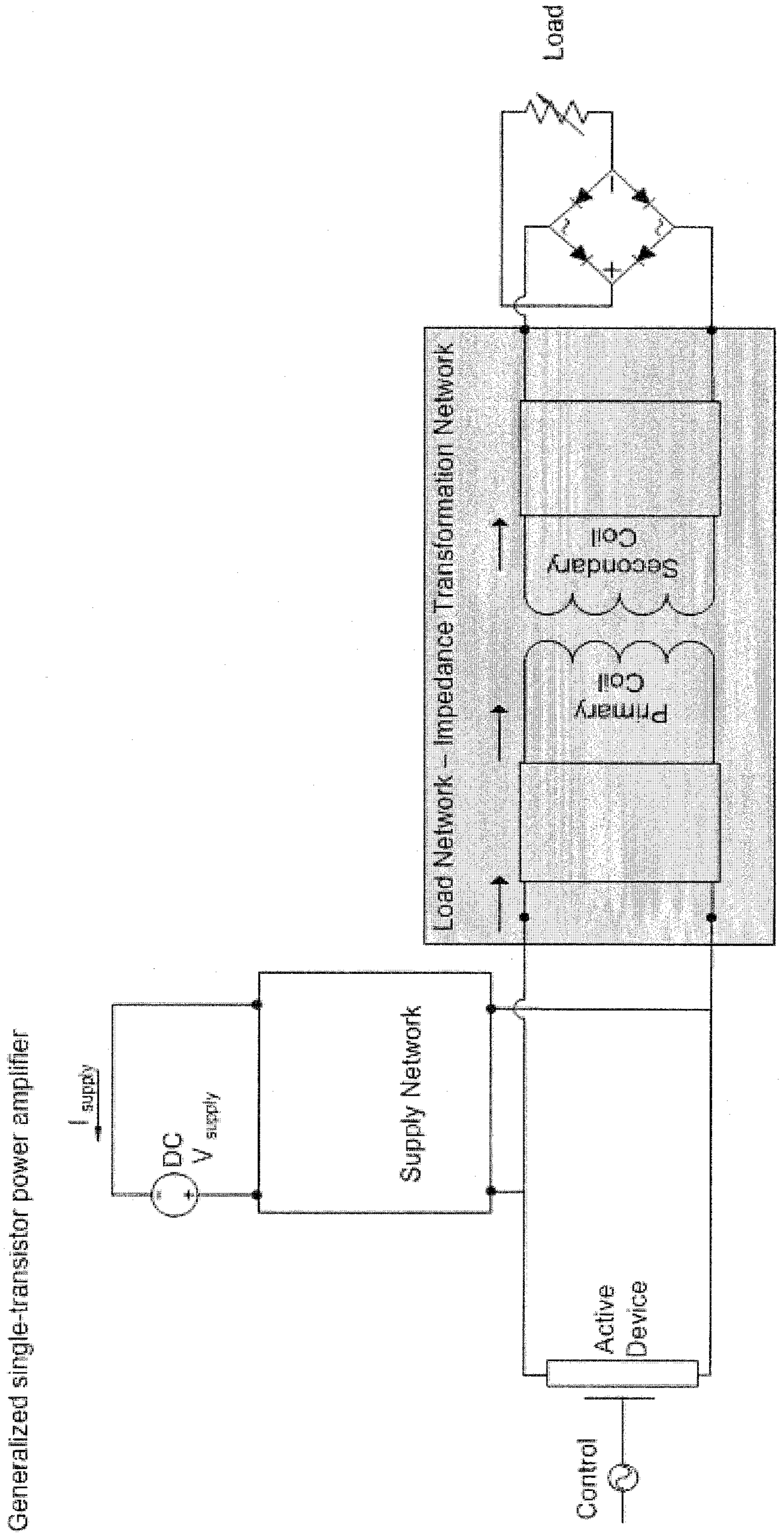

Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Active Device
Control
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load

FIG. 68

Generalized single-transistor amplifiers in a push-pull configuration

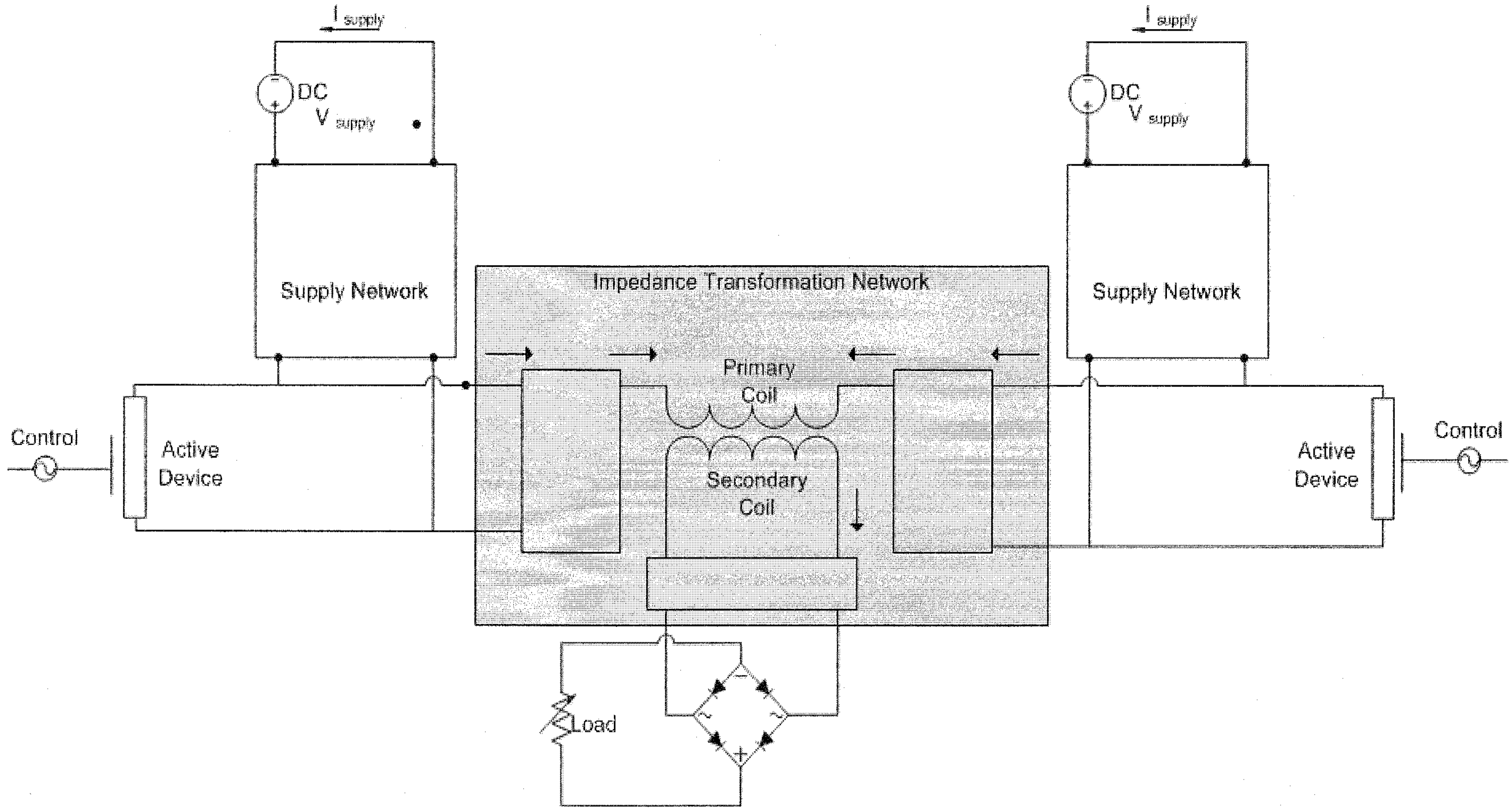


FIG. 69

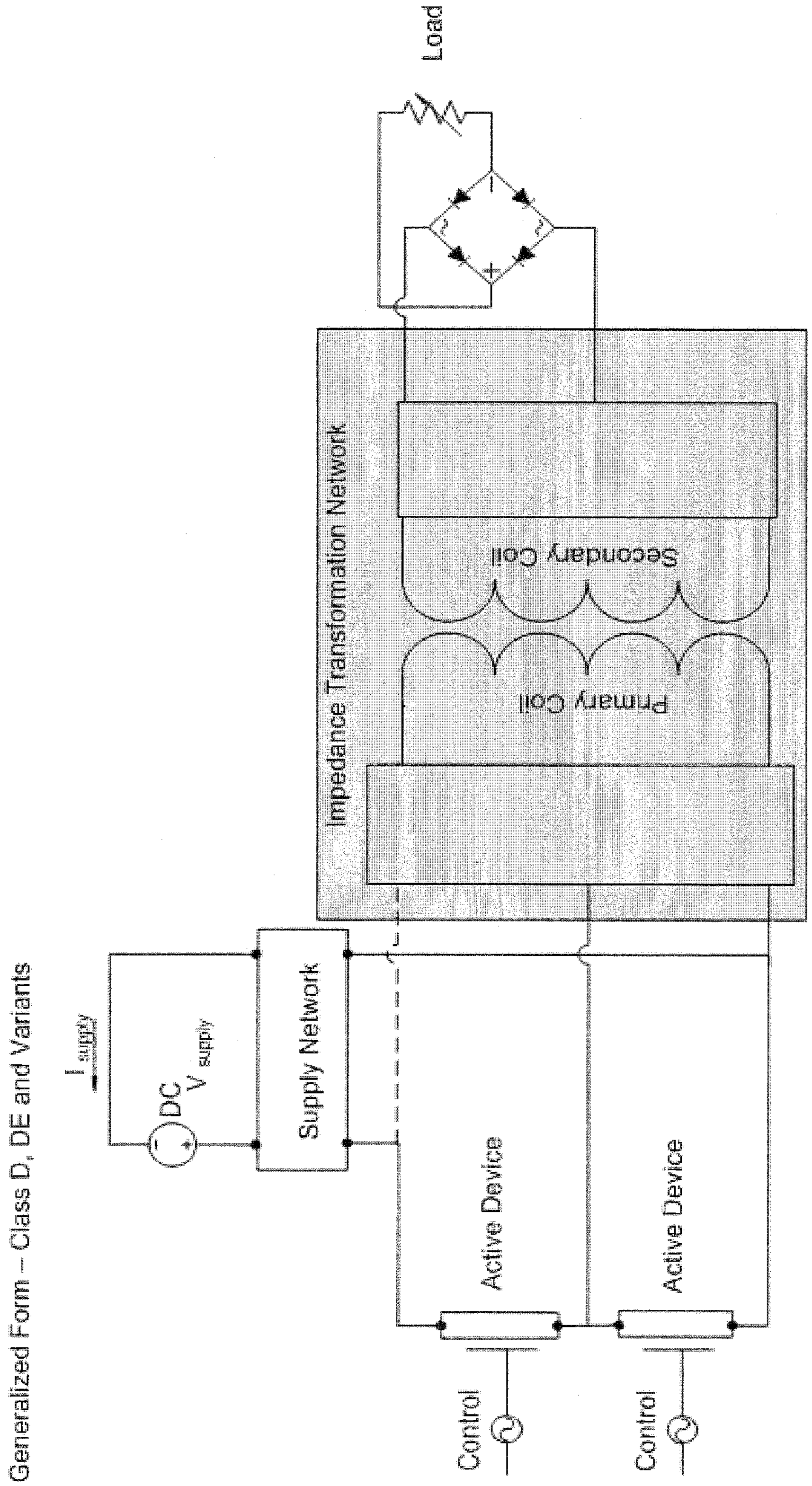

Generalized Form – Class D, DE and Variants
Load
Impedance Transformation Network
Secondary Coil
Primary Coil
Supply Network
DC
V_{supply}
I_{supply}
Active Device
Active Device
Control
Control

FIG. 70

Generalized Form – Class D, DE and Variants in a push-pull configuration

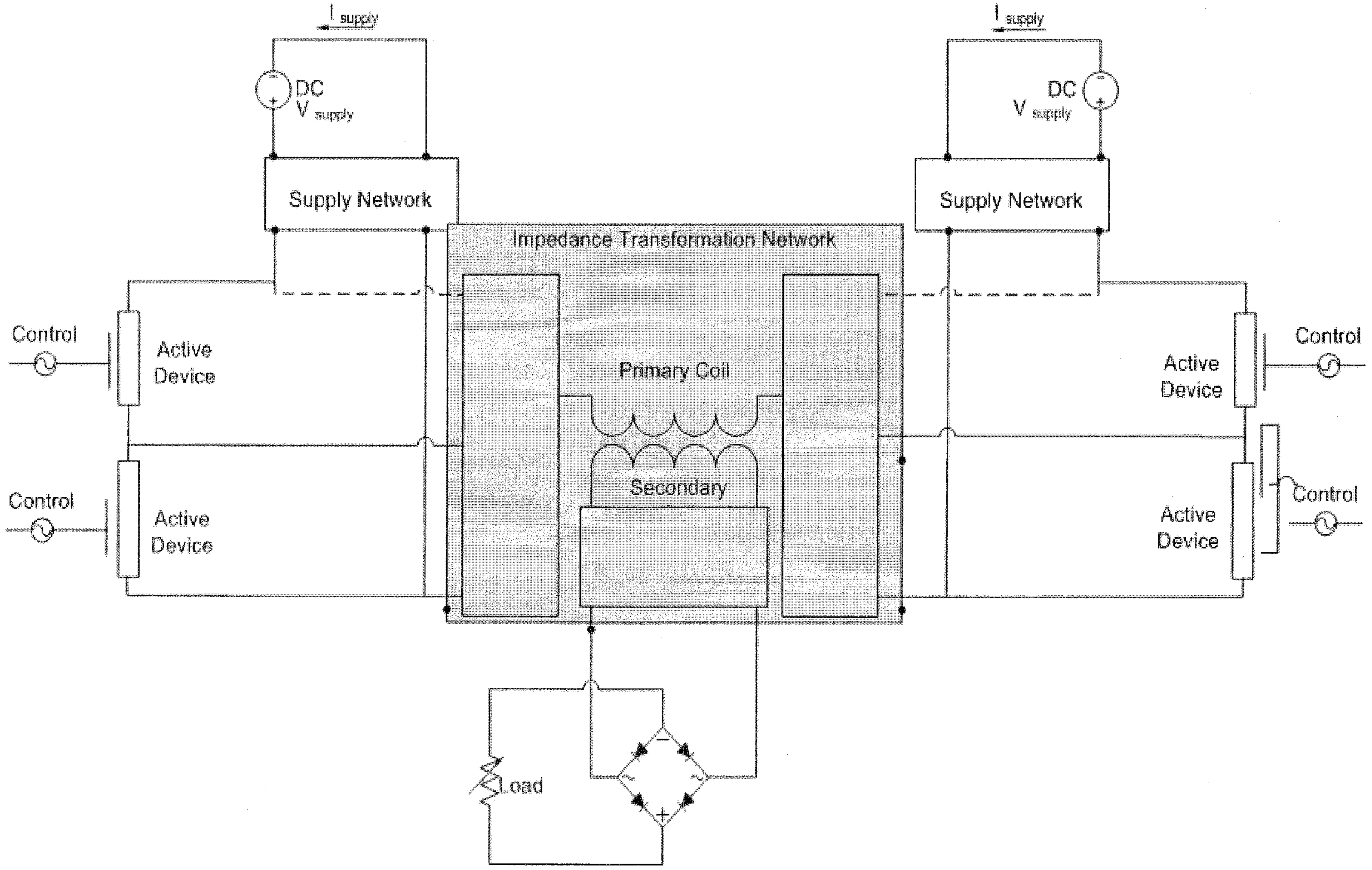


FIG. 71

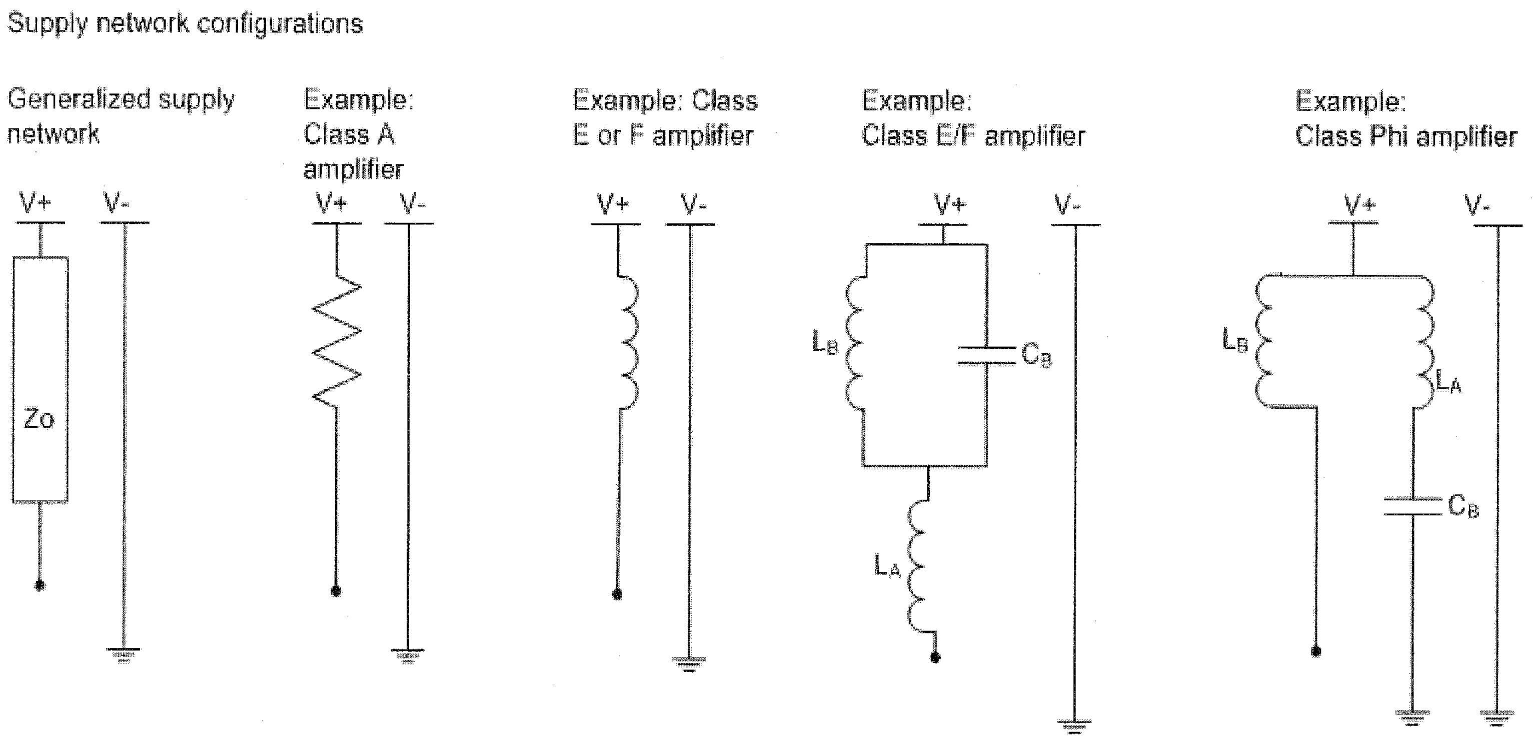

Supply network configurations
Generalized supply network
V+
V-
Zo
Example: Class A amplifier
V+
V-
Example: Class E or F amplifier
V+
V-
Example: Class E/F amplifier
V+
V-
L_B
C_B
L_A
Example: Class Phi amplifier
V+
V-
L_B
L_A
C_B

FIG. 72

Load network functions – Impedance Transformation Network

Generalized form - single-end drive

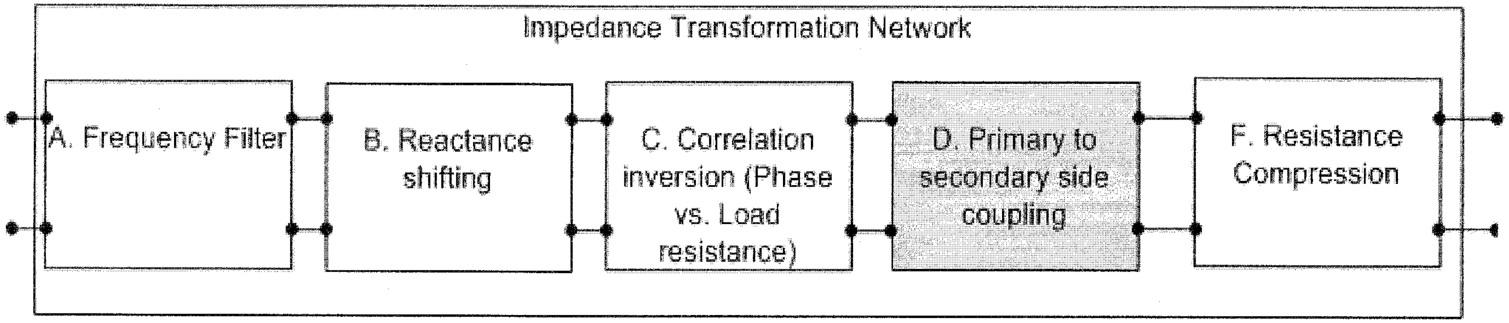


FIG. 73

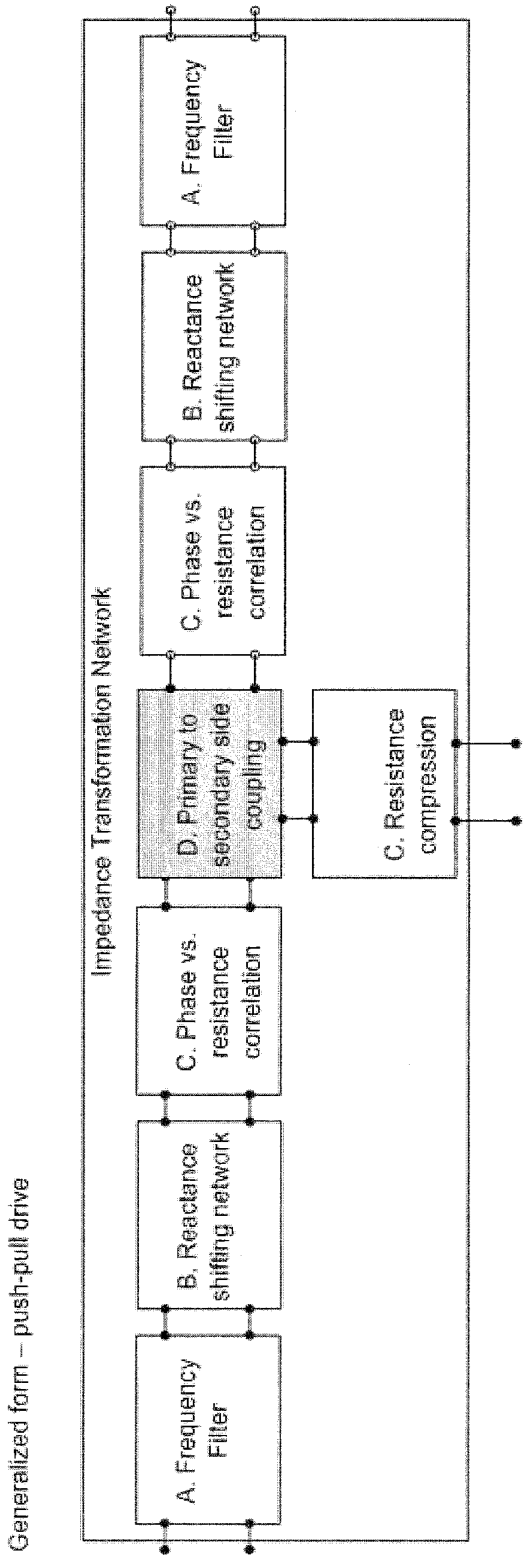

Generalized form – push-pull drive
Impedance Transformation Network
A. Frequency Filter
B. Reactance shifting network
C. Phase vs. resistance correlation
D. Primary to secondary side coupling
C. Resistance compression
C. Phase vs. resistance correlation
B. Reactance shifting network
A. Frequency Filter

FIG. 74

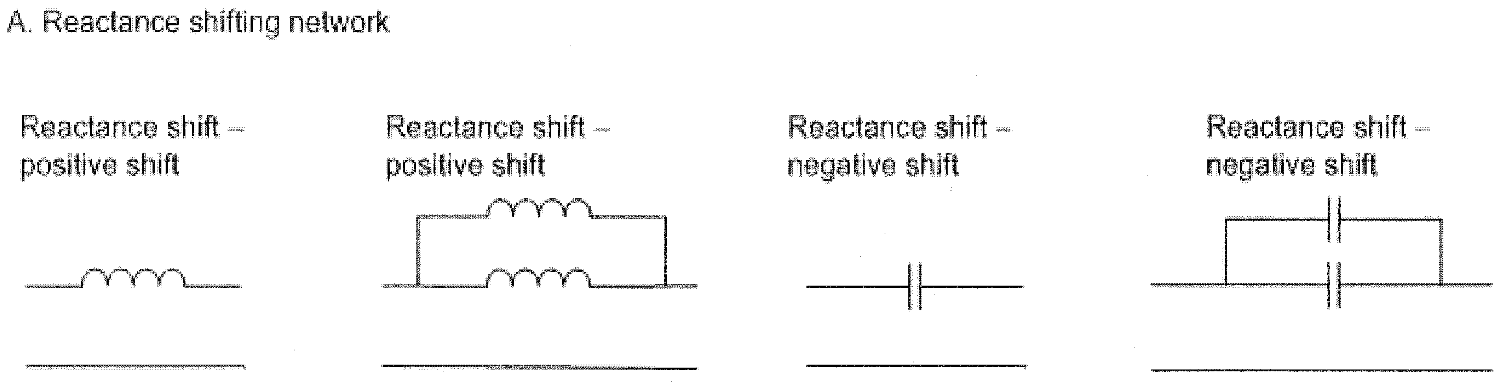

A. Reactance shifting network
Reactance shift – positive shift
Reactance shift – positive shift
Reactance shift – negative shift
Reactance shift – negative shift

FIG. 75

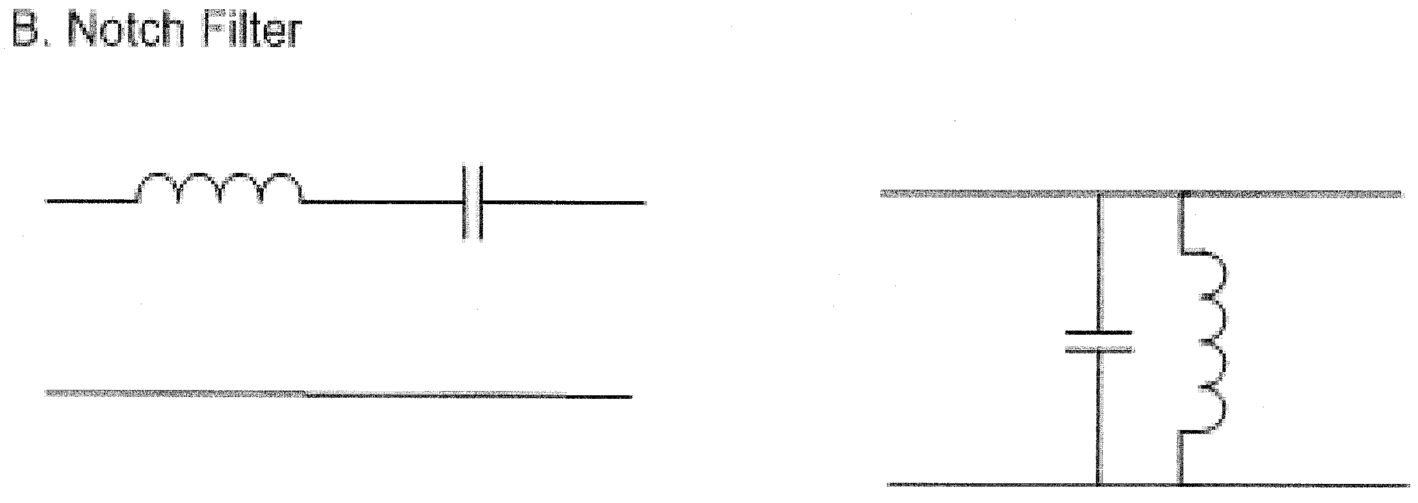


FIG. 76

C. Phase vs. resistance correlation

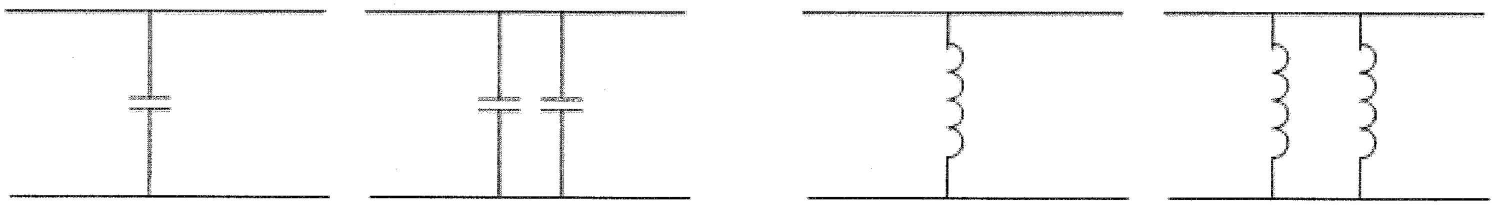


FIG. 77

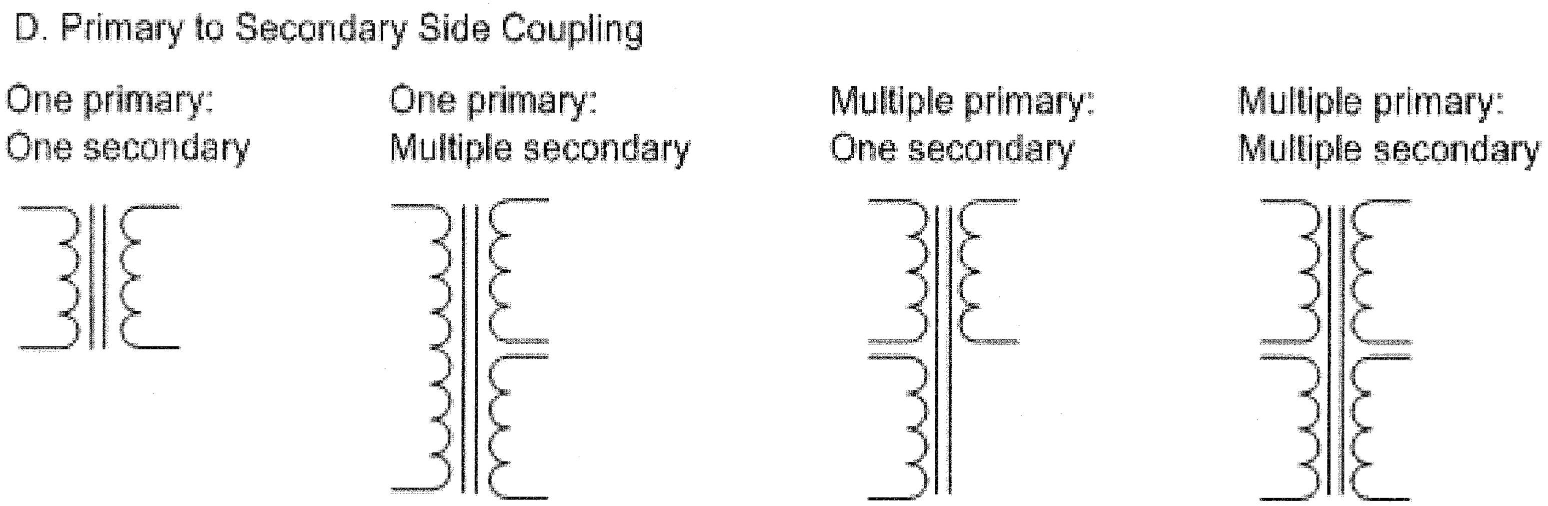
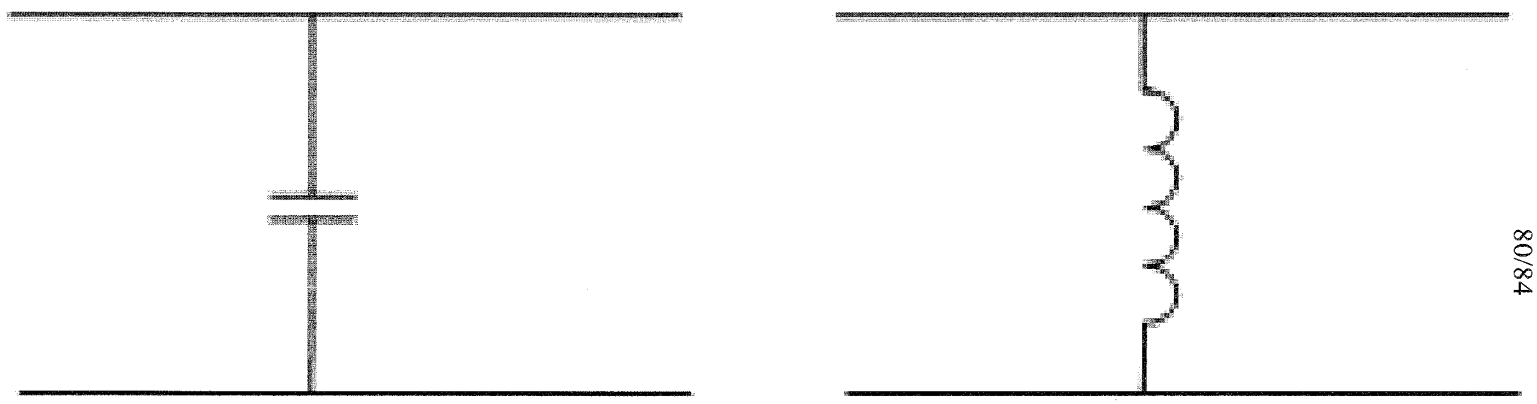

D. Primary to Secondary Side Coupling
One primary:
One secondary
One primary:
Multiple secondary
Multiple primary:
One secondary
Multiple primary:
Multiple secondary

FIG. 78



E. Resistance compression

FIG. 79

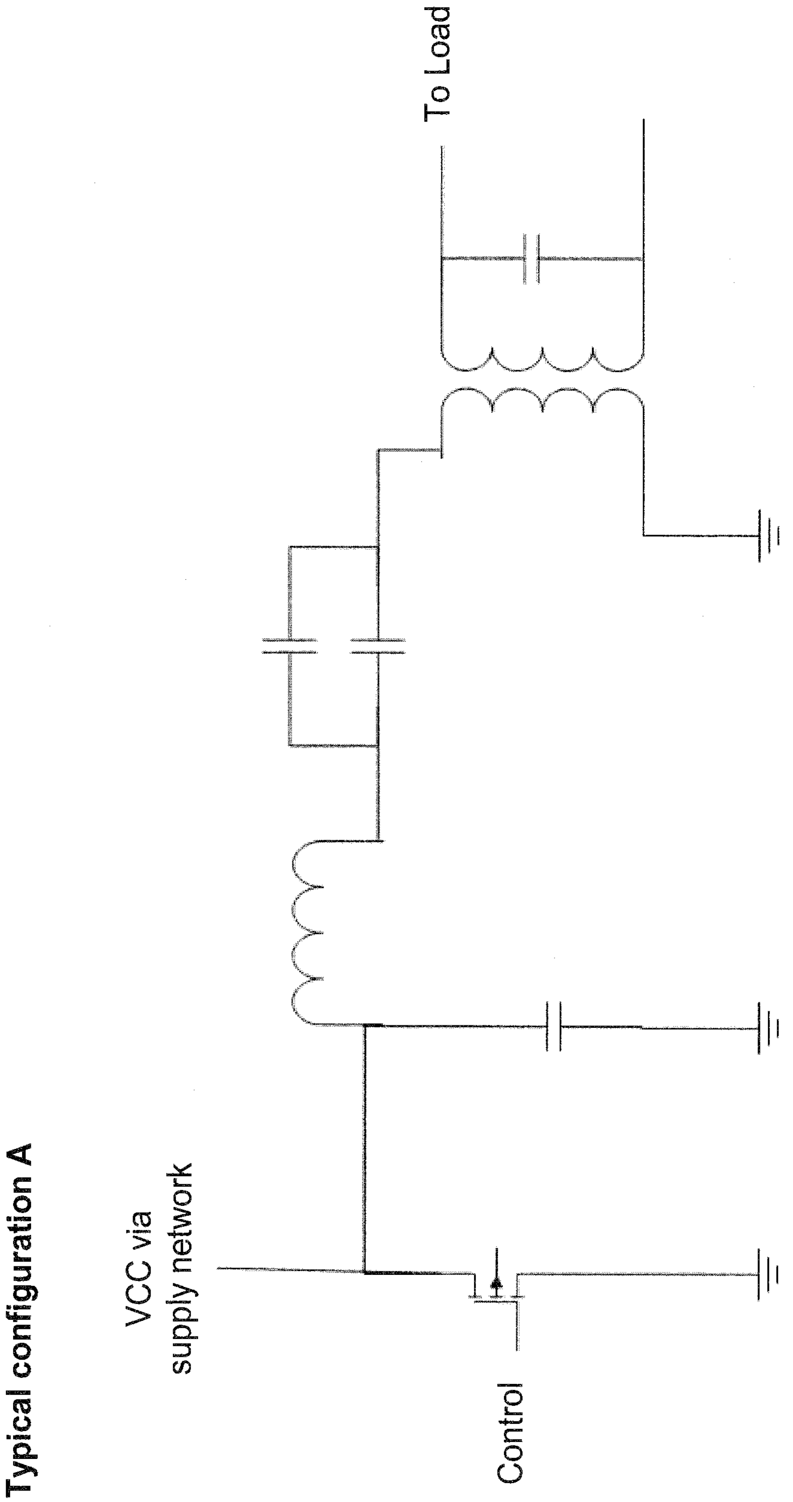

Typical configuration A
VCC via
supply network
Control
To Load

FIG. 80

Typical configuration B

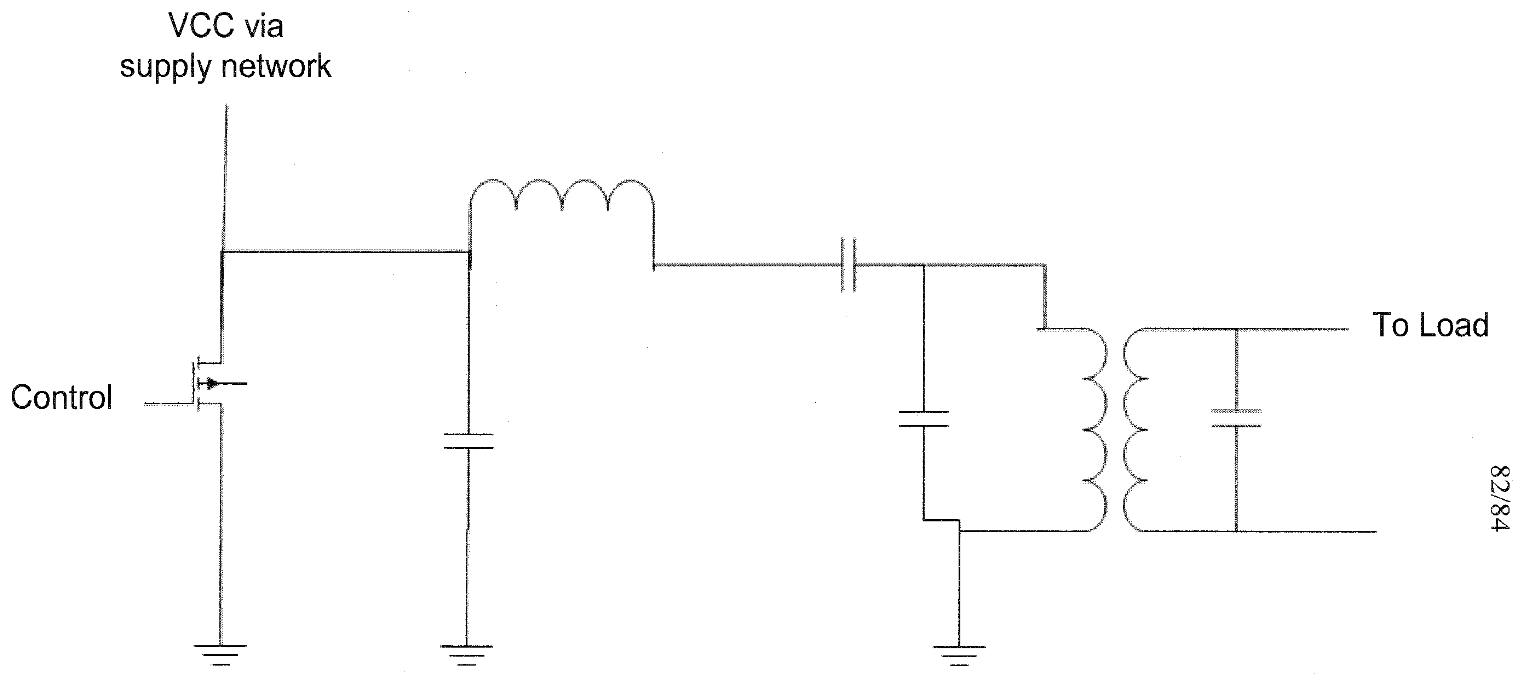


FIG. 81

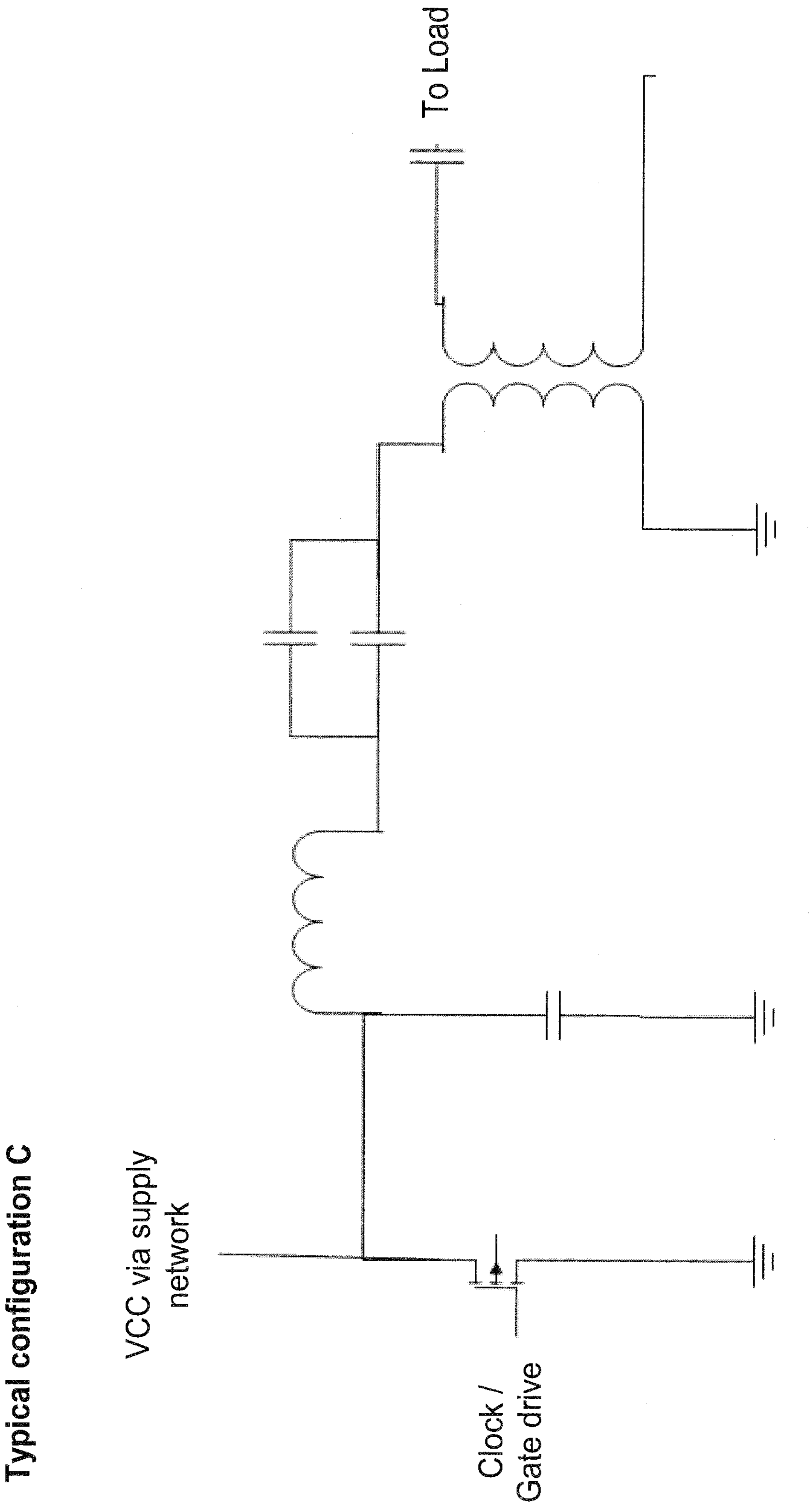
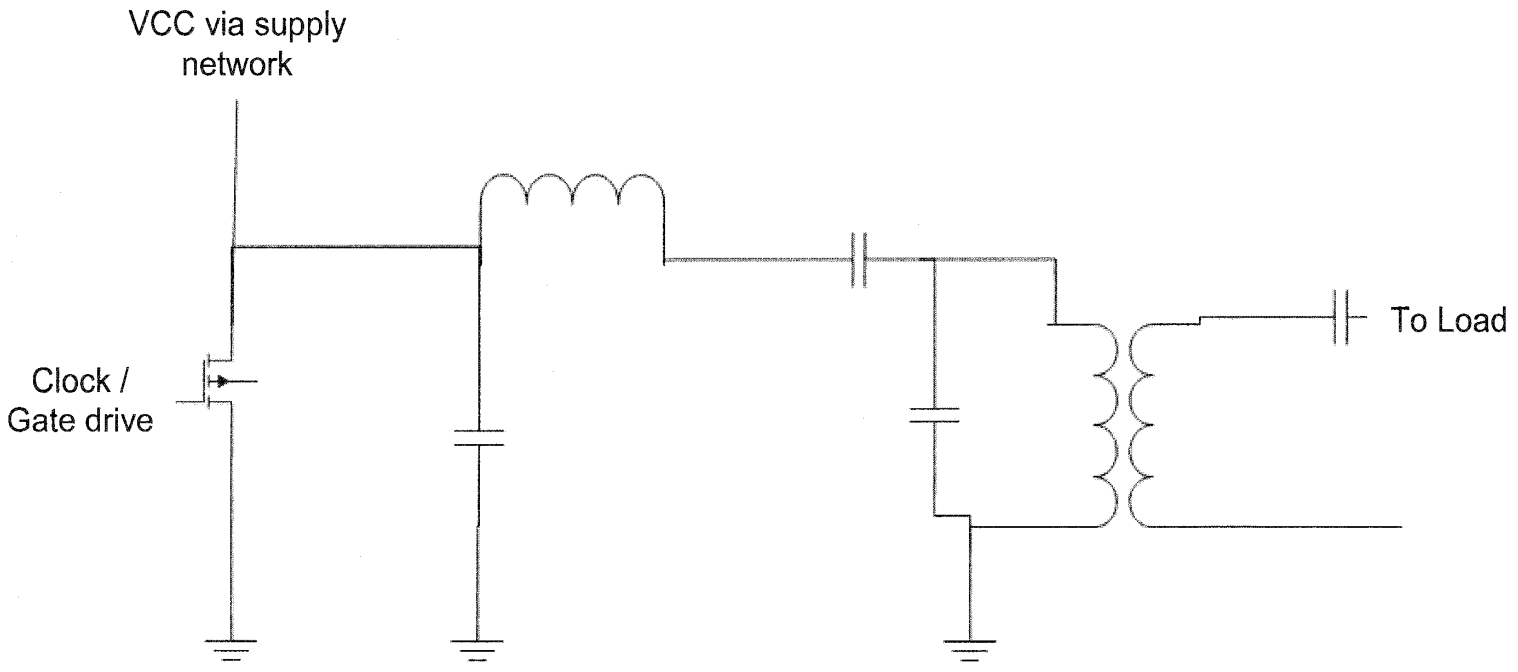

Typical configuration C
VCC via supply network
Clock / Gate drive
To Load

FIG. 82



Typical configuration D

FIG. 83

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(75) Inventors/Applicants *(for US only)*: **LIN, Jenshan** [US/US]; 910 S.W. 105th Terrace, Gainesville, FL 32607 (US). **LOW, Zhen, Ning** [SG/US]; 712 S.W. 16th Avenue, #311, Gainesville, FL 32601 (US).

(74) Agents: **PARKER, James, S.** et al.; Saliwanchik, Lloyd, Saliwanchik, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: METHOD AND APPARATUS FOR LOAD DETECTION FOR A PLANAR WIRELESS POWER SYSTEM

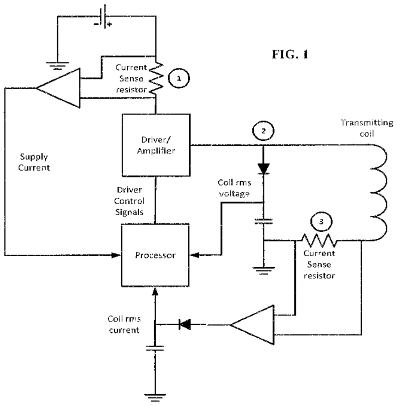
FIG. 1

(57) Abstract: Embodiments of the subject invention relate to a method and apparatus for determining information regarding a load in a planar wireless power transfer system by extracting system operating parameters from one or more test points in the transmitter circuit. As shown in Figure 1, a specific embodiment showing three test points in the transmitter circuit from which operating parameters can be extracted. The transmitter circuit is designed to produce a magnetic field, by driving the transmitter coil, which inductively couples to a receiver coil such that power is provided to a receiver. By extracting operating parameters from the transmitter circuit, the receiver does not need to incorporate sophisticated signal processing and can be manufactured with low cost.

WO 2010/030977 A2

DESCRIPTION

METHOD AND APPARATUS FOR LOAD DETECTION FOR A PLANAR WIRELESS POWER SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Application Serial No. 12/209,784, filed September 12, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Portable electronic devices such as laptop computers, LCD digital photo frames, mobile phones, and mp3 players require power to operate. Often, these devices use rechargeable batteries to provide power. The batteries are typically recharged by plugging a charger into the portable device or by removing the battery from the portable device and separately recharging the battery using a wired charger.

The cables that once restricted electronic devices are gradually being rendered unnecessary by wireless communication technology, and as the circuits that constitute the electronic devices shrink, only the power cords and batteries continue to restrict the portability of mobile electronic devices.

Current trends are leading towards going completely wireless. This means that portable devices can remain portable and can avoid having to 'plug-in' for power charging. Electro-magnetic inductive charging uses a coil to create an electromagnetic field across a charging station surface. The device then converts power from the electromagnetic field back into usable electricity, which is put to work charging the battery. Two coils are brought close to each other and when current is passed through one, the generated magnetic flux causes electromotive force to be generated in the other.

In order to reduce unnecessary generation of magnetic flux, for example when no receiver is positioned to receive the magnetic flux or when the battery associated with the receiver is already charged, techniques to determine whether a valid load is placed in position with respect to the transmitting coil and to determine the charging status of the load have been developed. In order to determine if a valid load is placed on the transmitting coil and to determine the charging status, a communication link is often used between the transmitting unit and the receiving unit. Such a link is often also used to determine whether multiple loads are placed on the transmitter. However, a communication link adds cost and size to the system, which is not desirable for a compact receiving unit to be integrated inside a portable device. Alternatively to a communication system, such as a complex DSP system, can be used to extract system operating parameters from the transmitter to determine the operating status of the system. However, such systems are typically complicated and consume large amounts of power which reduce system efficiency and increase system cost.

Accordingly, there still exists a need in the art for an efficient method and apparatus to determine whether a valid load is positioned to be charged and the charging status of the load.

BRIEF SUMMARY

Embodiments of the subject invention relate to a method and apparatus for determining information regarding a load in a planar wireless power transfer system by extracting system operating parameters from one or more test points in the transmitter circuit. As shown in Figure 1, a specific embodiment showing three test points in the transmitter circuit from which operating parameters can be extracted. The transmitter circuit is designed to produce a magnetic field, by driving the transmitter coil, which inductively couples to a receiver coil such that power is provided to a receiver. By extracting operating parameters from the transmitter circuit, the receiver does not need to incorporate sophisticated signal processing and can be manufactured with low cost.

Test point 1 in Figure 1 shows where the supply current of the system can be measured. The embodiment shown in Figure 1 is to use a current sense resistor and a differential amplifier located on the high side of the power supply to measure the transmitter supply current. In an alternative embodiment, the transmitter supply current can be measured on the low side of the power supply. Other techniques can also be used. The output voltage of the differential amplifier, which is proportional to the supply current, is then fed into the analog-to-digital conversion (ADC) port of a processor.

Test point 2 in Figure 1 shows where the RMS coil voltage can be measured. The embodiment shown in Figure 1 extracts the RMS coil voltage by rectifying the coil voltage across a diode and holding the charge using a charge holding capacitor. A resistor can be added in parallel to the capacitor to control the response time of the circuit. Other techniques can also be used to extract the RMS coil voltage. The rectified DC voltage is then fed into the ADC port of a processor.

Test point 3 in Figure 1 shows where the RMS coil current of the coil can be measured. The RMS coil current can be extracted before or after the coil. The embodiment shown in Figure 1, which is positioned after the coil, transforms the coil current to its voltage equivalent by using a current sense resistor and a differential amplifier. A diode charge holding capacitor is then used to further extract the RMS coil current. A resistor can be added in parallel to the capacitor to control the response time of the circuit. The rectified DC voltage is then fed into the ADC port of a processor. Other techniques can also be used to extract the RMS coil current.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a system block diagram for system operating parameters extraction in accordance with an embodiment of the subject invention.

Figure 2 shows measurement results of RMS coil voltage and supply current space diagram in accordance with an embodiment of the subject invention.

Figure 3 shows measurement results of RMS coil current and supply current space diagram in accordance with an embodiment of the subject invention.

Figure 4 shows simulation results of system operation for different number of loads in accordance with an embodiment of the subject invention.

Figure 5 shows power delivery versus transmitting coil voltage in accordance with an embodiment of the subject invention.

DETAILED DISCLOSURE

Embodiments of the subject invention relate to a method and apparatus for determining information regarding a load in a planar wireless transfer system by extracting system operating parameters from one or more test points in the transmitter circuit. As shown in Figure 1, a specific embodiment showing three test points in the transmitter circuit from which operating parameters can be extracted. The transmitter circuit is designed to produce a magnetic field, by driving the transmitter coil, which inductively couples to a receiver coil such that power is provided to a receiver. By extracting operating parameters from the transmitter circuit, the receiver does not need to incorporate sophisticated signal processing and can be manufactured with low cost.

Test point 1 in Figure 1 shows where the supply current of the system can be measured. The embodiment shown in Figure 1 is to use a current sense resistor and a differential amplifier located on the high side of the power supply to measure the transmitter supply current. In an alternative embodiment, the transmitter supply current can be measured on the low side of the power supply. Other techniques can also be used. The output voltage of the differential amplifier, which is proportional to the supply current, is then fed into the analog-to-digital conversion (ADC) port of a processor.

Test point 2 in Figure 1 shows where the RMS coil voltage can be measured. The embodiment shown in Figure 1 extracts the RMS coil voltage by rectifying the coil voltage across a diode and holding the charge using a charge holding capacitor. A resistor can be added in parallel to the capacitor to control the response time of the circuit. Other techniques can also be used to extract the RMS coil voltage. As an example, the real time AC voltage can be measured with a fast enough ADC. The rectified DC voltage is then fed into the ADC port of a processor.

Test point 3 in Figure 1 shows where the RMS coil current of the coil can be measured. The RMS coil current can be extracted before or after the coil. The embodiment shown in Figure 1, which is positioned after the coil, transforms the coil current to its voltage equivalent by using a current sense resistor and a differential amplifier. A diode charge holding capacitor is then used to further extract the RMS coil current. The diode can be removed by using a fast ADC. A resistor can be added in parallel to the capacitor to control the response time of the circuit. The rectified DC voltage is then fed into the ADC port of a processor. Other techniques can also be used to extract the RMS coil current. As an example, a loop can be used to measure the AC current.

Figure 2 shows the coil RMS voltage and supply current space diagram of the operation of an embodiment of a planar wireless power transfer system measured in accordance with an embodiment of the invention. Figure 3 shows the coil RMS current and supply current space diagram of the operation of the wireless power transfer system measured in accordance with an embodiment of the invention. As the threshold and location of the various regions in the space diagrams of Figure 2 and Figure 3 depend primarily on the size of the transmitter coil and supply voltage of the transmitter, each transmitter can have different thresholds and locations of regions. In a specific embodiment, the coil voltage or the coil current can be used to track the charge status of the load and/or whether the load is operation properly. The method and system are able to determine invalid load conditions such as no load and metal sheet, and distinguish them clearly from normal operation with valid load. This is because the distance between the invalid load conditions and valid load conditions is large in either the coil RMS voltage and supply current space diagram or coil RMS current and supply current space diagram. In one embodiment, the system extracts supply current and coil RMS voltage. In another embodiment, the system extracts supply current and coil RMS current. In a further embodiment, the system extracts all three of the parameters. Measurements of these parameters at a point in time can be used to determine whether there is a valid load or not proximate the transmitter coil, or whether there is a fault conditioning by comparing the measurements to a known space diagram such as in Figure 2 or Figure 3.

In addition, it is possible to differentiate the number of loads being placed on the transmitting pad by comparing with either space diagram. An example is shown in Figure 4. It should be noted that there are overlaps of certain load conditions but they occur at very light loads (low current). Light load operation does not occur during the power-up state. Therefore, the system is able to easily detect the number of loads on the transmitting coil when powering up. Adding or removing a receiver from the transmitting coil can also be detected by observing any sharp transitions in either space diagram. The direction of the transition can be used to determine if a receiver is added or removed from the transmitting coil.

Power delivered and other system operating parameters can be determined by the coil RMS voltage. Figure 5 shows the direct correlation between the coil RMS voltage and the power delivered to the load. Figure 5 was produced by using a variable resistor as the load, which models the behavior of a battery charging for the portion of the curve below about 70V. As the battery begins charging the space diagram would read about 70V, 6W and would tend to go down and to the left as charging proceeded. In this way, measuring the coil voltage over a period of time and comparing with a curve such as shown in Figure 5 for the receiver, a determination of the charging status of the load, and/or type of load, can be made. In another embodiment, a plot of transmitter coil current versus power delivered to load (W) can be used to also determine the charge status of a load, and/or the type of load, based on the measurement of coil current over a period of time. In this way, having prior knowledge of the coil voltage versus power delivered, or the coil current versus power delivered, for a receiver can allow the determination of the charging status for the receiver by measuring coil voltage, or coil current, respectively.

In a further embodiment, power delivered can be determined by measuring the coil voltage or the coil current and using, for example, a look up table and microprocessor to determine power delivered, and charge status from following power delivered.

The information regarding the load can be used to modify the behavior of the transmitter. As examples, if a faulty load is determined the transmitter can be shut off to prevent damage, if a charged load is determined, the transmitter can shut off and come on in intervals to check for new loads, if no load is determined then the transmitter can be shut off until a load is determined.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

1. A method of determining information regarding a load for a planar wireless power transfer system, comprising:

driving a transmitter coil of a planar wireless power transfer system with a drive amplifier;

measuring a transmitter coil voltage provided to the transmitter coil by the drive amplifier; and

determining information regarding a load positioned proximate the transmitter coil.

2. A method of determining information regarding a load for planar wireless power transfer system, comprising:

driving a transmitter coil of a planar wireless power transfer system with a drive amplifier;

measuring a transmitter coil current passing through the transmitter coil; and

determining information regarding a load positioned proximate the transmitter coil.

3. The method according to claim 1, wherein determining information regarding the load proximate the transmitter coil comprises comparing the transmitter coil voltage over a period of time with an *a priori* curve in the transmitter coil voltage and power delivered to load space.

4. The method according to claim 2, wherein determining information regarding the load proximate the transmitter coil comprises comparing the transmitter coil current over a period of time with *a priori* curve in the transmitter coil current and power delivered to load space.

5. The method according to claim 1, further comprising:

measuring a transmitter supply current provided to the drive amplifier.

6. The method according to claim 2, further comprising:
measuring a transmitter supply current provided to the drive amplifier.

7. The method according to claim 1, wherein the information regarding the load is the charging status of the load.

8. The method according to claim 5, wherein the transmitter supply current is measured on a high side of a power supply, wherein the power supply supplies power to the drive amplifier.

9. The method according to claim 8, wherein the transmitter supply current is measured via a current sensing resistor.

10. The method according to claim 9, wherein the transmitter supply current is measured via an amplifier across the current sensing resistor.

11. The method according to claim 5, wherein the transmitter supply current is measured on a low side of a power supply, wherein the power supply supplies power to the driver amplifier.

12. The method according to claim 11, wherein the transmitter supply current is measured via a current sensing resistor.

13. The method according to claim 12, wherein the transmitter supply current is measured via an amplifier across the current sensing resistor.

14. The method according to claim 6, wherein the transmitter coil current is measured on high side of the transmitting coil.

15. The coil method according to claim 14, wherein the transmitter coil current is measured via a current sensing resistor.

16. The method according to claim 15, wherein the transmitter coil current is measured via an amplifier across the current sensing resistor.

17. The method according to claim 16, wherein an output of the amplifier is input into a rectification circuit.

18. The method according to claim 17, wherein the rectification circuit comprises a diode and a charge holding capacitor.

19. The method according to claim 6, wherein the transmitter coil current is measured at a low side of the transmitting coil.

20. The method according to claim 19, wherein the transmitter coil current is measured via a current sensing resistor.

21. The method according to claim 20, wherein the transmitter coil current is measured via an amplifier across the current sensing resistor.

22. The method according to claim 21, wherein an output of the amplifier is input to a rectification circuit.

23. The method according to claim 22, wherein the rectification circuit comprises a diode and a charge holding capacitor.

24. The method according to claim 5, wherein the transmitter coil voltage is measured at a high side of the transmitter coil.

25. The coil method according to claim 24, wherein the transmitter coil voltage is measured via a rectification circuit.

26. The method according to claim 25, wherein the rectification circuit comprises a diode and a charge holding capacitor.

27. The method according to claim 5, wherein information regarding the load is determined via analysis of the transmitter supply current and the transmitter coil voltage space.

28. The method according to claim 6, wherein information regarding the load is determined via analysis of the transmitter supply current and the transmitter coil current space.

29. The method according to claim 5, further comprising:

measuring a transmitter coil current passing through the transmitter coil.

30. The method according to claim 29, wherein information regarding the load is determined via analysis of the transmitter supply current, the transmitter coil voltage, and the transmitter coil current space.

31. The method according to claim 5, wherein the transmitter supply current is measured over a period of time, wherein the transmitter coil voltage is measured over the period of time.

32. The method according to claim 6, wherein the transmitter supply current is measured over a period of time, wherein the transmitter coil current is measured over a period of time.

33. The method according to claim 5, wherein the information regarding the load comprises the charge status of the load.

34. The method according to claim 6, wherein the information regarding the load comprises the charge status of the load.

35. The method according to claim 5, wherein the information regarding the load comprises whether load operating properly.

36. The method according to claim 6, wherein the information regarding the load comprises whether the load is operating properly.

37. The method according to claim 5, wherein the information regarding the load comprises whether a valid load is proximate the transmitter coil.

38. The method according to claim 6, wherein the information regarding the load comprises whether a valid load is proximate the transmitter coil.

39. The method according to claim 5, wherein the transmitter supply current and the transmitter coil voltage are measured at a point in time, wherein the information regarding the load is whether there is no load, a valid load, or a faulty load.

40. The method according to claim 6, wherein the transmitter supply current and the transmitter coil current are measured at a point in time, wherein the information regarding the load is whether there is no load, a valid load, or a faulty load.

41. The method according to claim 5, wherein the transmitter supply current and the transmitter coil voltage are measured at a point in time, wherein the information regarding the load is whether the load is operating properly.

42. The method according to claim 6, wherein the transmitter supply current and the transmitter coil current are measured at a point in time, wherein the information regarding the load is whether the load is operating properly.

43. The method according to claim 31, wherein the information regarding the load comprises the charge status of the load.

44. The method according to claim 32, wherein the information regarding the load comprises the charge status of the load.

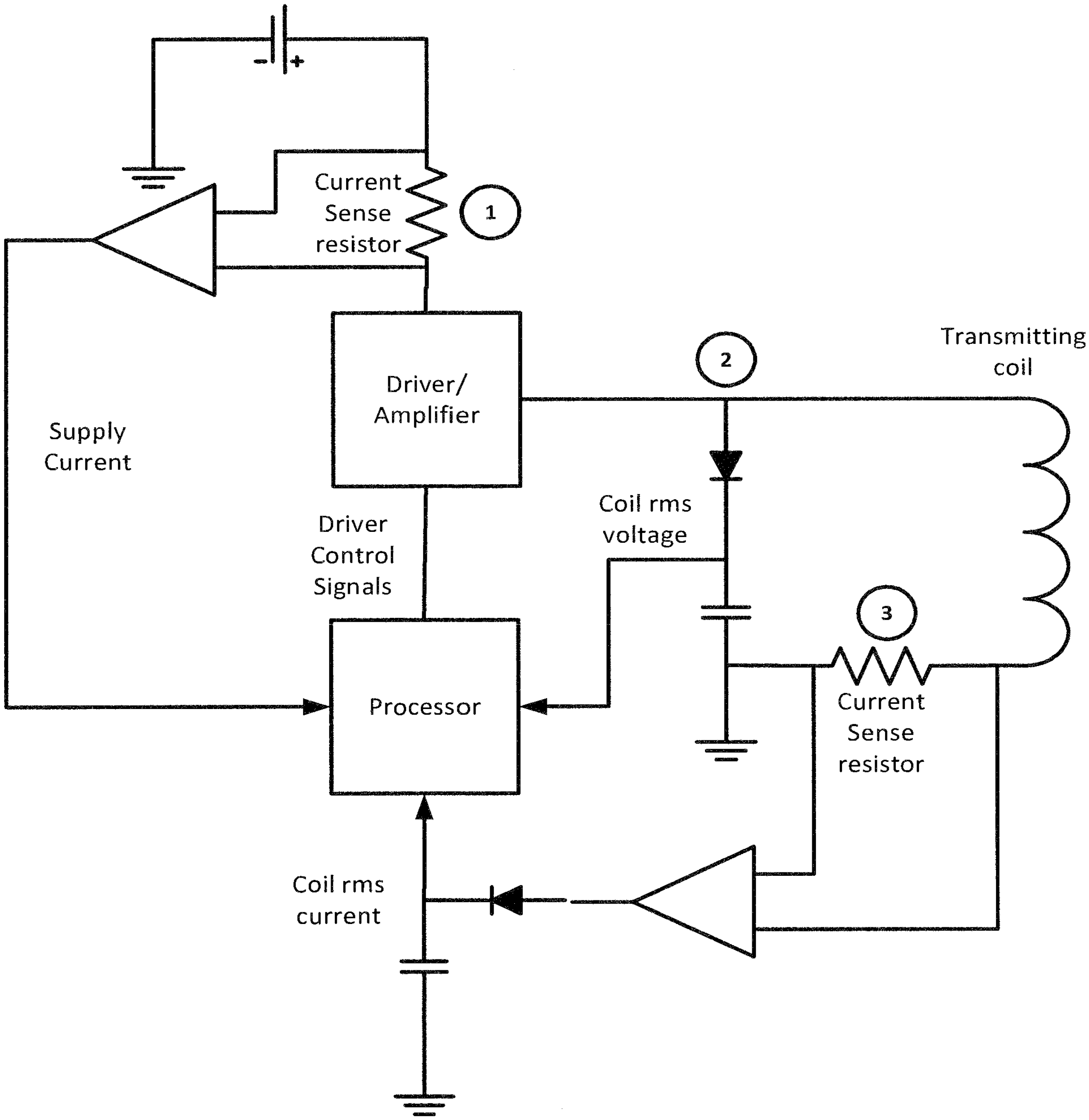
-
+
Current
Sense
resistor
1
Transmitting
coil
2
Driver/
Amplifier
Supply
Current
Coil rms
voltage
Driver
Control
Signals
3
Processor
Current
Sense
resistor
Coil rms
current

FIG. 1

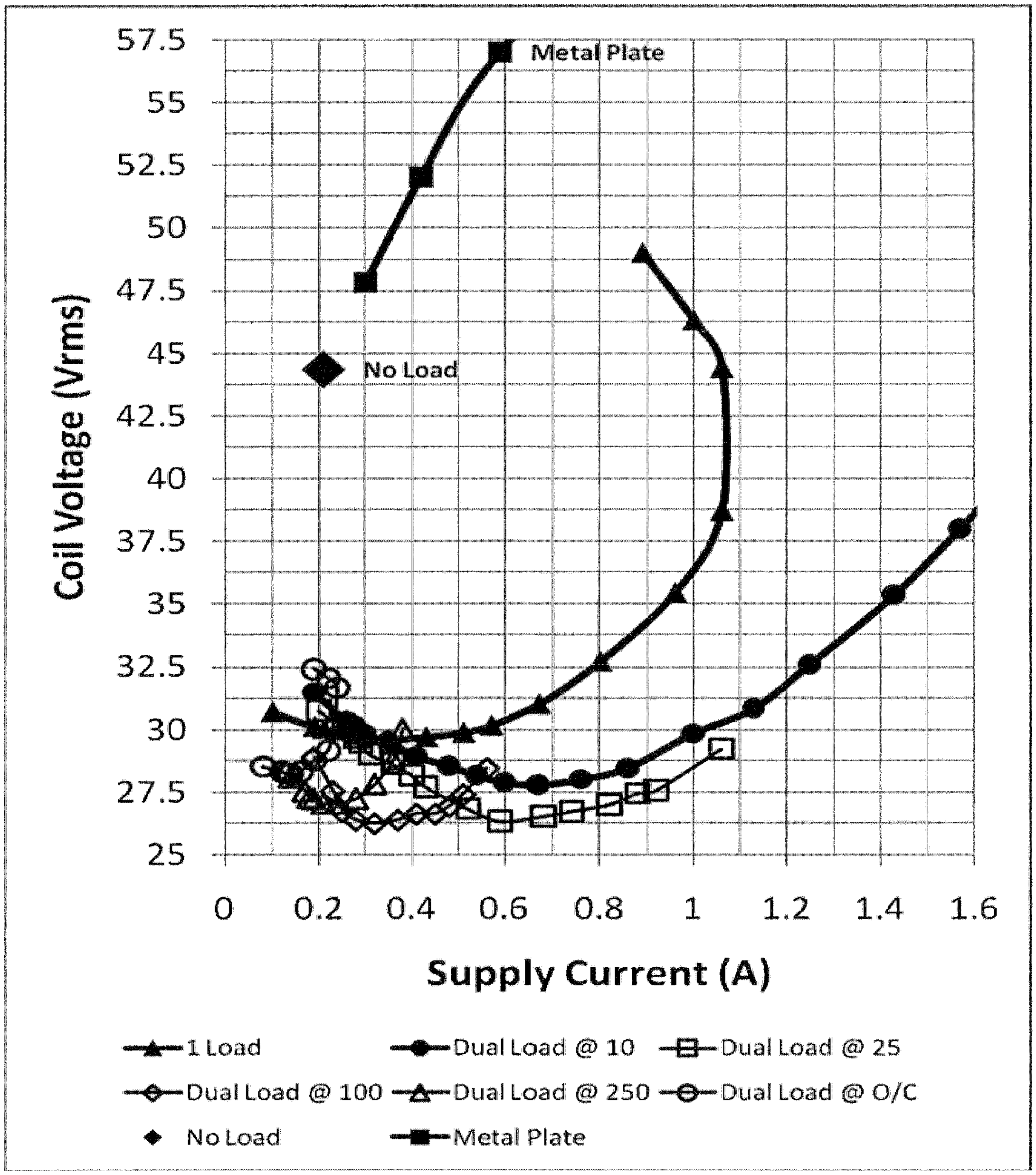
Metal Plate
No Load
Coil Voltage (Vrms)
57.5
55
52.5
50
47.5
45
42.5
40
37.5
35
32.5
30
27.5
25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Supply Current (A)
1 Load
Dual Load @ 10
Dual Load @ 25
Dual Load @ 100
Dual Load @ 250
Dual Load @ O/C
No Load
Metal Plate

FIG. 2

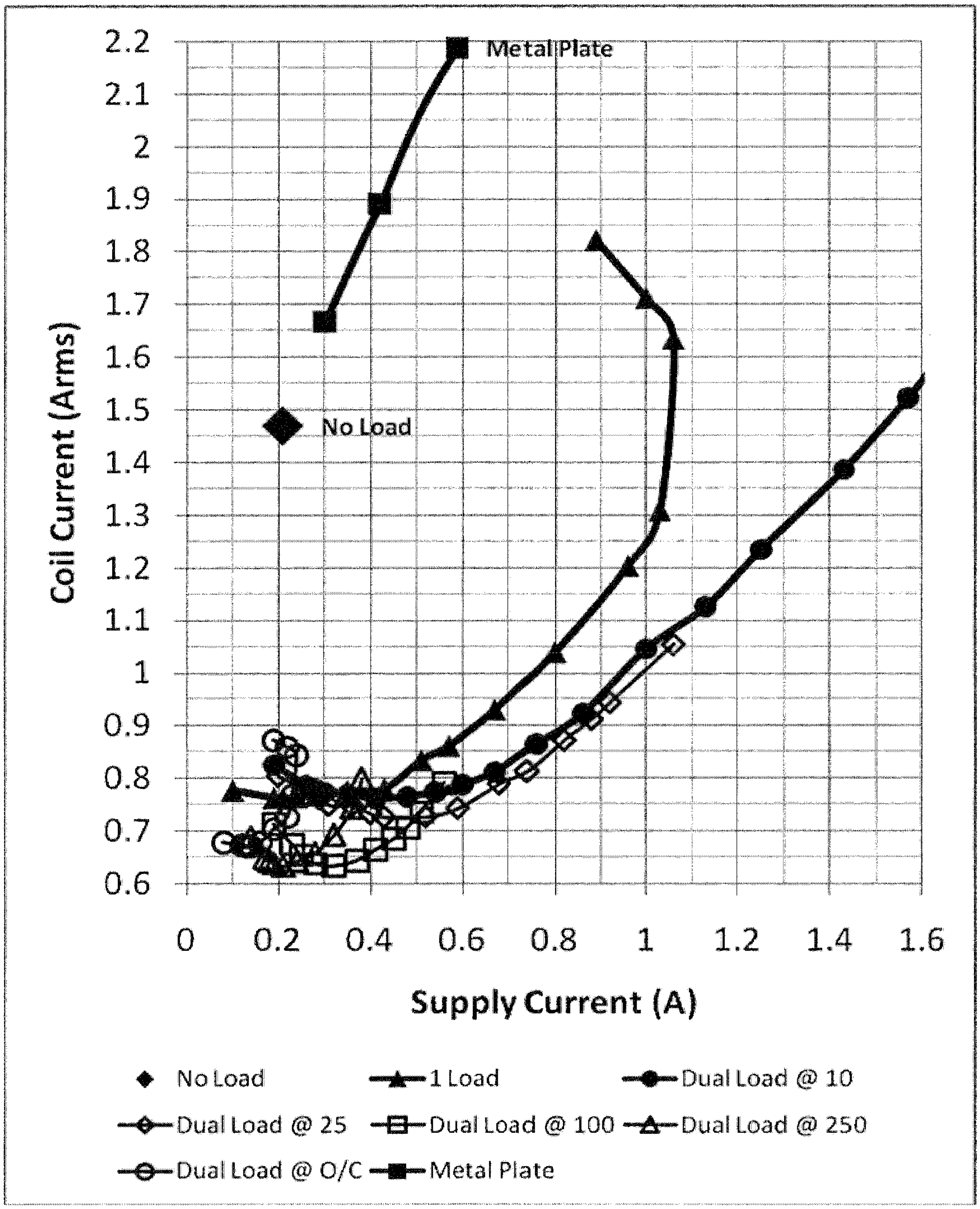

FIG. 3

SUBSTITUTE SHEET (RULE 26)

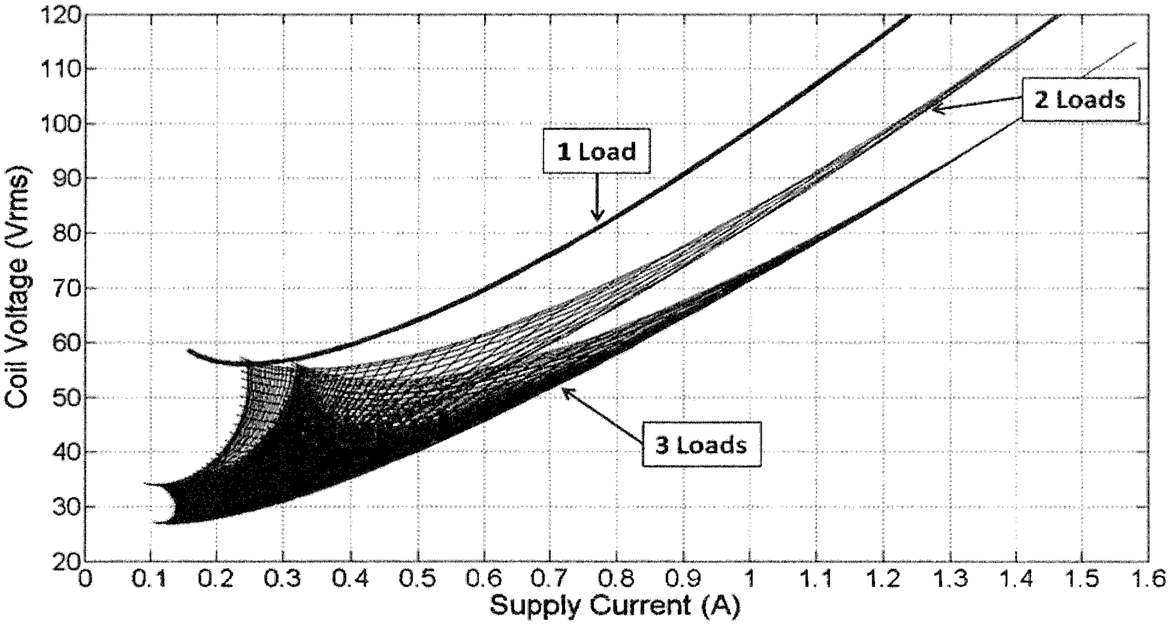

FIG. 4

SUBSTITUTE SHEET (RULE 26)

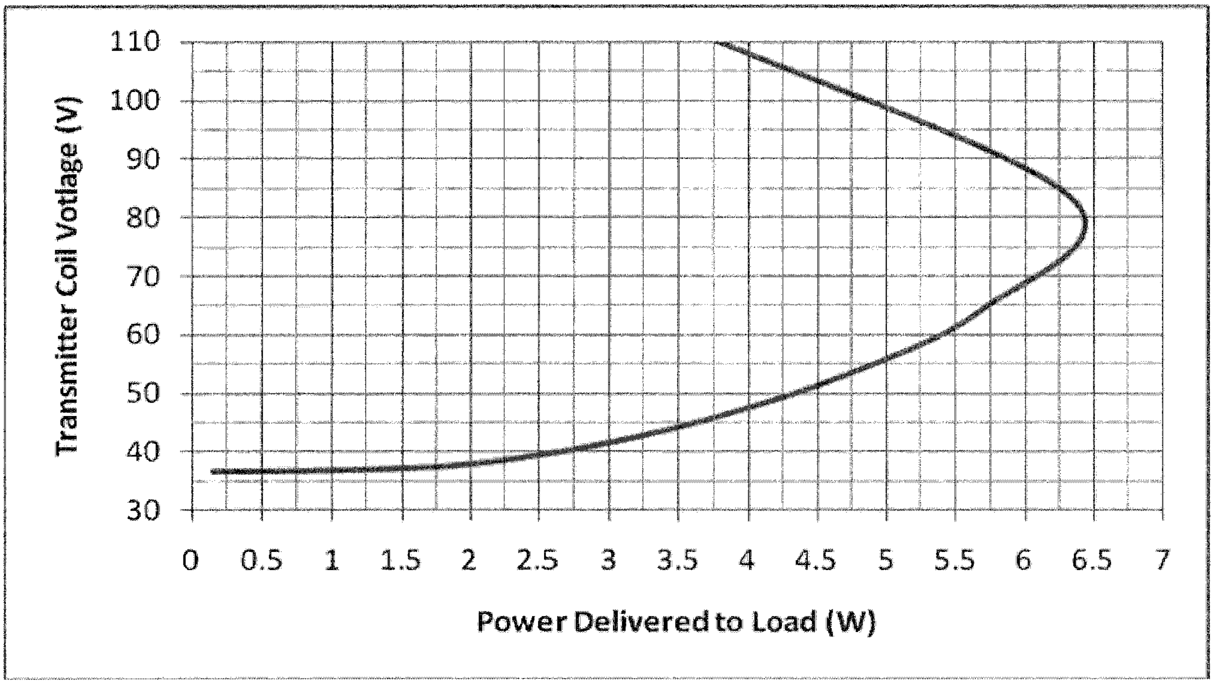
Transmitter Coil Votlage (V)
110
100
90
80
70
60
50
40
30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
Power Delivered to Load (W)

FIG. 5

80157. E29W01

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To:
JOHN H. NORTRUP
STRATEGIC PATENTS, P.C.
C/O INTELLEVATE
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing *(day/month/year)* 14 MAY 2010
Applicant's or agent's file reference WTCY0014PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
   1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 8270

   For more detailed instructions, see the notes on the accompanying sheet.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to the protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with the applicant's request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau as provided in Rules 90*bis*.1 and 90*bis*.3, respectively, before the completion of the technical preparations for international publication.

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. These comments would also be made available to the public but not before the expiration of 30 months from the priority date.

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   See the Annex to Form PCT/IB/301 and, for details about the applicable time limits, Office by Office, see the *PCT Applicant's Guide*, Volume II, National Chapters and the WIPO Internet site.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/220 (January 2004)

(See notes on accompanying sheet)

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MAY 17 2010
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Coded ________ Verified ________

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY0014PWO	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)	(Earliest) Priority Date *(day/month/year)* 13 February 2009 (13.02.2009)
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into __________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. ☐ **Certain claims were found unsearchable** (see Box No. II).

3. ☐ **Unity of invention is lacking** (see Box No. III).

4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/24199

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01F 27/42 (2010.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): H01F 27/42 (2010.01)
USPC: 307/104

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): H01F 27/42 (2010.01) (text search)
USPC: 307/104; 340/855.8 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, EPAB, JPAB); Google Patent; Google Scholar: Search Terms: wireless power transmission coil magnetic field capacitive coupling dielectric ring electric conductive wire loop wireless resonant ferromagnetic medium contact-less power frequency amplitude

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2007/0222542 A1 (Joannopoulos) 27 September 2007 (27.09.2007), entire document, especially; para. [0001] through [0045], Fig. 1-6B	1-11, 16-26, 31 --- 12-15, 27-30
X --- Y	US 2008/0012569 A1 (Hall et al.) 17 January 2008 (17.01.2008), entire document, especially; para. [0034] through [0055], Fig. 1-14	32, 33 --- 14, 15, 29, 30
Y	US 2008/0030415 A1 (Homan et al.) 07 February 2008 (07.02.2008), para. [0005], [0042] through [0073], Fig. 9, 10	12, 13, 27, 28
A	US 2008/0278264 A1 (Karalis et al.) 13 November 2008 (13.11.2008), entire document	1 - 33
A	US 2009/0015075 A1 (Cook et al.) 15 January 2009 (15.01.2009), entire document	1 - 33

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 03 May 2010 (03.05.2010)	Date of mailing of the international search report 14 MAY 2010
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN H. NORTRUP
STRATEGIC PATENTS, P.C.
C/O INTELLEVATE
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

	Date of mailing *(day/month/year)* 14 MAY 2010	
Applicant's or agent's file reference WTCY0014PWO	**FOR FURTHER ACTION** See paragraph 2 below	
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)	Priority date *(day/month/year)* 13 February 2009 (13.02.2009)

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H01F 27/42 (2010.01)
USPC - 307/104

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:

☒ Box No. I Basis of the opinion
☐ Box No. II Priority
☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐ Box No. IV Lack of unity of invention
☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐ Box No. VI Certain documents cited
☐ Box No. VII Certain defects in the international application
☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Date of completion of this opinion 03 May 2010 (03.05.2010)	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 10/24199

Box No. I **Basis of this opinion**

1. With regard to the **language**, this opinion has been established on the basis of:
   - ☒ the international application in the language in which it was filed.
   - ☐ a translation of the international application into __________________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:
   a. (means)
      - ☐ on paper
      - ☐ in electronic form

   b. (time)
      - ☐ in the international application as filed
      - ☐ together with the international application in electronic form
      - ☐ subsequently to this Authority for the purposes of search

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.

PCT/US 10/24199

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	12-15, 27-30	YES
	Claims	1-11, 16-26, 31-33	NO
Inventive step (IS)	Claims	None.	YES
	Claims	1 - 33	NO
Industrial applicability (IA)	Claims	1 - 33	YES
	Claims	None.	NO

2. Citations and explanations:

Claims 1-11, 16-26 and 31 lack novelty under PCT Article 33(2) as being anticipated by US 2007/0222542 A1 (Joannopoulos).

Regarding claim 1, Joannopoulos discloses a wireless power transfer system (source 1 and device 2; loop 10, loop 12, of N coils of radius r of conducting wire with circular cross-section, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising: at least one source magnetic resonator (source 1; loop 10, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) coupled to a power source (external power supply, para. [0005], [0006]) and configured to generate an oscillating magnetic field (long-lived oscillatory resonant electromagnetic modes, resonant frequency/Omega, para. [0002], [0013], [024], [0025], [0026], [0031]); and at least one device magnetic resonator (device 2; loop 12, para. [0015], [0024], [0025], [0028], Fig. 1, 3), distal from said source resonators (distances D, para. [0034], Fig. 1, 3), comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) configured to convert said oscillating magnetic fields into electrical energy (para. [0012], Fig. 6A, 6B); wherein at least one said resonator has a keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) around the resonator that surrounds the resonator with a layer of non-lossy material (air, para. [0017], [0018], [0020], [0024], [0025], [0032], [0037], Fig. 2A, 2B).

Regarding claim 2, Joannopoulos discloses the system of claim 1, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a symmetric distance around the resonator (air, supports high-Q whispering-gallery modes, para. [0008], [0017], [0018], [0020], Fig. 2A).

Regarding claim 3, Joannopoulos discloses the system of claim 1, wherein the keep-out zone (near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a asymmetric distance around the resonator (air, supports high-Q whispering-gallery modes, dielectric waveguides, can support guided modes, para. [0008], [0017], [0018], [0020], [0024], Fig. 2B).

Regarding claim 4, Joannopoulos discloses the system of claim 3, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is largest around regions of the resonator where the electric fields are the largest (proximal cavity 20, para. [0008], [0020], [0024], Fig. 2B)

Regarding claim 5, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 0.25 mm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 6, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 1 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 7, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 10 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 8, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 1.0 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

Continued in supplemental boxes.

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

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V.2. Citations and explanations:

Regarding claim 9, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 0.1 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

Regarding claim 10, Joannopoulos discloses the system of claim 1, wherein the magnetic resonator further comprises a magnetic material (metallodielectric photonic crystals, para. [0022]).

Regarding claim 11, Joannopoulos discloses the system of claim 1, wherein at least one magnetic resonator has an intrinsic Q greater than 100 (Q.sub.rad = 1988, 1258, 702, 226; Q.sub.abs = 312530, 86980, 21864, 1662, para. [0034]).

Regarding claim 16, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is located inside a living creature (human, para. [0012], [0032], [0038] through [0041]).

Regarding claim 17, Joannopoulos discloses a method for wireless power transfer (source 1 and device 2; loop 10, loop 12, of N coils of radius r of conducting wire with circular cross-section, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising: energizing at least one source magnetic resonator (source 1; loop 10, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) to generate an oscillating magnetic field (long-lived oscillatory resonant electromagnetic modes, resonant frequency/Omega, para. [0002], [0013], [024], [0025], [0026], [0031]); and providing at least one device magnetic resonator (device 2; loop 12, para. [0015], [0024], [0025], [0028], Fig. 1, 3), distal from said source resonators (distances D, para. [0034], Fig. 1, 3), comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) configured to convert said oscillating magnetic fields into electrical energy (para. [0012], Fig. 6A, 6B); maintaining a keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) around at least one resonator to maintain a separation distance between the resonator and lossy material of the environment (background dielectric (free space/air, para. [0024], [0025]).

Regarding claim 18, Joannopoulos discloses the method of claim 17, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a symmetric distance around the resonator (air, supports high-Q whispering-gallery modes, para. [0008], [0017], [0018], [0020], Fig. 2A).

Regarding claim 19, Joannopoulos discloses the method of claim 17, wherein the keep-out zone (near field, para. [0014], [0018], [0021], [0026], [0027]) extends at an asymmetric distance around the resonator (air, supports high-Q whispering-gallery modes, dielectric waveguides, can support guided modes, para. [0008], [0017], [0018], [0020], [0024], Fig. 2B).

Regarding claim 20, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 0.25 mm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 21, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 1 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 22, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 10 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 23, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 1.0 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

See Continuation sheet.

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V.2. Citations and explanations:

Regarding claim 24, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 0.1 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

Regarding claim 25, Joannopoulos discloses the method of claim 17, wherein the magnetic resonator further comprises a magnetic material (metallodielectric photonic crystals, para. [0022]).

Regarding claim 26, Joannopoulos discloses the method of claim 17, wherein at least one magnetic resonator has an intrinsic Q greater than 100 (Q.sub.rad = 1988, 1258, 702, 226; Q.sub.abs = 312530, 86980, 21864, 1662, para. [0034]).

Regarding claim 31, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is located inside a living creature (human, para. [0012], [0032], [0038] through [0041]).

Claims 32 and 33 lack novelty under PCT Article 33(2) as being anticipated by US 2008/0012569 A1 to Hall et al. (hereinafter 'Hall').

Regarding claim 32, Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a capacitively-loaded conducting loop (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) wrapped around a core of magnetic material (magnetic coupler 302 also comprises a coil 303 and an annular trough 404 made of magnetic material, para. [0042], [0043], [0045], Fig. 5, 6) and coupled to a power source (first coupler 304 may be optimized for the transfer of power; electronic device 210 is a power source 1301, para. [0041], [0049]) and configured to generate an oscillating magnetic field (magnetic coupler and the adjacent magnetic coupler may then be adapted to induce magnetic fields in each other when their coils are electrically energized; inductive couplers 302, 1102 may act as band pass filters due to their inherent inductance, capacitance and resistance such that a first frequency is allowed to pass at a first resonant frequency, and a second frequency is allowed to pass at a second resonant frequency, para. [0014], [0046], [0047]); wherein the conducting loops are oriented to be coaxial with length of the shaft (pin end 203 of downhole component 200, para. [0041], Fig.3).

Regarding claim 33, Hall discloses the source of claim 32, further comprising a plurality of capacitively-loaded conducting loops (magnetic coupler 302 comprises a coil 303 having a plurality of windings 601 of wire strands 602, para. [0043], Fig. 6) wrapped around cores of magnetic material (annular trough 404 made of magnetic material, para. [0042], [0043], [0045], Fig. 5, 6) arranged around the diameter of the shaft (pin end 203 of downhole component 200, para. [0041], Fig.3).

Claims 12, 13, 27 and 28 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos, in view of US 2008/0030415 A1 to Homan et al. (hereinafter 'Homan').

Regarding claim 12, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the magnetic resonator is immersed in water. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in water (water; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Regarding claim 13, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in oil. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in oil (oil; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Regarding claim 27, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the magnetic resonator is immersed in water. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in water (water; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

See Continuation sheet.

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V.2. Citations and explanations:

Regarding claim 28, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in oil. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in oil (oil; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Claims 14, 15, 29 and 30 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos, in view of Hall.

Regarding claim 14, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in earthen materials. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in earthen materials (formation 18, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the earthen material application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 15, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is located in a well. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in well (formation 18 to form a borehole 20, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the well application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 29, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in earthen materials. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in earthen materials (formation 18, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the earthen material application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 30, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is located in a well. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in well (formation 18 to form a borehole 20, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the well application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Claims 1 - 33 have industrial applicability as defined by PCT Article 33(4) because the subject matter can be made or used in industry.

NOTES TO FORM PCT/ISA/220

These Notes are intended to give the basic instructions concerning the filing of amendments under Article 19. The Notes are based on the requirements of the Patent Cooperation Treaty, the Regulations and the Administrative Instructions under that Treaty. In case of discrepancy between these Notes and those requirements, the latter are applicable. For more detailed information, see also the *PCT Applicant's Guide*.

In these Notes, "Article," "Rule" and "Section" refer to the provisions of the PCT, the PCT Regulations and the PCT Administrative Instructions, respectively.

INSTRUCTIONS CONCERNING AMENDMENTS UNDER ARTICLE 19

The applicant has, after having received the international search report and the written opinion of the International Searching Authority, one opportunity to amend the claims of the international application. It should however be emphasized that, since all parts of the international application (claims, description and drawings) may be amended during the international preliminary examination procedure, there is usually no need to file amendments of the claims under Article 19 except where, e.g. the applicant wants the latter to be published for the purposes of provisional protection or has another reason for amending the claims before international publication. Furthermore, it should be emphasized that provisional protection is available in some States only (see *PCT Applicant's Guide*, Annex B).

The attention of the applicant is drawn to the fact that amendments to the claims under Article 19 are not allowed where the International Searching Authority has declared, under Article 17(2), that no international search report would be established (see *PCT Applicant's Guide*, International Phase, paragraph 296).

What parts of the international application may be amended?

Under Article 19, only the claims may be amended.

During the international phase, the claims may also be amended (or further amended) under Article 34 before the International Preliminary Examining Authority. The description and drawings may only be amended under Article 34 before the International Preliminary Examining Authority.

Upon entry into the national phase, all parts of the international application may be amended under Article 28 or, where applicable, Article 41.

When? Within 2 months from the date of transmittal of the international search report or 16 months from the priority date, whichever time limit expires later. It should be noted, however, that the amendments will be considered as having been received on time if they are received by the International Bureau after the expiration of the applicable time limit but before the completion of the technical preparations for international publication (Rule 46.1).

Where not to file the amendments?

The amendments may only be filed with the International Bureau and not with the receiving Office or the International Searching Authority (Rule 46.2).

Where a demand for international preliminary examination has been/is filed, see below.

How? Either by cancelling one or more entire claims, by adding one or more new claims or by amending the text of one or more of the claims as filed.

A replacement sheet or sheets containing a complete set of claims in replacement of all the claims previously filed must be submitted.

Where a claim is cancelled, no renumbering of the other claims is required. In all cases where claims are renumbered, they must be renumbered consecutively in Arabic numerals (Section 205(a)).

The amendments must be made in the language in which the international application is to be published.

What documents must/may accompany the amendments?

Letter (Section 205(b)):

The amendments must be submitted with a letter.

The letter will not be published with the international application and the amended claims. It should not be confused with the "Statement under Article 19(1)" (see below, under "Statement under Article 19(1)").

The letter must be in English or French, at the choice of the applicant. However, if the language of the international application is English, the letter must be in English; if the language of the international application is French, the letter must be in French.

SEQUENCE LISTINGS AND TABLES RELATED THERETO IN INTERNATIONAL APPLICATIONS FILED IN THE U.S. RECEIVING OFFICE

The Administrative Instructions (AIs) under the Patent Cooperation Treaty (PCT), in force as of **July 1, 2009**, contain important changes relating to the manner of filing, and applicable fees for, sequence listings and/or tables related thereto (sequence-related tables) in international applications. The complete text may be accessed at http://www.wipo.int/pct/en/texts/index.htm.

Effective July 1, 2009, Part 8 and Annex C-*bis* will no longer form part of the AIs. Part 8 was introduced in 2001 as a temporary solution to problems arising from the filing of very large sequence listings on paper and provided for a *sequence listing forming part of the international application* to be filed in electronic form on physical medium (*e.g.*, CD), together with the remainder of the application on paper. In 2002, Part 8 was expanded to include sequence-related tables and Annex C-*bis* was added to provide technical requirements. All applicants may now file complete international applications in electronic form, eliminating the need for these temporary provisions.

I. AIS PART 8 AND ANNEX C-*BIS DELETED AS OF JULY 1, 2009*

A) **Sequence-related tables cannot be filed as a separate part of the description or in text format.** They must be provided as an integral part of the international application either:

- in PDF format as part of an international application filed in electronic form via EFS-Web; or
- on paper as part of an international application filed on paper.

B) A ***sequence listing forming part of an international application*** may be provided either:

- in electronic form, as part of an international application filed in electronic form via EFS-Web, in
  - Annex C/ST.25 text format (preferred), or
  - PDF format; or
- on paper as part of an international application filed on paper.

C) A ***sequence listing not forming part of the international application*** **(for search under PCT Rule 13*ter*) in Annex C/ST.25 text format**

- is not required where the *sequence listing forming part of the international application* was filed in Annex C/ST.25 text format as part of an international application filed in electronic form via EFS-Web
- is required for search where the *sequence listing forming part of the international application* was filed in PDF
- is required for search on physical medium (*e.g.*, CD) where the *sequence listing forming part of the international application* was filed on paper as part of an international application filed on paper.

II. CALCULATION OF THE INTERNATIONAL FILING FEE AND FEE REDUCTION UNDER AI § 707

A) **A sequence-related table** must form an integral part of the international application and will incur FULL page fees with no upper limit.

B) A ***sequence listing forming part of an international application*** filed:

- via EFS-Web in Annex C/ST.25 text format will incur NO page fees;
- on paper or in PDF format will incur FULL page fees with no upper limit.

III. AVAILABILITY OF SEQUENCE LISTINGS SUBMITTED FOR SEARCH UNDER PCT RULE *13TER*

International Searching Authorities will be required to transmit to the International Bureau a copy of an Annex C/ST.25 text format sequence listing provided for search under PCT Rule 13*ter*. Any such sequence listing will be made available on PATENTSCOPE® (*sequence listings forming part of the international application* are already available).

IV. JULY 2009 REQUEST (PCT/RO/101)

The Request now has two options for the last sheet: one for paper filings; and one for EFS-Web filings. The July 2009 Request may be accessed at http://www.wipo.int/pct/en/forms/index.htm.

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To:
JOHN H. NORTRUP
STRATEGIC PATENTS, P.C.
C/O INTELLEVATE
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing *(day/month/year)*
Applicant's or agent's file reference WTCY0014PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

Filing of amendments and statement under Article 19:
The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 8270

For more detailed instructions, see the notes on the accompanying sheet.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to the protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with the applicant's request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau as provided in Rules 90*bis*.1 and 90*bis*.3, respectively, before the completion of the technical preparations for international publication.

The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. These comments would also be made available to the public but not before the expiration of 30 months from the priority date.

Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

See the Annex to Form PCT/IB/301 and, for details about the applicable time limits, Office by Office, see the *PCT Applicant's Guide*, Volume II, National Chapters and the WIPO Internet site.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

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Form PCT/ISA/220 (January 2004)

(See notes on accompanying sheet)

Electronic Acknowledgement Receipt

EFS ID:	9566134
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	43520
Filer:	John H. Nortrop/Elizabeth Nortrup
Filer Authorized By:	John H. Nortrop
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	02-MAR-2011
Filing Date:	28-DEC-2009
Time Stamp:	10:23:34
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Transmittal Letter	WTCY-0026-P07_030211_IDSCommunication.pdf	89940 0119f232cf1e9bba2937de34be315521f6792055	no	2

Warnings:

Information:

2	Information Disclosure Statement (IDS) Filed (SB/08)	WTCY-0026-P07_030211_Form1449.pdf	169889 0ac62ae653eae2c30bdf25b12d2aa801fce3521b	no	7
Warnings:					
Information:					
This is not an USPTO supplied IDS fillable form					
3	Foreign Reference	WO2009033043_A2.pdf	919252 a0fdefc316ef4131b675c03754cf48929aaacd92	no	24
Warnings:					
Information:					
4	Foreign Reference	WO2009070730_A2.pdf	894187 4d703dfe98912e53bb97035c630984edee86ea07	no	27
Warnings:					
Information:					
5	Foreign Reference	WO2009126963_A2.pdf	717487 6e9fce27f70d4ea827d55b4aef84b6c86dc0fdab	no	14
Warnings:					
Information:					
6	Foreign Reference	WO2009155000_A2.pdf	835685 2a9f58be16d39885e97da14b2c80ed10029c0509	no	22
Warnings:					
Information:					
7	Foreign Reference	WO2010090538.pdf	923778 ad2cc603a06afe6099fd941d7a66b42d835d0aac	no	29
Warnings:					
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8	Foreign Reference	WO2010090539.pdf	1512605 380a7feeb3a83b04e6c1940526723aef7908b045	no	32
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9	Foreign Reference	WO09140506.pdf	5242650 8b68bf3904de9853b2d7538db476cc9b61b297ac	no	124
Warnings:					
Information:					
10	Foreign Reference	WO10039967.pdf	5864239 5d0b4843f7170e7aa57836339e9ec68626730fa7	no	128

Warnings:					
Information:					
11	Foreign Reference	WO10093997.pdf	11836766 66019d92b858e8cb06e4e4db0e17ffaf9b032c29	no	254
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Information:					
12	Foreign Reference	WO2007008646.pdf	1182701 8f9565ebfe47f4ae8aa44fc6e0d84cd3bca993b2	no	26
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13	Foreign Reference	WO2009149464_A2.pdf	6112375 ff96b202a23fed1f645758fa419f18dec77de9b1	no	144
Warnings:					
Information:					
14	Foreign Reference	WO2010030977_A2.pdf	658814 3bea86696a645c3bfdd0f68b6408311473a74c3e	no	17
Warnings:					
Information:					
15	NPL Documents	NPL-103_PCTUS2010024199_ISR-05142010.pdf	844718 1311c82e5cf24b05e0d830a49d0d980f4f5c30fa	no	12
Warnings:					
Information:					
16	NPL Documents	NPL-104_SN12613686_NoA-010611.PDF	459052 37325f95e4fb1ba5c27746904044b09f3592447d	no	10
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Information:					
17	NPL Documents	NPL-105_Sekiya-070104.pdf	393457 0d17031639ec69c28637af4ad11c061ffd0fe246	no	11
Warnings:					
Information:					
18	NPL Documents	NPL-106_Mediano-030107.pdf	741860 b9243a2d77caa09670295b2ec485f1c0c4251c7a	no	9
Warnings:					
Information:					
			Total Files Size (in bytes):	39399455	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

ATTORNEY'S DOCKET NO. WTCY-0026-P07

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Serial No.:	12/647,763
Filing Date:	December 28, 2009
Applicant:	Aristeidis Karalis et al.
Title:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
Group Art Unit:	2828
Examiner:	Not Yet Known
Conf. No.:	2576

SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

In compliance with the duty imposed by 37 C.F.R. § 1.56, and in accordance with 37 C.F.R. §§ 1.97 *et seq*., the referenced materials are brought to the attention of the Examiner for consideration in connection with the above-identified patent application. Applicants respectfully request that this Supplemental Information Disclosure Statement be entered and the documents listed on the attached Form 1449 be considered by the Examiner and made of record. Pursuant to the provisions of MPEP 609, Applicants request that a copy of the 1449 form, initialed as being considered by the Examiner, be returned to the Applicants with the next official communication.

Pursuant to 37 C.F.R. §1.97(b), it is believed that no fee or statement is required with the Supplemental Information Disclosure Statement. However, if an Office Action on the merits has been mailed, the Commissioner is hereby authorized to charge the required fees to Deposit Account No. 50-4262 in order to have this Supplemental Information Disclosure Statement considered.

Pursuant to 37 C.F.R. 1.98(a)(2), Applicant believes that copies of cited U.S. Patents and Published and Non-Published Applications identifiable by USPTO Serial Number are no longer required to be provided to the Office. Notification of this change to this effect was provided in the United States Patent and Trademark Office OG Notices dated October 12, 2004 and October 19, 2004. Thus, Applicant has not included copies of any US Patents or US Patent Applications identifiable by serial number that may be cited with this submission. Should the Office require copies to be provided, Applicant respectfully requests that notice of such requirement be directed to Applicant's below-signed representative. Applicant acknowledges the requirement to submit copies of foreign patent documents and non-patent literature in accordance with 37 C.F.R. 1.98(a)(2).

The Examiner is invited to contact the Applicants' Representative at the below-listed telephone number if there are any questions regarding this communication.

Respectfully submitted on March 2, 2011,

STRATEGIC PATENTS, P.C.

/John H. Nortrup, Reg. No. 59,063/
John H. Nortrup
Telephone: 207-985-2126

Customer Number 43520

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	**Application Number**	12/647,763
	Filing Date	Dec 28, 2009
	First Named Inventor	Aristeidis Karalis
	Art Unit	2828
	Examiner Name	Not Yet Known
Sheet 1 of 3	**Attorney Docket No.**	WTCY-0026-P07

U.S. PATENTS

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear

U.S. PATENT APPLICATION PUBLICATIONS

Examiner Initial*	Cite No	Publication Number	Kind Code[1]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		US-2011/0043046	A8	Feb 24, 2011	Joannopoulos, John D., et al.	
		US-2010/0225272	A8	Sep 9, 2010	Kirby, Miles A., et al.	
		US-2009/0067198	A8	Mar 12, 2009	Graham, David J.	

FOREIGN PATENT DOCUMENTS

Examiner Initial*	Cite No	Foreign Document Number[3]	Cnty Code[2]	Kind Code[4]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines where Relevant Passages or Relevant Figures Appear	T[5]
		WO-2010/093997			Aug 19, 2010	Kurs, Andre B., et al.		
		WO-2010/039967			Apr 8, 2010	Hamam, Rafif E., et al.		
		WO-2010/030977			Mar 18, 2010	Lin, Jenshan et al.		
		WO-2009/149464			Dec 10, 2009	Low, Zhen N., et al.		
		WO-2009/140506			Nov 19, 2009	Karalis, Aristeidis et al.		
		WO-2007/008646_A2			Jan 18, 2007	Joannopoulos, John D., et al.		
		WO-92/17929			Oct 15, 1992	Boys, John T., et al.		

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	**Application Number**	12/647,763
	Filing Date	Dec 28, 2009
	First Named Inventor	Aristeidis Karalis
	Art Unit	2828
	Examiner Name	Not Yet Known
Sheet 2 of 3	**Attorney Docket No.**	WTCY-0026-P07

NON-PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T5
	NPL-107	"International Search Report & WO for PCT/US09/43970", PCT/US09/43970 07/14/2009 , all	
	NPL-108	"Application Serial No. 12/613,686 (Atty Ref WTCY-0026-P02), Notice of Allowance mailed 03/07/2011", SN12/613,686 , 27	

EXAMINER SIGNATURE

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document.
[4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	**Application Number**	12/647,763
	Filing Date	Dec 28, 2009
	First Named Inventor	Aristeidis Karalis
	Art Unit	2828
	Examiner Name	Not Yet Known
Sheet 3 of 3	**Attorney Docket No.**	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e) (1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e) (2).

☒ See attached certification statement.

☐ Fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☐ None

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John H. Nortrup/	Date (YYYY-MM-DD)	2011-05-06
Name/Print	John H. Nortrup	Registration Number	59,063

Pursuant to 37 C.F.R. §1.98(d), copies of the listed foreign and non-patent literature documents are not provided as these references were previously cited by or submitted to the U.S. Patent Office in connection with Applicants' prior U.S. application, Serial No. 12/567,716, filed on September 25, 2009, which is relied upon for an earlier filing date under 35 U.S.C. §120.

Electronic Acknowledgement Receipt

EFS ID:	10039117
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	43520
Filer:	John H. Nortrop/Elizabeth Nortrup
Filer Authorized By:	John H. Nortrop
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	06-MAY-2011
Filing Date:	28-DEC-2009
Time Stamp:	15:47:23
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Information Disclosure Statement (IDS) Filed (SB/08)	WTCY-0026-P07_050611_Form1449.pdf	117455 08be4b9845f0a75cb5f58675d4e66a04835a2416	no	3

Warnings:

Information:

This is not an USPTO supplied IDS fillable form

Total Files Size (in bytes):	117455

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Serial No.: See Appendix A
Filing Date: See Appendix A
Applicant(s): See Appendix A
Title: See Appendix A

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

REVOCATION OF POWER OF ATTORNEY
AND
CHANGE OF CORRESPONDENCE ADDRESS

The undersigned hereby revokes all previous powers of attorney given in the applications identified in Appendix A, which is attached hereto, and appoints Practitioner(s) associated with Customer Number 87084 as the attorney(s) or agent(s) to prosecute the applications identified on Appendix A, and to transact all business in the United States Patent and Trademark Office connected therewith.

Change of Correspondence Address

Please direct all correspondence in the applications and patent identified in Appendix A to:

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis MN 55402
Customer No. 87084

Certificate Under 37 C.F.R. § 3.73(b)

WiTricity Corporation hereby certifies that it is the Assignee of the entire right, title and interest in the patent applications identified in Appendix A by virtue of assignments from the respective inventors. The Appendix includes a reel and frame number for the assignment of each application identified therein. To the best of the undersigned's knowledge and belief, title to all listed applications is in WiTricity Corporation. Pursuant to 37 C.F.R. § 3.73(b), the undersigned hereby declares that s/he is empowered to sign this certificate on behalf of the Assignee.

I declare that all statements made herein of my own knowledge are true and that all statements made on information and believe are believed to be true.

Respectfully submitted,

WiTricity Corporation

Date: 9/8/11

By:
Name: eric giler
Title: CEO

APPENDIX

Listing of Pending Applications

Title	Serial No.	Filing Date	Reel	Frame
WIRELESS ENERGY TRANSFER IN LOSSY ENVIRONMENTS	12/705,582	02/13/2010	024087	0019
OPTIMIZED LOW RESISTANCE ELECTRICAL CONDUCTOR FOR THE MULTI-MHZ RANGE	61/411,490	11/09/2010	025488	0595
WIRELESS ENERGY TRANSFER USING VARIABLE SIZE RESONATORS AND SYSTEM MONITORING	12/647,705	12/28/2009	023918	0152
WIRELESS ENERGY TRANSFER BETWEEN A SOURCE AND A VEHICLE	12/770,137	04/29/2010	024475	0241
WIRELESS ENERGY TRANSFER SYSTEMS	12/567,716	09/25/2009	023599	0845
WIRELESS ENERGY TRANSFER USING PLANAR CAPACITIVELY LOADED CONDUCTING LOOP RESONATORS	12/613,686	11/06/2009	023482	0945
WIRELESS ENERGY TRANSFER USING HIGH Q RESONATORS FOR LIGHTING APPLICATIONS	12/636,891	12/14/2009	023652	0026
WIRELESS ENERGY TRANSFER FOR SUPPLYING POWER AND HEAT TO A DEVICE	12/650,916	12/31/2009	023918	0560
WIRELESS ENERGY TRANSFER WITH FREQUENCY HOPPING	12/651,005	12/31/2009	023918	0312
WIRELESS ENERGY TRANSFER RESONATOR KIT	12/639,718	12/16/2009	023918	0407
WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS	12/647,763	12/28/2009	023918	0491

WIRELESS ENERGY TRANSFER USING CONDUCTING SURFACES TO SHAPE FIELDS AND REDUCE LOSS	12/647,916	12/28/2009	023918	0560
WIRELESS ENERGY TRANSFER USING MAGNETIC MATERIALS TO SHAPE FIELD AND REDUCE LOSS	12/648,013	12/28/2009	023918	0613
WIRELESS ENERGY TRANSFER USING OBJECT POSITIONING FOR LOW LOSS	12/648,539	12/29/2009	023918	0645
WIRELESS ENERGY TRANSFER WITH HIGH-Q RESONATORS USING FIELD SHAPING TO IMPROVE K	12/648,604	12/29/2009	023918	0664
WIRELESS ENERGY TRANSFER USING CONDUCTING SURFACES TO SHAPE FIELD AND IMPROVE K	12/648,688	12/29/2009	023918	0696
WIRELESS ENERGY TRANSFER WITH HIGH-Q RESONATORS USING FIELD SHAPING TO IMPROVE K	12/648,793	12/29/2009	023918	0702
WIRELESS ENERGY TRANSFER USING OBJECT POSITIONING FOR IMPROVED K	12/649,173	12/29/2009	023918	0716
WIRELESS ENERGY TRANSFER OVER DISTANCE USING FIELD SHAPING TO IMPROVE THE COUPLING FACTOR	12/650,114	12/29/2009	023918	0739
WIRELESS ENERGY TRANSFER ACROSS VARIABLE DISTANCES USING FIELD SHAPING WITH MAGNETIC MATERIALS TO IMPROVE THE COUPLING FACTOR	12/650,386	12/30/2009	023918	0763
LOW AC RESISTANCE CONDUCTOR DESIGNS	12/639,489	12/16/2009	023664	0119
WIRELESS ENERGY TRANSFER FOR COMPUTER PERIPHERAL APPLICATIONS	12/612,880	11/05/2009	023781	0772

WIRELESS ENERGY TRANSFER WITH FEEDBACK CONTROL FOR LIGHTING APPLICATIONS	12/698,523	02/02/2010	023886	0778
WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION	12/722,050	03/11/2010	024087	0298
TUNABLE WIRELESS ENERGY TRANSFER SYSTEMS	12/986,018	01/06/2011	025894	0154
TEMPERATURE COMPENSATION IN A WIRELESS TRANSFER SYSTEM	12/749,571	03/30/2010	024157	0308
WIRELESS ENERGY TRANSFER USING REPEATER RESONATORS	12/720,866	03/10/2010	024449	0202
WIRELESS ENERGY TRANSFER USING REPEATER RESONATORS	12/759,047	04/13/2010	024223	0755
WIRELESS ENERGY TRANSFER RESONATOR ENCLOSURES	12/721,118	03/10/2010	024229	0361
RESONATOR OPTIMIZATIONS FOR WIRELESS ENERGY TRANSFER	12/757,716	04/09/2010	024377	0407
WIRELESS ENERGY TRANSFER FOR MEDICAL APPLICATIONS	13/090,369	04/20/2011	026432	0443
WIRELESS ENERGY TRANSFER CONVERTERS	12/767,633	04/26/2010	024414	0980
RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER	12/789,611	05/28/2010	024454	0741
INTEGRATED RESONATOR-SHIELD STRUCTURES	12/860,375	08/20/2010	024868	0172
WIRELESS ENERGY TRANSFER FOR IMPLANTABLE DEVICES	13/154,131	06/06/2011	026524	0592
WIRELESS AND INTELLIGENT FLOORING	61/382,806	09/14/2010	025034	0051
WIRELESS ENERGY TRANSFER RESONATOR THERMAL MANAGEMENT	13/021,965	02/07/2011	025752	0765
WIRELESS ENERGY TRANSFER	61/466,783	03/23/2011	026043	0122

Electronic Acknowledgement Receipt

EFS ID:	10901865
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	43520
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	08-SEP-2011
Filing Date:	28-DEC-2009
Time Stamp:	12:27:05
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	WitricityPOA.pdf	687821 0a6e6cd5c02dd7ebf85730f845774938933 2ba6f	no	5

Warnings:

Information:

Total Files Size (in bytes):	687821

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

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UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07

CONFIRMATION NO. 2576

POA ACCEPTANCE LETTER

OC000000049831682

87084
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

Date Mailed: 09/16/2011

NOTICE OF ACCEPTANCE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 09/08/2011.

The Power of Attorney in this application is accepted. Correspondence in this application will be mailed to the above address as provided by 37 CFR 1.33.

/atesfai/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07

CONFIRMATION NO. 2576

POWER OF ATTORNEY NOTICE

43520
STRATEGIC PATENTS P.C..
C/O CPA Global
P.O. BOX 52050
MINNEAPOLIS, MN 55402

OC000000049830920

Date Mailed: 09/16/2011

NOTICE REGARDING CHANGE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 09/08/2011.

- The Power of Attorney to you in this application has been revoked by the assignee who has intervened as provided by 37 CFR 3.71. Future correspondence will be mailed to the new address of record(37 CFR 1.33).

/atesfai/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

87084 7590 11/25/2011
GTC Law Group LLP & Affiliates
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P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	

ART UNIT	PAPER NUMBER
2836	

NOTIFICATION DATE	DELIVERY MODE
11/25/2011	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

jsammartin@gtclawgroup.com
jmonocello@gtclawgroup.com
gtcdocketing@cpaglobal.com

PTOL-90A (Rev. 04/07)

Office Action Summary	**Application No.** 12/647,763	**Applicant(s)** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE *3* MONTH(S) OR THIRTY (30) DAYS, WHICHEVER IS LONGER, FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *15 March 2010*.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.

4)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

5)☒ Claim(s) *1-14* is/are pending in the application.

5a) Of the above claim(s) _____ is/are withdrawn from consideration.

6)☐ Claim(s) _____ is/are allowed.

7)☒ Claim(s) *1-14* is/are rejected.

8)☐ Claim(s) _____ is/are objected to.

9)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

10)☐ The specification is objected to by the Examiner.

11)☒ The drawing(s) filed on *28 December 2009* is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

12)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

13)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)
3) ☒ Information Disclosure Statement(s) (PTO/SB/08)
Paper No(s)/Mail Date *5/6/11,3/2/11,1/11/11,3/29/10*.

4) ☐ Interview Summary (PTO-413)
Paper No(s)/Mail Date. _____ .
5) ☐ Notice of Informal Patent Application
6) ☐ Other: _____.

DETAILED ACTION

Claim Rejections - 35 USC § 103

The following is a quotation of 35 U.S.C. 103(a) which forms the basis for all obviousness rejections set forth in this Office action:

> (a) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

Claims 1-14 are rejected under 35 U.S.C. 103(a) as being unpatentable over KIRBY et al. 20100225272 in view of KURS 20100308939.

CLAIM 1

KIRBY et al. discloses wireless power for chargeable and charging devices such as receiver may be configured to receive wireless power transmitted from a wireless power source within an associated near-field region (paragraph 0063) comprising:

a source resonator optionally coupled to an energy source; and

a second resonator located a distance from the source resonator.

KIRBY et al. dose not disclose wherein the field of at least one of the source resonator and the second resonator is shaped to avoid a loss-inducing object.

KURS discloses in the presents of loss inducing objects, the perturbed quality factor of a magnetic resonator may be improved if the electromagnetic fields associated with the magnetic resonator are reshaped to avoid the loss inducing objects (paragraph 0306).

It would have been obvious to one having ordinary skill in the art at the time the invention was made to shape the resonators wherein the field of at least one of the source resonator and the second resonator is shaped to avoid a loss-inducing object.

CLAIMS 2-4

KIRBY in view of KURS disclose the system of claim 1.

KURS discloses wherein at least one of the source resonator and the second resonator have a quality factor, Q> 100 (paragraph 0262).

CLAIM 5-7

KIRBY in view of KURS disclose the system of claim 1.

KURS discloses more than one resonator (paragraph 0672)

CLAIM 8

KIRBY in view of KURS disclose the method:

providing a source resonator optionally coupled to an energy source and a second resonator located a distance from the source resonator, wherein the source resonator and the second resonator are coupled to provide near-field wireless energy transfer among the source resonator and the second resonator and wherein the field of at least one of the source resonator and the second resonator is shaped to avoid a loss-inducing object.

CLAIMS 9-14

REJECTED, SEE ABOVE CORRESPONDING SYSTEM REJECTIONS.

Any inquiry concerning this communication should be directed to Robert L. DeBeradinis whose number is (571) 272-2049. The Examiner can normally be reached Monday-Friday from 8:30 am to 5:00 pm.

If attempts to reach the Examiner by telephone are unsuccessful, the Examiner's supervisor, Jared Fureman can be reached on (571) 272-2391. The Fax phone number for this Group is (571) 272-8300.

RLD

NOVEMBER 18, 2011

/Robert DeBeradinis/

Primary Examiner, Art Unit 2836

Notice of References Cited	Application/Control No. 12/647,763	Applicant(s)/Patent Under Reexamination KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	Art Unit 2836	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
*	A	US-2010/0308939	12-2010	Kurs, Andre B.	333/219.2
*	B	US-2010/0225272	09-2010	Kirby et al.	320/108
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

U.S. Patent and Trademark Office
PTO-892 (Rev. 01-2001) **Notice of References Cited** Part of Paper No. 20111118

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	**Application Number**	12/647,763
	Filing Date	Dec 28, 2009
	First Named Inventor	Aristeidis Karalis
	Art Unit	2828
	Examiner Name	Not Yet Known
Sheet 1 of 3	**Attorney Docket No.**	WTCY-0026-P07

U.S. PATENTS

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear

U.S. PATENT APPLICATION PUBLICATIONS

Examiner Initial*	Cite No	Publication Number	Kind Code[1]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
		US-2011/0043046	A8	Feb 24, 2011	Joannopoulos, John D., et al.	
		US-2010/0225272	A8	Sep 9, 2010	Kirby, Miles A., et al.	
		US-2009/0067198	A8	Mar 12, 2009	Graham, David J.	

FOREIGN PATENT DOCUMENTS

Examiner Initial*	Cite No	Foreign Document Number[3]	Cnty Code[2]	Kind Code[4]	Publication Date	Name of Patentee or Applicant of cited Document	Pages, Columns, Lines where Relevant Passages or Relevant Figures Appear	T[5]
		WO-2010/093997			Aug 19, 2010	Kurs, Andre B., et al.		
		WO-2010/039967			Apr 8, 2010	Hamam, Rafif E., et al.		
		WO-2010/030977			Mar 18, 2010	Lin, Jenshan et al.		
		WO-2009/149464			Dec 10, 2009	Low, Zhen N., et al.		
		WO-2009/140506			Nov 19, 2009	Karalis, Aristeidis et al.		
		WO-2007/008646 _A2			Jan 18, 2007	Joannopoulos, John D., et al.		
		WO-92/17929			Oct 15, 1992	Boys, John T., et al.		

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	**Application Number**	12/647,763
	Filing Date	Dec 28, 2009
	First Named Inventor	Aristeidis Karalis
	Art Unit	2828
	Examiner Name	Not Yet Known
Sheet 2 of 3	**Attorney Docket No.**	WTCY-0026-P07

NON-PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc.), date, page(s), volume-issue number(s), publisher, city and/or country where published.	T^5
	NPL-107	"International Search Report & WO for PCT/US09/43970", PCT/US09/43970 07/14/2009 , all	
	NPL-108	"Application Serial No. 12/613,686 (Atty Ref WTCY-0026-P02), Notice of Allowance mailed 03/07/2011", SN12/613,686 , 27	

EXAMINER SIGNATURE

Examiner Signature	/Robert Deberadinis/	Date Considered	11/18/2011

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document.
[4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L1	142	wireless same resonator same shape	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/18 09:47
L3	22	wireless same resonator same shape and loss adj inducing	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/18 10:28

11/18/2011 12:03:43 PM
C:\ Users\ rdeberadinis\ Documents\ EAST\ Workspaces\ 743.wsp

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Use as many sheets as necessary)

Complete if Known

Application Number	12/647,763
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Art Unit	2828
Examiner Name	Not Yet Known

Sheet 1 of 7

Attorney Docket No: WTCY-0026-P07

US PATENT DOCUMENTS

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		2005/0288740	Dec 29, 2005	Hassler, Jr., William L.	
		2007/0182367	Aug 9, 2007	Partovi, Afshin	
		2008/0067874	Mar 20, 2008	Tseng, Ryan	
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		2009/0146892	Jun 11, 2009	Shimizu, Kanjiro et al.	
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		2009/0174263	Jul 9, 2009	Baarman, David W., et al.	
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EXAMINER /Robert Deberadinis/ **DATE CONSIDERED** 11/18/2011

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Examiner Name	Not Yet Known

Sheet	2	of	7	Attorney Docket No: WTCY-0026-P07

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
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		2010/0052431	Mar 4, 2010	Mita, Hiroyuki	
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		2010/0065352	Mar 28, 2010	Ichikawa, Shinji	
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		2010/0081379	Apr 1, 2010	Cooper, Emily B., et al.	
		2010/0094381	Apr 15, 2010	Kim, Yong Hae et al.	
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Sheet 3 of 7

Attorney Docket No: WTCY-0026-P07

US PATENT DOCUMENTS

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		2010/0133919	Jun 3, 2010	Joannopoulos, John D.	
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		2010/0190435	Jul 29, 2010	Cook, Nigel P., et al.	
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		2010/0194334	Aug 5, 2010	Kirby, Miles A., et al.	
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		2010/0201313	Aug 12, 2010	Vorenkamp, Pieter et al.	
		2010/0201316	Aug 12, 2010	Takada, Kazuyoshi et al.	
		2010/0201513	Aug 12, 2010	Vorenkamp, Pieter et al.	
		2010/0207458	Aug 19, 2010	Joannopoulos, John D.	
		2010/0210233	Aug 19, 2010	Cook, Nigel P., et al.	
		2010/0213770	Aug 26, 2010	Kikuchi, Hideo	

EXAMINER /Robert Deberadinis/ **DATE CONSIDERED** 11/18/2011

Substitute Disclosure Statement Form (PTO-1449)

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Sheet 4 of 7

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US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT

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Complete if Known

Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet 5 of 7

Attorney Docket No: WTCY-0026-P07

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Sheet	6	of	7	Attorney Docket No: WTCY-0026-P07

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Examiner Name	Not Yet Known

Sheet 7 of 7

Attorney Docket No: WTCY-0026-P07

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BIB DATA SHEET

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SERIAL NUMBER	FILING or 371(c) DATE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
12/647,763	12/28/2009 **RULE**	307	2836	WTCY-0026-P07

APPLICANTS

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**** CONTINUING DATA *****************************

This application is a CIP of 12/567,716 09/25/2009
which claims benefit of 61/100,721 09/27/2008
and claims benefit of 61/108,743 10/27/2008
and claims benefit of 61/147,386 01/26/2009
and claims benefit of 61/152,086 02/12/2009
and claims benefit of 61/178,508 05/15/2009
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**** FOREIGN APPLICATIONS *****************************

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		STATE OR COUNTRY	SHEETS DRAWINGS	TOTAL CLAIMS	INDEPENDENT CLAIMS
Foreign Priority claimed ☐ Yes ☑ No 35 USC 119(a-d) conditions met ☐ Yes ☐ No Verified and Acknowledged /ROBERT L DEBERADINIS/ Examiner's Signature	☐ Met after Allowance Initials	MA	53	14	2

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Search Notes	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836

SEARCHED			
Class	Subclass	Date	Examiner
307	104	11/18/11	RLD

SEARCH NOTES (INCLUDING SEARCH STRATEGY)		
	DATE	EXMR
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EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L3	46	source adj resonator same second adj resonator	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 19:28
L5	23	source adj resonator and second adj resonator and loss same inducing and shape	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 19:35
L7	23	source adj resonator and second adj resonator and shape same loss same inducing	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 19:36
L10	67	resonator same shape same magnetic adj coupling	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 19:57
L12	382	resonator same magnetic adj coupling and q	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 20:07
L13	81	resonator same magnetic adj coupling same q	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2011/11/17 20:07

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First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet 1 of 13

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First Named Inventor	Aristeidis Karalis
Art Unit	2828
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First Named Inventor	Aristeidis Karalis
Art Unit	2828
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	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
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	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☒ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-02-23
Name/Print	John A. Monocello, III	Registration Number	51022

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant: Aristeidis Karalis et al. Examiner: Robert L. Deberadinis
Serial No.: 12/647,763 Group Art Unit: 2836
Filed: December 28, 2009 Docket No: WTCY-0026-P07
Title: WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS

SUPPLEMENTAL INFORMATION DISCLOSURE STATEMENT

Commissioner for Patents
P.O.Box 1450
Alexandria, VA 22313-1450

Dear Sir:

Pursuant to the requirements of 37 C.F.R. § 1.97(c)(2), Applicant hereby submits this Supplemental Information Disclosure Statement.

Applicant hereby submits on this Supplemental Information Disclosure Statement the following four non-patent documents which were previously submitted and filed on January 11, 2011 to correct the author name "Altchev," to correct the title in the Sekitani reference, and to correct the dates regarding International Application Nos. PCT/US2007/070892 and PCT/US09/43970. The citations are as follows:

Altchev et al. Efficient Resonant Inductive Coupling Energy Transfer Using New Magnetic and Design Criteria". IEEE, pp. 1293-1298, 2005

Sekitani et al. "A large-area flexible wireless power transmission sheet using printed plastic MEMS switches and organic field-effect transistors". [PUBLICATION UNKNOWN]

Copy of International Preliminary Report on Patentability with regard to International Application No. PCT/US2007/070892 by Examiner Philippe Becamel dated September 29, 2009

Copy of International Search Report and Written Opinion for International Application No. PCT/US09/43970, dated July 14, 2009

These are the only changes to the Supplemental Information Disclosure Statement that was filed on January 11, 2011. Copies of non-patent literature documents were submitted with the previously filed Supplemental Information Disclosure Statement on January 11, 2011.

In this Supplemental Information Disclosure Statement, Applicant's are also citing the references on the attached PTO/SB/08a.

Applicant hereby authorizes the Commissioner to charge any additional fees, or to credit any overage, to Deposit Account 50-3912.

Respectfully submitted,

ARISTEIDIS KARALIS ET AL.

By their Representatives,

Customer No. 87084

Date February 23, 2012

By /John A. Monocello, III/
John A. Monocello, III
Reg. No. 51,022
Tele. (412) 953-0696

PCT/US2009/058499 10.12.2009

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY0026PWO	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US 09/58499	International filing date *(day/month/year)* 25 September 2009 (25.09.2009)	(Earliest) Priority Date *(day/month/year)* 27 September 2008 (27.09.2008)
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.
2. ☐ **Certain claims were found unsearchable** (see Box No. II).
3. ☐ **Unity of invention is lacking** (see Box No. III).
4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:
5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/58499

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H03B 19/00 (2009.01)
USPC - 327/113
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 327/113

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 327/113, 306, 530, 555; 375/323; 307/134 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, USOC, EPAB, JPAB); GOOGLE
Search Terms: energy, power, power generator, generator, wireless, resonator, first resonator, second resonator, third resonator, Q-factor, distance, tunable, oscillating, impedance, capacitance, load

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0222542 A1 (Joannopoulos et al.) 27 September 2007 (27.09.2007), entire document, especially; abstract, para. [0004], [0005], [0013], [0014], [0019], [0023], [0025], [0029], [0033]	1 - 26
Y	US 6,452,465 B1 (Brown et al.) 17 September 2002 (17.09.2002), entire document, especially; abstract, col. 2, ln 4-6, col. 3, ln 7-12, 66-67	1 - 26

☐ Further documents are listed in the continuation of Box C. ☐

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier application or patent but published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 24 November 2009 (24.11.2009)	Date of mailing of the international search report 10 DEC 2009
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

P80157.V01W01

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

Date of mailing *(day/month/year)* 05 JUL 2011

Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011

Applicant WITRICITY CORPORATION

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
   1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 Telephone No. PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

CPA GLOBAL
JUL 11 2011
RECEIVED
Coded
Verified

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP STRATEGIC PATENTS, P.C. C/O CPA GLOBAL P.O. BOX 52050 MINNEAPOLIS, MN 55402	**PCT** NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION (PCT Rule 44.1) Date of mailing *(day/month/year)* 05 JUL 2011
Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
   1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 Telephone No. PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** see Form PCT/ISA/220 as well as, where applicable, item 5 below.	
International application No. PCT/US2011/027868	International filing date *(day/month/year)* 10 March 2011	(Earliest) Priority Date *(day/month/year)* 10 March 2010
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.
2. ☐ **Certain claims were found unsearchable** (see Box No. II).
3. ☐ **Unity of invention is lacking** (see Box No. III).
4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:
5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/027868

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H04B 5/00 (2011.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H04B 5/00; H01F 38/00; H02J 17/00; H01P 7/00, 7/06 (2011.01)
USPC - 307/104, 333/219, 230; 455/41.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent, Questel Orbit, USPTO EAST System (US-PGPUB; USPAT; USOCR; EPO; JPO; DERWENT), Google Patent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 2009/0085408 A1 (BRUHN) 02 April 2009 (02.04.2009) entire document	1-4, 11-12, 14-15, 17 ----- 5-10, 13, 16, 18-19
Y	US 2009/0243397 A1 (COOK et al) 01 October 2009 (01.10.2009) entire document	5, 8-10, 16, 18
Y	US 2007/0021140 A1 (KEYES, IV et al) 25 January 2007 (25.01.2007) entire document	6-7
Y	US 2008/0266748 A1 (LEE) 30 October 2008 (30.10.2008) entire document	13, 19
A	US 2008/0036588 A1 (IVERSON et al) 14 February 2008 (14.02.2008) entire document	20-25
A	US 6,664,770 B1 (BARTELS) 16 December 2003 (16.12.2003) entire document	1-25
A	US 2004/0000974 A1 (ODENAAL et al) 01 January 2004 (01.01.2004) entire document	1-25

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
27 June 2011

Date of mailing of the international search report
05 JUL 2011

Name and mailing address of the ISA/US
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
Facsimile No. 571-273-3201

Authorized officer:
Blaine R. Copenheaver
PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN NORTRUP
STRATEGIC PATENTS, P.C.
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing *(day/month/year)*	05 JUL 2011
Applicant's or agent's file reference WTCY0053PWO	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2011/027868	10 March 2011	10 March 2010

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H04B 5/00 (2011.01)
USPC - 307/104

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:

☒ Box No. I Basis of the opinion
☐ Box No. II Priority
☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐ Box No. IV Lack of unity of invention
☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐ Box No. VI Certain documents cited
☐ Box No. VII Certain defects in the international application
☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Date of completion of this opinion 27 June 2011	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/027868

Box No. I Basis of this opinion

1. With regard to the **language**, this opinion has been established on the basis of:

☒ the international application in the language in which it was filed.

☐ a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

a. (means)

☐ on paper

☐ in electronic form

b. (time)

☐ in the international application as filed

☐ together with the international application in electronic form

☐ subsequently to this Authority for the purposes of search

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Form PCT/ISA/237 (Box No. I) (July 2009)

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	3, 5-10, 13, 16, 18-19	YES
	Claims	1-2, 4, 11-12, 14-15, 17	NO
Inventive step (IS)	Claims	20-25	YES
	Claims	1-19	NO
Industrial applicability (IA)	Claims	1-25	YES
	Claims	None	NO

2. Citations and explanations:

Claims 1-2, 4, 11-12, 14-15, 17 lack novelty under PCT Article 33(2) as being anticipated by Bruhn.

Regarding claim 1, Bruhn discloses a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) comprising at least one receiving magnetic resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a first oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); and at least one transferring magnetic resonator 126, 128 (Fig. 9) configured to generate (through resonance, para 0017-0018, Fig. 9) a second oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), wherein the electrical energy from the at least one receiving magnetic resonator 130, 132 is used to energize the at least one transferring magnetic resonator 126, 128 (Fig. 9) to generate the second oscillating magnetic field (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9).

Regarding claim 2, Bruhn discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

Regarding claim 4, Bruhn discloses wherein the second frequency is approximately an integer multiple of the first frequency (second resonator has twice the resonant frequency of first resonator, para 0018).

Regarding claim 11, Bruhn discloses wherein the at least one receiving magnetic resonator 130, 132 is configurable to capture energy from magnetic fields with different parameters (resonator 130 can receive energies with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 12, Bruhn discloses wherein the at least one transferring magnetic resonator 126, 128 is configurable to generate magnetic fields with different parameters (resonator 126 can generate and transmit energy with different frequencies, para 0017-0018, 0040, Fig. 9).

Regarding claim 14, Bruhn discloses a system (para 0017, 0043) comprising a source resonator 126, 128 configured to generate a first oscillating magnetic field (transferred to the secondary winding 20, para 0017-0018, 0031, Fig. 9) characterized by a first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9); a device resonator 130, 132 configured to capture electrical energy received wirelessly (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) through a second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) characterized by a second plurality of parameters different from the first plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018); and a wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) including conversion circuitry (circuits as seen in Fig. 9) configured to capture energy from the second oscillating magnetic field (developed by generator 16 and primary winding 18, Fig. 9, para 0034) and to energize the source resonator 126, 128 to generate the first oscillating magnetic field (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Regarding claim 15, Bruhn discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and the second plurality of parameters are different in at least a frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018).

Supplemental Box

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Regarding claim 17, Bruhn discloses wherein the wireless power converter (apparatus for wireless energy transmission, para 0017, Fig. 9) is powered by electrical energy captured by the device resonator 130, 132 (transferred to the secondary winding 20, energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0017-0018, 0031, Fig. 9).

Claim 3 lacks an inventive step under PCT Article 33(3) as being obvious over Bruhn.

Regarding claim 3, Bruhn discloses the invention above, the invention above, and discloses a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) and a second frequency (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose wherein the first frequency is approximately an integer multiple of the second frequency. It would have been obvious to one of ordinary skill in the art at the time of the invention to provide a first frequency that is approximately an integer multiple of the second frequency, in order to provide a system that can handle different power levels for providing wireless energy to multiple devices, and because discovering the optimal value of a result effective variable involves only routine skill in the art.

Claims 5, 8-10, 16, 18 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Cook et al. (hereinafter referred to as Cook).

Regarding claim 5, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters. Cook is in the field of wireless power systems (para 0044) and teaches wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 8, Bruhn discloses the invention above, and further discloses electrical energy captured by the at least one receiving magnetic resonator 130 (resonator 130 captures energy developed by generator 16 and primary winding 18, Fig. 9, para 0034), but does not specifically disclose a first converter circuit configured to convert the electrical energy into a direct current signal. Cook teaches a first converter circuit 1550 configured to convert the electrical energy into a direct current signal (a DC/DC or DC/AC converter 1550 converts the electrical energy received by resonator antenna into direct current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 9, Bruhn discloses the invention above, and further discloses wherein the alternating current signal (power source 16 provides AC current signal, Fig. 9, para 0040) is used to energize the at least one transferring magnetic resonator 126, 128 (energy coupling is present between the first and second magnetic resonators when they are arranged in the near field, as they are here: the free-space wavelength at even the 60th harmonic of the shortest wavelength contemplated (at 5 MHz) would be 1 meter, such that the spacing here would be understood to be "sub-wavelength" or "near-field", para 0018, Fig. 9), but does not disclose a second converter circuit configured to convert the direct current signal from the first converter circuit into an alternating current signal. Cook teaches a second converter circuit (two converter circuits for converting current signals, para 0194-0195, as shown in Fig. 15) configured to convert the direct current signal from the first converter circuit into an alternating current signal (a DC/DC or DC/AC converter 1550 can convert the electrical energy received by resonator antenna into alternating current, para 0194-0195, Fig. 15). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the direct current conversion as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

Regarding claim 10, Bruhn discloses the invention above, and further discloses at least one receiving magnetic resonator 130, 132 (resonator is "electrically isolated", i.e. galvanically isolated from the primary and secondary circuits, Fig. 9, para 0034) and at least one transferring magnetic resonator 126, 128 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Regarding claim 16, Bruhn discloses the invention above, but does not specifically disclose wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude. Cook teaches wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude (transmit power converter unit converts the supply voltage and frequency, such as 110V/60Hz, into another voltage [different voltage] and into another frequency, such as under 50Hz, that is more appropriate for wireless transmission, para 0155-0158). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the different magnitudes as taught in Cook with the invention of Bruhn in order to provide an efficient power transfer system to charge electronic devices (see Cook, para 0017, 0042).

WRITTEN OPINION OF THE
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International application No.
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Regarding claim 18, Bruhn discloses the invention above, and further discloses the source resonator 126, 128 and the device resonator 130, 132 (Fig. 9), but does not disclose wherein at least one of the resonators has a quality factor Q>100. Cook teaches a resonator with a quality factor Q>100 (magnetic resonant antennas used in system must provide a Q-factor as high as possible, and can provide Q-factors up to 300, para 0060-0061). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the high quality factor resonator as taught in Cook with the invention of Bruhn in order to provide a very efficient wireless power transmission system with minimal power losses (see Cook, para 0047).

Claims 6-7 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Keyes, IV et al. (hereinafter referred to as Keyes).

Regarding claim 6, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters includes a first frequency (operating at the fundamental frequency, para 0017, 0031, Fig. 9) different from a second frequency of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose a frequency hopping sequence. Keyes is in the field of wireless energy transfer systems (para 0008-0009, Fig. 43), and teaches a frequency hopping sequence (power transmitted wirelessly using frequency hopping technique, para 0056-0058). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the frequency hopping sequence as taught in Keyes with the invention of Bruhn in order to avoid wireless interference (see Keyes, para 0056).

Regarding claim 7, Bruhn discloses the invention above, and discloses wherein the first plurality of parameters (operating at the fundamental frequency, para 0017, 0031, Fig. 9) includes a sequence different from a second sequence of the second plurality of parameters (different at least for operating at the second harmonic or other multiple of the fundamental frequency, para 0017-0018), but does not disclose an on/off sequence. Keyes teaches an on/off sequence (wireless reception of on or off control commands for wireless base units, para 0094). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the on/off sequence as taught in Keyes with the invention of Bruhn in order to provide a method of wirelessly powering devices on and off (see Keyes, para 0007-0008).

Claims 13, 19 lack an inventive step under PCT Article 33(3) as being obvious over Bruhn in view of Lee.

Regarding claim 13, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor. Lee is in the field of wireless power converters (para 0001) and teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Regarding claim 19, Bruhn discloses the invention above, and discloses a loop inductor 130 (Fig. 9), but does not disclose wherein the source resonator and the device resonator include a shared loop inductor. Lee teaches wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor (transmitter and receiver are combined, para 0048, and constructed by winding transmission coil outputting power generated from electromagnetic wave generating source, para 0051, Fig. 10). It would have been obvious to one of ordinary skill in the art at the time of the invention to combine the shared loop as taught in Lee with the invention of Bruhn to provide a more efficient wireless power system for transferring power by maximizing generation and reception of electromagnetic waves in the resonance circuit (see Lee, para 0051).

Claims 20-25 meet the criteria set out in PCT Article 33(2)-(3), because the prior art does not teach or fairly suggest:

Regarding claim 20, a method of wireless power conversion comprising: providing a configurable magnetic resonator; tuning the configurable magnetic resonator to capture a first oscillating magnetic field characterized by a first plurality of parameters; converting the oscillating magnetic field into electrical energy; storing the electrical energy as stored energy in an energy storage element; tuning the configurable magnetic resonator to generate a second oscillating magnetic field characterized by a second plurality of parameters; and energizing the configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field.

Claims 21-25 meet the criteria due to their dependence on novel claim 20.

The prior art, as shown below, details some aspects of the invention, however, none of the prior art teaches all the missing limitations either alone or in combination as specified.

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(54) **Title**: WIRELESS POWER UTILIZATION IN A LOCAL COMPUTING ENVIRONMENT

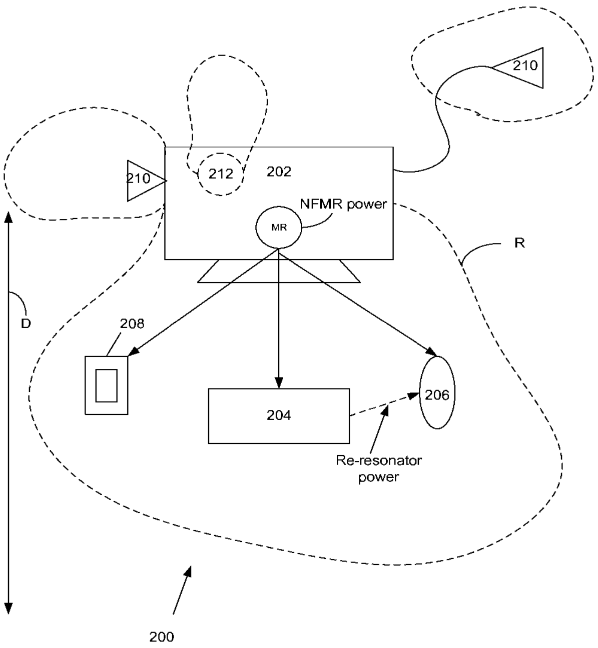

Fig. 2

(57) **Abstract**: Various embodiments of a wirelessly powered local computing environment are described. The wireless powered local computing environment includes at least a near field magnetic resonance (NFMR) power supply arranged to wirelessly provide power to any of a number of suitably configured devices. In the described embodiments, the devices arranged to receive power wirelessly from the NFMR power supply must be located in a region known as the near field that extends no further than a distance D of a few times a characteristic size of the NFMR power supply transmission device. Typically, the distance D can be on the order of 1 meter or so.

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TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

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WIRELESS POWER UTILIZATION IN A LOCAL COMPUTING ENVIRONMENT

TECHNICAL FIELD

[0001] The described embodiments relate generally to utilizing a wireless power transmission in a portable computing environment.

BACKGROUND

[0002] Historically, transferring power wirelessly has been successful for fairly limited applications. In particular, only those applications where a wireless power source and a wireless power receiver are located very close to each other have been successful. In this arrangement, the wireless power source and the wireless power receiver are typically coupled inductively by way of a magnetic field that can entangle both the power source and receiver. Although well suited for applications requiring relatively low power (on the order of mW), this same process is not suitable for those applications requiring either more power (on the order of at least a few watts to hundreds of watts) or where the power source and power receiver are located further apart from each other, such as a few inches to a few feet.

[0003] However, it has been discovered (see "Efficient wireless non-radiative mid-range energy transfer" by Karalis et al., Annals of Physics 323 (2008) pgs. 34 - 38) that useable power can be transferred wirelessly from a power source to a receiver located within a distance referred to as a near field. By near field it is meant that within a distance a few times larger than that of both objects involved in the transfer (about one meter or so for most applications) a relatively large amount of power (at least on the order of a few watts) can be transferred between a wireless source device and a receiver with an acceptable efficiency. In this way, a realistic and practical approach to wireless transferring useable amounts of power over distances suitable for limited applications can be realized. Typically, each battery powered device such as a wireless electronic device requires its own charger and power source, which is usually an alternating current (AC) power outlet. Such a wired configuration becomes unwieldy when many devices need charging.

[0004] Various over-the-air or wireless power transmission between a transmitter and a receiver coupled to the electronic device to be charged have been carried out that generally fall into two categories. One category is based on the coupling of plane wave radiation between a transmit antenna and a receive antenna on the device to be charged. The receive antenna collects the radiated power and rectifies it for charging the battery. Antennas are generally of resonant length in order to improve the coupling efficiency. This approach suffers from the fact that the power coupling falls off quickly with distance between the antennas, so charging over reasonable distances (e.g., less than 1 to 2 meters) becomes difficult.

[0005] Other techniques rely upon inductive coupling between a transmit antenna embedded, for example, in a "charging" mat or surface and a receive antenna (plus a rectifying circuit) embedded in the electronic device to be charged. This approach has the disadvantage that the spacing between transmit and receive antennas must be very close (e.g., within thousandths of meters). Though this approach does have the capability to simultaneously charge multiple devices in the same area, this area is typically very small and requires the user to accurately locate the devices to a specific area.

[0006] With wireless power transmission there is a need for apparatuses and methods for transmitting and relaying wireless power at varying power levels and multiplexed times to increase power transmission efficiency.

[0007] Furthermore, what is desired are methods, systems, and apparatus for efficient and user friendly interaction between peripheral devices in a wirelessly powered local computing environment. In particular, in order to enhance the user's experience and provide efficient power utilization, cooperation between the plurality of peripheral devices in the context of the wireless power environment is desired.

SUMMARY

[0008] The present invention provides a system and method for utilizing wireless near field magnetic resonance (NFMR) power transmission in a computing environment.

[0009] In various embodiments, methods, systems, and apparatus for interacting between a plurality of peripheral devices receiving power wirelessly from a wireless power supply is described. In one embodiment, a virtual charging area can be created. The virtual charging area can extend to about about one (1) meter from a central station that incorporates a NFMR power supply. The virtual charging area can define a region in which suitably configured peripheral devices, such as a mouse, keyboard, and so on can receive power by way of a NFMR channel formed between the NFRM power supply and a NFMR resonator circuit included in the peripheral device. In this way, when both the NFMR power supply and the NFMR resonator circuit are tuned to each other, then useable power can be transferred over a power conduction channel formed between the two resonant devices.

[0010] In some embodiments, at least one of the peripheral devices can have a tunable resonator circuit having at least one circuit element (such as a resistor, inductor, or capacitor) having a value that can be changed. In this way, the tunable resonator circuit can be de-coupled from the NFMR power supply by de-tuning the tunable resonator circuit in relation to the resonance frequency of the NFMR power supply. In this way, the effective Q value of the tunable circuit is reduced to the point that essentially no power is transferred. In one embodiment, at least one of the plurality of peripheral devices can include a secondary NFMR resonator circuit adapted to re-resonant power to another one of the plurality of peripheral devices by establishing a NFMR channel to the other peripheral device over which useable power can be transferred. In some embodiments, the NFMR power supply can eliminate any voids in the virtual charging area by modifying resonance characteristics such as frequency.

[0011] A method of wirelessly transmitting power can be performed by creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna, coupling the electromagnetic field and a receiver antenna of a first receiver device within the coupling mode region, creating a second coupling mode region of the electromagnetic field different from the first coupling mode region within a near field of a transmit antenna of the first receiver device, coupling the electromagnetic field to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device, wirelessly delivering power from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field; and wirelessly delivering at least some of the power wirelessly delivered to the first receiver device is wirelessly by re-transmitting the at least some power to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The included drawings are for illustrative purposes and serve only to provide examples of possible structures and arrangements for the disclosed embodiments. These drawings in no way limit any changes in form and detail that may be made to the described embodiments by one skilled in the art without departing from the spirit and scope of the embodiments.

[0013] Fig. 1 illustrates representative tunable resonator circuits in accordance with the described embodiments.

[0014] Fig. 2 shows representative virtual charging area in accordance with the described embodiments.

[0015] Fig. 3 shows representative hybrid power circuit in accordance with the described embodiments.

[0016] Fig. 4 shows representative time multiplexing for distributing power in accordance with the described embodiments.

[0017] Fig. 5 illustrates a wireless transmission or charging system, in accordance with various exemplary embodiments.

[0018] Fig. 6 shows a simplified schematic diagram of a wireless power transfer system.

[0019] Fig. 7 shows an antenna used in exemplary embodiments configured as a "loop" antenna that can also be referred to herein as a "magnetic" antenna.

[0020] Fig. 8 shows a flowchart detailing process 800 in accordance with the described embodiments.

DETAILED DESCRIPTION

[0021] Various embodiments of a wirelessly powered local computing environment are described. The wireless powered local computing environment includes at least a near field magnetic resonance (NFMR) power supply arranged to wirelessly provide power to any of a number of suitably configured devices. In the described embodiments, the devices arranged to receive power wirelessly from the NFMR power supply can be located in a region known as the near field that extends no further than a distance D that can be a few times a characteristic size of the NFMR power supply transmission device. Typically, the distance D can be on the order of 1 meter or so.

[0022] Fig. 1 shows various representative tunable circuits in accordance with the described embodiments. The representative tunable circuits can include series RLC (resistor (R), inductor (L), capacitor(C)) circuit 102. In this arrangement, a resonant frequency can be tuned (i.e., changed) by changing any of the component values. For example, circuit 102, capacitor C can be a variable capacitor used to tune circuit 102. Similarly, circuit 104 (known as a Hartlely oscillator) can be used as a tunable circuit in the described embodiments as can tuned LC circuit 106.

[0023] Fig. 2 shows representative virtual charging area 200 in accordance with the described embodiments. Virtual charging area 200 provides region R of charging for suitably configured devices placed within the region R. NFMR power supply can be placed in central unit such as desktop computer. In this way, the desktop computer can provide the NFMR power supply with computing resources. It should be noted that the near field magnetic resonance (NFMR) power supply can include high Q circuit that relies upon near field magnetic coupling by way of a resonance channel formed between resonances of the power source and sink to transfer power. The NFMR power supply can be a standalone unit such as, for example, included in a desk top computer, laptop computer, tablet computer, and so on. In other embodiments, the NFMR power supply can take the form of a portable type unit such as a dongle that can be connected to a legacy device such as a desktop computer thereby providing the ability to retrofit devices. In still other embodiments, housing or a portion of a housing used to enclose the NFMR power source can act to extend a useful range of the NFMR power supply.

[0024] In this way, suitably configured peripheral devices can be powered directly from the NFMR power supply. In so doing, the peripheral devices when tuned to the appropriate frequency can receive power wirelessly from the NFMR power supply. In so doing, the appropriately tuned peripheral device can be considered to be part of a resonance circuit that can include the NFMR power supply and any other peripheral devices so tuned. As part of such a circuit, each device has associated with it a corresponding load that can be sensed by the NFMR power supply. As such, the resonance circuit can have a characteristic load that can change by the addition or deletion of devices from the resonance circuit. For example, if a suitably configured device such as a portable media player is brought within range of the NFMR power supply, then the load associated with the portable media player can be sensed by the NFMR power supply when (and if) the portable media player is appropriately tuned. It should be noted that in some cases, the device being brought into the range of the NFMR power supply can communicate its initial presence using a standard communication protocol such as WiFi or Bluetooth. However, once incorporated into the resonance circuit, the device can use a communication back channel described in detail below. Accordingly, any change in the characteristic load factor of the resonance circuit can convey information that can be used by the NFMR power supply to control the various devices in the resonance circuit by, for example, distributing power, and so on.

[0025] In some embodiments, certain of the peripheral devices can be configured to include a re-resonator circuit that can receive power directly from the NFMR power supply. Such devices can also transfer a portion of the power received to other of the peripheral devices. For example, as shown in Fig. 2 virtual charging area 200 includes central unit 202 (desktop computer) that can include the NFMR power supply, keyboard 204, mouse 206, and portable media player 208. In one embodiment, keyboard 204 can be configured to receive power directly from the NFMR power supply included in desktop computer 202 as can mouse 206 and portable media player 208 (when located within range R).

[0026] In some cases, the ability of desktop computer 202 to provide power directly to mouse 206, for example, can be reduced due to any number of factors. Such factors can include, for example, the addition of other devices into region R that require power from the NFMR power supply, obstacles interfering with the direct power channel formed between the NFMR and mouse 206, and so on. In this case, keyboard 204 can act as a re-resonator such that a portion of the power delivered to keyboard 204 from the NFMR power supply can be passed on by way of a re-resonator transmission unit (not shown) in keyboard 204. In this way, any power loss experienced by mouse 206 can be ameliorated by the power received from keyboard 204. This arrangement can be transitory or can last for as long as mouse 206 is not able to receive adequate power directly from the NFMR power supply. In other cases, the locating of portable media player 208 within region R can reduce the amount of power available to keyboard 204 and mouse 206. In this case, if a battery in keyboard 206 is fully charged (or additional charge is not necessary) then keyboard 206 can decouple a charging circuit while still maintaining a re-resonator circuit providing power to mouse 206.

[0027] In some embodiments, dongle 210 can be connected to desktop computer 202 (by way of a USB port or cable, for example). So connected, dongle 210 can, in turn, act as a range extender for the NFMR power supply. In this way, dongle 210 can extend a range that power can be provided by the NFMR power supply included in desktop computer 202. In some cases, dongle 210 can re-resonate power already received from the NFMR power supply while in other cases, dongle 210 can include its own NFMR power supply. By having its own NFMR power supply, dongle 210 can provide additional power wirelessly to those devices within virtual charging region 200 separate from the power provided by the NFMR power supply included in desktop 202. It should be noted that in some embodiments, the housing of desktop computer 202 (or a portion thereof) can be used as a resonator as part of the NFMR power supply.

[0028] Fig. 3 shows representative hybrid power circuit 300 in accordance with the described embodiments. As described, hybrid power circuit 300 can match the low power delivery capability of the NFMR power supply to a large power requirement of required for long term storage devices, such as lithium ion polymer (LiPO) battery. Batteries in such devices as portable phones, portable media players, and so on, can require relatively large amount of power to charge that can be greater than that available from the NFMR power supply. Therefore, it is difficult to charge these high capacity batteries such as LiPO using the NFMR power supply. However, a short term charge storage device (such as a capacitor, ultra capacitor, and so on) that can be charged up by power delivered by the NFMR power supply can be used to temporarily store charge prior to being passed to the battery. In this way, once sufficient charge is stored in the short term charge storage device, the stored charge can be used to charge a long term charge storage device (such as a LiPO battery). For example, Fig. 3 shows representative hybrid power circuit 300 having capacitor 302, capacitor charging circuit 304 (that can receive power P from the NFMR power supply), long term power storage unit 306 (that can take the form of battery 306), and battery charging circuit 308. In the described embodiment, power P provided by the NFMR power supply can "trickle" charge capacitor 302. Once sufficient charge is stored in capacitor 302, capacitor charging circuit 304 can sense capacitor voltage VC and switch fully charged capacitor 302 to battery 306 by way of battery charging circuit 308. In this way, charge Q stored in capacitor 302 can be used to increase the charge of battery 306. Once capacitor 302 is discharged (as determined by capacitor charging circuit 304), capacitor 302 can again receive power P from the NFMR power supply.

[0029] One of the advantages of a wirelessly powered local computing environment is the potential to provide an enhanced user experience. For example, by doing away with clumsy and annoying cables and eliminating the need to replace batteries, an easy to use and efficient local computing environment can be provided to the user. However, in order to provide this enhanced user experience, it would be advantageous for the various devices that make up the wirelessly powered local computing environment to be able to interact with each other as well as with the NFMR power supply. Such interaction can include, for example, providing power by the NFMR power supply to any of the devices within range in whatever amount is required. For example, an amount of power transferred between the NFMR power supply (having a first resonator circuit) and receiving device (having a second resonator circuit) can be controlled by tuning (or de-tuning) the second resonator circuit along the lines described above. It should be noted that when a device is tuned, the tuned device can become part of the resonance circuit. As part of the resonance circuit, a load associated with the device can be "seen" by the NFMR power supply. This load can, in turn, be used by the NFMR power supply to determine the power requirements of the resonance circuit as well as how the required power must be distributed amongst the various devices included in the resonance circuit. On the other hand, when a device "de-tunes", then the device no longer resonates with the NFMR power supply and is effectively removed from the resonance circuit and receives little or no additional power.

[0030] It should be noted that various environmental factors can have an effect on the efficiency of power transfer from the NFMR power supply to those devices included in the resonance circuit. For example, any object (metallic, for example) that can interfere with the magnetic coupling between the NFMR power supply and those device wirelessly receiving power can adversely affect both the amount of power supplied and the efficiency of the power transfer. This reduction in power transferred or power transfer efficiency can put an undue strain on the NFMR power supply as well as increase the likelihood that particular devices may not have sufficient power to operate at peak efficiency, to execute important functions, or in some cases, not be able to operate at all. In one embodiment, feedback provided by a device to the NFMR power supply indicating that the device requires more power or has experienced a reduction in power can cause the NFMR power supply to try to ascertain the reason or reasons why the device has experienced this reduction in power. For example, if the device is moving within a void region (a void being defined as that region having a substantially reduced power transmission or efficiency factor), then the NFMR power supply can attempt to move the void region by modifying selected resonance factors (such as resonance frequency) thereby having the effect of moving the void region (hopefully beyond the range of the operating region of the devices wirelessly coupled to the NFMR power supply). In one embodiment, the NFMR power supply can determine that the power transfer efficiency has dropped below a threshold for a device(s) based upon, for example, feedback from the affected device(s). In response, the NFMR power supply can respond by modifying the frequency of the magnetic resonance signal until the power efficiency has recovered to above the threshold, by increasing power, or by, in some cases, causing less important or less used devices, to de-tune themselves (thereby removing themselves from the resonance circuit) so as to free up power that can be provided to those devices requiring more power. It should be noted that these operations can be carried out in the background in such a way that the user is unaware of the operations taking place. In still another embodiment, the power source can alter phase, frequency and or signal amplitude relative to other links in order to optimize power delivery.

[0031] In order to provide more robust communication between the various devices coupled with the NFMR power supply, each device can provide affirmative feedback to the NFMR power supply using a direct communication channel such as Bluetooth or WiFi. It should be noted, however, that an indirect communication channel can also be used. Such an indirect communication channel can be formed using the resonance circuit load factor mediated by the number (and type) of devices wirelessly coupled with the NFMR power supply. Since each device has an associated resonance load (i.e., load perceived by the NFMR power supply when a device is tuned to the proper resonance frequency), an indirect communication channel mediated by load state of the device, or devices in the resonance circuit can be established with the NFMR power supply. For example, the NFMR power supply can characterize a particular load state of a resonance circuit by ascertaining the overall resonance load (i.e., sense load on resonant circuit). Any changes to the load state can indicate a change in the status of the resonance circuit which, in turn, can infer that one or more of the devices previously included in the resonance circuit (i.e., tuned to the NFMR power supply resonant frequency) has dropped out, or de-tuned. In some cases, a Morse code like communication protocol can be established between the NFRM power supply and each of the devices. This Morse code like communication protocol can be based upon a device tuning and de-tuning itself using an identifiable pattern. In this way, a simple device identifier, for example, can be communicated to the NFMR power supply. Using this arrangement, a device that has determined to de-tune itself and to remove itself from the resonance circuit, can signal the NFMR power supply its intent as well as identify itself. In this way, the NFRM power supply can have a more clear understanding of the condition of the resonance circuit and the devices included therein. This device to device communication channel (also referred to as a back channel) can be capable of communicating simple information. Such information can include, for example, a device identifier, a synchronization flag, and so on. It should be noted that this communication channel is independent and separate from other communication channels provided by, for example, WiFi or Bluetooth.

[0032] For example, if keyboard is using power wirelessly provide by the NFMR power supply to charge its battery, when the keyboard determines that the battery is substantially fully charged, then the keyboard can determine that power from the NFMR power supply is no longer required (at least until the battery discharges to a pre-set level). In this case, the keyboard can notify the NFMR power supply that it no longer requires power (or at least until it signals that it requires power at some future point in time). In this case, the NFMR can redirect power away from the keyboard (using, for example, a different resonant frequency when the NFMR power supply is equipped to transmit power on a number of frequency ranges, or bands) or the keyboard can remove itself from the resonance circuit (either on its own or as directed) by de-tuning itself. In this way, the load of the resonance circuit can be reduced allowing more power to be wirelessly delivered to the other devices in the resonance circuit. It should be noted that for efficiency and environmental reasons, the NFMR power supply will provide only as much power as is needed. For example, as battery charges up then less power is required. In this way, the charge state of the battery can be communicated to the NFMR power supply that can respond by reducing, or throttling back, the power provided to the keyboard.

[0033] It should be noted that while a device can be removed from the resonance circuit by the process of de-tuning, the device can be added to the resonance circuit by tuning it. By tuning (and conversely de-tuning) it is meant that circuit characteristics (such as resistance) can be changed resulting in the circuit Q increasing in the case of tuning or decreasing in the case of de-tuning. It should be noted that the relative increase or decrease in Q for a circuit can be dependent upon the circuit and applications to which the circuit is used.

[0034] When a device is brought within range R of the power supply, then the load experienced by the power supply increases by that amount corresponding to the device. In this way, proximity detection can be thought as having taken place that can trigger an action to be taken. For example, if a portable media player is brought within range R of a desktop computer, then the proximity signal generated by the change in load experienced by the power supply can cause the desktop computer to initiate a synchronization process, for example, between the portable media player and the desktop computer.

[0035] The communication channels established between the various devices in the resonance circuit can be used for the devices to determine amongst themselves which device takes priority with regards to power supplied by the NFMR power supply. In other cases, a host device (that includes the NFMR power supply and any associated computing resources) can act as aggregator. By aggregator, it is meant that the host device can determine the priority of those devices for receiving power, how much power to receive, and for how long. It should be noted that some devices and or some operations performed by a device can have a higher priority than other devices and or operations. For example, a high priority device(s) may require guaranteed power for operation (such as using a mouse vs charging a portable media player). The host device can use any suitable priority mechanism (round robin, for example).

[0036] In another embodiment, the devices receiving power can communicate amongst themselves to determine which device has priority. The devices understand their own operating points, such as a minimum amount of power to perform certain function, maximum power required to perform all functions. In this way, each device can provide a desired amount of power, a list of functions that can be performed, and a minimum amount of power required for operation. The source can determine how much power can be delivered and which device can get the power it needs. In some cases, the devices themselves set the priority, in other cases, the host device sets the priority. When a device is not receiving power, it removes itself from the resonance circuit by de-tuning, and returns to the circuit by re-tuning.

[0037] It should be noted that the NFMR power supply can use any number of protocols to wirelessly provide power to the various devices included in the resonance circuit. For example, the NFMR power supply can include a plurality of resonator circuits each arranged to resonate at a particular frequency. In this way, the NFMR power supply can provide power orthogonally using different frequency bands. In this way, a device can have multiple resonant frequencies in order to take advantage of the frequency bands provided by the NFMR power supply. For example, the NFMR power supply can wirelessly provide power using multiple frequency bands where a number of devices can each tune themselves to a particular frequency. In this way, frequency shifting techniques can be used to more efficiently transfer power to the plurality of devices within range of the NFMR power supply.

[0038] Other mechanisms for a single NFMR power supply to independently transmit power to more than one device includes time multiplexing as shown in Fig. 4. As illustrated, devices 400, 402 and 404 can each take turns tuning and de-tuning themselves such that at any one time only one of the devices if receiving power. For example, during a period 1, device 400 receives power by tuning itself to at least one of the available resonant frequencies while devices 402 and 404 are de-tuned. Once device 400 has completed its power cycle, device 400 de-tunes itself and device 402 tunes itself and receives power wirelessly from the NFMR power supply. Once device 402 completes its power cycle, device 402 de-tunes itself and device 404 tunes itself to at least one of the resonance frequencies to receive power from the NFMR power supply. In other embodiments, the NFMR power supply can use frequency multiplexing in which the NFMR can toggle amongst a number of frequencies each one tuned to a particular device. The device can receive power only when the device resonates with a current frequency of the power supply.

[0039] The closed loop control can also affect the modes of operation of the devices in the resonance circuit. For example, a keyboard can determine an amount of power received from the source which will depend upon the distance between the source and the keyboard (as well as the presence of any interfering objects). If the power received falls below a threshold, then the keyboard can use more battery power or request that the source increase power. In some cases, if the power provided can not be increased to meet the current operating requirements of the keyboard, then the keyboard can take action to reduce its power requirements by, for example, reducing backlight, etc. It should be noted that as discussed above, the reduction on power received by the keyboard can be caused by many other factors other than an increase in distance. Such factors can include, for example, the presence of voids, objects, other devices added to the circuit, and so on.

[0040] Fig. 5 illustrates a wireless transmission or charging system 500, in accordance with various exemplary embodiments. Input power 502 is provided to a transmitter 504 for generating a radiated field 506 for providing energy transfer. A receiver 508 couples to the radiated field 506 and generates an output power 510 for storing or consumption by a device (not shown) coupled to the output power 510. Both the transmitter 504 and the receiver 508 are separated by a distance 512. In one exemplary embodiment, transmitter 504 and receiver 508 are configured according to a mutual resonant relationship and when the resonant frequency of receiver 508 and the resonant frequency of transmitter 504 are very close, transmission losses between the transmitter 504 and the receiver 508 are minimal when the receiver 508 is located in the "near-field" of the radiated field 506.

[0041] Transmitter 504 further includes a transmit antenna 514 for providing a means for energy transmission and receiver 508 further includes a receive antenna 518 for providing a means for energy reception. The transmit and receive antennas are sized according to applications and devices to be associated therewith. As stated, an efficient energy transfer occurs by coupling a large portion of the energy in the near-field of the transmitting antenna to a receiving antenna rather than propagating most of the energy in an electromagnetic wave to the far field. When in this near-field a coupling mode may be developed between the transmit antenna 514 and the receive antenna 518. The area around the antennas 514 and 518 where this near-field coupling may occur is referred to herein as a coupling-mode region.

[0042] Fig. 6 shows a simplified schematic diagram of a wireless power transfer system. The transmitter 604 includes an oscillator 622, a power amplifier 624 and a filter and matching circuit 626. The oscillator is configured to generate a desired frequency, which may be adjusted in response to adjustment signal 623. The oscillator signal may be amplified by the power amplifier 624 with an amplification amount responsive to control signal 625. The filter and matching circuit 626 may be included to filter out harmonics or other unwanted frequencies and match the impedance of the transmitter 604 to the transmit antenna 514.

[0043] The receiver 608 may include a matching circuit 632 and a rectifier and switching circuit 634 to generate a DC power output to charge a battery 636 as shown in FIG. 6 or power a device coupled to the receiver (not shown). The matching circuit 632 may be included to match the impedance of the receiver 508 to the receive antenna 518. The receiver 508 and transmitter 504 may communicate on a separate communication channel 619 (e.g., Bluetooth, zigbee, cellular, etc).

[0044] As illustrated in Fig. 7, antennas used in exemplary embodiments may be configured as a “loop” antenna 750, which may also be referred to herein as a “magnetic” antenna. Loop antennas may be configured to include an air core or a physical core such as a ferrite core. Air core loop antennas may be more tolerable to extraneous physical devices placed in the vicinity of the core. Furthermore, an air core loop antenna allows the placement of other components within the core area. In addition, an air core loop may more readily enable placement of the receive antenna 518 (FIG. 5, 6) within a plane of the transmit antenna5 (FIG. 5, 6) where the coupled-mode region of the transmit antenna 514 (FIG. 5, 6) may be more powerful.

[0045] As stated, efficient transfer of energy between the transmitter 104 and receiver 508 occurs during matched or nearly matched resonance between the transmitter 504 and the receiver 508. However, even when resonance between the transmitter 504 and receiver 508 are not matched, energy may be transferred at a lower efficiency. Transfer of energy occurs by coupling energy from the near-field of the transmitting antenna to the receiving antenna residing in the neighborhood where this near-field is established rather than propagating the energy from the transmitting antenna into free space.

[0046] The resonant frequency of the loop or magnetic antennas is based on the inductance and capacitance. Inductance in a loop antenna is generally simply the inductance created by the loop, whereas, capacitance is generally added to the loop antenna's inductance to create a resonant structure at a desired resonant frequency. As a non-limiting example, capacitor 752 and capacitor 754 may be added to the antenna to create a resonant circuit that generates resonant signal 756. Accordingly, for larger diameter loop antennas, the size of capacitance needed to induce resonance decreases as the diameter or inductance of the loop increases. Furthermore, as the diameter of the loop or magnetic antenna increases, the efficient energy transfer area of the near-field increases. Of course, other resonant circuits are possible. As another non-limiting example, a capacitor may be placed in parallel between the two terminals of the loop antenna. In addition, those of ordinary skill in the art will recognize that for transmit antennas the resonant signal 756 may be an input to the loop antenna 750.

[0047] Exemplary embodiments of the invention include coupling power between two antennas that are in the near-fields of each other. As stated, the near-field is an area around the antenna in which electromagnetic fields exist but may not propagate or radiate away from the antenna. They are typically confined to a volume that is near the physical volume of the antenna. In the exemplary embodiments of the invention, magnetic type antennas such as single and multi-turn loop antennas are used for both transmit (Tx) and receive (Rx) antenna systems since magnetic near-field amplitudes tend to be higher for magnetic type antennas in comparison to the electric near-fields of an electric-type antenna (e.g., a small dipole). This allows for potentially higher coupling between the pair. Furthermore, "electric" antennas (e.g., dipoles and monopoles) or a combination of magnetic and electric antennas is also contemplated.

[0048] The Tx antenna can be operated at a frequency that is low enough and with an antenna size that is large enough to achieve good coupling (e.g., >-4 dB) to a small Rx antenna at significantly larger distances than allowed by far field and inductive approaches mentioned earlier. If the Tx antenna is sized correctly, high coupling levels (e.g., -1 to -4 dB) can be achieved when the Rx antenna on a host device is placed within a coupling-mode region (i.e., in the near-field) of the driven Tx loop antenna.

[0049] Fig. 8 shows a flowchart detailing process 800 in accordance with the described embodiments. Process 800 can begin at 802 by creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna. Next at 804, the electromagnetic field and a receiver antenna of a first receiver device are coupled with the coupling mode region. At 806, a second coupling mode region of the electromagnetic field different from the first coupling mode region is created with a near field of a transmit antenna of the first receiver device. At 808, the electromagnetic field is coupled to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device. At

810, power is wirelessly delivered from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field. At 812, at least some of the power wirelessly delivered to the first receiver device is wirelessly re-transmitted to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

WHAT IS CLAIMED IS:

1. A wirelessly powered local computing environment, the local computing environment including a near field magnetic resonance wireless power supply arranged to use a resonance channel to transfer useable energy to resonance circuits within a near field distance D, the distance D defining an outermost range of the NFMR power supply, comprising:

a central processing unit, the central processing unit providing processing resources to the NFMR power supply; and

a plurality of peripheral devices each having a tunable resonance circuit suitably adapted to receive power wirelessly from the NFMR power supply, wherein when at least one of the plurality of devices is within range of the NFMR power supply, the device tunes the resonance circuit to at least one of the resonance frequencies of the NFMR power supply and subsequently de-tunes the resonance circuit to provide a device identification to the NFMR power supply using a change in a resonance circuit load factor.

2. The local computing environment as recited in claim 1, wherein at least one of the peripheral devices includes a re-resonator circuit, the re-resonator circuit arranged to wirelessly provide a portion of the power received by the peripheral device from the NFMR power supply to at least one other peripheral client device.

3. A battery charging circuit, comprising:

a first node arranged to receive wirelessly provided power;

a short term charge storage device having a first charge capacity; and

a long term storage device having a second charge capacity, wherein the second charge capacity is substantially greater than the first charge capacity, wherein the long term storage device is charged by,

(A) storing charge corresponding to the power wirelessly received at the first node into the short term charge storage device,

(B) when the stored charge is equal to about the first charge capacity, then passing the stored charge from the short term storage device to the long term storage device, and

(C) repeating (A) and (B) until the charge stored in the long term storage device is about equal to the second charge capacity.

4. The circuit as recited in claim 3, wherein the short term charge storage device is an ultracapacitor and wherein the long term charge storage device is a LiPO battery.

5. A method of wirelessly transmitting power, comprising:

creating a first coupling mode region of an electromagnetic field within a near field of a power supply transmit antenna;

coupling the electromagnetic field and a receiver antenna of a first receiver device within the coupling mode region;

creating a second coupling mode region of the electromagnetic field different from the first coupling mode region within a near field of a transmit antenna of the first receiver device;

coupling the electromagnetic field to a receive antenna of second receiver device in the near field of the transmit antenna of the first receiver device;

wirelessly delivering power from the power supply to the first receiver device by way of the power supply transmit antenna using the first coupling mode region of the electromagnetic field; and

wirelessly delivering at least some of the power wirelessly delivered to the first receiver device is wirelessly by re-transmitting the at least some power to the second receiver device by way of the first receiver transmit antenna using the second coupling mode region of the electromagnetic field.

6. The method as recited in claim 5, wherein the first receiver device is a keyboard.

7. The method as recited in claim 6, wherein the second receiver device is a mouse.

8. The method as recited in claim 7, wherein the power supply is included in a host computing device.

9. The method as recited in claim 8, wherein the second coupling mode region is between the keyboard and the mouse.

10. The method as recited in claim 9, wherein the first coupling mode region is between the host computing device and the keyboard.

11. The method as recited in claim 9, wherein the first coupling mode region is between the host computing device and the mouse.

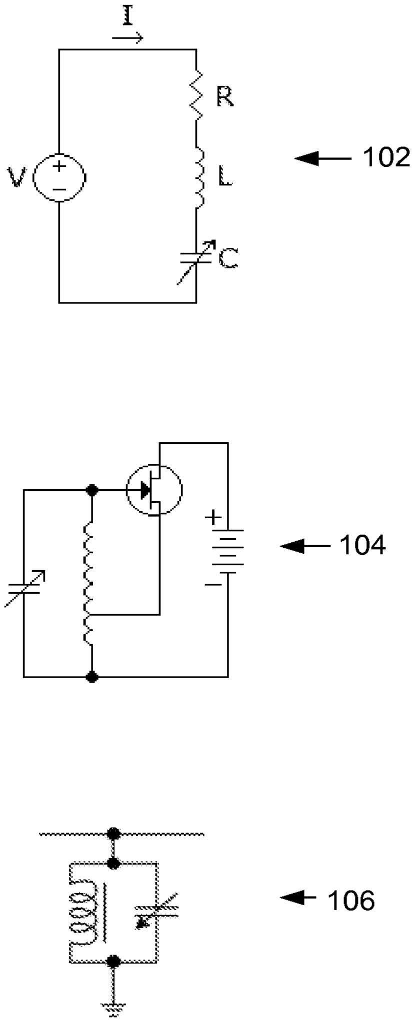

Fig. 1

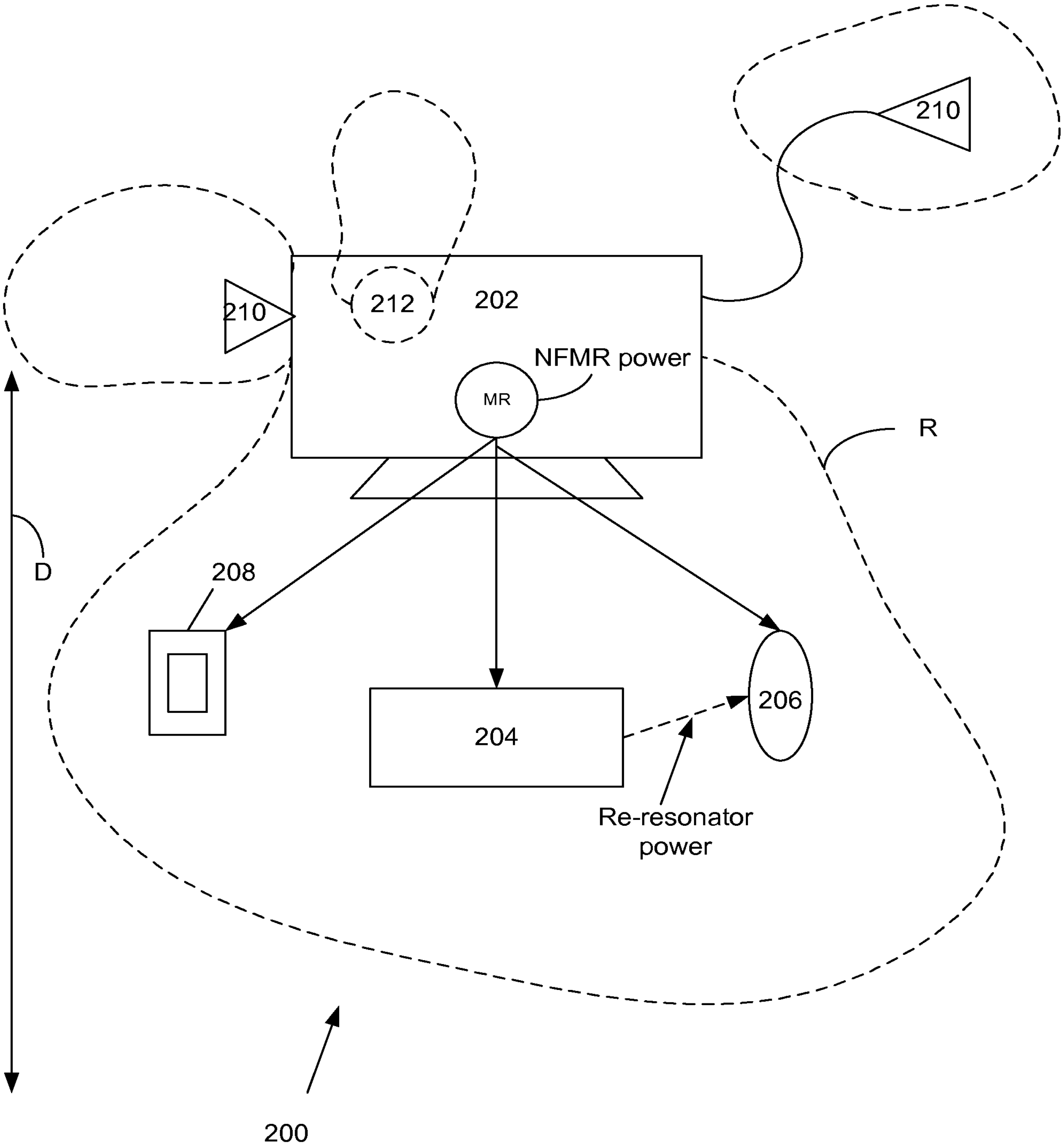
210
210
212
202
NFMR power
MR
R
D
208
206
204
Re-resonator
power
200

Fig. 2

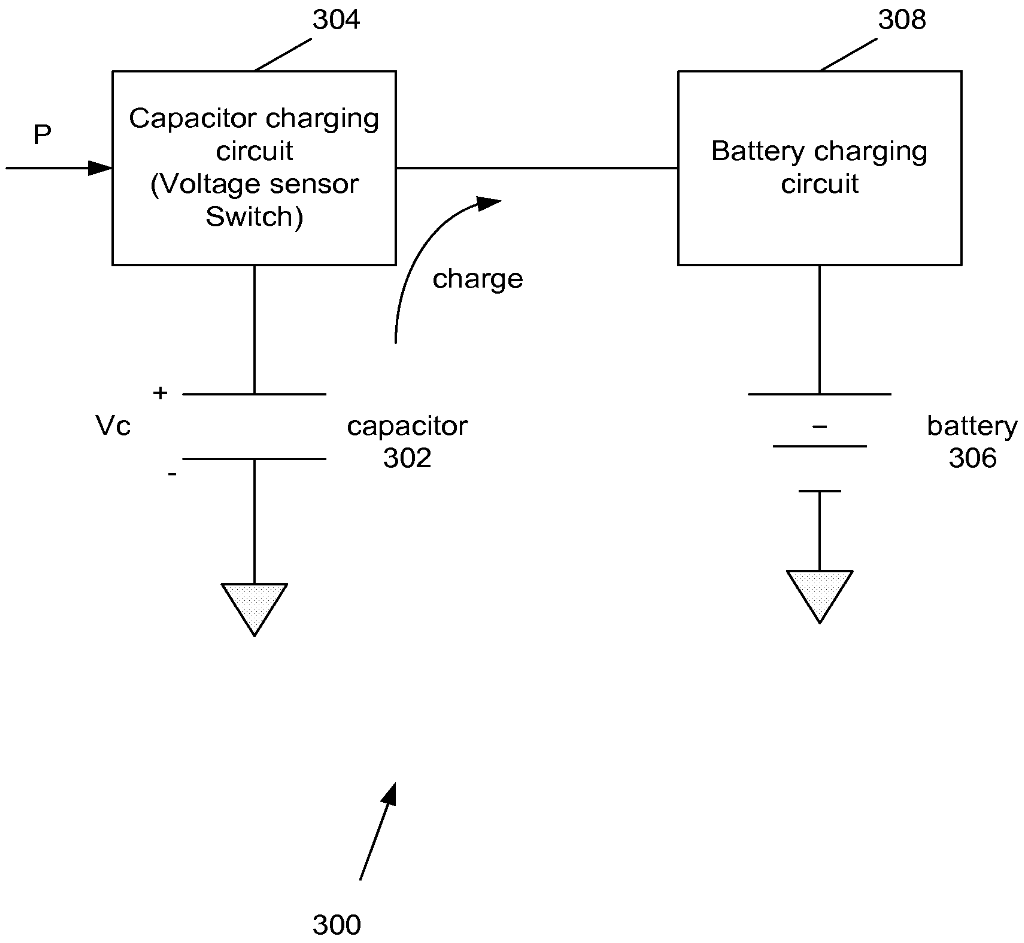
304
308
P
Capacitor charging circuit (Voltage sensor Switch)
Battery charging circuit
charge
+
Vc
-
capacitor 302
battery 306
300

Fig. 3

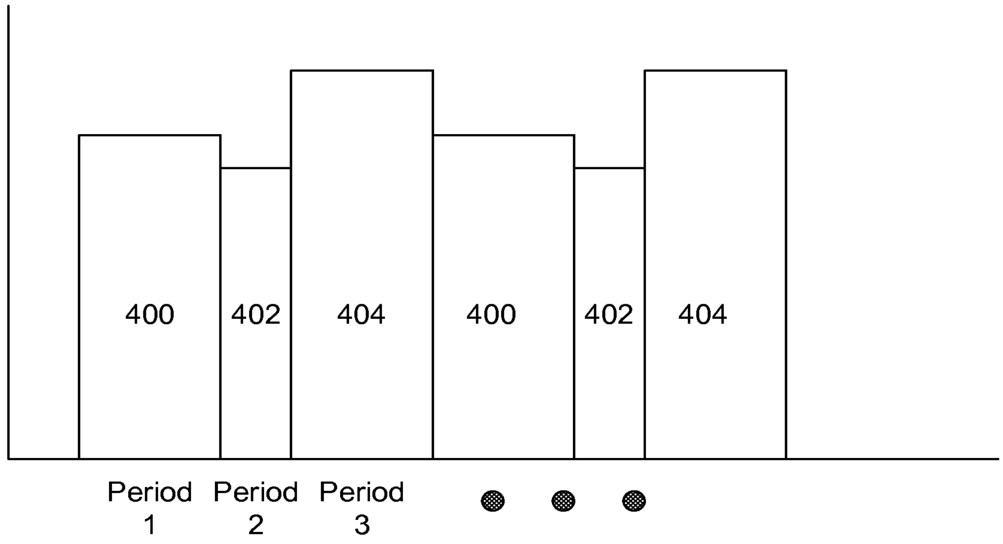

Fig. 4

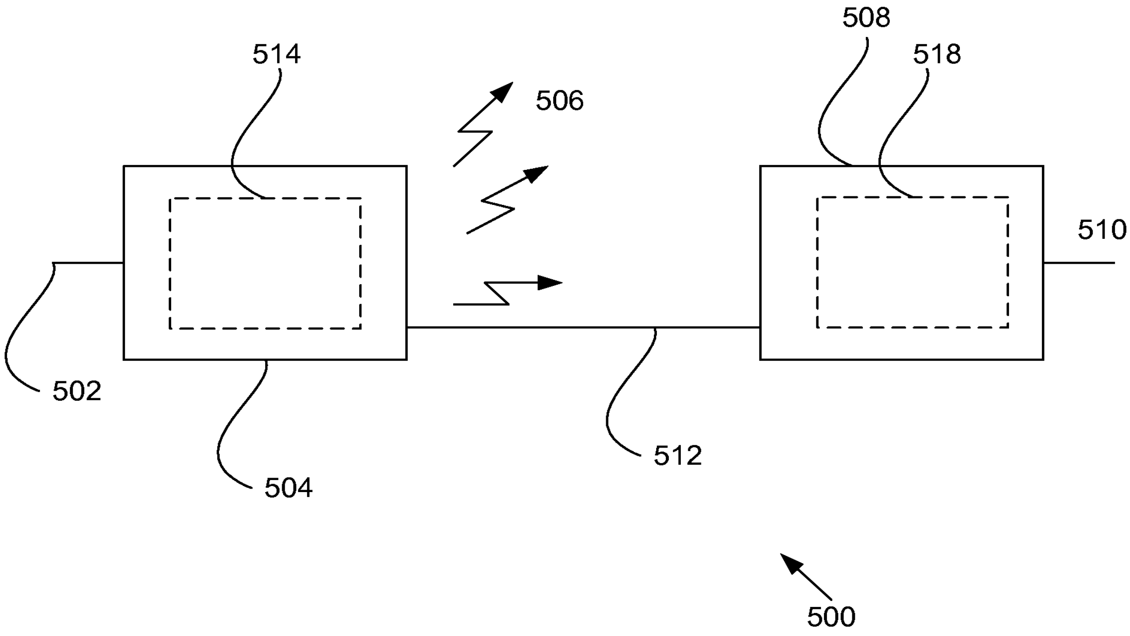

Fig. 5

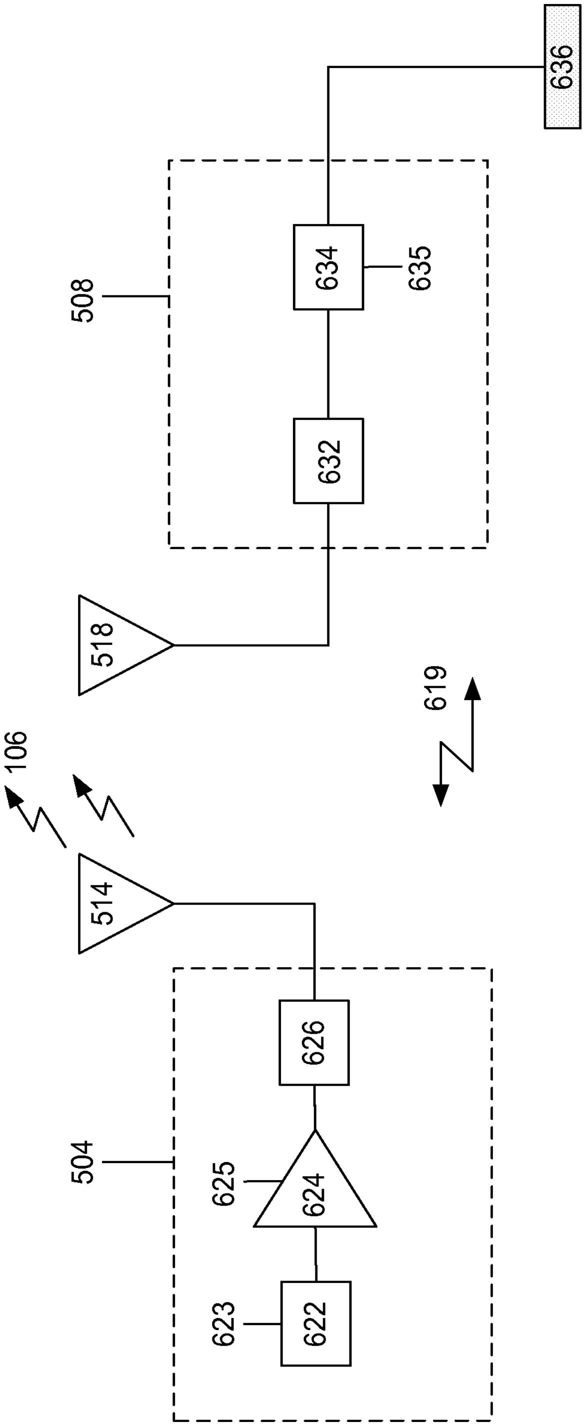

Fig. 6

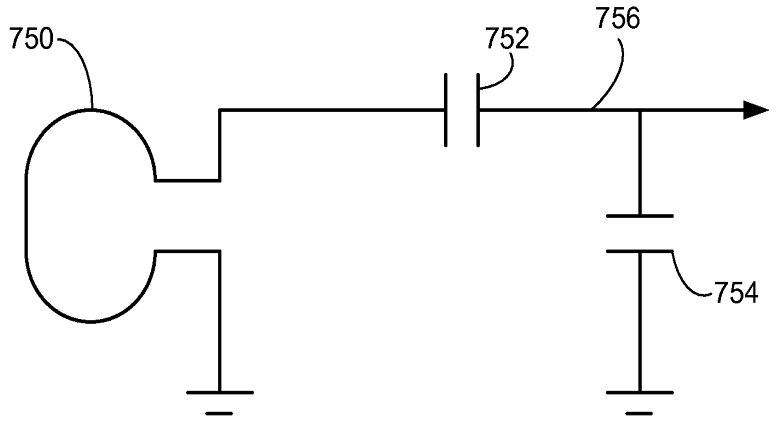

Fig. 7

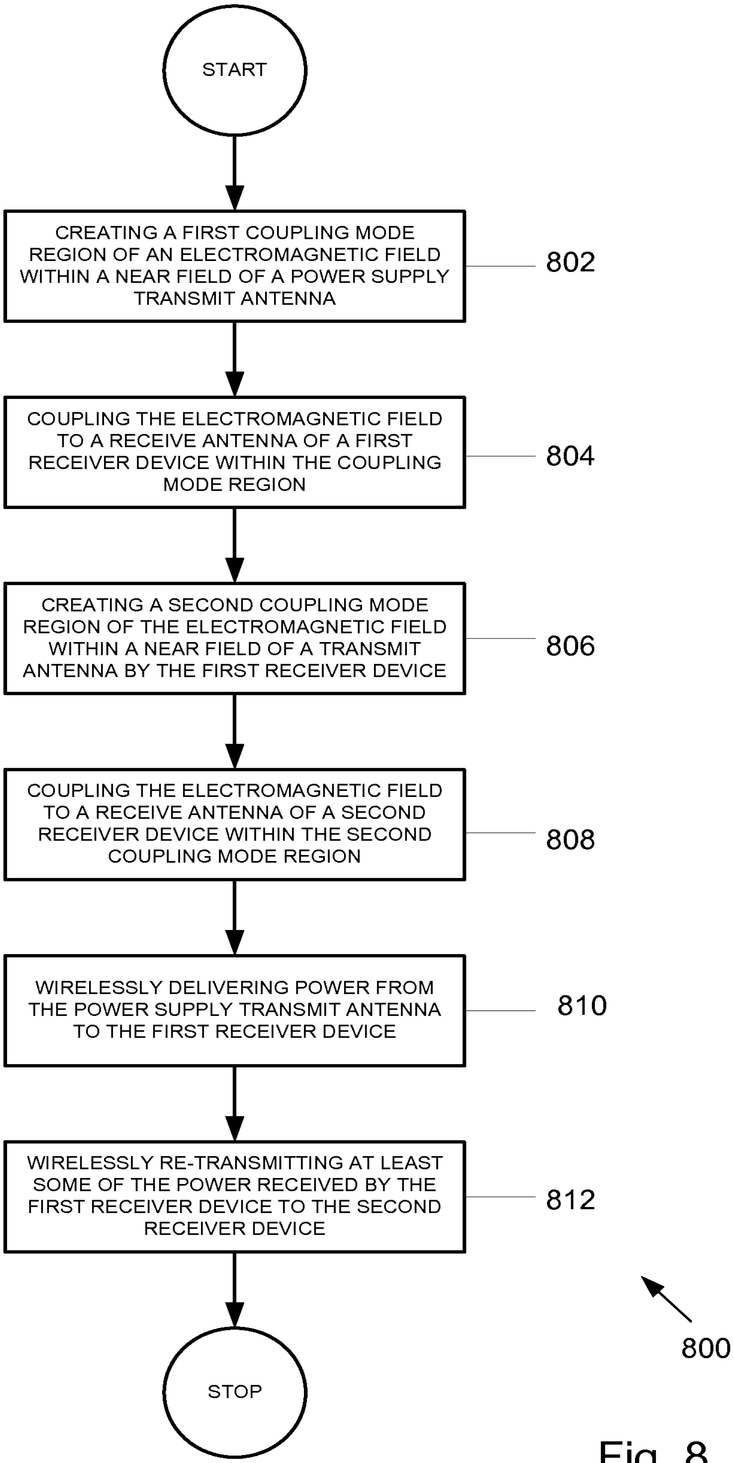
START
CREATING A FIRST COUPLING MODE REGION OF AN ELECTROMAGNETIC FIELD WITHIN A NEAR FIELD OF A POWER SUPPLY TRANSMIT ANTENNA
802
COUPLING THE ELECTROMAGNETIC FIELD TO A RECEIVE ANTENNA OF A FIRST RECEIVER DEVICE WITHIN THE COUPLING MODE REGION
804
CREATING A SECOND COUPLING MODE REGION OF THE ELECTROMAGNETIC FIELD WITHIN A NEAR FIELD OF A TRANSMIT ANTENNA BY THE FIRST RECEIVER DEVICE
806
COUPLING THE ELECTROMAGNETIC FIELD TO A RECEIVE ANTENNA OF A SECOND RECEIVER DEVICE WITHIN THE SECOND COUPLING MODE REGION
808
WIRELESSLY DELIVERING POWER FROM THE POWER SUPPLY TRANSMIT ANTENNA TO THE FIRST RECEIVER DEVICE
810
WIRELESSLY RE-TRANSMITTING AT LEAST SOME OF THE POWER RECEIVED BY THE FIRST RECEIVER DEVICE TO THE SECOND RECEIVER DEVICE
812
800
STOP

Fig. 8

Electronic Patent Application Fee Transmittal

Application Number:	12647763
Filing Date:	28-Dec-2009
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Filer:	John A. Monocello/Debbie Peterson
Attorney Docket Number:	WTCY-0026-P07

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
Submission- Information Disclosure Stmt	1806	1	180	180
	Total in USD ($)			**180**

Electronic Acknowledgement Receipt

EFS ID:	12141992
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Debbie Peterson
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	23-FEB-2012
Filing Date:	28-DEC-2009
Time Stamp:	13:39:45
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$180
RAM confirmation Number	12265
Deposit Account	503912
Authorized User	

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Charge any Additional Fees required under 37 C.F.R. Section 1.17 (Patent application and reexamination processing fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.19 (Document supply fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.20 (Post Issuance fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Information Disclosure Statement (IDS) Form (SB08)	WTCY-0026-P07_IDS.pdf	614823 2d7882866ce47050c970a5ffd7c3171dcf41bc14	no	9
Warnings:					
Information:					
2	Transmittal Letter	WTCY-0026-P07_SIDSComm.pdf	75919 bcd767a0be58227ba593161656cae888fbd92f7e	no	2
Warnings:					
Information:					
3	Non Patent Literature	132.pdf	112226 9724758182e76b4931418dedd86665b0240dc3b7	no	3
Warnings:					
Information:					
4	Non Patent Literature	143.pdf	6786039 98bb64a6e040227d05933f0dfac28144b97efefd	no	14
Warnings:					
Information:					
5	Non Patent Literature	175.pdf	182756 6b1342fe460a3ffa5646febe07a03a8606caee76	no	2
Warnings:					
Information:					
6	Non Patent Literature	198.pdf	96336 9152fee4745685051239a5846addfb27f2b7b529	no	2
Warnings:					
Information:					
7	Non Patent Literature	513.pdf	194656 36b69cc8ed8e9adf06c010cb2e5bcea5a43c7c09	no	7
Warnings:					
Information:					
8	Non Patent Literature	514.pdf	5756325 89fe6760a72370181146b86a20c0beb3c52b0e02	no	8

Warnings:					
Information:					
9	Non Patent Literature	515.pdf	4491852 8fbcf98d1a903476344aeaac66533b7cdd0c1453	no	9
Warnings:					
Information:					
10	Non Patent Literature	517.pdf	120017 7ccfa22a5c1149f37ea91bb46e9f0de9d1f72e6f	no	3
Warnings:					
Information:					
11	Non Patent Literature	518.pdf	2636887 ebbafc12e22fcff1e4bd8465fdaa03f8b1e72268	no	15
Warnings:					
Information:					
12	Non Patent Literature	523.pdf	8798492 885d38792211ca48dc862c2a72cf0589052d391c	no	9
Warnings:					
Information:					
13	Non Patent Literature	522_Part1.pdf	5524839 535e0ef898a1960cdbfe03e2dbbe887ee4681a6b	no	100
Warnings:					
Information:					
14	Non Patent Literature	522_Part2.pdf	8086178 4408cab9e1cb57bf2eac7d3e7cbaa9698e6cb8f5	no	147
Warnings:					
Information:					
15	Foreign Reference	WO2011062827.pdf	1088810 4730cb574a904730a8eb7d8be3660c238217a236	no	28
Warnings:					
Information:					
16	Non Patent Literature	527.pdf	3603339 c3438ff3a743b815bb595c5ebd9ab342c2387a52	no	6
Warnings:					
Information:					
17	Fee Worksheet (SB06)	fee-info.pdf	30463 2976cf523e5efeb0b68cab75e5ec57b95385a1be	no	2

Warnings:	
Information:	
Total Files Size (in bytes):	48199957

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New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: Aristeidis Karalis et al.	Group Art Unit: 2836
Serial No.: 12/647,763	Confirmation No. 2576
Filed: December 28, 2009	Examiner: Robert L. Deberadinis

RESPONSE UNDER 37 CFR § 1.111

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

Applicants have reviewed the Office Action mailed on November 25, 2011 ("Office Action"), and provide this response thereto.

Applicants respectfully request that the Examiner consider this Response as set forth below and pass the Application to allowance.

A **Listing of Claims** begins at page 2 of this Response.

Remarks begin at page 5 of this Response.

Listing of Claims:

This listing of claims will replace all prior versions of claims in the application.

1. (Currently Amended) A system, comprising:

a source resonator optionally coupled to an energy source; and

a second resonator located a distance from the source resonator,

wherein the source resonator and the second resonator are coupled to provide near-field wireless energy transfer among the source resonator and the second resonator and wherein the field of at least one of the source resonator and the second resonator is shaped using a conducting material and a magnetic material ~~to avoid loss-inducing object~~.

2. (Original) The system of claim 1, wherein at least one of the source resonator ad the second resonator have a quality factor, Q>100.

3. (Original) The system of claim 1, wherein the source resonator Q is greater than 100 and the second resonator Q is greater than 100.

4. (Original) The system of claim 1, wherein the square root of the resonator Q times the second resonator Q is greater than 100.

5. (Original) The system of claim 1, comprising more than one resonator.

6. (Original) The system of claim 1, comprising more than one second resonator.

7. (Original) The system of claim 1, comprising more than three resonators.

8. (Currently Amended) A method, comprising:

providing a source resonator optionally coupled to an energy source and a second resonator located a distance from the source resonator,

coupling the ~~wherein the~~ source resonator and the second resonator ~~are coupled~~ to provide near-field wireless energy transfer among the source resonator and the second resonator, and

shaping ~~wherein~~ the field of at least one of the source resonator and the second resonator ~~is shaped~~ using a conducting surface and a magnetic material ~~to avoid a loss-inducing object~~.

9. (Original) The method claim 8, wherein at least one of the source resonator and the second resonator have a quality factor, Q>100.

10. (Original) The method of claim 8, wherein the source resonator Q is greater than 100 and the second resonator Q is greater than 100.

11. (Original) The method of claim 8, wherein the square root of the source resonator Q times the second resonator Q is greater than 100.

12. (Original) The method of claim 8, comprising more than one source resonator.

13. (Original) The method of claim 8, comprising more than one second resonator.

14. (Original) The method of claim 8, comprising more than three resonators.

15. (New) The system of claim 1, wherein the loss-inducing object is completely covered by the conducting material and the magnetic material.

16. (New) The system of claim 1, wherein the loss-inducing object is partially covered by the conducting material and the magnetic material.

17. (New) The system of claim 1, wherein the loss-inducing object is nearer to at least one of the source resonator and the second resonator, and wherein a portion of the loss-inducing object facing the nearer resonator is partially covered by the conducting material and the magnetic material.

18. (New) The system of claim 1, wherein the conducting material comprises a first layer that covers the loss-inducing object, and wherein the magnetic material comprises a second layer that covers the first layer.

19. (New) The system of claim 1, wherein the conducting material comprises a first layer that partially covers the loss-inducing object, and wherein the magnetic material comprises a second layer that partially covers the first layer.

20. (New) The system of claim 1, wherein the loss-inducing object is a mobile electronic device.

21. (New) The system of claim 1, wherein the field is shaped to avoid a loss-inducing object.

22. (New) The method of claim 8, wherein the step of shaping is to avoid a loss-inducing object.

23. (New) A system, comprising:

a resonator coupled to power and control circuitry;

wherein the resonator and the power and control circuitry are configured to provide near-field wireless energy transfer among other resonators,

and wherein the power and control circuitry is at least partially covered by high permeability materials and conducting surfaces to shape magnetic fields of the resonator around the power and control circuitry.

REMARKS

Status of the Claims

Claims 1-23 are now pending in the present application. Claims 1 and 8 have been amended in this response, and claims 15-23 have been added as new. No new matter has been added.

Claim Rejections - 35 U.S.C. § 103

The Examiner has rejected claims 1-14 under section 103(a) as allegedly being obvious over published U.S. Patent Application No. 2010/0225272 of Kirby et al. ("Kirby") in view of U.S. Patent Application No. 2010/0308939 of Kurs ("Kurs").

Respectfully, Kurs does not qualify as prior art against the present application. Kurs is assigned to the owner of the present application, and claims priority to commonly-owned. Application No. 12/567,716 (applicant docket WTCY-0026-P01), where Kurs is listed as inventor. Kurs is also an inventor in the present application. Like the Kurs reference, the present application also claims priority to commonly-owned U.S. Application No. 12/567,716, and thus indirectly claims priority to all the priority applications to which U.S. Application No. 12/567,716, and therefore the Kurs reference, claims. In sum, the present application and Kurs are in the same commonly-owned family of applications, which trace their roots to identical priority applications. As such, Kurs's earliest priority date is identical to the present application and, notably, Paragraph 0306 of Kurs as referenced in the Office Action on Page 2 is identical to Paragraph 0252 of the current application.

With respect to the teachings of Kirby, the Examiner cited it for the purposes of allegedly teaching wireless power transmission generally. The Examiner noted that Kirby does not teach "wherein the field of at least one of the source resonator and the second resonator is shaped ..." and thus cited Kurs to ameliorate the deficiency. Since Kurs does not qualify as prior art, the deficiency remains.

Moreover, as stated above, the Examiner cites on Page 2 of the Office Action that Kirby "discloses wireless power for chargeable and charging devices such as receiver may be configured to receive wireless power transmitted from a wireless power source within an associated near-field region (paragraph 0063)", thus using Kirby as an example of a wireless power system using the near field. . However, the present application contains a priority claim to applications having filing dates prior to Kirby's earliest priority date and disclosing near-field wireless power transfer. To elaborate, Kirby's earliest claimed priority is to U.S. Provisional Application No. 61/152,359, filed February 13, 2009. The current application claims priority to earlier provisional applications that describe wireless energy transfer systems, for example, U.S. Provisional Application No. 61/108,743 (the '743 application), which was filed on October 27, 2008. In one instance, Paragraph 0022 of the '743 application states "Fig. 1 shows a schematic diagram illustrating a general description of a wireless power transmission system of the present invention. The invention uses as least one source and at least one device to perform energy transferring. Both the source 1 and device 2 are resonator structures, and are separated a distance D from each other." The '743 application then goes on to describe several example embodiments of said system, including explicit reference in Paragraph [0059] to the systems utilizing near field in both the transmission of information and power, "[i]n embodiments, the present invention may also use the near-field nonradiative resonant scheme for information transfer rather than, or in addition to, power transfer." Therefore, Kirby is not prior art to the current application with regard to disclosure of a wireless power system using the near field.

Even in light of Applicants' arguments above, Applicants have chosen to amend Claims 1 and 8, and to add new claims 15-23 in order to further clarify the embodiments of the invention for which Applicants wish to obtain an allowance.

Accordingly, Applicants respectfully request that the Examiner allow Claims 1-23.

CONCLUSION

Applicants believe they have addressed all issues related to this matter. However, if the Examiner believes any issues remain, Applicants invite Examiner to contact their representatives at the number below.

Respectfully submitted,

ARISTEIDIS KARALIS ET AL.

By their Representatives,

Customer No. 87084

Date: February 24, 2012 By /John A. Monocello, III/
John A. Monocello, III
Reg. No. 51,022
Tel: 412-953-0696

Electronic Patent Application Fee Transmittal

Application Number:	12647763
Filing Date:	28-Dec-2009
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Filer:	John A. Monocello/Jennifer Sammartin
Attorney Docket Number:	WTCY-0026-P07

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Claims in excess of 20	1202	3	60	180
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
		Total in USD ($)		**180**

Electronic Acknowledgement Receipt

EFS ID:	12158546
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	24-FEB-2012
Filing Date:	28-DEC-2009
Time Stamp:	18:35:58
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$180
RAM confirmation Number	5900
Deposit Account	505087
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Amendment/Req. Reconsideration-After Non-Final Reject	WTCY-0026-P07_NFOAR.pdf	108633 2d04917d8274f4675e591f6d621acc8db6a676f9	no	7
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	30365 8ba46d2ac42803cb3e747dac05808298ab2336ed	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	138998		

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National Stage of an International Application under 35 U.S.C. 371
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PTO/SB/06 (07-06)
Approved for use through 1/31/2007. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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PATENT APPLICATION FEE DETERMINATION RECORD Substitute for Form PTO-875	Application or Docket Number 12/647,763	Filing Date 12/28/2009	☐ To be Mailed

APPLICATION AS FILED – PART I

	(Column 1)	(Column 2)	SMALL ENTITY ☐		OR	OTHER THAN SMALL ENTITY	
FOR	NUMBER FILED	NUMBER EXTRA	RATE ($)	FEE ($)		RATE ($)	FEE ($)
☐ BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A	N/A			N/A	
☐ SEARCH FEE (37 CFR 1.16(k), (i), or (m))	N/A	N/A	N/A			N/A	
☐ EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A	N/A			N/A	
TOTAL CLAIMS (37 CFR 1.16(i))	minus 20 =	*	X $ =		OR	X $ =	
INDEPENDENT CLAIMS (37 CFR 1.16(h))	minus 3 =	*	X $ =			X $ =	
☐APPLICATION SIZE FEE (37 CFR 1.16(s))	If the specification and drawings exceed 100 sheets of paper, the application size fee due is $250 ($125 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR 1.16(s).						
☐ MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))							
* If the difference in column 1 is less than zero, enter "0" in column 2.			TOTAL			TOTAL	

APPLICATION AS AMENDED – PART II

		(Column 1)		(Column 2)	(Column 3)	SMALL ENTITY		OR	OTHER THAN SMALL ENTITY	
AMENDMENT	02/24/2012	CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA	RATE ($)	ADDITIONAL FEE ($)		RATE ($)	ADDITIONAL FEE ($)
	Total (37 CFR 1.16(i))	* 23	Minus	** 20	= 3	X $ =		OR	X $60=	180
	Independent (37 CFR 1.16(h))	* 3	Minus	***3	= 0	X $ =		OR	X $250=	0
	☐ Application Size Fee (37 CFR 1.16(s))									
	☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							OR		
						TOTAL ADD'L FEE		OR	TOTAL ADD'L FEE	**180**

		(Column 1)		(Column 2)	(Column 3)					
AMENDMENT		CLAIMS REMAINING AFTER AMENDMENT		HIGHEST NUMBER PREVIOUSLY PAID FOR	PRESENT EXTRA	RATE ($)	ADDITIONAL FEE ($)		RATE ($)	ADDITIONAL FEE ($)
	Total (37 CFR 1.16(i))	*	Minus	**	=	X $ =		OR	X $ =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	X $ =		OR	X $ =	
	☐ Application Size Fee (37 CFR 1.16(s))									
	☐ FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))							OR		
						TOTAL ADD'L FEE		OR	TOTAL ADD'L FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

Legal Instrument Examiner:
/NICOLLE L. SCRIVNER/

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If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT
(Not for submission under 37 CFR 1.99)

Application Number	12647763
Filing Date	2009-12-28
First Named Inventor	Karalis, Aristeidis
Art Unit	2836
Examiner Name	DEBERADINIS, ROBERT L
Attorney Docket Number	WTCY-0026-P07

U.S.PATENTS
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Examiner Initial*	Cite No	Patent Number	Kind Code1	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
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Examiner Initial*	Cite No	Publication Number	Kind Code1	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	20120032522		2012-02-09	Schatz et al.	

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Examiner Initial*	Cite No	Foreign Document Number3	Country Code2 j	Kind Code4	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear	T5
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Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T5

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

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If you wish to add additional non-patent literature document citation information please click the Add button Add			

EXAMINER SIGNATURE

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☒ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-02-29
Name/Print	John A. Monocello, III	Registration Number	51022

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The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

EFS Web 2.1.17

Electronic Patent Application Fee Transmittal

Application Number:	12647763
Filing Date:	28-Dec-2009
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Filer:	John A. Monocello/Debbie Peterson
Attorney Docket Number:	WTCY-0026-P07

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
Submission- Information Disclosure Stmt	1806	1	180	180
		Total in USD ($)		**180**

Electronic Acknowledgement Receipt

EFS ID:	12193961
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Debbie Peterson
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	29-FEB-2012
Filing Date:	28-DEC-2009
Time Stamp:	16:54:12
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$180
RAM confirmation Number	4673
Deposit Account	505087
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

Charge any Additional Fees required under 37 C.F.R. Section 1.16 (National application filing, search, and examination fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.17 (Patent application and reexamination processing fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.19 (Document supply fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.20 (Post Issuance fees)

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Information Disclosure Statement (IDS) Form (SB08)	WTCY-0026-P07_IDS.pdf	612139 4a28450f297d9b1cf23952bed78994c11ecec96c	no	4
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	30463 78a16369bb1c84d923abab3d74470bfe455f9250	no	2
Warnings:					
Information:					
			Total Files Size (in bytes):	642602	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

NOTICE OF ALLOWANCE AND FEE(S) DUE

87084 7590 03/26/2012
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	
ART UNIT	PAPER NUMBER
2836	

DATE MAILED: 03/26/2012

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

TITLE OF INVENTION: WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS

APPLN. TYPE	SMALL ENTITY	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	$1740	$300	$0	$2040	06/26/2012

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the SMALL ENTITY status shown above.

If the SMALL ENTITY is shown as YES, verify your current SMALL ENTITY status:

A. If the status is the same, pay the TOTAL FEE(S) DUE shown above.

B. If the status above is to be removed, check box 5b on Part B - Fee(s) Transmittal and pay the PUBLICATION FEE (if required) and twice the amount of the ISSUE FEE shown above, or

If the SMALL ENTITY is shown as NO:

A. Pay TOTAL FEE(S) DUE shown above, or

B. If applicant claimed SMALL ENTITY status before, or is now claiming SMALL ENTITY status, check box 5a on Part B - Fee(s) Transmittal and pay the PUBLICATION FEE (if required) and 1/2 the ISSUE FEE shown above.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: Mail

Mail Stop ISSUE FEE
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450

or Fax (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

87084 7590 03/26/2012

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

(Depositor's name)

(Signature)

(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

TITLE OF INVENTION: WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS

APPLN. TYPE	SMALL ENTITY	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	$1740	$300	$0	$2040	06/26/2012

EXAMINER	ART UNIT	CLASS-SUBCLASS
DEBERADINIS, ROBERT L	2836	307-104000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

(1) the names of up to 3 registered patent attorneys or agents OR, alternatively,

(2) the name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 ____________________
2 ____________________
3 ____________________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☐ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:

☐ Issue Fee
☐ Publication Fee (No small entity discount permitted)
☐ Advance Order - # of Copies ____________

4b. Payment of Fee(s): **(Please first reapply any previously paid issue fee shown above)**

☐ A check is enclosed.
☐ Payment by credit card. Form PTO-2038 is attached.
☐ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment, to Deposit Account Number ____________ (enclose an extra copy of this form).

5. **Change in Entity Status** (from status indicated above)

☐ a. Applicant claims SMALL ENTITY status. See 37 CFR 1.27.
☐ b. Applicant is no longer claiming SMALL ENTITY status. See 37 CFR 1.27(g)(2).

NOTE: The Issue Fee and Publication Fee (if required) will not be accepted from anyone other than the applicant; a registered attorney or agent; or the assignee or other party in interest as shown by the records of the United States Patent and Trademark Office.

Authorized Signature ____________________ Date ____________________

Typed or printed name ____________________ Registration No. ____________________

This collection of information is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

PTOL-85 (Rev. 02/11) Approved for use through 08/31/2013. OMB 0651-0033 U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

UNITED STATES PATENT AND TRADEMARK OFFICE

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United States Patent and Trademark Office
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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

87084 7590 03/26/2012

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P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	
ART UNIT	**PAPER NUMBER**
2836	

DATE MAILED: 03/26/2012

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)

(application filed on or after May 29, 2000)

The Patent Term Adjustment to date is 265 day(s). If the issue fee is paid on the date that is three months after the mailing date of this notice and the patent issues on the Tuesday before the date that is 28 weeks (six and a half months) after the mailing date of this notice, the Patent Term Adjustment will be 265 day(s).

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

PTOL-85 (Rev. 02/11)

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Notice of Allowability	**Application No.** 12/647,763	**Applicant(s)** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☒ This communication is responsive to *2/24/12*.
2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.
3. ☒ The allowed claim(s) is/are *1-23*.
4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).
   a) ☐ All b) ☐ Some* c) ☐ None of the:
      1. ☐ Certified copies of the priority documents have been received.
      2. ☐ Certified copies of the priority documents have been received in Application No. _____ .
      3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

   * Certified copies not received: _____.

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5. ☐ A SUBSTITUTE OATH OR DECLARATION must be submitted. Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL PATENT APPLICATION (PTO-152) which gives reason(s) why the oath or declaration is deficient.
6. ☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.
   (a) ☐ including changes required by the Notice of Draftsperson's Patent Drawing Review (PTO-948) attached
      1) ☐ hereto or 2) ☐ to Paper No./Mail Date _____.
   (b) ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____.

   Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).
7. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1. ☐ Notice of References Cited (PTO-892)
2. ☐ Notice of Draftperson's Patent Drawing Review (PTO-948)
3. ☒ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date 2/29/12,2/23/12
4. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material
5. ☐ Notice of Informal Patent Application
6. ☐ Interview Summary (PTO-413), Paper No./Mail Date _____ .
7. ☐ Examiner's Amendment/Comment
8. ☒ Examiner's Statement of Reasons for Allowance
9. ☐ Other _____.

DETAILED ACTION

The reply filed 2/29/12 consists of amending claims 1,8, adding new claims 15-23 and arguments related to rejection of claims.

Allowable Subject Matter

Claims 1-23 allowed.

The following is an examiner's statement of reasons for allowance: Applicant's arguments are persuasive.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled "Comments on Statement of Reasons for Allowance."

Any inquiry concerning this communication should be directed to Robert L. DeBeradinis whose number is (571) 272-2049. The Examiner can normally be reached Monday-Friday from 8:30 am to 5:00 pm.

If attempts to reach the Examiner by telephone are unsuccessful, the Examiner's supervisor, Jared Fureman can be reached on (571) 272-2391. The Fax phone number for this Group is (571) 272-8300.

RLD

MARCH 16, 2012

/Robert DeBeradinis/

Primary Examiner, Art Unit 2836

2/29/12

Doc code: IDS
Doc description: Information Disclosure Statement (IDS) Filed

PTO/SB/08a (01-10)
Approved for use through 07/31/2012. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

U.S.PATENTS Remove

Examiner Initial*	Cite No	Patent Number	Kind Code1	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
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U.S.PATENT APPLICATION PUBLICATIONS Remove

Examiner Initial*	Cite No	Publication Number	Kind Code1	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	20120032522		2012-02-09	Schatz et al.	

If you wish to add additional U.S. Published Application citation information please click the Add button. Add

FOREIGN PATENT DOCUMENTS Remove

Examiner Initial*	Cite No	Foreign Document Number3	Country Code2 j	Kind Code4	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear	T5
	1							☐

If you wish to add additional Foreign Patent Document citation information please click the Add button Add

NON-PATENT LITERATURE DOCUMENTS Remove

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T5

EFS Web 2.1.17

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

	1		☐

If you wish to add additional non-patent literature document citation information please click the Add button Add

EXAMINER SIGNATURE

Examiner Signature	/Robert Deberadinis/	Date Considered	03/16/2012

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☒ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-02-29
Name/Print	John A. Monocello, III	Registration Number	51022

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

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9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L1	65	ENERGY ADJ SOURCE SAME RESONATOR SAME SHAPE	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/03/16 10:45
L2	145	ENERGY ADJ SOURCE SAME RESONATOR SAME SHAPED	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/03/16 10:45
L3	39	ENERGY ADJ SOURCE SAME RESONATOR SAME SHAPED SAME MATERIAL	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/03/16 10:46
L4	7	(ENERGY ADJ SOURCE SAME RESONATOR SAME SHAPED).CLM.	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/03/16 10:47

3/16/2012 10:51:47 AM
C:\Users\rdeberadinis\Documents\EAST\Workspaces\623.wsp

EAST Search History

EAST Search History (Interference)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L5	6	(ENERGY ADJ SOURCE SAME RESONATOR SAME SHAPED).CLM.	US-PGPUB	OR	ON	2012/03/16 10:48

3/16/2012 10:51:55 AM
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BIB DATA SHEET

CONFIRMATION NO. 2576

SERIAL NUMBER	FILING or 371(c) DATE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
12/647,763	12/28/2009 RULE	307	2836	WTCY-0026-P07

APPLICANTS

Aristeidis Karalis, Boston, MA;
Andre B. Kurs, Chestnut Hill, MA;
Andrew J. Campanella, Waltham, MA;
Konrad J. Kulikowski, Somerville, MA;
Katherine L. Hall, Westford, MA;
Marin Soljacic, Belmont, MA;
Morris P. Kesler, Bedford, MA;

** **CONTINUING DATA** *************************

This application is a CIP of 12/567,716 09/25/2009
which claims benefit of 61/100,721 09/27/2008
and claims benefit of 61/108,743 10/27/2008
and claims benefit of 61/147,386 01/26/2009
and claims benefit of 61/152,086 02/12/2009
and claims benefit of 61/178,508 05/15/2009
and claims benefit of 61/182,768 06/01/2009
and claims benefit of 61/121,159 12/09/2008
and claims benefit of 61/142,977 01/07/2009
and claims benefit of 61/142,885 01/06/2009
and claims benefit of 61/142,796 01/06/2009
and claims benefit of 61/142,889 01/06/2009
and claims benefit of 61/142,880 01/06/2009
and claims benefit of 61/142,818 01/06/2009
and claims benefit of 61/142,887 01/06/2009
and claims benefit of 61/156,764 03/02/2009
and claims benefit of 61/143,058 01/07/2009
and claims benefit of 61/152,390 02/13/2009
and claims benefit of 61/163,695 03/26/2009
and claims benefit of 61/172,633 04/24/2009
and claims benefit of 61/169,240 04/14/2009
and claims benefit of 61/173,747 04/29/2009

** **FOREIGN APPLICATIONS** *************************

** **IF REQUIRED, FOREIGN FILING LICENSE GRANTED** **

		STATE OR COUNTRY	SHEETS DRAWINGS	TOTAL CLAIMS	INDEPENDENT CLAIMS
Foreign Priority claimed ☐ Yes ☑ No 35 USC 119(a-d) conditions met ☐ Yes ☐ No Verified and Acknowledged /ROBERT L DEBERADINIS/ Examiner's Signature	☐ Met after Allowance Initials	MA	53	14	2

ADDRESS

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050

BIB (Rev. 05/07).

Issue Classification	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836

ISSUE CLASSIFICATION

ORIGINAL					CROSS REFERENCE(S)							
CLASS			SUBCLASS		CLASS	SUBCLASS (ONE SUBCLASS PER BLOCK)						
307			104									
INTERNATIONAL CLASSIFICATION												
H	0	1	F	27/42								
				/								
				/								
				/								
				/								

NONE (Assistant Examiner) (Date)	/ROBERT L. DEBERADINIS/ 3/16/12 (Primary Examiner) (Date)	**Total Claims Allowed: 23**
(Legal Instruments Examiner) (Date)		O.G. Print Claim(s): 1 O.G. Print Fig.: 1

☐ **Claims renumbered in the same order as presented by applicant** ☐ CPA ☐ T.D. ☐ R.1.47

Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original
1	1		31		61		91		121		151		181
2	2		32		62		92		122		152		182
3	3		33		63		93		123		153		183
4	4		34		64		94		124		154		184
5	5		35		65		95		125		155		185
6	6		36		66		96		126		156		186
7	7		37		67		97		127		157		187
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	29		59		89		119		149		179		209
	30		60		90		120		150		180		210

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Part of Paper No. 20120316

Search Notes	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

SEARCHED

Class	Subclass	Date	Examiner
307	140	3/16/12	RLD

SEARCH NOTES (INCLUDING SEARCH STRATEGY)

	DATE	EXMR
TEXT	3/16/12	RLD

INTERFERENCE SEARCHED

Class	Subclass	Date	Examiner
INTERFERENCE		3/16/12	RLD

2/23/12

Doc code: IDS
Doc description: Information Disclosure Statement (IDS) Filed

PTO/SB/08a (01-10)
Approved for use through 07/31/2012. OMB 0651-0031
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

U.S.PATENTS Remove

Examiner Initial*	Cite No	Patent Number	Kind Code1	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	0645576		1900-03-20	Tesla	
	2	0649621		1900-05-15	Tesla	
	3	6664770		2003-12-16	Bartels	
	4	7514818		2009-04-07	Abe et al.	
	5	7795708		2010-09-14	Katti	
	6	8022576		2011-09-20	Joannopoulos et al.	
	7	5940509		1999-08-17	Jovanovich et al	

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number		12647763
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Examiner Initial*	Cite No	Publication Number	Kind Code1	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	20040100338		2004-05-27	Clark	
	2	20040227057		2004-11-18	Tuominen et al.	
	3	20060066443		2006-03-30	Hall	
	4	20060202665		2006-09-14	Hsu	
	5	20070013483		2007-01-18	Stewart	
	6	20070021140		2007-01-25	Keyes, IV et al.	
	7	20070096875		2007-05-03	Waterhouse	
	8	20070145830		2007-06-28	Lee et al.	
	9	20080266748		2008-10-30	Lee	
	10	20080273242		2008-11-06	Woodgate et al	

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	11	20110049996		2011-03-03	Karalis et al.	
	12	20110049998		2011-03-03	Karalis et al.	
	13	20110074218		2011-03-31	Karalis et al.	
	14	20110074347		2011-03-31	Karalis et al.	
	15	20110089895		2011-04-21	Karalis et al.	
	16	20110095618		2011-04-28	Schatz et al.	
	17	20110121920		2011-05-26	Kurs et al.	
	18	20110193416		2011-08-11	Campanella et al.	
	19	20110193419		2011-08-11	Karalis et al.	
	20	20110241618		2011-10-06	Karalis et al.	
	21	20110254377		2011-10-20	Widmer et al.	

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	22	20110254503		2011-10-20	Widmer et al.	
	23	20110140544		2011-06-16	Karalis et al.	
	24	20110148219		2011-06-23	Karalis et al.	
	25	20110162895		2011-07-07	Karalis et al.	
	26	20110169339		2011-07-14	Karalis et al.	
	27	20110181122		2011-07-28	Karalis et al.	
	28	20110198939		2011-08-18	Karalis et al.	
	29	20110221278		2011-09-15	Karalis et al.	
	30	20110227528		2011-09-22	Karalis et al.	
	31	20110227530		2011-09-22	Karalis et al.	

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	Examiner Name	DEBERADINIS, ROBERT L
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Examiner Initial*	Cite No	Foreign Document Number3	Country Code2 i	Kind Code4	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear	T5
	1	2011062827	WO		2011-05-26	Culbert et al.		☐

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NON-PATENT LITERATURE DOCUMENTS Remove

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T5
	1	Andre Kurs et al., "Simultaneous mid-range power transfer to multiple devices", Applied Physics Letters, Vol. 96, No. 044102 (2010)	☐
	2	Copy of International Search Report and Written Opinion of the International Searching Authority for International Application No. PCT/US2011/027868 by Examiner Blaine R. Copenheaver dated July 5, 2011	☐
	3	Copy of International Search Report for International Application No. PCT/US09/58499 by Examiner Lee W. Young dated December 10, 2009	☐
	4	David Schneider, "Electrons Unplugged. Wireless power at a distance is still far away," IEEE SPECTRUM, May 2010	☐
	5	J. C. Schuder et al., "Energy Transport Into the Closed Chest From a Set of Very-Large Mutually Orthogonal Coils", Communication Electronics, Vol. 64, pp. 527-534 (January 1963)	☐
	6	John C. Schuder et al., "An Inductively Coupled RF System for the Transmission of 1 kW of Power Through the Skin", IEEE Transactions on Bio-Medical Engineering, Vol. BME-18, No. 4 (July 1971)	☐
	7	John C. Schuder "Powering an Artificial Heart: Birth of the Inductively Coupled-Radio Frequency System in 1960", Artificial Organs, Vol. 26, No. 11, pp. 909-915 (2002)	☐

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	Filing Date		2009-12-28
	First Named Inventor	Karalis, Aristeidis	
	Art Unit		2836
	Examiner Name	DEBERADINIS, ROBERT L	
	Attorney Docket Number		WTCY-0026-P07

	8	Joseph C. Stark III, "Wireless Power Transmission Utilizing a Phased Array of Tesla Coils", Master Thesis, Massachusetts Institute of Technology (2004)	☐
	9	"Look, Ma – no wires! - Electricity broadcast through the air may someday run your home", by Gregory M. Lamb, Staff writer, The Christian Science Monitor, (See http://www.csmonitor.com/2006/1116/p14s01-stct.html) (November 15, 2006)	☐
	10	Marin Soljacic, "Wireless nonradiative energy transfer", Visions of Discovery New Light on Physics, Cosmology, and Consciousness, Cambridge University Press, New York, NY pp. 530-542 (2011)	☐
	11	MIT Team Experimentally Demonstrates Wireless Power Transfer, Potentially Useful for Power Laptops, Cell-Phones Without Cords - Goodbye Wires ..., by Franklin Hadley, Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology (June 7, 2007)	☐
	12	Soljacic. "Wireless Non-Radiative Energy Transfer – PowerPoint presentation". Massachusetts Institute of Technology, October 6, 2005	☐
	13	Altchev et al. Efficient Resonant Inductive Coupling Energy Transfer Using New Magnetic and Design Criteria". IEEE, pp. 1293-1298, 2005.	☐
	14	Copy of International Preliminary Report on Patentability with regard to International Application No. PCT/ US2007/070892 by Examiner Philippe Becamel dated September 29, 2009	☐
	15	Copy of International Search Report and Written Opinion for International Application No. PCT/US09/43970, dated July 14, 2009	☐
	16	Sekitani et al. "A large-area flexible wireless power transmission sheet using printed plastic MEMS switches and organic field-effect transistors". [PUBLICATION UNKNOWN]	☐

If you wish to add additional non-patent literature document citation information please click the Add button Add

EXAMINER SIGNATURE

Examiner Signature	/Robert Deberadinis/	Date Considered	03/16/2012

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (**Not for submission under 37 CFR 1.99)**	Application Number	12647763
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	Attorney Docket Number	WTCY-0026-P07

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

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	Examiner Name	DEBERADINIS, ROBERT L
	Attorney Docket Number	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☒ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-02-23
Name/Print	John A. Monocello, III	Registration Number	51022

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ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: Aristeidis Karalis et al.	Group Art Unit: 2836
Serial No.: 12/647,763	Confirmation No. 2576
Filed: December 28, 2009	Examiner: Robert L. Deberadinis

REQUEST FOR AMENDMENT UNDER 37 CFR § 1.312

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Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

Applicants have reviewed the Notice of Allowance mailed on March 26, 2012 ("Notice of Allowance"), and provide this Request for an Amendment under 37 C.F.R. 1.312.

A listing of claims begins at **Page 2** of this Response.

Remarks begin at **Page 6** of this response.

Listing of Claims:

This listing of claims will replace all prior versions of claims in the application.

1. (Previously Presented) A system, comprising:

a source resonator optionally coupled to an energy source; and

a second resonator located a distance from the source resonator,

wherein the source resonator and the second resonator are coupled to provide near-field wireless energy transfer among the source resonator and the second resonator and wherein the field of at least one of the source resonator and the second resonator is shaped using a conducting material and a magnetic material.

2. (Currently Amended) The system of claim 1, wherein at least one of the source resonator [[ad]] <u>and</u> the second resonator have a quality factor, Q>100.

3. (Original) The system of claim 1, wherein the source resonator Q is greater than 100 and the second resonator Q is greater than 100.

4. (Original) The system of claim 1, wherein the square root of the resonator Q times the second resonator Q is greater than 100.

5. (Original) The system of claim 1, comprising more than one resonator.

6. (Original) The system of claim 1, comprising more than one second resonator.

7. (Original) The system of claim 1, comprising more than three resonators.

8. (Previously Presented) A method, comprising:

providing a source resonator optionally coupled to an energy source and a second resonator located a distance from the source resonator,

coupling the source resonator and the second resonator to provide near-field wireless energy transfer among the source resonator and the second resonator, and

shaping the field of at least one of the source resonator and the second resonator using a conducting surface and a magnetic material.

9. (Original) The method claim 8, wherein at least one of the source resonator and the second resonator have a quality factor, Q>100.

10. (Original) The method of claim 8, wherein the source resonator Q is greater than 100 and the second resonator Q is greater than 100.

11. (Original) The method of claim 8, wherein the square root of the source resonator Q times the second resonator Q is greater than 100.

12. (Original) The method of claim 8, comprising more than one source resonator.

13. (Original) The method of claim 8, comprising more than one second resonator.

14. (Original) The method of claim 8, comprising more than three resonators.

15. (Currently Amended) The system of claim [[1]] 21, wherein the loss-inducing object is completely covered by the conducting material and the magnetic material.

16. (Currently Amended) The system of claim [[1]] 21, wherein the loss-inducing object is partially covered by the conducting material and the magnetic material.

17. (Currently Amended) The system of claim [[1]] 21, wherein the loss-inducing object is nearer to at least one of the source resonator and the second resonator, and wherein a portion of the loss-inducing object facing the nearer resonator is partially covered by the conducting material and the magnetic material.

18. (Currently Amended) The system of claim [[1]] 21, wherein the conducting material comprises a first layer that covers the loss-inducing object, and wherein the magnetic material comprises a second layer that covers the first layer.

19. (Currently Amended) The system of claim [[1]] 21, wherein the conducting material comprises a first layer that partially covers the loss-inducing object, and wherein the magnetic material comprises a second layer that partially covers the first layer.

20. (Currently Amended) The system of claim [[1]] 21, wherein the loss-inducing object is a mobile electronic device.

21. (Previously Presented) The system of claim 1, wherein the field is shaped to avoid a loss-inducing object.

22. (Previously Presented) The method of claim 8, wherein the step of shaping is to avoid a loss-inducing object.

23. (Previously Presented) A system, comprising:

a resonator coupled to power and control circuitry;

wherein the resonator and the power and control circuitry are configured to provide near-field wireless energy transfer among other resonators,

and wherein the power and control circuitry is at least partially covered by high permeability materials and conducting surfaces to shape magnetic fields of the resonator around the power and control circuitry.

REMARKS

Applicants are requesting for minor amendments to be entered for Claims 2 and 15-20 to correct a typographical error and to correct antecedent basis. Applicants submit that the amendments do not affect the scope of the claim. As the scope of the claim is unchanged, no further searching or additional examination is necessary, and the claims remain patentable for the reasons in the Notice of Allowance. The amendment was not presented earlier because it did not come to the Applicants' attention until now.

CONCLUSION

Applicants believe they have addressed all issues related to this matter. However, if the Examiner believes any issues remain, Applicants invite Examiner to contact their representatives at the number below.

Respectfully submitted,

ARISTEIDIS KARALIS ET AL.

By their Representatives,

Customer No. 87084

Date: April 26, 2012 By /John A. Monocello, III/
John A. Monocello, III
Reg. No. 51,022
Tel: 412-953-0696

Electronic Acknowledgement Receipt

EFS ID:	12635494
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	26-APR-2012
Filing Date:	28-DEC-2009
Time Stamp:	12:47:59
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Amendment after Notice of Allowance (Rule 312)	WTCY-0026-P07_312amendment.pdf	87791 f7ebff5477c91f0f67977a4ac2c9c720b1c8e0a3	no	6

Warnings:

Information:

Total Files Size (in bytes):	87791

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Issue Classification	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

ISSUE CLASSIFICATION

ORIGINAL		CROSS REFERENCE(S)							
CLASS	SUBCLASS	CLASS	SUBCLASS (ONE SUBCLASS PER BLOCK)						
307	104								

INTERNATIONAL CLASSIFICATION				
H	0	1	F	27/42
				/
				/
				/
				/

NONE
(Assistant Examiner) (Date)

(Legal Instruments Examiner) (Date)

/ROBERT L. DEBERADINIS/
5/7/12
(Primary Examiner) (Date)

Total Claims Allowed: 23

O.G. Print Claim(s)	O.G. Print Fig.
1	1

☐ **Claims renumbered in the same order as presented by applicant** ☐ CPA ☐ T.D. ☐ R.1.47

Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original
1	1		31		61		91		121		151		181
2	2		32		62		92		122		152		182
3	3		33		63		93		123		153		183
4	4		34		64		94		124		154		184
5	5		35		65		95		125		155		185
6	6		36		66		96		126		156		186
7	7		37		67		97		127		157		187
15	8		38		68		98		128		158		188
16	9		39		69		99		129		159		189
17	10		40		70		100		130		160		190
18	11		41		71		101		131		161		191
19	12		42		72		102		132		162		192
20	13		43		73		103		133		163		193
21	14		44		74		104		134		164		194
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14	20		50		80		110		140		170		200
8	21		51		81		111		141		171		201
22	22		52		82		112		142		172		202
23	23		53		83		113		143		173		203
	24		54		84		114		144		174		204
	25		55		85		115		145		175		205
	26		56		86		116		146		176		206
	27		57		87		117		147		177		207
	28		58		88		118		148		178		208
	29		59		89		119		149		179		209
	30		60		90		120		150		180		210

Response to Rule 312 Communication	**Application No.** 12/647,763	**Applicant(s)** KARALIS ET AL.
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address –

1. ☒ The amendment filed on *26 April 2012* under 37 CFR 1.312 has been considered, and has been:
   - a) ☒ entered.
   - b) ☐ entered as directed to matters of form not affecting the scope of the invention.
   - c) ☐ disapproved because the amendment was filed after the payment of the issue fee. Any amendment filed after the date the issue fee is paid must be accompanied by a petition under 37 CFR 1.313(c)(1) and the required fee to withdraw the application from issue.
   - d) ☐ disapproved. See explanation below.
   - e) ☐ entered in part. See explanation below.

/Robert DeBeradinis/
Primary Examiner, Art Unit 2836

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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

87084 7590 06/14/2012
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	

ART UNIT	PAPER NUMBER
2836	

NOTIFICATION DATE	DELIVERY MODE
06/14/2012	ELECTRONIC

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Notice of the Office communication was sent electronically on above-indicated "Notification Date" to the following e-mail address(es):

jsammartin@gtclawgroup.com
jmonocello@gtclawgroup.com
gtcdocketing@cpaglobal.com

PTOL-90A (Rev. 04/07)

Response to Rule 312 Communication	**Application No.** 12/647,763	**Applicant(s)** KARALIS ET AL.
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836

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   - d) ☐ disapproved. See explanation below.
   - e) ☐ entered in part. See explanation below.

/Robert DeBeradinis/
Primary Examiner, Art Unit 2836

Doc code: RCEX
Doc description: Request for Continued Examination (RCE)

PTO/SB/30EFS (07-09)
Approved for use through 07/31/2012. OMB 0651-0031
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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REQUEST FOR CONTINUED EXAMINATION(RCE)TRANSMITTAL
(Submitted Only via EFS-Web)

Application Number	12647763	Filing Date	2009-12-28	Docket Number (if applicable)	WTCY-0026-P07	Art Unit	2836
First Named Inventor	Karalis, Aristeidis			Examiner Name	Deberadinis, Robert L.		

This is a Request for Continued Examination (RCE) under 37 CFR 1.114 of the above-identified application.
Request for Continued Examination (RCE) practice under 37 CFR 1.114 does not apply to any utility or plant application filed prior to June 8, 1995, or to any design application. The Instruction Sheet for this form is located at WWW.USPTO.GOV

SUBMISSION REQUIRED UNDER 37 CFR 1.114

Note: If the RCE is proper, any previously filed unentered amendments and amendments enclosed with the RCE will be entered in the order in which they were filed unless applicant instructs otherwise. If applicant does not wish to have any previously filed unentered amendment(s) entered, applicant must request non-entry of such amendment(s).

☐ Previously submitted. If a final Office action is outstanding, any amendments filed after the final Office action may be considered as a submission even if this box is not checked.

- ☐ Consider the arguments in the Appeal Brief or Reply Brief previously filed on ____________
- ☐ Other ____________

☒ Enclosed

- ☐ Amendment/Reply
- ☒ Information Disclosure Statement (IDS)
- ☐ Affidavit(s)/ Declaration(s)
- ☐ Other ____________

MISCELLANEOUS

☐ Suspension of action on the above-identified application is requested under 37 CFR 1.103(c) for a period of months ____________
(Period of suspension shall not exceed 3 months; Fee under 37 CFR 1.17(i) required)

☐ Other ____________

FEES

☐ **The RCE fee under 37 CFR 1.17(e) is required by 37 CFR 1.114 when the RCE is filed.**
The Director is hereby authorized to charge any underpayment of fees, or credit any overpayments, to Deposit Account No ____________

SIGNATURE OF APPLICANT, ATTORNEY, OR AGENT REQUIRED

☒ Patent Practitioner Signature
☐ Applicant Signature

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Signature of Registered U.S. Patent Practitioner			
Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-06-22
Name	John A. Monocello, III	Registration Number	51022

This collection of information is required by 37 CFR 1.114. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450.

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2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

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Doc code: IDS
Doc description: Information Disclosure Statement (IDS) Filed

PTO/SB/08a (01-10)
Approved for use through 07/31/2012. OMB 0651-0031
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Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

INFORMATION DISCLOSURE STATEMENT BY APPLICANT
(**Not for submission under 37 CFR 1.99)**

Application Number	12647763
Filing Date	2009-12-28
First Named Inventor	Karalis, Aristeidis
Art Unit	2836
Examiner Name	Deberadinis, Robert L.
Attorney Docket Number	WTCY-0026-P07

U.S.PATENTS Remove

Examiner Initial*	Cite No	Patent Number	Kind Code1	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	3780425		1973-12-25	Penn et al.	
	2	3871176		1975-03-18	Schukei, Glen Elwin	
	3	4095998		1978-06-20	Hanson, Charles M.	
	4	4280129		1981-07-21	Wells, Donald H.	
	5	5053774		1991-10-01	Schuermann et al.	
	6	5287112	A	1994-02-15	Schuermann, Josef H.	
	7	5455467	A	1995-10-03	Young et al.	
	8	5522856	A	1996-06-04	Reineman, Henk	

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

	9	5565763	A	1996-10-15	Arrendale et al.	
	10	5697956	A	1997-12-16	Bornzin, Gene A.	
	11	5742471	A	1998-04-21	Barbee, Jr. et al.	
	12	5957956	A	1999-09-28	Kroll et al.	
	13	5993996	A	1999-11-30	Firsich, David W.	
	14	6012659	A	2000-01-11	Nakazawa et al.	
	15	6066163	A	2000-05-23	John, Michael Sasha	
	16	6067473	A	2000-05-23	Greeninger et al.	
	17	6108579	A	2000-08-22	Snell et al.	
	18	6127799	A	2000-10-03	Krishnan, Rajesh	
	19	6207887	B1	2001-03-27	Bass et al.	

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Attorney Docket Number	WTCY-0026-P07

	20	6252762	B1	2001-06-26	Amatucci, Glenn G.	
	21	6483202	B1	2002-11-19	Bozs, John Talbot	
	22	6609023	B1	2003-08-19	Fischell et al.	
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	25	6858970	B2	2005-02-22	Malkin et al.	
	26	6961619	B2	2005-11-01	Casey, Don E.	
	27	6967462	B1	2005-11-22	Landis, Geoffrey A.	
	28	7027311	B2	2006-04-11	Vanderelli et al.	
	29	7035076	B1	2006-04-25	Stevenson, Robert A.	
	30	7084605	B2	2006-08-01	Mickle et al.	

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	31	7127293	B2	2006-10-24	MacDonald, Stuart G.	
	32	7251527	B2	2007-07-31	Lyden, Michael J.	
	33	7288918	B2	2007-10-30	DiStefano, Michael Vincent	
	34	7340304	B2	2008-03-04	MacDonald, Stuart G.	
	35	7885050	B2	2011-02-08	Lee, Hyung-Joo	
	36	8035255	B2	2011-10-11	Kurs et al.	
	37	8076800	B2	2011-12-13	Joannopoulos et al.	
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	First Named Inventor	Karalis, Aristeidis
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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

	42	8115448	B2	2012-02-14	John, Michael Sasha	

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Examiner Initial*	Cite No	Publication Number	Kind Code1	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	20020167294	A1	2002-11-14	Odaohhara, Shigefumi	
	2	20030124050	A1	2003-07-03	Yadav et al.	
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT (**Not for submission under 37 CFR 1.99)**	Application Number	12647763
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	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

	9	20050194926	A1	2005-09-08	DiStefano, Michael Vincent	
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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT (**Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
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	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☐ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-06-22
Name/Print	John A. Monocello, III	Registration Number	51022

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Bibliographic data: CN102239633 (A) — 2011-11-09

Wireless energy transfer systems

Inventor(s):	KESLER MORRIS P; ARISTEIDIS KARALIS; KURS ANDRE B; CAMPANELLA ANDREW J; RON FIORELLO; QIANG LI; KONRAD KULIKOWSKI; GILER ERIC R; PERGAL FRANK J; SCHATZ DAVID A; HALL KATHERINE L; MARIN SOLJACIC +
Applicant(s):	WITRICITY CORP +
Classification:	**- international:** ***H03B19/00*** **- European:**
Application number:	CN20098147815 20090925
Priority number(s):	WO2009US58499 20090925; US20080100721P 20080927; US20080108743P 20081027; US20080121159P 20081209; US20090142889P 20090106; US20090142796P 20090106; US20090142880P 20090106; US20090142818P 20090106; US20090142885P 20090106; US20090142887P 20090106; US20090142977P 20090107

Abstract of CN102239633 (A)

Described herein are improved capabilities for a source resonator having a Q factor Q1>100 and a characteristic size x1 coupled to an energy source, and a second resonator having a Q factor Q2 is more than 100 and a characteristic size x2 coupled to an energy drain located a distance D from the source resonator, where the source resonator and the second resonator are coupled to exchange energy wirelessly among the source resonator and the second resonator.

Last updated: 14.03.2012 Worldwide Database 5.7.38; 92p

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权利要求书 2 页 说明书 75 页 附图 45 页

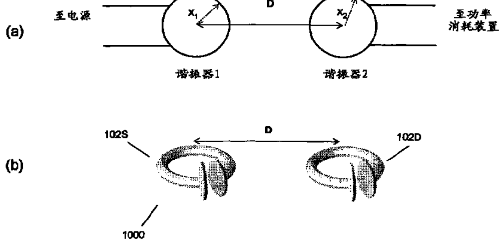
(54) 发明名称

无线能量转移系统

(57) 摘要

本文所述的是用于具有 Q 因数 Q_1＞100 和特性尺寸 x_1 的被耦合到能量源的源谐振器和具有 Q 因数 Q_2＞100 和特性尺寸 x_2 的被耦合到位于与源谐振器相距距离 D 处的能量消耗装置的第二谐振器的改进的能力，其中，源谐振器和第二谐振器被耦合以在源谐振器与第二谐振器之间无线地交换能量。

CN 102239633 A



1. 一种系统，包括：

源谐振器，其具有Q因数Q_1和特性尺寸x_1，被耦合到发电机，以及第二谐振器，其具有Q因数Q_2和特性尺寸x_2，被耦合到位于与源谐振器相距距离D处的负载，其中，源谐振器和第二谐振器被耦合以在源谐振器和第二谐振器之间无线地交换能量，并且其中$\sqrt{Q_1Q_2} > 100$。

2. 权利要求1的所述的系统，其中，$Q_1 < 100$，

3. 权利要求1的所述的系统，其中，$Q_2 < 100$。

4. 权利要求1的所述的系统，还包括具有Q因数Q_3的第三谐振器，其被配置为非辐射地与源和第二谐振器转移能量，其中$\sqrt{Q_1Q_3} > 100$且$\sqrt{Q_2Q_3} > 100$。

5. 权利要求4的所述的系统，其中，$Q_3 < 100$。

6. 权利要求1的所述的系统，其中，所述源谐振器被耦合到具有直接电连接的发电机。

7. 权利要求1的所述的系统，还包括阻抗匹配网络，其中，源谐振器被用直接电连接耦合并阻抗匹配到发电机。

8. 权利要求1的所述的系统，还包括可调谐电路，其中，源谐振器用直接电连接通过可调谐电路耦合到发电机。

9. 权利要求6、7或8的所述的系统，其中，直接电连接中的至少一个被配置为基本上保持源谐振器的谐振模。

10. 权利要求6的所述的系统，其中，源谐振器具有第一端子、第二端子和中心端子，并且其中，第一端子和中心端子之间和第二端子与中心端子之间的阻抗基本上是相等的。

11. 权利要求6的所述的系统，其中，源谐振器包括具有第一端子、第二端子和中心端子的电容加载环路，并且其中，第一端子和中心端子之间和第二端子与中心端子之间的阻抗基本上是相等的。

12. 权利要求6的所述的系统，其中，源谐振器被耦合到阻抗匹配网络且阻抗匹配网络还包括第一端子、第二端子和中心端子，并且其中，第一端子与中心端子之间和第二端子与中心端子之间的阻抗是基本上相等的。

13. 权利要求10、11或12的所述的系统，其中，第一端子和第二端子被直接耦合到发电机，并且用异相接近180度的振荡信号来驱动。

14. 权利要求10、11或12的所述的系统，其中，所述源谐振器具有谐振频率ω_1，并且第一端子和第二端子被直接耦合到发电机，并用基本上等于谐振频率ω_1的振荡信号来驱动。

15. 权利要求10、11或12的所述的系统，其中，所述中心端子被连接到电接地。

16. 权利要求15的所述系统，其中，所述源谐振器具有谐振频率ω_1且第一端子和第二端子被直接耦合到发电机，并且用基本上等于谐振频率ω_1的频率来驱动。

17. 权利要求2的所述的系统，包括被耦合到发电机和负载的多个电容器。

18. 权利要求1的所述的系统，其中，源谐振器和第二谐振器均被封闭在低损耗角正切材料中。

19. 权利要求1的所述的系统，还包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送DC功率。

20. 权利要求1的所述的系统，还包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送AC功率。

21. 权利要求 1 的所述的系统，还包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送 AC 和 DC 功率两者。

22. 权利要求 1 的所述的系统，还包括功率转换电路和多个负载，其中，第二谐振器被耦合到功率转换电路，并且功率转换电路被耦合到所述多个负载。

23. 权利要求 7 的所述的系统，其中，所述阻抗匹配网络包括电容器。

24. 权利要求 7 的所述的系统，其中，所述阻抗匹配网络包括电感器。

25. 权利要求 8 的所述的系统，其中，所述可调谐电路包括可变电容器。

26. 权利要求 8 的所述的系统，其中，所述可调谐电路包括可变电感器。

无线能量转移系统

[0001] 相关申请的交叉引用

[0002] 本申请要求以下美国专利申请的优先权，其中的每一个整体地通过引用结合到本文中：

[0003] 2008年9月27日提交的美国申请No.61/100,721；2008年10月27日提交的美国申请No.61/108,743；2009年1月26日提交的美国申请No.61/147,386；2009年2月12日提交的美国申请No.61/152,086；2009年5月15日提交的美国申请No.61/178,508；2009年6月1日提交的美国申请No.61/182,768；2008年12月9日提交的美国申请No.61/121,159；2009年1月7日提交的美国申请No.61/142,977；2009年1月6日提交的美国申请No.61/142,885；2009年1月6日提交的美国申请No.61/142,796；2009年1月6日提交的美国申请No.61/142,889；2009年1月6日提交的美国申请No.61/142,880；2009年1月6日提交的美国申请No.61/142,818；2009年1月6日提交的美国申请No.61/142,887；2009年3月2日提交的美国申请No.61/156,764；2009年1月7日提交的美国申请No.61/143,058；2009年2月13日提交的美国申请No.61/152,390；2009年3月26日提交的美国申请No.61/163,695；2009年4月24日提交的美国申请No.61/172,633；2009年4月14日提交的美国申请No.61/169,240；及2009年4月29日提交的美国申请No.61/173,747。

[0004] 背景

技术领域

[0005] 本公开涉及亦被称为无线功率传输的无线能量转移（transfer）。

背景技术

[0006] 可以使用多种已知辐射或远场和非辐射或近场技术来无线地转移能量或功率。例如，可以将使用低方向性天线的辐射无线信息转移（诸如在无线电和蜂窝式通信系统和家用计算机网络中使用的那些）视为无线能量转移。然而，此类辐射转移是非常低效的，因为仅获取了供应或辐射的功率的很小一部分，即沿着接收机的方向并与之重叠的那部分。大多数功率沿着所有其它方向被辐射开并损耗在自由空间中。此类低效功率转移对于数据传输而言是可接受的，但是对于为了做工目的（诸如为了向电气设备供电或充电）而转移有用量的电能而言是不实际的。改善某些能量转移方案的转移效率的一种方式是使用定向天线来约束并优选地指引辐射能量朝向接收机。然而，这些定向辐射方案在移动发射机和/或接收机的情况下可能要求不中断的视线和潜在地复杂的跟踪和转向机构。另外，此类方案可能对正在传送中度或大量功率时穿过或横穿射束的对象或人造成危险。常常称为感应或传统感应的已知非辐射或近场无线能量转移方案并非（故意地）辐射功率，而是使用流过初级线圈的振荡电流来产生在附近接收或次级线圈中感生电流的振荡磁近场。传统感应方案已经证明了适中到大量功率的传输，然而仅仅是在非常短的距离上，并且在主电源单元与辅助接收机单元之间具有非常小的偏移容差。电变压器和接近充电器（proximity charger）是利用此已知近程、近场能量转移方案的设备的示例。

[0007] 因此，需要一种能够在中程（mid-range）距离或对准偏移内传送有用量的电功率的无线功率转移方案。此类无线功率转移方案应能够相较传统感应方案所实现的那些在更大的距离和对准偏移内实现有用能量转移，但是没有辐射传输方案所固有的限制和风险。

发明内容

[0008] 本文公开了一种能够在中程距离和对准偏移内传送有用量的功率的非辐射或近场无线能量转移方案。本发明的技术使用具有长寿命的振荡谐振模的耦合电磁谐振器来从电源向功率消耗装置（power drain）转移功率。该技术是全面的，并且可以应用于大范围的谐振器，即使在本文公开的涉及电磁谐振器的特定示例的情况下。如果谐振器被设计使得由电场存储的能量被主要约束在结构内且由磁场存储的能量主要在谐振器周围的区域中。则主要由谐振磁近场来调解（mediate）能量交换。可以将这些类型的谐振器称为磁谐振器。如果谐振器被设计使得由磁场存储的能量被主要约束在结构内且由电场存储的能量主要在谐振器周围的区域中。则主要由谐振电近场来调解能量交换。可以将这些类型的谐振器称为电谐振器。还可以将两种中任一类型的谐振器称为电磁谐振器。在本文中公开了这两种类型的谐振器。

[0009] 我们公开的谐振器的近场的全向但固定（无损耗）性质在很宽的方向和谐振器取向的范围内实现在中程距离上的高效无线能量转移，适合于充电、供电或同时对多种电子设备供电和充电。结果，一种系统可以具有多种可能的应用，其中，被连接到电源的第一谐振器在一个位置，并且潜在地连接到电气 / 电子设备、电池、供电和充电电路的第二谐振器等处于第二位置，并且其中，从第一谐振器到第二谐振器的距离约为几厘米至几米。例如，连接到有线电力网的第一谐振器可以位于房间的天花板上，而被连接到诸如机器人、交通工具、计算机、通信设备、医疗设备等设备的其它谐振器等在房间内来回移动，并且其中，这些设备恒定地或间歇地从源谐振器无线地接收功率。对于这一个示例而言，一个人可以想象许多应用，其中本文公开的系统和方法可以跨越中程的距离提供无线功率，包括消费者电子装置、工业应用、基础设施供电和照明、运输交通工具、电子游戏、军事应用等。

[0010] 当谐振器被调谐至基本相同的频率且系统中的损耗最小时，能够使两个电磁谐振器之间的能量交换最优化。无线能量转移系统可以被设计使得谐振器之间的“耦合时间”比谐振器的“损耗时间”短得多。因此，本文所述的系统和方法可以利用具有低固有损耗率的高品质因数（高 Q）谐振器。另外，本文所述的系统和方法可以使用具有明显比谐振器的特性尺寸更长地延伸的近场的亚波长谐振器，使得交换能量的谐振器的近场在中程距离处重叠。这是之前尚未实践的操作区，并且明显不同于传统感应设计。

[0011] 重要的是认识到这里公开的高 Q 磁谐振器方案与已知近程或接近感应方案之间的差别，即那些已知方案按照惯例没有利用高 Q 谐振器。使用耦合模理论（CMT）（参见例如 Waves and Fields in Optoelectronics，H. A. Haus，Prentice Hall，1984），可以显示高 Q 谐振器耦合机制能够实现比传统感应方案所实现的间隔开中程距离的谐振器之间的功率递送高几个数量级的高效功率递送。耦合高 Q 谐振器已经证明了在中程距离上实现高效能量转移及在短程能量转移应用中改善效率和偏移容差。

[0012] 本文所述的系统和方法可以提供经由强耦合高 Q 谐振器的近场无线能量转移，

一种具有安全地且在比使用传统感应技术实现的大得多的距离上转移从皮可瓦到千瓦的功率水平的潜力的技术。针对强耦合谐振器的多种一般系统，可以实现高效的能量转移，诸如强耦合声谐振器、原子能谐振器、机械谐振器等的系统，如最初由 M.I.T. 在其出版物“Efficient wireless non-radiative mid-range energy transfer”，Annals of Physics，vol.323，Issue 1，p.34(2008) 和“Wireless Power Transfer via Strongly Coupled Magnetic Resonances”，Science，vol.317，no.5834，p.83，(2007) 中描述的那样。本文公开的是电磁谐振器和耦合电磁谐振器的系统，更具体地也称之为耦合磁谐振器和耦合电谐振器，具有 10GHz 之下的工作频率。

[0013] 本公开内容描述了也称为无线功率传输技术的无线能量转移技术。综观本公开内容，我们可互换使用术语无线能量转移、无线功率转移、无线功率传输等。我们可以提到将来自源、AC 或 DC 源、电池、源谐振器、电源、发电机、太阳能电池板和集热器等的能量或功率供应给设备、远程设备、多个远程设备、一个或多个设备谐振器等。我们可以描述中间谐振器，其通过允许能量跳跃、转移通过、被临时存储、被部分地耗散、或允许以任何方式来调解从源谐振器到其它设备与中间谐振器的任何组合的转移来扩展无线能量转移系统的范围，从而可以实现能量转移网络或串或延长的路径。设备谐振器可以从源谐振器接收能量，将该能量的一部分转换成用于对设备供电和充电的电功率，并同时将接收到的能量的一部分传到其它设备或移动设备谐振器上。能量可以从源谐振器转移至多个设备谐振器，显著地延长可无线地转移能量的距离。可以使用多种系统架构和谐振器设计来实现无线功率传输系统。该系统可包括向单个设备或多个设备传送功率的单个源或多个源。可以将谐振器设计为源或设备谐振器，或者可以将其设计为重发器 (repeater)。在某些情况下，谐振器可以同时是设备和源谐振器，或者可以将其从作为源进行操作切换至作为设备或重发器进行操作。本领域的技术人员将理解的是可以由在本申请中描述的大范围的谐振器设计和功能来支持多种系统架构。

[0014] 在我们描述的无线能量转移系统中，可以使用无线供应的功率或能量直接对远程设备供电，或者可以将设备耦合到诸如电池、法拉电容器、超级电容器等的储能单元（或其它种类的功率消耗装置），其中，可以无线地对储能元件充电或再充电，和 / 或其中，无线功率转移机制仅仅是设备的主电源的补充。可以由诸如具有集成存储电容器等的混合电池 / 储能设备来对设备供电。此外，可以将新型电池和储能设备设计为利用由无线功率传输系统实现的操作改进。

[0015] 其它功率管理方案包括使用无线地供应的功率来对电池再充电或对储能单元充电，同时其进行供电的设备被关断、处于空闲状态、处于睡眠模式等。可以以高（快）或低（慢）速率对电池或储能单元充电或再充电。可以对电池或储能单元涓流充电或浮动充电。可以并行地同时对多个设备充电或供电，或者可以使到多个设备的功率递送串行化，使得一个或多个设备在其它功率递送被切换到其它设备之后的一段时间内接收功率。多个设备可以同时地或以时间复用方式或以频率复用方式或以空间复用方式或以取向复用方式或以时间和频率和空间和取向复用的任何组合来与一个或多个其它设备共享来自一个或多个源的功率。多个设备可以相互共享功率，至少一个设备被连续地、间歇地、周期性地、偶尔地或临时地重新配置以作为无线功率源进行操作。本领域的技术人员应理解的是存在向设备供电和 / 或充电的多种方式，并且所述多种方式可以应用于本文所述的技术和应用。

[0016]　无线能量转移具有多种可能的应用，包括例如将源（例如连接到有线电力网的一个）放置在房间的天花板上、在地板下或在墙壁中，同时将诸如机器人、交通工具、计算机、PDA 等放置在室内或其在室内自由地移动。其它应用可以包括对电引擎交通工具供电或再充电，诸如公交车和 / 或混合汽车和医疗设备，诸如可穿戴或可植入设备。附加示例性应用包括对独立电子装置（例如膝上型计算机、蜂窝电话、便携式音乐播放器、家务机器人、GPS 导航系统、显示器等）、传感器、工业和制造设备、医疗设备和监视器、家用器具和工具（例如灯、风扇、钻、锯、加热器、显示器、电视、柜台上器具等）、军用设备、保暖或照明衣物、通信和导航设备，包括嵌入交通工具、衣物和保护性衣物中诸如头盔、防弹服和背心的设备等供电或再充电的能力，以及向被物理隔离的设备传送功率的能力，诸如向植入的医疗设备，向隐藏、掩埋、植入或嵌入的传感器或标签，和 / 或从屋顶太阳能电池板向室内配电盘等。

[0017]　在一方面，本文公开的系统包括具有品质因数 Q_1 和特性尺寸 x_1 并被耦合到发电机的源谐振器，和具有品质因数 Q_2 和特性尺寸 x_2 并被耦合到位于与源谐振器相距距离 D 的负载的第二谐振器，其中，所述源谐振器和第二谐振器被耦合以在源谐振器和第二谐振器之间无线地交换能量，并且其中 $\sqrt{Q_1Q_2} > 100$。

[0018]　Q_1 可以小于 100。Q_2 可以小于 100。该系统可以包括被配置为用源和第二谐振器来非辐射地转移能量的具有品质因数 Q_3 的第三谐振器，其中，$\sqrt{Q_1Q_3} > 100$ 且 $\sqrt{Q_2Q_3} > 100$。Q_3 可以小于 100。

[0019]　可以用直接电连接将源谐振器耦合到发电机。系统可以包括阻抗匹配网络，其中，所述源谐振器通过直接电连接而耦合并阻抗匹配到发电机。所述系统可以包括可调谐电路，其中，所述源谐振器通过具有直接电连接的可调谐电路而耦合到发电机。所述可调谐电路可以包括可变电容器。所述可调谐电路可以包括可变电感器。至少一个直接电连接可以配置为基本上保持源谐振器的谐振模。源谐振器可以具有第一端子、第二端子和中心端子，并且第一端子与中心端子之间和第二端子与中心端子之间的阻抗可以是基本上相等的。源谐振器可以包括具有第一端子、第二端子和中心端子的电容性加载环路，其中，第一端子与中心端子之间和第二端子与中心端子之间的阻抗基本上是相等的。可以将源谐振器耦合到阻抗匹配网络，并且阻抗匹配网络还可以包括第一端子、第二端子和中心端子，其中，第一端子与中心端子之间和第二端子与中心端子之间的阻抗基本上是相等的。

[0020]　可以将第一端子和第二端子直接耦合到发电机并用异相约 180 度的振荡信号来驱动。源谐振器可以具有谐振频率 ω_1，并且可以将第一端子和第二端子直接耦合到发电机并用基本上等于谐振频率 ω_1 的振荡信号来驱动。可以将中心端子连接到电接地。源谐振器可以具有谐振频率 ω_1，并且可以将第一端子和第二端子直接耦合到发电机并用基本上等于谐振频率的频率来驱动。所述系统可以包括被耦合到发电机和负载的多个电容器。所述源谐振器和第二谐振器每个可以被封闭在低损耗角正切材料（tangent material）中。所述系统可以包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送 DC 功率。所述系统可以包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送 AC 功率。所述系统可以包括功率转换电路，其中，第二谐振器被耦合到功率转换电路以向负载递送 AC 和 DC 功率这二者。所述系统可以包括功率转换电路和多个负载，其中，第二谐振器被耦合到功率转换电路，并且功率转换电路被耦合到所述多个负载。所述阻抗匹

配网络可以包括电容器。所述阻抗匹配网络可以包括电感器。

[0021] 纵观本公开内容，我们可以将诸如电容器、电感器、电阻器、二极管、开关等某些电路组件称为电路组件或元件。我们还可以将这些组件的串联和并联组合称为元件、网络、拓扑结构、电路等。我们可以将电容器、二极管、变抗器、晶体管和／或开关的组合描述为可调整阻抗网络、调谐网络、匹配网络、调整元件等。我们还可以提到使电容和电感这二者遍及整个对象分布（或部分地分布，与单独地集总相反）的“自谐振”对象。本领域的技术人员将理解的是在电路或网络内调整和控制可变组件可以调整该电路或网络的性能，并且那些调整可以一般描述为调谐、调整、匹配、修正等。除调整诸如电感器和电容器或成组的电感器和电容器的可调谐组件之外，其它调谐或调整无线功率转移系统的方法可以单独使用。

[0022] 除非另外定义，本文所使用的所有技术和／或科学术语具有与本公开所属领域的技术人员通常理解的意义相同的意义。在与出版物、专利申请、专利和通过引用在本文中提及或结合到本文中的其它参考文献冲突的情况下，本说明书（包括定义）将具有支配权。

[0023] 在不脱离本公开的范围的情况下，可以单独地或组合地使用任何上述特征。通过以下详细说明和附图，本文公开的系统和方法的其它特征、目的和优点将是显而易见的。

附图说明

[0024] 图1(a)和(b)描绘了包含以距离D分隔开的源谐振器1和设备谐振器2的示例性无线功率系统。

[0025] 图2示出根据本公开中描述的加标签惯例被加标签的示例性谐振器。请注意，在谐振器1的附近未示出无关对象或附加谐振器。

[0026] 图3示出在存在“加载”对象的情况下，根据本公开中描述的加标签惯例被加标签的示例性谐振器。

[0027] 图4示出在存在“扰动”对象的情况下，根据本公开中描述的加标签惯例被加标签的的示例性谐振器。

[0028] 图5示出效率 η 对比强耦合系数$U=\kappa/\sqrt{\Gamma_s\Gamma_d}=k\sqrt{Q_sQ_d}$的绘图。

[0029] 图6(a)示出谐振器的一个示例的电路图，(b)示出电容加载电感器环路磁谐振器的一个示例的图示，(c)示出具有分布式电容和电感的自谐振线圈的图，(d)示出与本公开的示例性磁谐振器相关联的电场和磁场线的简化图，以及(e)示出电谐振器的一个示例的图示。

[0030] 图7示出可以用于MHz频率下的无线功率传输的示例性谐振器的作为频率的函数的“品质因数”Q（实线）的图。吸收性Q（短划线）随着频率增加，而辐射性Q（点线）随着频率减小，因此，促使总的Q在特定频率处达到峰值。

[0031] 图8示出谐振器结构的图，其特性尺寸、厚度和宽度均被指示。

[0032] 图9(a)和(b)示出示例性感应环路元件的图。

[0033] 图10(a)和(b)示出在印刷电路板上形成并用来实现磁谐振器结构中的感应元件的迹线(trace)结构的两个示例。

[0034] 图11(a)示出平面磁谐振器的透视图，(b)示出具有各种几何结构的两个平面磁谐振器的透视图，以及(c)示出以距离D分隔开的两个平面磁谐振器的透视图。

[0035] 图12是平面磁谐振器的示例的透视图。

[0036] 图 13 是具有圆形谐振器 (circular resonator) 线圈的平面磁谐振器布置的透视图。

[0037] 图 14 是平面磁谐振器的有效区域 (active area) 的透视图。

[0038] 图 15 是无线功率转移系统的应用的透视图，其中处于桌子中心处的源对放置在源周围的多个设备供电。

[0039] 图 16(a) 示出由绕其中心处的阻塞点的电流的正方形环路驱动的铜和磁性材料结构的 3D 有限元模型。在本示例中，结构可以由用诸如铜的导电材料制成、被一层磁性材料覆盖并通过一块磁性材料连接的两个盒子组成。本示例中的两个导电盒子的内部将与在盒子外面产生的 AC 电磁场屏蔽开来，并且可以容纳可能降低谐振器的 Q 的有损耗对象或可能被 AC 电磁场负面地影响的敏感组件。还示出了所计算的由此结构生成的磁场流线，指示磁场线趋向于遵循磁性材料中的较低磁阻路径。图 16(b) 示出如图 (a) 所示的两个相同结构之间的如所计算的磁场流线所指示的交互作用。由于对称性以及为了降低计算复杂性，仅对系统的一半进行建模（但是，该计算假定了另一半的对称布置）。

[0040] 图 17 示出包括绕结构缠绕 N 次的导线的磁谐振器的等效电路表示，可能包含可透磁材料。使用绕包括磁性材料的结构缠绕的导电环路来实现电感，并且电阻器表示系统中的损耗机构 (R_{wire} 用于环路中的电阻损耗，R_{ll} 表示被环路围绕的结构的等效串联电阻）。可以将损耗最小化以实现高 Q 谐振器。

[0041] 图 18 示出频率 6.78MHz 的外部磁场中的由有损耗电介质材料组成的圆盘之上和之下的两个高导电率表面的有限元法 (FEM) 模拟。请注意，磁场在圆盘之前是均匀的，并且导电材料被引入模拟环境。在圆柱形坐标系中执行此模拟。图像是绕 $r = 0$ 轴方位角对称的。有损耗电解质圆盘具有 $\varepsilon_r = 1$ 和 $\sigma = 10S/m$。

[0042] 图 19 示出在其附近具有被高导电率表面完全地覆盖的有损耗对象的磁谐振器的图。

[0043] 图 20 示出在其附近具有被高导电率表面部分地覆盖的有损耗对象的磁谐振器的图。

[0044] 图 21 示出在其附近具有被设置在高导电率表面之上的有损耗对象的磁谐振器的图。

[0045] 图 22 示出完全无线投影仪的图示。

[0046] 图 23 示出沿着包含圆形环路电感器的直径和沿着环路电感器的轴的电场和磁场的幅值。

[0047] 图 24 示出磁谐振器和其外壳以及被放置在 (a) 外壳的角落中，尽可能远离谐振器结构或 (b) 在被磁谐振器中的电感元件封闭的表面的中心上的必需但有损耗的对象的图。

[0048] 图 25 示出具有在其上方的高导电率表面和有损耗对象的磁谐振器的图，所述有损耗对象可以被带到谐振器的附近，但是在高导电率片材上方。

[0049] 图 26(a) 示出被暴露于沿着 z 轴的最初均匀的外加磁场（灰色磁通线）的薄导电（铜）圆柱或圆盘（直径为 20cm，高度为 2cm）的轴向对称 FEM 模拟。对称轴在 $r = 0$ 处。所示的磁流线在源于 $z = -\infty$，其中，其被以 1cm 的间隔间隔开 $r = 3cm$ 至 $r = 10cm$。轴刻度以米为单位。图 26(b) 示出与在 (a) 中相同的结构和外加场，除导电圆柱已被修改为在其外表面上包括具有 $\mu_r' = 40$ 的 0.25mm 的磁性材料层（不可见）。请注意，磁流线偏转远离

圆柱的程度明显比在 (a) 中小。

[0050] 图 27 示出基于图 26 所示的系统的变化的轴对称视图。有损耗材料仅有一个表面被铜和磁性材料的分层结构覆盖。如图所示，电感器环路被放置在与有损耗材料相对的铜和磁性材料结构的一侧。

[0051] 图 28(a) 描绘了包括到高 Q 电感元件的间接耦合的匹配电路的一般拓扑结构。

[0052] 图 28(b) 示出了包括导体环路电感器和可调谐阻抗网络的磁谐振器的方框图。可以将到此谐振器的物理电连接进行至端子连接。

[0053] 图 28(c) 描绘了被直接耦合到高 Q 电感元件的匹配电路的一般拓扑结构。

[0054] 图 28(d) 描绘了被直接耦合到高 Q 电感元件并被反对称地驱动（平衡驱动）的对称匹配电路的一般拓扑结构。

[0055] 图 28(e) 描绘了被直接耦合到高 Q 电感元件并在主谐振器的对称点处接地（非平衡驱动）的匹配电路的一般拓扑结构。

[0056] 图 29(a) 和 29(b) 描绘了被耦合（即间接地或电感地）到高 Q 电感元件的匹配电路变压器的两个拓扑结构。(c) 中的史密斯图的突出显示部分描绘了在 $\omega L_2 = 1/\omega C_2$ 的情况下从可以被图 31(b) 的拓扑结构匹配到任意实阻抗 Z_0 的复数阻抗（从电感元件的 L 和 R 产生）。

[0057] 图 30(a)、(b)、(c)、(d)、(e)、(f) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电容器的匹配电路的六个拓扑结构。用输入端子处的共模信号来驱动图 30(a)、(b)、(c) 所示的拓扑结构，而图 30(d)、(e)、(f) 所示的拓扑结构是对称的，并接收平衡驱动。图 30(g) 中的史密斯图的突出显示部分描绘了可以通过这些拓扑结构匹配的复数阻抗。图 30(h)、(i)、(j)、(k)、(l)、(m) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电感器的匹配电路的六个拓扑结构。

[0058] 图 31(a)、(b)、(c) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电容器的匹配电路的三个拓扑结构，其在电容器的中心点处接地并接收不平衡驱动。图 31(d) 中的史密斯图的突出显示部分描绘了可以通过这些拓扑结构匹配的复数阻抗。图 31(e)、(f)、(g) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电感器的匹配电路的三个拓扑结构。

[0059] 图 32(a)、(b)、(c) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电容器的匹配电路的三个拓扑结构。其通过电感器环路的中心点处的分接 (tapping) 接地并接收不平衡驱动。(d) 中的史密斯图的突出显示部分描绘了可以被这些拓扑结构匹配的复数阻抗，(e)、(f)、(g) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 串联的电感器的匹配电路的三个拓扑结构。

[0060] 图 33(a)、(b)、(c)、(d)、(e)、(f) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 并联的电容器的匹配电路的六个拓扑结构。用输入端子处的共模信号来驱动图 33(a)、(b)、(c) 所示的拓扑结构，而图 33(d)、(e)、(f) 所示的拓扑结构是对称的，并接收平衡驱动。图 33(g) 中的史密斯图的突出显示部分描绘了可以被这些拓扑结构匹配的复数阻抗。图 33(h)、(i)、(j)、(k)、(l)、(m) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 并联的电感器的匹配电路的六个拓扑结构。

[0061] 图 34(a)、(b)、(c) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 并联的电容器

的匹配电路的三个拓扑结构。其在电容器的中心点处接地并接收不平衡驱动。(d) 中的史密斯图的突出显示部分描绘了可以被这些拓扑结构匹配的复数阻抗。图 34(e)、(f)、(g) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 并联的电感器的匹配电路的三个拓扑结构。

[0062] 图 35(a)、(b)、(c) 描绘了被直接耦合到高 Q 电感元件并包括与 Z_0 并联的电容器的匹配电路的三个拓扑结构。其通过电感器环路的中心点处的分接接地并接收不平衡驱动。图 35(d)、(e) 和 (f) 中的史密斯图的突出显示部分描绘了可以被这些拓扑结构匹配的复数阻抗。

[0063] 图 36(a)、(b)、(c)、(d) 描绘了被设计为在可变电容器上产生具有更细调谐分辨率的总可变电容和某些具有降低的电压的固定和可变电容器的四个网络拓扑结构。

[0064] 图 37(a) 和 37(b) 描绘了被设计为产生总可变电容的固定电容器和可变电感器的两个网络拓扑结构。

[0065] 图 38 描绘了无线功率传输系统的高级方框图。

[0066] 图 39 描绘了示例性被无线供电的设备的方框图。

[0067] 图 40 描绘了示例性无线功率转移系统的源的方框图。

[0068] 图 41 示出了磁谐振器的等效电路图。通过电容器符号的短斜线指示所表示的电容器可以是固定或可变的。可以将端口参数测量电路配置为测量某些电信号，并且可以测量信号的幅值和相位。

[0069] 图 42 示出其中用电压控制电容器来实现可调谐阻抗网络的磁谐振器的电路图。可以由包括可编程或可控电压源和 / 或计算机处理器的电路来调整、调谐或控制此类实施方式。可以响应于由端口参数测量电路测量并由测量分析和控制算法和硬件处理的数据来调整电压控制电容器。电压控制电容器可以是开关电容器组。

[0070] 图 43 示出了端到端无线功率传输系统。在本示例中，源和设备都包含端口测量电路和处理器。标记为“耦合器 / 开关”的方框指示可以由定向耦合器或开关将端口测量电路连接到谐振器，使得能够与功率转移功能相结合地或分开地进行源和设备谐振器的测量、调整和控制。

[0071] 图 44 示出端到端无线功率传输系统。在本示例中，仅源包含端口测量电路和处理器。在这种情况下，所述设备谐振器工作特性可以是固定的，或者可以由模拟控制电路来调整，并且不需要由处理器生成的控制信号。

[0072] 图 45 示出端到端无线功率传输系统。在本示例中，源和设备这二者都包含端口测量电路，但是仅源包含处理器。通过可以用单独天线或通过源驱动信号的某种调制来实现的无线通信信道来传送来自设备的数据。

[0073] 图 46 示出端到端无线功率传输系统。在本示例中，仅源包含端口测量电路和处理器。通过可以用单独天线或通过源驱动信号的某种调制来实现的无线通信信道来传送来自设备的数据。

[0074] 图 47 示出可以使用利用处理器或计算机实现的算法来自动地调整其频率和阻抗的耦合磁谐振器。

[0075] 图 48 示出变抗器阵列。

[0076] 图 49 示出由源无线地供电或充电的设备（膝上型计算机），其中，源和设备谐振器在物理上与源和设备分离，但是被电连接到源和设备。

[0077] 图 50(a) 是被无线地供电或充电的膝上型计算机应用的图示，其中设备谐振器在膝上型计算机外壳内且不可见。

[0078] 图 50(b) 是被无线地供电和充电的膝上型计算机应用的图示，其中谐振器在膝上型计算机底座下面且通过线缆电连接到膝上型计算机功率输入端。

[0079] 图 50(c) 是被无线地供电或充电的膝上型计算机应用的图示，其中谐振器被附着于膝上型计算机底座。

[0080] 图 50(d) 是被无线地供电和充电的膝上型计算机应用的图示，其中谐振器被附着于膝上型计算机显示器。

[0081] 图 51 是具有无线功率转移的屋顶 PV 板的图示。

具体实施方式

[0082] 如上所述，本公开涉及具有可以从电源向功率消耗装置无线地转移功率的长寿命振荡谐振模的耦合电磁谐振器。然而，本技术不限于电磁谐振器，但是具有一般性，并且可以应用于多种谐振器和谐振对象。因此，我们首先描述一般技术，然后公开用于无线能量转移的电磁示例。

[0083] 谐振器

[0084] 可以将谐振器定义为能够以至少两种不同的形式储存能量的系统，并且其中储存的能量在两种形式之间振荡。谐振具有特定的振荡模，其具有谐振（模态）频率 f 和谐振（模态）场。可以将角谐振频率 ω 定义为 $\omega = 2\pi f$，可以将谐振波长 λ 定义为 $\lambda = c/f$，其中，c 是光速，并且可以将谐振周期 T 定义为 $T = 1/f = 2\pi/\omega$。在不存在损耗机制、耦合机制或外部能量供应或消耗机制的情况下，总谐振器储存能量 W 将保持固定，并且两种能量形式将振荡，其中，一个在另一个是最小值时将是最大值，反之亦然。

[0085] 在不存在无关材料或对象的情况下，图 1 所示的谐振器 102 中的能量可能衰减或被固有损耗所损耗。谐振器场则服从以下线性等式：

[0086] $$\frac{da(t)}{dt} = -i(\omega - i\Gamma)a(t),$$

[0087] 其中，变量 a(t) 是谐振场振幅，其被定义使得由 $|a(t)|^2$ 来给定包含在谐振器内的能量。Γ 是固有能量衰减或损耗率（例如由于吸收和辐射损耗）。

[0088] 表征能量衰减的谐振器的品质因数或 Q 因数或 Q 与这些能量损耗成反比。可以将其定义为 $Q = \omega * W/P$，其中，P 是在稳态下损耗的时间平均功率。也就是说，具有高 Q 的谐振器 102 具有相对低的固有损耗，并且能够相对长时间地储存能量。由于谐振器以其固有的衰减速率 2Γ 损耗能量，所以由 $Q = \omega/2\Gamma$ 来给定也称为其固有 Q 值的其 Q。质量因数还表示振荡周期 T 的数目，其使得谐振器中的能量以 e 的因数衰减。

[0089] 如上所述，我们将谐振器的品质因数或 Q 定义为仅仅是由于固有损耗机制引起的。诸如 Q_1 的下标指示 Q 所指代的谐振器（在这种情况下为谐振器 1）。图 2 示出根据此惯例标记的电磁谐振器 102。请注意，在本图中，在谐振器 1 的附近不存在无关对象或附加谐振器。

[0090] 根据诸如谐振器和对象或其它谐振器之间的距离、对象或其它谐振器的材料组成、第一谐振器的结构、第一谐振器中的功率等多种因数，在第一谐振器附近的无关对象和

/ 或附加谐振器可以对第一谐振器造成扰动或加载，从而对第一谐振器的 Q 造成扰动或加载。可以将在谐振器附近的非故意的外部能量损耗或到无关材料和对象的耦合机制称为对谐振器的 Q 造成“扰动”，并且可以由圆括号 () 内的下标来指示。可以将与经由到无线能量转移系统中的其它谐振器和发电机和负载的耦合所进行的能量转移相关联的预期外部能量损耗称为对谐振器的 Q 进行“加载”，并且可以由方括号 [] 内的下标来指示。

[0091] 可以将被连接或耦合到发电机 g 或负载 3021 的谐振器 102 的 Q 称为“加载品质因数”或“加载 Q”，并且如图 3 所示，可以用 $Q_{[g]}$ 或 $Q_{[1]}$ 来表示。通常，不止一个发电机或负载 302 可以连接到谐振器 102。然而，我们未单独地列出那些发电机或负载，而是使用“g”和“1”来指代由发电机和负载的组合施加的等效电路加载。在一般性说明中，我们可以使用下标“1”来指代被连接到谐振器的发电机或负载。

[0092] 在本文的某些讨论中，我们将由于被连接到谐振器的发电机或负载而引起的“加载品质因数”或“加载 Q”定义为 $\delta Q_{[1]}$，其中 $1/\delta Q_{[1]} \equiv 1/Q_{[1]}-1/Q$。请注意，发电机或负载的加载 Q、即 $\delta Q_{[1]}$ 越大，被加载 Q、即 $Q_{[1]}$ 越少地偏离谐振器的未加载 Q。

[0093] 在存在并非意在作为能量转移系统的一部分的无关对象 402p 的情况下，谐振器的 Q 可以称为“被扰动品质因数”或“被扰动 Q”，并且如图 4 所示可以用 $Q_{(p)}$ 来表示。通常，可以存在被表示为 p1、p2 等的许多无关对象或对谐振器 102 的 Q 造成扰动的一组无关对象 {p}。在这种情况下，可以将被扰动 Q 表示为 $Q_{(p1+p2+...)}$ 或 $Q_{(\{p\})}$。例如，$Q_{1(brick+wood)}$ 可以表示在存在砖或一块木材的情况下，用于无线功率交换的系统中的第一谐振器的被扰动品质因数，并且 $Q_{2(\{office\})}$ 可以表示在办公室环境中的用于无线功率交换的系统中的第二谐振器的被扰动品质因数。

[0094] 在本文的某些讨论中，我们将由于无关对象 p 而引起的“扰动品质因数”或“扰动 Q”定义为 $\delta Q_{(p)}$，其中 $1/\delta Q_{(p)} \equiv 1/Q_{(p)}-1/Q$。如上所述，扰动品质因数可以是由于多个无关对象 p1、p2 等或一组无关对象 {p} 引起的。对象的扰动 Q、即 $\delta Q_{(p)}$ 越大，被扰动 Q、即 $Q_{(p)}$ 越少地偏离谐振器的未扰动 Q。

[0095] 在本文的某些讨论中，我们还定义了 $\Theta_{(p)} \equiv Q_{(p)}/Q$ 并在存在无关对象的情况下，将其称为谐振器的“品质因数不灵敏度”或“Q 不灵敏度”。诸如 $\Theta_{1(p)}$ 的下标指示被扰动或未扰动品质因数所指的谐振器，即 $\Theta_{1(p)} \equiv Q_{1(p)}/Q_1$。

[0096] 请注意，还可以在必要时将品质因数 Q 表征为“未扰动”以将其与被扰动品质因数 $Q_{(p)}$ 区别开，并在必要时将其表征为“未加载”以将其与加载品质因数 $Q_{[1]}$ 区别开。同样地，还可以在必要时将被扰动品质因数 $Q_{(p)}$ 表征为“未加载”，以将其与被加载被扰动品质因数 $Q_{(p)[1]}$ 区别开。

[0097] 耦合谐振器

[0098] 通过其近场的任何部分被耦合，具有基本上相同的谐振频率的谐振器可以交互并交换能量。存在可以用来理解、设计、优化并表征此能量交换的多种物理图片和模型。描述两个耦合谐振器并对其之间的能量交换进行建模的一种方式是使用耦合模理论 (CMT)。

[0099] 在耦合模理论中，谐振器场服从以下线性方程组：

[0100]
$$\frac{da_m(t)}{dt}=-i(\omega_m-i\Gamma_m)a_m(t)+i\sum_{n\neq m}\kappa_{mn}a_n(t)$$

[0101] 其中，指数表示不同的谐振器，并且 κ_{mn} 是谐振器之间的耦合系数。对于相反系

统，耦合系数可以服从关系 $\kappa_{mn}=\kappa_{nm}$。请注意，出于本说明书的目的，将忽视远场辐射干扰效应，并因此将耦合系数视为实值。此外，由于在本说明中的系统性能的所有后续计算中，耦合系数几乎以其平方κ_{mn}^2出现，所以我们使用 κ_{mn} 来表示实耦合系数的绝对值。

[0102] 请注意，来自上述 CMT 的耦合系数 κ_{mn} 通过$k_{mn}=2\kappa_{mn}/\sqrt{\omega_m\omega_n}$与谐振器 m 和 n 之间的所谓耦合因数 κ_{mn} 相关。我们用$U_{mn}=\kappa_{mn}/\sqrt{\Gamma_m\Gamma_n}=k_{mn}\sqrt{Q_mQ_n}$将“强耦合系数”$U_{mn}$ 定义为谐振器 m 和 n 之间的耦合和损耗率的比率。

[0103] 以与由所连接的功率生成或消耗设备对谐振器进行加载的类似方式，可以由该谐振器 n 或附加谐振器对存在类似频率的谐振器 n 或附加谐振器的情况下的谐振器 m 的品质因数进行加载。可以由谐振器 n 对谐振器 m 进行加载且反之亦然这一事实，仅仅是以不同方式看待谐振器被耦合。

[0104] 可以将这些情况下的谐振器的被加载 Q 表示为 $Q_{m[n]}$ 和 $Q_{n[m]}$。对于多个谐振器或加载源或设备而言，可以通过将每个负载建模为电阻损耗并以适当的并行和 / 或串行组合将多个负载相加以确定系综的等效负载来确定谐振器的总加载。

[0105] 在本文的某些讨论中，我们将由于谐振器 n 而引起的谐振器 m 的“加载品质因数”或“加载 Q_m”定义为 $\delta Q_{m[n]}$，其中 $1/\delta Q_{m[n]}\equiv 1/Q_{m[n]}-1/Q_m$。请注意，谐振器 m 也来对谐振器 n 造成加载，并由 $1/\delta Q_{n[m]}\equiv 1/Q_{n[m]}-1/Q_n$ 来给定其“加载 Q_n”。

[0106] 当一个或多个谐振器被连接到发电机或负载时，将线性方程组修改为：

[0107] $$\frac{da_m(t)}{dt}=-i(\omega_m-i\Gamma_m)a_m(t)+i\sum_{n\neq m}\kappa_{mn}a_n(t)-\kappa_m a_m(t)+\sqrt{2\kappa_m}s_{+m}(t)$$

[0108] $$s_{-m}(t)=\sqrt{2\kappa_m}a_m(t)-s_{+m}(t)\quad,$$

[0109] 其中，$s_{-m}(t)$ 和 $s_{-m}(t)$ 分别是从发电机到谐振器 m 中并从谐振器 m 出来朝着发电机返回或进入负载的场的振幅，其被定义使得由 $|s_{+m}(t)|^2$ 和 $|s_{-m}(t)|^2$ 来给定其载送的功率。加载系数 κ_m 涉及在谐振器 m 和与之相连的发电机或负载之间交换能量的速率。

[0110] 请注意，来自上述 CMT 的加载系数 κ_m 通过 $\delta Q_{m[1]}=\omega_m/2\kappa_m$ 与早先定义的加载品质因数 $\delta Q_{m[1]}$ 相关。

[0111] 我们将“强加载因数”$U_{m[1]}$ 定义为谐振器 m 的加载和损耗率的比 $U_{m[1]}=\kappa_m/\Gamma_m=Q_m/\delta Q_{m[1]}$。

[0112] 图 1(a) 示出两个耦合谐振器 1000、即被配置为源谐振器的第一谐振器 102S 和被配置为设备谐振器的第二谐振器 102D 的示例。可以在谐振器之间的距离 D 上转移能量。可以由电源或发电机（未示出）来驱动源谐振器 102S。可以由功率消耗装置或负载（例如，负载电阻器，未示出）来从设备谐振器 102D 提取功。让我们将下标“s”用于表示源、“d”用于表示设备，“g”用于表示发电机，并且“1”用于表示负载，并且由于在本示例中仅存在两个谐振器且 $\kappa_{sd}=\kappa_{ds}$，让我们放弃 κ_{sd}、k_{sd} 和 U_{sd} 上的下标，并分别将其表示为 κ、k 和 U。

[0113] 发电机可以以对应于角驱动频率 ω 的恒定驱动频率 f 来恒定地驱动源谐振器，其中 $\omega=2\pi f$。

[0114] 在这种情况下，从发电机到负载（经由源和设备谐振器）的功率传输的效率 $\eta=|s_{-d}|^2/|s_{+s}|^2$ 在以下条件下被最大化：必须使源谐振频率、设备谐振频率和发电机驱动频率匹配，即

[0115] $\omega_s = \omega_d = \omega$.

[0116] 此外，必须使由于发电机而引起的源谐振器的加载Q $\delta Q_{s[g]}$与由于设备谐振器和负载而引起的源谐振器的被加载Q $Q_{s[dl]}$匹配（相等），并且相反地，必须使由于负载而引起的设备谐振器的加载Q $\delta Q_{d[l]}$与由于源谐振器和发电机而引起的设备谐振器的被加载Q $Q_{d[sg]}$匹配（相等），即

[0117] $\delta Q_{s[g]} = Q_{s[dl]}$且$\delta Q_{d[l]} = Q_{d[sg]}$。

[0118] 这些等式将通过发电机的源谐振器，以及通过负载的设备谐振器的最佳加载率确定为

[0119]

$$U_{d[l]} = \kappa_d/\Gamma_d = Q_d/\delta Q_{d[l]} = \sqrt{1+U^2} = \sqrt{1+\left(\kappa/\sqrt{\Gamma_s\Gamma_d}\right)^2} = Q_s/\delta Q_{s[g]} = \kappa_s/\Gamma_s = U_{s[g]}.$$

[0120] 请注意，以上频率匹配和Q匹配条件在电气工程中被一起称为“阻抗匹配”。

[0121] 在上述条件下，最大化效率是源与设备谐振器之间的仅强耦合因数的单调递增函数，$U = \kappa/\sqrt{\Gamma_s\Gamma_d} = k\sqrt{Q_sQ_d}$，并且由$\eta = U^2/\left(1+\sqrt{1+U^2}\right)^2$给出，如图5所示。请注意，耦合效率η在U大于0.2时大于1%，在U大于0.7时大于10%，在U大于1时大于17%，在U大于3时大于52%，在U大于9时大于80%，在U大于19时大于90%，并且在U大于45时大于95%。在某些应用中，可以将其中U＞1的操作区称为“强耦合”区。

[0122] 由于在某些情况下期望大的$U = \kappa/\sqrt{\Gamma_s\Gamma_d} = \left(2\kappa/\sqrt{\omega_s\omega_d}\right)\sqrt{Q_sQ_d}$，所以可以使用高Q的谐振器。每个谐振器的Q可以是高的。谐振器的Q的几何平均数$\sqrt{Q_sQ_d}$也可以是或替代地是高的。

[0123] 耦合因数k是0≤k≤1之间的数，并且其可以独立于（或几乎独立于）源和设备谐振器的谐振频率，确切地说，其可以主要由其相对几何结构和调解其耦合的场的物理衰变定律来确定。相比之下，耦合系数$\kappa = k\sqrt{\omega_s\omega_d}/2$可以是谐振频率的强函数。可以优选地将谐振器的谐振频率选择为实现高Q而不是实现低Γ，因为这两个目标在两个单独的谐振频率区处是可实现的。

[0124] 可以将高Q谐振器定义为具有Q＞100的谐振器。两个耦合谐振器可称为高Q谐振器的系统，当其中每个谐振器具有大于100的Q、$Q_s > 100$且$Q_d > 100$时。在其它实施方式中，当谐振器的Q的几何平均数大于100时，$\sqrt{Q_sQ_d} > 100$，可以将两个耦合谐振器称为高Q谐振器的系统。

[0125] 可以将谐振器命名或编号。可以将其称为源谐振器、设备谐振器、第一谐振器、第二谐振器、重发器谐振器等。应理解的是虽然在图1中示出两个谐振器，但在以下许多示例中，其它实施方式可以包括三个(3)或更多谐振器。例如，单个源谐振器102S可以将能量转移至多个设备谐振器102D或多个设备。可以将能量从第一设备转移至第二个，然后从第二设备转移至第三个，以此类推。多个源可以将能量转移至单个设备或连接到单个设备谐振器的多个设备或连接到多个设备谐振器的多个设备。谐振器102可以交替地或同时地作为源、设备，或者其可以用来将功率从一个位置上的源中继到另一位置上的设备。可以使用中间电磁谐振器102来扩展无线能量转移系统的距离范围。多个谐振器102可以被菊链式

连接在一起，在扩展的距离上与大范围的源和设备交换能量。高功率水平可以被在多个源 102S 之间拆分，转移至多个设备并在远距离位置处重新组合。

[0126] 可以单个源和单个设备谐振器的分析扩展至多个源谐振器和 / 或多个设备谐振器和 / 或多个中间谐振器。在此类分析中，结论可以是所述多个谐振器的至少某些或全部之间的大的强耦合因数 U_{mn} 对于无线能量转移中的高系统效率而言是优选的。再次地，实施方式可以使用具有高 Q 的源、设备和中间谐振器。每个谐振器的 Q 可以是高的。用于谐振器对 m 和 n（对于它们而言期望大的 U_{mn}）的 Q 的几何平均数 $\sqrt{Q_mQ_n}$ 也可以或替代地是高的。

[0127] 请注意，由于可以由两个谐振器之间的耦合机制和每个谐振器的损耗机制的相对幅值来确定两个谐振器的强耦合因数，所以可以在如上所述的谐振器附近存在无关对象的情况下扰动任何或所有这些机制的强度。

[0128] 延续来自前面部分的用于标记的惯例，我们将 k 描述为在不存在无关对象或材料的情况下的耦合因数。我们将存在无关对象的情况下的耦合因数 p 表示为 $k_{(p)}$，并且将其称为“被扰动耦合因数”或“被扰动 k”。请注意，必要时还可以将耦合因数 k 表征为“未扰动”，以与被扰动耦合因数 $k_{(p)}$ 区别开。

[0129] 我们定义 $\delta k_{(p)}\equiv k_{(p)}-k$，并且我们将其称为由于无关对象 p 而引起的“耦合因数的扰动”或“k 的扰动”。

[0130] 我们还定义 $\beta_{(p)}\equiv k_{(p)}/k$，并且我们将其称为“耦合因数不灵敏度”或“k 不灵敏度”。诸如 $\beta_{12(p)}$ 的下标指示被扰动和未扰动耦合因数所涉及的谐振器，即 $\beta_{12(p)}\equiv k_{12(p)}/k_{12}$。

[0131] 同样地，我们将 U 描述为不存在无关对象的情况下的强耦合因数。我们将存在无关对象的情况下的强耦合因数 p 表示为 $U_{(p)}$，$U_{(p)}=k_{(p)}\sqrt{Q_{1(p)}Q_{2(p)}}$，并且我们将其称为“被扰动强耦合因数”或“被扰动 U”。请注意，必要时还可以将强耦合因数 U 表征为“未扰动”，以与被扰动强耦合因数 $U_{(p)}$ 区别开。请注意，必要时还可以将强耦合因数 U 表征为“未扰动”，以与被扰动强耦合因数 $U_{(p)}$ 区别开。

[0132] 我们定义 $\delta U_{(p)}\equiv U_{(p)}-U$ 并将其称为由于无关对象 p 而引起的“强耦合因数的扰动”或“U 的扰动”。

[0133] 我们还定义 $\Xi(p)\equiv U(p)/U$ 并将其称为“强耦合因数不灵敏度”或“U 不灵敏度”。诸如 $\Xi_{12(p)}$ 的下标指示被扰动和未扰动耦合因数所涉及的谐振器，即 $\Xi_{12(p)}\equiv U_{12(p)}/U_{12}$。

[0134] 可以由给出未扰动系统的效率的相同公式给出被扰动系统中的能量交换的效率，其中，诸如强耦合因数、耦合因数和品质因数的所有参数由其被扰动等价参数所代替。例如，在包括一个源和一个设备谐振器的无线能量转移的系统中，可以将最佳效率计算为 $\eta_{(p)}=\left[U_{(p)}\Big/\left(1+\sqrt{1+U_{(p)}^{2}}\right)\right]^{2}$。因此，在被无关对象扰动的无线能量交换的系统中，对于无线能量转移中的高系统效率而言，可能期望至少某些或全部的多个谐振器之间的大的扰动强耦合因数 $U_{mn(p)}$。源、设备和 / 或中间谐振器可以具有高 $Q_{(p)}$。

[0135] 某些无关扰动有时对于被扰动强耦合因数而言是不利的（经由耦合因数或品质因数的大的扰动）。因此，可以使用技术来减少无关扰动对系统的影响并保持大的强耦合因数不灵敏度。

[0136] <u>能量交换效率</u>

[0137] 有用能量交换中的所谓“有用能量”是必须被转移至一个或多个设备以便对设备供电或充电的能量或功率。对应于有用能量交换的转移效率可以是系统或应用相关的。例如，转移几千瓦的功率的高功率交通工具充电应用可能需要具有至少 80％的效率以便供应有用的功率量，带来足够向交通工具电池重新充电的有用能量交换，而不显著地对转移系统的各种组件加热。在某些消费者的电子装置应用中，有用能量交换可以包括任何大于10％的能量转移效率，或者任何其它可接受的保持可再充电电池“填满(topped off)”并长时间运行的量。对于某些无线传感器应用而言，比1％小得多的转移效率可能适合于从位于距离传感器相当远的距离处的单个源向多个低功率传感器供电。对于不可能有线功率转移或有线功率转移不切实际的其它应用而言，大范围的转移效率对于有用能量交换而言可以是可接受的，并且可认为是向那些应用中的设备供应有用功率。通常，操作距离是根据本文所述的原理保持或能够保持有用功率交换的任何距离。

[0138] 用于供电或再充电应用中的无线能量转移的有用能量交换可以是高效、高度高效或足够高效的，只要浪费的能量水平、热耗散和相关场强度在可容许极限内即可。可容许极限可以取决于应用、环境和系统位置。用于供电或再充电应用中的无线能量转移的有用能量交换可以是高效、高度高效或足够高效的，只要对于合理的成本限制、重量限制、尺寸限制等而言可以获得期望的系统性能即可。可以相对于使用非高 Q 系统的传统感应技术所能实现的来确定高效的能量转移。然后，如果递送了比在传统感应方案中由类似尺寸的线圈结构在类似距离或对准偏移内可以递送的能量更多的能量，则可以将能量转移定义为高效、高度高效或足够高效的。

[0139] 请注意，即使某些频率和 Q 匹配条件可以使能量转移的系统效率最优化，也不需要完全满足这些条件以便具有用于有用能量交换的足够高效的能量转移。只要谐振频率的相对偏移($|\omega_m-\omega_n|/\sqrt{\omega_m\omega_n}$)小于 $1/Q_{m(p)}$，$1/Q_{n(p)}$ 和 $k_{mn(p)}$ 之中的近似最大值，就可以实现高效的能量交换。对于高效能量交换而言，Q 匹配条件可以不像频率匹配条件那么严格。由发电机和／或负载而引起的谐振器的强加载因数 $U_{m[1]}$ 可以偏离其最优值但仍具有足够高效的能量交换的程度取决于特定的系统，是否所有或某些发电机和／或负载都是 Q 不匹配的等。

[0140] 因此，谐振器的谐振频率可以不是完全匹配的，而是在以上容差内是匹配的。由于发电机和／或负载而引起的至少某些谐振器的强加载因数可以不是完全与其最优值匹配的。电压水平、电流水平、阻抗值、材料参数等可以不处于在本公开中描述的精确值，但是将在那些值的某些可接受容差内。除效率、Q、频率、强耦合因数等考虑因素之外，系统最优化可以包括成本、尺寸、重量、复杂性等考虑因素。某些系统性能参数、规格和设计可能远非最佳的，以便使其它系统性能参数、规格和设计最优化。

[0141] 在某些应用中，至少某些系统参数可以在时间上改变，例如因为诸如源或设备的组件可能移动或老化，或者因为负载可能是可变的，或者因为扰动或环境条件正在改变等。在这些情况下，为了实现可接受匹配条件，可能需要至少某些系统参数是可动态地调整或调谐的。所有系统参数可以是可动态地调整或调谐的以实现近似的最佳工作条件。然而，基于上述讨论，即使某些系统参数不是可变的，也可以实现足够高效的能量交换。在某些例子中，至少某些设备可以不被动态地调整。在某些例子中，至少某些源可以不被动态地调整。在某些例子中，至少某些中间谐振器可以不被动态地调整。在某些例子中，系统参数中没有

一个可以被动态地调整。

[0142]　<u>电磁谐振器</u>

[0143]　用来交换能量的谐振器可以是电磁谐振器。在此类谐振器中，由谐振器的吸收（或电阻）损耗和辐射损耗来给出固有能量衰变率 Γ_m。

[0144]　可以将谐振器构造为使得由电场存储的能量被主要约束在结构内且由磁场存储的能量主要在谐振器周围的区域中。然后，主要由谐振磁近场来调解能量交换。可以将这些类型的谐振器称为磁谐振器。

[0145]　可以将谐振器构造为使得由磁场存储的能量被主要约束在结构内且由电场存储的能量主要在谐振器周围的区域中。则主要由谐振电近场来调解能量交换。可以将这些类型的谐振器称为电谐振器。

[0146]　请注意，由谐振器存储的总电能和磁能必须是相等的，但是其局部化可以是相当不同的。在某些情况下，可以使用在距谐振器一定距离处指定的平均电场能与平均磁场能的比来表征或描述谐振器。

[0147]　电磁谐振器可以包括电感元件、分布电感或具有电感 L 的电感的组合、以及电容元件、分布电容、或具有电容 C 的电容的组合。在图 6a 中示出了电磁谐振器 102 的最小电路模型。谐振器可以包括电感元件 108 和电容元件 104。被提供诸如存储在电容器 104 中的电场能的初始能量，系统将随着电容器放电而振荡，将能量转移至存储在电感器 108 中的磁场能中，电感器 108 又将能量转移回至存储在电容器 104 中的电场能。

[0148]　可以将图 6(b)(c)(d) 所示的谐振器 102 称为磁谐振器。对于居住环境中的无线能量转移应用而言，磁谐振器可能是优选的，因为包括动物、植物和人的大多数日常材料是非磁性的（即 $\mu_r \approx 1$），因此其与磁场的交互是最小的，并且主要是由于由磁场的时变而感生的涡流（其为二阶效应）。由于安全原因，并且由于其降低了与可能改变系统性能的无关环境对象和材料的交互的可能，此特性是重要的。

[0149]　图 6d 示出与示例性磁谐振器 102B 相关联的某些电场和磁场线的简化图。磁谐振器 102B 可以包括充当电感元件 108 和电容元件 104（在导体环路的末端处）的导体环路。请注意，本图描绘了被存储在磁场中的谐振器周围区域中的大部分能量和被存储在电场中的谐振器中（电容器极板之间）的大部分能量。由于边缘场、自由电荷和时变磁场而引起的某些电场可以被存储在谐振器周围的区域中，但是可以将磁谐振器设计为使电场局限于尽可能地接近于谐振器或在谐振器本身内。

[0150]　电磁谐振器 102 的电感器 108 和电容器 104 可以是体电路元件，或者电感和电容可以是分布式的，并且可以由在结构中对导体进行形成、成形和定位的方式而产生。例如，如图 6(b)(c)(d) 所示，可以通过将导体成形为封闭表面面积来实现电感器 108。可以将此类谐振器 102 称为电容加载环路电感器。请注意，我们可以使用术语“环路”或“线圈”来泛指导电结构（导线、管、条带等），其以任何匝数封闭任何形状和尺寸的表面。在图 6b 中，封闭的表面区域是圆形的，但是该表面可以是多种其它形状和尺寸中的任何一个，并且可以被设计为实现某些系统性能规格。作为指示电感如何随着物理尺寸缩放的示例，用于被布置为形成圆形单匝环路的一段圆形导体的电感近似为

[0151]　$$L = \mu_0 x(\ln\frac{8x}{a} - 2),$$

[0152] 其中，μ_0 是自由空间的磁导率，x 是封闭的圆形表面区域的半径，并且 a 是用来形成电感器环路的导体的半径。可以分析性或数值性地计算环路的更精确电感值。

[0153] 可以分析性或数值性地计算用于被布置为形成其它封闭表面形状、面积、尺寸等并具有任何匝数的其它横截面导体的电感，或可以通过测量来确定该电感。可以使用电感器元件、分布式电感、网络、阵列、电感器和电感的串联和并联组合等来实现电感。电感可以是固定的或可变的，并且可以用来改变阻抗匹配以及谐振频率工作条件。

[0154] 存在多种方式来实现为达到谐振器结构的期望谐振频率所需的电容。可以如图 6b 所示地形成和利用电容器极板 110，或者如图 6c 所示，可以在多环路导体 114 的相邻绕组之间分布并实现电容。可以使用电容器元件、分布式电容、网络、阵列、电容的串联和并联组合等来实现电容。电容可以是固定的或可变的，并且可以用来改变阻抗匹配以及谐振频率工作条件。

[0155] 应理解的是电磁谐振器 102 中的电感和电容可以是集总的、分布式的或集总和分布式电感和电容的组合，并且可以通过本文所述的各种元件、技术和效果的组合来实现电磁谐振器。

[0156] 电磁谐振器 102 可以包括电感器、电感、电容器、电容以及诸如电阻器、二极管、开关、放大器、二极管、晶体管、变压器、导体、连接器等附加电路元件。

[0157] 电磁谐振器的谐振频率

[0158] 电磁谐振器 102 可以具有由其物理性质确定的特性、自然或谐振频率。此谐振频率是谐振器存储的能量在电场存储的能量 W_E($W_E = q^2/2C$，其中，q 是电容器 C 上的电荷) 与谐振器的磁场存储的能量 W_B($W_B = Li^2/2$，其中，i 是通过电感器 L 的电流) 之间振荡的频率。在系统中不存在任何损耗的情况下，将连续地在电容器 104 中的电场与电感器 108 中的磁场之间交换能量。交换此能量的频率可以称为谐振器的特性频率、自然频率或谐振频率，并且由 ω 给出，

[0159]
$$\omega = 2\pi f = \sqrt{\frac{1}{LC}}.$$
。

[0160] 可以通过调谐谐振器的电感 L 和 / 或电容 C 来改变谐振器的谐振频率。可以将谐振频率设计为在由 FCC 指定的所谓 ISM(工业、科学和医疗) 频率下操作。可以将谐振器频率选择为满足某些场极限规格、比吸收率 (SAR) 极限规格、电磁兼容性 (EMC) 规格、电磁干扰 (EMI) 规格、组件尺寸、成本或性能规格等。

[0161] 电磁谐振器的品质因数

[0162] 图 6 所示的谐振器 102 中的能量可以衰减，或者由于包括吸收性损耗 (也称为欧姆或电阻损耗) 和 / 或辐射性损耗在内的固有损耗而被损耗。表征能量衰减的谐振器的品质因数或 Q 与这些损耗成反比。吸收性损耗可以是由用来形成电感器的导体的有限电导率以及谐振器中的其它元件、组件、连接器等中的损耗引起的。可以将由低损耗材料形成的电感器称为“高 Q 电感元件”，并且可以将具有低损耗的元件、组件、连接器等称为具有“高电阻 Q”。通常，可以将谐振器的总吸收性损耗计算为构成谐振器的各种元件和组件的电阻性损耗的适当串联和 / 或并联组合。也就是说，在不存在任何显著的辐射性或组件 / 连接损耗的情况下，可以由 Q_{abs} 来给出谐振器的 Q，

[0163] $Q_{abs} = \frac{\omega L}{R_{abs}}$,

[0164] 其中，ω 是谐振频率，L 是谐振器的总电感，并且例如可以由 $R_{abs} = l\rho/A$ 给出用于用来形成电感器的导体的电阻（l 是导线的长度，ρ 是导体材料的电阻率，并且 A 是电流在导线中流动的横截面面积）。对于交流电而言，电流在其上流动的横截面面积可以由于趋肤效应而小于导体的物理横截面面积。因此，高 Q 磁谐振器可以由具有高导电性、相对大的表面面积和／或具有具体设计的轮廓（例如利兹线）的导体组成以使接近效应最小化并减小 AC 电阻。

[0165] 磁谐振器结构可以包括由高导电性导线、涂层线、利兹线、带、条或板、管、涂料、凝胶、迹线等组成的高 Q 电感元件。磁谐振器可以是自谐振的，或者其可以包括诸如电容器、电感器、开关、二极管、晶体管、变压器等的外部耦合元件。磁谐振器可以包括分布式和集总电容和电感。通常，将由谐振器的所有单独组件的 Q 来确定谐振器的 Q。

[0166] 由于 Q 与电感 L 成比例，所以可以将谐振器设计为在某些其它约束内增加 L。例如，增加 L 的一种方式是使用多于一匝的导体的来形成谐振器中的电感器。设计技术和权衡可以取决于应用，并且在高 Q 磁谐振器的设计中可以选择多种结构、导体、组件和谐振频率。

[0167] 在不存在显著吸收损耗的情况下，可以主要由辐射损耗来确定谐振器的 Q，并且由 $Q_{rad} = \omega L/R_{rad}$ 来给出，其中，R_{rad} 是谐振器的辐射损耗，并且可以取决于谐振器相对于操作的频率 ω 或波长 λ 的尺寸。对于上文讨论的磁谐振器而言，辐射损耗可以随着 $R_{rad} \sim (x/\lambda)^4$（磁偶极子辐射的特性）而缩放，其中，x 是谐振器的特性尺寸，诸如图 6b 所示的电感元件的半径，并且这里 $\lambda = c/f$，其中，c 是光速且 f 是如上文所定义的。磁谐振器的尺寸可以比操作的波长小得多，因此辐射损耗可以非常小。可以将此类结构称为子波长谐振器。辐射可以是用于非辐射无线能量转移系统的损耗机制，并且可以将设计选择为减小 R_{rad} 或使其最小化。请注意，对于非辐射无线能量转移方案而言，高 Q_{rad} 可能是期望的。

[0168] 还请注意，用于非辐射无线能量转移的谐振器的设计不同于出于通信或远场能量传输的目的设计的天线。具体地，可以使用电容加载导电环路作为谐振天线（例如，在蜂窝电话中），但是对于那些在远场区中操作的，其中辐射 Q 被故意地设计成小的以使得天线在辐射能量下是高效的。此类设计不适合于在本申请中公开的高效近场无线能量转移技术。

[0169] 包括辐射和吸收损耗两者的谐振器的品质因数是 $Q = \omega L(R_{abs}+R_{rad})$。请注意，对于特定谐振器而言可以存在最大 Q 值，并且可以出于对谐振器的尺寸、用来构造谐振器的材料和元件、工作频率、连接机构等的特殊考虑来设计谐振器，以便实现高 Q 谐振器。图 7 示出可以用于 MHz 频率处的无线功率传输的示例性磁谐振器（在这种情况下，为由具有 4cm 的外径（OD）的铜管制成的具有 60cm 的直径的线圈）的 Q 的绘图。吸收性 Q（虚线）702 随着频率增加，而辐射性 Q（点线）704 随着频率减小，因此，促使总的 Q 在特定频率处达到峰值 708。请注意，此示例性谐振器的 Q 在大频率范围内是大于 100 的。可以将磁谐振器设计为在一定的频率范围内具有高 Q，并且可以将系统工作频率设置为该范围内的任何频率。

[0170] 当在损耗率方面来描述谐振器时，如前所述，可以使用固有衰变率 2Γ，来定义 Q。固有衰变率是未耦合和未驱动谐振器损失能量的速率。对于上述磁谐振器而言，可以由 $\Gamma = (R_{abs}+R_{rad})/2L$ 来给出固有损耗，并且由 $Q = \omega/2\Gamma$ 来给出谐振器的品质因数 Q。

[0171] 请注意，可以将仅与特定损耗机制有关的品质因数表示为 $Q_{mechanism}$（如果未指定谐振器）或 $Q_{1,mechanism}$（如果指定了谐振器（例如谐振器 1））。例如，$Q_{1,rad}$ 是用于谐振器 1 的品质因数，与其辐射损耗有关。

[0172] 电磁谐振器近场

[0173] 在这里公开的近场无线能量转移系统中使用的高 Q 电磁谐振器可以是子波长对象。也就是说，谐振器的物理尺寸可以比对应于谐振频率的波长小得多。子波长磁谐振器可以将谐振器周围的区域中的大部分能量存储在其磁近场中，并且还可以将这些场描述为固定不动或不传播的，因为其不远离谐振器进行辐射。通常由波长来设置谐振器周围区域中的近场的范围，因此对于子波长谐振器而言，近场的范围可以延伸超过谐振器本身很多。可以将其中场特性从近场特性变成远场特性的限制表面称为“辐射焦散曲面 (radiation caustic)”。

[0174] 更加远离谐振器时，近场的强度减小。虽然谐振器近场的场强度随远离谐振器而衰减，但是场仍可以与进入谐振器的一般附近区域的对象相交互。场进行交互的程度取决于多种因素，其中的某些是可以控制和设计的，而某些不可以。当耦合谐振器之间的距离使得一个谐振器在另一个的辐射焦散表面内时，可以实现本文所述的无线能量转移方案。

[0175] 电磁谐振器的近场分布可以类似于一般与偶极子谐振器或振荡器相关联的那些场分布。可以将此类场分布描述为全向的，意味着场的幅值在离开对象的所有方向上是非零的。

[0176] 电磁谐振器的特性尺寸

[0177] 足够 Q 的空间分离和/或偏移的磁谐振器可以在比在现有技术中所见的大得多的距离上实现高效的无线能量转移，即使谐振器结构的尺寸和形状是不同的。还可以操作此类谐振器以实现在较短范围距离上的比前述技术可实现的更高效的能量转移。我们将此类谐振器描述为能够实现中程能量转移。

[0178] 可以将中程距离定义为比转移中涉及的谐振器中的最小的一个的特性尺寸大的距离，其中，测量从一个谐振器结构的中心到空间分离的第二谐振器结构的中心的距离。在此定义中，当由其电感元件限制的区域未相交时，二维谐振器是空间分离的，并且当其体积未相交时，三维谐振器是空间分离的。当由二维谐振器限制的区域在三维谐振器的体积之外时，前者与后者被空间分离。

[0179] 图 8 示出其特性尺寸被标记的某些示例性谐振器。应理解的是可以在导体的尺寸和由磁谐振器中的电感元件限制或封闭的面积及形成电谐振器的电容元件的导体的长度方面定义谐振器 102 的特性尺寸 802。然后，谐振器 102 的特性尺寸 $802x_{char}$ 可以等于能够分别拟合在磁或电谐振器的电感或电容元件周围的最小球体的半径，并且谐振器结构的中心是该球体的中心。谐振器 102 的特性厚度 $804t_{char}$ 可以是从其所在的平坦表面测量的磁或电容谐振器各自的电感或电容元件的最高点的最小可能高度。谐振器 102 的特性宽度 $808w_{char}$ 可以是最小可能圆圈的半径，磁或电谐振器各自的电感或电容元件可以在沿着直线行进的同时通过该最小可能圆圈。例如，圆柱形谐振器的特性宽度 808 可以是圆柱的半径。

[0180] 在本发明的无线能量转移技术中，可以在大的距离范围内高效地交换能量，但是本技术以在中程距离上并在具有不同物理尺寸、组件和取向的谐振器之间交换有用能量以

便对设备进行供电或再充电的能力而著名。请注意，虽然在这些情况下 k 可能是小的，但是可以通过使用高 Q 谐振器来实现高 U 而实现强耦合和高效的能量转移，$U = k\sqrt{Q_sQ_d}$。也就是说，可以使用 Q 的增加来至少部分地克服 k 的减小，以保持有用的能量转移效率。

[0181] 还请注意，虽然可以将单个谐振器的近场描述为全向的，但两个谐振器之间的能量交换的效率可以取决于谐振器的相对位置和取向。也就是说，可以针对谐振器的特定相对取向使能量交换的效率最大化。可以在 k 或 κ 的计算中捕捉转移效率对两个无补偿谐振器的相对位置和取向的灵敏度。虽然可以在相互之间偏移和／或旋转的谐振器之间实现耦合，但交换的效率可以取决于定位的细节和在操作期间实现的任何反馈、调谐和补偿技术。

[0182] 高 Q 磁谐振器

[0183] 在子波长电容加载环路磁谐振器的近场区中（$x \leqslant \lambda$），与由 N 匝导线（其半径大于趋肤深度）组成的圆形导电环路电感器相关联的电阻约为 $R_{abs} = \sqrt{\mu_o\rho\omega/2}\cdot Nx/a$ 和 $R_{rad} = \pi/6\cdot\eta_o N^2(\omega x/c)^4$，其中，ρ 是导体材料的电阻率且 $\eta_o \approx 120\pi\,\Omega$ 是自由空间的阻抗。用于此类 N 匝环路的电感 L 约为先前给出的单匝环路的电感的 N^2 倍。此类谐振器的品质因数 $Q = \omega L/(R_{abs}+R_{rad})$ 对于由系统参数（图 4）确定的特定频率而言是最高的。如前所述，在较低频率处，主要由吸收损耗来确定 Q，并且在较高频率处，主要由辐射损耗来确定 Q。

[0184] 请注意，上文给出的公式是近似的，并且意在说明 R_{abs}、R_{rad} 和 L 对结构的物理参数的函数依赖关系。对于谐振器结构的精确设计而言，将与严格准静态极限（例如沿着导体的非均匀电流／电荷分布）的偏差考虑在内的这些参数的更准确数值计算可能是有用的。

[0185] 请注意，可以通过使用低损耗导体来形成电感元件而使吸收性损耗最小化。例如，可以通过使用诸如电感管、条、带、机器加工对象、板等的大表面面积导体、通过使用诸如利兹线、编织线、任何横截面的导线和具有低接近损耗的其它导体的特别设计导体（在这种情况下上述频率缩放性质可也是不同的）以及通过使用诸如高纯度铜和银的低电阻率材料来使导体的损耗最小化。在较高工作频率处使用导电管作为导体的一个优点是其可以比类似直径的实心导体更便宜且更轻，并且可以具有类似的电阻，因为大部分电流由于趋肤效应而沿着导体的外表面行进。

[0186] 为了获得由铜线或铜管制成并适合于在微波区中操作的可实现的谐振器设计的粗略估计，可以计算用于由各种横截面的铜线（$\rho = 1.69\cdot 10^{-8}\,\Omega\mathrm{m}$）的一个圆形电感元件（N ＝ 1）组成的谐振器的最佳 Q 和谐振频率。然后，对于具有特性尺寸 x ＝ 1cm 和导体直径 a ＝ 1mm 的电感元件（例如适合于蜂窝电话）而言，当 f ＝ 380MHz 时，品质因数在 Q ＝ 1225 处达到峰值。对于 x ＝ 30cm 和 a ＝ 2mm，可能适合于膝上型计算机或家用机器人的电感元件尺寸而言，在 f ＝ 17MHz 处，Q ＝ 1103。对于例如可能位于天花板中的较大源电感元件而言，x ＝ 1m 且 a ＝ 4mm，在 f ＝ 5MHz 处，Q 可以高达 Q ＝ 1315。请注意，许多实际示例在 $\lambda/x \approx 50\text{-}80$ 处提供 $Q \approx 1000\text{-}1500$ 的预期品质因数。比上述的更多种类的线圈形状、尺寸、材料和工作频率的测量显示，使用一般可获得的材料，可以针对多种磁谐振器结构实现 Q ＞ 100。

[0187] 如上所述，可以由 κ 来给出用于具有特性尺寸 x_1 和 x_2 且在其中心之间分离距离 D 的两个谐振器之间的能量转移的速率。为了给出定义参数如何缩放的示例，在三 (3) 个距离处，考虑来自上文的蜂窝电话、膝上型计算机和天花板谐振器示例 ;D/x ＝ 10、8、6。在这

里考虑的示例中，源和设备谐振器是相同的尺寸 ($x_1 = x_2$) 和形状，并且如图 1(b) 所示地取向。在蜂窝电话的示例中，分别地，$\omega/2\kappa = 3033$、1553、655。在膝上型计算机示例中，分别地，$\omega/2\kappa = 7131$、3651、1540，并且对于天花板谐振器示例而言，$\omega/2\kappa = 6481$、3318、1400。相应的耦合损耗比在其中电感元件 Q 达到峰值的频率处达到峰值，并且，对于上述的三个电感元件尺寸和距离而言，$\kappa/\Gamma = 0.4$、0.79、1.97 和 0.15、0.3、0.72 和 0.2、0.4、0.94。使用不同尺寸的电感元件的示例是分开距离 $D = 3m$（例如房间高度）的 $x_1 = 1m$ 电感器（例如天花板中的源）和 $x_2 = 30cm$ 电感器（例如，地板上的家用机器人）。在本示例中，对于近似 14% 的效率而言，在 $f = 6.4MHz$ 的最佳工作频率处，强耦合质量因数 (figure of merit)，$U=\kappa/\sqrt{\Gamma_1\Gamma_2}=0.88$。这里，最佳系统工作频率在单独谐振器 Q 的峰值之间。

[0188] 可以形成在高 Q 磁谐振器中使用的电感元件。我们已经示范了基于被形成为封闭表面的电感元件的铜导体的多种高 Q 磁谐振器。可以使用以多种形状布置的多种导体（封闭任何尺寸或形状的区域）来形成电感元件，并且它们可以是单匝或多匝元件。在图 9 中示出示例性电感元件 900A-B 的图。可以将电感元件形成为封闭圆形、矩形、正方形、三角形、具有圆角的形状、遵循特定结构和设备的轮廓的形状、遵循、填充或利用结构或设备内的专用空间的形状等。可以针对尺寸、成本、重量、外观、性能等使设计最优化。

[0189] 这些导体可以被弯曲或形成为期望的尺寸、形状和匝数。然而，可能难以使用手动技术来准确地再现导体形状和尺寸。另外，可能难以在电感元件的相邻匝中的导体段之间保持均匀或期望的中心间距。例如，准确或均匀的间距在确定结构的自电容以及任何接近效应感生的 AC 电阻的增加方面可能是重要的。

[0190] 可以使用模具 (mold) 来复制用于高 Q 谐振器设计的电感器元件。另外，可以使用模具来准确地将导体成形为任何种类的形状而不在导体中产生扭结、扣子或其它潜在的有害效果。可以使用模具来形成电感器元件，并且然后可以从这些模板 (form) 中去除电感器元件。一旦被去除，就可以将这些电感元件构建成可以容纳高 Q 磁谐振器的外壳或设备。所形成的元件还可以或替代地保持在用来形成它们的模具中。

[0191] 可以使用标准 CNC（计算机数控）打槽 (routing) 或磨铣工具或用于成块地切割或形成凹槽的任何其它已知技术来形成模具。还可以或替代地使用机器加工技术、注塑成型技术、铸造技术、浇铸技术、真空技术、热成形技术、原位切割技术、压缩成形技术等来形成模具。

[0192] 可以从模具去除所形成的元件，或者其可以保持在模具中。可以用内部的电感元件来修改模具。可以对模具进行覆盖、机器加工、附着、涂漆等。可以将模具和导体组合集成到另一外壳、结构或设备中。切割到模具中的凹槽可以是任何尺寸，并且可以被设计以将导电管、导线、条、带、块等形成为期望的电感器形状和尺寸。

[0193] 在磁谐振器中使用的电感元件可以包含不止一个环路，并且可以向内或向外或向上或向下或沿着某些方向组合螺旋。通常，磁谐振器可以具有多种形状、尺寸和匝数，并且其可以由多种导电材料组成。

[0194] 磁谐振器可以是独立式的，或者其可以被封闭在外壳、容器、套筒或壳体中。磁谐振器可以包括用来制造电感元件的模板。这些不同的模板和外壳可以由几乎任何种类的材料组成。对于某些应用而言，诸如特氟隆、REXOLITE、苯乙烯等低损耗材料可能是优选的。这些外壳可以包含保持电感元件的固定装置。

[0195] 磁谐振器可以由铜线或铜管的自谐振线圈组成。由自谐振导线线圈组成的磁谐振器可以包括长度为 l 的导线和半径为 a 的横截面，被缠绕成半径 x、高度 h 和匝数 N 的螺旋形线圈，其可以例如被表征为$N=\sqrt{l^2-h^2}/2\pi x$。

[0196] 可以将磁谐振器结构配置为使得 x 约为 30cm，h 约为 20cm，a 约为 3mm 且 N 约为 5.25，并且在操作期间，被耦合到磁谐振器的电源可以以谐振频率 f 驱动谐振器，其中 f 约为 10.6MHz。在 x 约为 30cm，h 约为 20cm，a 约为 1cm 且 N 约为 4 的情况下，可以以频率 f 驱动谐振器，其中 f 约为 13.4MHz。在 x 约为 10cm，h 约为 3cm，a 约为 2cm 且 N 约为 6 的情况下，可以以频率 f 驱动谐振器，其中 f 约为 21.4MHz。

[0197] 可以使用印刷电路板迹线来设计高 Q 电感元件。与机械地形成的电感元件相比，印刷电路板迹线可以具有多种优点，包括可以使用已确定的印刷电路板制造技术将其准确地再现并容易地集成，可以使用自定义设计的导体迹线来减小其 AC 电阻，并且可以显著地降低对其进行大量生产的成本。

[0198] 可以在诸如 FR-4（环氧树脂 E- 型玻璃）、多功能环氧树脂、高性能环氧树脂、双马来酰亚胺三嗪树脂 / 环氧树脂、聚酰亚胺、氰酸盐酯、聚四氟乙烯 (Teflon)、FR-2、FR-3、CEM-1、CEM-2、Rogers、Resolute 等任何 PCB 材料上使用标准 PCB 技术来制造高 Q 电感元件。可以在具有较低损耗角正切的印刷电路板材料上形成导体迹线。

[0199] 导体迹线可以由铜、银、金、铝、镍等组成，并且其可以由油漆、油墨或其它固化材料组成。电路板可以是柔性的，并且其可以是可挠式电路。可以通过化学沉积、蚀刻、平版印刷、喷雾沉积、切割等来形成导电迹线。可以应用导电迹线来形成期望的图案，并且其可以使用晶体和结构生长技术来形成。

[0200] 可以将导电迹线的维度以及包含导电迹线的层的数目、那些迹线的位置、尺寸和形状以及用于将其互连的架构设计为实现某些系统规格或使其最优化，诸如谐振器 Q、$Q_{(p)}$、谐振器尺寸、谐振器材料和制造成本、U、$U_{(p)}$ 等。

[0201] 作为示例，如图 10(a) 所示，使用矩形铜迹线图案在四层印刷电路板上制造三匝高 Q 电感元件 1001A。用黑色示出铜迹线并用白色示出 PCB。本示例中的铜迹线的宽度和厚度分别约为 1cm(400mils) 和 43μm(1.7mils)。单层上的导电迹线的匝之间的边缘间距约为 0.75cm(300mils)，并且每个板层厚度约为 100μm(4mils)。在板的每个层上重复图 10(a) 所示的图案，并且并联地连接导体。3 环路结构的外部尺寸约为 30cm 乘 20cm。此 PCB 环路的测量电感为 5.3μH。使用此电感器元件和可调谐电容器的磁谐振器在 6.78MHz 的其设计谐振频率处具有 550 的品质因数 Q。可以通过改变磁谐振器中的电感和电容值来调谐谐振频率。

[0202] 作为另一示例，如图 10(b) 所示，使用矩形铜迹线图案在四层印刷电路板上制造两匝电感器 1001B。用黑色示出铜迹线并用白色示出 PCB。本示例中的铜迹线的宽度和高度分别约为 0.75cm(300mils) 和 43μm(1.7mils)。单层上的导电迹线的匝之间的边缘间距约为 0.635cm(250mils)，并且每个板层厚度约为 100μm(4mils)。在板的每个层上重复图 10(b) 所示的图案，并且并联地连接导体。双环结构的外部尺寸约为 7.62cm 乘 26.7cm。此 PCB 环路的测量电感为 1.3μH。以约 0.635cm(250mils) 的垂直间隔将两个板堆叠在一起并将两个板串联地连接一起产生具有约 3.4μH 的电感的 PCB 电感器。使用此堆叠电感器环路和可调谐电容器的磁谐振器在 6.78MHz 的其设计谐振频率处具有 390 的品质因数 Q。

可以通过改变磁谐振器中的电感和电容值来调谐谐振频率。

[0203] 可以使用任何尺寸、形状、厚度等的磁性材料和具有大范围的磁导率和损耗值的材料来形成电感元件。这些磁性材料可以是实心块，其可以封闭空心体积，其可以由许多被平铺或堆叠在一起的小片的磁性材料形成，并且可以将其与由高度导电的材料制成的导电片材或外壳集成。可以绕磁性材料缠绕导线以产生磁近场。可以将这些导线绕结构的一个或不止一个轴缠绕。可以将多个导线绕磁性材料缠绕且并联地或串联地或经由开关来组合以形成自定义近场图案。

[0204] 磁谐振器可以包括绕 3F3 铁氧体材料的 19.2cm×10cm×5mm 平铺的块缠绕的 15 匝利兹线。可以沿着任何方向或方向的组合将利兹线绕铁氧体材料缠绕以实现期望的谐振器性能。导线的匝数、匝之间的间距、导线的类型、磁性材料的尺寸和形状及磁性材料的类型全部是可以针对不同的应用方案改变或最优化的设计参数。

[0205] <u>使用磁性材料结构的高 Q 磁谐振器</u>

[0206] 可以使用组装的磁性材料来形成开放磁路（虽然是具有约为整个结构的尺寸的空隙的一个），以实现磁谐振器结构。在这些结构中，将高导电性材料绕由磁性材料制成的结构缠绕以形成磁谐振器的电感元件。可以将电容元件连接到高导电性材料，然后如上所述地确定谐振频率。这些磁谐振器在二维谐振器结构的平面中（而不是像在电容加载电感器环路谐振器的情况中一样与之垂直）具有其偶极矩。

[0207] 在图 11(a) 中示出单个平面谐振器结构的图。平面谐振器结构由磁性材料 1121 的芯 (core) 构成，诸如具有绕芯 1121 缠绕的导电材料 1122 的一个或多个环路的铁氧体。可以使用该结构作为转移功率的源谐振器和捕捉能量的设备谐振器。当被用作源时，可以将导体的末端耦合到电源。流过导体环路的交流电流激发交变磁场。当使用该结构来接收功率时，可以将导体的末端耦合到功率消耗装置或负载。改变磁场在绕芯磁性材料缠绕的导体的一个或多个环路中感生电动势。这些类型的结构的偶极矩在结构的平面中，并且例如沿着如图 11(a) 中的结构的 Y 轴定向。当基本上被放置在同一平面（即图 11 的 X、Y 平面）中时，两个此类结构具有强耦合。图 11(a) 的结构在当谐振器沿着其 Y 轴在同一平面中对准时具有最适宜的取向。

[0208] 对于某些应用而言，所述平面谐振器的几何结构和耦合取向可能是优选的。平面或平坦谐振器形状可能更容易被集成到相对平坦和平面的许多电子设备中。可以在不要求设备的几何结构变化的情况下将平面谐振器集成到设备的整个背面或侧面。由于许多设备的平坦形状，在被放置在平面上时设备的自然位置是平放于与其所被放置的表面平行的其最大维度上。被集成到平坦设备中的平面谐振器自然地平行于表面的平面，并且相对于被放置在平坦表面上的其它设备的谐振器或平面谐振器源而言处于适宜的耦合取向。

[0209] 如所述的，平面谐振器的几何结构可以允许更容易的集成到设备中。其小断面 (low profile) 可以允许将谐振器集成到设备的整个侧面中或作为其整个侧面的一部分。当设备的整个侧面被谐振器覆盖时，磁通可以在不被可以是设备或设备电路的一部分的有损耗材料所阻碍的情况下流过谐振器芯。

[0210] 平面谐振器结构的芯可以具有多种形状和厚度，并且其可以是平坦或平面的，使得最小尺寸不超过结构的最大尺寸的 30%。芯可以具有复杂的几何结构，并且可以具有缺口、凹口、脊等。可以使用几何增强来减少对取向的耦合依赖性，并且它们可以被用来促进

到设备、封装、包装、外壳、盖、表皮等的集成。在图 11(b) 中示出芯几何结构的两个示例性变化。例如，可以将平面芯 1131 成形为使得末端比结构的中间宽很多以产生用于导体绕组的缺口。芯材料可以具有变化的厚度，其中末端比中间粗且宽。芯材料 1132 可以具有各种深度、宽度和形状的任何数目的凹口或切口 1133 以容纳导体环路、外壳、封装等。

[0211]　还可以由被集成到其中的设备的尺寸和特性来规定芯的形状和尺寸。芯材料可以弯曲以遵循设备的轮廓，或者可以要求非对称的凹口或切口以允许有用于设备各部分的余隙。芯结构可以是单片整体的磁性材料，或者可以由被布置在一起的多个瓦(tile)、块或片组成以形成较大结构。结构的不同的层、瓦、块或片可以是类似的材料，或者可以是不同的材料。可以期望在结构的不同位置上使用具有不同磁导率的材料。具有不同磁导率的芯结构可以对引导磁通、改善耦合并影响系统的有效区域的形状或范围有用。

[0212]　可以将平面谐振器结构的导体绕该芯缠绕至少一次。在某些情况下，可以优选的是缠绕至少三圈。导体可以是任何良导体，包括导线、利兹线、导电管、片、条、凝胶、墨、迹线等。

[0213]　还可以通过使用阻挡、屏蔽或引导磁场的材料来进一步增强、改变或修改源的有效区域的尺寸、形状或维度。为了在源周围产生非对称有效区域，可以用磁屏蔽来覆盖源的侧面以减小沿特定方向的磁场的强度。该屏蔽可以是能够用来远离特定方向引导磁场的导体或导体与磁性材料的分层组合。由导体和磁性材料层组成的结构可以用来减少可能由于源的屏蔽而发生的能量损耗。

[0214]　可以将所述多个平面谐振器集成或组合成一个平面谐振器结构。可以将一个或多个导体绕芯结构缠绕，使得由两个导体形成的环路不是共轴的。此类结构的示例在图 12 中示出，其中，两个导体 1201、1202 被以正交角绕平面矩形芯 1203 缠绕。芯可以是矩形的，或者其可以是具有多个延伸部分或突出部分的各种几何结构。突出部分可以对导体的缠绕有用，减小芯的重量、尺寸或质量，或者可以用来增强谐振器的方向性或全向性。在图 13 中用内部结构 1310 示出具有四个突出部分的多缠绕平面谐振器，其中，四个导体 1301、1302、1303、1304 被绕芯缠绕。芯可以包含具有一个或多个导体环路的延伸部分 1305、1306、1307、1308。可以绕芯缠绕单个导体以形成不共轴的环路。例如，可以用一个连续的导体片或者使用其中使用单个导体来实现所有共轴环路的两个导体来形成图 13 的四个导体环路。

[0215]　可以通过用不相同参数来驱动某些导体环路而生成包括多个导体环路的谐振器周围的不均匀或不对称场分布。可以由具有不同频率、电压、功率水平、占空比等的电源来驱动具有多个导体环路的源谐振器的某些导体环路，其全部可以用来影响由每个导体产生的磁场的强度。

[0216]　可以将平面谐振器结构与电容加载电感器谐振器线圈组合以提供全面的全向有效区域，包括在源之上和之下，同时保持平坦谐振器结构。如图 13 所示，可以在与平面谐振器结构 1310 共同的平面中放置包括一个或多个导体环路的附加谐振器环路线圈 1309。外部谐振器线圈提供基本上在源之上和之下的有效区域。谐振器线圈可以布置有任何数目的平面谐振器结构和本文所述的布置。

[0217]　可以将平面谐振器结构封闭在可透磁封装中或集成到其它设备中。单个公共平面内的谐振器的平面轮廓允许到平坦设备中的封装和集成。在图 14 中示出举例说明谐振器

的应用的图示。包括一个或多个平面谐振器 1414 的平坦源 1411（每个具有一个或多个导体环路）可以向与其它平面谐振器 1415、1416 集成并被放置在源的有效区域 1417 内的设备 1412、1413 转移功率。设备可以包括多个平面谐振器，使得无论设备相对于源的取向如何，源的有效区域不变。除对于旋转不对准（rotational misalignment）的不变性之外，可以在基本上不影响有效区域的情况下将包括平面谐振器的平坦设备完全翻转，因为平面谐振器仍在源的平面中。

[0218] 在图 15 中示出举例说明使用平面谐振器结构的功率转移系统的可能使用的另一图示。放置在表面 1525 之上的平面源 1521 可以产生覆盖基本表面区域的有效区域，其产生“赋能（energized）表面”区域。诸如计算机 1524、移动电话 1522、游戏机以及被耦合到其各自平面设备谐振器的其它电子装置 1523 的设备可以在被放置在源的有效区域内（其可以在表面之上的任何地方）时从源接收能量。可以在没有严格的放置或对准约束的情况下将具有不同尺寸的多个设备放置在有效区域中并在从源充电或供电的同时正常地使用。可以将源放置在桌子、柜台、书桌、柜等的表面下面，允许其在对桌子、柜台、书桌、柜等的顶面赋能的同时被完全隐藏，在表面上产生比源大得多的有效区域。

[0219] 源可以包括显示器或其它视觉、听觉或振动指示器以示出充电设备的方向或什么设备正在被充电、充电的错误或问题、功率水平、充电时间等。

[0220] 可以将源谐振器和电路集成到任何数目的其它设备中。可以将源集成到诸如时钟、键盘、监视器、相框等设备中。例如，可以使用与平面谐振器和适当功率和控制电路集成的键盘作为用于被放置在键盘周围的设备（诸如计算机鼠标、网络照相机、移动电话等）的源，而不占用任何附加书桌空间。

[0221] 虽然已经在移动设备的背景下描述了平面谐振器结构，但是本领域的技术人员应清楚的是用于具有延伸超过其物理尺寸的有效区域的无线功率转移的平坦平面源具有许多其它消费者和工业应用。所述结构和构造可以对其中通常基本上在相同的平面和对准中对电子或电气设备和电源进行定位、设置或操纵的许多应用有用。某些可能的应用情形包括墙壁、地板、天花板或任何其它基本上平面的表面上的设备。

[0222] 可以将平坦源谐振器集成到相框中或悬挂在墙壁上，从而在墙壁的平面内提供有效区域，其中，可以在没有导线的情况下安装诸如数字相框、电视、灯等其它电子设备并进行供电。可以将平面谐振器集成到地板中，导致能够在上面放置设备以接收功率的赋能地板或地板上的有效区域。可以将音频扬声器、灯、加热器等放置在有效区域内并无线地接收功率。

[0223] 平面谐振器可以具有耦合到导体的附加组件。可以将诸如电容器、电感器、电阻器、二极管等的组件耦合到导体并可以用来调整或调谐用于谐振器的谐振频率和阻抗匹配。

[0224] 可以例如用 100 或更高的品质因数 Q 和甚至 1000 或更高的 Q 来产生上文所述和图 11（a）所示的类型的平面谐振器结构。如图 11（c）所示，可以在比谐振器的特性尺寸大的距离上无线地将能量从一个平面谐振器结构转移到另一个。

[0225] 除利用磁性材料来实现具有与磁谐振器中的电感元件类似的性质之外，还可以使用良导体材料和磁性材料的组合来实现此类电感结构。图 16（a）示出磁谐振器结构 1602，其可以包括由被至少一层磁性材料围绕并被磁性材料块 1604 链接的高导电率材料（其内

部可以与外面产生的 AC 电磁场屏蔽开来）制成的一个或多个外壳。

[0226]　结构可以包括在一侧被一层磁性材料覆盖的高导电率材料片。可以替代地将该分层结构共形地应用于电子设备，使得设备的各部分可以被高导电率和磁性材料层覆盖，同时可以使需要被容易地接近的其它部分（诸如按钮或屏幕）不被覆盖。该结构还可以或替代地仅包括磁性材料片的层或块体。因此，可以将磁谐振器结合到现有设备中，而不显著地与其现有功能相干扰且几乎不需要大范围的重新设计。此外，可以将良导体和 / 或磁性材料层制成足够薄的（一毫米左右或更小），使得其将几乎不增加成品设备的额外重量和体积。可以使用如所图 16 的结构中心上的正方形环路所示的应用于绕结构缠绕的一段导体的振荡电流来激励与此结构相关联的电磁场。

[0227]　<u>结构的品质因数</u>

[0228]　可以用约 1000 或更高的品质因数 Q 来产生上述类型的结构。如果跟与对象相关联的总磁能相比，磁性材料内的磁能的部分是小的，则即使磁性材料中的损耗是高的，此高 Q 也是可能的。对于由导电材料和磁性材料层组成的结构而言，可以通过如前所述的磁性材料的存在来减少导电材料中的损耗。在其中磁性材料层的厚度约为系统的最大尺寸的 1/100（例如，磁性材料约为 1mm 厚，而结构的面积约为 10cm×10cm）且相对磁导率约为 1000 的结构中，可以使得包含在磁性材料内的磁能的部分仅为与对象或谐振器相关联的总磁能的百分之几。为了看看那如何发生，请注意，用于包含在体积中的磁能的表达式是 $U_m = \int_V dr B(r)^2/(2\mu_r/\mu_0)$，只要 B（而不是 H）是跨越磁性材料 - 空气界面保持的主要场（在开放磁路中通常情况如此），与在空气中相比，可以显著地减小包含在高 μ_r 区中的磁能的分数。

[0229]　如果用 frac 来表示磁性材料中的磁能的分数，并且材料的损耗角正切是 $\tan\delta$，则谐振器的 Q 是 $Q = 1/(\mathrm{frac}\ x\ \tan\delta)$，假设磁性材料是唯一的损耗源。因此，甚至对于高达 0.1 的损耗角正切而言，对于这些类型的谐振器结构也可以实现约 1000 的 Q。

[0230]　如果用绕其缠绕的 N 匝导线来驱动该结构，则如果 N 是足够高的，则可以忽视激励电感器环路中的损耗。图 17 示出用于这些结构及损耗机制和电感随着绕由导电和磁性材料制成的结构缠绕的匝数 N 的缩放的等效电路 1700 示意图。如果能够忽略接近效应（通过使用适当的绕组，或被设计为使接近效应最小化的导线，诸如利兹线等），则由于环路导体中的导线而引起的电阻 1702 随着环路的长度线性地缩放，环路的长度又与匝数成比例。另一方面，这些特殊结构的等效电阻 1708 和等效电感 1704 两者与结构内部的磁场的平方成比例。由于此磁场与 N 成比例，所以等效电阻 1708 和等效电感 1704 两者与 N^2 成比例。因此，对于足够大的 N 而言，导线的电阻 1702 比磁性结构的等效电阻 1708 小得多，并且谐振器的 Q 渐进于 $Q_{max} = \omega L_\mu/R_\mu$。

[0231]　图 16(a) 示出由结构 1604 的中心处的缩窄段周围的正方形电流环路驱动的铜和磁性材料结构 1602 的图和由此结构产生的磁场流线 1608。此示例性结构包括被铜封闭并随后被具有性质 $\mu_r' = 1{,}400$、$\mu_r'' = 5$ 和 $\sigma = 0.5S/m$ 的 2mm 磁性材料层完全覆盖的两个 20cm×8cm×2cm 空心区域。这两个平行六面体间隔开 4cm，并被相同磁性材料的 2cm×4cm×2cm 块连接。激励环路被绕此块的中心缠绕。在 300kHz 的频率处，此结构具有计算的 890 的 Q。可以将导体和磁性材料结构成形为使某些系统参数最优化。例如，被激励环路封闭的结构的尺寸可以是小的，以减小激励环路的电阻，或者其可以是大的，以减轻与

大磁场相关联的磁性材料中的损耗。请注意，与由磁性材料组成的相同结构相关联的磁流线和 Q 将仅类似于这里所示的层导体和磁性材料设计。

[0232] 电磁谐振器与其它对象交互

[0233] 对于电磁谐振器而言，扰动固有 Q 值的非固有损耗机制可以包括附近无关对象的材料内部的吸收损耗和与来自附近无关材料的谐振场的散射有关的辐射损耗。可以使吸收损耗与在感兴趣的频率范围内具有非零但有限的电导率 σ（或等价地电介质电容率的非零且有限的虚部）的材料相关联，使得电磁场能够穿透它并在其中感生电流，这随后通过电阻损耗而耗散能量。如果对象至少部分地包括有损耗材料，则可以将其描述为有损耗的。

[0234] 考虑包括电导率 σ 和磁导率 μ 的均质各向同性材料的对象。由趋肤深度来给出此对象内部的电磁场的穿透深度$\delta=\sqrt{2/\omega\mu\sigma}$。可以根据 $P_d=\int_V d r\,\sigma|E|^2=\int_V d r|J|^2/\sigma$ 来确定在对象内部耗散的功率 P_d，其中，我们利用欧姆定律 $J=\sigma E$，并且其中，E 是电场且 J 是电流密度。

[0235] 如果在感兴趣的频率范围内，组成对象的材料的电导率 σ 足够低，使得可以认为材料的趋肤深度 δ 是长的（即，δ 比对象的特性尺寸长，或者 δ 比对象的有损耗部分的特性尺寸长），则电磁场 E 和 H（其中，H 是磁场）可以显著地穿透至对象中。然后，这些有限值的场可以产生随着 $P_d\sim\sigma V_{ol}\langle|E|^2\rangle$ 缩放的耗散功率，其中，在正在考虑的体积中，V_{ol} 是有损耗的对象的体积且 $\langle|E|^2\rangle$ 是电场平方的空间平均值。因此，在电导率下限处，耗散功率与电导率成比例地缩放并在不导电（纯电介质）材料的极限处归零。

[0236] 如果在感兴趣的频率范围内，组成对象的材料的电导率 σ 足够高，使得可以认为材料的趋肤深度是短的，则电磁场 E 和 H 可以仅向对象中穿透短的距离（即，其停留在材料的‘表皮’附近，其中，δ 小于对象的有损耗部分的特性厚度）。在这种情况下，在材料内部感生的电流可以与材料表面非常接近地集中，近似在趋肤深度内，并且可以用表面电流密度（主要由入射电磁场的形状确定，并且只要导体的厚度比趋肤深度大得多，则独立于第一阶的频率和电导率）$K(x,y)$（其中，x 和 y 是将表面参数化的坐标）与呈指数地向表面中衰减的函数：$\exp(-z/\delta)/\delta$（其中，z 表示局部地垂直于表面的坐标）的乘积来近似其幅值：$J(x,y,z)=K(x,y)\exp(-z/\delta)/\delta$。然后，可以用下式来估计耗散功率 P_d，

[0237]

$$P_d={}^{V}d\mathbf{r}\,|\mathbf{J}(\mathbf{r})|^2/\sigma\simeq\left({}^{S}\mathbf{dxdy}\,|\mathbf{K}(\mathbf{x},\mathbf{y})|^2\right)\left({}^{\infty}_{0}\mathbf{dz}\exp(2\mathbf{z}/\delta)/(\sigma\delta^2)\right)=\sqrt{\mu\omega/8\sigma}\left({}^{S}dxdy\,|K(x,y)|^2\right)$$

[0238] 因此，在高电导率极限处，耗散功率与电导率的平方根成反比地缩放，并在理想导电的材料的极限处归零。

[0239] 如果在感兴趣的频率范围内，组成对象的材料的电导率 σ 是有限的，则材料的趋肤深度 δ 可以向对象中穿透一定的距离，并且在对象内可能耗散一定量的功率，还取决于对象的尺寸和电磁场的强度。可以将此描述广义化为还描述包括具有不同性质和电导率的多个不同材料的对象的一般情况，诸如在对象内部具有电导率的任意不均质和各向异性分布的对象。

[0240] 请注意，上述损耗机制的幅值可以取决于无关对象相对于谐振器场的位置和取向以及无关对象的材料组成。例如，高电导率材料可以使谐振器的谐振频率移位，并将其与其它谐振对象解调谐（detune）。可以通过向谐振器施加修正其频率的反馈机制来固定此频

移，诸如通过谐振器的电感和 / 或电容变化。可以使用可变电容器和电感器来实现这些变化，在某些情况下通过谐振器中的组件的几何结构的变化来实现。还可以使用下述其它新型调谐机制来改变谐振器频率。

[0241] 在外部损耗高的情况下，被扰动 Q 可以是低的，并且可以采取步骤来限制此类无关对象和材料内的谐振器能量的吸收。由于耗散功率对电磁场强度的函数依赖关系，可以通过将系统设计为使得用在源谐振器处较短且在设备谐振器处较长的渐逝谐振场尾来实现期望耦合来使系统性能最优化，使得存在其它对象情况下的源的被扰动 Q 最优化（或者如果需要使设备的被扰动 Q 最优化，则反之亦然。）

[0242] 请注意，诸如人、动物、植物、建筑材料等许多常见的无关材料和对象可以具有低电导率，并因此可以几乎对这里公开的无线能量转移方案没有影响。与我们描述的磁谐振器设计有关的重要事实是可以将其电场主要约束在谐振器结构本身内，因此其应可以在在中程距离上提供无线功率交换的同时在用于人类安全的一般接受方针内操作。

[0243] 具有减少的交互的电磁谐振器

[0244] 用于近场无线功率传输的一个感兴趣的频率范围在 10kHz 与 100MHz 之间。在此频率范围内，例如多个类型的木材和塑料的多种普通非金属材料可以具有相对低的电导率，使得仅少量的功率可以在其内部被耗散。另外，具有低损耗角正切 $\tan\Delta$（其中 $\tan\Delta = \varepsilon'' / \varepsilon'$，并且 ε'' 和 ε' 分别是电容率的虚部和实部）的材料也可以使仅少量的功率在其内部被耗散。诸如铜、银、金等具有相对高的电导率的金属材料也可以几乎不具有在其中被耗散的功率，因为如前文所讨论的，电磁场不能显著地穿透这些材料。这些非常低和非常高电导率的材料和低损耗角正切材料和对象可以对磁谐振器的损耗具有可忽略的影响。

[0245] 然而，在感兴趣的频率范围内，存在诸如某些电子电路和某些低电导率金属的材料和对象，其可以具有中度（通常非均质且各向异性）的电导率和 / 或中至高的损耗角正切，并且其可以具有相对高的耗散损耗。在其内部可以耗散相对较大量的功率。这些材料和对象可以耗散足够的能量以将 $Q_{(p)}$ 减少显著的量，并且可以称为“有损耗对象”。

[0246] 减少有损耗材料对谐振器的 $Q_{(p)}$ 的影响的一种方式是使用高电导率材料来对谐振器场进行成形，使得其避开有损耗对象。可以通过将高电导率材料设想为使场偏转或重新成形的材料来理解使用高电导率材料来对电磁场进行调整以使得它们避开其附近的有损耗对象的过程。此构想在质量上是正确的，只要导体的厚度大于趋肤深度，因为用于良导体的表面处的电磁场的边界条件迫使电场接近于完全垂直于导体平面且磁场接近于完全与导体平面相切。因此，垂直磁场或相切电场将从导电表面“偏转开”。此外，甚至可以迫使相切磁场或垂直电场在一侧和 / 或特别是导电表面的位置在幅值上减小，其取决于场的源和导电表面的相对位置。

[0247] 作为示例，图 18 示出频率 f = 6.78MHz 的外部、最初均匀的磁场中的有损耗电介质材料 1804 之上和之下的两个高电导率表面 1802 的有限元法 (FEM) 模拟。系统是绕着 r = 0 轴方位角对称的。在此模拟中，有损耗电介质材料 1804 被夹在两个导体 1802（被示为近似 z = ±0.01m 处的白色线）之间。在电介质圆盘之上和之下不存在导电表面的情况下，磁场（用描绘的磁场线表示）仍将是基本上均匀的（场线笔直并与 z 轴平行），指示磁场将笔直地通过有损耗电介质材料。在这种情况下，功率将已在有损耗电介质圆盘中耗散。然而，在存在导电表面的情况下，此模拟显示磁场被重新成形。迫使磁场与导体的表面相

切，并因此在那些导电表面 1802 周围偏转，使可能在导电表面后面或之间的有损耗电介质材料 1804 中耗散的功率量最小化。如本文所使用的，电学对称的轴指的是任何轴，绕着该轴，固定或时变电场或磁场在如本文公开的能量交换期间基本上是对称的。

[0248] 即使使用在电介质圆盘之上或之下的仅一个导电表面，也观察到类似的效果。如果电介质圆盘是薄的，则电场在表面处基本上为零且连续且平滑地接近它这一事实意味着电场在接近于表面的任何地方（即在电介质圆盘内）是非常低的。用于使谐振器场远离有损耗对象偏转的单个表面实施方式对于其中不允许覆盖有损耗材料或表面的两侧的应用（例如 LCD 屏幕）而言可能是优选的。请注意，在存在有损耗材料的情况下，甚至与几个趋肤深度的导电材料的非常薄的表面可以足以 (6.78MHz 处的纯铜中的趋肤深度是～ 20μm，并且在 250kHz 处是～ 100μm) 显著地改善谐振器的 $Q_{(p)}$。

[0249] 有损耗无关材料和对象可以是其中将集成高 Q 谐振器的设备的部分。可以用许多技术来减少这些有损耗材料和对象中的能量耗散，包括：

[0250] 通过将有损耗材料和对象定位为远离谐振器，或者处于相对于谐振器的特殊位置和取向。

[0251] 通过使用高电导率材料或结构来在谐振器附近部分地或完全覆盖有损耗材料和对象。

[0252] 通过将高电导率材料的闭合表面（诸如片材或网）放置在有损耗对象周围以完全覆盖有损耗对象并将谐振器场成形为使得其避开有损耗对象。

[0253] 通过将高电导率材料的表面（诸如片材或网）放置在有损耗对象的仅一部分周围，诸如沿着对象或材料的顶部、底部、沿着侧边等。

[0254] 通过将高电导率材料的甚至单个表面（诸如片材或网）放置在有损耗对象之上或之下或一个侧面上以减小有损耗对象的位置处的场的强度。

[0255] 图 19 示出形成磁谐振器 102 的电容加载环路电感器和被放置在环路电感器内部的完全围绕有损耗对象 1804 的高电导率材料 1802 的盘状表面。请注意，某些有损耗对象可以是诸如电子电路的组件，其可能需要与外界环境交互、通信或相连并因此不能被完全地电磁隔离。用高电导率材料部分地覆盖有损耗材料仍可以在使得有损耗材料或对象适当地起作用的同时减少额外损耗。

[0256] 图 20 示出被用作谐振器 102 的电容加载环路电感器和被放置在电感器环路内部的围绕损耗对象 1804 的仅一部分的高电导率材料 1802 的表面。

[0257] 通过将高电导率材料的单个表面放置在有损耗对象或材料之上、之下或侧面上等，可以减少但不可以完全地消除额外损耗。在图 21 中示出示例，其中，电容加载环路电感器被用作谐振器 102，并且高电导率材料 1802 的表面被放置在有损耗对象 1804 下面的电感器环路内部以减小有损耗对象位置处的场的强度。由于成本、重量、组装复杂化、气流、视觉可达性、实体近用等的考虑，仅覆盖材料或对象的一侧可能是优选的。

[0258] 可以使用高电导率材料的单个表面来避开不能或不应都被从两侧覆盖的对象（例如 LCD 或等离子体屏幕）。可以使用光学透明的导体来避开此类有损耗对象。作为光学透明导体的替代或除光学透明导体之外，可以替代地将高电导率光学不透明材料放置在有损耗对象的仅一部分上。单面覆盖相对于多面覆盖实施方式的适合性和其中固有的设计权衡可以取决于无线能量转移情形的细节和有损耗材料和对象的性质。

[0259] 下面，我们描述使用高电导率表面来改善在无线能量转移系统中使用的集成磁谐振器的 Q 不灵敏度 $\Theta_{(p)}$ 的示例。图 22 示出无线投影仪 2200。无线投影仪可以包括如所示地布置的设备谐振器 102C、投影仪 2202、无线网络 / 视频适配器 2204 和功率转换电路 2208。设备谐振器 102C 可以包括被布置为封闭表面的三匝导体环路，和电容器网络 2210。可以将导体环路设置为使得设备谐振器 102C 在其工作谐振频率下具有高 Q(例如，＞ 100)。在完全无线的投影仪 2200 中的集成之前，此设备谐振器 102C 在 6.78MHz 的设计工作谐振频率下具有约 477 的 Q。在集成并将无线网络 / 视频适配器卡 2204 放置在谐振器环路电感器的中心上时，谐振器 $Q_{(integrated)}$ 被减小至约 347。从 Q 至 $Q_{(integrated)}$ 的减小中的至少某些归因于扰动无线网络 / 视频适配器卡中的损耗。如上所述，与磁谐振器 102C 相关联的电磁场可以在无线网络 / 视频适配器卡 2204 中和其上感生电流，该电流可以在组成该卡的有损耗材料中的电阻性损耗中被耗散。我们观察到根据放置在谐振器附近的对象和材料的组成、位置和取向，可以不同地影响谐振器的 $Q_{(integrated)}$。

[0260] 在完全无线的投影仪示例中，用薄铜袋（覆盖无线网络 / 视频适配器卡的顶部和底部的折叠铜片，但不是通信天线）来覆盖网络 / 视频适配器卡将磁谐振器的 $Q_{(integrated)}$ 改善为约 444 的 $Q_{(integrated+copper\ pocket)}$。换言之，使用铜袋来使谐振器场偏离有损耗材料，可以消除大部分由于由无关网络 / 视频适配器卡引起的扰动所造成的 $Q_{(integrated)}$ 的减小。

[0261] 在另一完全无线的投影仪示例中，用放置在卡下面的单个铜片来覆盖网络 / 视频适配器卡提供约等于 $Q_{(integrated+copper\ pocket)}$ 的 $Q_{(integrated+copper\ sheet)}$。在该示例中，可以用被用来使谐振器场远离有损耗适配器卡的单个高电导率片材来保持系统的高被扰动 Q。

[0262] 使有损耗材料和对象（其为包括高 Q 电磁谐振器的设备的一部分）定位或定向在由谐振器产生的场相对弱的位置可能是有利的，使得几乎没有功率在这些对象中被耗散，因此 Q 不灵敏度 $\Theta_{(p)}$ 可以是大的。如更早地示出的，不同电导率的材料可以不同地对电场对比磁场进行不同的响应。因此，根据无关对象的电导率，定位技术可以专用于一个或另一个场。

[0263] 图 23 示出在 10MHz 处谐振的沿着包含圆形环路电感器的直径的线的电场 2312 和磁场 2314 和沿着用于半径 30cm 的导线的电容加载圆形环路电感器的环路电感器的轴的电场 2318 和磁场 2320 的幅值。可以看到谐振近场的幅值在接近导线处达到其最大值并在远离环路 2312、2314 处衰减。在环路电感器 2318、2320 的平面中，场在环路的中心处达到局部最小值。因此，给定设备的有限尺寸，可能的是场在设备的极值处最弱，并且可能的是场幅值在设备内的某些地方具有局部最小值。此论证适用于任何其它类型的电磁谐振器 102 和任何类型的设备。在图 24a 和 24b 中示出示例，其中，电容加载电感器环路形成磁谐振器 102，并且无关有损耗对象 1804 位于电磁场具有最小幅值的位置处。

[0264] 在示范示例中，使用被布置为封闭正方形表面（具有圆角）的三匝导体环路和电容器网络来形成磁谐振器。谐振器的 Q 在 6.78MHz 的设计工作谐振频率下为约 619。此谐振器的扰动 Q 取决于扰动对象（在这种情况下为口袋式投影仪）相对于谐振器的放置。当扰动投影仪被放置在电感器环路内部和其中心处或电感器线匝之上时，$Q_{(projector)}$ 为约 96，比在扰动投影仪被放置在谐振器外面时低（在这种情况下，$Q_{(projector)}$ 为约 513）。这些测量结果支持显示电感器环路内部的场可以比在其外部的那些场大的分析，因此放置在此类环路电感器内部的有损耗对象与有损耗对象被放置在环路电感器外部时相比可以为系统提

供较低的扰动 Q。根据谐振器设计和有损耗对象的材料组成和取向，图 24b 所示的布置可以提供比图 24a 所示的布置高的 Q 不灵敏度 $\Theta_{(projector)}$。

[0265] 可以将高 Q 谐振器集成在设备内部。高电介质电容率、磁导率或电导率的无关材料和对象可以是高 Q 谐振器将被集成到其中的设备的一部分。对于在高 Q 电磁谐振器附近的这些无关材料和对象而言，根据其相对于谐振器的尺寸、位置和取向，谐振器场分布可变形并显著地偏离谐振器的原始未扰动场分布。谐振器的未扰动场的此类变形可以显著地将 Q 减小至较低的 $Q_{(p)}$，即使无关对象和材料是无损耗的。

[0266] 将高电导率对象（其为包括高 Q 电磁谐振器的设备的一部分）放置在使得这些对象的表面的取向尽可能地垂直于由未扰动谐振器产生的电场线并平行于由未扰动谐振器产生的磁场线的取向、因此以可能的最小量使谐振场分布变形可能是有利的。可以被设置为垂直于磁谐振器环路的平面的其它常见对象包括屏幕（LCD、等离子体等）、电池、外壳、连接器、辐射天线等。谐振器的 Q 不灵敏度 $\Theta_{(p)}$ 可以比在对象被设置在相对于谐振器场的不同取向的情况下大得多。

[0267] 不属于包括高 Q 谐振器的集成设备的一部分的有损耗无关材料和对象可位于或被带到谐振器附近，例如在设备的使用期间。在某些情况下，使用高电导率材料来调整谐振器场，使得其避开有损耗无关对象所位于或被引入的区域以减少这些材料和对象中的功率耗散并增加 Q 不灵敏度 $\Theta_{(p)}$ 可能是有利的。在图 25 中示出示例，其中，使用电容加载环路电感器和电容器作为谐振器 102，并且高电导率材料 1802 的表面被放置在电感器环路之上以减小谐振器之上的区域中的场的幅值，有损耗无关对象 1804 可以位于或被引入该区域。

[0268] 请注意，被带到谐振器的附近以使场重新成形的高电导率表面也可以引起 $Q_{(cond.\ surface)} < Q$。被扰动 Q 的减小可以是由于有损耗导体内部的能量耗散或与匹配导体表面处的场边界条件相关联的未扰动谐振器场的变形而引起的。因此，虽然可以使用高电导率表面来减少由于无关有损耗对象内部的耗散而引起的额外损耗，但在某些情况下，尤其是在其中这是通过显著地使电磁场重新成形来实现的某些情况下，使用此类高电导率表面使得场避开有损耗对象可以有效地得到 $Q_{(p+cond.\ surface)} < Q_{(p)}$ 而不是期望的结果 $Q_{(p+cond.\ surface)} > Q_{(p)}$。

[0269] 如上所述，在存在感生损耗的对象的情况下，如果与磁谐振器相关联的电磁场被重新成形以避开感生损耗的对象，则可以改善磁谐振器的被扰动品质因数。使未扰动谐振器场重新成形的另一个方式是使用高磁导率材料来完全地或部分地封闭或覆盖感生损耗的对象，从而减少磁场与感生损耗的对象的交互。

[0270] 先前已例如在 Electrodynamics 3rd Ed.，Jackson，pp.201 ～ 203 中描述了磁场屏蔽。其中，示出了将其内部与外部磁场屏蔽开来的可透磁材料的球形壳。例如，如果内径 a、外径 b 和相对磁导率 μ_r 的壳放置在最初均匀的磁场 H_0 中，则壳内部的场将具有恒定的幅值 $9\mu_r H_0/[(2\mu_r+1)(\mu_r+2)-2(a/b)^3(\mu_r-1)^2]$，如果 $\mu_r >> 1$，则其趋向于 $9H_0/2\mu_r(1-(a/b)^3)$。此结果显示入射磁场（但不一定是入射电场）在该壳内部可以被大大地衰减，即使壳是相当薄的，条件是磁导率足够高。在某些情况下，使用高磁导率材料来部分地或完全覆盖有损耗材料和对象、使得其被谐振器磁场避开并因此几乎没有功率在这些材料和对象中被耗散可能是有利的。在这种方法中，Q 不灵敏度 $\Theta_{(p)}$ 可以比在材料和对象未被覆盖的情况下大，可能大于 1。

[0271] 可期望保持电场和磁场两者远离感生损耗的对象。如上所述，以这种方式使场成

形的一种方法是使用高电导率表面来完全地或部分地封闭或覆盖感生损耗的对象。可以在高电导率表面上或周围放置一层可透磁材料，也称为磁性材料（具有显著磁导率的任何材料或元材料）。该附加磁性材料层可以呈现供已偏转磁场遵循的较低磁阻路径（与自由空间相比），并且可以部分地将其下面的电导体与入射磁通屏蔽开来。此设置可以减少由于高电导率表面中的感生电流而引起的损耗。在某些情况下，由磁性材料呈现的较低磁阻可以改善结构的被扰动 Q。

[0272] 图 26(a) 示出被暴露于沿着 z 轴的初始均匀、外加磁场（灰色磁通线）的薄导电 2604（铜）圆盘（直径为 20cm，高度为 2cm）的轴向对称 FEM 模拟。对称轴在 r ＝ 0 处。所示的磁流线源于 z ＝ －∞，其中，这些磁流线以 1cm 的间隔间隔开 r ＝ 3cm 至 r ＝ 10cm。轴刻度以米为单位。例如，设想着此导电圆柱将感生损耗的对象封闭在由图 19 所示的无线能量转移系统中的磁谐振器所限定的区域内。

[0273] 此高电导率外壳可以增加有损耗对象的扰动 Q，并因此增加系统的总被扰动 Q，但是被扰动 Q 由于导电表面中的感生损耗和电磁场分布的变化而可能仍小于未扰动 Q。可以通过沿着高电导率外壳的一个或多个外表面包括一层磁性材料来至少部分地恢复与高电导率外壳相关联的被扰动 Q 的减小。图 26b 示出来自图 26a 的薄导电 2604A（铜）圆盘（直径为 20cm，高度为 2cm）的轴向对称 FEM 模拟，但是具有被直接放置在高电导率外壳的外表面上的附加磁性材料层。请注意，磁性材料的存在可以为磁场提供较低磁阻路径，从而至少部分地屏蔽底层导体并减少由于导体中感生的涡流而引起的损耗。

[0274] 图 27 描绘了对图 26 所示的系统的修改（在轴对称视图中），其中，可能不是所有的有损耗材料 2708 都被高电导率表面 2706 覆盖。在某些情况下，诸如由于成本、重量、组装复杂度、气流、视觉可达性、实体近用等的考虑，仅覆盖材料或对象的一侧可能是有用的。在图 27 所示的示例性布置中，有损耗材料 2708 的仅一个表面被覆盖，并且谐振器电感器环路被放置在高电导率表面的相对侧。

[0275] 使用数学模型来模拟被放置在由磁谐振器限定的区域内的由铜制成且形状类似于 20cm 直径乘 2cm 高的圆柱形圆盘的高电导率外壳，所述磁谐振器的电感元件是具有环路半径 r ＝ 11cm 且导线半径 a ＝ 1mm 的单匝导线环路。用于施加的 6.78MHz 电磁场的模拟表明此高电导率外壳的扰动品质因数 $\delta Q_{(enclosure)}$ 是 1，870。当高电导率外壳被修改为包括具有实相对磁导率$\mu_r' = 40$和虚相对磁导率$\mu_r'' = 10^{-2}$的 0.25cm 厚的磁性材料层时，模拟显示扰动品质因数被增加至 $\delta Q_{(enclosure+magnetic\ material)}$ ＝ 5，060。

[0276] 如果高电导率外壳填充由谐振器的环路电感器 2704 限定的区域的较大部分，则由于添加磁性材料 2702 的薄层而引起的性能改善甚至可以更显著。在上述示例中，如果减小电感器环路 2704 的半径，使得其距离高电导率外壳的表面仅 3mm，则可以通过在外壳外部添加一层磁性材料 2702 的薄层来将扰动品质因数从 670（仅导电外壳）改善至 2，730（具有磁性材料薄层的导电外壳）。

[0277] 可以使用例如屏蔽或分布式电容器（例如，其效率高 (yield high)）将谐振器结构设计为具有高度受限的电场，即使当谐振器非常接近于通常将感生损耗的材料时。

[0278] <u>耦合电磁谐振器</u>

[0279] 可以由强耦合质量因数来确定两个谐振器之间的能量转移的效率，

$U=\kappa/\sqrt{\Gamma_s\Gamma_d}=\left(2\kappa/\sqrt{\omega_s\omega_d}\right)\sqrt{Q_sQ_d}$。在磁谐振器实施方式中，可以用$\kappa_{12}=\omega M/2\sqrt{L_1L_2}$使两个谐振器之间的耦合因数与谐振器中的每一个中的电感元件的电感 L_1 和 L_2 和其之间的互感 M 相关。请注意，此表达式假设存在通过电偶极子耦合的可忽略的耦合。对于其中由具有 N 匝、分开距离 D 并如图 1(b) 所示地取向的圆形导电环路来形成电感器环路的电容加载电感器环路谐振器而言，互感是 $M=\pi/4\cdot\mu_oN_1N_2(x_1x_2)^2/D^3$，其中，$x_1$、$N_1$ 和 x_2、N_2 分别是第一和第二谐振器的导体环路的特性尺寸和匝数。请注意，这是准静态结果，因此假设谐振器的尺寸比波长小得多，并且谐振器的距离比波长小得多，而且其距离是其尺寸的至少几倍。对于在准静态极限处和中程距离处操作的这些圆形谐振器而言，如上所述，$k=2\kappa/\sqrt{\omega_1\omega_2}\sim\left(\sqrt{x_1x_2}/D\right)^3$。当谐振器的品质因数大到足以补偿中程距离处的小 k 时，可以建立中程距离处的谐振器之间的强耦合（大 U）。

[0280] 对于电磁谐振器而言，如果两个谐振器包括导电部分，则耦合机制可以是由于从另一个谐振器产生的电场和磁场而在一个谐振器上感生电流。耦合因数可以与跨越第二谐振器的高 Q 电感元件的封闭区域的一个谐振器中的高 Q 电感元件产生的磁场的通量成比例。

[0281] 具有减少的交互的耦合电磁谐振器

[0282] 如前文所述，可以使用高电导率材料表面来使谐振器场成形，使得其避开谐振器附近的有损耗对象 p，从而减少总额外损耗并保持谐振器的高 Q 不灵敏度 $\Theta_{(p+cond..surface)}$。然而，此类表面可能在谐振器之间导致被扰动耦合因数 $k_{(p+cond.surface)}$，其小于被扰动耦合因数 $k_{(p)}$ 并取决于高电导率材料相对于谐振器的尺寸、位置和取向。例如，如果高电导率材料被放置在由无线能量转移系统中的磁谐振器中的至少一个的电感元件限定的平面中和区域内，则可以阻挡通过谐振器的区域的部分磁通（调节耦合），并且可以减小 k。

[0283] 再次考虑图 19 的示例。在不存在高电导率圆盘外壳的情况下，一定量的外部磁通量可以穿过环路的限定区域。在存在高电导率圆盘外壳的情况下，此磁通量中的某些可能被偏转或阻挡，并且可能不再穿过环路的该区域，因此导致较小的被扰动耦合因数 $k_{12(p+cond.surfaces)}$。然而，由于偏转磁场线可能紧密地遵循高电导率表面的边缘，所以通过限定圆盘的环路的通量的减少可能小于圆盘的面的面积与环路的面积的比。

[0284] 可以单独地或与磁性材料组合地使用高电导率材料结构来使被扰动品质因数、被扰动耦合因数或被扰动效率最优化。

[0285] 考虑图 21 的示例。使有损耗对象具有等于电容加载电感器环路谐振器的尺寸的尺寸，由此填充其区域 A 2102。可以将高电导率表面 1802 放置在有损耗对象 1804 下面。让此谐振器 1 在两个耦合谐振器 1 和 2 的系统中，并且让我们考虑随着导电表面的面积 A_S 2104 的增加 $U_{12(object+cond.surface)}$ 与 U_{12} 相比如何缩放。在有损耗对象 1804 下面没有导电表面 1802 的情况下，k 不灵敏度 $\beta_{12(object)}$ 可以约为 1，但是 Q 不灵敏度 $\Theta_{1(object)}$ 可以是小的，因此 U 不灵敏度 $\Xi_{12(object)}$ 可以是小的。

[0286] 在有损耗对象下面的高电导率表面覆盖电感器环路谐振器的整个面积时（$A_S=A$），$k_{12(object+cond.surface)}$ 可以接近于零，因为几乎不允许通量穿过电感器环路，因此 $U_{12(object+cond.surface)}$ 可以接近于零。对于高电导率表面的中间尺寸而言，非固有损耗的抑制和相关联的 Q 不灵敏度 $\Theta_{1(object+cond.surface)}$ 与 $\Theta_{1(object)}$ 相比可以是足够大的，而耦合的减少可

能不是显著的，并且相关联的 k 不灵敏度 $\beta_{12(object+cond.\ surface)}$ 可能不比 $\beta_{12(object)}$ 小得多，使得与 $U_{12(object)}$ 相比，可以增加总 $U_{12(object+cond.\ surface)}$。在无线能量转移系统中经由高电导率表面来避开无关有损耗对象的最佳程度可以取决于系统配置和应用的细节。

[0287]　我们描述了使用高电导率材料来完全地或部分地封闭或覆盖高 Q 谐振器附近的感生损耗的对象作为实现用于系统的高被扰动 Q 的一种潜在方法。然而，单独地使用良导体来覆盖对象可以如上所述地减少谐振器的耦合，从而降低无线功率转移的效率。随着导电表面的面积接近于磁谐振器的面积，例如，被扰动耦合因数 $k_{(p)}$ 可以接近于零，使得导电表面的使用与高效无线功率转移不相容。

[0288]　解决上述问题的一种方法是在高电导率材料周围放置一层磁性材料，因为附加的这层可透磁材料可以呈现供已偏转磁场遵循的较低磁阻路径（与自由空间相比），并且可以部分地将其下面的电导体与入射的磁通量屏蔽开来。在某些情况下，由磁性材料呈现的较低磁阻路径可以改善谐振器到其它谐振器的电磁耦合。可以通过沿着导电材料的一个或多个外表面包括一层磁性材料来至少部分地恢复与使用导电材料来调整谐振器场使得其避开高 Q 磁谐振器中和周围的有损耗对象相关联的被扰动耦合因数的减小。磁性材料可以相对于其初始未扰动值增加被扰动耦合因数。

[0289]　请注意，图 26 中的模拟结果显示与单独的导电结构相比，分层磁性材料和导电结构可以使入射磁场较小偏转。如果具有仅比图 26(a) 和图 26(b) 所示的圆盘略大的半径的磁谐振器圆环限定圆盘，则很明显，与图 26(a) 中所示出的情况相比，在图 26(b) 所示的情况下更多的磁通线将被捕获，因此对于图 26(b) 所示的情况而言，$k_{(disk)}$ 将较大。因此，在导电材料上包括一层磁性材料可以改善总体系统性能。可以执行系统分析以确定这些材料是否应被部分地、全部地或最低限度地集成到谐振器中。

[0290]　如上所述，图 27 描绘了可以适合于在不是所有有损耗材料 2708 都可以被导体和／或磁性材料结构覆盖时使用的分层导体 2706 和磁性材料 2702 结构。先前示出了对于具有由具有 11cm 的电感器环路半径和 a ＝ 1mm 的导线半径的谐振器限定的 20cm 直径和 2cm 高度的铜导体圆盘而言，针对铜圆柱计算的扰动 Q 是 1.870。如果谐振器和导电圆盘壳被放置在均匀磁场中（沿着电感器环路的对称轴对准），我们计算了铜导体具有 0.34 的相关耦合因数不灵敏度。为了比较，我们对相同的布置进行建模，但是包括具有实相对磁导率 $\mu_r' = 40$ 和虚相对磁导率 $\mu_r'' = 10^{-2}$ 的 0.25cm 厚的磁性材料层。使用上述相同的模型和参数，我们发现通过向导体的表面添加磁性材料，耦合因数不灵敏度被改善至 0.64。

[0291]　可以将磁性材料放置在被磁谐振器限定的区域内以增加无线能量转移系统中的耦合。考虑被放置在最初均匀磁场中的具有相对磁导率 μ_r 的磁性材料的实心球。在本示例中，由磁性材料提供的较低磁阻路径可以促使磁场集中在该球的体积中。我们发现通过添加磁性材料，通过由球的中纬线限定的区域的磁通量被增加到 $3\mu_r/(\mu_r+2)$ 倍。如果 $\mu_r >> 1$，则此增强因数可以接近于 3。

[0292]　还可以显示包括由磁谐振器中的电感元件限定的磁性球体的系统的偶极矩将使其磁偶极子增强到相同的倍数。因此，具有高磁导率的磁性球体实际上使谐振器的偶极子磁耦合增至三倍。如果我们使用具有 a 的内径和 b 的外径的磁性材料的球形壳体，可以保持耦合中大部分的该增加，即使此壳体在由高度导电材料制成的块体或外壳之上。在这种情况下，通过中维线的通量的增强是

[0293]
$$\frac{3\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)}{\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)+2\left(1+\frac{1}{2}\left(\frac{a}{b}\right)^3\right)}.$$
。

[0294] 对于 $\mu_r = 1,000$ 且 $(a/b) = 0.99$ 而言，此增强因数仍是 2.73，因此甚至用薄层磁性材料，也可以显著地改善该耦合。

[0295] 如上所述，可以使用包含磁性材料的结构来实现磁谐振器。图 16(a) 示出了由在其中心处的阻塞点周围的正方形电流环路驱动的铜和磁性材料结构 1600 的三维模型。图 16(b) 示出具有与图 16(a) 所示的一个相同的性质的两个相同结构 1600A-B 之间的由磁场流线指示的交互。由于对称，并且为了降低计算复杂性，仅对系统的一半进行建模。如果我们固定了两个对象之间的相对取向并改变其中心距离（所示的图像处于 50cm 的相对间隔），我们发现在 300kHz 处，耦合效率随着结构之间的间隔从 30cm 变成 60cm 而从 87％变成 55％。所示的每个示例性结构 1600A-B 包括被 4cm×4cm×2cm 磁性材料块接合并完全被 2mm 的相同磁性材料层（被假设为具有 $\mu_r = 1,400+j5$）覆盖的由铜制成的两个 20cm×8cm×2cm 平行六面体。忽略驱动环路中的电阻性损耗。每个结构具有计算的 815 的 Q。

[0296] 电磁谐振器和阻抗匹配

[0297] 用于低损耗电感元件的阻抗匹配架构

[0298] 出于本讨论的目的，电感元件可以是有或没有（有间隙或无间隙）由磁性材料制成的芯的任何导电材料的任何线圈或环路结构（‘环路’），其还可以被电感地或以任何其它无接触方式耦合到其它系统。元件是电感的，因为其阻抗（包括环路的阻抗和任何被潜在地耦合的系统的所谓‘反射’阻抗这二者）具有正电抗 X 和电阻 R。

[0299] 考虑电感元件可以被连接到的诸如驱动电路或被驱动负载或传输线的外部电路。外部电路（例如驱动电路）可以向电感元件递送功率，并且电感元件可以向外部电路（例如被驱动负载）递送功率。在期望频率处在电感元件与外部电路之间递送的功率的效率和量可以取决于相对于外部电路的性质而言的电感元件的阻抗。可以使用阻抗匹配网络和外部电路控制技术在期望频率 f 处调节外部电路与电感元件之间的功率递送。

[0300] 外部电路可以是被配置为形成 A、B、C、D、DE、E、F 类等的放大器的驱动电路，并且可以在驱动具有特定阻抗Z_o^*的谐振网络时以最大效率递送功率（即，以驱动电路内的最小损耗），其中，Z_0 可以是复数，并且＊表示复数共轭。外部电路可以是被配置为形成 A、B、C、D、DE、E、F 等类的整流器的被驱动负载，并且可以在其被具有特定阻抗Z_o^*的谐振网络驱动时以最大的效率接收功率（即以被驱动负载内的最小损耗），其中，Z_0 可以是复数。外部电路可以是具有特性阻抗 Z_0 的传输线，并且可以在被连接到阻抗Z_o^*时以最大效率（即以零反射）交换功率。我们将把外部电路的特性阻抗 Z_0 称为可以被与之相连以便以最大效率进行功率交换的阻抗的复数共轭。

[0301] 通常，电感元件的阻抗 R+jX 可以与Z_o^*相差悬殊。例如，如果电感元件具有低损耗（高 X/R），其电阻 R 可以比外部电路的特性阻抗 Z_0 的实部低得多。此外，电感元件本身可以不是谐振网络。连接到电感元件的阻抗匹配网络通常可以产生谐振网络，可以调节其阻抗。

[0302] 因此，可以将阻抗匹配网络设计为使在外部电路与电感元件之间递送的功率的效率最大化（包括任何耦合系统的反射阻抗）。可以通过在期望频率处使阻抗匹配网络和电感元件的组合的阻抗与外部电路（或传输线）的特性阻抗匹配来使递送功率的效率最大化。

[0303] 可以将阻抗匹配网络设计为在外部电路与电感元件之间递送指定功率量（包括任何耦合系统的反射阻抗）的。可以通过在期望的频率处调整阻抗匹配网络和电感元件的组合的阻抗与外部电路（或传输线）的阻抗的复数比来确定递送功率。

[0304] 被连接到电感元件的阻抗匹配网络可以产生磁谐振器。对于诸如使用强耦合的磁谐振器的无线功率传输的某些应用而言，谐振器可能期望高 Q。因此，可以将电感元件选择为具有低损耗的（高 X/R）。

[0305] 由于匹配电路通常可以在谐振器内部包括附加损耗源，所以还可以将匹配电路的组件选择为具有低损耗。此外，在高功率应用中和/或由于高谐振器 Q，大的电流在谐振器电路的一部分中行进，并且跨越谐振器内的某些电路元件存在大的电压。此类电流和电压可以超过用于特定电路元件的指定容差，并且对于特定组件而言可能太高而不能承受。在某些情况下，可能难以找到或实现具有足以实现用于某些应用的高 Q 和高功率谐振器的尺寸、成本和性能（损耗和电流/电压额定值）规格的组件（例如，诸如可调谐电容器）。我们公开了可以在降低对低损耗和/或高电流/电压额定值的组件要求的同时保持用于磁谐振器的高 Q 的匹配电路的设计、方法、实施方式和技术。

[0306] 可以设计使对匹配电路的某些元件的损耗和电流额定值要求最小化的匹配电路拓扑结构。可以将使低损耗电感元件与阻抗 Z_0 匹配的电路的拓扑结构选择为使得其组件中的一些在与外部电路串联的相关联的高 Q 谐振器外部。可以降低对用于这些组件的低串联损耗或高电流额定值的要求。减轻电路元件上的低串联损耗和/或高电流额定值要求在元件需要可变和/或具有大的电压额定值和/或低并联损耗时特别有用。

[0307] 可以设计使对匹配电路的某些元件的电压额定值要求最小化的匹配电路拓扑结构。可以选择将低损耗电感元件与阻抗 Z_0 匹配的电路的拓扑结构为使得其组件中的一些在与 Z_0 并联的相关联高 Q 谐振器外部。可以降低对用于这些组件的低并联损耗或高电压额定值的要求。减轻电路元件上的低并联损耗和/或高电压要求在元件需要可变和/或具有大的电流额定值和/或低串联损耗时特别有用。

[0308] 可以选择将低损耗电感元件与外部特性阻抗 Z_0 匹配的电路的拓扑结构为使得在将谐振器耦合到外部阻抗时保持相关联谐振模式的场图和因此其高 Q。否则，可能发生到期望谐振模式的低效耦合（可能由于到其它非期望谐振模式的耦合），导致谐振器 Q 的有效降低。

[0309] 对于其中低损耗电感元件或外部电路可能表现出变化的应用而言，可能需要动态地调整匹配电路以在期望频率 f 处使电感元件与外部电路阻抗 Z_0 匹配。由于通常可以存在两个调谐目标，其在期望频率 f 处匹配或控制阻抗水平 Z_0 的实部和虚部，所以在匹配电路中可以存在两个可变元素。对于电感元件而言，匹配电路可能需要包括至少一个可变电容元件。

[0310] 可以由使用两个可变电容器或两个可变电容器的网络的拓扑结构来匹配低损耗电感元件。例如，可变电容器可以是可调谐蝶式电容器，其具有例如用于连接到电源或负载

的地线或其它引线的中心端子和至少一个其它端子，跨越该端子，能够改变或调谐可调谐蝶式电容器的电容，或者可以是具有用户可配置、可变电容的任何其它电容器。

[0311] 可以由使用一个可变电容器或可变电容器的网络和一个可变电感器或可变电感器的网络的拓扑结构来匹配低损耗电感元件。

[0312] 可以通过使用一个可变电容器或可变电容器的网络和一个可变互感或可变互感的网络的拓扑结构来匹配低损耗电感元件，所述可变互感将电感元件变压器耦合到外部电路或其它系统。

[0313] 在某些情况下，可能难以找到或实现具有足以实现高 Q、高功率和潜在地高速度、可调谐谐振器设计的尺寸、成本和性能规格的可调谐集总元件。可以将使可变电感元件与外部电路匹配的电路的拓扑结构设计为使得通过改变施加于外部电路中的晶体管、二极管、开关等的驱动信号的频率、振幅、相位、波形、占空因数等来对外部电路赋予某些可变性。

[0314] 可以仅部分地补偿或根本不补偿在谐振频率处的电感元件的电阻 R 和电感 L 的变化。因此，可以由被设计到其它系统组件或规格中的容差来保持适当的系统性能。使用较少可调谐组件或不那么有能力的可调谐组件实现的部分调整可能是足够的。

[0315] 可以设计在使其可调谐元件上的电压 / 电流额定值要求最小化并实现更细（即更精确，具有较高的分辨率）的总体可调谐性的同时在高功率条件下实现阻抗匹配电路的期望可变性的匹配电路架构。使可变电感元件与阻抗 Z_0 匹配的电路的拓扑结构可以包括固定和可变元件的适当组合和放置，使得可以降低对可变组件的电压 / 电流要求，并且可以用更细的调谐分辨率来覆盖期望的调谐范围。可以降低不可变的组件上的电压 / 电流要求。

[0316] 可以使用公开的阻抗匹配架构和技术来实现以下各项 ：

[0317] 使从功率驱动发电机递送到源低损耗电感元件（和与之无线地耦合的任何其它系统）的功率最大化，或者使其之间的阻抗失配最小化。

[0318] 使从设备低损耗电感元件（和与之无线地耦合的任何其它系统）递送到功率驱动负载的功率最大化，或者使其之间的阻抗失配最小化。

[0319] 从功率驱动发电机向源低损耗电感元件（和与之无线地耦合的任何其它系统）递送受控量的功率，或者在其之间实现一定的阻抗关系。

[0320] 从设备低损耗电感元件（和被与之无线地耦合的任何其它系统）向功率驱动负载递送受控量的功率，或者在其之间实现一定的阻抗关系。

[0321] <u>用于模分布保持的拓扑结构（高 Q）</u>

[0322] 可以将谐振器结构设计为无线地（间接地）或用硬接线连接（直接地）连接到发电机或负载。

[0323] 考虑诸如由图 28(a) 中的框图所示的一般间接耦合匹配拓扑结构。在那里，标记为 (R，L) 并由用于电感器的电路符号表示的电感元件 2802 可以是在本公开中或在本文提供的参考文献中讨论的任何电感元件，并且其中，阻抗匹配电路 2402 包括部分 A 和 B 或由部分 A 和 B 组成。B 可以是经由无线连接（电感或电容耦合机制）将阻抗 2804、Z_0 连接到电路的其余部分 (A 和电感元件的组合 (A+(R，L))) 的匹配电路的一部分。

[0324] A 和电感元件 2802 的组合可以形成具有相关联的电流和电荷分布的谐振器 102，该谐振器 102 可以单独地支持高 Q 谐振器电磁模。外部电路 Z_0 和 B 与谐振器 A+(R，L) 之

间的有线连接的缺失可以保证高Q谐振器电磁模及其电流/电荷分布可以采取其固有（隔离）分布的形式，只要无线耦合的程度不太大即可。也就是说，使用间接耦合匹配拓扑结构，可以自动地保持电磁模、电流/电荷分布和由此的谐振器的高Q。

[0325] 在其中在外部电路与电感器环路之间使用电感耦合的情况下，可以将此匹配拓扑结构称为间接耦合或变压器耦合或电感耦合。在参考的Science文章中描述的中程距离内的无线能量转移的论证中，使用此类耦合类型来将电源耦合到源谐振器并将设备谐振器耦合到灯泡。

[0326] 接下来考虑其中电感元件可以包括电感元件和任何间接耦合的系统的示例。在这种情况下，如上文公开的，并且再次由于外部电路或耦合系统与谐振器之间的有线连接的缺失，耦合系统在对不太大程度的间接耦合的良好近似的情况下可以不影响谐振器的谐振器电磁模分布和电流/电荷分布。因此，如本文定义的，间接耦合匹配电路对于作为谐振器的一部分的任何一般电感元件而言以及无线地耦合到其它系统的电感元件而言可以同样起作用。遍及本公开，我们公开的匹配拓扑结构指的是用于此类一般电感元件的匹配拓扑结构，也就是说，其中，可以将任何附加系统间接地耦合到低损耗电感元件，并且应理解的是那些附加系统不会大大地影响谐振器的谐振器电磁模分布和电流/电荷分布。

[0327] 基于上述讨论，在任何数目的耦合源谐振器、设备谐振器和中间谐振器的无线功率传输系统中，谐振器之间的无线磁性（电感）耦合不影响每一个谐振器的电磁模分布和电流/电荷分布。因此，当这些谐振器具有高（未加载和未扰动）Q时，在存在无线耦合的情况下可以保持它们的（未加载和未扰动）Q。（请注意，在存在到另一谐振器的无线耦合的情况下可以减小谐振器的加载Q，但是我们可能对保持未加载Q感兴趣，其仅涉及损耗机制而不涉及耦合/加载机制）。

[0328] 考虑诸如图28(b)所示的匹配拓扑结构。图28(b)所示的电容器可以表示电容器电路或网络。可以使用所示的电容器来形成谐振器102并调整源和设备谐振器的频率和/或阻抗。可以使用标记为“端子连接”2808的端口将此谐振器102直接耦合到阻抗Z_0。图28(c)示出一般化直接耦合匹配拓扑结构，其中，阻抗匹配电路2602包括部分A、B和C或由其组成。这里，可以将A、B和C中的电路元件视为谐振器102的一部分以及阻抗匹配2402（和频率调谐）拓扑结构的一部分。B和C可以是经由每个单线连接是将阻抗$Z_0$2804（或网络端子）连接到电路的其余部分(A和电感元件)的匹配电路2402的部分。请注意，B和C可以是空的（短路）。如果我们将部分B和C（即那些单线连接）断开连接或开路，则A和电感元件(R，L)的组合可以形成谐振器。

[0329] 高Q谐振器电磁模可以使得沿着电感元件的电压分布的分布具有节点，即其中电压为零的位置。一个节点可以近似地在电感元件的长度的中心处，诸如用来形成电感元件的导体的中心（有或没有磁性材料），并且至少一个其它节点可以在A内。电压分布可以近似地相对于其电压节点沿着电感元件是反对称的。可以通过将匹配拓扑结构(A、B、C)和/或端子电压(V1、V2)设计为使得可以在电感元件上近似地保持此高Q谐振器电磁模分布来保持高Q。可以通过保持电感元件的电压节点（近似地在中心处）近似地在电感元件上保持此高Q谐振器电磁模分布。本文提供了实现这些设计目标的示例。

[0330] A、B和C可以是任意的（即不具有任何特殊对称），并且可以选择V1和V2为使得电感元件两端的电压是对称的（中心电感处的电压节点）。可以使用简单的匹配电路但潜

在地复杂的端子电压来实现这些结果，因为在两个端子上可能要求依赖拓扑结构的共模信号 (V1+V2)/2。

[0331] 考虑连接谐振器的所有电压节点的‘轴’，其中，再次地，一个节点近似地在电感元件的长度的中心处且其它的在 A 内。（请注意，‘轴’实际上是电路拓扑结构内的一组点（电压节点）且可能不一定对应于实际物理结构的直线轴。‘轴’在物理结构具有对称性的情况下可以与物理轴对准。）如果在两个点中的每一个与′轴′上的点（即谐振器的电压节点点）之间看到的阻抗是相同的，则谐振器的两个点相对于‘轴’是电气对称的。

[0332] B 和 C 可以是相同的 (C = B)，并且如图 28(d) 所示，可以将两个端子连接到相对于上文定义并由相反的电压 (V2 = -V1) 驱动的‘轴’而言电气对称的谐振器 (A+(R,L)) 的任何两个点。谐振器 102 的两个电气对称点可以是电感器环路上的两个电气对称点。谐振器的两个电气对称点可以是 A 内部的两个电气对称点。如果两个电气对称点（相等的部分 B 和 C 中的每一个被连接到该点）在 A 内部，则可能需要将 A 设计为使得这些电气对称点可作为电路内的连接点接入。可以将此拓扑结构称为‘平衡驱动’拓扑结构。这些平衡驱动示例可以具有优点，即例如由于外部电路或电力网处的扰动，可以自动地拒绝可以出现在地线上的任何共模信号（并且其可以不到达谐振器）。在某些平衡驱动示例中，此拓扑结构可能要求比其它拓扑结构更多的组件。

[0333] 在其它示例中，可以将 C 选择为短路，并且相应的端子被连接到地 (V = 0) 和谐振器的电气对称（零电压）‘轴’上的任何点，并且 B 被连接到不在电气对称‘轴’上的谐振器的任何其它点，如图 28(e) 所示。电气对称‘轴’上的接地点可以是电感元件上的电压节点，近似地在其导体长度的中心处。电气对称‘轴’上的接地点可以在电路 A 内部。在电气对称‘轴’上的接地点在 A 内部的情况下，可能需要将 A 设计为在电气对称‘轴’上包括可电气接入的一个此类点，即可以进行连接的地方。

[0334] 可以将此拓扑结构称为‘不平衡驱动’拓扑结构。可以近似地保持沿着电感元件的电磁模的近似反对称的电压分布，即使谐振器可能未被完全对称地驱动。原因是高 Q 和大的相关联 R 对比 Z_0 不匹配需要使得与可以在谐振器 (A+(R, L)) 内部流动的大得多的电流相比，小电流可以穿过 B 和地。在这种情况下，谐振器模上的扰动可以是弱的，并且电压节点的位置可以近似地保持在电感元件的中心位置处。这些不平衡驱动示例可以具有优点，即可以使用简单的匹配电路来将其实现，并且不存在对 V1 端子处的驱动电压的限制。在某些不平衡驱动示例中，可能要求附加设计以减少可能出现在接地端子处的共模信号。

[0335] 可以将如图 28(c) 所示的一般包括部分 A、B 和 C 或由其组成的直接耦合阻抗匹配电路设计为使得电路的导线和组件不扰动电感元件和 / 或谐振器的电磁模的电场和磁场分布并因此保持高谐振器 Q。可以使电路的导线和金属组件取向为垂直于电磁模的电场线。可以将电路的导线和组件放置在其中电磁模的电场和磁场弱的区域中。

[0336] 用于减轻元件上的低串联损耗和高电流额定值要求的拓扑结构

[0337] 如果可以认为被用来使低损耗电感元件的小电阻 R 与外部电路的较大特性阻抗 Z_0 匹配的匹配电路是无损耗的，则 $I_{Z_o}^2 Z_o = I_R^2 R \leftrightarrow I_{Z_o} / I_R = \sqrt{R / Z_o}$，并且流过端子的电流比流过电感元件的电流小得多。因此，与端子（诸如在直接耦合的 B、C（图 28(C)）中）直接串联地连接的元件可以不载送高电流。然后，即使匹配电路具有有损耗元件，出现在与端子串联的元件中的电阻性损耗可以不导致谐振器的高 Q 的显著减小。也就是说，那些串联元件

中的电阻性损耗可以不显著地降低从 Z_0 到电感元件或相反的功率传输的效率。因此，对于这些组件而言，可能不需要用对低串联损耗和／或高电流额定值的严格要求。通常，此类降低的要求可以得到可以被设计到高 Q 和／或高功率阻抗匹配和谐振器拓扑结构中的组件的更广泛选择。这些降低的要求在扩展可以在这些高 Q 和／或高功率阻抗匹配电路中使用的可变和／或高电压和／或低并联损耗组件的种类方面尤其有帮助。

[0338] 用于减轻元件上的低并联损耗和高电压额定值要求的拓扑结构

[0339] 如果如上所述用来使低损耗电感元件的小电阻 R 与外部电路的较大特性阻抗 Z_0 匹配的匹配电路是无损耗的，则使用前述分析，

[0340] $$|V_{Z_o}/V_{load}|=|I_{Z_o}Z_o/I_R(R+jX)|\approx\sqrt{R/Z_o}\cdot Z_o/X=\sqrt{Z_o/R}/(X/R),$$

[0341] 并且，对于低损耗（高 X/R）电感元件而言，端子两端的电压通常可以比电感元件两端的电压小得多。因此，被直接并联到端子的元件可能不需要耐受高电压。然后，即使匹配电路具有有损耗元件，出现在与端子并联的元件中的电阻性损耗可以不导致谐振器的高 Q 的显著减小。也就是说，那些并联元件中的电阻性损耗可以不显著地减小从 Z_0 到电感元件或相反的功率传输的效率。因此，对于这些组件而言，可能不需要用对低并联损耗和／或高电压额定值的严格要求。通常，此类降低的要求可以得到可以被设计到高 Q 和／或高功率阻抗匹配和谐振器拓扑结构中的组件的更广泛选择。这些降低的要求在扩展可以在这些高 Q 和／或高功率阻抗匹配和谐振器电路中使用的可变和／或高电流和／或低串联损耗组件的种类方面尤其有帮助。

[0342] 请注意，上述设计原理可以不同地减小各种元件上的电流和电压，因为其以不同的方式建议使用与 Z_0 串联的网络（诸如直接耦合的 B、C）或使用与 Z_0 并联的网络。用于给定应用的优选拓扑结构可以取决于低串联损耗／高电流额定值或低并联损耗／高电压额定值元件的可用性。

[0343] 用于实现细可调谐性并减轻可变元件上的高额定值要求的固定和可变元件的组合

[0344] 电路拓扑结构

[0345] 获得具有令人满意的低损耗和高电压或电流额定值的可变电路元件可能很难或花费太大。在本公开中，我们描述了可以结合固定和可变元件的组合、使得可以向电路中的固定元件（其更有可能具有适当的电压和电流额定值）分配大的电压或电流并减轻电路中的可变元件上的电压和电流额定值要求的阻抗匹配拓扑结构。

[0346] 可变电路元件可以具有比给定阻抗匹配应用所要求的那些更大的调谐范围，并且，在那些情况下，仅使用此类大范围元件可能难以获得细的调谐分辨率。在本公开中，我们描述了结合固定和可变元件两者、使得可以用相同的可变元件来实现更细的调谐分辨率的阻抗匹配拓扑结构。

[0347] 因此，使用固定和可变元件两者的组合的拓扑结构可以同时产生两种优点：电路中的灵敏调谐组件两端的减小的电压或从中通过的电流及更细的调谐分辨率。请注意，可以使最大可实现调谐范围与电路设计中的可调谐组件两端的电压或从中通过的电流的最大减小相关。

[0348] 元件拓扑结构

[0349] 可以由使用被串联地或并联地连接的固定和可变组件的组合来实现可变组件的额定值要求的降低和更细的调谐分辨率的拓扑结构来实现单个可变电路元件(与上文所讨论的元件的网络相反)。这可以通过以下事实用数学方式来证明:

[0350] 如果 $x_{|total|} = x_{|fixed|}+x_{|variable|}$,

[0351] 则 $\Delta x_{|total|}/x_{|total|} = \Delta x_{|variable|}/(x_{|fixed|}+x_{|variable|})$,

[0352] 并且 $X_{variable}/X_{total} = X_{variable}/(X_{fixed}+X_{variable})$,其中,$x_{|subscript|}$ 是任何元件值(例如电容、电感),X 是电压或电流,“+sign”表示元件的适当组合(串联加法或并联加法)。请注意,用于 $x_{|subscript|}$ 的下标格式被选择为容易将其与由圆形电感元件封闭的区域的半径区别开(例如,x、x_1 等)。

[0353] 此外,通过使用不同类型的可变元件,此原理可用来实现某种类型的可变电气元件(例如,电容或电感),如果不同类型的可变元件被适当地与其它固定元件组合。

[0354] 总之,可以应用拓扑结构最优化算法,其判定具有要求的可调谐范围的固定和可变元件的要求数目、位置、放置、类型和值作为最优化约束并判定可变元件上的电流和/或电压的最小化作为最优化目标。

[0355] 示例

[0356] 在以下示意图中,我们示出了用于低损耗电感元件的阻抗匹配和用于低损耗电感元件的谐振器设计的不同的特定拓扑结构实施方式。另外,我们对每个拓扑结构指出:使用上述原理中的哪些、给出可以用来实现匹配的可变元件的值的等式、可以匹配的复阻抗的范围(使用不等式和史密斯图描述)。对于这些示例而言,我们假设 Z_0 是实数,但是对具有非零虚部的特性阻抗的扩展是简单的,因为其仅仅暗示着匹配网络的组件的要求值的小调整。我们将使用量上的下标 n 暗示到 Z_0 的归一化(除以 Z_0)的惯例。

[0357] 图 29 示出变压器耦合阻抗匹配电路的两个示例,其中,两个可调谐元件是电容器和两个电感元件之间的互感。如果我们分别定义了用于图 29(a) 的 $X_2 = \omega L_2$ 和用于图 29(b) 的 $X_2 = \omega L_2-1/\omega C_2$,和 $X \equiv \omega L$,则可调谐元件的要求值是:

[0358] $$\omega C_1 = \frac{1}{X+RX_{2n}}$$

[0359] $$\omega M = \sqrt{Z_o R(1+X_{2n}^2)}\,.$$

[0360] 对于图 29(b) 的拓扑结构而言,特别简单的设计可以是选择 $X_2 = 0$。在这种情况下,这些拓扑结构可以匹配满足以下不等式的阻抗:

[0361] $R_n > 0, X_n > 0$,

[0362] 其由图 29(c) 的史密斯图上的粗线封闭的区域来示出。

[0363] 给定预先选择好的固定的 M,可以使用上述提到的具有可调谐 C_2 的匹配拓扑结构替代。

[0364] 图 30 示出直接耦合阻抗匹配电路的六个示例 (a) ~ (f)(其中,两个可调谐元件是电容器)和直接耦合阻抗匹配电路的六个示例 (h) ~ (m)(其中,两个可调谐元件是一个电容器和一个电感器)。对于图 30(a)、(b)、(c)、(h)、(i)、(j) 的拓扑结构,在两个端子处可能需要共模信号以保持在电感元件的中心处的谐振器的电压节点并因此保持高 Q。请注意,可以将这些示例描述为图 28(c) 所示的一般拓扑结构的实施方式。对于图 30(d)、(e)、 (f)、(k)、(l)、(m) 的对称拓扑结构而言，可能需要反对称地驱动两个端子（平衡驱动）以保持在电感元件的中心处的谐振器的电压节点并因此保持高 Q。请注意，可以将这些示例描述为图 28(d) 所示的一般拓扑结构的实施方式。将认识到的是本文所使用的电容器的网络通常可以指的是包括一个或多个电容器的任何电路拓扑结构，包括但不限于在此特别公开的使用电容器任何电路或任何其它等效或不同的电路结构（一个或多个），除非明确地规定了或从上下文可清楚另一意义。

[0365] 让我们分别定义用于图 30(a)、(d)、(h)、(k) 的 $Z = R+j\omega L$、用于图 30(b)、(e)、(i)、(l) 的 $Z = R+j\omega L+1/j\omega C_3$ 和用于图 30(c)、(f)、(j)、(m) 的 $Z = (R+j\omega L) \| (1/j\omega C_3)$，其中，符号“ ‖ 意指“... 的并联组合”，$R \equiv \mathrm{Re}\{Z\}$，$X \equiv \mathrm{Im}\{Z\}$。针对图 30(a) ～ (f)，可以由下式来给出可调谐元件的要求值：

[0366] $$\omega C_1 = \frac{X-\sqrt{X^2 R_n - R^2(1-R_n)}}{X^2+R^2},$$

[0367] $$\omega C_2 = \frac{R_n \omega C_1}{1-X\omega C_1 - R_n},$$

[0368] 并且这些拓扑结构可以匹配满足以下不等式的阻抗：

[0369] $$R_n \le 1,\ X_n \ge \sqrt{R_n(1-R_n)}$$

[0370] 其由图 30(g) 的史密斯图上的粗线封闭的区域来示出。

[0371] 针对图 30(h) ～ (m)，可以由下式来给出可调谐元件的要求值：

[0372] $$\omega C_1 = \frac{X+\sqrt{X^2 R_n - R^2(1-R_n)}}{X^2+R^2},$$

[0373] $$\omega L_2 = -\frac{1-X\omega C_1 - R_n}{R_n \omega C_1}.$$

[0374] 图 31 示出直接耦合阻抗匹配电路的三个示例 (a) ～ (c)（其中，两个可调谐元件是电容器）和直接耦合阻抗匹配电路的三个示例 (e) ～ (g)（其中，两个可调谐元件是一个电容器和一个电感器）。对于图 31(a)、(b)、(c)、(e)、(f)、(g) 的拓扑结构而言，接地端子被连接在两个相等值的电容器 $2C_1$ 之间（即在主谐振器的对称轴上），以保持在电感元件的中心处的谐振器的电压节点并因此保持高 Q。请注意，可以将这些示例描述为图 28(e) 所示的一般拓扑结构的实施方式。

[0375] 让我们分别定义用于图 31(a)、(e) 的 $Z = R+j\omega L$、用于图 31(b)、(f) 的 $Z = R+j\omega L+1/j\omega C_3$ 和用于图 31(c)、(g) 的 $Z = (R+j\omega L) \| (1/j\omega C_3)$，并且然后 $R \equiv \mathrm{Re}\{Z\}$，$X \equiv \mathrm{Im}\{Z\}$。然后，针对图 31(a) ～ (c)，可以由下式来给出可调谐元件的要求值：

[0376] $$\omega C_1 = \frac{X-\frac{1}{2}\sqrt{X^2 R_n - R^2(4-R_n)}}{X^2+R^2},$$

[0377] $$\omega C_2 = \frac{R_n \omega C_1}{1-X\omega C_1 - \frac{R_n}{2}},$$

[0378] 并且这些拓扑结构可以匹配满足以下不等式的阻抗：

[0379] $$R_n \le 1,\ \ X_n \ge \sqrt{\frac{R_n}{1-R_n}(2-R_n)}$$

[0380] 其由图 31(d) 的史密斯图上的粗线封闭的区域来示出。

[0381] 针对图 31(e) ～ (g)，可以由下式来给出可调谐元件的要求值：

[0382] $$\omega C_1 = \frac{X+\frac{1}{2}\sqrt{X^2R_n - R^2(4-R_n)}}{X^2+R^2},$$

[0383] $$\omega L_2 = -\frac{1-X\omega C_1-\frac{R_n}{2}}{R_n\omega C_1}.$$

[0384] 图 32 示出直接耦合阻抗匹配电路的三个示例 (a) ～ (c)（其中，两个可调谐元件是电容器）和直接耦合阻抗匹配电路的三个示例 (e) ～ (g)（其中，两个可调谐元件是一个电容器和一个电感器）。对于图 32(a)、(b)、(c)、(e)、(f)、(g) 的拓扑结构，可以在电感元件的中心处连接接地端子以保持在该点处的谐振器的电压节点并因此保持高 Q。请注意，可以将这些示例描述为图 28(e) 所示的一般拓扑结构的实施方式。

[0385] 让我们分别定义用于图 32(a) 的 $Z = R+j\omega L$、用于图 32(b) 的 $Z = R+j\omega L+1/j\omega C_3$ 和用于图 32(c) 的 $Z = (R+j\omega L) \parallel (1/j\omega C_3)$，然后 $R \equiv \mathrm{Re}\{Z\}$，$X \equiv \mathrm{Im}\{Z\}$。然后，针对图 32(a) ～ (c)，可以由下式来给出可调谐元件的要求值：

[0386] $$\omega C_1 = \frac{X-\sqrt{\frac{X^2R_n-2R^2(2-R_n)}{4-R_n}}}{X^2+R^2},$$

[0387] $$\omega C_2 = \frac{R_n\omega C_1}{1-X\omega C_1-\frac{R_n}{2}+\frac{R_nX\omega C_1}{2(1+k)}},$$

[0388] 其中，由 $M' = -kL'$ 来定义 k，其中，L' 是每一半电感器环路的电感，并且 M' 是两半之间的互感，这些拓扑结构可以匹配满足以下不等式的阻抗：

[0389] $$R_n \le 2,\ \ X_n \ge \sqrt{2R_n(2-R_n)}$$

[0390] 其由图 32(d) 的史密斯图上的粗线封闭的区域来示出。

[0391] 针对图 32(e) ～ (g)，可以由下式来给出可调谐元件的要求值：

[0392] $$\omega C_1 = \frac{X+\sqrt{\frac{X^2R_n-2R^2(2-R_n)}{4-R_n}}}{X^2+R^2},$$

[0393] 在图 30、31、32 的电路中，电容器 C_2 或电感器 L_2（或者两个电容器 $2C_2$ 或两个电感器 $L_2/2$）与端子串联连接，并且可以不需要具有非常低的串联损耗或耐受大的电流。

[0394] 图 33 示出直接耦合阻抗匹配电路的六个示例 (a) ～ (f)（其中，两个可调谐元件是电容器）和直接耦合阻抗匹配电路的六个示例 (h) ～ (m)（其中，两个可调谐元件是一个电容器和一个电感器）。对于图 33(a)、(b)、(c)、(h)、(i)、(j) 的拓扑结构，在两个端子处可能需要共模信号以保持在电感元件的中心处的谐振器的电压节点并且因此保持高 Q。请

注意，可以将这些示例描述为图 28(c) 所示的一般拓扑结构的实施方式，其中，B 和 C 是短路且 A 是不平衡的。对于图 33(d)、(e)、(f)、(k)、(l)、(m) 的对称拓扑结构而言，可能需要反对称地驱动两个端子（平衡驱动）以保持在电感元件的中心处的谐振器的电压节点并且因此保持高 Q。请注意，可以将这些示例描述为图 28(d) 所示的一般拓扑结构的实施方式，其中，B 和 C 是短路且 A 是平衡的。

[0395] 让我们分别定义用于图 33(a)、(d)、(h)、(k) 的 $Z=R+j\omega L$、用于图 33(b)、(e)、(i)、(l) 的 $Z=R+j\omega L+1/j\omega C_3$ 和用于图 33(c)、(f)、(j)、(m) 的 $Z=(R+j\omega L)\parallel(1/j\omega C_3)$，并且然后 $R\equiv\mathrm{Re}\{Z\}$，$X\equiv\mathrm{Im}\{Z\}$。然后，针对图 33(a) ～ (f)，可以由下式来给出可调谐元件的要求值：

[0396] $$\omega C_1=\frac{1}{X-Z_o\sqrt{R_n(1-R_n)}},$$

[0397] $$\omega C_2=\frac{1}{Z_o}\sqrt{\frac{1}{R_n}-1},$$

[0398] 并且这些拓扑结构可以匹配满足以下不等式的阻抗：

[0399] $$R_n\leq 1,\ \ X_n\geq\sqrt{R_n(1-R_n)}$$

[0400] 其用由图 33(g) 的史密斯图上的粗线封闭的区域来示出。

[0401] 针对图 35(h) ～ (m)，可以由下式来给出可调谐元件的要求值：

[0402] $$\omega C_1=\frac{1}{X+Z_o\sqrt{R_n(1-R_n)}},$$

[0403] $$\omega L_2=\frac{Z_o}{\sqrt{\frac{1}{R_n}-1}}.$$

[0404] 图 34 示出直接耦合阻抗匹配电路的三个示例 (a) ～ (c)（其中，两个可调谐元件是电容器）和直接耦合阻抗匹配电路的三个示例 (e) ～ (g)（其中，两个可调谐元件是一个电容器和一个电感器）。对于图 34(a)、(b)、(c)、(e)、(f)、(g) 的拓扑结构而言，接地端子被连接在两个相等值的电容器 $2C_2$ 之间（即在主谐振器的对称轴上），以保持在电感元件的中心处的谐振器的电压节点并因此保持高 Q。请注意，可以将这些示例描述为图 28(e) 所示的一般拓扑结构的实施方式。

[0405] 让我们分别定义用于图 34(a)、(e) 的 $Z=R+j\omega L$、用于图 34(b)、(f) 的 $Z=R+j\omega L+1/j\omega C_3$ 和用于图 34(c)、(g) 的 $Z=(R+j\omega L)\parallel(1/j\omega C_3)$，然后 $R\equiv\mathrm{Re}\{Z\}$，$X\equiv\mathrm{Im}\{Z\}$。针对图 34(a) ～ (c)，可以由下式来给出可调谐元件的要求值：

[0406] $$\omega C_1=\frac{1}{X-Z_o\sqrt{\frac{1-R_n}{R_n}(2-R_n)}},$$

[0407] $$\omega C_2=\frac{1}{2Z_o}\sqrt{\frac{1}{R_n}-1},$$

[0408] 并且这些拓扑结构可以匹配满足以下不等式的阻抗：

[0409] $$R_n \le 1,\ X_n \ge \sqrt{\frac{R_n}{1-R_n}(2-R_n)}$$

[0410] 其由图 34(d) 的史密斯图上的粗线封闭的区域来示出。

[0411] 针对图 34(e) ～ (g)，可以由下式来给出可调谐元件的要求值：

[0412] $$\omega C_1 = \frac{1}{X + Z_o\sqrt{\frac{1-R_n}{R_n}(2-R_n)}},$$

[0413] $$\omega L_2 = \frac{2Z_o}{\sqrt{\frac{1}{R_n}-1}}.$$

[0414] 图 35 示出直接耦合阻抗匹配电路的三个示例，其中，两个可调谐元件是电容器。对于图 35 的拓扑结构而言，可以在电感元件的中心处连接接地端子以保持在该点处的谐振器的电压节点并因此保持高 Q。请注意，可以将这些示例描述为图 28(e) 所示的一般拓扑结构的实施方式。

[0415] 让我们分别定义用于图 35(a) 的 $Z = R+j\omega L$、用于图 35(b) 的 $Z = R+j\omega L+1/j\omega C_3$ 和用于图 35(c) 的 $Z = (R+j\omega L) \parallel (1/j\omega C_3)$，然后 $R \equiv \mathrm{Re}\{Z\}$，$X \equiv \mathrm{Im}\{Z\}$。然后，可以由下式给出可调谐元件的要求值：

[0416] $$\omega C_1 = \frac{2}{X(1+a) - \sqrt{Z_o R(4-R_n)(1+a^2)}},$$

[0417] $$\omega C_2 = \frac{2}{X(1+a) + \sqrt{Z_o R(4-R_n)(1+a^2)}},$$

[0418] 其中，由 $M' = -kL'$ 来定义 $a = \frac{R}{2Z_o - R}\cdot\frac{k}{1+k}$ 和 k，其中，L’是每一半电感元件的电感，并且 M’是两半之间的互感。这些拓扑结构可以匹配满足以下不等式的阻抗：

[0419]

$$R_n \le 2 \,\&\, \frac{2}{\gamma} \le R_n \le 4,$$

[0420] $$X_n \ge \sqrt{\frac{R_n(4-R_n)(2-R_n)}{2-\gamma R_n}},$$

[0421] 其中

[0422] $$\gamma = \frac{1-6k+k^2}{1+2k+k^2} \le 1$$

[0423] 由针对 k ＝ 0 的图 35(d)、针对 k ＝ 0.05 的图 35(e) 和针对 k ＝ 1 的图 35(f) 所示的三个史密斯图上的粗线封闭的区域来示出。请注意，对于 0 ＜ k ＜ 1 而言，此拓扑结构能够匹配史密斯图的两个不连接区域。

[0424] 在图 33、34、35 的电路中，电容器 C_2 或电感器 L_2（或两个电容器 $2C_2$ 中的一个或两个电感器 $2L_2$ 中的一个）被与端子并联，因此可以不需要具有高电压额定值。就两个电容器 $2C_2$ 或两个电感器 $2L_2$ 来说，两者可能不需要具有高电压额定值，因为近似相同的电流从

其中流过，因此它们在其两端经历近似相同的电压。

[0425] 对于使用电容器 C_3 示出的图 30 ～ 35 的拓扑结构而言，电容器 C_3 的使用可以导致频率和阻抗的更细调谐。对于图 30 ～ 35 的拓扑结构而言，与电感元件串联的固定电容器 C_3 的使用可以保证大部分的高电感元件电压将在此固定电容器 C_3 两端，因此，潜在地减轻了对阻抗匹配电路的其它元件（其中的某些可以是可变的）的电压额定值要求。此类拓扑结构是否是优选的取决于适当固定的、可调谐组件的可用性、成本和规格。

[0426] 在所有上述示例中，可以使用成组电容器或被偏压并控制以作为系综来调谐其值的变抗器或二极管组或阵列来实现没有公共端子的一对等值可变电容器。可以使用可调谐蝶式电容器或任何其它可调谐或可变电容器或被偏压并控制以作为系综来调谐其电容值的变抗器或二极管组或阵列来实现具有一个公共端子的一对等值可变电容器。

[0427] 在选择阻抗匹配网络时可以考虑的另一标准是网络对与期望工作频率不同的频率的响应。在电感元件被耦合到的外部电路中生成的信号在期望频率下可以不是单调的(monochromatic)，而是具有期望频率的周期性的，例如开关放大器的驱动信号或开关整流器的反射信号。在某些此类情况下，可能期望抑制进入电感元件的高阶谐波的量（例如，以减少来自此元件的这些谐波的辐射）。然后，阻抗匹配网络的选择可以是充分地抑制进入电感元件的此类谐波的量的一个。

[0428] 阻抗匹配网络可以使得当外部周期信号是可以被视为起到电压源信号（诸如具有串联谐振负载的 D 类放大器的驱动信号）的作用的信号时，外部电路在比基波高的频率下经历的阻抗是高的，使得在较高的频率下几乎没有电流流过电感元件。在图 30 ～ 35 的拓扑结构之间，使用电感器 L_2 的那些则可以是优选的，因为此电感器在高频处呈现出高阻抗。

[0429] 阻抗匹配网络可以使得当外部周期信号是可以被视为起到电流源信号的作用的信号时，外部电路在比基波高的频率下经历的阻抗是低的，使得在较高频率处在电感元件两端几乎不感生电压。在图 30 ～ 35 的拓扑结构之间，使用电容器 C_2 的那些则是优选的，因为此电容器在高频处呈现出低阻抗。

[0430] 图 36 示出使用一个可变电容器和其余固定电容器的网络的可变电容的四个示例。使用这些网络拓扑结构，可以实现总电容器值的细可调谐性。此外，图 36(a)、(c)、(d) 的拓扑结构可以用来减小可变电容器两端的电压，因为大部分电压可以被分配在固定电容器两端。

[0431] 图 37 示出使用一个可变电感器和固定电容器的网络的可变电容的两个示例。特别地，这些网络可以提供用于可变电抗的实施方式，并且在感兴趣的频率下，可以使用可变电感器的值，使得每个网络符合于净负可变电抗，其可以有效地是可变电容。

[0432] 诸如可调谐电容器和可调谐电感器的可调谐元件可以是可机械地调谐的、可电气地调谐的、可热调谐的等。可调谐元件可以是可变电容器或电感器、变抗器、二极管、肖特基二极管、反向偏置 PN 二极管、变抗器阵列、二极管阵列、肖特基二极管阵列等。二极管可以是 Si 二极管、GaN 二极管、SiC 二极管等。GaN 和 SiC 二极管对于高功率应用而言可能特别具有吸引力。可调谐元件可以是电开关电容器组、电开关机械可调谐电容器组、电开关变抗器阵列组、电开关变压器耦合电感器组等。可调谐元件可以是上列元件的组合。

[0433] 如上所述，耦合的高 Q 磁谐振器之间的功率传输的效率可能受到谐振器在谐振频

率处多紧密地匹配和其阻抗多好地与系统中的电源和功率消耗装置匹配的影响。由于包括系统中的无关对象或其它谐振器的相对位置或那些相对位置的变化的多种外界因素可以改变高Q磁谐振器的谐振频率和/或输入阻抗，所以可能要求可调谐阻抗网络在各种环境或操作情形中保持足够的功率传输水平。

[0434] 所示的电容器的电容值可以被调整以调整磁谐振器的谐振频率和/或阻抗。可以电气地、机械地、热学地或用任何其它已知方法来调整电容器。可以手动地或自动地、诸如响应于反馈信号对其进行调整。可以对其进行调整以实现电源与功率消耗装置之间的某些功率传输效率或其它工作特性。

[0435] 可以调整谐振器中的电感器和电感元件的电感值以调整磁谐振器的频率和/或阻抗。可以使用包括诸如可调谐电容器、电感器和开关之类的可调谐组件的耦合电路来调整电感。可以使用变压器耦合调谐电路来调整电感。可以通过开启和关闭电感元件中的导体的不同区段和/或使用铁磁调谐和/或动铁调谐等来调整电感。

[0436] 可以将谐振器的谐振频率调整为或者可以允许其变成更低或更高的频率。可以将谐振器的输入阻抗调整为或者允许其变成更低或更高的阻抗值。可以将由源递送和/或由设备接收到的功率的量调整为或者允许其变成更低或更高的功率水平。可以将被递送到源和/或由设备从设备谐振器接收到的功率的量调整为或者可以允许其变成更低或更高的功率水平。可以根据系统中的功率消耗装置和根据谐振器附近的对象或材料来调整谐振器输入阻抗、谐振频率和功率水平。可以手动地或自动地调整谐振器输入阻抗、频率和功率水平，并且可以响应于反馈或控制信号或算法而进行调整。

[0437] 可以将电路元件直接地（亦即通过物理电接触）连接到谐振器，例如连接到形成电感元件和/或端子连接器的导体的末端。可以将电路元件焊接到、熔接到、卷曲至、粘合至、夹紧至或紧密地定位于导体，或者使用多种电气组件、连接器或连接技术来将其附着。可以直接地或间接地或电感地将电源和功率消耗装置连接到磁谐振器。可以通过端子连接向谐振器供应电信号或从谐振器获取电信号。

[0438] 本领域的技术人员应理解的是在本文所述的原理的实际实施方式中，可能存在实际组件（电容器、电感器、电阻器等）的值与经由上述等式计算的值、实际信号（电压、电流等）的值与通过对称性或反对称性提出的值以及点（诸如接近于电感元件中心的接地端子的连接点或‘轴’点等）的真实几何位置的值与由对称性或反对称性提出的位置的相关联容差或可接受变化。

[0439] 实施例

[0440] 系统方框图

[0441] 我们公开了用于可以在中程距离处无线地对设备供电或充电的无线功率传输系统的高Q谐振器的实施例。高Q谐振器无线功率传输系统还可以用在尺寸、形状、组成、布置等方面与系统中的任何源谐振器不同的磁谐振器无线地对设备供电或充电。

[0442] 图1(a)(b)示出了两个示例性双谐振器系统的高级图示。这些示例性系统中的每个都具有单个源谐振器102S或104S和单个设备谐振器102D或104D。图38示出具有被突出显示的一些特征的系统的高级方框图。被无线地供电或充电的设备2310可以包括设备谐振器102D、设备功率和控制电路2304等，以及DC或AC或AC和DC两者的功率被转移到的一个或多个设备2308，或者由其组成。用于系统的能量或功率源可以包括源功率和控制

电路 2302、源谐振器 102S 等。从设备谐振器 102D 及功率和控制电路 2304 接收功率的一个或多个设备 2308 可以是如前所述的任何种类的设备 2308。设备谐振器 102D 和电路 2304 在处于源谐振器 102S 附近时向一个或多个设备 2308 递送功率，其可以用来对所述一个或多个设备的电池重新充电、直接地对所述一个或多个设备供电或两者同时进行。

[0443] 源和设备谐振器可以分离很多米，或者其可以相互非常接近，或者其可以在中间分离任何距离。源和设备谐振器可以横向地或轴向地相互偏离。源和设备谐振器可以直接地对准（无横向偏移），或者其可以偏移几米，或者是其之间的任何情况。可以使源和设备谐振器取向为使得由其电感元件封闭的表面面积近似地相互平行。可以使源和设备谐振器取向为使得由其电感元件封闭的表面面积近似地相互垂直，或者可以使其针对其之间的任何相对角 (0 至 360 度）取向。

[0444] 源和设备谐振器可以是独立式的，或者可以将其封闭在外壳、容器、套筒或壳体中。这些不同的外壳可以由几乎任何种类的材料组成。对于某些应用而言，诸如特氟隆、REXOLITE、苯乙烯等低损耗角正切材料可能是优选的。可以将源和设备谐振器集成在电源和功率消耗装置中。例如，可以将源和设备谐振器集成到键盘、计算机鼠标、显示器、蜂窝电话等中，使得其在这些设备外面是不可见的。源和设备谐振器可以与系统中的电源和功率消耗装置分开，并且可以通过标准或定制导线、线缆、连接器或插头将其连接。

[0445] 可以从包括计算机的USB端口的许多DC或AC电压、电流和功率源对源 102S 供电。可以从电力网、从墙壁插头、从电池、从电源、从引擎、从太阳能电池、从发电机、从另一源谐振器等对源 102S 供电。源功率和控制电路 2302 可以包括将源电子装置与电源隔离的电路和组件，使得任何反射功率或信号不会通过源输入端子被耦合到外面。源功率和控制电路 2302 可以包括功率因数修正电路，并且可以被配置为监视功率使用以便监视帐户、帐单、控制和类似功能。

[0446] 系统可以是双向操作的。也就是说，在设备谐振器中生成或存储的能量或功率可以被反馈到包括电力网、电池、任何种类的储能单元等电源。源功率和控制电路可以包括功率因数修正电路，并且可以被配置为监视功率使用以便监视用于双向能量流动的帐户、帐单、控制和类似功能。无线能量转移系统可以实现或促进交通工具到电网 (V2G) 的应用。

[0447] 源和设备可以具有允许工作点的调整以补偿变化的环境条件、扰动和负载条件（其能够影响源和设备谐振器的操作和能量交换的效率）的调谐能力。调谐能力还可以用来将功率递送复用到多个设备、从多个源到多个系统、到多个重发器或中继器等。可以手动地控制或自动地控制调谐能力，并且可以连续地、周期性地、间歇地或以预定的时间或间隔执行该调谐能力。

[0448] 例如，可以将设备谐振器及设备功率和控制电路集成到设备的任何部分中，诸如电池舱或设备盖或套筒或母板上，并且可以集成在标准可再充电电池或其它储能元件旁边。设备谐振器可以包括设备场重新成形器，其可以将设备谐振器元件与设备功率和控制电子装置的任何组合与用于功率转移的电磁场屏蔽开来，并且其可以使谐振器场偏转远离有损耗设备谐振器元件以及设备功率和控制电子装置。磁性材料和/或高电导率场重新成形器可以用来增加谐振器的被扰动品质因数 Q 并增加源和设备谐振器的被扰动耦合因数。

[0449] 可以将源谐振器及源功率和控制电路集成到任何类型的家具、结构、垫子、地毯、相框（包括数字相框、电子框）、插件、电子设备、交通工具等中。源谐振器可以包括源场重

新成形器，其可以将源谐振器元件与源功率和控制电子装置的任何组合与用于功率转移的电磁场屏蔽开来，并且其可以使谐振器场偏转远离有损耗源谐振器元件以及源功率和控制电子装置。磁性材料和 / 或高电导率场重新成形器可以用来增加谐振器的被扰动品质因数 Q 并增加源和设备谐振器的被扰动耦合因数。

[0450] 在图 39 中示出了无线供电设备的示例中的子系统的方框图。可以将功率和控制电路设计为变换来自设备谐振器 102D 的交流电功率并将其转换成适合于对设备供电或充电的稳定直流电功率。可以将功率和控制电路设计为将来自设备谐振器的一个频率处的交流电功率变换成适合于对设备供电或充电的不同频率处的交流电功率。功率和控制电路可以包括阻抗匹配电路 2402D、整流电路 2404、限压电路（未示出）、限流电路（未示出）、AC 至 DC 转换器 2408 电路、DC 至 DC 转换器 2408 电路、DC 至 AC 转换器 2408 电路、AC 至 AC 转换器 2408 电路、电池充电控制电路（未示出）等，或者由其组成。

[0451] 可以将阻抗匹配 2402D 网络设计为在期望频率处使在设备谐振器 102D 与设备功率和控制电路 2304 之间递送的功率最大化。可以选择并连接阻抗匹配元件，使得保持谐振器的高 Q。根据操作条件，可以改变或调谐阻抗匹配电路 2402D 以控制从源向设备、从源向设备谐振器、在设备谐振器与设备功率和控制电路之间等递送的功率。可以在设备电路中的任何点处监视功率、电流和电压信号，并且可以使用反馈算法电路和技术来控制组件以实现期望的信号水平和系统操作。可以使用模拟或数字电路技术来实现反馈算法，并且电路可以包括微处理器、数字信号处理器、现场可编程门阵列处理器等。

[0452] 图 39 的第三方框示出可以将来自设备谐振器的 AC 电压功率整流成 DC 电压的整流器电路 2404。在此结构中，整流器 2404 的输出功率可以是到电压钳位电路的输入。电压钳位电路（未示出）可以限制到 DC 至 DC 转换器 2408D 或 DC 至 AC 转换器 2408D 的输入端处的最大电压。通常，可能期望使用具有大的输入电压动态范围的 DC 至 DC/AC 转换器，使得可以在足够的功率被递送到设备的同时容忍设备位置和操作的大的变化。例如，整流器的输出端处的电压水平可以随着设备的功率输入和负载特性的变化而波动并达到高水平。在设备执行不同的任务时，其可以具有变化的功率需求。变化的功率需求能够随着负载特性的变化在整流器的输出端处引起高电压。同样地，在使设备和设备谐振器更接近于和更加远离源时，递送到设备谐振器的功率可以改变，并引起整流器的输出端处的电压水平的变化。电压钳位电路可以防止来自整流器电路的电压输出超过在 DC 至 DC/AC 转换器的工作范围内的预定值。可以使用电压钳位电路来扩展无线能量转移系统的工作模式和范围。

[0453] 设备的功率和控制电路的下一个方框是可以产生稳定的 DC 输出电压的 DC 至 DC 转换器 2408D。DC 至 DC 转换器可以是升压转换器、降压转换器、升压降压转换器、单端初级电感转换器 (SEPIC) 或符合特定应用的要求的任何其它 DC-DC 拓扑结构。如果设备要求 AC 功率，则可以用 DC 至 AC 转换器代替 DC 至 DC 转换器，或者在 DC 至 DC 转换器后面可以跟着 DC 至 AC 转换器。如果设备包含可再充电电池，则设备功率和控制电路的最后方框可以是可以管理电池供电设备中电池的充电和维护的电池充电控制单元。

[0454] 设备功率和控制电路 2304 可以包含处理器 2410D，诸如微控制器、数字信号处理器、现场可编程门阵列处理器、微处理器或任何其它类型的处理器。可以使用处理器来读取或检测功率和控制电路和设备谐振器的状态或工作点。处理器可以实现算法以解释并调整电路、元件、组件、子系统和谐振器的工作点。可以使用处理器来调整无线供电设备的阻抗

匹配、谐振器、DC 至 DC 转换器、DC 至 AC 转换器、电池充电单元、整流器等。

[0455] 处理器可以具有到其它设备或源的无线或有线数据通信链路，并且可以传送或接收可以用来调整系统的工作点的数据。可以在设备电路中的任何点处监视单个频率处或频率范围内的功率、电压和电流信号的任何组合。可以使用模拟或数字或组合模拟和数字技术来监视这些信号。可以在反馈环路中使用这些监视信号，或者可以以多种方式将其报告给用户，或者可以将其存储并在稍后的时间获取。这些信号可以用来向用户警告系统故障，以指示性能或向系统的用户提供音频、视觉、振动等反馈。

[0456] 图 40 示出被配置为向单个或多个设备供应功率的示例性无线功率转移系统的源功率和控制电路 2302 的组件。可以从诸如家用插座的 AC 电压源 2502、诸如电池的 DC 电压源、计算机的 USB 端口、太阳能电池、另一无线功率源等对示例性系统的源功率和控制电路 2302 供电。源功率和控制电路 2302 可以用交流电（诸如用大于 10kHz 并小于 100MHz 的频率）来驱动源谐振器 102S。源功率和控制电路 2302 可以用小于 10GHz 的频率的交流电来驱动源谐振器 102S。源功率和控制电路 2302 可以包括 DC 至 DC 转换器 2408S、AC 至 DC 转换器 2408S、或 AC 至 DC 转换器 2408S 和 DC 至 DC 2408S 转换器两者、振荡器 2508、功率放大器 2504、阻抗匹配网络 2402S 等。

[0457] 可以从多个 AC 至 DC 电压源 2502 对源功率和控制电路 2302 供电，并且其可以包含 AC 至 DC 和 DC 至 DC 转换器 2408S 以提供用于电路组件的所需电压水平以及用于可以用来驱动源谐振器的功率放大器的 DC 电压。可以调整 DC 电压，并且其可以用来控制功率放大器的输出功率水平。源可以包含功率因数修正电路。

[0458] 振荡器 2508 输出可以用作到驱动源谐振器 102S 的功率放大器 2504 的输入。振荡器频率可以是可调谐的，并且可以改变振荡器信号的振幅作为控制来自功率放大器的输出功率水平的一种手段。可以由模拟电路、由数字电路或由模拟和数字电路的组合来控制振荡器信号的频率、振幅、相位、波形和占空比。控制电路可以包括处理器 2410S，诸如微处理器、数字信号处理器、现场可编程门阵列处理器等。

[0459] 可以使用源和设备调谐器的阻抗匹配块 2402 来调谐源和控制电路及源和设备谐振器。例如，可以针对由于无关对象或系统中的源与设备之间的距离变化而引起的源或设备谐振器的品质因数 Q 的扰动来调整这些电路的调谐。还可以使用这些电路的调谐来感测工作环境，控制到一个或多个设备的功率流，控制到无线功率网络的功率，在检测到不安全或故障模式条件时减少功率等。

[0460] 可以在源电路中的任何点处监视功率、电压和电流信号的任何组合。可以使用模拟或数字或组合模拟和数字技术来监视这些信号。可以在反馈电路中使用这些监视信号，或者可以以多种方式将其报告给用户，或者可以将其存储并在稍后的时间获取。这些信号可以用来向用户警告系统故障，以向用户警告超过的安全阈值，指示性能或向系统的用户提供音频、视觉、振动等反馈。

[0461] 源功率和控制电路可以包含处理器。可以使用处理器来读取功率和控制电路及源谐振器的状态或工作点。处理器可以实现算法以解释并调整电路、元件、组件、子系统和谐振器的工作点。可以使用处理器来调整阻抗匹配、谐振器、DC 至 DC 转换器、AC 至 DC 转换器、振荡器、源的功率放大器等。可以使用系统的处理器和可调整组件来实现频率和／或时间功率递送复用方案。处理器可以具有到设备及其它源的无线或有线数据通信链路，并且

可以传送或接收可以用来调整系统的工作点的数据。

[0462] 虽然在这些方框图中示出了详细和特定的设计，但本领域的技术人员应清楚的是在示例性系统的精神内可以进行组件和构建块的许多不同修改和重新布置。出于说明的目的概述了电路的划分，并且本领域的技术人员应清楚的是还可以将每个块的组件进一步划分成更小的块或合并或共享。在等效示例中，功率和控制电路可以由单独的离散组件或较大的集成电路组成。例如，整流器电路可以由离散二极管组成，或者使用被集成在单个芯片上的二极管。根据诸如功率或尺寸或成本或应用的设计标准，可以在设计中替换许多其它电路和集成器件。可以将整个功率和控制电路或源或设备电路的任何部分集成到一个芯片中。

[0463] 设备和 / 或源的阻抗匹配网络可以包括电容器或电容器的网络、电感器或电感器的网络、或电容器、电感器、二极管、开关、电阻器等的任何组合。阻抗匹配网络的组件可以是可调整和可变的，并且可以被控制以影响系统的效率和工作点。可以通过控制谐振器的连接点、调整磁性材料的磁导率、控制偏压场、调整激励的频率等来执行阻抗匹配。阻抗匹配可以使用或包括任何数目的变抗器、变抗器阵列、开关元件、电容器组、开关和可调谐元件、反偏压二极管、空隙电容器、压缩电容器、BZT 电调谐电容器、MEMS 可调谐电容器、电压可变电介质、变压器耦合调谐电路等或其组合。可变组件可以被机械地调谐、热学地调谐、电气地调谐、压电地调谐等。阻抗匹配的元件可以是硅器件、氮化镓器件、碳化硅器件等。可以将元件选择为耐受高电流、高电压、高功率或电流、电压和功率的任何组合。可以将元件选择为高 Q 元件。

[0464] 可以通过对设备供电的 USB 端口在外部设备上执行源的匹配和调谐计算。设备可以是计算机、PDA 或其它计算平台。

[0465] 示范系统使用被耦合到设备谐振器的源谐振器来无线地对多个电子消耗设备进行供电 / 再充电，所述电子消耗设备包括但不限于笔记本计算机、DVD 播放器、投影仪、蜂窝电话、显示器、电视、投影仪、数字相框、灯、TV/DVD 播放器、便携式音乐播放器、断路器、手持式工具、个人数字助手、外部电池充电器、鼠标、键盘、照相机、有源负载等。可以同时地从单个设备谐振器对多种设备供电。设备谐振器可以同时作为源谐振器进行操作。被提供给设备谐振器的功率可以在被转移到其预定设备谐振器之前穿过附加谐振器。

[0466] 监视、反馈和控制

[0467] 所谓的端口参数测量电路可以测量或监视系统中的某些功率、电压和电流信号，并且处理器或控制电路可以基于那些测量来调整某些设定或工作参数。除这些端口参数测量结果之外，还可以访问通过系统的电压和电流信号的幅值和相位及功率信号的幅值以测量或监视系统性能。遍及本公开提到的被测量信号可以是端口参数信号以及电压信号、电流信号、功率信号等的任何组合。可以使用模拟或数字信号来测量这些参数，可以对其进行采样和处理，并且可以使用许多已知模拟和数字处理技术对其进行数字化或转换。被测量或监视信号可以在反馈电路或系统中用来控制谐振器和 / 或系统的操作。通常，我们可以将这些被监视或测量信号称为参考信号或端口参数测量或信号，虽然有时也将其称为错误信号、监视器信号、反馈信号等。我们将把用来控制电路元件的信号（例如，用来驱动电压控制电容器的电压）称为控制信号。

[0468] 在某些情况下，可以调整电路元件以实现用于源和设备谐振器的指定的或预定的

阻抗值。在其它情况下，可以调整阻抗以在设备谐振器被连接到一个或多个功率消耗装置时实现用于源和设备谐振器的期望阻抗值。在其它情况下，可以调整阻抗以减少谐振频率的变化、由于源和／或设备谐振器的移动而引起的阻抗或功率水平的变化或谐振器附近的环境的变化（诸如交互材料或对象的移动）。在其它情况下，可以将源和设备谐振器的阻抗调整为不同的阻抗值。

[0469] 耦合谐振器可以由不同的材料制成，并且可以包括不同的电路、组件和结构设计，或者其可以是相同的。耦合谐振器可以包括性能监视和测量电路、信号处理和控制电路或测量和控制电路的组合。某些或所有的高 Q 磁谐振器可以包括可调谐阻抗电路。某些或所有的高 Q 磁谐振器可以包括自动控制的可调谐阻抗电路。

[0470] 图 41 示出具有被配置为测量谐振器的某些参数的端口参数测量电路 3802 的磁谐振器。端口参数测量电路可以测量结构的输入阻抗或反射功率。端口参数测量电路可以被包括在源和／或设备谐振器设计中，并且可以用来测量两个端口电路参数，诸如 S 参数（散射参数）、Z 参数（阻抗参数）、Y 参数（导纳参数）、T 参数（传输参数）、H 参数（混合参数）、ABCD 参数（链、级联或传输参数）等。这些参数可以用来在施加各种类型的信号时描述线性电力网的电气性能。

[0471] 在不同的工作或耦合方案中可以使用不同的参数来表征电力网络。例如，可以使用 S 参数来测量匹配和不匹配负载。另外，可以在多种点处监视磁谐振器内和／或源和设备本身内的电压和电流信号的幅值和相位以提供系统性能信息。可以经由灯、读数、喇叭、噪声、振动等用户接口将此信息呈现给系统的用户，或者可以将其作为数字信号呈现，或者可以将其提供给系统中的处理器并在系统的自动控制中使用。可以记录、存储此信息，或者其可以被高级监视和控制系统使用。

[0472] 图 42 示出其中可以用电压控制电容器 3902 或电容器网络来实现可调谐阻抗网络的磁谐振器的电路图。可以由诸如可编程电压源 3908 等之类的电路和／或计算机处理器来调整、调谐或控制此类实施方式。例如，可以响应于由端口参数测量电路 3802 获取并由测量分析和控制算法子系统 3904 处理的数据来调整电压控制电容器。可以从端口参数测量电路或被设计为测量与期望系统工作点的偏差度的其它监视电路导出参考信号。所测量的参考信号可以包括系统中的单个或多个点处和单个频率或多个频率处的电压、电流、复阻抗、反射系数、功率水平等。

[0473] 可以将参考信号提供给测量结果分析和控制算法子系统模块，其可以生成控制信号以改变可调谐阻抗匹配网络中的各种组件的值。控制信号可以改变磁谐振器的谐振频率和／或输入阻抗或由源供应的功率水平或由设备吸取的功率水平以实现电源／发电机与功率消耗装置／负载之间的期望的功率交换。

[0474] 可以使用调整算法来调整磁谐振器的频率和／或阻抗。所述算法可以接受关于与用于系统的期望工作点的偏差度的参考信号并输出与该偏差有关的控制系统的可变或可调谐元件的修正或控制信号以使得系统朝着一个或多个期望的工作点返回。可以在谐振器正在无线功率传输系统中交换功率的同时获取用于磁谐振器的参考信号，或者可以在系统操作期间将其从电路中切换出来。可以连续地、周期性地、在越限时、数字地、使用模拟方法等来施加或执行对系统的修正。

[0475] 图 43 示出了端到端无线功率传输系统。源和设备两者可以包括端口测量电路

3802 和处理器 2410。标记为“耦合器 / 开关”4002 的方框指示可以由定向耦合器或开关将端口测量电路 3802 连接到谐振器 102，使得能够与功率转移功能相结合地或分开地进行源和设备谐振器的测量、调整和控制。

[0476] 端口参数测量和 / 或处理电路可以与系统中的某些、任何或所有谐振器处于一起。端口参数测量电路可以利用功率传输信号的一部分或者可以利用一定频率范围内的激励信号来测量源 / 设备谐振器响应（即系统中的任何两个端口之间的传输和反射），并且可以包含振幅和 / 或相位信息。可以用扫频单频信号或多频信号来实现此类测量。可以由包括数模转换器 (DAC)、模数转换器 (ADC)、放大器、信号发生芯片、无源组件等的一个或多个处理器和标准输入 / 输出 (I/O) 电路来生成用来测量和监视谐振器和无线功率传输系统的信号。可以使用诸如网络分析器之类的测试设备或使用自定义电路来实现测量。可以由 ADC 将所测量的参考信号数字化并使用在计算机、微处理器、DSP 芯片、ASIC 等上运行的自定义算法来进行处理。可以在模拟控制环路中处理所测量的参考信号。

[0477] 测量电路可以测量两个端口参数的任何集合，诸如 S 参数、Y 参数、Z 参数、H 参数、G 参数、T 参数、ABCD 参数等。可以使用测量电路来表征驱动和谐振器电路中的各种点处的电流和电压信号，系统的相对两端处的源和设备谐振器的阻抗和 / 或导纳（即朝着设备向源谐振器匹配网络中看（图 43 中的“端口 1”）且反之亦然）。

[0478] 该设备可以测量相关信号和 / 或端口参数，解释测量数据，并调整其匹配网络以独立于源的动作使向耦合系统中看的阻抗最优化。源可以测量相关端口参数，解释测量数据，并调整其匹配网络以独立于设备的动作使向耦合系统中看的阻抗最优化。

[0479] 图 43 示出了无线功率传输系统中的源和设备的方框图。可以将系统配置为执行控制算法，该控制算法主动地调整源和设备调谐器中的任一者或两者中的调谐 / 匹配网络以使耦合系统中的性能最优化。端口测量电路 3802S 可以测量源中的信号并将那些信号传送到处理器 2410。处理器 2410 可以在性能最优化或稳定化算法中使用所测量的信号并基于那些算法的输出来生成控制信号。可以将控制信号施加于调谐 / 阻抗匹配电路 2402S 中的可变电路元件以调整源的工作特性，诸如谐振器中的功率和到设备的耦合。可以将控制信号施加于电源或发电机以开启或关闭电源，增加或降低功率水平，调制供应信号等。

[0480] 在源与设备之间交换的功率可以取决于多种因素。这些因素可以包括源和设备的有效阻抗、源和设备的 Q、源和设备的谐振频率、源和设备之间的距离、源和设备附近的材料和对象的交互等。端口测量电路和处理算法可以同时地工作以在动态和稳态工作条件下调整谐振器参数以使功率转移最大化，保持功率转移恒定，可控制地调整功率转移等。

[0481] 系统实现中的某些、所有或没有源和设备可以包括端口测量电路 3802S 和处理 2410 能力。图 44 示出其中仅源 102S 包含端口测量电路 3802 和处理器 2410S 的端到端无线功率传输系统。在这种情况下，设备谐振器 102D 工作特性可以是固定的，或者可以由模拟控制电路来调整，并且不需要由处理器生成的控制信号。

[0482] 图 45 示出端到端无线功率传输系统。源和设备这二者可以包括端口测量电路 3802，但是在图 45 的系统中，仅源包含处理器 2410S。源和设备可以相互通信，并且某些系统参数的调整可以响应于已经在源与设备之间诸如通过无线通信电路 4202 无线传送的控制信号。无线通信信道 4204 可以与无线功率转移信道 4208 分离，或者其可以是相同的。也就是说，用于功率交换的谐振器 102 还可以用来交换信息。在某些情况下，可以通过调制源

或设备电路的组件并感测端口参数或其它监视设备的变化来交换信息。

[0483] 其中源仅包含处理器 2410 的实现可以对其中源能够处理所有调谐和调整“判定”并简单地将控制信号传送回设备（一个或多个）的多设备系统有益。此实现可以使得设备更小且更便宜，因为该实现可以消除对设备中的处理器的需要，或者降低其要求的功能。可以将来自每个设备处的每个端口测量的整个数据集的一部分送回到源微处理器以进行分析，并且可以将控制指令送回到设备。这些通信可以是无线通信。

[0484] 图 46 示出端到端无线功率传输系统。在本示例中，源仅包含端口测量电路 3802 和处理器 2410S。源和设备可以诸如经由无线通信电路 4202 相互通信，并且某些系统参数的调整可以响应于已经在源与设备之间无线地传送的控制信号。

[0485] 图 47 示出可以使用处理器或计算机来自动地调整其频率和阻抗的耦合电磁谐振器 102。可以用包含在被示为图 47 中的 C1、C2 和 C3 示出的电容器网络内的反向偏置二极管、肖特基二极管和／或变抗器元件来实现源和设备谐振器的谐振频率调谐和连续阻抗调整。已被构建且说明并在这里描述的电路拓扑结构是示例性的，并且并不意图以任何方式限制自动系统调谐和控制的讨论。可以与在本公开中讨论的测量和控制架构一起利用其它电路拓扑结构。

[0486] 可以用网络分析器 4402A ～ B 或用上述其它手段来测量并用控制器（诸如用 Lab View 4404）来实现设备和源谐振器阻抗和谐振频率。测量电路或设备可以向计算机或处理器输出数据，所述计算机或处理器实现反馈算法并经由可编程 DC 电压源动态地调整频率和阻抗。

[0487] 在一个布置中，用来实现可调谐电容的反向偏置二极管（肖特基、半导体结等）几乎不吸取 DC 电流，并且可以被具有大的串联输出电阻的放大器反向偏置。此实现可以使得能够在保持磁谐振器中的非常高的 Q 的同时直接向谐振器电路中的可控电路元件施加 DC 控制信号。

[0488] 如果所要求的 DC 偏置电压是不同的，则可以用如图 47 所示的隔直流电容器将 C2 偏置信号与 C1 和／或 C3 偏置信号隔离。可以使偏置放大器的输出旁路至电路地以将 RF 电压与偏置放大器隔离，并防止非基波 RF 电压被注入到谐振器中。可以替代地通过谐振器本身中的电感元件来施加用于某些电容器的反向偏置电压，因为电感元件在 DC 下充当短路。

[0489] 端口参数测量电路可以与作为反馈或控制系统的一部分的处理器（包括任何要求的 ADC 和 DAC）交换信号，所述反馈或控制系统用来自动地调整谐振频率、输入阻抗、由谐振器储存或捕捉的能量或由源递送到设备负载的功率。处理器还可以向在磁谐振器中或被附着于磁谐振器的调谐或调整电路发送控制信号。

[0490] 当利用变抗器或二极管作为可调谐电容器时，在调谐／匹配电路中设置与在高反向偏压下操作的可调谐电容器并联和串联的固定电容器可能是有益的。此布置可以通过使可调谐电容器上的工作电压最优化来提供电路和系统稳定性及功率处理能力的改进。

[0491] 可以使用变抗器或其它反向偏置二极管作为电压控制电容器。当要求比单个变抗器组件更高的电压一致性或与之不同的电容时，可以使用变抗器阵列。可以将变抗器布置为被串联地和并联地连接并被视作具有与阵列中的单独变抗器不同的特性的单个双端子组件的 N 乘 M 阵列。例如，可以使用相等变抗器的 N 乘 N 阵列（其中，每个行中的组件被并联地连接并且每个列中的组件被串联地连接）作为具有与阵列中的任何单个变抗器相同

的电容但具有是阵列中的单个变抗器的 N 倍的电压一致性的双端子器件。根据阵列中的单独变抗器的参数的可变性和差异，可能需要由电阻器、电感器等组成的附加偏置电路。图 48 中示出了可以适合于磁谐振器应用的未偏置变抗器 4502 的四乘四阵列的示意图。

[0492] 可以通过被设置为与可调谐（变抗器 / 二极管 / 电容器）元件并联和 / 或串联的固定值电容器（一个或多个）的谨慎选择来实现系统性能的进一步改善。切换到电路中或从电路切换出来的多个固定电容器可以能够补偿在测试、开发和可操作无线功率转移系统中可能遇到的谐振器 Q、阻抗、谐振频率、功率水平、耦合强度等的变化。可以使用开关电容器组及其它开关元件组来保证到系统设计所要求的工作频率和阻抗值的收敛。

[0493] 可以针对图 47 所示的电路和系统元件来描述用于隔离和耦合磁谐振器的示例性控制算法。一个控制算法首先“孤立地”调整每个源和设备谐振器环路，也就是，系统中的其它谐振器被“短路”并从系统“去除”。实际上，可以通过使得谐振器在低得多的频率处谐振（诸如通过使 C1 和 / 或 C3 的值最大化）来使谐振器“短路”。此步骤有效地减少谐振器之间的耦合，从而在特定频率和阻抗下有效地将系统简化为单个谐振器。

[0494] 孤立地调谐磁谐振器包括改变调谐和匹配电路中的可调谐元件，直至由端口参数测量电路测量的值处于其预定、计算或测量的相对值为止。可以基于期望的匹配阻抗、频率、强耦合参数等来选择由端口参数测量电路测量的量的期望值。对于下文讨论的示例性算法而言，端口参数测量电路测量一定频率范围内的 S 参数。用来表征谐振器的频率范围可以是所获得的系统性能信息与计算 / 测量速度之间的折衷。对于下文描述的算法而言，频率范围可以是工作谐振频率的近似 +/-20％。

[0495] 可以如下调谐每个隔离谐振器。首先，使不被调整的谐振器短路。接下来，使正被表征和调整的谐振器中的 C1、C2 和 C3 最小化。在大多数情况下，将存在与 C1、C2 和 C3 并联的固定电路元件，因此，此步骤不将电容值减小至零。接下来，开始增加 C2 直至谐振器阻抗在上述测量频率范围内的任何频率处与“目标”实阻抗匹配为止。初始“目标”阻抗可以小于用于耦合系统的预期工作阻抗。

[0496] 可以调整 C2，直至针对测量范围内的频率实现初始“目标”阻抗为止。然后，可以调整 C1 和 / 或 C3，直至环路在期望工作频率处谐振为止。

[0497] 可以根据上述算法来调整每个谐振器。在孤立地调谐每个谐振器之后，可以应用第二反馈算法以使用于在耦合系统中无线转移功率的谐振频率和 / 或输入阻抗最优化。

[0498] 可以通过测量并处理来自图 43 所示的任一个和 / 或两个“端口”的输入阻抗的实部和虚部的值来确定对耦合系统中的每个谐振器中的 C1 和 / 或 C2 和 / 或 C3 的所要求调整。对于耦合谐振器而言，改变一个谐振器的输入阻抗可以改变另一谐振器的输入阻抗。控制和跟踪算法可以基于一个端口的测量结果来将该端口调整至期望的工作点，并且然后基于另一端口处的测量结果来调整该另一端口。可以重复这些步骤直至两侧收敛至期望的工作点为止。

[0499] 可以在源和设备端口两者处测量 S 参数，并且可以进行以下系列的测量和调整。在随后的说明中，Z_0 是输入阻抗且可以是目标阻抗。在某些情况下，Z_0 是 50 欧姆或接近于 50 欧姆。Z_1 和 Z_2 是可以是与 Z_0 相同的值或者可以不同于 Z_0 的中间阻抗值。Re{value} 意指值的实部且 Im{value} 意指值的虚部。

[0500] 下面阐述可以用来调整两个耦合谐振器的输入阻抗和谐振频率的算法：

[0501]　1）如上所述地“孤立地”调整每个谐振器。

[0502]　2）调整源 C1/C3 直至在下，$\mathrm{Re}\{S11\} = (Z_1 +/- \varepsilon_{Re})$ 如下：

[0503]　- 如果 $\mathrm{Re}\{S11@\omega_o\} > (Z_1 + \varepsilon_{Re})$，则减小 C1/C3。如果 $\mathrm{Re}\{S11@\omega_o\} < (Zo - \varepsilon_{Re})$，则增加 C1/C3。

[0504]　3）调整源 C2 直至在 ω_o 下，$\mathrm{Im}\{S11\} = (+/- \varepsilon_{Im})$ 如下：

[0505]　- 如果 $\mathrm{Im}\{S11@\omega_o\} > \varepsilon_{Im}$，则减小 C2。如果 $\mathrm{Im}\{S11@\omega_o\} < -\varepsilon_{Im}$，则增加 C2。

[0506]　4）调整设备 C1/C3 直至在 ω_o 下，$\mathrm{Re}\{S22\} = (Z_2 +/- \varepsilon_{Re})$ 如下：

[0507]　- 如果 $\mathrm{Re}\{S22@\omega_o\} > (Z_2 + \varepsilon_{Re})$，则减小 C1/C3。如果 $\mathrm{Re}\{S22@\omega_o\} < (Zo - \varepsilon_{Re})$，则增加 C1/C3。

[0508]　5）调整设备 C2 直至在 ω_o 下，$\mathrm{Im}\{S22\} = 0$ 如下：

[0509]　- 如果 $\mathrm{Im}\{S22@\omega_o\} > \varepsilon_{Im}$，则减小 C2。如果 $\mathrm{Im}\{S22@\omega_o\} < -\varepsilon_{Im}$，则增加 C2。

[0510]　我们已通过重复步骤 1 ～ 4 直至 (Re{S11}，Im{S11}) 和 (Re{S22}，Im{S22}) 两者在 ω_o 下收敛到 $((Z_0 +/- \varepsilon_{Re}), (+/- \varepsilon_{Im}))$ 为止实现了工作系统，其中，Z_0 是期望匹配阻抗且是期望工作频率。这里，ε_{Im} 表示 ω_o 下的虚部与 0 的期望值的最大偏差，并且 ε_{Re} 表示实部与 Z_0 的期望值的最大偏差。应理解的是可以调整 ε_{Im} 和 ε_{Re} 以便以系统性能（效率）的潜在代价来增加或减少到收敛的步骤数目。还应理解的是可以按照除上述之外的多种序列并以多种方式来执行步骤 1 ～ 4（即，首先调整源虚部，然后是源实部；或者首先调整设备实部，然后是设备虚部等）。可以在步骤 1 ～ 4 期间调整中间阻抗 Z_1 和 Z_2 以减少收敛所需的步骤的数目。期望或目标阻抗值可以是复数，并且在时间方面或在不同的操作方案中可以改变。

[0511]　可以按照任何次序、以任何组合和任何次数来执行步骤 1 ～ 4。已经描述了上述算法，对步骤或所述实施方式的修改对于本领域的技术人员来说可以是显而易见的。以与能够替换地使用阻抗或导纳来分析线性电路以导出相同结果的相同方式，可以用任何等效线性网络端口参数测量（即，Z 参数、Y 参数、T 参数、H 参数、ABCD 参数等）或上述其它监视信号来实现上述算法。

[0512]　由于由源和设备谐振器之间的互感 M（耦合）的变化引起的“加载”电阻 Rs 和 Rd 的变化，可能需要重新调谐谐振器。电感元件本身的电感 Ls 和 Ld 的变化可以是由外部对象的影响引起的（如先前所讨论的），并且还可能要求补偿。可以用上述调整算法来缓解此类变化。

[0513]　可以使用定向耦合器或开关来将端口参数测量电路连接到源谐振器和调谐 / 调整电路。端口参数测量电路可以在其在无线功率传输系统中交换功率的同时测量磁谐振器的性质，或者可以在系统操作期间将其从电路中切换出来。端口参数测量电路可以测量参数且处理器可以在启动时或在某些间隔或响应于某些系统工作参数的变化来控制磁谐振器的某些可调谐元件。

[0514]　无线功率传输系统可以包括改变或调谐源和设备谐振器的阻抗和 / 或谐振频率的电路。请注意，虽然在源和设备谐振器两者中示出了调谐电路，但可以替代地仅在源或设备谐振器中包括该电路，或者可以仅在某些源和 / 或设备谐振器中包括该电路。还请注意虽然我们将该电路称为“调谐”谐振器的阻抗和 / 或谐振频率，但此调谐操作仅仅意味着正在改变诸如结构的电感或电容的各种电气参数。在某些情况下，可以改变这些参数以实现

特定的预定值，在其它情况下，可以响应于控制算法将其改变或者稳定正在变化的目标性能值。在某些情况下，参数可以根据温度、区域中的其它源或设备、环境等而变。

[0515] 应用

[0516] 对于每个所列应用而言，本领域的技术人员应认识到存在可以将用来实现无线功率传输的谐振器结构与正在进行供电或被供电的对象连接或集成的多种方式。谐振器可以在物理上与源和设备对象分离。谐振器可以使用传统电感技术或通过用例如导线或线缆的直接电连接供应功率或从对象去除功率。所述电连接可以是从谐振器输出到对象上的 AC 或 DC 功率输入端口。所述电连接可以是从对象的输出功率端口到谐振器输入。

[0517] 图 49 示出在物理上与电源分离的源谐振器 4904 和在物理上与设备 4900（在此图示中为膝上型计算机）分离的设备谐振器 4902。通过电连接，可以将功率供应给源谐振器，并且可以直接从设备谐振器获取功率。本领域的技术人员通过经引用结合的材料将理解的是上述谐振器的形状、尺寸、材料组成、布置、位置和取向是以非限制性示例的方式提供的，并且可以由针对多种应用公开的技术来支持任何和所有这些参数的广泛变化。

[0518] 继续膝上型计算机的示例，并且在没有限制的情况下，可以将设备谐振器在物理上连接到其正在供电或充电的设备。例如，如图 50a 和图 50b 所示，可以将设备谐振器 5002(a) 集成到设备 5000 的外壳中或 (b) 可以由适配器来将其附着。谐振器 5002 可以是（图 50b ～ d）或者可以不是（图 50a）在设备上可见的。可以将谐振器附着于设备、集成到设备中、用插头插入设备中等等。

[0519] 可以将源谐振器在物理上连接到向系统供应功率的源。如上文针对设备和设备谐振器所述，存在可以将谐振器附着于、连接到电源或与电源集成的多种方式。本领域的技术人员将理解的是存在可以在无线功率传输系统中集成谐振器的多种方式，并且源和设备可以利用相似或不同的集成技术。

[0520] 再次继续技术膝上型计算机的示例，并且在没有限制的情况下，可以由无线功率传输系统来对膝上型计算机供电、充电或再充电。可以使用源谐振器来供应无线功率，并且可以使用设备谐振器来捕捉无线功率。可以如图 50d 所示将设备谐振器 5002 集成到屏幕（显示器）的边缘中，和／或如图 50c 所示集成到膝上型计算机的底座中。可以将源谐振器 5002 集成到膝上型计算机的底座中，并且可以将设备谐振器集成到屏幕的边缘中。还可以或替代地将谐振器附着于电源和／或膝上型计算机。还可以或替代地将源和设备谐振器在物理上与电源和膝上型计算机分离，并且可以用线缆进行电连接。还可以或替代地将源和设备谐振器在物理上与电源和膝上型计算机分离，并且可以使用传统电感技术来进行电耦合。本领域的技术人员将理解的是虽然先前的示例涉及到膝上型计算机的无线功率传输，但针对本申请公开的方法和系统可以适当地适合于与其它电气或电子设备一起使用。通常，源谐振器可以在源的外部并向设备谐振器供应功率，所述设备谐振器又为设备供应功率，或者可以将源谐振器连接到源并向设备谐振器供应功率，设备谐振器又向设备的一部分供应功率，或者源谐振器可以在源内部并向设备谐振器供应功率，设备谐振器又向设备的一部分供应功率，以及这些的任何组合。

[0521] 本文公开的系统或方法可以向电气或电子设备提供功率，所述电气或电子设备诸如但不限于电话、蜂窝电话、无绳电话、智能电话、PDA、音频设备、音乐播放器、MP3 播放器、无线电、便携式无线电和播放器、无线头戴式受话器、无线耳机、计算机、膝上型计算机、无

线键盘、无线鼠标、电视、显示器、平面屏幕显示器、计算机显示器、嵌入家具中的显示器、数字相框、电子书（例如Kindle、电子墨书、杂志等）、遥控单元（也称为控制器、游戏控制器、命令器、表决器等，并用于多个电子设备的遥控，诸如电视、视频游戏、显示器、计算机、视听设备、灯等）、照明设备、冷却设备、空气循环设备、净化设备、个人助听器、电动工具、安全系统、警报、钟、闪光灯、警报器、传感器、扩音器、电子锁、电子键区、照明开关、其它电气开关等。这里，术语电子锁用来指示位于门上的以电子方式操作（例如，具有电子组合钥匙、磁卡、RFID卡等）的门锁而不是机械钥匙锁。此类锁常常是电池操作的，具有当电池耗尽时所可能停止工作、将用户锁在外面的可能性的风险。在用如本文所述的无线功率传输实施方式来对电池充电或完全替换的情况下可以避免这一点。

[0522] 这里，术语照明开关（或其它电子开关）意图指示开启/关闭房间的另一部分中的设备（例如天花板的中心处的照明灯具）的房间的一个部分中的任何开关（例如，在房间的墙壁上）。为了用直接连接来安装此类开关，将必须一路铺设从设备到开关的导线。一旦此类开关被安装在特定地点处，则其可能非常难以移动。可替换地，可以设想‘无线开关’，其中，“无线”意指无线地传送开关（开/关）命令，但是此类开关传统上需要电池以进行操作。通常，在房子周围具有太多电池操作的开关可能是不切实际的，因为那么多电池将需要周期性地更换。因此，无线通信开关可能更方便，条件是无线地对其进行供电。例如，已经存在电池供电的通信无线门铃，但是其中，仍必须周期性地更换其中的电池。可以使得远程门铃按钮完全是无线的，其中，可能不会再次需要不断地更换电池。请注意，在这里，术语‘无绳’或‘无线’或‘通信无线’用来指示在设备与另一电气组件之间存在无绳或无线通信装置，诸如用于无绳电话的基站、用于无线键盘的计算机等。本领域的技术人员将认识到任何电气或电子设备可以包括无线通信装置，并且本文所述的系统和方法可以用来向设备添加无线功率传输。如本文所述，到电气或电子设备的功率可以是从外部或内部源谐振器递送来，到设备或设备的一部分。无线功率传输可以显著地减少对用于进入源谐振器附近区域的设备的电池进行充电和/或更换的需要并从而可以减少常常与电池相关联的停机时间、成本和处理问题。

[0523] 本文所述的系统和方法可以在不需要有线功率或电池的情况下向灯提供功率。也就是说，本文所述的系统和方法可以在没有到任何电源的有线连接的情况下向灯提供功率，并且跨越中程距离（诸如跨越四分之一米、一米、三米等的距离）非辐射地向灯提供能量。本文所使用的‘灯’可以指的是光源本身，诸如白炽灯泡、荧光灯泡灯、卤素灯、气体放电灯、荧光灯、霓虹灯、高强度放电灯、钠蒸气灯、汞蒸气灯、电致发光灯、发光二极管(LED)灯等；作为灯固定装置的一部分的灯，诸如台灯、落地灯、吊灯、轨道灯、凹陷灯固定装置等；与其它功能集成的灯固定装置，诸如灯具/吊扇固定装置和照明相框等。同样地，本文所述的系统和方法可以降低用于安装灯的复杂性，诸如通过最小化电气布线的安装，并允许用户以对有线功率源的最小注意力来放置或安装灯。例如，可以将灯放置在源谐振器附近的任何地方，其中，可以相对于灯的位置将源谐振器安装在多个不同的位置上，诸如在上面房间的地板上（例如，在吊灯的情况下，并且尤其是当上面房间是阁楼时）；在隔壁房间的墙壁上、在下面房间的天花板上（例如，在落地灯的情况下）；如本文所述的在房间内的组件中或在房间的基础设施中；等等。例如，常常将灯/吊扇组合安装在主卧室中，并且主卧室常常具有在其上面的阁楼。在这种情况下，用户可以更容易地将灯具/吊扇组合安装在主

卧室中，诸如通过简单地将灯/吊扇组合安装到天花板，并将源线圈（用插头插入房屋有线AC电源）放置在安装的固定装置之上的阁楼中。在另一示例中，灯可以是外部灯，诸如泛光灯或安全灯以及安装在结构内部的源谐振器。安装照明的方式可以特别地对租用房子的用户有益，因为现在其可能能够在不需要安装新的电气布线的情况下安装灯和此类其它电气组件。还可以通过如本文所述的近场通信或由传统无线通信方法来传送对于灯的控制。

[0524] 本文所述的系统和方法可以从源谐振器向被嵌入设备组件中或在设备组件外面的设备谐振器提供功率，使得设备组件可以是传统电气组件或固定装置。例如，可以用被集成到固定装置中的设备谐振器来设计或改装吊灯，或者吊灯可以是传统有线固定装置，并用插头插入装配有设备谐振器的单独电气装置。在示例中，电气机构可以是被设计为具有用于例如从被放置在上面房间（例如阁楼）的地板上的源谐振器接收无线功率的设备谐振器的无线分线盒，并且其包含从设备谐振器供电的许多传统电源插座(outlet)。安装在天花板上的无线分线盒现在可以向天花板上的传统有线电气组件提供功率（例如，吊灯、轨道灯、吊扇）。因此，现在可以在不需要将导线穿过建筑物的基础设施的情况下将吊灯安装到天花板。可以在多个应用中使用到传统电源插座分线盒的此类设备谐振器，包括被设计成用于建筑物的内部或外部、被制成便携式的、被制成用于交通工具等。无线功率可以被转移通过诸如木材、壁板、绝缘、玻璃、砖头、石头、混凝土等常见建筑物材料。降低的安装成本、可重配置性和增加的应用灵活性的益处相对于传统有线安装而言可以为用户提供显著的益处。用于传统电源插座分线盒的设备谐振器可以包括用于促进从设备谐振器到传统电源插座的功率转移的多个电气组件，诸如将实现高效的功率转移所需的特定频率转换成线电压的电源电子装置、可以将高频AC转换成可用电压和频率(AC和/或DC)的功率捕捉电子装置、使捕捉设备和功率输出同步并保证一致、安全且最大程度地高效的功率转移的控制等。

[0525] 本文所述的系统和方法可以为在潮湿、严酷、受控等的环境中（其在外面且暴露于雨）、在游泳池/桑拿浴/淋浴中、在海洋应用中、在密闭组件中、在防爆间中、在外部标志上、挥发性环境中的严酷工业环境（例如来自挥发性蒸气或空气传播有机物，诸如在谷粮仓或面包店中）等操作的灯或电气组件提供优点。例如，安装在游泳池的水位下面的灯正常地难以用导线接起，并且需要是水封的，尽管需要外部导线。但是，使用本文公开的原理的游泳池灯可以被更容易地制成水封的，因为可以不需要外部导线。在另一示例中，诸如包含挥发性蒸气的防爆间可能不仅需要是密闭的，而且可能需要使所有电接点（其可以产生火花）被密封。再次地，本文公开的原理可以提供为此类应用供应密封电气组件的方便方式。

[0526] 本文公开的系统和方法可以向游戏控制器应用提供功率，诸如向远程手持式游戏控制器。这些游戏控制器传统上可能已经单独地由电池来供电，其中，游戏控制器的使用和功率分布导致了电池、电池组、可再充电电池等的频繁更换，这对于在游戏控制器的一贯使用而言可能是不理想的，诸如在延长的玩游戏期间。可以将设备谐振器放置到游戏控制器中，并且可以将连接到电源的源谐振器放置在附近。此外，游戏控制器中的设备谐振器可以在没有电池的情况下直接向游戏控制器电子装置提供功率；向电池、电池组、可再充电电池等提供功率，其随后向游戏控制器电子装置提供功率；等等。游戏控制器可以利用多个电池组，其中每个电池组装配有设备谐振器，因此，无论是否用插头接通游戏控制器电源，在处

于源谐振器附近时就可以不断地再充电。源谐振器可以位于用于游戏的主游戏控制器装置中，其中可以从 AC ‘房屋’电源向主游戏控制器装置和源谐振器供应功率 ；位于扩展装置形式的 AC 电源中，诸如在被集成到‘延长线’中的源谐振器中 ；位于游戏椅中，其是被用插头插入墙壁 AC 中、用插头插入主游戏控制器装置、由游戏椅中的电池组供电中的至少一种方式 ；等等。可以以本文所述的任何配置来设置并实现源谐振器。

[0527] 本文公开的系统和方法可以将设备谐振器集成到电池组中，诸如可与其它电池组互换的电池组。例如，某些便携式设备可能以高速率耗尽电能，使得用户可能需要在手边具有多个可互换电池组以供使用，或者用户可能在源谐振器范围之外操作设备并需要额外的电池组以继续操作，诸如电动工具、便携式灯、遥控交通工具等。使用本文公开的原理不仅提供了设备谐振器使能的电池组在使用中且在范围内时被再充电的方式，而且提供了用于不在使用中且被放置在源谐振器的范围内的电池组的再充电的方式。这样，电池组可以在用户耗尽正被使用的电池组的电量时随时准备好被使用。例如，用户可能正在用无线电动工具进行工作，其中，当时需求可能大于直接从源谐振器供电所能够实现的。在这种情况下，尽管本文所述的系统和方法可以向处于范围内的使用中的电池组提供充电功率，电池组仍可能耗尽，因为功率使用可能已超过再充电速率。而且，在使用设备时，用户可能仅是移入和移出范围，或者完全在范围外。然而，用户可以将额外电池组放置在源谐振器附近，其已在未使用时被再充电，并且现在被充分地充电以供使用。在另一示例中，用户可能正在用远离源谐振器附近的电动工具进行工作，但是留下补充电池组在源谐振器的附近充电，诸如在具有便携式源谐振器或延长线源谐振器的房间中、在用户的交通工具中、在用户的工具箱中等等。这样，用户可能不用担心花费时间和 / 或记住将其电池组插上电源以供将来使用。用户可能只需用已充电的电池组来替换已使用的电池组并将已使用的一个放置在源谐振器附近以再充电。可以将设备谐振器构建到具有已知电池形状因数和覆盖区的外壳中，并且可以替换已知设备和应用中的传统化学电池。例如，可以将设备谐振器构建到具有相当于 AA 电池、AAA 电池、D 电池、9V 电池、膝上型计算机电池、蜂窝电话电池等的机械尺寸的外壳中。除设备谐振器之外，该外壳可以包括较小的“纽扣电池”以存储电量并在时间或距离方面提供延长操作。除纽扣电池之外或作为其替代，可以将其它储能设备与设备谐振器或任何相关联的功率转换电路集成起来。这些新的能量组可以提供与传统电池所提供的类似的电压和电流水平，但是可以由设备谐振器、能量转换电子装置、小电池等组成。这些新的能量组可以比传统电池更持久，因为其可以被更容易地再充电，并且可以在其位于无线功率区中时不断地再充电。另外，此类能量组可以比传统电池更轻，使用和储存起来可以更安全，可以在更广的温度和湿度范围内操作，在被丢弃时对环境的损害更少等等。如本文所述，当在如本文所述的无线功率区中使用这些能量组时，其可以超过产品的寿命。

[0528] 本文所述的系统和方法可以用来为视觉显示器供电，诸如膝上型计算机屏幕的情况，但是更一般地，将包括现在的电气和电子组件中利用的大量各种各样的显示器，诸如在电视、计算机监视器、台式计算机监视器、膝上型计算机显示器、数字相框、电子书、移动设备显示器（例如在电话、PDA、游戏机、导航设备、DVD 播放器上）等中。可以通过本文所述的无线功率传输系统中的一个或多个来供电的显示器还可以包括嵌入式显示器，诸如被嵌入电子组件（例如，音频设备、家用电器、汽车显示器、娱乐设备、现金出纳机、遥控器）中、家具中、建筑物基础设施中、交通工具中、物体的表面上（例如在交通工具、建筑物、衣物、

标志、运输工具的表面上）等。显示器可以是非常小的，具有微小的谐振器件，诸如在如本文所述的智能卡中，或者是非常大的，诸如在广告牌中。使用本文公开的原理供电的显示器还可以是多种成像技术中的任何一个，诸如液晶显示器（LCD）、薄膜晶体管 LCD、无源 LCD、阴极射线管（CRT）、等离子体显示器、投影仪显示器（例如，LCD、DLP、LCOS）、表面传导电子发射显示器（SED）、有机发光二极管（OLED）等。源线圈配置可以包括通过如本文所述的无线延长线附着于主电源，诸如建筑物电源、交通工具电源等；附着于组件电源，诸如电气组件的底座（例如，计算机的底座、TV 的线缆箱）；中间继电器源线圈等等。例如，将数字显示器悬挂在墙壁上可能是非常吸引人的，诸如无线的或通过便携式存储器件来接收其信息信号的数字相框的情况，但是由于需要不雅观的电源线可使得其不美观。然而，使用嵌入数字相框中的设备线圈（诸如被缠绕在框架部分内）可以允许在根本没有导线的情况下悬挂数字相框。然后可以将源谐振器放置在数字相框附近，诸如在墙壁另一面的隔壁房间中，通过诸如本文所述的无线延长线、通过房间中央源谐振器等直接用插头插入传统电源插座中。

[0529] 本文所述的系统和方法可以提供电子装置的不同部分之间的无线功率传输。继续膝上型计算机的示例，并且在没有限制的情况下，膝上型计算机的屏幕可能要求来自膝上型计算机的底座的功率。在这种情况下，在传统上已经通过屏幕与底座之间的膝上型计算机的铰链连接部分从膝上型计算机的底座到屏幕直接电连接来传送电功率。当利用有线连接时，有线连接可能易磨坏并破损，膝上型计算机的设计功能可能受到要求的直接电连接的限制，膝上型计算机的设计美感可能受到要求的直接电连接的限制等等。然而，可以在底座与屏幕之间进行无线连接。在这种情况下，可以将设备谐振器放置在屏幕部分中以对显示器供电，并且可以由第二设备谐振器、由传统有线连接、由谐振器 - 电池 - 直接电连接的混合等来对底座供电。这样，不仅由于去除物理有线连接而可以改善功率连接的可靠性，而且，由于没有与铰链相关联的物理导线，可以允许设计师来改善膝上型计算机的铰链部分的功能和 / 或美学设计。在这里已经再次地使用膝上型计算机来举例说明本文公开的原理如何可以改善电气或电子设备的设计，并且不应以任何方式将其视为限制性的。例如，具有分离的物理部分的许多其它电气设备可以受益于本文所述的系统和方法，诸如在门上具有电气功能件的冰箱，包括制冰机，传感器系统、灯等；被接头分离的具有活动部分的机器人；汽车的动力系统和汽车门中的组件等等。本领域的技术人员将认识到经由设备谐振器从外部源谐振器向设备提供功率或经由设备谐振器从外部或内部源谐振器向设备的一部分提供功率的能力可跨越电气和电子设备的范围广泛地适用。

[0530] 本文公开的系统和方法可以提供设备之间（诸如已充电设备与未充电设备之间）的电功率的共享。例如，已充电设备或器具可以充当源并向附近的设备或器具发送预定量的能量、拨入量的能量、请求和批准量的能量等。例如，用户可能具有蜂窝电话和数字式照相机，两者都能够通过嵌入式源和设备谐振器来传送和接收功率，并且发现设备中的一个（例如蜂窝电话）的电量是低的。用户然后可以从数字式照相机向蜂窝电话转移电量。这些设备中的源和设备谐振器可以利用相同物理谐振器进行传输和接收，利用单独的源和设备谐振器，可以将一个设备设计为接收并传送，并将另一个设计为仅接收，可以将一个设备设计为仅传送并将另一个设计为仅接收等等。

[0531] 为了防止完全耗尽设备的电池，可以具有允许用户指定接收设备有权获得多少电源的设定。例如，对可用于外部设备的功率的量施加限制并有能力在电池功率降到低于阈

值时关闭功率传输可能是有用的。

[0532] 本文所述的系统和方法可以向与电气装置相关联的附近电气或电子组件提供无线功率转移，其中，源谐振器在电气装置中且设备谐振器在电子组件中。还可以将源谐振器连接到、用插头插入、附着到电气装置，诸如通过电气装置的通用接口（例如，USB 接口、PC 卡接口）、附加电源插座、万用附着点等。例如，源谐振器可以在书桌上的计算机的结构内部，或者被集成到某一对象、垫子等中，其被连接到计算机，诸如到计算机的 USB 接口之一中。在被嵌入对象、垫子等中并通过 USB 接口供电的源谐振器的示例中，可以在不需要集成到任何其它电子设备中的情况下容易地将源谐振器添加到用户的台式计算机，因此，方便地提供无线能量区，在该无线能量区周围可以对多个电气和 / 或电子设备供电。所述电气装置可以是计算机、照明灯具、专用源谐振器电气装置等，并且所述附近组件可以是计算机外围设备、外围电子组件、基础设施设备等的，诸如计算机键盘、计算机鼠标、传真机、打印机、扬声器系统、蜂窝电话、音频设备、对讲机、音乐播放器、PDA、灯、电动削铅笔器、风扇、数字相框、计算器、电子游戏等。例如，计算机系统可以是具有利用‘无线键盘’和‘无线鼠标’的集成源谐振器的电气装置，其中，使用术语无线在这里意在表明每个设备与计算机之间存在无线通信装置，并且其中，每个设备仍必须包含单独的电池电源。结果，将需要周期性地更换电池，并且在大公司中，可能为支持人员造成用于电池更换、电池成本和电池的适当处理的相当大的负担。可替换地，本文所述的系统和方法可以提供从计算机的主体到这些外围设备中的每一个的无线功率传输，如本文所述，包括不仅到键盘和鼠标的功率，而且到诸如传真机、打印机、扬声器系统等的其它外围组件的功率。被集成到电气装置中的源谐振器可以提供到多个外围设备、用户设备等的无线功率传输，使得对用于源谐振器集成电气装置附近区域中的设备的电池进行充电和 / 或更换的需要显著减少。电气装置还可以为调整电气装置与无线供电设备之间的功率转移参数提供调谐或自动调谐软件、算法、装置等。例如，电气装置可以是用户桌面上的计算机，并且可以将源谐振器集成到计算机中或用插头插入计算机中（例如，通过 USB 连接），其中，计算机提供用于提供调谐算法的装置（例如，通过在计算机上运行的软件程序）。

[0533] 本文公开的系统和方法可以提供到与机构基础设施组件相关联的附近电气或电子组件的无线功率转移，其中，源谐振器被安装在机构基础设施组件中或其上，并且设备谐振器在电子组件中。例如，机构基础设施组件可以是一件家具、固定墙壁、活动墙壁或分隔物、天花板、地板和被附着或集成到桌子或书桌中的源谐振器（例如，刚好在表面之下 / 之上、在侧面上、被集成到桌面或桌腿中）、放置在地板上的垫子（例如，在书桌下面、放置在书桌上）、车库地板上的垫子（例如，将对汽车和 / 或汽车中的设备充电）、在停车场 / 车库中（例如，在停车处附近的柱子上）、电视（例如用于对遥控器充电）、计算机监视器（例如将对无线键盘、无线鼠标、蜂窝电话供电 / 充电）、椅子（例如用于对电热毯、医疗设备、个人健康监视器供电）、图画、办公室家具、常见家用电器等。例如，机构基础设施组件可以是办公室隔间中的照明灯具，其中，源谐振器和照明器具内的灯这二者可以被直接连接到该机构的有线电源。然而，用现在在照明灯具中提供的源谐振器，被连接到设备谐振器或与设备谐振器集成的那些附近电气或电子组件将不需要具有任何附加有线连接。另外，如本文所述，可以减少对更换具有设备谐振器的设备的电池的需要。

[0534] 使用本文所述的系统和方法来从中央位置（诸如从电气装置中的源谐振器、从机

构基础设施组件等）向电气和电子设备供应功率可以使周围工作区域的电气布线基础设施最小化。例如，在企业办公空间中，通常存在需要由有线连接来供电的大量电气和电子设备。在利用本文所述的系统和方法的情况下，可以消除此布线的大部分，为企业节省安装成本，降低与具有电气布线的办公室墙壁相关联的物理限制，使对电源插座和电源板的需要最小化等等。本文所述的系统和方法可以通过减少与安装、重新安装（例如重配置办公空间）、维护等相关联的电气基础设施来为企业省钱。在另一示例中，本文公开的原理可以允许在房间当中无线地设置电源插座。在这里，可以将源放置在期望在其上放置电源插座的地板的位置之下的地下室的天花板上。可以将设备谐振器放置在正好在其上面的房间的地板上。由于相同的原因，在天花板的中心处安装新的照明灯具（或关于此方面的任何其它电气设备，例如照相机、传感器等）现在实质上是更容易的。

[0535] 在另一示例中，本文所述的系统和方法可以"通过"墙壁来提供功率。例如，假设在一个房间中（例如，在墙壁上）具有电源插座，但是想要在隔壁房间中具有电源插座，不需要呼叫电气工人或钻通墙壁或在墙壁周围牵引导线等。于是可以将源谐振器放置在一个房间中的墙壁上，并且在墙壁的另一侧放置设备谐振器电源插座/拾波器(outlet/pickup)。这可以对平面屏幕TV或立体音响系统等供电（例如，一个人可能不想在起居室中具有爬上墙壁的丑陋的导线，但是不介意在隔壁房间中具有沿着墙壁走的类似导线，例如储藏室或壁橱，或有使看不到沿着墙壁铺设的导线的家具的房间）。本文所述的系统和方法可用来在不需要通过外墙钻孔或在其中安装导管的情况下从室内源向在家庭或建筑物外面的各种电气设备转移功率。在这种情况下，可以在没有美学或结构损坏或与通过墙壁和墙板钻孔相关联的风险的情况下在建筑物外面对设备无线地供电。另外，本文所述的系统和方法可以提供放置传感器以帮助为装配有外部设备谐振器的电气组件放置内部源谐振器。例如，家的主人可以在他们家的外面放置安全灯，其包括无线设备谐振器，并且现在需要适当地或最佳地将源谐振器放置于家的内部。在源和设备谐振器之间起作用的放置传感器可以通过诸如以视觉指示、音频指示、显示指示等来指示何时放置是好的或好到什么程度来使得该放置更好。在另一示例中，并且以相似的方式，本文所述的系统和方法可以提供设备在家庭或建筑物的屋顶上的安装，诸如无线电发射机和接收机、太阳能电池板等。在太阳能电池的情况中，可以将源谐振器与电池板相关联，并且可以在不需要通过屋顶钻孔的情况下向建筑物内部的配电板无线地转移功率。本文所述的系统和方法可以允许在不需要钻孔的情况下跨越交通工具的墙壁（诸如通过顶棚）来安装电或电气设备，诸如用于汽车、船舶、飞机、火车等。这样，可以在不钻孔的情况下保持交通工具的壁完整，因此保持交通工具的价值、保持水密性、消除对布线的需要等。例如，将警报器或灯安装到警车的顶棚减少了汽车将来的转售，但是用本文所述的系统和方法，可以在不需要钻孔的情况下将任何灯、喇叭、警报器等附着于顶棚。

[0536] 本文所述的系统和方法可以用于从太阳能光伏(PV)电池板无线转移功率。具有无线功率转移能力的PV电池板可以具有多个益处，包括更简单的安装、更灵活、可靠和防风雨设计。可以使用无线功率转移来从PV电池板向设备、房屋、交通工具等转移功率。太阳能PV电池板可以具有允许PV电池板直接对被使能以接收无线功率的设备供电的无线源谐振器。例如，可以将PV电池板直接安装到交通工具、建筑物等的顶棚上。可以将由PV电池板捕捉的能量直接无线地转移至交通工具内部或建筑物屋顶下面的设备。具有谐振器的

设备可以无线地从PV电池板接收功率。可以使用来自PV电池板的无线功率来向被耦合到房屋、交通工具等的有线电气系统的谐振器转移能量，从而在不要求外部PV电池板与内部电气系统之间的任何直接接触的情况下允许常规设备的传统配电和供电。

[0537]　用无线功率转移，可以实现屋顶PV电池板的明显更简单的安装，因为可以无线地从电池板向房屋中的捕捉谐振器传送功率，从而消除所有室外布线、连接器和导管以及通过结构的屋顶或墙壁的任何孔。与太阳能电池一起使用的无线功率转移可以具有这样的益处，即其能够减少屋顶危险，因为其消除了对电气工人在屋顶上工作以将电池板、线和分线盒互连的需要。安装与无线功率转移集成的太阳能电池板可以要求不那么熟练的工人，因为需要进行较少的电接触。用无线功率转移，可以需要较少的现场具体设计，因为该技术为安装者提供了对每个太阳能PV电池板单独地进行最优化和定位的能力，从而显著地减少了对昂贵的工程和电池板布局服务的需要。可能需要谨慎地平衡每个电池板上的太阳能负载，并且不需要专用的DC布线布局和互连。

[0538]　对于PV电池板的屋顶或墙上安装而言，可以将捕捉谐振器安装在屋顶的下侧，在墙壁内部，或者在太阳能PV电池板的一个底部或两个内的任何其它容易接近的内部空间。在图51中示出了示出可能的一般屋顶PV电池板安装的图。可以将各种PV太阳能收集器安装在屋顶的顶部，其中无线功率捕捉线圈被安装在屋顶下面的建筑物内。PV电池板中的谐振器线圈能够通过屋顶将其能量无线地转移至无线捕捉线圈。可以收集来自PV电池的捕捉能量并将其耦合到房屋的电气系统以对电气和电子设备供电或在产生比需要的更多功率时耦合到电力网。在不要求穿透建筑物的屋顶或墙壁的孔或导线的情况下从PV电池捕捉能量。每个PV面板可以具有被耦合到交通工具或建筑物内部上的相应谐振器的谐振器。多个电池板可以利用相互之间的无线功率转移来向被耦合到交通工具或房屋内部上的谐振器的一个或多个指定电池板转移或收集功率。电池板可以在其侧面或在其周界中具有无线功率谐振器，其能够耦合到位于其它类似电池板中的谐振器，允许从电池板向电池板转移功率。可以提供附加总线或连接结构，其从建筑物或交通工具外部上的多个电池板无线地耦合功率并将功率转移至建筑物或交通工具内部上的一个或多个谐振器。

[0539]　例如，如图51所示，可以将源谐振器5102耦合到安装在建筑物的屋顶5104之上的PV电池5100。相应的捕捉谐振器5106被放置在建筑物内部。然后能够在不具有通过建筑物的直接孔和连接的情况下从外面的源谐振器5102向建筑物内部的设备谐振器5106转移由PV电池捕捉的太阳能。

[0540]　具有无线功率转移的每个太阳能PV电池板可以具有其自己的逆变器，通过单独地对每个电池板的功率产生效率进行最优化来显著地改善这些太阳能系统的经济效益，支持单个安装中的电池板尺寸和类型的混合，包括单个电池板“按需付费”系统扩展。安装成本的降低可以使得对于安装而言单个电池板是经济的。消除了对电池板串设计和多个电池板的小心定位和定向的需要，并消除了系统的单点故障。

[0541]　PV太阳能电池板中的无线功率转移可以实现更多的太阳能部署方案，因为防风雨的太阳能PV电池板消除了用于通过诸如汽车顶棚和船甲板的密封表面布线而钻孔的需要，并消除了将电池板安装在固定位置的要求。用无线功率转移，可以临时地部署PV电池板，然后移动或去除，而不留下对周围结构的永久性变更。可以在阳光充足的日子将其放置在院子中，并跟随者太阳来回移动，或者例如带到内部以进行清洁和储存。对于后院或移动

太阳能 PV 应用而言，可以在地面上投掷具有无线能量捕捉器件的延长线或放置在太阳能单元附近。捕捉延长线能够相对于元件被完全密封并被电隔离，使得可以在任何室内或室外环境中使用它。

[0542] 用无线功率转移，可能不需要导线或外部连接，或者 PV 太阳能电池板可以是完全防风雨的。能够预期显著改善在太阳能 PV 功率产生和传输电路中的电气组件的可靠性和寿命，因为防风雨外壳能够保护组件免受 UV 辐射、湿度、天气等的影响。用无线功率转移和防风雨外壳，可以使用不那么昂贵的组件，因为其将不再被直接暴露于外部因素和天气要素，并且其可以降低 PV 电池板的成本。

[0543] PV 电池板与建筑物或交通工具内部的捕捉谐振器之间的功率转移可以是双向的。可以从房屋电力网向 PV 电池板传送能量以在电池板不具有足以执行某些此类任务的能量时提供功率。相反的功率流动可以用来从电池板熔化雪，或对将相对于太阳能量将电池板定位于更适宜的位置的电动机进行供电。一旦雪被熔化或电池板被重新定位且 PV 电池板能够产生其自己的能量，功率转移的方向就能够恢复正常，从 PV 电池板向建筑物、交通工具或设备递送功率。

[0544] 具有无线功率转移的 PV 电池板可以包括安装时的自动调谐以保证到无线收集器的最大且高效的功率转移。不同安装中的屋顶材料的变化或 PV 电池板与无线功率收集器之间的距离变化可能影响无线功率转移的谐振器的性能或扰动其性质。为了降低安装复杂性，无线功率转移组件可以包括自动地调整其工作点以补偿由于材料或距离而引起的任何效应的调谐能力。可以调整频率、阻抗、电容、电感、占空比、电压水平等以保证高效且安全的功率转移。

[0545] 本文所述的系统和方法可以用来临时地或在传统电源插座到无线功率区的扩展中提供无线功率区，诸如通过使用无线功率延长线。例如，可以将无线功率延长线配置为用于连接到传统电源插座的插头、诸如在传统功率延长线中的长导线和在另一端的谐振器源线圈（例如，代替扩展部分的传统插座的替代或除此之外）。还可以配置其中在沿着无线延长线的多个位置处存在源谐振器的无线延长线。然后，此配置可以替换其中存在无线功率配置设备的任何传统延长线，诸如向不存在方便的电源插座的位置（诸如其中不存在电源插座的起居室中的位置）提供无线功率、其中不存在有线功率基础设施的临时无线功率（例如施工现场）、到其中不存在电源插座的院子中（例如，对于被无线地供电以减少切断传统电线的机会的各方或庭院装饰设备）等。还可以使用无线延长线作为墙壁或结构内的落差 (drop) 以在该落差附近内提供无线功率区。例如，可以在新的或整修的房间的墙壁内敷设无线延长线以在不需要安装传统电气布线和电源插座的情况下提供无线功率区。

[0546] 可以利用本文所述的系统和方法来在交通工具的活动部分或旋转组件、机器人、机械设备、风力涡轮机或具有活动部分的任何其它类型的旋转设备或结构（诸如机器人臂、建筑用运输工具、活动平台等）之间提供功率。传统上，可以由例如集电环或由旋转接头来提供此类系统中的功率。使用如本文所述的无线功率转移，可以显著地改善这些设备的设计简化、可靠性和寿命，因为能够在没有可能随着时间的推移磨损或损坏的任何物理连接或接触点的情况下在一定范围的距离内转移功率。特别地，源和设备线圈内的优选共轴和平行对准可以提供不会严重地受到两个线圈的相对旋转运动所调制的无线功率传输。

[0547] 可以利用本文所述的系统和方法通过提供一系列的源－设备－源－设备谐振器来

扩展超过单个源谐振器的范围的功率需要。例如，假设现有独立车库不具有电源且所有者现在想要安装新的供电服务。然而，所有者可能不想遍及车库敷设导线，或者不得不打入墙壁中以遍及该结构对电源插座进行布线。在这种情况下，所有者可以选择将源谐振器连接到新的供电服务，使得能够遍及车库的后面将无线功率供应至设备谐振器电源插座。然后，所有者可以安装设备－源‘中继器’以向在车库前面的设备谐振器电源插座供应无线功率。也就是说，功率中继器现在可以从主源谐振器接收无线功率，然后向第二源谐振器供应可用功率以向在车库前面的第二组设备谐振器供应功率。可以反复地重复此配置以扩展供应的无线功率的有效范围。

[0548] 可以使用多个谐振器来扩展能量阻挡材料周围的功率需要。例如，可能期望将源谐振器集成到计算机或计算机监视器中，使得谐振器可以对放置在监视器或计算机的周围且尤其是前面的设备供电，诸如键盘、计算机鼠标、电话等。由于美学、空间约束等，可以将可以用于源谐振器的能量源仅定位于或连接到监视器或计算机的后面。在计算机或监视器的许多设计中，在设计和封装中使用包含电路的金属和金属组件，这可能限制和阻止从在监视器或计算机后面的源谐振器到监视器或计算机前面的功率转移。可以将附加重发器谐振器集成到监视器或计算机的底座或基座中，其耦合至监视器或计算机后面的源谐振器并允许到监视器或计算机前面的空间的功率转移。被集成到监视器或计算机的底座或基座中的中间谐振器不要求附加电源，其从源谐振器捕捉功率并将功率转移至监视器或计算机的阻挡或功率屏蔽金属组件周围的前面。

[0549] 可以将本文所述的系统和方法构建到空间的结构部分中、放置在空间的结构部分上、从空间的结构部分悬挂、嵌入空间的结构部分中、集成到空间的结构部分中等，所述空间诸如为交通工具、办公室、家庭、房间、建筑物、室外结构、道路基础设施等。例如，可以将一个或多个源构建到、放置于、悬挂于、嵌入或集成到墙壁、天花板或顶棚嵌板、地板、分隔物、门口、楼梯、隔室、道路表面、人行道、坡道、围栏、外部结构等。可以将一个或多个源构建到结构内或周围的实体中，例如床、书桌、椅子、地毯、镜子、钟表、显示器、电视、电子设备、柜台、桌子、一件家具、一件艺术品、外壳、隔间、顶棚嵌板、地板或门板、挡泥板、树干、轮舱、支柱、横梁、支撑体或任何类似实体。例如，可以将源谐振器集成到用户的汽车的挡泥板中，以便可以从挡泥板源谐振器为装配有或被连接到设备谐振器的任何设备供应功率。这样，被带进或集成到汽车中的设备可以在处于汽车中的同时被不断地充电或供电。

[0550] 本文所述的系统和方法可以通过诸如船、汽车、卡车、公交车、火车、飞机、卫星等交通工具的壁来提供功率。例如，用户可能不想通过交通工具的壁钻孔以便向在交通工具外面的电气设备提供功率。可以将源谐振器放置在交通工具内部，并且可以将设备谐振器放置在交通工具外面（例如，在窗户、墙壁或结构的相对侧）。这样，用户可以实现使外部设备到交通工具的放置、定位和附着最优化方面的更大灵活性（诸如不考虑供应或敷设到设备的电气连接）。另外，用无线地供应的电功率，可以将外部设备密封，使得其是水密的，使得其在电气设备被暴露于天气（例如雨）、或者甚至被淹没在水中的情况下是安全的。可以在多种应用中采用类似技术，诸如在对混合动力交通工具、导航和通信设备、施工设备、遥控或机器人设备等充电或供电时，其中由于暴露的导体而存在电学风险。本文所述的系统和方法可以通过真空室或其它封闭空间的墙壁来提供功率，诸如在半导体生长和处理、材料涂敷系统、养鱼池、危险物品搬运系统等中使用的那些。可以向转换级、机器人臂、旋转

级、操纵和收集设备、清洁设备等提供功率。

[0551] 本文所述的系统和方法可以向厨房环境提供无线功率，诸如向台面器具，包括混合器、咖啡壶、烤面包器、烤面包器烘箱、烤架、烘培盘、电煮锅、电热壶、电炒锅、松饼机、搅拌器、食物加工机、瓦罐锅、电热餐盘、电磁炉、灯、计算机、显示器等。本技术可以改善设备的移动性和 / 或定位灵活性，减少储存在和散布在整个台面上的电源线的数目，改善设备的可洗性等。例如，电煮锅传统上可以具有单独的部分，诸如可浸入水中以便清洗的一个和不可浸入水中的一个，因为其包括外部电连接（例如，线缆或用于可去除线缆的插座）。然而，用被集成到该单元中的设备谐振器，所有电连接可以是密封的，因此现在可以将整个设备浸没以进行清洁。另外，外部线缆的不存在可以消除对可用电气壁装电源插座的需要，并且不再需要跨越台面放置电源线或将电烤盘的位置局限于可用电气壁装电源插座的位置。

[0552] 本文所述的系统和方法可以提供到装配有设备谐振器的设备的持续供电 / 充电，因为该设备不离开原谐振器的附近，诸如固定电气设备、个人计算机、内部通信系统、安全系统、家庭机器人、灯具、遥控单元、电视、无绳电话等。例如，可以经由无线功率对家庭机器人（例如 ROOMBA）供电 / 充电，因此在没有再充电的情况下任意地工作。这样，可以修改用于家庭机器人的电源设计以利用此持续的无线功率源，诸如将机器人设计为在不需要电池的情况下仅使用来自源谐振器的功率，使用来自源谐振器的功率来对机器人的电池再充电，使用来自源谐振器的功率对机器人的电池进行涓流充电，使用来自源谐振器的功率来对电容储能单元充电等。对于本文公开的任何和所有设备，可以启用、设计和实现电源和电源电路的类似最优化。

[0553] 本文所述的系统和方法可以向电热毯、加热垫 / 片等提供无线功率。这些电热设备可以用于多种室内和室外用途。例如，可以从与附近交通工具、建筑物、电线杆、交通灯、便携式电源单元等相关联或被构建到其中的源谐振器对提供给诸如保安、警察、建筑工人等室外工作人员的手和脚取暖器远程地供电。

[0554] 本文所述的系统和方法可以用来对包含设备谐振器且可以在信息设备处于包含源谐振器的信息源附近时被上电的便携式信息设备供电。例如，信息设备可以是在用户的口袋、钱夹、钱包、交通工具、自行车等中携带的卡（例如，信用卡、智能卡、电子卡等）。便携式信息设备可以在其在信息源附近时被上电，所述信息源随后向便携式信息设备传送信息，所述便携式信息设备可以包括电子逻辑、电子处理器、存储器、显示器、LCD 显示器、LED、RFID 标签等。例如，便携式信息设备可以是具有在处于信息源附近时“开启”的显示器的信用卡，并且为用户提供诸如“您刚刚接收到用于您下一次购买可口可乐的扣除 50％的赠券”的某些信息。信息设备可以存储诸如可以在后续购买时使用的赠券或折扣信息的信息。便携式信息设备可以被用户编程为包含任务、日历约会、备忘录、警报和提示等。信息设备可以接收现时价格信息并将先前选择和识别的项目的位置和价格的信息告知用户。

[0555] 本文所述的系统和方法可以提供无线功率传输以直接地对传感器中的电池供电或充电，所述传感器诸如为环境传感器、安全传感器、农业传感器、电器传感器、食物腐败传感器、功率传感器等，其可以被安装到结构内部、结构外部、掩埋在地下、安装在墙壁中等。例如，此能力可以取代将旧的传感器掘出以在物理上更换电池或由于旧的传感器没有能力且不再可操作而掩埋新传感器的需要。可以通过使用便携式传感器源谐振器充电单元周期性地对这些传感器充电。例如，承载装配有源谐振器的电源（例如提供～ kW 的功率）的卡

车可以在几分钟内向～ mW 传感器提供足够的功率以将传感器的操作持续时间延长超过一年。还可以直接对传感器供电，诸如对处于难以用导线将其连接但其仍处于源谐振器附近区域内的位置处的传感器供电，诸如在房屋外面的设备（安全照相机）、在墙壁另一面上、在门上的电动锁上等。在另一示例中，可以通过本文所述的系统和方法对原本可能需要为其提供有线功率连接的传感器供电。例如，接地故障中断器断路器将残余电流和过电流保护组合在一个设备中以便安装到维修面板中。然而，传统上必须独立地对传感器进行布线以便供电，并且这使安装变得复杂。然而，用本文所述的系统和方法，可以用设备谐振器对传感器供电，其中，在维护面板内提供单个源谐振器，由此简化维护面板内的安装和布线配置。另外，单个源谐振器可以对安装在被安装在维护面板内、遍布维护面板、安装到附加的附近维护面板等的源谐振器的任一侧上的设备谐振器供电。本文所述的系统和方法可以用来向与配电板、电气室、配电等相关联的任何电气组件提供无线功率，诸如在配电盘、配电板、断路器、变压器、备用电池、火警控制面板等中。通过使用本文所述的系统和方法，可以更容易地安装、维护和修改配电和保护组件和系统安装。

[0556] 在另一示例中，由电池供电的传感器可以连续地运行而不需要更换电池，因为可以供应无线功率以周期性地或连续地对电池进行再充电或涓流充电。在此类应用中，甚至低水平的功率可以充分地对电池再充电或保持电池中的电量，显著地延长其寿命和扩展其有用性。在某些情况下，可以将电池寿命延长至比其供电的设备的寿命更长，使其本质上成为“用不完”电池。

[0557] 本文所述的系统和方法可以用于对植入的医疗器件电池充电，诸如在人工心脏、起搏器、心脏泵、胰岛素泵、用于神经或针压止血 / 穴位刺激的植入线圈等中。例如，使导线粘在病人体外可能是不方便或不安全的，因为导线可以是可能的传染的恒定来源，并且通常对于病人来说是非常令人不愉快的。本文所述的系统和方法还可以用来从外部源对病人身体里或身体上的医疗器件充电或供电，诸如从具有源谐振器的病床或医院墙壁或天花板。此类医疗器件可能更容易附着、读取、使用和监视病人。本文所述的系统和方法可以缓解对将导线附着于病人和病人的床或床边的需要，使得病人来回移动和起身离开床更加方便，而没有无意中断开医疗器件的连接的风险。这可以例如有用地用于具有对其进行监视的多个传感器的病人，诸如用于测量脉搏、血压、葡萄糖等。对于利用电池的医疗和监视器件而言，可能需要相当频繁地更换电池，可能一周多次。这可以引起与人们忘记更换电池、未注意到设备或监视器由于电池耗尽而不工作、与电池盖和舱室的不适当清洁相关联的感染等相关联的风险。

[0558] 本文所述的系统和方法可以降低医疗器件植入程序的风险和复杂性。现在，诸如心室辅助器件、起搏器、除颤器等许多可植入医疗器件由于其器件外形因素而要求手术植入，这可能在很大程度上受到被集成在器件中的长寿命电池的体积和形状的影响。在一方面，本文描述了对电池再充电以使得电池尺寸可以被大大地减小且可以诸如经由导管来植入整个器件的非侵入式方法。导管可植入器件可以包括集成捕捉或设备线圈。可以将导管可植入捕捉或设备线圈设计为使得其可以诸如在植入之后在内部进行布线。可以经由导管来部署捕捉或设备线圈作为卷起的柔性线圈（例如，卷起的例如两个卷轴，在内部用简单的扩展器（spreader）机构容易地展开）。电源线圈可以被穿戴在被裁减为适合将源放置在适当位置的背心或衣物中；可以被放置在椅垫或床垫里；可以被集成到床或家具中等。

[0559] 本文所述的系统和方法可以使得病人能够具有‘传感器背心’、传感器补丁等，其可以包括可以在处于源谐振器附近时被供电或充电的设备谐振器和多个医学传感器中的至少一个。传统上，此类医疗监视机构可以具有要求的电池，因此使得背心、补丁等沉重且可能不切实际。但是，使用本文公开的原理，可以不要求电池（或较轻的可再充电电池），因此使得此类设备更加方便和实际，尤其是在可能没有带子的情况下（诸如在没有电池或具有明显更轻的电池的情况下用粘合剂）将此类医疗设备固定就位的情况下。医疗机构可以能够远程地读取传感器数据，目的是预见中风、心脏病发作等（例如提前几分钟）。当由在远离医疗机构的位置处（诸如在其家中）的人来使用背心时，则可以将背心与蜂窝电话或通信设备集成以在事故或医学事件的情况下呼叫救护车。本文所述的系统和方法在背心将被老年人使用时的情况下可能特别有用，其中，可能未按要求遵循传统的非无线再充电实践（例如，更换电池、在晚上插上电源等）。本文所述的系统和方法还可以用于对残障或残废人（其可能具有更换电池或对电池再充电方面的困难）使用或对其进行帮助的设备充电，或可靠地向其享用或依赖的设备供应功率。

[0560] 本文所述的系统和方法可以用于假肢的充电和供电。假肢在取代原始肢体（诸如手臂、腿、手和脚）的功能方面已变得非常有能力。然而，电动假肢可能要求相当大的功率（诸如 10 ～ 20W），其可以转换成相当大的电池。在这种情况下，截肢者可以在持续时间不是很长的轻电池和持续时间长得多但更加难以来回‘携带’的重电池之间进行选择。本文所述的系统和方法可以使得能够用设备谐振器对假肢供电，其中，源谐振器由用户携带并被附着于可以更容易地支撑重量的身体的一部分（例如，诸如腰周围的带子）或位于其中用户将花费大量的时间以保持设备被充电或供电的外部位置上，诸如在其书桌处、其汽车中、其床上等。

[0561] 本文所述的系统和方法可以用于电动外骨骼的充电和供电，诸如在工业和军事应用中使用的那些，以及用于老年 / 体弱 / 生病的人。电动外骨骼可以向一个人提供“力量”的高达 10 至 20 倍的增加，使得那个人能够在没有太多疲劳的情况下在物理上反复地执行辛苦的任务。然而，外骨骼在某些使用情形中可能要求超过 100W 的功率，因此电池供电操作可能局限于 30 分钟或更少。本文所述的无线功率的递送可以为外骨骼的用户提供用于对外骨骼的结构运动供电和用于对遍及该结构分布的各种监视器和传感器供电的连续功率供应。例如，可以从本地源谐振器为具有（一个或多个）嵌入式设备谐振器的外骨骼提供功率。对于工业外骨骼而言，可以将源谐振器放置在机构的墙壁中。对于军用外骨骼而言，可以由装甲车来承载源谐振器。对于用来帮助老年人护理者的外骨骼而言，可以将（一个或多个）源谐振器安装或放置在一个人的家的（一个或多个）房间中。

[0562] 本文所述的系统和方法可以用于便携式医疗设备的供电 / 充电，诸如供氧系统、通风机、除颤器、注药泵、监视器和救护车或移动医疗单元中的设备等。能够将病人从事故现场运送到医院，或者为了将病人从其床上移动至其它房间或区域，并带着与之附着并始终被供电的所有设备为病人的健康和最后的康复提供很大的益处。当然，能够理解因为其电池耗尽或因为必须在以任何方式运送或移动病人的同时将其拔出插头而停止工作的医疗设备引起的风险和问题。例如，在汽车事故现场的紧急医疗队可能需要在现场的病人的紧急护理中利用便携式医疗设备。此类便携式医疗设备必须被适当地维护，使得存在足够的电池寿命以在紧急状态的持续时间内对设备供电。然而，情况常常是设备未被适当地维

护，使得电池未充满电，并且在某些情况下，所需的设备对于第一反应者不可用。本文所述的系统和方法可以以自动地且在没有人工干预的情况下提供电池和功率包的充电和维护的方式来向便携式医疗设备（和病人身体上的相关联传感器输入端）提供无线功率。此类系统还受益于不受被附着于在病人的治疗中使用的许多医疗监视器和设备的多种电源线妨碍的改善的病人移动性。

[0563] 本文所述的系统和方法可以用于对个人助听器进行供电／充电。个人助听器需要小且轻以配置到人的耳朵中或周围。尺寸和重量约束限制能够使用的电池的尺寸。同样地，设备的尺寸和重量限制由于组件的精密而使得难以进行电池更换。设备的尺寸和卫生问题使得难以集成附加的充电端口以允许电池的再充电。本文所述的系统和方法可以被集成到助听器中并可以减小所需电池的尺寸，这可以允许有甚至更小的助听器。使用本文公开的原理，可以在不要求外部连接和充电端口的情况下对助听器的电池再充电。充电和设备电路和小型可再充电电池可以被集成到常规助听器电池的外形因素中，允许对现有助听器进行改装。可以在助听器被人使用和佩戴的同时对其进行再充电。可以将能量源集成到垫子或杯子中，允许在助听器被放置在此类结构中时进行再充电。可以将充电源集成到助听器干燥器盒中，允许在助听器正在干燥或被消毒的同时进行无线再充电。所述源和设备谐振器还可以用来将设备加热，减少或消除对附加加热元件的需要。可以使用由电池或AC适配器供电的便携式充电外壳作为储存和充电站。

[0564] 用于上述医疗系统的源谐振器可以在某些或所有医疗设备的主体中，设备谐振器在病人的传感器和设备上；源谐振器可以在救护车中，设备谐振器在病人的传感器和某些或所有设备的主体上；主源谐振器可以在救护车中以便在医疗设备处于救护车中的同时向医疗设备上的设备谐振器转移无线功率，并且当设备远离救护车时，第二源谐振器可以在医疗设备的主体和病人传感器上的第二设备谐振器中等等。本文所述的系统和方法可以显著地改善医务人员能够将病人从一个位置运送到另一位置的容易性，其中，现在可以减少电线和更换相关电池或手动地对其充电的需要。

[0565] 本文所述的系统和方法可以用于军用交通工具或机构内部的设备的充电，诸如坦克、装甲运输车、移动式掩体等。例如，当士兵在“行动”或任务之后返回交通工具中时，其通常可以开始对其电子设备充电。如果其电子设备装配有设备谐振器，并且在交通工具内部存在源谐振器（例如，集成在交通工具的座位中或顶棚上），则其设备将立即开始充电。事实上，相同交通工具可以向站在外面或在交通工具旁边行走的士兵／机器人（例如来自iRobot的packbot）提供功率。此能力可能在以下方面是有用的：使与其他人的意外电池交换最小化（这可能是重要的问题，因为士兵趋向于仅信任其自己的电池）；使得能够快速离开受到攻击的交通工具；对坦克内部的膝上型计算机或其它电子设备供电或充电，因为坦克内部的过多导线可能引起在降低在“有麻烦”和／或能见度降低的情况下快速地来回移动的能力方面的危险。本文所述的系统和方法可以提供与在军用环境中对便携式电力设备供电相关的显著改善。

[0566] 本文所述的系统和方法可以向诸如高尔夫球车或其它类型的手推车、全地形车、电动自行车、小型摩托车、汽车、割草机、bobcats和通常用于施工和景观美化等的其它交通工具的移动交通工具提供无线供电和充电能力。本文所述的系统和方法可以向微型移动交通工具提供无线供电或充电能力，诸如微型直升机、无人驾驶机、遥控飞机、遥控船、遥控或

机器人飞行器、遥控或机器人割草机或设备、炸弹检测机器人等。例如，在军用交通工具之上飞行以增加其视场的微型直升机在标准电池情况下可以飞行几分钟。如果这些微型直升飞机装备有设备谐振器，并且控制交通工具具有源谐振器，则微型直升飞机可能能够无限期地飞行。本文所述的系统和方法可以提供对电池进行再充电或更换以便在微型移动交通工具中使用的有效替换。另外，本文所述的系统和方法可以向甚至更小的设备提供功率/充电，诸如微型机电系统(MEMS)、纳米机器人、纳米器件等。另外，可以通过将源设备安装在移动交通工具或飞行设备中以使其能够充当野外或飞行中再充电器（其可以自己自发地定位于装配有设备谐振器的移动交通工具附近）来实现本文所述的系统和方法。

[0567] 本文所述的系统和方法可以用来提供用于临时机构的电力网，诸如兵营、石油钻探布置、外景拍摄场所等，其中要求电功率，诸如用于发电机，并且其中通常在临时设备周围敷设电力线缆。当需要设立要求功率的临时机构时存在许多情况。本文所述的系统和方法可以使得能够实现快速地设立并拆掉这些设备的更高效的方式，并且可以减少必须遍及这些设备敷设以供应功率的导线的数目。例如，当特种部队移动至一个区域中时，他们可以支起帐篷并在驻地周围牵引许多导线以提供要求的电力。替代地，本文所述的系统和方法可以使得提供有电源和源谐振器的军用交通工具停泊在驻地的中心处，并将所有的功率提供给其中可以将设备谐振器集成到帐篷中的附近帐篷，或与每个帐篷或区域相关联的某件其它设备。可以使用一系列的源-设备-源-设备谐振器来将功率扩展到更远的帐篷。也就是说，距离交通工具最近的帐篷然后可以向其后面的帐篷提供功率。本文所述的系统和方法可以提供对可以设立和拆掉临时安装的效率的显著改善，由此提高相关联设备的移动性。

[0568] 本文所述的系统和方法可以在交通工具中使用，诸如用于更换导线，安装新设备，对被带入交通工具中的设备供电，对交通工具的电池充电（例如，用于传统气体供电引擎，用于混合动力汽车，用于电车等），对被安装到交通工具内部或外部的设备供电，对在交通工具附近的设备供电等。例如，本文所述的系统和方法可以用来更换导线，诸如用来对遍布于交通工具的灯、风扇和传感器供电。作为示例，典型的汽车可以具有与之相关联的50kg的导线，并且本文所述的系统和方法的使用可以使得能够消除相当数量的此布线。诸如飞机或卫星的较大且更加重量敏感的交通工具的性能可以大大地受益于使必须遍布于交通工具敷设的线缆的数目减少。本文所述的系统和方法可以允许在不需要电线的情况下用电动和电气设备来适应交通工具的可去除或附加部分。例如，摩托车可以具有在骑车人正在进行长途旅行时充当临时行李箱容积的可去除侧箱。这些侧箱可以具有外部灯、内部灯、传感器、自动设备等，并且如果没有装配有本文所述的系统和方法，则可能要求电连接和配线。

[0569] 交通工具内无线功率传输系统可以对在汽车中使用的一个或多个移动设备充电或供电：手持移动电话、蓝牙耳机、蓝牙免提扬声器电话、GPS、MP3播放器、用于经由FM、蓝牙等通过汽车用立体声系统来流式传输MP3音频的无线音频收发机。交通工具内无线功率源可以利用以多个可能结构中的任何一个布置的源谐振器，包括对仪表板上的垫子充电、对安装在地板上或在座位与中央控制台之间的垫子充电、对装配在杯架中或仪表板上的“杯子”或插孔充电等。

[0570] 无线功率传输源可以利用可再充电电池系统，使得所述电源电池每当交通工具电

源被开启时被充电，使得当交通工具被关闭时，无线电源能够从电源电池吸取功率，并且能够继续无线地对仍在汽车中的移动设备充电或供电。

[0571] 未来的带插头电动汽车、混合动力汽车等需要被充电，并且用户可能需要在其回家时或去充电站时插入电源充电。基于一次夜间再充电，用户可能能够在次日驾驶达到50英里。因此，在混合动力汽车的情况下，如果一个人在大多数日子驾驶路程小于50英里，则其将主要靠电力来驾驶。然而，如果其不必记住在晚上将汽车插上电源将是有益的。也就是说，简单地行驶到车库中并使汽车自己负责其自己的充电将是美好的。为此，可以将源谐振器构建到车库地板和／或车库侧壁中，并且可以将设备谐振器构建到汽车的底部（或侧面）中。甚至几kW的转移可能足以在夜间对汽车进行再充电。交通工具内设备谐振器可以测量磁场性质以提供反馈以帮助交通工具（或任何类似设备）到固定谐振源的对准。交通工具可以使用此位置反馈来自动地对其本身进行定位以实现最佳对准，因此实现最佳功率传输效率。另一方法可以是使用位置反馈来帮助人类操作员适当地对交通工具或设备进行定位，诸如通过在其被很好地定位时使LED点亮，提供噪声等。在其中正在传送的功率的量可能对侵入有源场体积的人或动物造成安全威胁的情况下，源或接收器设备可以装配有能够感测到有源场体积的入侵且能够关掉源设备并警告人类操作员的有源照明幕或某个其它外部设备。另外，源设备可以装配有自动感测能力，使得其可以检测到其预期功率传输速率已被入侵元素中断，并且在这种情况下，关掉源设备并警告人类操作员。可以将诸如铰链门或可膨胀气囊的物理或机械结构作为物理障碍结合以防止不期望的入侵。还可以使用诸如光学、磁性、电容、电感等传感器来检测源和设备谐振器之间的外来结构或干扰。可以将源谐振器的形状成形为防止水和碎屑积聚。可以将源谐振器放置在锥形外壳中，或者其可以具有带有有角度顶部以允许水和碎屑滚落的外壳。系统的源可以使用交通工具的电池功率或其自己的电池功率来将其存在传送到源以发起功率传输。

[0572] 可以将源谐振器安装在嵌入式或悬挂支柱上、墙壁上、支架上等以便耦合到安装在电动交通工具的减震器、盖、主体面板等上的设备谐振器。可以将源谐振器封闭或嵌入到诸如靠垫、垫子、波纹管、弹簧加载外壳等柔性外壳中，使得电动交通工具可以在不以任何方式损坏汽车的情况下与包含源线圈的结构进行接触。包含源的结构可以防止对象到达源和设备谐振器之间。由于无线功率转移可能对源和设备线圈之间的不对准相对不敏感，所以多种柔性源结构和停泊程序可能适合于此应用。

[0573] 本文所述的系统和方法可以用来对电动、混合动力或内燃机交通工具的电池进行涓流充电。交通工具可能需要少量的功率以保持或补充电池功率。可以将功率无线地从源转移至可以被结合到交通工具的正面格板、顶棚、底部或其它部分的设备谐振器。可以将设备谐振器设计为符合交通工具的正面上或格板周围的徽标的形状，从而不妨碍气流通过辐射体。设备或源谐振器可以具有附加操作模式，其允许谐振器被用作能够用来融化交通工具上雪或冰的加热元件。

[0574] 电动交通工具或混合式动力交通工具可能要求多个设备谐振器，从而增加交通工具接近源谐振器以便充电的容易性（即，设备谐振器的数目和变化位置越大，交通工具能够进站并与多种充电站对接的机会越大），增加能够在一段时间内递送的功率量（例如，可以要求附加设备谐振器以阻止由于将电流充电至可接受水平而引起的局部加热），帮助将交通工具停泊／停靠于充电站等。例如，交通工具可以具有具有反馈系统的多个谐振器（或

单个谐振器），所述反馈系统向驾驶员或自动化停泊 / 停靠结构提供针对最优化充电条件的交通工具停泊的指导（即，交通工具的设备谐振器到充电站的源谐振器的最佳定位可以提供更大的功率转移效率）。自动化停泊 / 停靠设备可以允许基于交通工具被多好地耦合的交通工具的自动停泊。

[0575] 功率传输系统可以用来对交通工具的设备和外围设备供电。可以在交通工具正在充电的同时或不在充电的同时向外围设备提供功率，或者可以向不需要充电的常规交通工具递送功率。例如，可以将功率无线地转移至常规非电动汽车以在被停泊的同时对空调、制冷单元、加热器、灯等供电以避免运行引擎，这对于避免在车库停车位或装载站台中耗尽积累是非常重要的。例如可以在公交车停泊的同时无线地向其转移功率以允许灯、外围设备、乘客设备等的供电，避免机载引擎或电源的使用。可以在飞机停在停机坪上或吊架中的同时无线地向其转移功率在不必使用机载引擎或电源的情况下对仪器、气候控制机构、除冰设备等供电。

[0576] 交通工具上的无线功率传输可以用来实现交通工具至电网 (V2G) 的概念。交通工具至电网是基于利用电动交通工具和插电式混合电动交通工具 (PHEV) 作为分布式储能设备，在电力网被利用不足时的夜间充电，并且可用于在日间发生的峰值需求时段期间向电力网放电。可以以使得能够在不要求连接插头的情况下实现双向能量流动—使得能量从交通工具回流至电力网—的方式来实现交通工具和各基础设施上的无线功率传输系统。可以将停泊在工厂、办公室、停车场处的巨大的交通工具队视为智能电力网的“峰值功率容量”。车辆上的无线功率传输能够使此类 V2G 设想成为现实。通过简化将交通工具连接到电力网的过程（即，通过简单地将其停泊在无线充电使能停车场），一定数目的交通工具在电力网需要分接其功率时将是“可派遣的”变得更加可能。没有无线充电，电和 PHEV 所有者可能将在家里为其交通工具充电，并在工作时将其停在常规停车场中。谁想在工作时将其交通工具插上电，如果其不需要充电的话？用能够处理 3kW 的无线充电系统，100,000 台交通工具能够向电力网返回 300 兆瓦—使用以成本效益基准负载发电能力在前一天晚上产生的能量。使其成为可行 V2G 能量源的是无声自动充电 PHEV 和电动交通工具的流线型人类工程学。

[0577] 本文所述的系统和方法可以用来对交通工具上的传感器供电，诸如轮胎中的传感器以测量气压，或运行交通工具中的外围设备，诸如蜂窝电话、GPS 设备、导航设备、游戏机、音频或视频播放器、DVD 播放器、无线路由器、通信设备、防盗设备、雷达设备等。例如，可以将本文所述的源谐振器构建到汽车的主舱中，以便向位于汽车主舱内部和外部的多种设备供应功率。在交通工具是摩托车等的情况下，可以将本文所述的设备集成到摩托车的主体中，诸如在座位下面，并且可以在用户的头盔中提供设备谐振器，诸如用于通信、娱乐、信令等，或者可以在用户的夹克中提供设备谐振器，诸如用于出于安全着想向驾驶员显示信号等。

[0578] 本文所述的系统和方法可以与运输基础设施相结合地使用，诸如道路、火车、飞机、船等。例如，可以将源谐振器构建到道路、停车场、铁轨线等中。可以将源谐振器构建到交通灯、信号等中。例如，使用嵌入道路中的源谐振器和构建到交通工具中的设备谐振器，可以在交通工具沿着道路行驶时或在其被停在停车场中或道路的一侧时为其提供功率。本文所述的系统和方法可以提供在交通工具穿过道路网络或道路网络的一部分的同时为交

通工具中的电气系统供电和／或充电的有效方式。这样，本文所述的系统和方法可以对自主交通工具、自动导向交通工具等的供电／充电有所贡献。本文所述的系统和方法可以向在交通工具通常空闲或停止的位置处的交通工具提供功率，诸如在交通灯或标志附近、在公路斜坡上或在停车场中。

[0579] 本文所述的系统和方法可以在工业环境中使用，诸如在工厂内部以便对机器供电、对机器人供电／充电、对机器人臂上的无线传感器供电／充电、对工具供电／充电等。例如，使用本文所述的系统和方法来向机器人臂上的设备供应功率可以帮助消除跨越机器人臂的接头的直接导线连接。这样，可以减少此类直接导线连接的磨损，并增加机器人的可靠性。在这种情况下，设备谐振器可以在机器人臂上的外面，并且源谐振器可以在机器人的底座处，在机器人附近的中心位置处，集成到机器人正在提供服务的工业设施中等等。本文所述的系统和方法的使用可以帮助消除原本与工业设施内的配电相关联的布线，并因此有益于设施的总体可靠性。

[0580] 本文所述的系统和方法可以用于地下应用，诸如钻孔、采矿、挖掘等。例如，与钻孔或挖掘相关联的电气组件和传感器可以利用本文所述的系统和方法来消除与挖掘机构、钻头等相关联的线缆敷设，由此消除挖掘点附近的线缆敷设或使其最小化。在另一示例中，可以使用本文所述的系统和方法来向采矿应用中的挖掘设备提供功率，其中，对设备的功率要求可能是高的且距离是大的，但是其中，没有人将经受相关的要求场。例如，挖掘区域可能具有谐振器供电挖掘设备，其具有高功率要求，并且可以相对距离源谐振器更远地进行挖掘。结果，源谐振器可能需要提供高场强度以满足这些要求，但是人员足够远地在这些高强度场之外。此高功率无人员方案可以适用于多个工业应用。

[0581] 本文所述的系统和方法还可以使用近场非辐射谐振方案进行信息转移而不是功率转移（或除此之外）。例如，由近场非辐射谐振技术传送的信息可能对窃听不敏感，因此与传统无线通信方案相比可以提供增加的安全水平。另外，由近场非辐射谐振技术传送的信息可以不与EM辐射谱相干扰，因此可以不是EM干扰源，从而允许扩展频率范围内且完全在由任何管理组织设定的极限内的通信。可以在远程、不可接近或难以到达的位置之间提供通信服务，诸如在远程传感器之间、在设备或交通工具的各部之间、在隧道、洞穴和井中（例如，油井、其它钻场）和水下或地下设备之间等。可以在其中磁场比电场经历较少的损耗的地方提供通信服务。

[0582] 本文所述的系统和方法可以实现无线功率传输系统中的源和设备之间的功率和通信信号的同时传输，或者其可以实现在不同时间段期间或不同的频率处进行功率和通信信号的传输。可以可控地改变谐振器的性能特性以优先地支持或限制能量或信息传送的效率或范围。例如，可以控制谐振器的性能特性以通过缩小信息传送的范围来改善安全性。可以连续地、周期性地、根据预定、计算或自动调整的算法来改变谐振器的性能特性。例如，可以以时间复用或频率复用的方式来提供由本文所述的系统和方法实现的功率和信息传送。源和设备可以通过调谐、改变、改动、抖动等谐振器阻抗来相互发送信号，所述谐振器阻抗可以影响能够检测的其它谐振器的反射阻抗。如本文所述地传送的信息可以包括关于设备识别、设备功率要求、握手协议等的信息。

[0583] 源和设备可以感测、传送、处理和利用关于电力网中的任何其它源和／或设备的位置和定位信息。源和设备可以捕捉或使用来自可以被构建到源和设备中或者可以是源

或设备连接的组件的多种传感器和源的信息，诸如海拔、倾斜度、经度和纬度等。定位和取向信息可以包括诸如全球定位传感器（GPS）、指南针、加速度计、压力传感器、常压气压传感器、使用 Wi-Fi 或蜂窝式网络信号的定位系统等源。源和设备可以使用位置和定位信息来找到附近的无线功率传输源。源可以广播或与识别其位置的中央站或数据库通信。设备可以获得来自中央站或数据库或来自本地广播的源位置信息，并且可以借助于听觉、振动或音频信号来将用户或操作员引导至源。源和设备可以是电力网、通信网络、传感器网络、导航网络等中或各种组合功能网络中的节点。

[0584] 位置和定位信息还可以用来使功率递送最优化或协调功率递送。可以使用关于源和设备的相对位置的附加信息来使磁场方向和谐振器对准最优化。例如，可以使用可以从加速度计和磁性传感器等获得的设备和源的取向来识别谐振器的取向和磁场的最适宜方向，使得磁通不被设备电路阻挡。用此类信息，可以使用具有最适宜的取向的源或源的组合。同样地，可以使用位置和取向信息来移动或给设备的用户或操作员提供反馈以将设备置于适宜的取向或位置以使功率传输效率最大化、使损耗最小化等。

[0585] 源和设备可以包括功率计量和测量电路和能力。可以使用功率计量来跟踪多少功率被递送到设备或由源传递了多少功率。可以处于开帐单的目的在基于费用的功率递送布置中使用功率计量和功率使用信息。还可以使用功率计量来使得功率递送策略能够保证根据特定的标准来向多个设备分配功率。例如，功率计量可以用来基于接收到的功率的量将设备分类并在递送方面优先考虑已接收到最少功率的那些。功率计量可以用来提供可以被以单独的费率开帐单的分层递送服务，诸如“保证功率”和“尽力服务功率”。功率计量可以用来组成并实行分级功率递送结构，并且可以使得优先权设备在某些情况下或使用方案下能够要求并接收更多功率。

[0586] 功率计量可以用来使功率递送效率最优化并使吸收和使辐射损耗最小化。源可以将关于由设备接收到的功率的信息与关于源的功率输出的信息相结合地使用来识别不适宜的工作环境或频率。例如，源可以将由设备接收到的功率的量与其传送的功率的量相比较以确定传输损耗是否可能异常地或不可接受地大。大量的传输损耗可能是由于从源接收功率的未授权设备而引起的，并且源和其它设备可以发起谐振频率的跳频或其它防范措施以防止或阻止未授权使用。大的传输损耗可能是由于例如吸收损耗而引起的，并且设备和源可以调谐至交变谐振频率以使此类损耗最小化。大量的传输损耗还可以指示不想要或不明对象或材料的存在，并且源可以关小或关闭其功率水平，直至去除或识别了不想要或不明对象，在这时，源可以重新开始对远程设备供电。

[0587] 源和设备可以包括认证能力。认证可以用来保证仅兼容的源和设备能够传送和接收功率。认证可以用来保证仅是特定制造商的可信设备且不是克隆或来自其它制造商的设备和源或仅作为特定订阅或计划的一部分的设备能够从源接收功率。认证可以基于加密请求和应答协议，或者其可以基于允许其基于与物理上不可克隆功能类似的性质被使用和认证的特定设备的扰动的唯一签名。可以用本地通信在每个源与设备之间本地地执行认证，或者可以将其与第三人认证方法一起使用，其中，源和设备用通信向中央权威机构进行认证。认证协议可以使用位置信息来向真正设备的本地源报警。

[0588] 源和设备可以使用跳频技术来防止无线功率源的未授权使用。该源可以连续地调整或改变功率递送的谐振频率。可以以已知、可再现或被传送到授权设备但难以预测的伪

随机或预定方式来执行频率改变。跳频的速率和所使用的各种频率的数目可以大量且频繁到足以保证未授权使用是困难且不切实际的。可以通过调谐阻抗网络、调谐任何驱动电路、使用被调谐或可调谐至多个谐振频率的多个谐振器等来实现跳频。

[0589]　源可以具有用户通知能力以示出关于源是否被耦合到设备谐振器并正在传送功率、其是否处于待机模式或者源谐振器是否解调谐或被外部对象扰动的源状态。通知能力可以包括视觉、听觉和振动方法。该通知可以如三色灯一样简单，每个状态一个，并且可选地是扬声器在操作错误的情况下提供通知。可替换地，通知能力可以涉及显示源的状态并可选地提供关于如何确定或解决所识别的任何错误或问题的指令的交互式显示器。

[0590]　作为另一示例，可以使用无线功率转移来改善电子爆炸雷管的安全性。可以以电子雷管、电气雷管或激波管雷管来引爆爆炸设备。用传导地或通过无线电传送的低能量触发信号，电子雷管利用所储存的电能（通常在电容器中）来激活点火器电荷。电气雷管利用高能量传导触发信号来提供激活点火器电荷所需的信号和能量两者。激波管通过涂敷有爆炸物的空心管将受控爆炸从发电机发送到点火器电荷。存在与电气和电子雷管相关联的安全问题，因为存在意外的电磁能引起非故意激活的情况。经由锐谐振磁耦合的无线功率转移能够改善此类系统的安全性。

[0591]　使用本文公开的无线功率转移方法，可以构建不具有本地储存的能量的电子起爆系统，因此减少非故意激活的风险。可以将无线功率源放置在雷管附近（几米内）。雷管可以装配有谐振捕捉线圈。可以在无线功率源已被触发时传送激活能量。可以由任何数目的机制来发起无线功率源的触发：无线电、磁性近场无线电、传导性信令、超声波、激光。基于谐振磁耦合的无线功率转移还具有能够通过诸如岩石、土壤、混凝土、水及其它稠密材料之类的材料来转移功率的益处。使用非常高Q的线圈作为接收机和源（具有非常窄带的响应并被锐调谐至专用频率）进一步保证雷管电路不能捕捉意外的EMI和非故意地激活。

[0592]　无线供电设备的谐振器可以在设备外部或外面，并被接线到设备的电池。可以修改设备的电池以包括适当的整流和控制电路以接收设备谐振器的交流电。这可以使得能够实现具有较大外部线圈的结构，诸如可以被构建到键盘或鼠标或数字式静止照相机的电池门中，或者具有被附着到设备但被是用带状线缆背接线到电池/转换器的甚至更大线圈。可以修改电池门以提供从外部线圈到电池/转换器的互连（其将需要能够接触电池门触点的暴露触点）。

[0593]　虽然已经结合某些优选实施例描述了本发明，但本领域的技术人员将认识到其它实施例，并且其意在落入以法律允许的最广泛意义来解释的本公开的范围内。

[0594]　本文参考的所有文献通过引用结合到本文中。

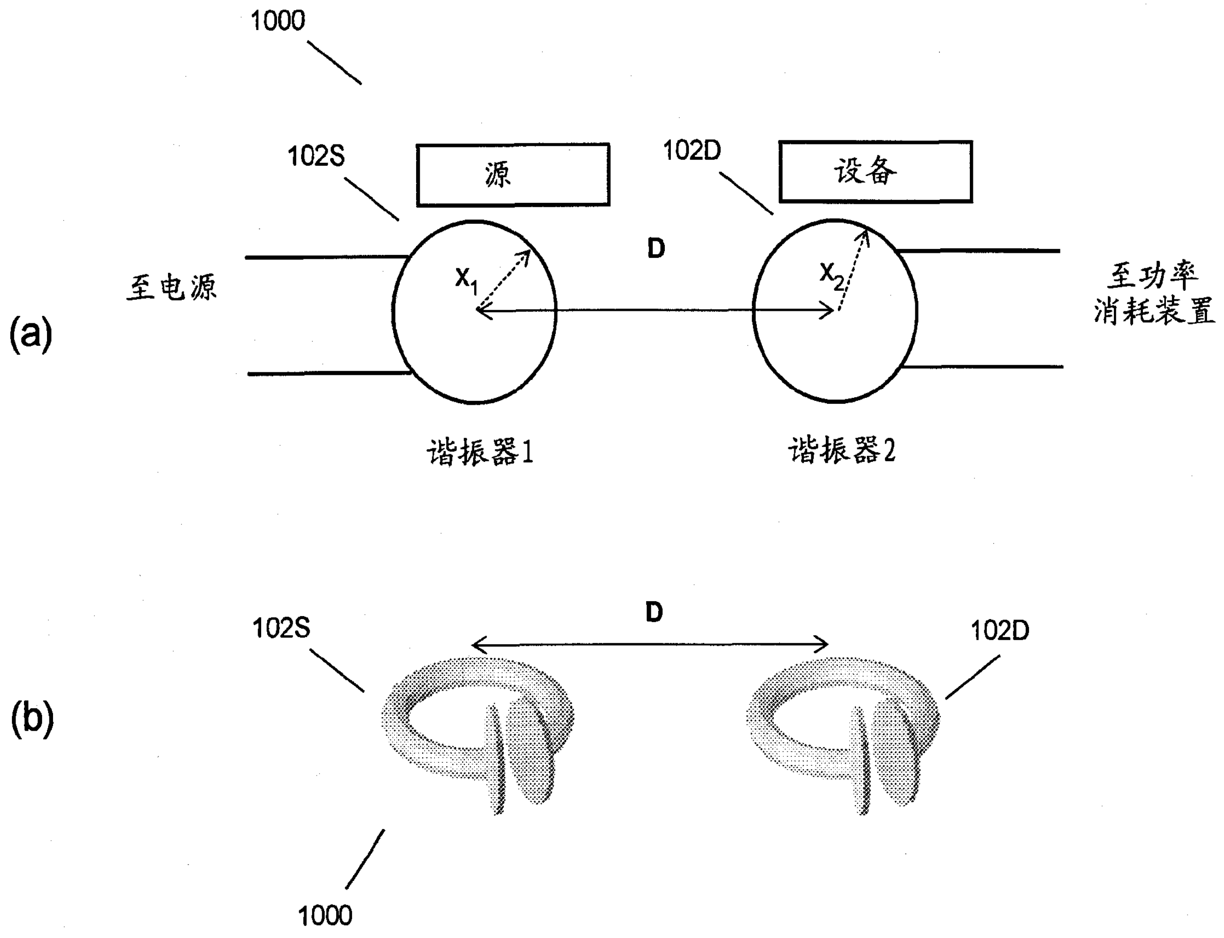

1000
102S
源
102D
设备
D
至电源
x1
x2
至功率消耗装置
(a)
谐振器1
谐振器2
102S
D
102D
(b)
1000

图 1

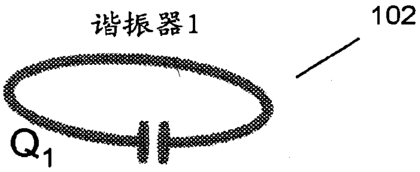


图 2

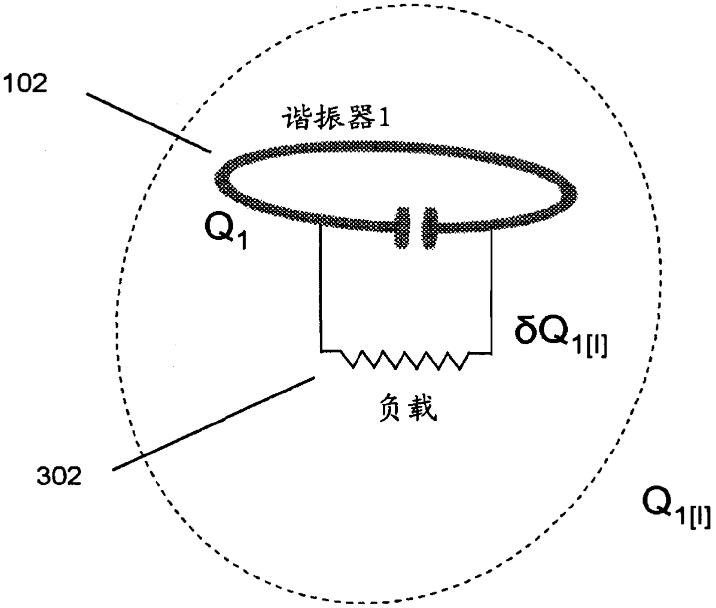


图 3

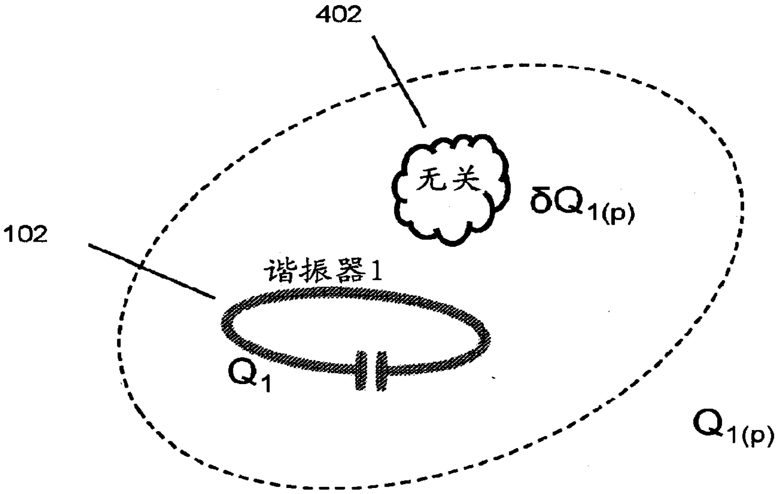

402
无关
$\delta Q_{1(p)}$
102
谐振器1
Q_1
$Q_{1(p)}$

图 4

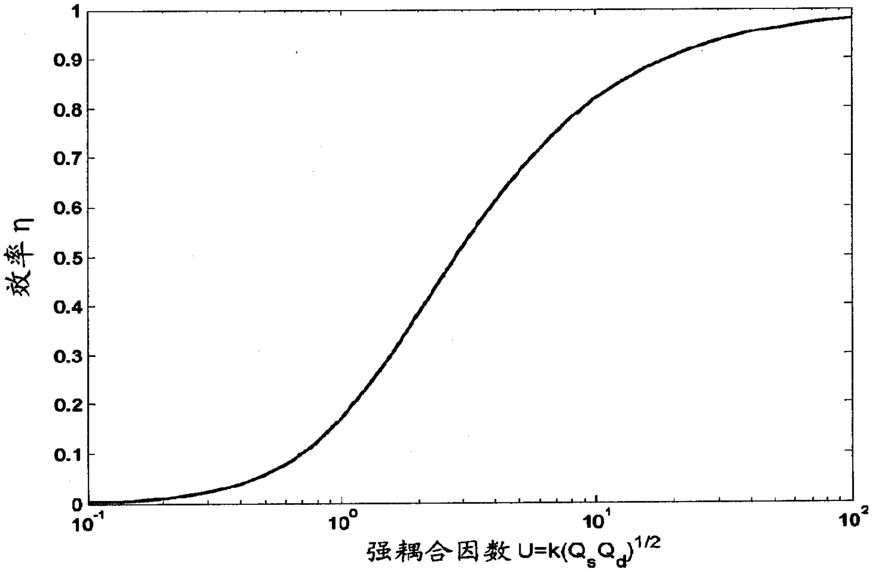

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
效率 η
10^{-1}
10^{0}
10^{1}
10^{2}
强耦合因数 $U=k(Q_sQ_d)^{1/2}$

图 5

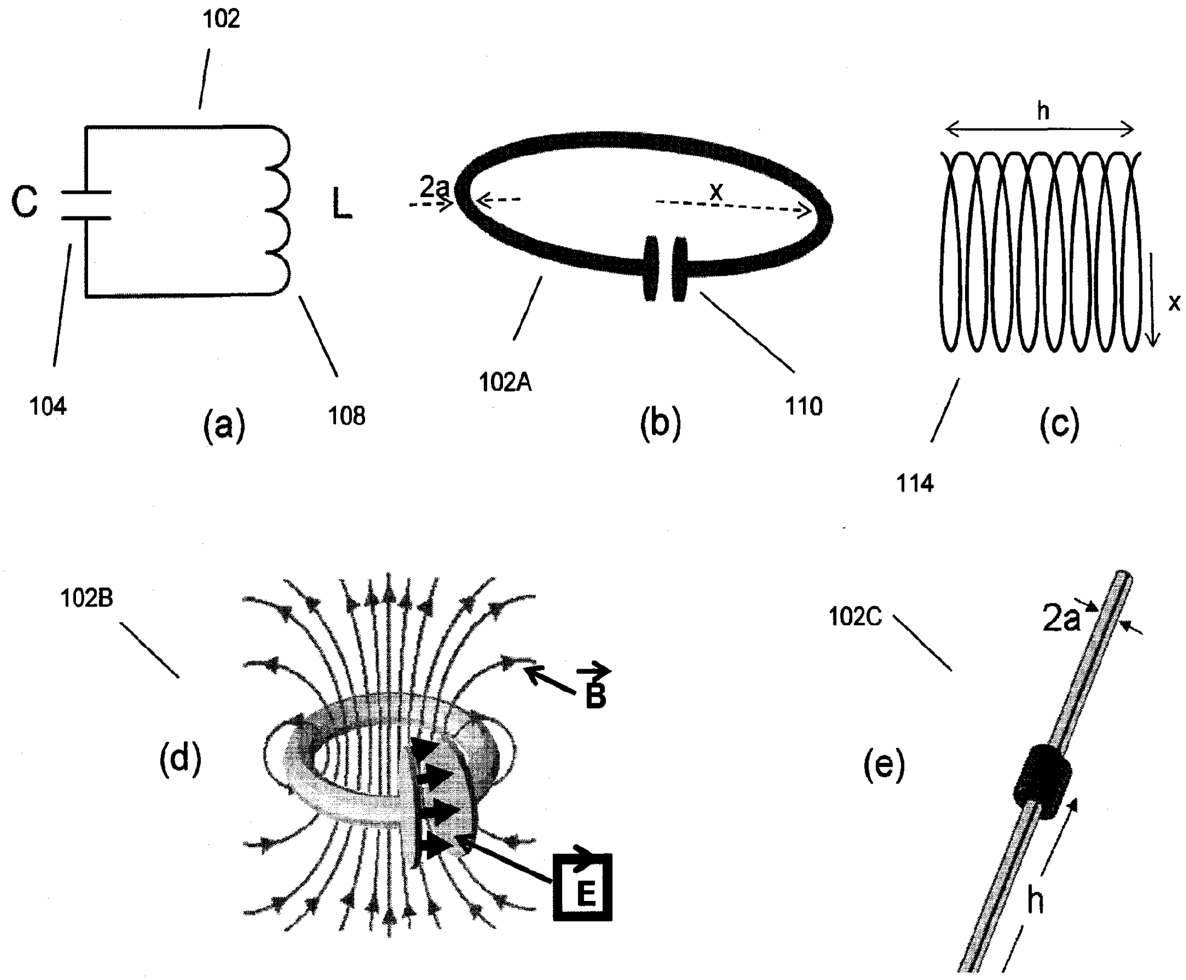


图 6

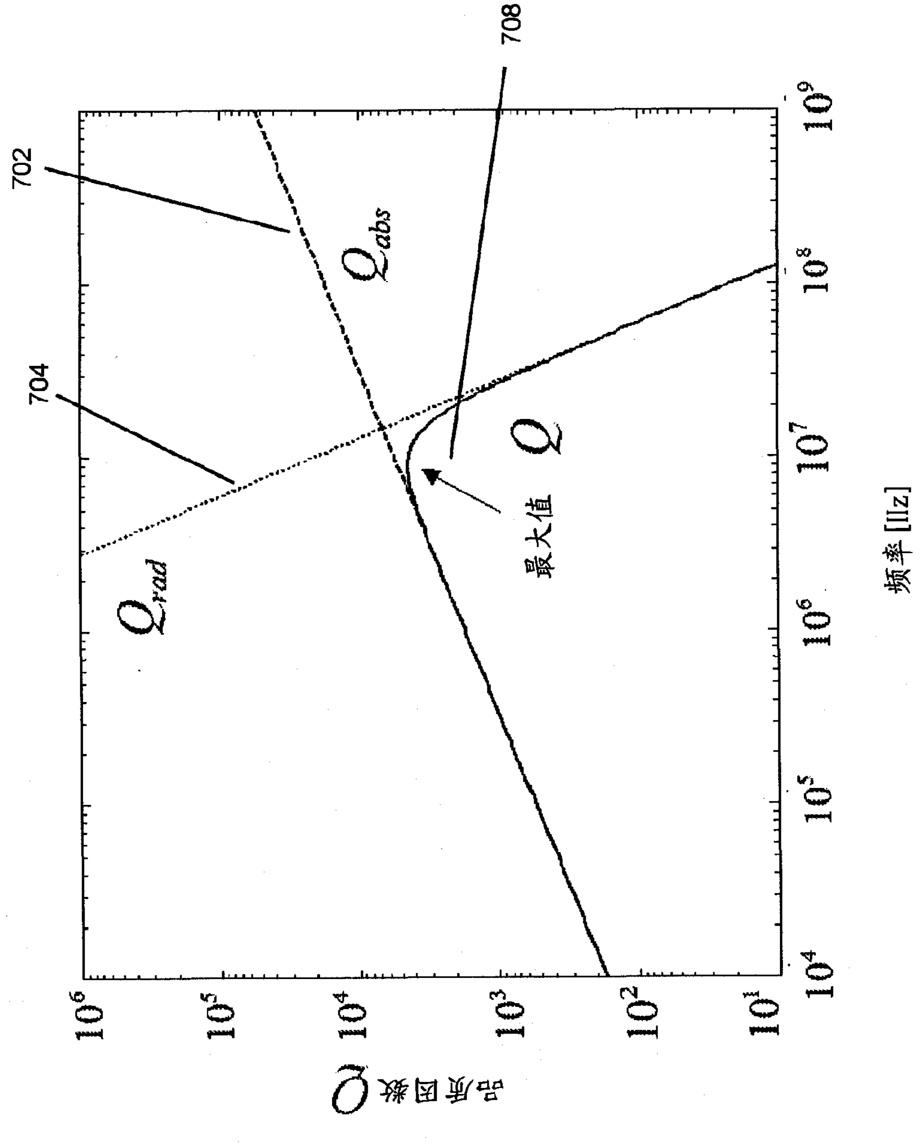

702
704
708
Q_{abs}
Q_{rad}
Q
最大值
频率 [Hz]
品质因数 Q
10^4
10^5
10^6
10^7
10^8
10^9
10^1
10^2
10^3
10^4
10^5
10^6

图 7

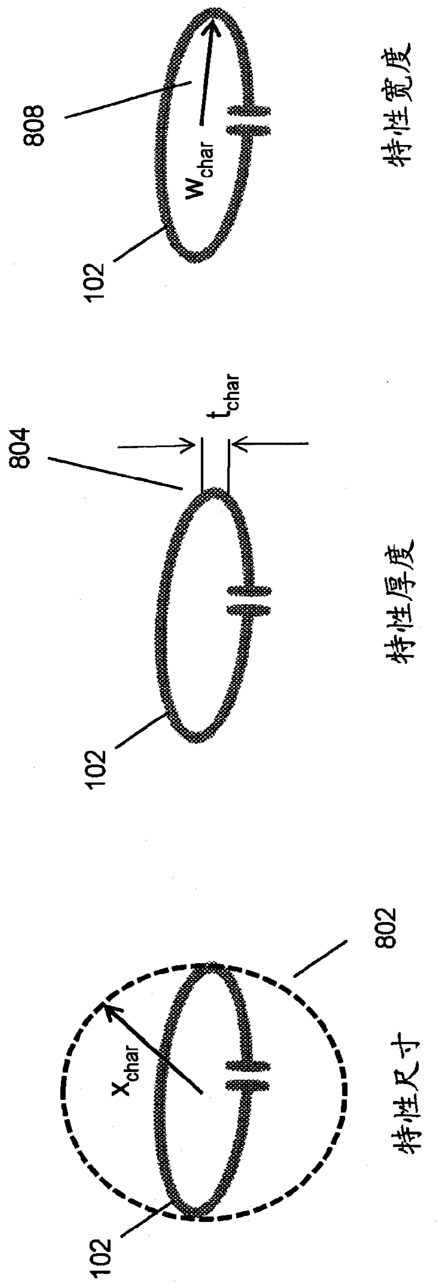


图 8

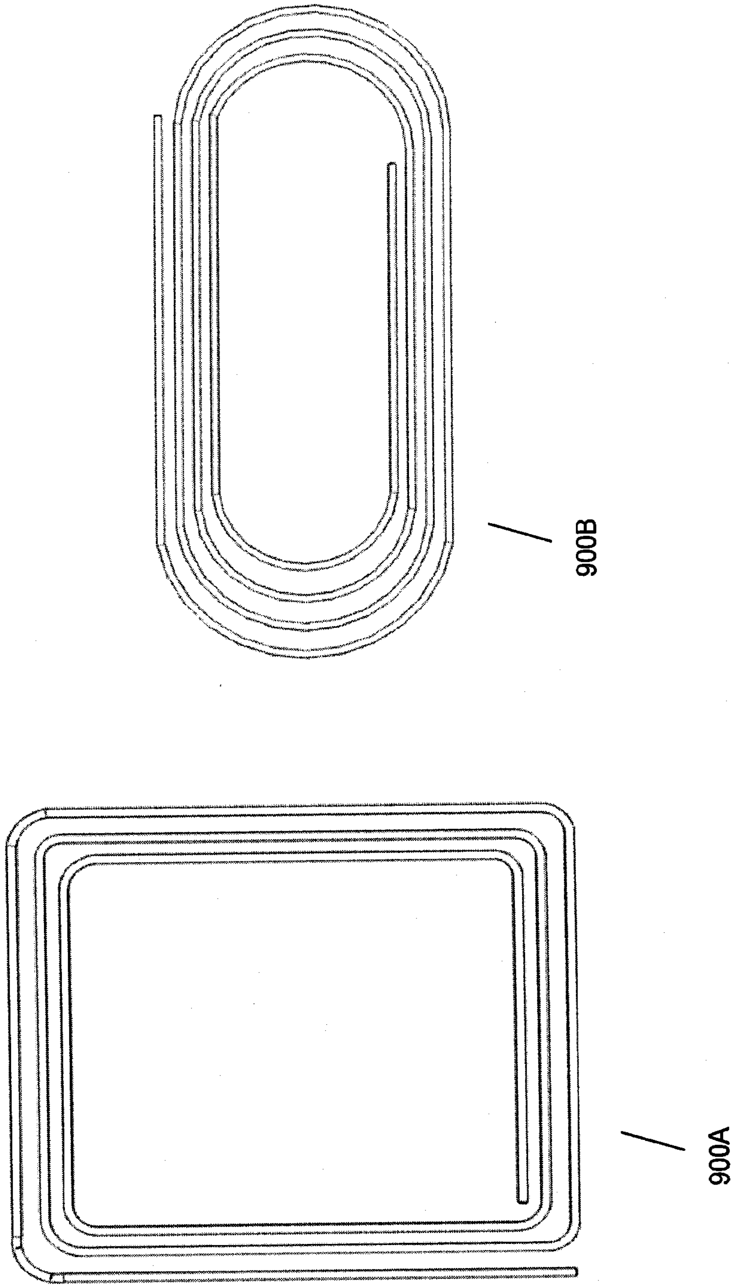


图 9

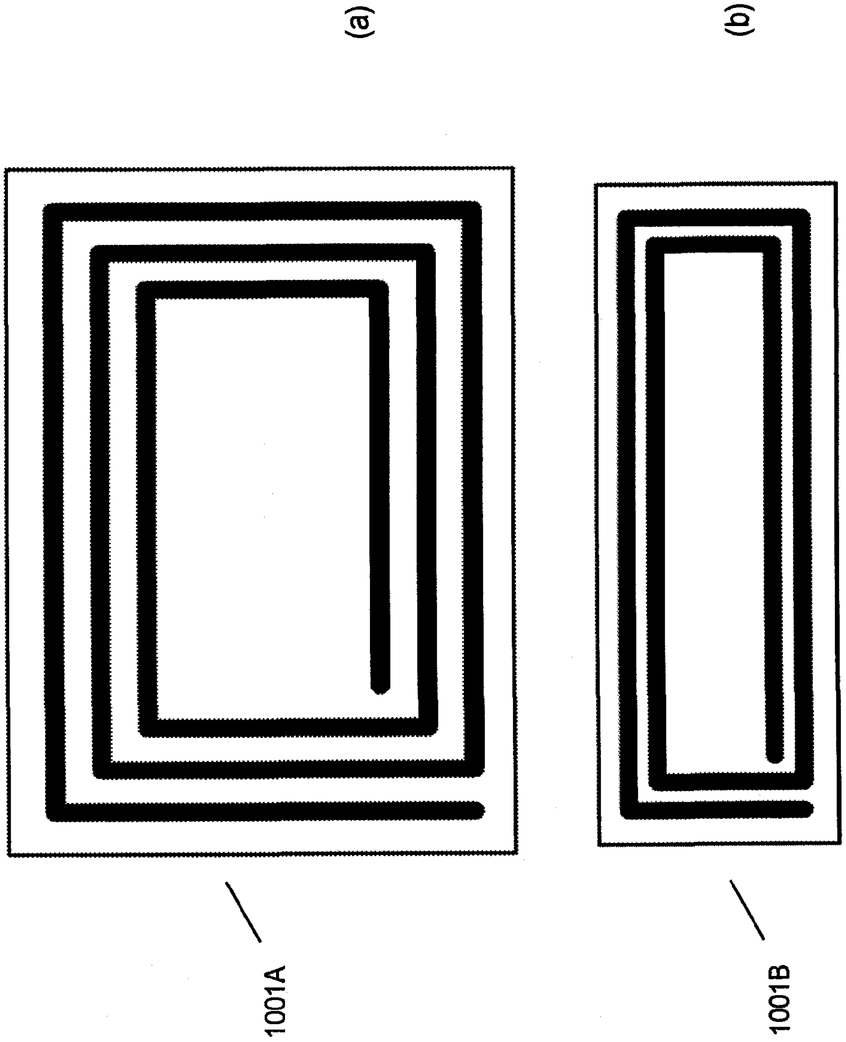


图 10

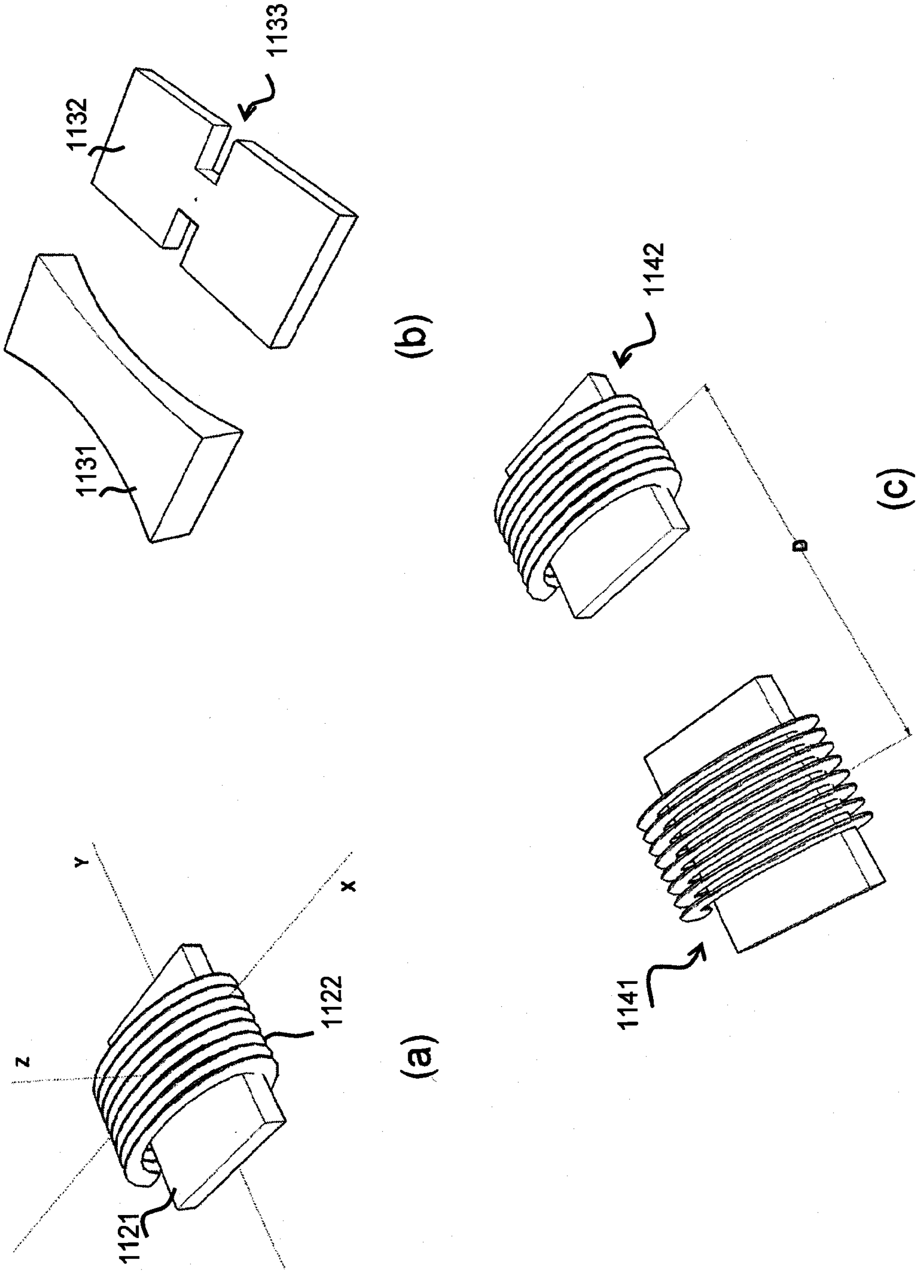


图 11

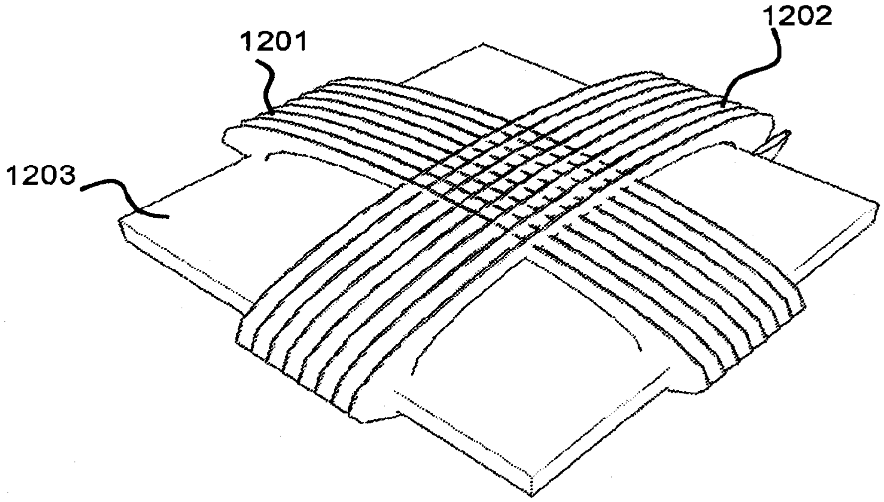


图 12

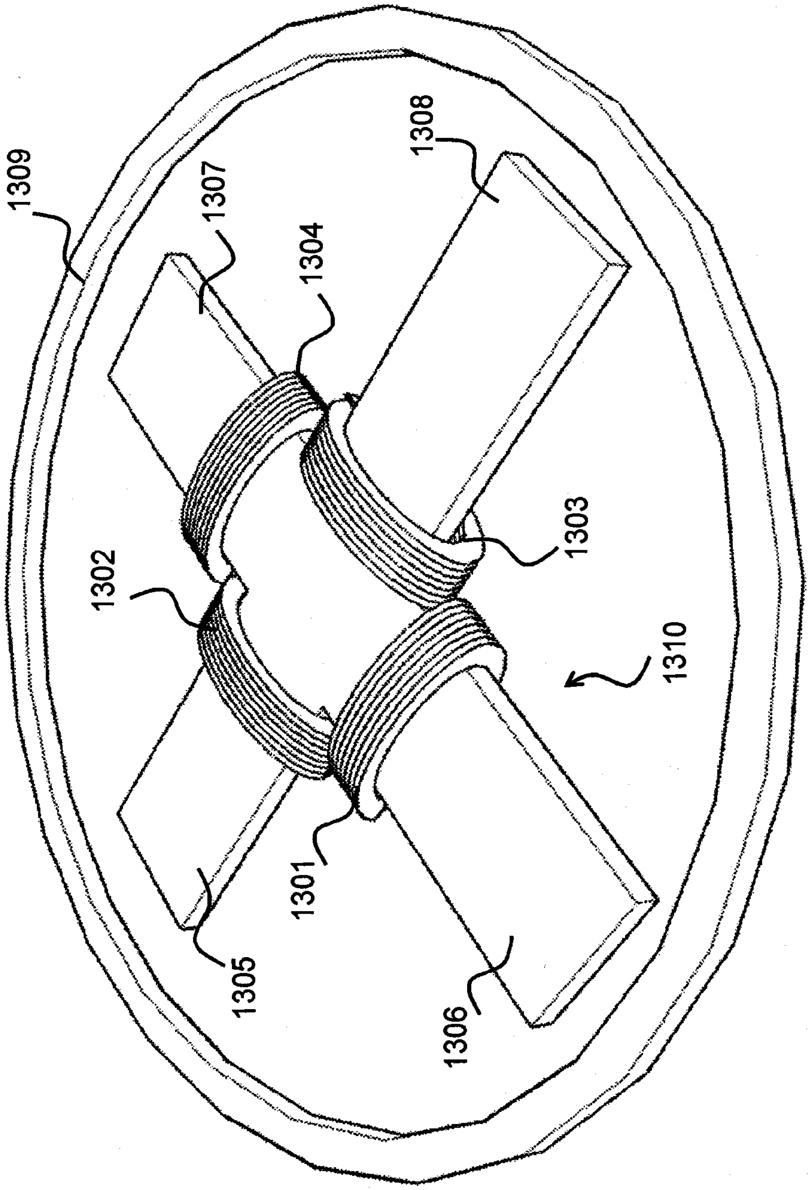


图 13

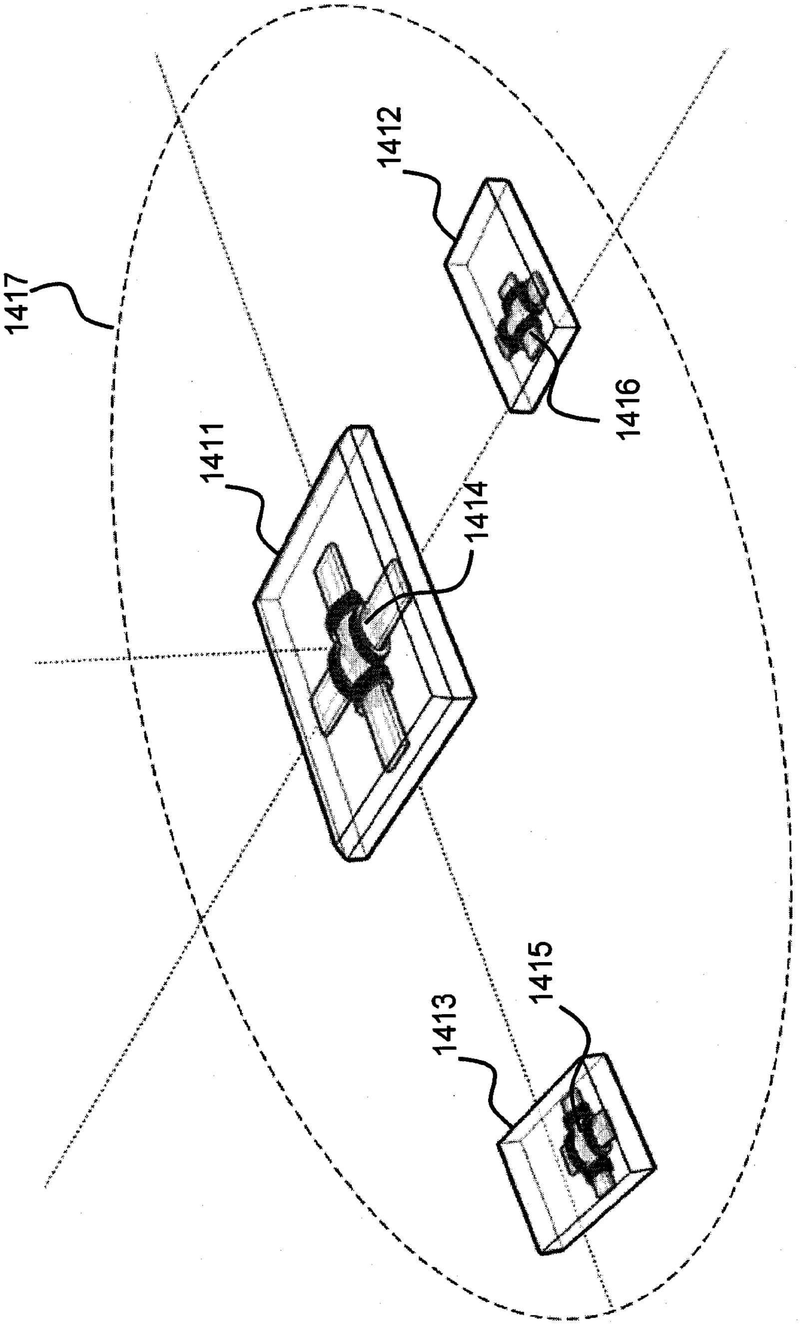


图 14

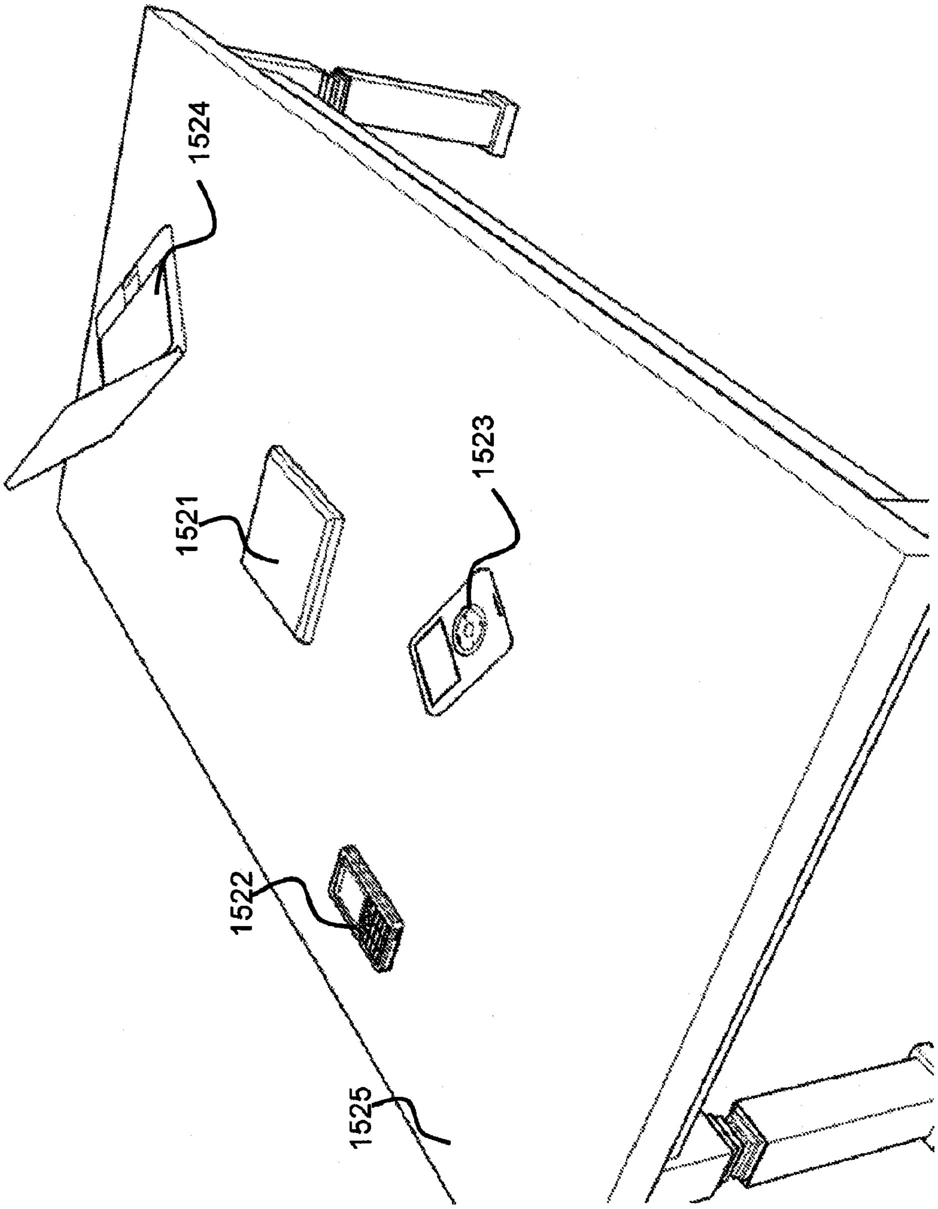
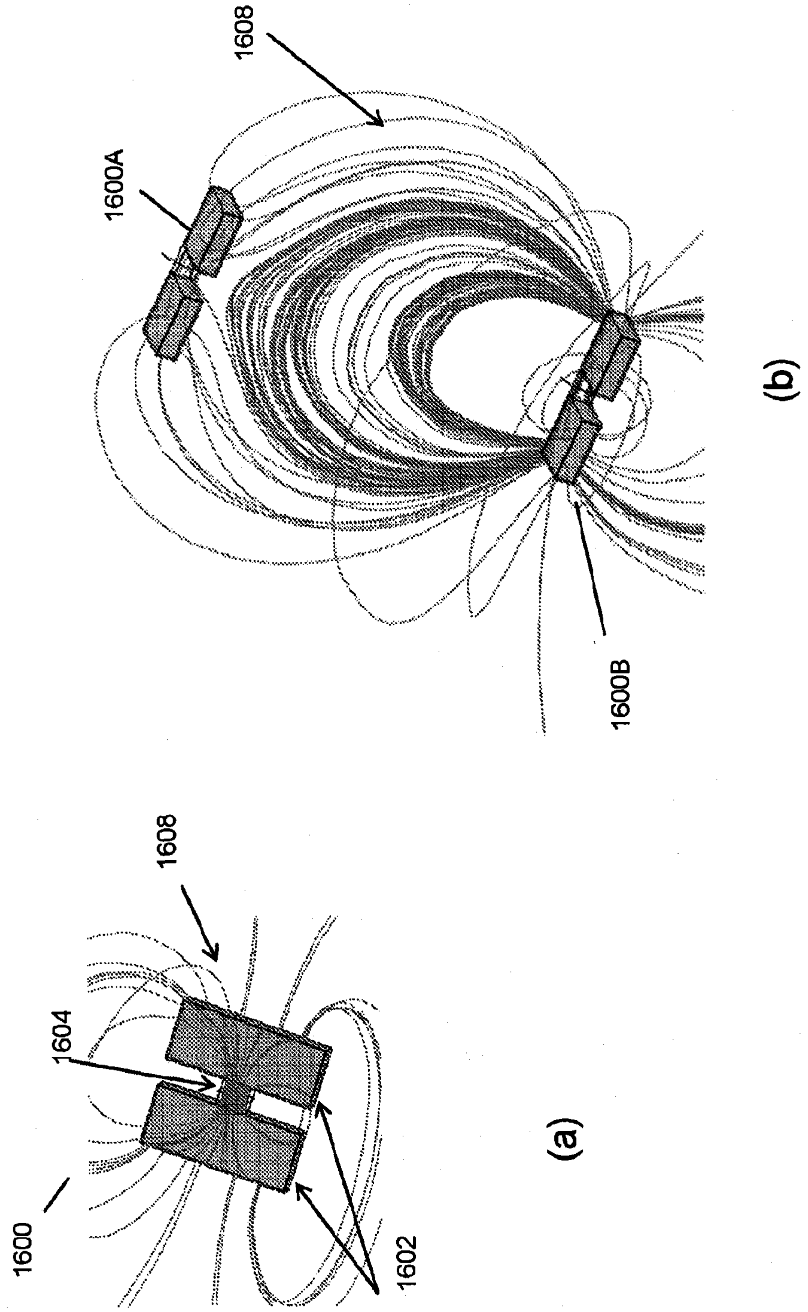


图 15



(b)

(a)

图 16

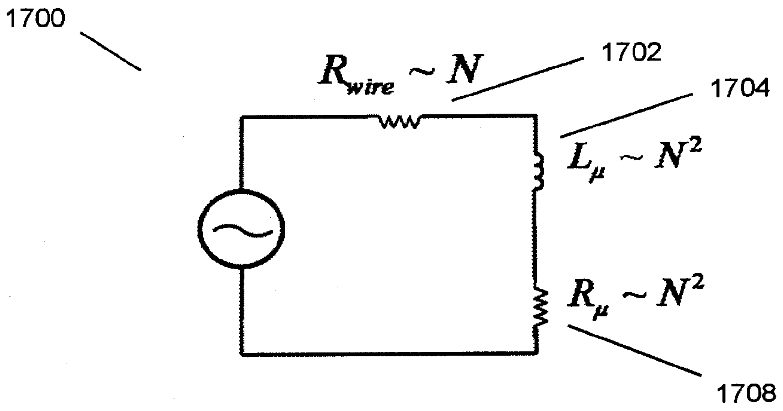

1700
$R_{wire} \sim N$
1702
1704
$L_\mu \sim N^2$
$R_\mu \sim N^2$
1708

图 17

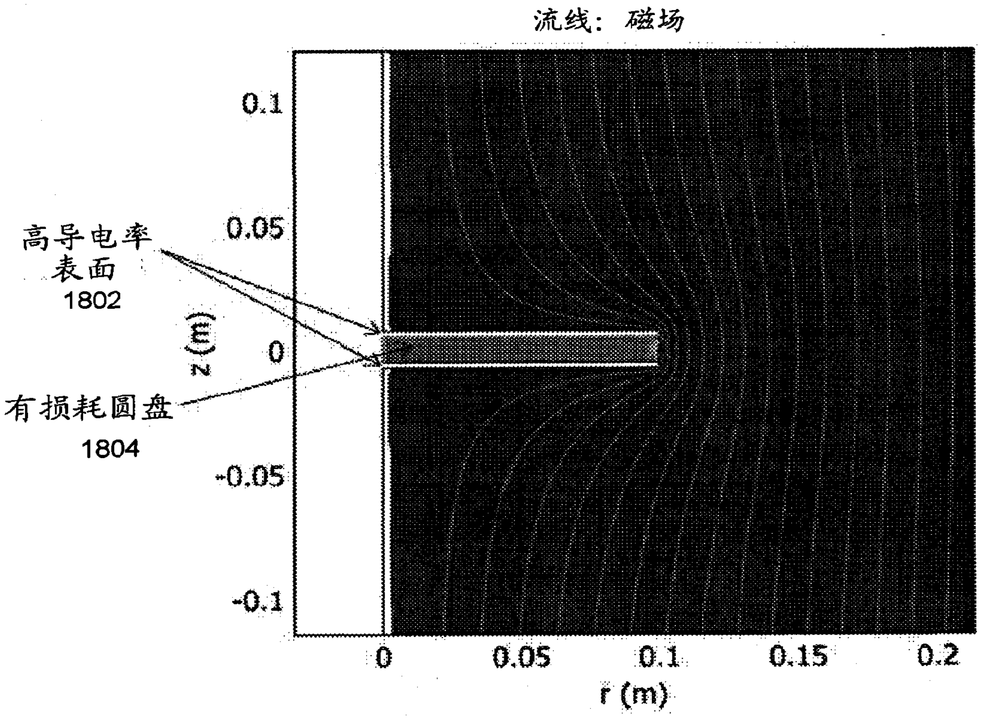

流线：磁场
0.1
0.05
0
-0.05
-0.1
z (m)
高导电率表面
1802
有损耗圆盘
1804
0
0.05
0.1
0.15
0.2
r (m)

图 18

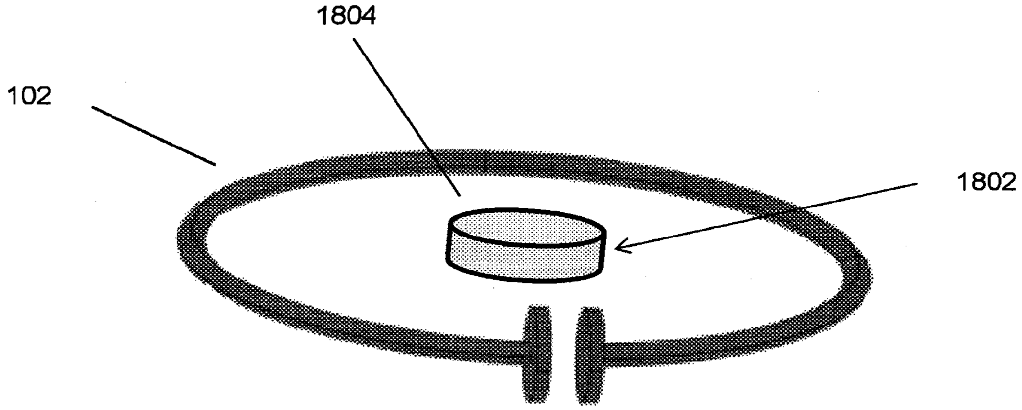


图 19

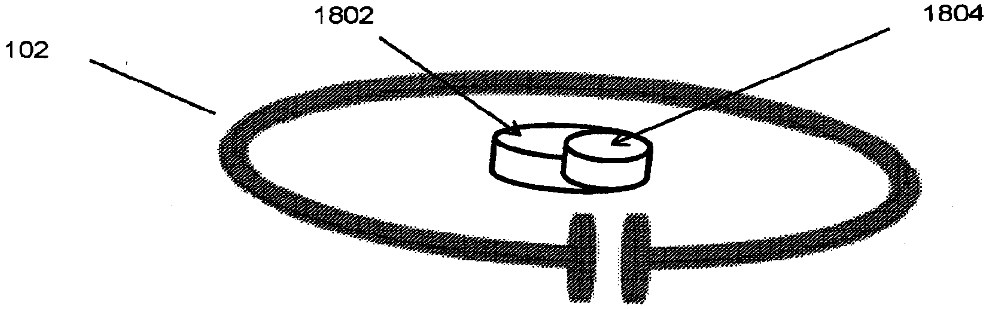


图 20

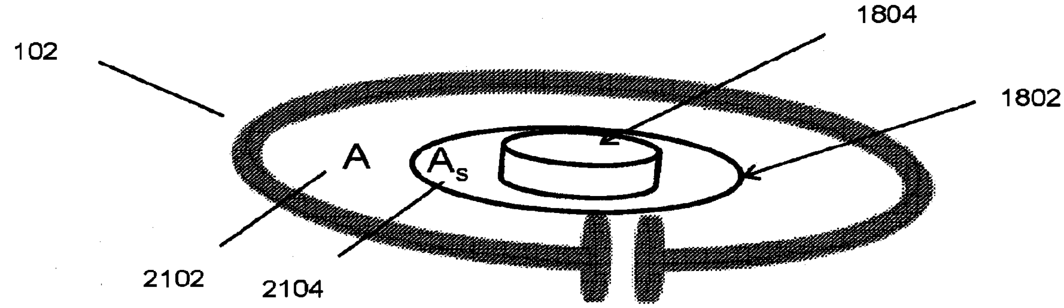


图 21

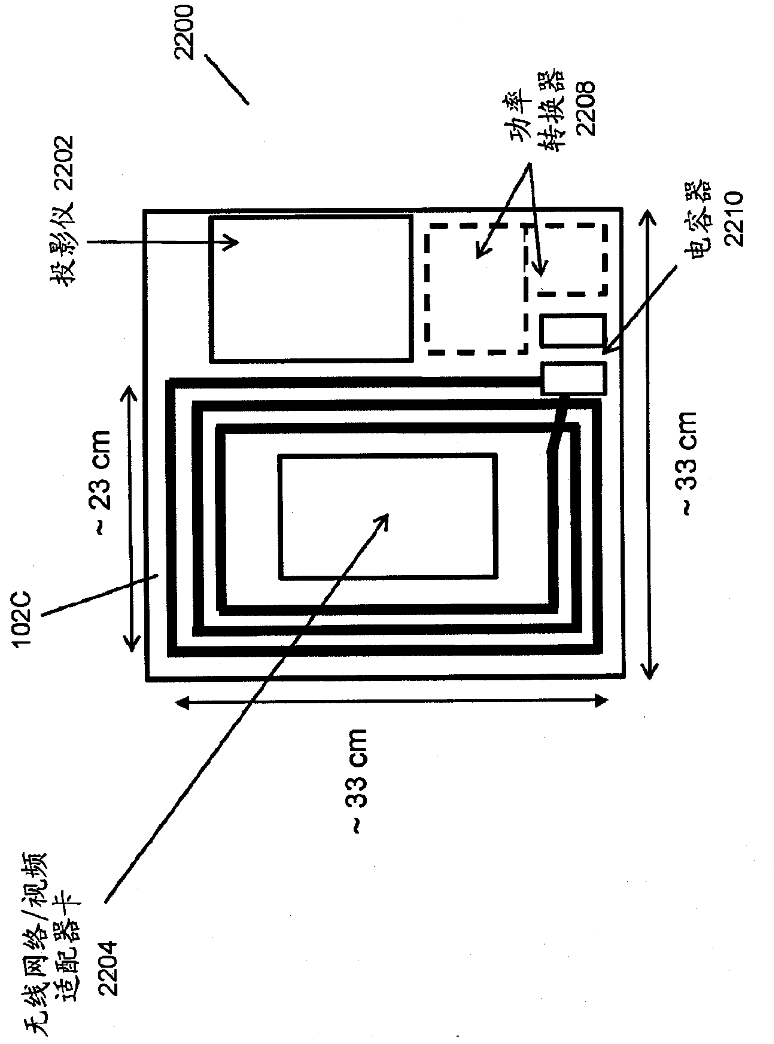

2200
投影仪 2202
功率转换器 2208
电容器 2210
102C
~ 23 cm
~ 33 cm
~ 33 cm
无线网络/视频适配器卡 2204

图 22

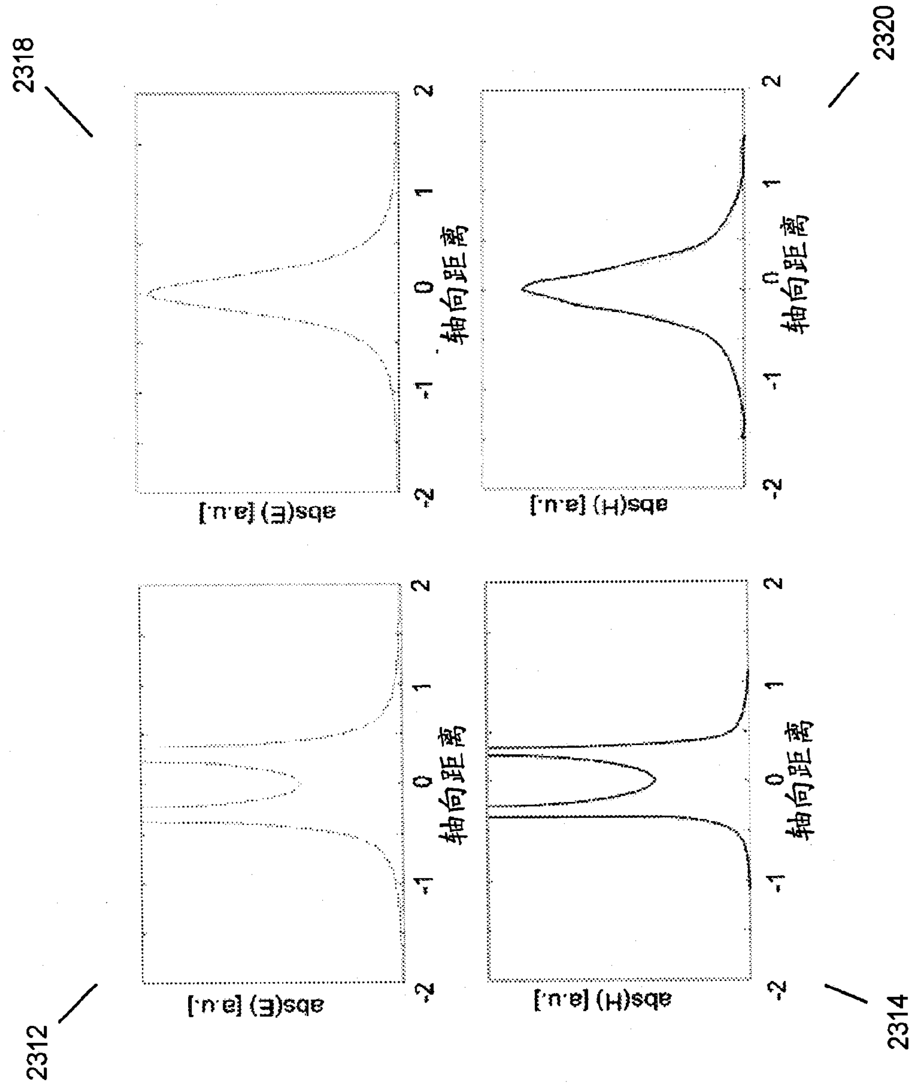

2318
2320
2312
2314
abs(E) [a.u.]
abs(H) [a.u.]
abs(E) [a.u.]
abs(H) [a.u.]
轴向距离
轴向距离
轴向距离
轴向距离
-2
-1
0
1
2

图 23

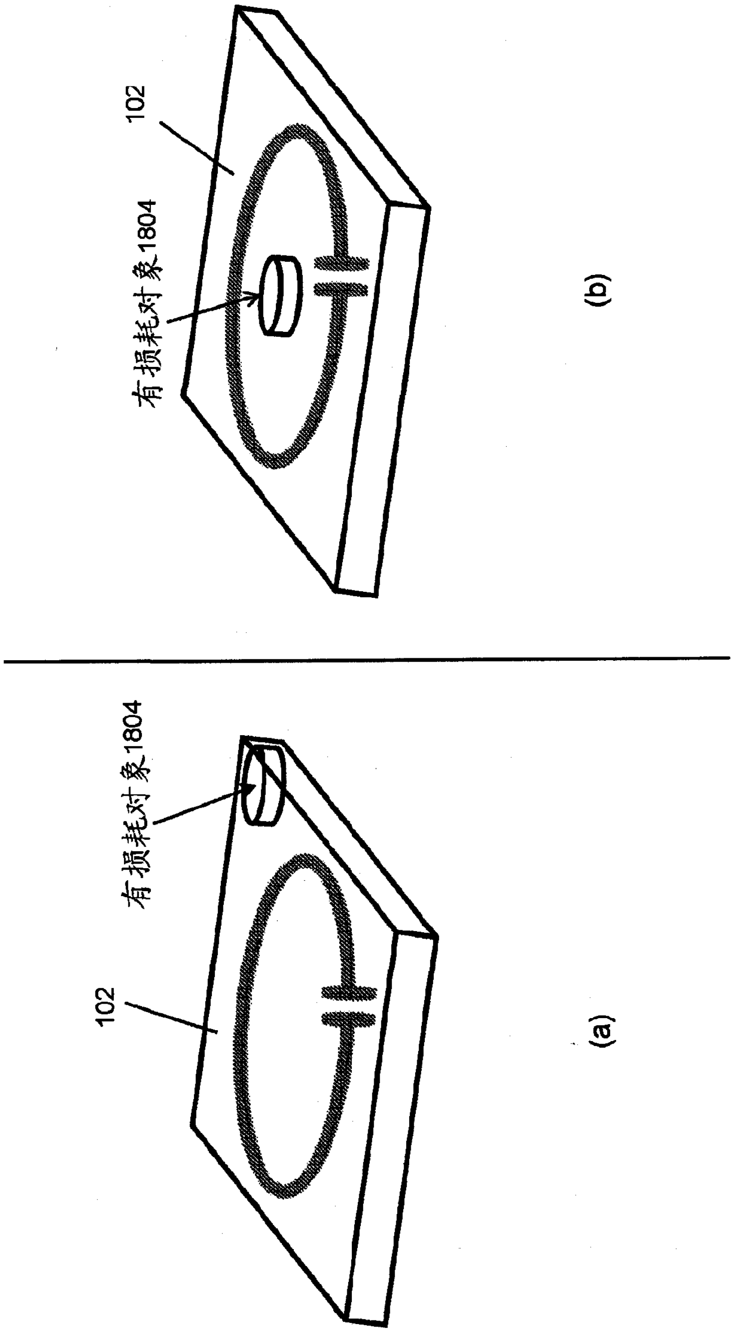


图 24

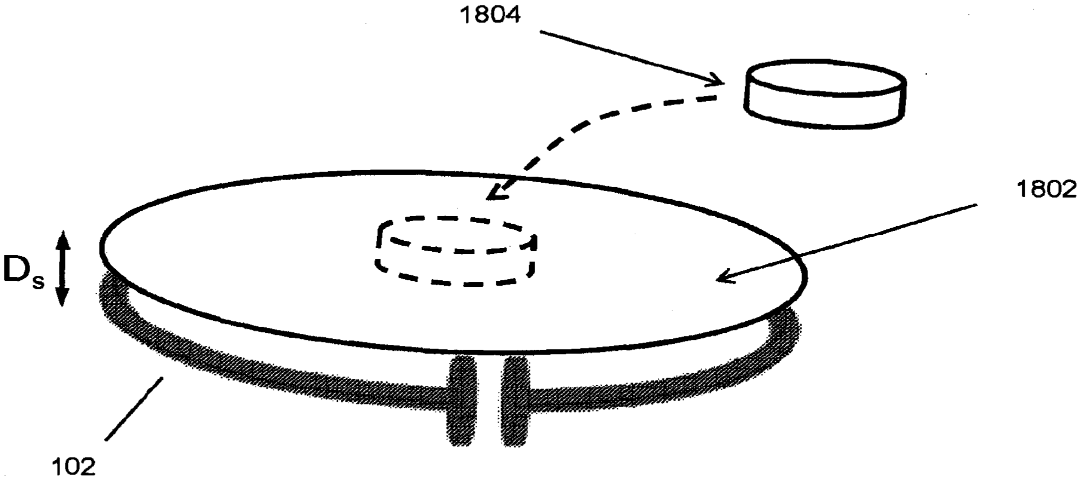


图 25

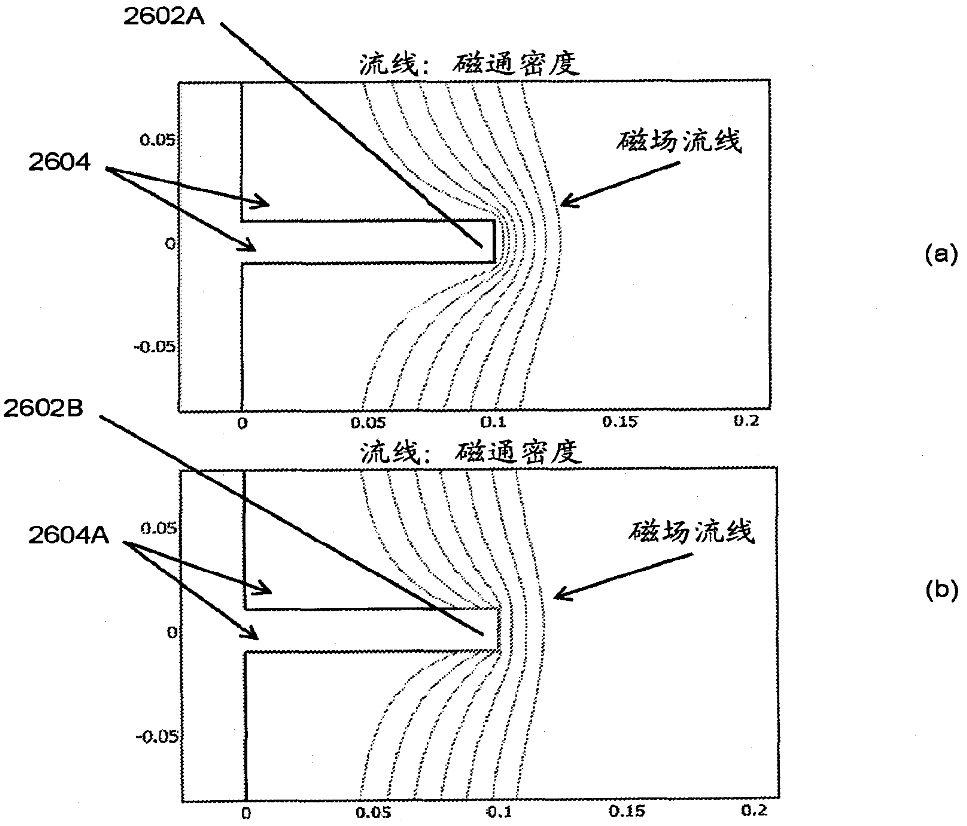

2602A
流线：磁通密度
2604
0.05
0
-0.05
0
0.05
0.1
0.15
0.2
磁场流线
(a)
2602B
流线：磁通密度
2604A
0.05
0
-0.05
0
0.05
0.1
0.15
0.2
磁场流线
(b)

图 26

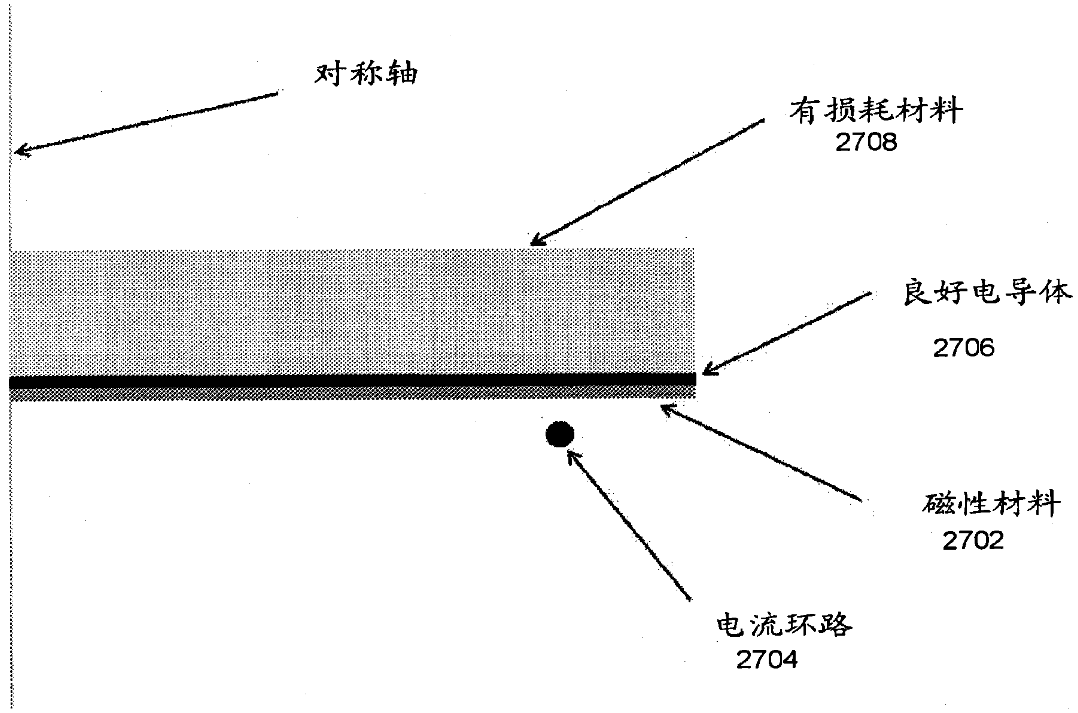


图 27

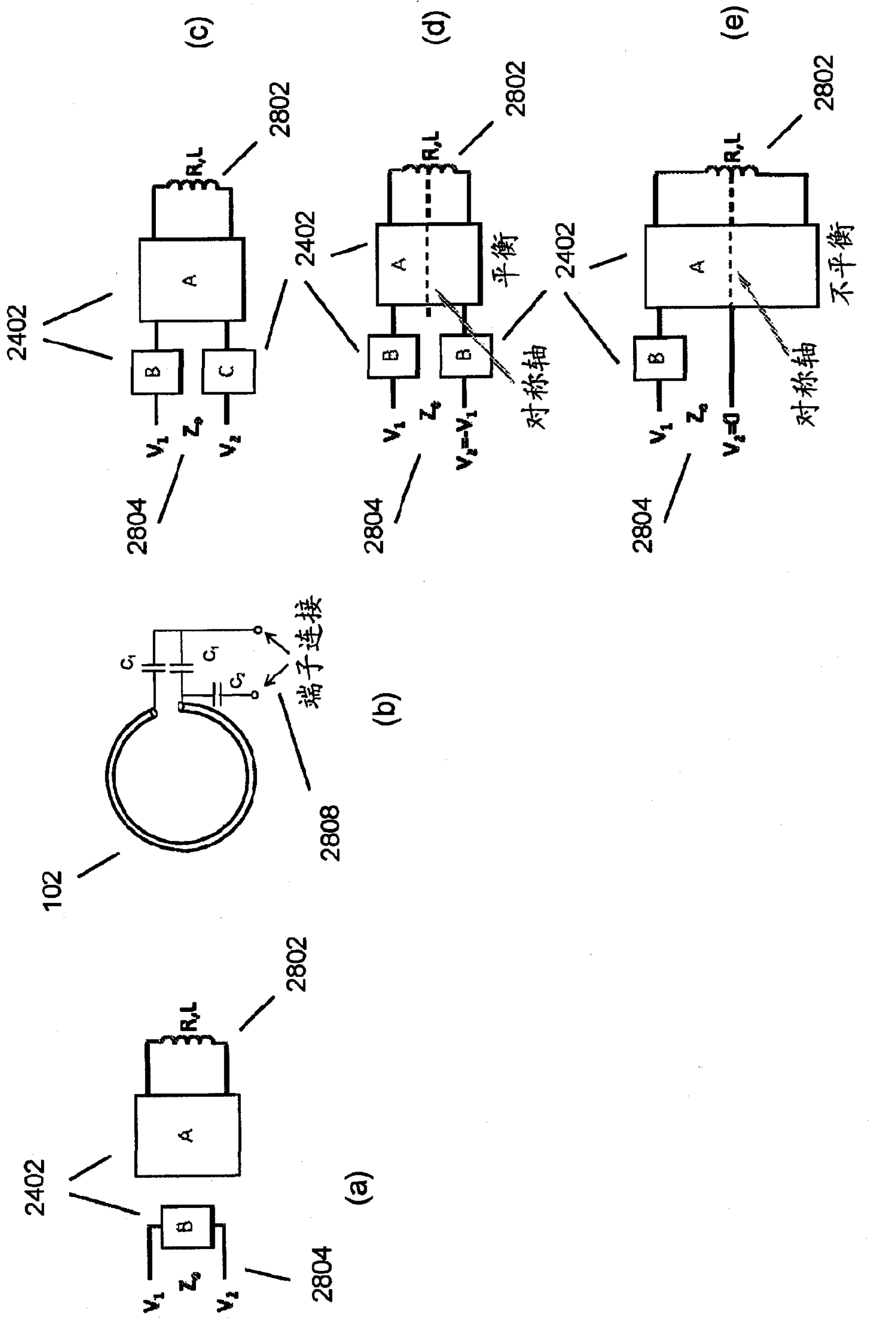

(a)
(b)
(c)
(d)
(e)
2402
2802
2804
2808
102
R,L
A
B
C
V_1
Z_0
V_2
$V_2=-V_1$
$V_2=0$
C_1
C_2
端子连接
平衡
不平衡
对称轴

图 28

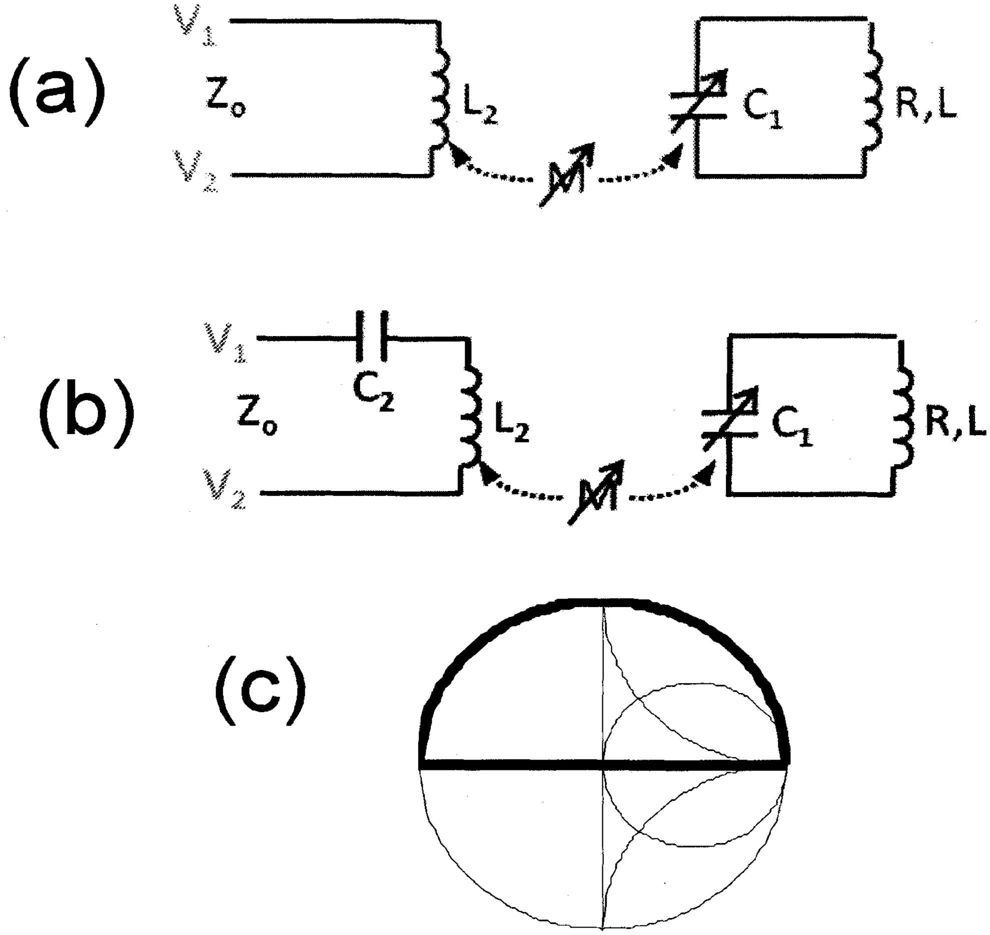


图 29

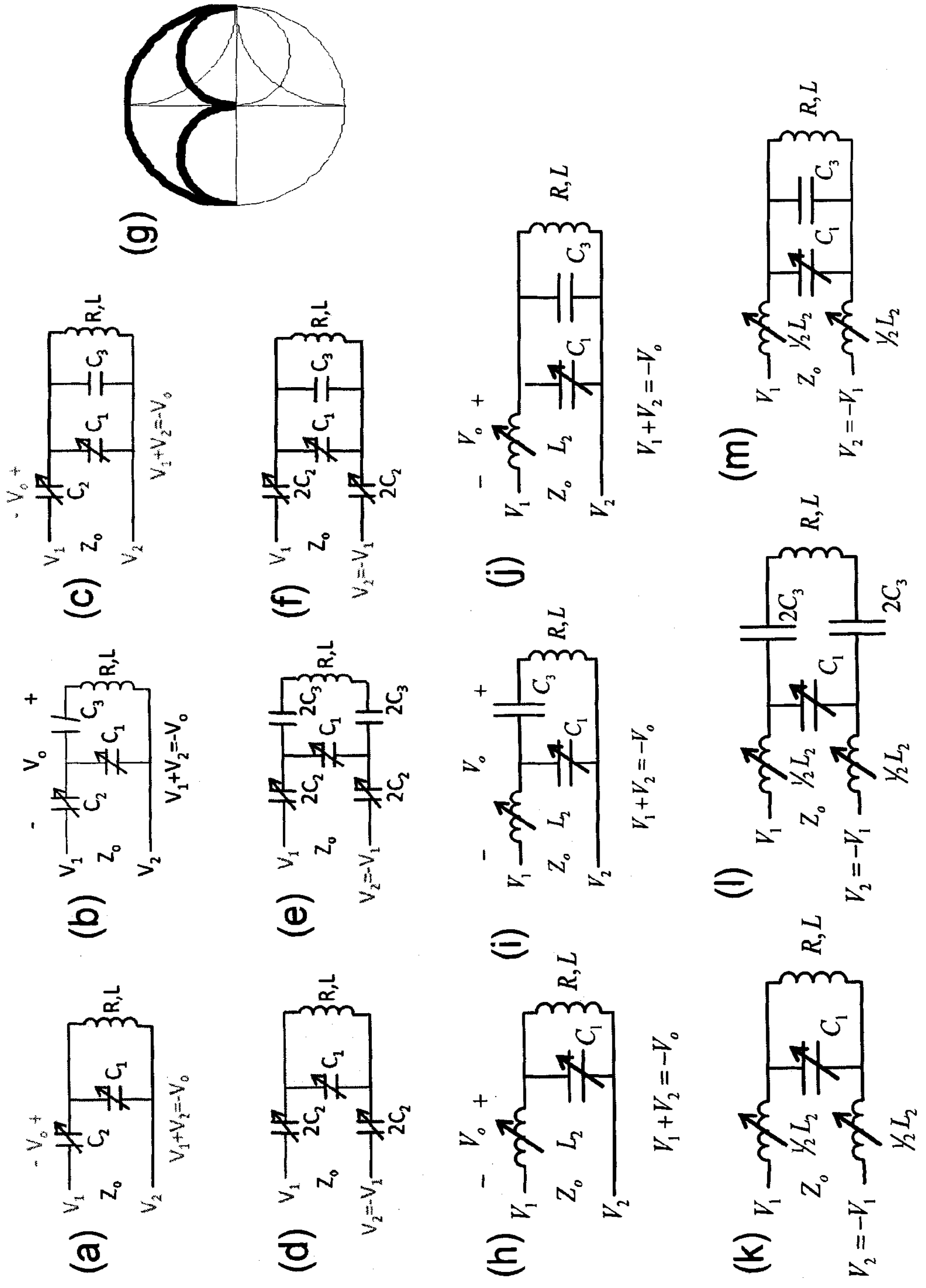

(a)
V_1
Z_o
V_2
- V_o +
C_2
C_1
R,L
$V_1+V_2=-V_o$
(b)
V_1
Z_o
V_2
- V_o +
C_2
C_1
C_3
R,L
$V_1+V_2=-V_o$
(c)
V_1
Z_o
V_2
- V_o +
C_2
C_1
C_3
R,L
$V_1+V_2=-V_o$
(d)
V_1
Z_o
$V_2=-V_1$
$2C_2$
$2C_2$
C_1
R,L
(e)
V_1
Z_o
$V_2=-V_1$
$2C_2$
$2C_2$
C_1
$2C_3$
$2C_3$
R,L
(f)
V_1
Z_o
$V_2=-V_1$
$2C_2$
$2C_2$
C_1
C_3
R,L
(g)
(h)
V_1
Z_o
V_2
- V_o +
L_2
C_1
R,L
$V_1+V_2=-V_o$
(i)
V_1
Z_o
V_2
- V_o +
L_2
C_1
C_3
R,L
$V_1+V_2=-V_o$
(j)
V_1
Z_o
V_2
- V_o +
L_2
C_1
C_3
R,L
$V_1+V_2=-V_o$
(k)
V_1
Z_o
$V_2=-V_1$
$\frac{1}{2}L_2$
$\frac{1}{2}L_2$
C_1
R,L
(l)
V_1
Z_o
$V_2=-V_1$
$\frac{1}{2}L_2$
$\frac{1}{2}L_2$
C_1
$2C_3$
$2C_3$
R,L
(m)
V_1
Z_o
$V_2=-V_1$
$\frac{1}{2}L_2$
$\frac{1}{2}L_2$
C_1
C_3
R,L

图 30

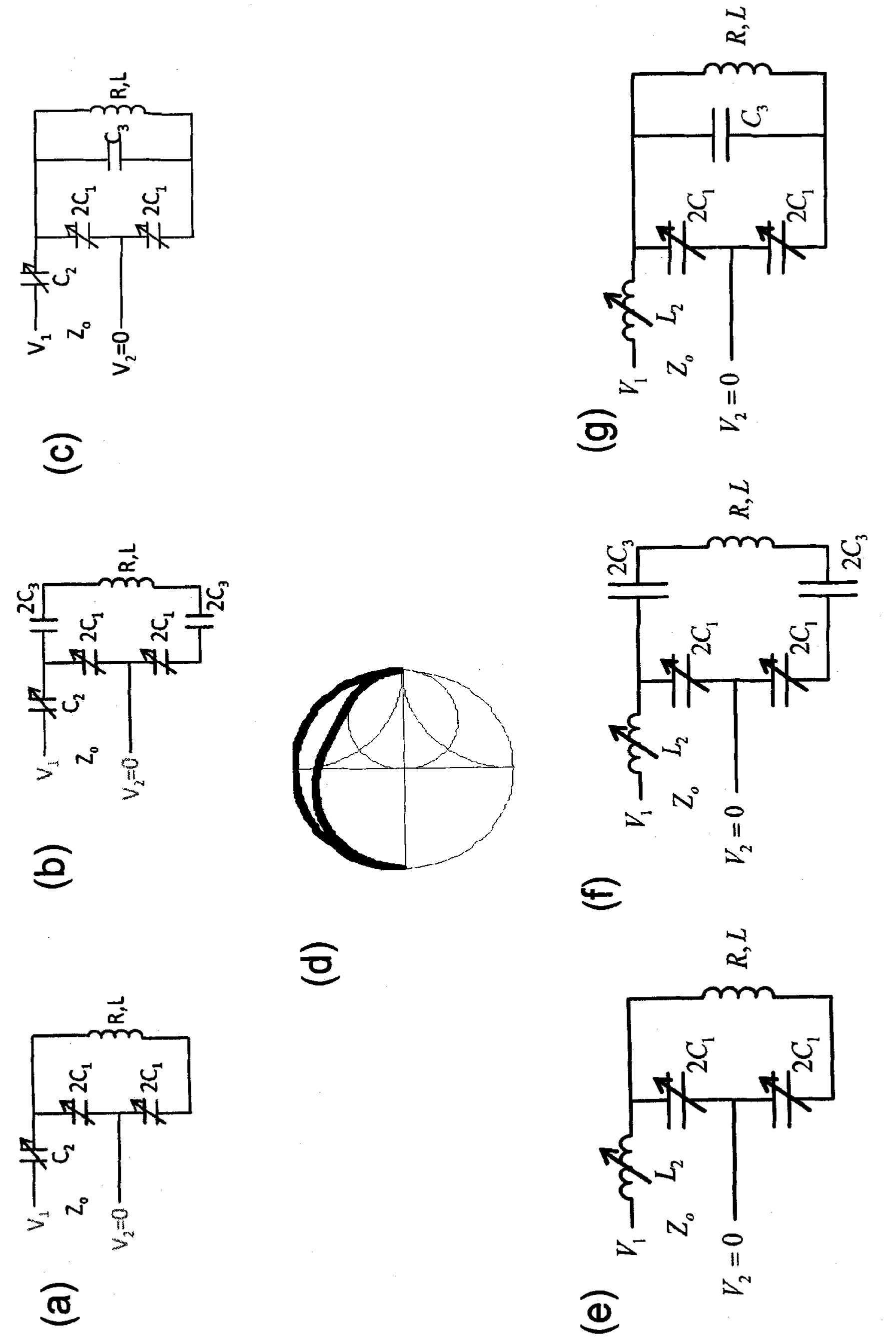

(a)
V_1
Z_o
$V_2=0$
C_2
$2C_1$
$2C_1$
R,L
(b)
V_1
Z_o
$V_2=0$
C_2
$2C_1$
$2C_1$
$2C_3$
$2C_3$
R,L
(c)
V_1
Z_o
$V_2=0$
C_2
$2C_1$
$2C_1$
C_3
R,L
(d)
(e)
V_1
Z_o
$V_2=0$
L_2
$2C_1$
$2C_1$
R,L
(f)
V_1
Z_o
$V_2=0$
L_2
$2C_1$
$2C_1$
$2C_3$
$2C_3$
R,L
(g)
V_1
Z_o
$V_2=0$
L_2
$2C_1$
$2C_1$
C_3
R,L

图 31

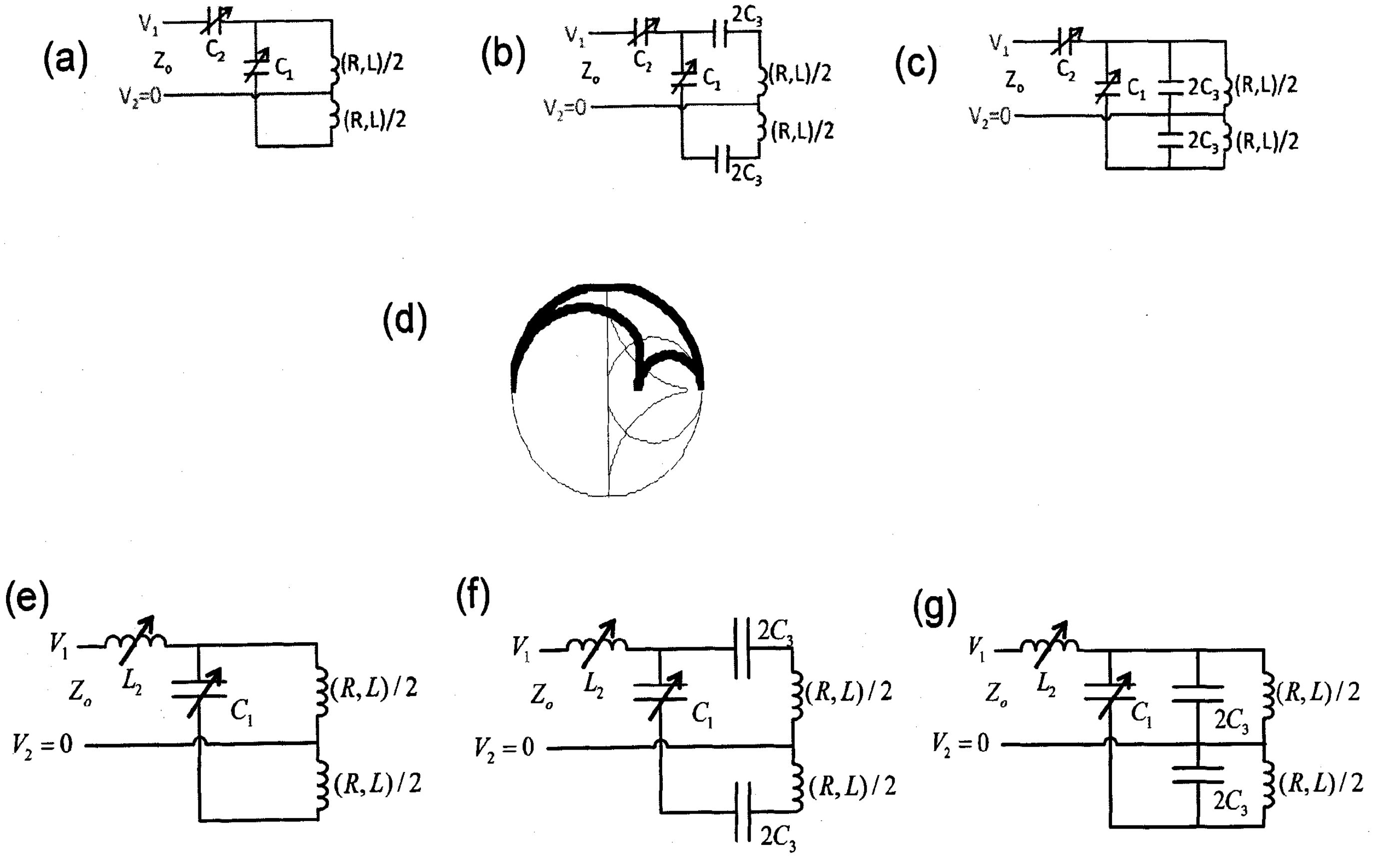

(a)
V_1
Z_o
$V_2=0$
C_2
C_1
(R,L)/2
(R,L)/2
(b)
V_1
Z_o
$V_2=0$
C_2
C_1
$2C_3$
(R,L)/2
(R,L)/2
$2C_3$
(c)
V_1
Z_o
$V_2=0$
C_2
C_1
$2C_3$
(R,L)/2
$2C_3$
(R,L)/2
(d)
(e)
V_1
Z_o
$V_2=0$
L_2
C_1
(R,L)/2
(R,L)/2
(f)
V_1
Z_o
$V_2=0$
L_2
C_1
$2C_3$
(R,L)/2
(R,L)/2
$2C_3$
(g)
V_1
Z_o
$V_2=0$
L_2
C_1
$2C_3$
(R,L)/2
$2C_3$
(R,L)/2

图 32

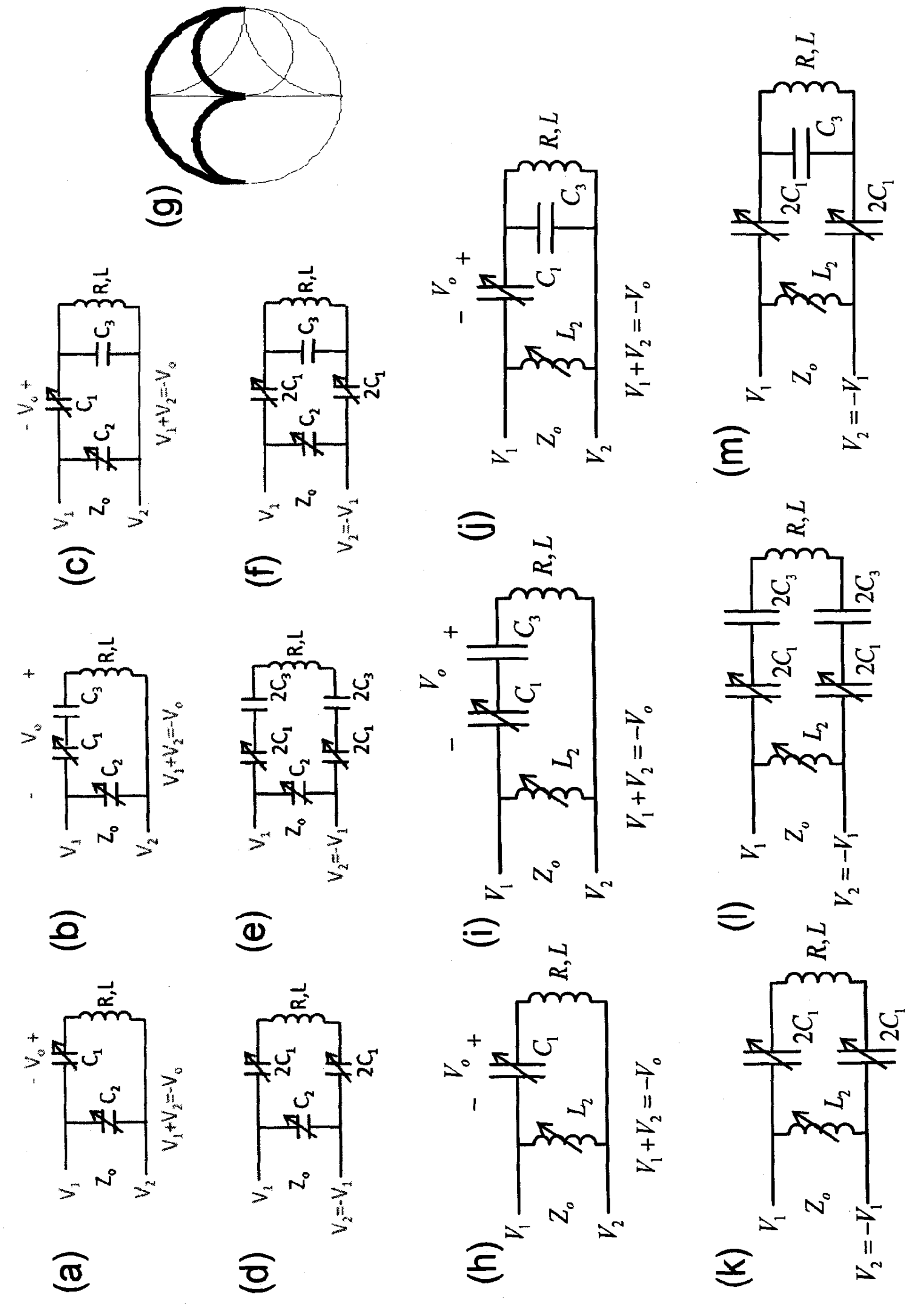

(a)
V1
Z0
V2
C2
- V0 +
C1
R,L
V1+V2=-V0
(b)
V1
Z0
V2
C2
-
V0
+
C1
C3
R,L
V1+V2=-V0
(c)
V1
Z0
V2
C2
- V0 +
C1
C3
R,L
V1+V2=-V0
(d)
V1
Z0
V2=-V1
C2
2C1
2C1
R,L
(e)
V1
Z0
V2=-V1
C2
2C1
2C1
2C3
2C3
R,L
(f)
V1
Z0
V2=-V1
C2
2C1
2C1
C3
R,L
(g)
(h)
V1
Z0
V2
L2
-
V0
+
C1
R,L
V1+V2=-V0
(i)
V1
Z0
V2
L2
-
V0
+
C1
C3
R,L
V1+V2=-V0
(j)
V1
Z0
V2
L2
-
V0
+
C1
C3
R,L
V1+V2=-V0
(k)
V1
Z0
V2=-V1
L2
2C1
2C1
R,L
(l)
V1
Z0
V2=-V1
L2
2C1
2C1
2C3
2C3
R,L
(m)
V1
Z0
V2=-V1
L2
2C1
2C1
C3
R,L

图 33

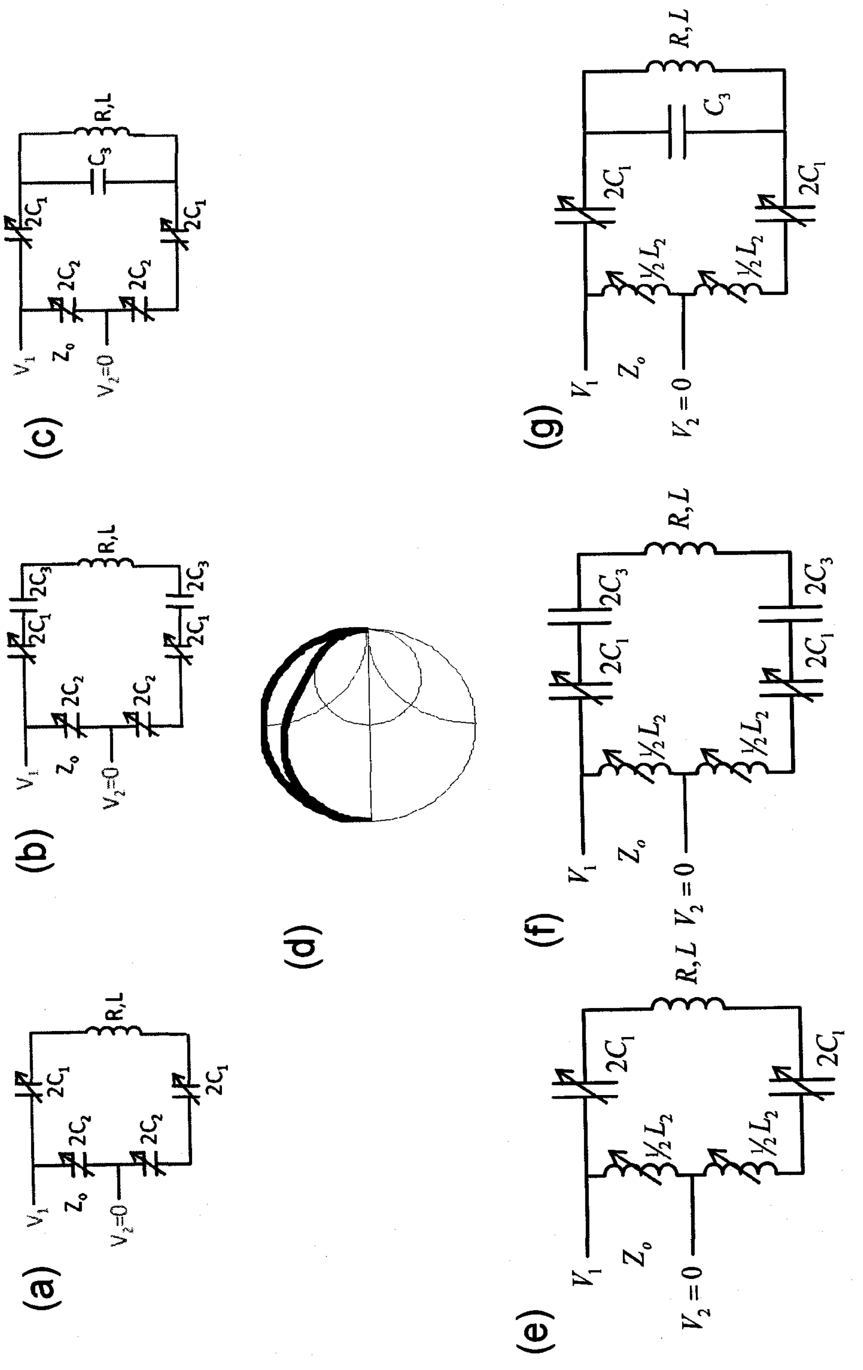

(a)
V₁
Z₀
V₂=0
2C₂
2C₂
2C₁
2C₁
R,L
(b)
V₁
Z₀
V₂=0
2C₂
2C₂
2C₁
2C₁
2C₃
2C₃
R,L
(c)
V₁
Z₀
V₂=0
2C₂
2C₂
2C₁
2C₁
C₃
R,L
(d)
(e)
V₁
Z₀
V₂ = 0
½L₂
½L₂
2C₁
2C₁
R,L
(f)
V₁
Z₀
V₂ = 0
½L₂
½L₂
2C₁
2C₁
2C₃
2C₃
R,L
(g)
V₁
Z₀
V₂ = 0
½L₂
½L₂
2C₁
2C₁
C₃
R,L

图 34

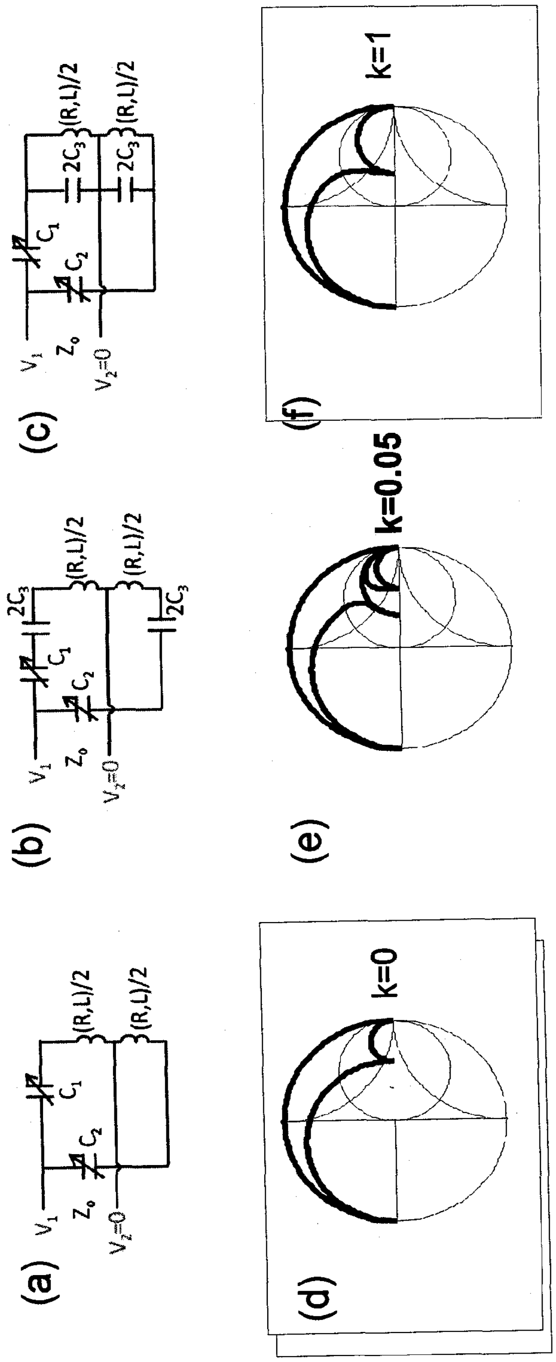


图 35

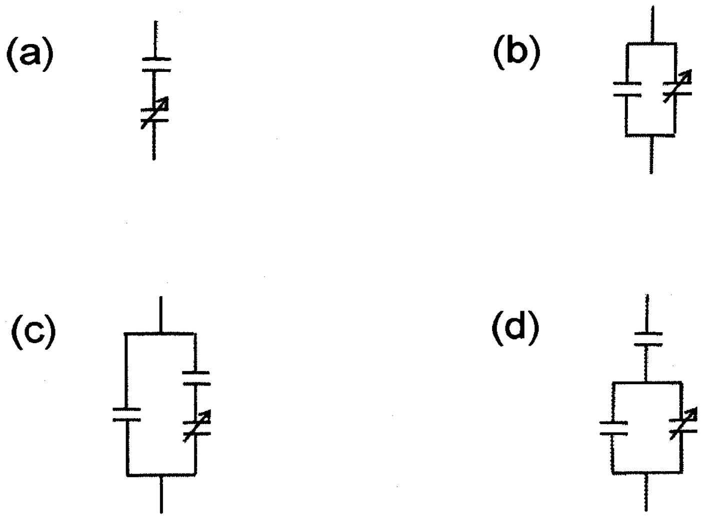


图 36

图 37

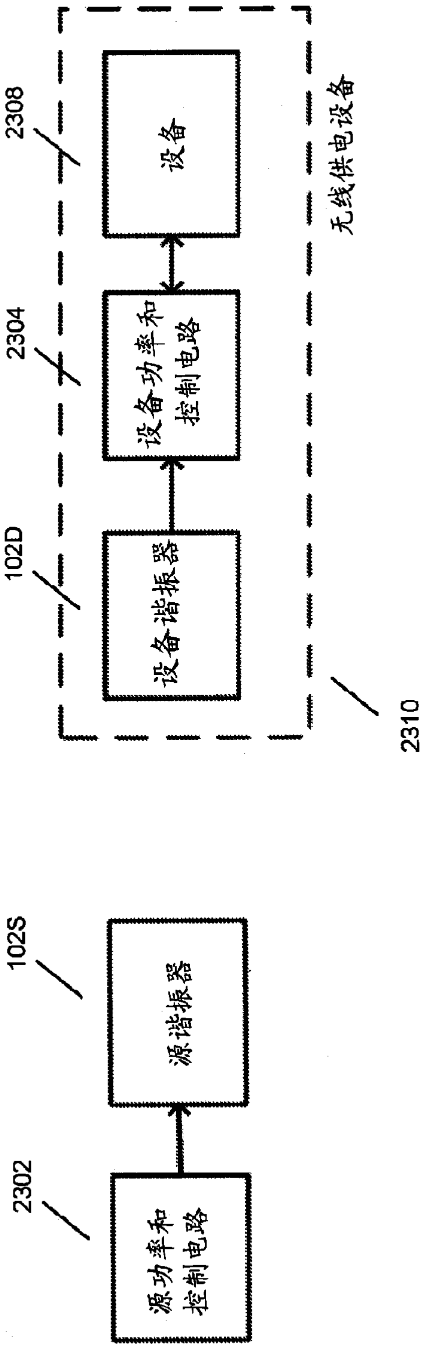

2308
设备
2304
设备功率和控制电路
102D
设备谐振器
无线供电设备
2310
102S
源谐振器
2302
源功率和控制电路

图 38

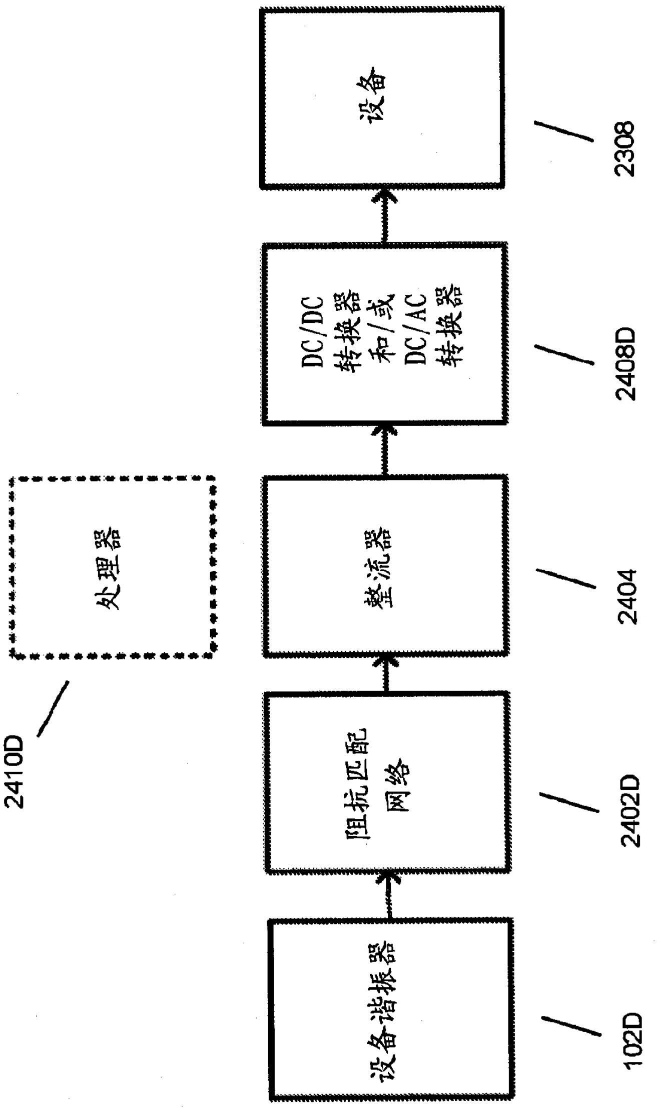

设备谐振器
102D
阻抗匹配网络
2402D
整流器
2404
DC/DC转换器和/或DC/AC转换器
2408D
设备
2308
处理器
2410D

图 39

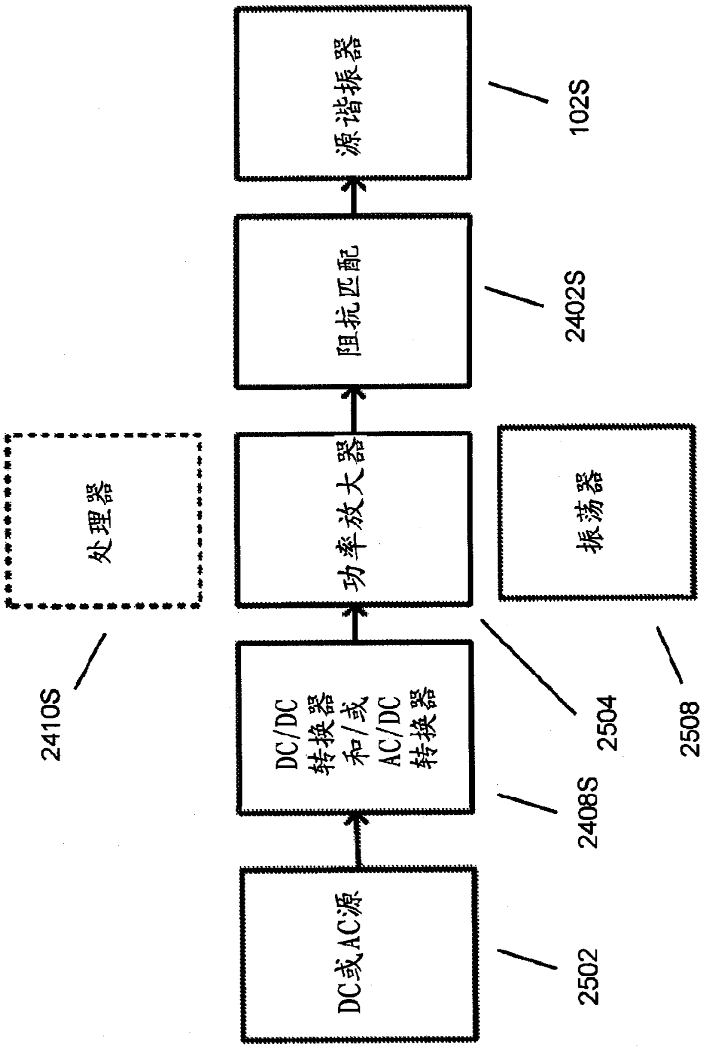

DC或AC源
2502
DC/DC 转换器 和/或 AC/DC 转换器
2408S
功率放大器
2504
处理器
2410S
振荡器
2508
阻抗匹配
2402S
源谐振器
102S

图 40

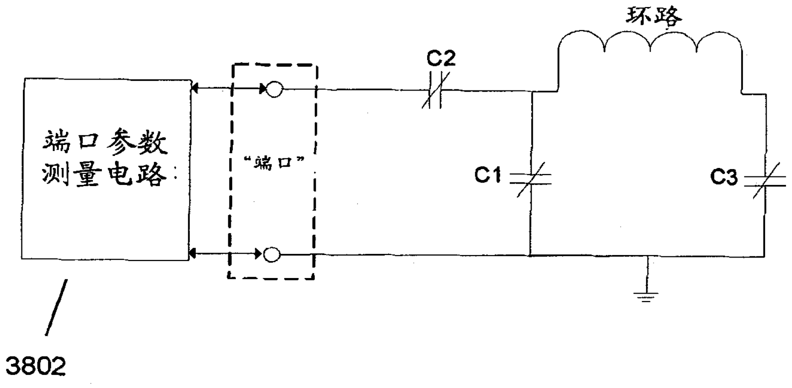


图 41

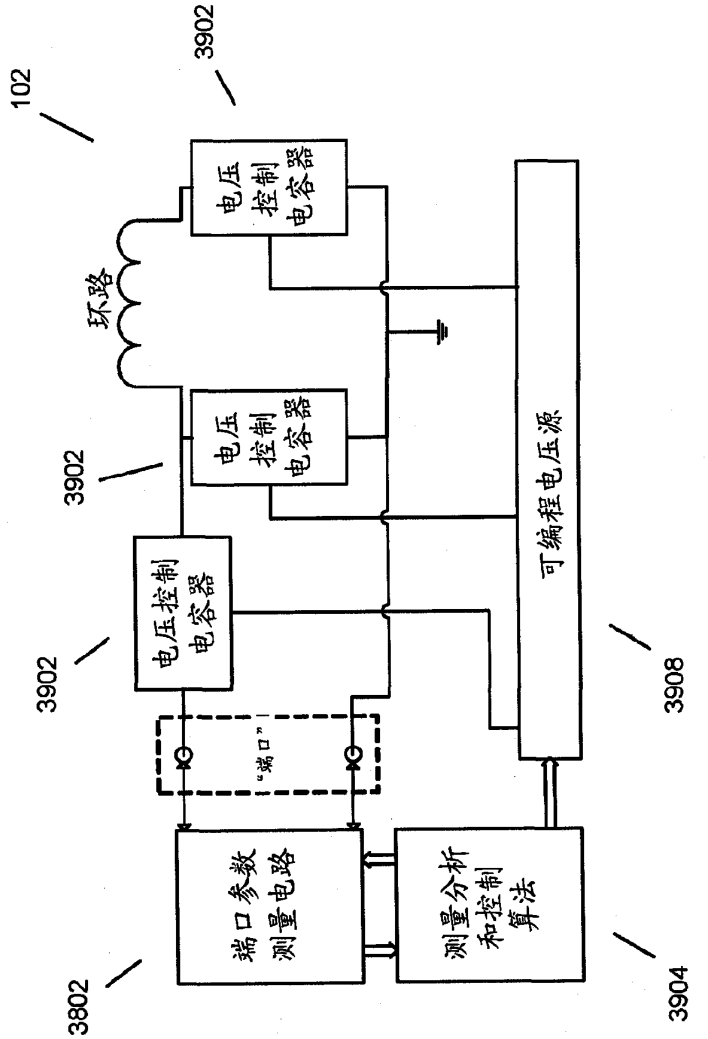

102
3902
环路
电压控制电容器
3902
电压控制电容器
3902
电压控制电容器
可编程电压源
3908
"端口"
端口参数测量电路
3802
测量分析和控制算法
3904

图 42

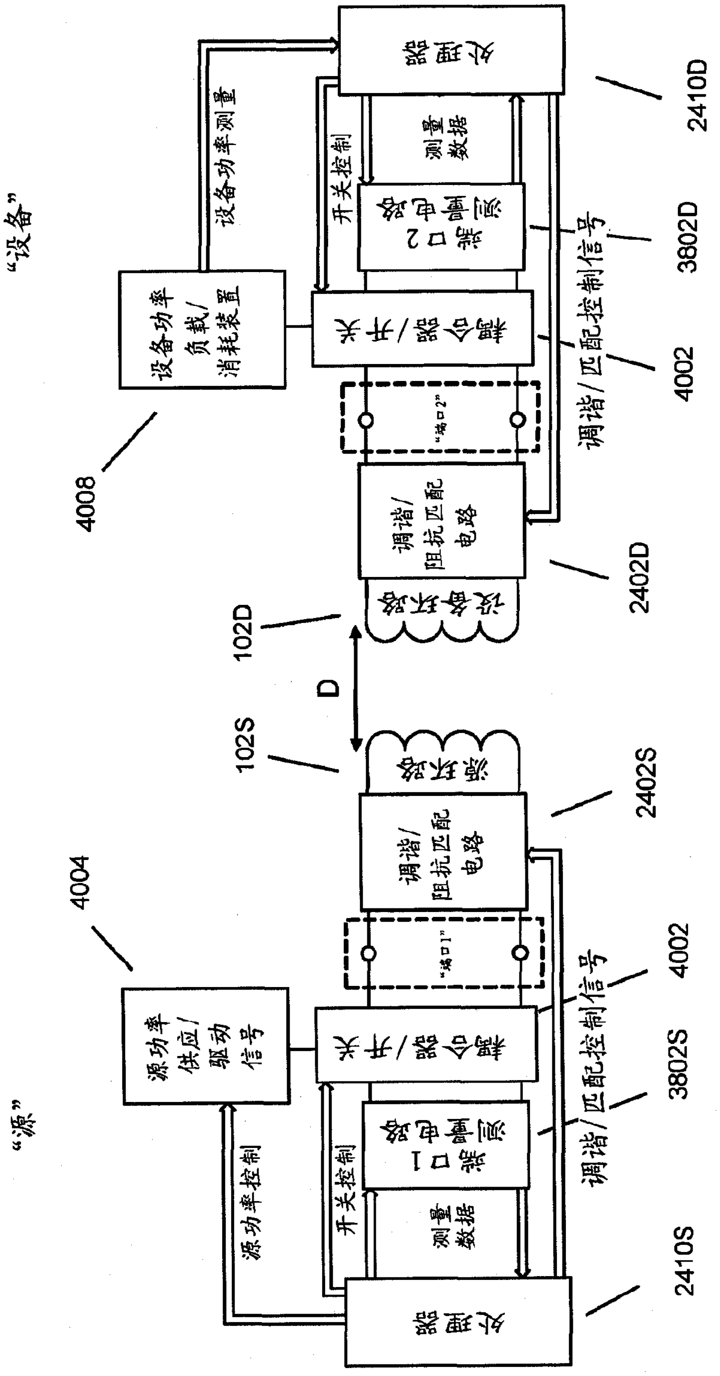

"源"
"设备"
处理器
测量数据
开关控制
端口1 测量电路
端口2 测量电路
耦合器/开关
源功率供应/驱动信号
源功率控制
"端口1"
"端口2"
调谐/阻抗匹配电路
源环路
设备环路
D
调谐/匹配控制信号
设备功率负载/消耗装置
设备功率测量
2410S
3802S
4002
4004
2402S
102S
102D
2402D
4008
2410D
3802D

图 43

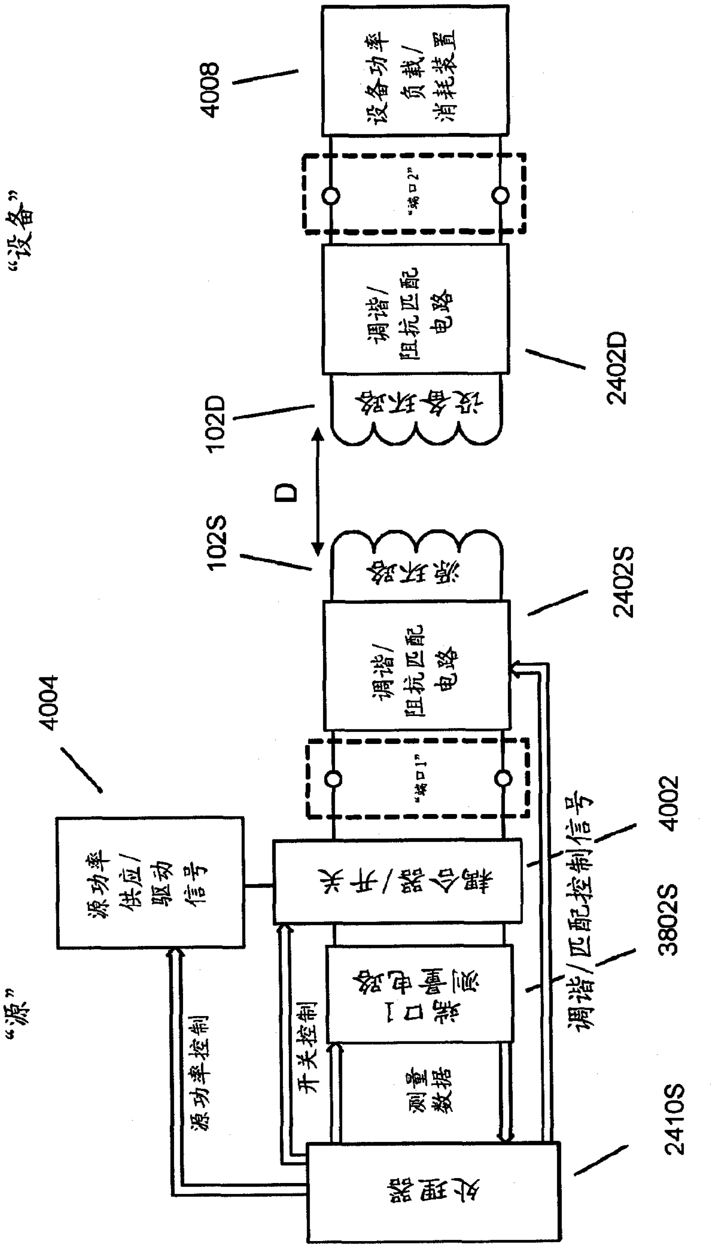

“源”
“设备”
4008
设备功率负载/消耗装置
“端口2”
调谐/阻抗匹配电路
2402D
设备环路
102D
D
102S
源环路
2402S
调谐/阻抗匹配电路
4004
“端口1”
源功率供应/驱动信号
耦合器/开关
4002
调谐/匹配控制信号
3802S
端口1测量电路
开关控制
测量数据
源功率控制
处理器
2410S

图 44

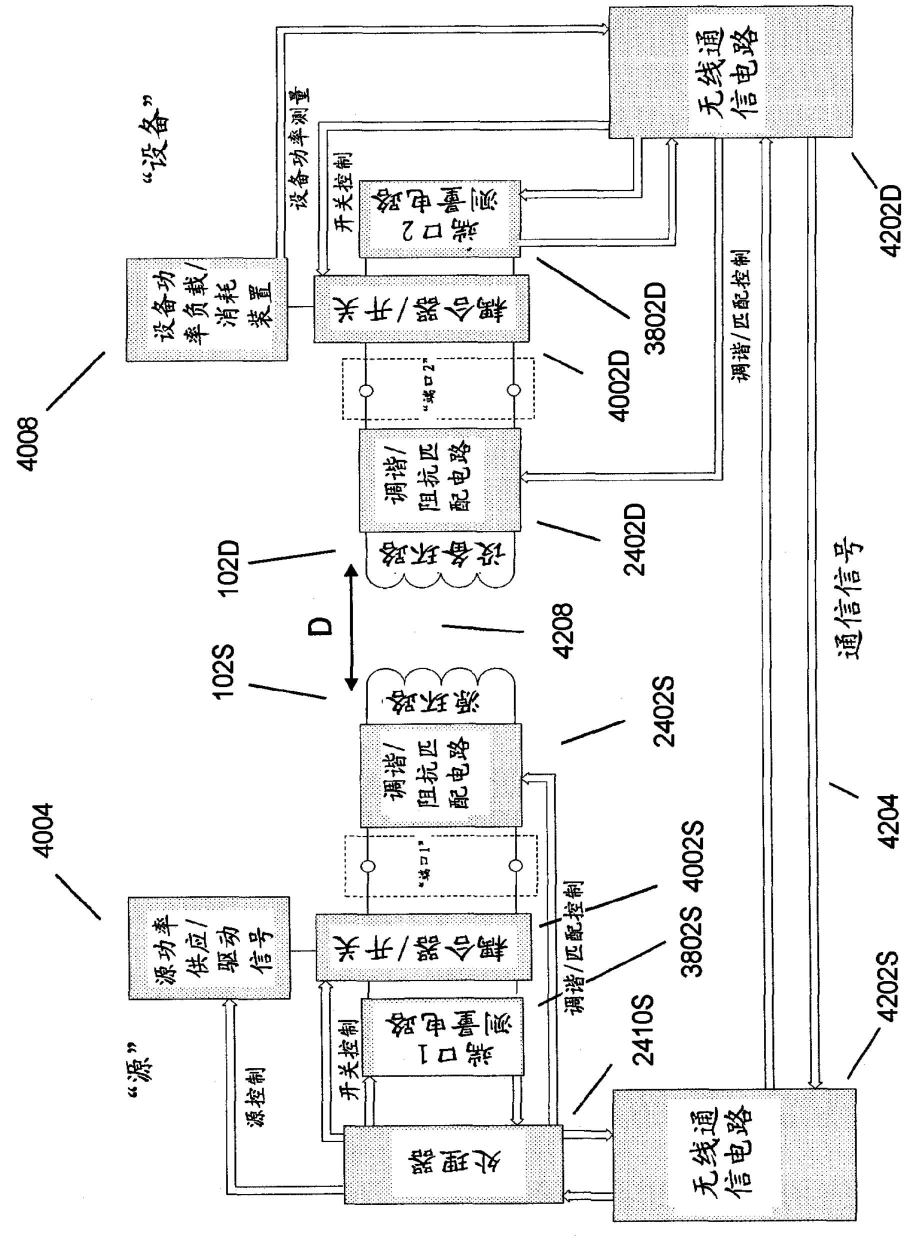

“设备”
“源”
4008
4004
设备功率负载/消耗装置
源功率供应/驱动信号
耦合器/开关
耦合器/开关
端口2测量电路
端口1测量电路
“端口2”
“端口1”
调谐/阻抗匹配电路
调谐/阻抗匹配电路
设备环路
源环路
D
无线通信电路
无线通信电路
处理器
设备功率测量
开关控制
开关控制
调谐/匹配控制
调谐/匹配控制
源控制
通信信号
102D
102S
4208
2402D
2402S
4002D
3802D
4002S
3802S
2410S
4202D
4202S
4204

图 45

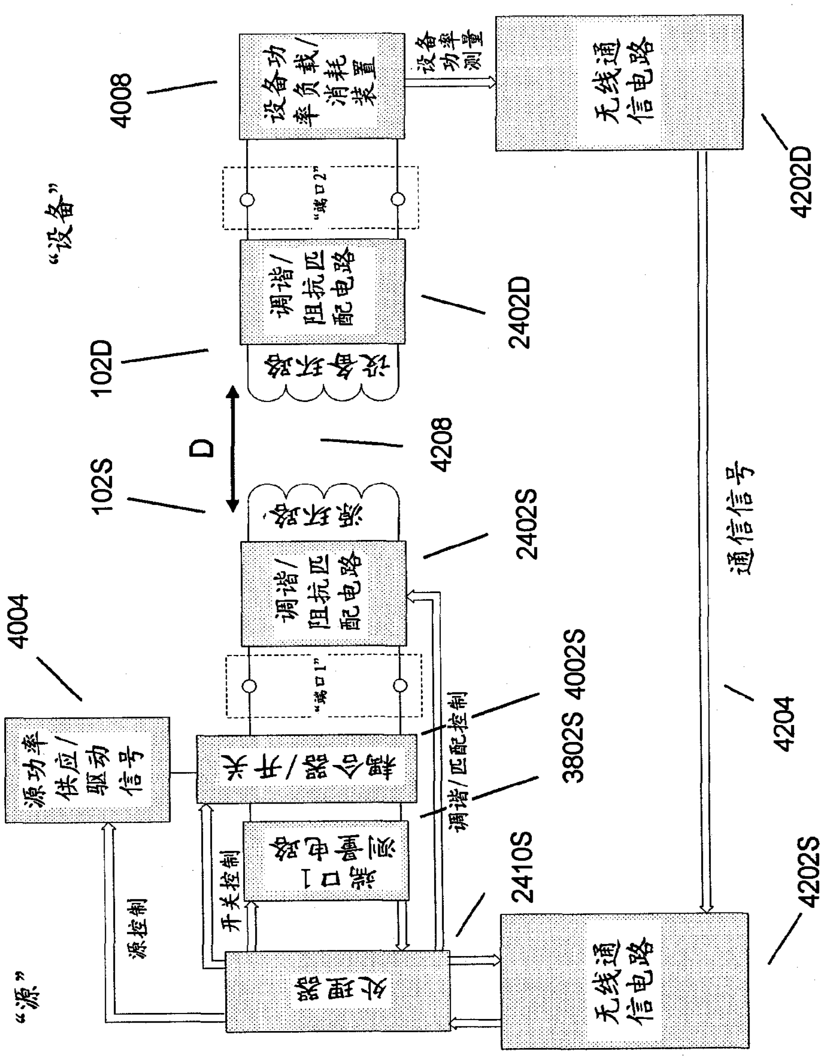

“源”
“设备”
4004
源功率供应/驱动信号
源控制
处理器
开关控制
端口1测量电路
耦合器/开关
调谐/匹配控制
3802S
4002S
2410S
“端口1”
调谐/阻抗匹配电路
2402S
源环路
102S
D
4208
102D
设备环路
调谐/阻抗匹配电路
2402D
“端口2”
设备功率负载/消耗装置
4008
设备功率测量
无线通信电路
4202D
通信信号
4204
无线通信电路
4202S

图 46

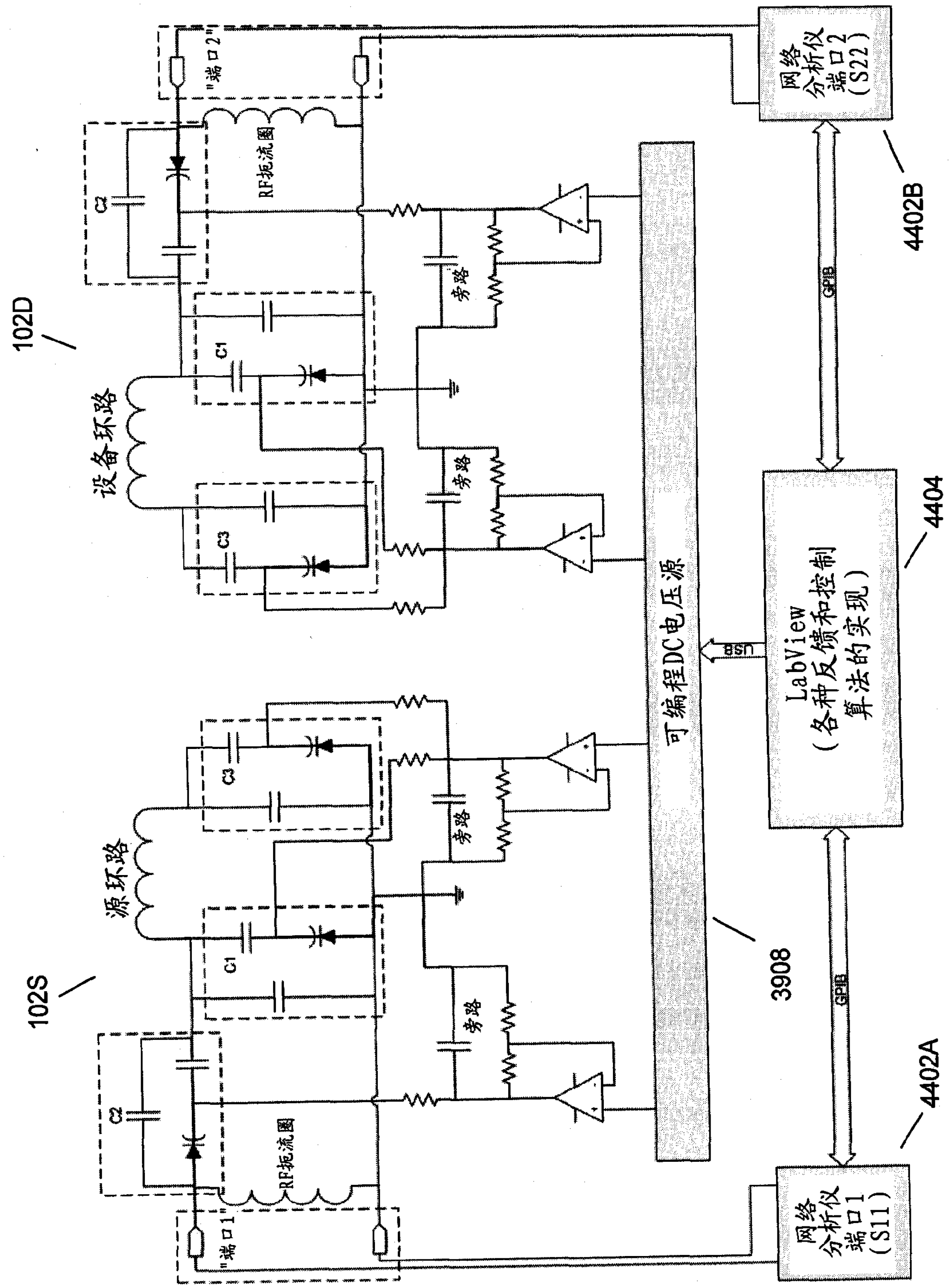

102D
设备环路
C1
C2
C3
RF扼流圈
"端口2"
网络分析仪端口2（S22）
4402B
GPIB
旁路
可编程DC电压源
USB
LabView（各种反馈和控制算法的实现）
4404
3908
102S
源环路
C1
C2
C3
RF扼流圈
旁路
"端口1"
GPIB
网络分析仪端口1（S11）
4402A

图 47

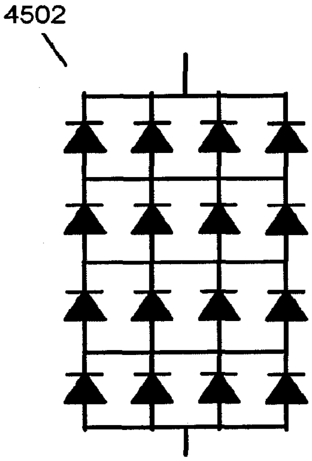


图 48

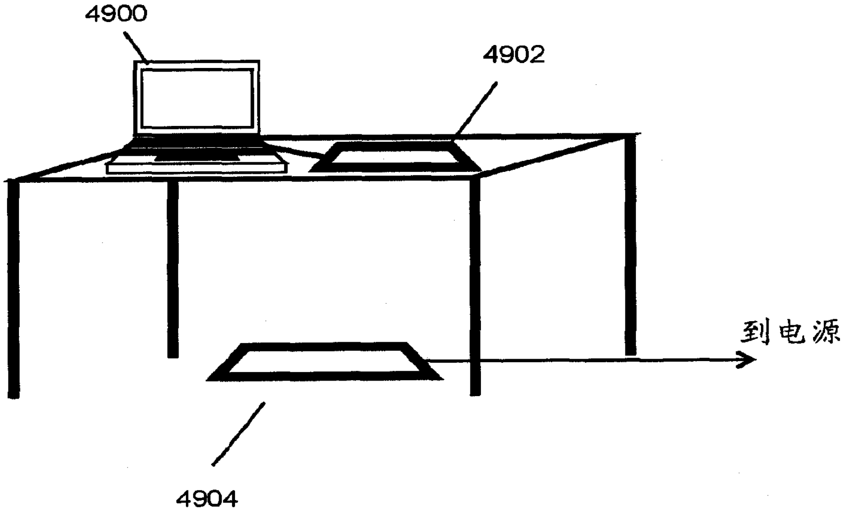


图 49

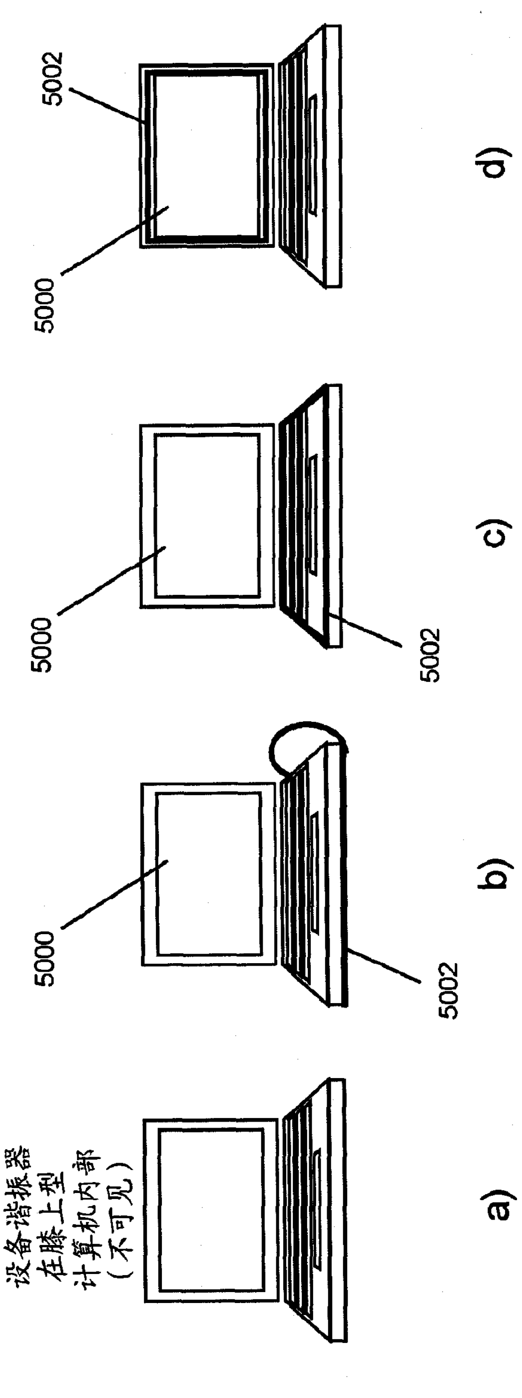


图 50

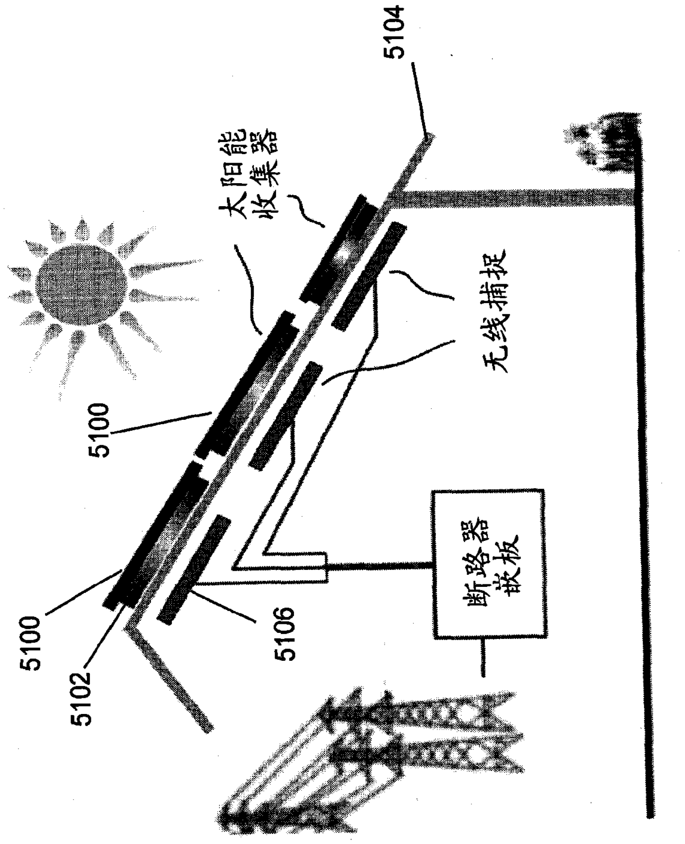


图 51

Espacenet
Bibliographic data: EP2340611 (A1) — 2011-07-06

WIRELESS ENERGY TRANSFER SYSTEMS

Inventor(s):	KESLER MORRIS P [US]; KARALIS ARISTEIDIS [US]; KURS ANDRE B [US]; CAMPANELLA ANDREW J [US]; FIORELLO RON [US]; LI QIANG [US]; KULIKOWSKI KONRAD J [US]; GILER ERIC R [US]; PERGAL FRANK J [US]; SCHATZ DAVID A [US]; HALL KATHERINE L [US]; SOLJACIC MARIN [US] +	
Applicant(s):	WITRICITY CORP [US] +	
Classification:	**- international:**	***H03B19/00***
	- European:	H02J5/00T
Application number:	EP20090816961 20090925	
Priority number(s):	WO2009US58499 20090925; US20090147386P 20090126; US20080108743P 20081027; US20080100721P 20080927; US20090152086P 20090212; US20090169240P 20090414; US20090163695P 20090326; US20090142887P 20090106; US20090182768P 20090601; US20090142796P 20090106; US20080121159P 20081209; US20090152390P 20090213; US20090173747P 20090429; US20090142889P 20090106; US20090142885P 20090106; US20090172633P 20090424; US20090142977P 20090107; US20090156764P 20090302; US20090178508P 20090515; US20090142880P 20090106; US20090142818P 20090106; US20090143058P 20090107	
Also published as:	WO2010036980 (A1) US2010181843 (A1) US8106539 (B2) US2010109445 (A1) US8035255 (B2) more	

Abstract not available for EP2340611 (A1)
Abstract of corresponding document: WO2010036980 (A1)

Described herein are improved capabilities for a source resonator having a Q- factor Q1>100 and a characteristic size x1 coupled to an energy source, and a second resonator having a Q-factor Q2>100 and a characteristic size x2 coupled to an energy drain located a distance D from the source resonator, where the source resonator and the second resonator are coupled to exchange energy wirelessly among the source resonator and the second resonator.

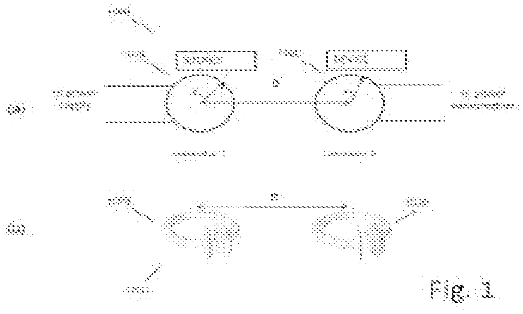


Fig. 1

(19) **Europäisches Patentamt**
European Patent Office
Office européen des brevets

(11) Veröffentlichungsnummer:
(11) Publication number:
(11) Muméro de publication:

EP 2 340 611 A0

Internationale Anmeldung veröffentlich durch die Weltorganisation für geistiges Eigentum unter der Nummer:

WO 2010/036980 (art. 158 des EPÜ).

International application published by the World Intellectual Property Organisation under number:

WO 2010/036980 (art. 158 of the EPC).

Demande internationale publiée par l'Organisation Mondiale de la Propriété sous le numéro:

WO 2010/036980 (art. 158 de la CBE).

Espacenet
Bibliographic data: EP2396796 (A1) — 2011-12-21

WIRELESS ENERGY TRANSFER IN LOSSY ENVIRONMENTS

Inventor(s):	KURS ANDRE B [US]; HALL KATHERINE L [US]; KESLER MORRIS P [US]; SOLJACIC MARIN [US]; GILER ERIC R [US] +
Applicant(s):	WITRICITY CORP [US] +
Classification:	**- international:** ***H01F27/42*** **- European:** H01Q1/24E; H02J5/00T; H04B5/00C
Application number:	EP20100741851 20100213
Priority number(s):	WO2010US24199 20100213; US20090567716 20090925; US20090152390P 20090213; US20090182768P 20090601; US20090639489 20091216; US20090173747P 20090429; US20090647705 20091228; US20090169240P 20090414; US20090156764P 20090302; US20090172633P 20090424; US20090178508P 20090515; US20090163695P 20090326
Also published as:	WO2010093997 (A1) KR20110127203 (A) CA2752573 (A1) AU2010213557 (A1)

Abstract not available for EP2396796 (A1)
Abstract of corresponding document: WO2010093997 (A1)

Described herein are improved configurations for a wireless power transfer for electronic devices that include at least one source magnetic resonator including a capacitively- loaded conducting loop coupled to a power source and configured to generate an oscillating magnetic field and at least one device magnetic resonator, distal from said source resonators, comprising a capacitively-loaded conducting loop configured to convert said oscillating magnetic fields into electrical energy, wherein at least one said resonator has a keep-out zone around the resonator that surrounds the resonator with a layer of non-lossy material.

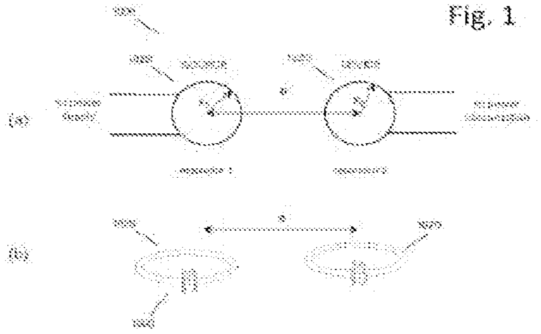


Fig. 1

(19)

Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Veröffentlichungsnummer:
(11) Publication number:
(11) Muméro de publication:

EP 2 396 796 A0

Internationale Anmeldung veröffentlich durch die Weltorganisation für geistiges Eigentum unter der Nummer:

WO 2010/093997 (art. 158 des EPÜ).

International application published by the World Intellectual Property Organisation under number:

WO 2010/093997 (art. 158 of the EPC).

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Ministry of Commerce and Industry

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Detail

APPLICATION NUMBER	1734/KOLNP/2011
APPLICANT NAME	WITRICITY CORPORATION
DATE OF FILING	28/04/2011 16:54:39
PCT INTERNATIONAL FILING DATE	25/09/2009
PRIORITY DATE	27/09/2008
TITLE OF INVENTION	WIRELESS ENERGY TRANSFER SYSTEMS
PUBLICATION DATE (U/S 11A)	02/09/2011

Application Status

Status	Request For Examination not filed

Application Number Search Format
Delhi
172/DEL/2001 or 172/DELNP/2001
Kolkata
172/KOL/2001 or 172/KOLNP/2001 or 172/CAL/2001
Mumbai
172/MUM/2001 or 172/MUMNP/2001 or 172/BOM/2001
Chennai
172/CHE/2001 or 172/CHENP/2001 or 172/MAS/2001

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Complete Specification

WIRELESS ENERGY TRANSFER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to the following U.S. patent applications, each of which is hereby incorporated by reference in its entirety:

[0002] U.S. App. No. 61/100,721 filed September 27,2008; U.S. App. No. 61/108,743 filed October 27, 2008; U.S. App. No. 61/147,386 filed January 26, 2009; U.S. App. No. 61/152,086 filed February 12, 2009; U.S. App. No. 61/178,508 filed May 15, 2009; U.S. App. No. 61/182,768 filed June 1, 2009; U.S. App. No. 61/121,159 filed December 9, 2008; U.S. App. No. 61/142,977 filed January 7, 2009; U.S. App. No. 61/142,885 filed January 6, 2009; U.S. App. No. 61/142,796 filed January 6, 2009; U.S. App. No. 61/142,889 filed January 6, 2009; U.S. App. No. 61/142,880 filed January 6, 2009; U.S. App. No. 61/142,818 filed January 6, 2009; U.S. App. No. 61/142,887 filed January 6, 2009; U.S. App. No. 61/156,764 filed March 2, 2009; U.S. App. No. 61/143,058 filed January 7, 2009; U.S. App. No. 61/152,390 filed February 13, 2009; U.S. App. No. 61/163,695 filed March 26, 2009; U.S. App. No. 61/172,633 filed April 24, 2009; U.S. App. No. 61/169,240 filed April 14, 2009, and U.S. App. No. 61/173,747 filed April 29, 2009.

BACKGROUND

[0003] Field:

[0004] This disclosure relates to wireless energy transfer, also referred to as wireless power transmission.

[0005] Description of the Related Art:

[0006] Energy or power may be transferred wirelessly using a variety of known radiative, or far-field, and non-radiative, or near-field, techniques. For example, radiative wireless information transfer using low-directionality antennas, such as those used in radio and cellular communications systems and home computer networks, may be considered wireless energy transfer. However, this type of radiative transfer is very inefficient because only a tiny portion of the supplied or radiated power, namely, that portion in the direction of," and overlapping with, the receiver is picked up. The vast majority of the power is radiated away in all the other directions and lost in free space. Such inefficient power transfer may be acceptable for data transmission, but is not practical for transferring useful amounts of electrical energy for the purpose of doing work, such as for powering or charging electrical devices. One way to improve the transfer efficiency of some radiative energy transfer schemes is to use directional antennas to confine and preferentially direct the radiated energy towards a receiver. However, these directed radiation schemes may require an uninterruptible line-of-sight and potentially complicated tracking and steering mechanisms in the case of mobile transmitters and/or receivers. In addition, such schemes may pose hazards to objects or people that cross or intersect the beam when modest to high amounts of power are being transmitted. A known non-radiative, or near-field, wireless energy transfer scheme, often referred to as either induction or traditional induction, does not (intentionally) radiate power, but uses an oscillating current passing through a primary coil, to generate an oscillating magnetic near-field that induces currents in a near-by receiving or secondary coil. Traditional induction schemes have demonstrated the transmission of modest to large amounts of power, however only over very short distances, and with very small offset tolerances between the primary power supply unit and the secondary receiver unit. Electric transformers and proximity chargers are examples of devices that utilize this known short range, near-field energy transfer scheme.

[0007] Therefore a need exists for a wireless power transfer scheme that is capable of transferring useful amounts of electrical power over mid-range distances or alignment offsets. Such a wireless power transfer scheme should enable useful energy transfer over greater distances and alignment offsets than those realized with traditional induction schemes, but without the limitations and risks inherent in radiative transmission schemes.

SUMMARY

[0008] There is disclosed herein a non-radiative or near-field wireless energy transfer scheme that is capable of transmitting useful amounts of power over mid-range distances and alignment offsets. This inventive technique uses coupled electromagnetic resonators with long-lived oscillatory resonant modes to transfer power from a power supply to a power drain. The technique is general and may be applied to a wide range of resonators, even where the specific examples disclosed herein relate to electromagnetic resonators. If the resonators are designed such that the energy stored by the electric field is primarily confined within the structure and that the energy stored by the magnetic field is primarily in the region surrounding the resonator. Then, the energy exchange is mediated primarily by the resonant magnetic near-field. These types of resonators may be referred to as magnetic resonators. If the resonators are designed such that the energy stored by the magnetic field is primarily confined within the structure and that the energy stored by the electric field is primarily in the region surrounding the resonator. Then, the energy exchange is mediated primarily by the resonant electric near-field. These types of resonators may be referred to as electric resonators. Either type of resonator may also be referred to as an electromagnetic resonator. Both types of resonators are disclosed herein.

[0009] The omni-directional but stationary (non-lossy) nature of the near-fields of the resonators we disclose enables efficient wireless energy transfer over mid-range distances, over a wide range of directions and resonator orientations, suitable for charging, powering, or simultaneously powering and charging a variety of electronic devices. As a result, a system may have a wide variety of possible applications where a first resonator, connected to a power source, is in one location, and a second resonator, potentially connected to electrical/electronic devices, batteries, powering or charging circuits, and the like, is at a second location, and where the distance from the first resonator to the second resonator is on the order of centimeters to meters. For example, a first resonator connected to the wired electricity grid could be placed on the ceiling of a room, while other resonators connected to devices, such as robots, vehicles, computers, communication devices, medical devices, and the like, move about within the room, and where these devices are constantly or intermittently receiving power wirelessly from the source resonator. From this one example, one can imagine many applications where the systems and methods disclosed herein could provide wireless power across mid-range distances, including consumer electronics, industrial applications, infrastructure power and lighting, transportation vehicles, electronic games, military applications, and the like.

[0010] Energy exchange between two electromagnetic resonators can be optimized when the resonators are tuned to substantially the same frequency and when the losses in the system are minimal. Wireless energy transfer systems may be designed so that the "coupling-time" between resonators is much shorter than the resonators' "loss-times". Therefore, the systems and methods described herein may utilize high quality factor (high-Q) resonators with low intrinsic-loss rates. In addition, the systems and methods described herein may use sub-wavelength, resonators with near-fields that extend significantly longer than the characteristic sizes of the resonators, so that the near-fields of the resonators that exchange energy overlap at mid-range distances. This is a regime of operation that has not been practiced before and that differs significantly from traditional induction designs.

[0011] It is important to appreciate the difference between the high-Q magnetic resonator scheme disclosed here and the known close-range or proximity inductive schemes, namely, that those known schemes do not conventionally utilize high-Q resonators. Using coupled-mode theory (CMT), (see, for example, Waves and Fields in Optoelectronics, H.A. Haus, Prentice Hall, 1984), one may show that a high-Q resonator-coupling mechanism can enable orders of magnitude more efficient power delivery between resonators spaced by mid-range distances than is enabled by traditional inductive schemes. Coupled high-Q resonators have demonstrated efficient energy transfer over mid-range distances and improved efficiencies and offset tolerances in short range energy transfer applications.

[0012] The systems and methods described herein may provide for near-field wireless energy transfer via strongly coupled high-Q resonators, a technique with the potential to transfer power levels from picowatts to kilowatts, safely, and over distances much larger than have been achieved using traditional induction techniques. Efficient energy transfer may be realized for a variety of general systems of strongly coupled resonators, such as systems of strongly coupled acoustic resonators, nuclear resonators, mechanical resonators, and the like, as originally described by researchers at M.I.T. in their publications, "Efficient wireless non-radiative mid-range energy transfer", Annals of Physics, vol. 323, Issue 1, p. 34 (2008) and "Wireless Power Transfer via Strongly Coupled Magnetic Resonances", Science, vol. 317, no. 5834, p. 83, (2007). Disclosed herein are electromagnetic resonators and systems of coupled electromagnetic resonators, also referred to more specifically as coupled magnetic resonators and coupled electric resonators, with operating frequencies below 10 GHz.

[0013] This disclosure describes wireless energy transfer technologies, also referred to as wireless power transmission technologies. Throughout this disclosure, we may use the terms wireless energy transfer, wireless power transfer, wireless power transmission, and the like, interchangeably. We may refer to supplying energy or power from a source, an AC or DC source, a battery, a source resonator, a power supply, a generator, a solar panel, and thermal collector, and the like, to a device, a remote device, to multiple remote devices, to a device resonator or resonators, and the like. We may describe intermediate resonators that extend the range of the wireless energy transfer system by allowing energy to hop, transfer through, be temporarily stored, be partially dissipated, or for the transfer to be mediated in any way, from a source resonator to any combination of other device and intermediate resonators, so that energy transfer networks, or strings, or extended paths may be realized. Device resonators may receive energy from a source resonator, convert a portion of that energy to electric power for powering or charging a device, and simultaneously pass a portion of the received energy onto other device or mobile device resonators. Energy may be transferred from a source resonator to multiple device resonators, significantly extending the distance over which energy may be wirelessly transferred. The wireless power transmission systems may be implemented using a variety of system architectures and resonator designs. The systems may include a single source or multiple sources transmitting power to a single device or multiple devices. The resonators may be designed to be source or device resonators, or they may be designed to be repeaters. In some cases, a resonator may be a device and source resonator simultaneously, or it may be switched from operating as a source to operating as a device or a repeater. One skilled in the art will understand that a variety of system architectures may be supported by the wide range of resonator designs and functionalities described in this application.

[0014] In the wireless energy transfer systems we describe, remote devices may be powered directly, using the wirelessly supplied power or energy, or the devices may be coupled to an energy storage unit such as a battery, a super-capacitor, an ultra-capacitor, or the like (or other kind of power drain), where the energy storage unit may be charged or re-charged wirelessly, and/or where the wireless power transfer mechanism is simply supplementary to the main power source of the device. The devices may be powered by hybrid battery/energy storage devices such as batteries with integrated storage capacitors and the like. Furthermore, novel

battery and energy storage devices may be designed to take advantage of the operational improvements enabled by wireless power transmission systems.

[0015] Other power management scenarios include using wirelessly supplied power to recharge batteries or charge energy storage units while the devices they power are turned off, in an idle state, in a sleep mode, and the like. Batteries or energy storage units may be charged or recharged at high (fast) or low (slow) rates. Batteries or energy storage units may be trickle charged or float charged. Multiple devices may be charged or powered simultaneously in parallel or power delivery to multiple devices may be serialized such that one or more devices receive power for a period of time after which other power delivery is switched to other devices. Multiple devices may share power from one or more sources with one or more other devices either simultaneously, or in a time multiplexed manner, or in a frequency multiplexed manner, or in a spatially multiplexed manner, or in an orientation multiplexed manner, or in any combination of time and frequency and spatial and orientation multiplexing. Multiple devices may share power with each other, with at least one device being reconfigured continuously, intermittently, periodically, occasionally, or temporarily, to operate as wireless power sources. It would be understood by one of ordinary skill in the art that there are a variety of ways to power and/or charge devices, and the variety of ways could be applied to the technologies and applications described herein.

[0016] Wireless energy transfer has a variety of possible applications including for example, placing a source (e.g. one connected to the wired electricity grid) on the ceiling, under the floor, or in the walls of a room, while devices such as robots, vehicles, computers, PDAs or similar are placed or move freely within the room. Other applications may include powering or recharging electric-engine vehicles, such as buses and/or hybrid cars and medical devices, such as wearable or implantable devices. Additional example applications include the ability to power or recharge autonomous electronics (e.g. laptops, cell-phones, portable music players, household robots, GPS navigation systems, displays, etc), sensors, industrial and manufacturing equipment, medical devices and monitors, home appliances and tools (e.g. lights, fans, drills, saws, heaters, displays, televisions, counter-top appliances, etc.), military devices, heated or illuminated clothing, communications and navigation equipment, including equipment built into vehicles, clothing and protective-wear such as helmets, body armor and vests, and the like, and the ability to transmit power to physically isolated devices such as to implanted medical devices, to hidden, buried, implanted or embedded sensors or tags, to and/or from roof-top solar panels to indoor distribution panels, and the like.

[0017] In one aspect, a system disclosed herein includes a source resonator having a Q-factor Q1 and a characteristic size x1, coupled to a power generator, and a second resonator having a Q-factor Q2 and a characteristic size x2, coupled to a load located a distance D from the source resonator, wherein the source resonator and the second resonator are coupled to exchange energy wirelessly among the source resonator and the second resonator, and wherein 100.

[0018] Q1 may be less than 100. Q2 may be less than 100. The system may include a third resonator having a Q-factor Q3 configured to transfer energy non-raditively with the source and second resonators , wherein . Q3 may be less than 100.

[0019] The source resonator may be coupled to the power generator with direct electrical connections. The system may include an impedance matching network wherein the source resonator is coupled and impedance matched to the power generator with direct electrical connections. The system may include a tunable circuit wherein the source resonator is coupled to the power generator through the tunable circuit with direct electrical connections. The tunable circuit may include variable capacitors. The tunable circuit may include variable inductors. At least one of the direct electrical connections may be configured to substantially preserve a resonant mode of the source resonator. The source resonator may have a first terminal, a second terminal, and a center terminal, and an impedance between the first terminal and the center terminal and between the second terminal and the center terminal may be substantially equal. The source resonator may include a capacitive loaded loop having a first terminal, a second terminal, and a center terminal, wherein an impedance between the first terminal and the center terminal and between the second terminal and the center terminal are substantially equal. The source resonator may be coupled to an impedance matching network and the impedance matching network further comprises a first terminal, a second terminal, and a center terminal, wherein an impedance between the first terminal and the center terminal and between the second terminal and the center terminal are substantially equal.

[0020] The first terminal and the second terminal may be directly coupled to the power generator and driven with oscillating signals that are near 180 degrees out of phase. The source resonator may have a resonant frequency ?1 and the first terminal and the second terminal may be directly coupled to the power generator and driven with oscillating signals that are substantially equal to the resonant frequency ?1 . The center terminal may be connected to an electrical ground. The source resonator may have a resonant frequency ?1 and the first terminal and the second terminal may be directly coupled to the power generator and driven with a frequency substantially equal to the resonant frequency ?1. The system may include a plurality of capacitors coupled to the power generator and the load. The source resonator and the second resonator may each be enclosed in a low loss tangent material. The system may include a power conversion circuit wherein the second resonator is coupled to the power conversion circuit to deliver DC power to the load. The system may include a power conversion circuit wherein the second resonator is coupled to the power conversion circuit to deliver AC power to the load. The system may include a power conversion circuit, wherein the second resonator is coupled to the power conversion circuit to deliver both AC and DC power to the load. The system may include a power conversion circuit and a plurality of loads, wherein the second resonator is coupled to the power conversion circuit, and the power conversion circuit is coupled to the plurality of loads. The impedance matching network may include capacitors. The impedance matching network may include inductors.

[0021] Throughout this disclosure we may refer to the certain circuit components such as capacitors, inductors, resistors, diodes, switches and the like as circuit components or elements. We may also refer to series and parallel combinations of these components as elements, networks, topologies, circuits, and the like. We may describe combinations of capacitors, diodes, varactors, transistors, and/or switches as adjustable impedance networks, tuning networks, matching networks, adjusting elements, and the like. We may also refer to "self-resonant" objects that have both capacitance, and inductance distributed (or partially distributed, as opposed to solely lumped) throughout the entire object. Tt would be understood by one of ordinary skill in the art that adjusting and controlling variable components within a circuit or network may adjust the performance of that circuit or network and that those adjustments may be described generally as tuning, adjusting, matching, correcting, and the like. Other methods to tune or adjust the operating point of the wireless power transfer system may be used alone, or in addition to adjusting tunable components such as inductors and capacitors, or banks of inductors and capacitors.

[0022] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of conflict with publications, patent applications, patents, and other references mentioned or incorporated herein by reference, the present specification, including definitions, will control.

[0023] Any of the features described above may be used, alone or in combination, without departing from the scope of this disclosure. Other features, objects, and advantages of the systems and methods disclosed herein will be apparent from the following detailed description and figures.

BRIEF DESCRIPTION OF FIGURES

[0024] Fig. 1 (a) and (b) depict exemplary wireless power systems containing a source resonator 1 and device resonator 2 separated by a distance D.

[0025] Fig. 2 shows an exemplary resonator labeled according to the labeling convention described in this disclosure. Note that there are no extraneous objects or additional resonators shown in the vicinity of resonator 1.

[0026] Fig. 3 shows an exemplary resonator in the presence of a "loading" object, labeled according to the labeling convention described in this disclosure.

[0027] Fig. 4 shows an exemplary resonator in the presence of a "perturbing" object, labeled according to the labeling convention described in this disclosure.

[0028] Fig. 5 shows a plot of efficiency, ?, vs. strong coupling factor,

[0029] Fig. 6 (a) shows a circuit diagram of one example of a resonator (b) shows a diagram of one example of a capacitively-loaded inductor loop magnetic resonator, (c) shows a drawing of a self-resonant coil with distributed capacitance and inductance, (d) shows a simplified drawing of the electric and magnetic field lines associated with an exemplary magnetic resonator of the current disclosure, and (e) shows a diagram of one example of an electric resonator.

[0030] Fig. 7 shows a plot of the "quality factor", Q (solid line), as a function of frequency, of an exemplary resonator that may be used for wireless power transmission at MHz frequencies. The absorptive Q (dashed line) increases with frequency, while the radiative Q (dotted line) decreases with frequency, thus leading the overall Q to peak at a particular frequency.

[0031] Fig. 8 shows a drawing of a resonator structure with its characteristic size, thickness and width indicated.

[0032] Fig. 9 (a) and (b) show drawings of exemplary inductive loop elements.

[0033] Fig. 10 (a) and (b) show two examples of trace structures formed on printed circuit boards and used to realize the inductive element in magnetic resonator structures.

[0034] Fig. 11 (a) shows a perspective view diagram of a planar magnetic resonator, (b) shows a perspective view diagram of a two planar magnetic resonator with various geometries, and c) shows is a perspective view diagram of a two planar magnetic resonators separated by a distance D.

[0035] Fig. 12 is a perspective view of an example of a planar magnetic resonator.

[0036] Fig. 13 is a perspective view of a planar magnetic resonator arrangement with a circular resonator coil.

[0037] Fig. 14 is a perspective view of an active area of a planar magnetic resonator.

[0038] Fig. 15 is a perspective view of an application of the wireless power transfer system with a source at the center of a table powering several devices placed around the source.

[0039] Fig. 16(a) shows a 3D finite element model of a copper and magnetic material structure driven by a square loop of current around the choke point at its center. In this example, a structure may be composed of two boxes made of a conducting material such as copper, covered by a layer of magnetic material, and connected by a block of magnetic material. The inside of the two conducting boxes in this example would be shielded from AC electromagnetic fields generated outside the boxes and may house lossy objects that might lower the Q of the resonator or sensitive components that might be adversely affected by the AC electromagnetic fields. Also shown are the calculated magnetic field streamlines generated by this structure, indicating that the magnetic field lines tend to follow the lower reluctance path in the magnetic material. Fig. 16(b) shows interaction, as indicated by the calculated magnetic field streamlines, between two identical structures as shown in (a). Because of symmetry, and to reduce computational complexity, only one half of the system is modeled (but the computation assumes the symmetrical arrangement of the other half).

[0040] Fig. 17 shows an equivalent circuit representation of a magnetic resonator including a conducting wire wrapped N times around a structure, possibly containing magnetically permeable material. The inductance is realized using conducting loops wrapped around a structure comprising a magnetic material and the resistors represent loss mechanisms in the system (Rwire for resistive losses in the loop, Rμ denoting the equivalent series resistance of the structure surrounded by the loop). Losses may be minimized to realize high-Q resonators.

[0041] Fig. 18 shows a Finite Element Method (FEM) simulation of two high conductivity surfaces above and below a disk composed of lossy dielectric material, in an external magnetic field of frequency 6.78 MHz. Note that the magnetic field was uniform before the disk and conducting materials were introduced to the simulated environment. This simulation is performed in cylindrical coordinates. The image is azimuthally symmetric around the r= 0 axis. The lossy dielectric disk has er = 1 and s= 10 S/m.

[0042] Fig. 19 shows a drawing of a magnetic resonator with a lossy object in its vicinity completely covered by a high-conductivity surface.

[0043] Fig. 20 shows a drawing of a magnetic resonator with a lossy object in its vicinity partially covered by a high-conductivity surface.

[0044] Fig. 21 shows a drawing of a magnetic resonator with a lossy object in its vicinity placed on top of a high-conductivity surface.

[0045] Fig. 22 shows a diagram of a completely wireless projector.

[0046] Fig. 23 shows the magnitude of the electric and magnetic fields along a line that contains the diameter of the circular loop inductor and along the axis of the loop inductor.

[0047] Fig. 24 shows a drawing of a magnetic resonator and its enclosure along with a necessary but lossy object placed either (a) in the corner of the enclosure, as far away from the resonator structure as possible or (b) in the center of the surface enclosed by the inductive element in the magnetic resonator.

[0048] Fig. 25 shows a drawing of a magnetic resonator with a high-conductivity surface above it and a lossy object, which may be brought into the vicinity of the resonator, but above the high-conductivity sheet.

[0049] Fig. 26(a) shows an axially symmetric FEM simulation of a thin conducting (copper) cylinder or disk (20 cm in diameter, 2 cm in height) exposed to an initially uniform, externally applied magnetic field (gray flux lines) along the z-axis. The axis of symmetry is at r=0. The magnetic streamlines shown originate atz = -oo, where they are spaced from r=3 cm to r=10 cm in intervals of 1 cm. The axes scales are in meters. Fig. 26 (b) shows the same structure and externally applied field as in (a), except that the conducting cylinder has been modified to include a 0.25 mm layer of magnetic material (not visible) with μr =40, on its outside surface. Note that the magnetic streamlines are deflected away from the cylinder significantly less than in (a).

[0050] Fig. 27 shows an axi-symmetric view of a variation based on the system shown in Fig. 26. Only one surface of the lossy material is covered by a layered structure of copper and magnetic materials. The inductor loop is placed on the side of the copper and magnetic material structure opposite to the lossy material as shown.

[0051] Fig. 28 (a) depicts a general topology of a matching circuit including an indirect coupling to a high-Q inductive element.

[0052] Fig. 28 (b) shows a block diagram of a magnetic resonator that includes a conductor loop inductor and a tunable impedance network. Physical electrical connections to this resonator may be made to the terminal connections.

[0053] Fig. 28 (c) depicts a general topology of a matching circuit directly coupled to a high-Q inductive element.

[0054] Fig. 28 (d) depicts a general topology of a symmetric matching circuit directly coupled to a high-Q inductive element and driven anti-symmetrically (balanced drive).

[0055] Fig. 28 (e) depicts a general topology of a matching circuit directly coupled to a high-Q inductive element and connected to ground at a point of symmetry of the main resonator (unbalanced drive).

[0056] Figs. 29(a) and 29(b) depict two topologies of matching circuits transformer-coupled (i.e. indirectly or inductively) to a high-Q inductive element. The highlighted portion of the Smith chart in (c) depicts the complex impedances (arising from L and R of the inductive element) that may be matched to an arbitrary real impedance Zo by the topology of Fig. 31 (b) in the case ?L2=1/?C2.

[0057] Figs. 30(a),(b),(c),(d),(e),(f) depict six topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in series with Z0. The topologies shown in Figs. 30(a),(b),(c) are driven with a common-mode signal at the input terminals, while the topologies shown in Figs 30(d),(e),(f) are symmetric and receive a balanced drive. The highlighted portion of the Smith chart in 30(g) depicts the complex impedances that may be matched by these topologies. Figs. 30(h),(i),(j),(k),(l),(m) depict six topologies of matching circuits directly coupled to a high-Q inductive element and including inductors in series with Zo.

[0058] Figs. 3 l(a),(b),(c) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in series with Zo. They are connected to ground at the center point of a capacitor and receive an unbalanced drive. The highlighted portion of the Smith chart in Fig. 31(d) depicts the complex impedances that may be matched by these topologies. Figs. 31(e),(f),(g) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including inductors in series with Zq.

[0059] Figs. 32(a),(b),(c) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in series with Zq. They are connected to ground by tapping at the center point of the inductor loop and receive an unbalanced drive. The highlighted portion of the Smith chart in (d) depicts the complex impedances that may be matched by these topologies, (e),(f),(g) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including inductors in series with Zq.

[0060] Figs. 33(a),(b),(c),(d),(e),(f) depict six topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in parallel with Z0. The topologies shown in Figs. 33(a),(b),(c) are driven with a common-mode signal at the input terminals, while the topologies shown in Figs 33(d),(e),(f) are symmetric and receive a balanced drive. The highlighted portion of the Smith chart in Fig. 33(g) depicts the complex impedances that may be matched by these topologies. Figs. 33(h),(i),(j),(k),(l),(m) depict six topologies of matching circuits directly coupled to a high-Q inductive element and including inductors in parallel with Z0.

[0061] Figs. 34(a),(b),(c) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in parallel with Z0. They are connected to ground at the center point of a capacitor and receive an unbalanced drive. The highlighted portion of the Smith chart in (d) depicts the complex impedances that may be matched by these topologies. Figs. 34(e),(f),(g) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including inductors in parallel with Z0.

[0062] Figs. 35(a),(b),(c) depict three topologies of matching circuits directly coupled to a high-Q inductive element and including capacitors in parallel with Zq. They are connected to ground by tapping at the center point of the inductor loop and receive an unbalanced drive. The highlighted portion of the Smith chart in Figs. 35(d),(e), and (f) depict the complex impedances that may be matched by these topologies.

[0063] Figs. 36(a),(b),(c),(d) depict four topologies of networks of fixed and variable capacitors designed to produce an overall variable capacitance with finer tuning resolution and some with reduced voltage on the variable capacitor.

[0064] Figs. 37(a) and 37(b) depict two topologies of networks of fixed capacitors and a variable inductor designed to produce an overall variable capacitance.

[0065] Fig. 38 depicts a high level block diagram of a wireless power transmission system.

[0066] Fig. 39 depicts a block diagram of an exemplary wirelessly powered device".

[0067] Fig. 40 depicts a block diagram of the source of an exemplary wireless power transfer system.

[0068] Fig. 41 shows an equivalent circuit diagram of a magnetic resonator. The slash through the capacitor symbol indicates that the represented capacitor may be fixed or variable. The port parameter measurement circuitry may be configured to measure certain electrical signals and may measure the magnitude and phase of signals.

[0069] Fig. 42 shows a circuit diagram of a magnetic resonator where the tunable impedance network is realized with voltage controlled capacitors. Such an implementation may be adjusted, tuned or controlled by electrical circuits including programmable or controllable voltage sources and/or computer processors. The voltage controlled capacitors may be adjusted in response to data measured by the port parameter measurement circuitry and processed by measurement analysis and control algorithms and hardware. The voltage controlled capacitors may be a switched bank of capacitors.

[0070] Fig. 43 shows an end-to-end wireless power transmission system. In this example, both the source and the device contain port measurement circuitry and a processor. The box labeled "coupler/switch" indicates that the port measurement circuitry may be connected to the resonator by a directional coupler or a switch, enabling the measurement, adjustment and control of the source and device resonators to take place in conjunction with, or separate from, the power transfer functionality.

[0071] Fig. 44 shows an end-to-end wireless power transmission system. In this example, only the source contains port measurement circuitry and a processor. In this case, the device resonator operating characteristics may be fixed or may be adjusted by analog control circuitry and without the need for control signals generated by a processor.

[0072] Fig. 45 shows an end-to-end wireless power transmission system. In this example, both the source and the device contain port measurement circuitry but only the source contains a processor. Data from the device is transmitted through a wireless communication channel, which could be implemented either with a separate antenna, or through some modulation of the source drive signal.

[0073] Fig. 46 shows an end-to-end wireless power transmission system. In this example, only the source contains port measurement circuitry and a processor. Data from the device is transmitted through a wireless communication channel, which could be implemented either with a separate antenna, or through some modulation of the source drive signal.

[0074] Fig. 47 shows coupled magnetic resonators whose frequency and impedance may be automatically adjusted using algorithms implemented using a processor or a computer.

[0075] Fig. 48 shows a varactor array.

[0076] Fig. 49 shows a device (laptop computer) being wirelessly powered or charged by a source, where both the source and device resonator are physically separated from, but electrically connected to, the source and device.

[0077] Fig. 50 (a) is an illustration of a wirelessly powered or charged laptop application where the device resonator is inside the laptop case and is not visible.

[0078] Fig. 50 (b) is an illustration of a wirelessly powered or charged laptop application where the resonator is underneath the laptop base and is electrically connected to the laptop power input by an electrical cable.

[0079] Fig. 50 (c) is an illustration of a wirelessly powered or charged laptop application where the resonator is attached to the laptop base.

[0080] Fig. 50 (d) is an illustration of a wirelessly powered or charged laptop application where the resonator is attached to the laptop display.

[0081] Fig. 51 is a diagram of rooftop PV panels with wireless power transfer.

DETAILED DESCRIPTION

[0082] As described above, this disclosure relates to coupled electromagnetic resonators with long-lived oscillatory resonant modes that may wirelessly transfer power from a power supply to a power drain. However, the technique is not restricted to electromagnetic resonators, but is general and may be applied to a wide variety of resonators and resonant objects. Therefore, we first describe the general technique, and then disclose electromagnetic examples for wireless energy transfer.

[0083] Resonators

[0084] A resonator may be defined as a system that can store energy in at least two different forms, and where the stored energy is oscillating between the two forms. The resonance has a specific oscillation mode with a resonant (modal) frequency,f, and a resonant (modal) field. The angular resonant frequency, ?, may be defined as ?=2pf the resonant wavelength, ?, may be defined as ? = c/f , where c is the speed of light, and the resonant period, T, may be defined as T=1/f = 2p/?. In the absence of loss mechanisms, coupling mechanisms or external energy supplying or draining mechanisms, the total resonator stored energy, W, would stay fixed and the two forms of energy would oscillate, wherein one would be maximum when the other is minimum and vice versa.

[0085] In the absence of extraneous materials or objects, the energy in the resonator 102 shown in Fig. 1 may decay or be lost by intrinsic losses. The resonator fields then obey the following linear equation:

where the variable a(t) is the resonant field amplitude, defined so that the energy contained within the resonator is given by ?is the intrinsic energy decay or loss rate (e.g. due to absorption and radiation losses).

[0086] The Quality Factor, or Q-factor, or Q, of the resonator, which characterizes the energy decay, is inversely proportional to these energy losses. It may be defined as Q=?*W/P, where P is the time-averaged power lost at steady state. That is, a resonator 102 with a high-Q has relatively low intrinsic losses and can store energy for a relatively long time. Since the resonator loses energy at its intrinsic decay rate, 2?, its Q, also referred to as its intrinsic Q, is given by Q = ?/2?. The quality factor also represents the number of oscillation periods, T, it takes for the energy in the resonator to decay by a factor of e.

[0087] As described above, we define the quality factor or Q of the resonator as that due only to intrinsic loss mechanisms. A subscript index such as Q1, indicates the resonator (resonator 1 in this case) to which the Q refers. Fig. 2 shows an electromagnetic resonator 102 labeled according to this convention. Note that in this figure, there are no extraneous objects or additional resonators in the vicinity of resonator 1.

[0088] Extraneous objects and/or additional resonators in the vicinity of a first resonator may perturb or load the first resonator, thereby perturbing or loading the Q of the first resonator, depending on a variety of factors such as the distance between the resonator and object or other resonator, the material composition of the object or other resonator, the structure of the first resonator, the power in the first resonator, and the like. Unintended external energy losses or coupling mechanisms to extraneous materials and objects in the vicinity of the resonators may be referred to as "perturbing" the Q of a resonator, and may be indicated by a subscript within rounded parentheses, (). Intended external energy losses, associated with energy transfer via coupling to other resonators and to generators and loads in the wireless energy transfer system may be referred to as "loading" the Q of the resonator, and may be indicated by a subscript within square brackets, [].

[0089] The Q of a resonator 102 connected or coupled to a power generator, g, or load 302 , 1, may be called the "loaded quality factor" or the "loaded Q" and may be denoted by Q[g] or Q[l], as illustrated in Fig. 3. In general, there may be more than one generator or load 302 connected to a resonator 102. However, we do not list those generators or loads separately but rather use "g" and "l" to refer to the equivalent circuit loading imposed by the combinations of generators and loads. In general descriptions, we may use the subscript"l" to refer to either generators or loads connected to the resonators.

[0090] In some of the discussion herein, we define the "loading quality factor" or the "loading Q" due to a power generator or load connected to the resonator, as dQ[l], where, 1/Q[l]=1/Q[l] - 1/Q. Note that the larger the loading Q, dQ[l], of a generator or load, the less the loaded Q, Q[l] , deviates from the unloaded Q of the resonator.

[0091] The Q of a resonator in the presence of an extraneous object 402, p, that is not intended to be part of the energy transfer system may be called the "perturbed quality factor" or the "perturbed Q" and may be denoted by Q(p), as illustrated in Fig. 4. In general, there may be many extraneous objects, denoted as p1, p2, etc., or a set of extraneous objects {p}, that perturb the Q of the resonator 102. In this case, the perturbed Q may be denoted Q(p1+p2+...) or Q({p}). For example, Q1(brick+wood) may denote the perturbed quality factor of a first resonator in a system for wireless power exchange in the presence of a brick and a piece of wood, and Q2({office}) may denote the perturbed quality factor of a second resonator in a system for wireless power exchange in an office environment.

[0092] In some of the discussion herein, we define the "perturbing quality factor" or the "perturbing Q" due to an extraneous object, p, as dQ(p), where As stated before, the perturbing quality factor may be due to multiple extraneous objects, pi, p2, etc. or a set of extraneous objects, {p}. The larger the perturbing Q, dQ(p), of an object, the less the perturbed Q, Q(p), deviates from the unperturbed Q of the resonator.

[0093] In some of the discussion herein, we also define and call it the "quality factor insensitivity" or the "Q-insensitivity" of the resonator in the presence of an extraneous object. A subscript index, such as T1(p), indicates the resonator to which the perturbed and unperturbed quality factors are referring, namely,

[0094] Note that the quality factor, Q, may also be characterized as "unperturbed", when necessary to distinguish it from the perturbed quality factor, Q(p), and "unloaded", when necessary to distinguish it from the loaded quality factor, Q[l]. Similarly, the perturbed quality factor, Q(p), may also be characterized as "unloaded", when necessary to distinguish them from the loaded perturbed quality factor, Q(p)[l].

[0095] Coupled Resonators

[0096] Resonators having substantially the same resonant frequency, coupled through any portion of their near-fields may interact and exchange energy. There are a variety of physical pictures and models that may be employed to understand, design, optimize and characterize this energy exchange. One way to describe and model the energy exchange between two coupled resonators is using coupled mode theory (CMT).

[0097] In coupled mode theory, the resonator fields obey the following set of linear equations:

where the indices denote different resonators and and Kmn are the coupling coefficients between the resonators. For a reciprocal system, the coupling coefficients may obey the relation Km = kmn . Note that, for the purposes of the present specification, far-field radiation interference effects will be ignored and thus the coupling coefficients will be considered real. Furthermore, since in all subsequent calculations of system performance in this specification the coupling coefficients appear only with their square, k2m, we use Kmn to denote the absolute value of the real coupling coefficients.

[0098] Note that the coupling coefficient, Kmn, from the CMT described above is related to the so-called coupling factor, kmn, between resonators m and n by
We define a "strong-coupling factor", Umn, as the ratio of the coupling and loss rates between resonators m and n, by

[0099] The quality factor of a resonator m, in the presence of a similar frequency resonator n or additional resonators, may be loaded by that resonator n or additional resonators, in a fashion similar to the resonator being loaded by a connected power generating or consuming device. The fact that resonator m may be loaded by resonator n and vice versa is simply a different way to see that the resonators are coupled.

[00100] The loaded Q 's of the resonators in these cases may be denoted as Qm[n] and Qn[m]. For multiple resonators or loading supplies or devices, the total loading of a resonator may be determined by modeling each load as a resistive loss, and adding the multiple loads in the appropriate parallel and/or series combination to determine the equivalent load of the ensemble.

[00101] In some of the discussion herein, we define the "loading quality factor" or the "loading Qm" of resonator m due to resonator n as . Note that resonator n is also loaded by resonator m and its "loading Qn" is given by

[00102] When one or more of the resonators are connected to power generators or loads, the set of linear equations is modified to:

where s+m(t) and s.m(t) are respectively the amplitudes of the fields coming from a generator into the resonator m and going out of the resonator m either back towards the generator or into a load, defined so that the power they carry is given by . The loading coefficients Km relate to the rate at which energy is exchanged between the resonator m and the generator or load connected to it.

[00103] Note that the loading coefficient, Km , from the CMT described above is related to the loading quality factor, SQm[l], defined earlier, by

100104] We define a "strong-loading factor", Um[l], as the ratio of the loading and loss rates of resonator m,

[00105] Fig. 1(a) shows an example of two coupled resonators 1000, a first resonator 102S, configured as a source resonator and a second resonator 102D, configured as a device resonator. Energy may be transferred over a distance D between the resonators. The source resonator 102S may be driven by a power supply or generator (not shown). Work may be extracted from the device resonator 102D by a power consuming drain or load (e.g. a load resistor, not shown). Let us use the subscripts "s" for the source, "d" for the device, "g" for the generator, and "1" for the load, and, since in this example there are only two resonators and Ksd=Kds, let us drop the indices on KSd, kSd, and USd, and denote them as k, k, and U, respectively.

[00106] The power generator may be constantly driving the source resonator at a constant driving frequency,f, corresponding to an angular driving frequency, ?, where ?=2pf.

[00107] In this case, the efficiency, of the power transmission from the generator to the load (via the source and device resonators) is maximized under the following conditions: The source resonant frequency, the device resonant frequency and the generator driving frequency have to be matched, namely
?s= ?d = ?.
Furthermore, the loading Q of the source resonator due to the generator, dQs[g], has to be matched (equal) to the loaded Q of the source resonator due to the device resonator and the load, Qs[dl], and inversely the loading Q of the device resonator due to the load, dQd[l], has to be matched (equal) to the loaded Q of the device resonator due to the source resonator and the generator, Qd[sg], namely

These equations determine the optimal loading rates of the source resonator by the generator and of the device resonator by the load as

Note that the above frequency matching and Q matching conditions are together known as "impedance matching" in electrical engineering.

[00108] Under the above conditions, the maximized efficiency is a monotonically increasing function of only the strong-coupling factor, between the source and device resonators and is given by, , as shown in Fig. 5. Note that the coupling efficiency, ?, is greater than 1% when U is greater than 0.2, is greater than 10% when U is greater than 0.7, is greater than 17% when U is greater than 1, is greater than 52% when U is greater than 3, is greater than 80% when 27 is greater than 9, is greater than 90% when U is greater than 19, and is greater than 95% when |/is greater than 45. In some applications, the regime of operation where U>1 may be referred to as the "strong-coupling" regime.

[00109] Since a large is desired in certain circumstances, resonators may be used that are high-Q. The Q of each resonator may be high. The geometric mean of the resonator Q's, vQgQd may also or instead be high.

[00110] The coupling factor, k, is a number between 0 = k = 1, and it may be independent (or nearly independent) of the resonant frequencies of the source and device resonators, rather it may determined mostly by their relative geometry and the physical decay-law of the field mediating their coupling. In contrast, the coupling coefficient, may be a strong function of the resonant frequencies. The resonant frequencies of the resonators may be chosen preferably to achieve a high Q rather than to achieve a low ?, as these two goals may be achievable at two separate resonant frequency regimes.

[00111] A high-Q resonator may be defined as one with Q>100. Two coupled resonators may be referred to as a system of high-Q resonators when each resonator has a Q greater than 100, Qs>100 and Qd>100. In other implementationss, two coupled resonators may be referred to as a system of high-Q resonators when the geometric mean of the resonator Q 's is greater than 100, vQsQd > 100.

[00112] The resonators may be named or numbered. They may be referred to as source resonators, device resonators, first resonators, second resonators, repeater resonators, and the like. It is to be understood that while two resonators are shown in Fig. 1, and in many of the examples below, other implementations may include three (3) or more resonators. For example, a single source resonator 102S may transfer energy to multiple device resonators 102D or multiple devices. Energy may be transferred from a first device to a second, and then from the second device to the third, and so forth. Multiple sources may transfer energy to a single device or to multiple devices connected to a single device resonator or to multiple devices connected to multiple device resonators. Resonators 102 may serve alternately or simultaneously as sources, devices, or they may be used to relay power from a source in one location to a device in another location. Intermediate electromagnetic resonators 102 may be used to extend the distance range of wireless energy transfer systems. Multiple resonators 102 may be daisy chained together, exchanging energy over extended distances and with a wide range of sources and devices. High

power levels may be split between multiple sources 102S, transferred to multiple devices and recombined at a distant location.

[00113] The analysis of a single source and a single device resonator may be extended to multiple source resonators and/or multiple device resonators and/or multiple intermediate resonators. In such an analysis, the conclusion may be that large strong-coupling factors, Umn, between at least some or all of the multiple resonators is preferred for a high system efficiency in the wireless energy transfer. Again, implementations may use source, device and intermediate resonators that have a high Q. The Q of each resonator may be high. The geometric mean vQmQn of the Q's for pairs of resonators m and n, for which a large Umn is desired, may also or instead be high.

[00114] Note that since the strong-coupling factor of two resonators may be determined by the relative magnitudes of the loss mechanisms of each resonator and the coupling mechanism between the two resonators, the strength of any or all of these mechanisms may be perturbed in the presence of extraneous objects in the vicinity of the resonators as described above.

[00115] Continuing the conventions for labeling from the previous sections, we describe k as the coupling factor in the absence of extraneous objects or materials. We denote the coupling factor in the presence of an extraneous object, p, as k(p), and call it the "perturbed coupling factor" or the "perturbed k". Note that the coupling factor, k, may also be characterized as "unperturbed", when necessary to distinguish from the perturbed coupling factor k(p).

[00116] We define and we call it the "perturbation on the coupling factor" or the "perturbation on k" due to an extraneous object, p.

[00117] We also define and we call it the "coupling factor insensitivity" or the "k-insensitivity". Lower indices, such as ß12(p), indicate the resonators to which the perturbed and unperturbed coupling factor is referred to, namely

[00118] Similarly, we describe U as the strong-coupling factor in the absence of extraneous objects. We denote the strong-coupling factor in the presence of an extraneous object, p, as and call it the "perturbed strong-coupling factor" or the "perturbed U". Note that the strong-coupling factor [/may also be characterized as "unperturbed", when necessary to distinguish from the perturbed strong-coupling factor U(p). Note that the strong-coupling factor U may also be characterized as "unperturbed", when necessary to distinguish from the perturbed strong-coupling factor U(p).

[00119] We define and call it the "perturbation on the strong-coupling factor" or the "perturbation on if due to an extraneous object, p.

[00120] We also define, and call it the "strong-coupling factor insensitivity" or the "U-insensitivity ". Lower indices, such as ?12(p), indicate the resonators to which the perturbed and unperturbed coupling factor refers, namely

[00121] The efficiency of the energy exchange in a perturbed system may be given by the same formula giving the efficiency of the unperturbed system, where all parameters such as strong-coupling factors, coupling factors, and quality factors are replaced by their perturbed equivalents. For example, in a system of wireless energy transfer including one source and one device resonator, the optimal efficiency may calculated as

Therefore, in a system of wireless energy exchange which is perturbed by extraneous objects, large perturbed strong-coupling factors, U mn(p), between at least some or all of the multiple resonators may be desired for a high system efficiency in the wireless energy transfer. Source, device and/or intermediate resonators may have a high Q(p).

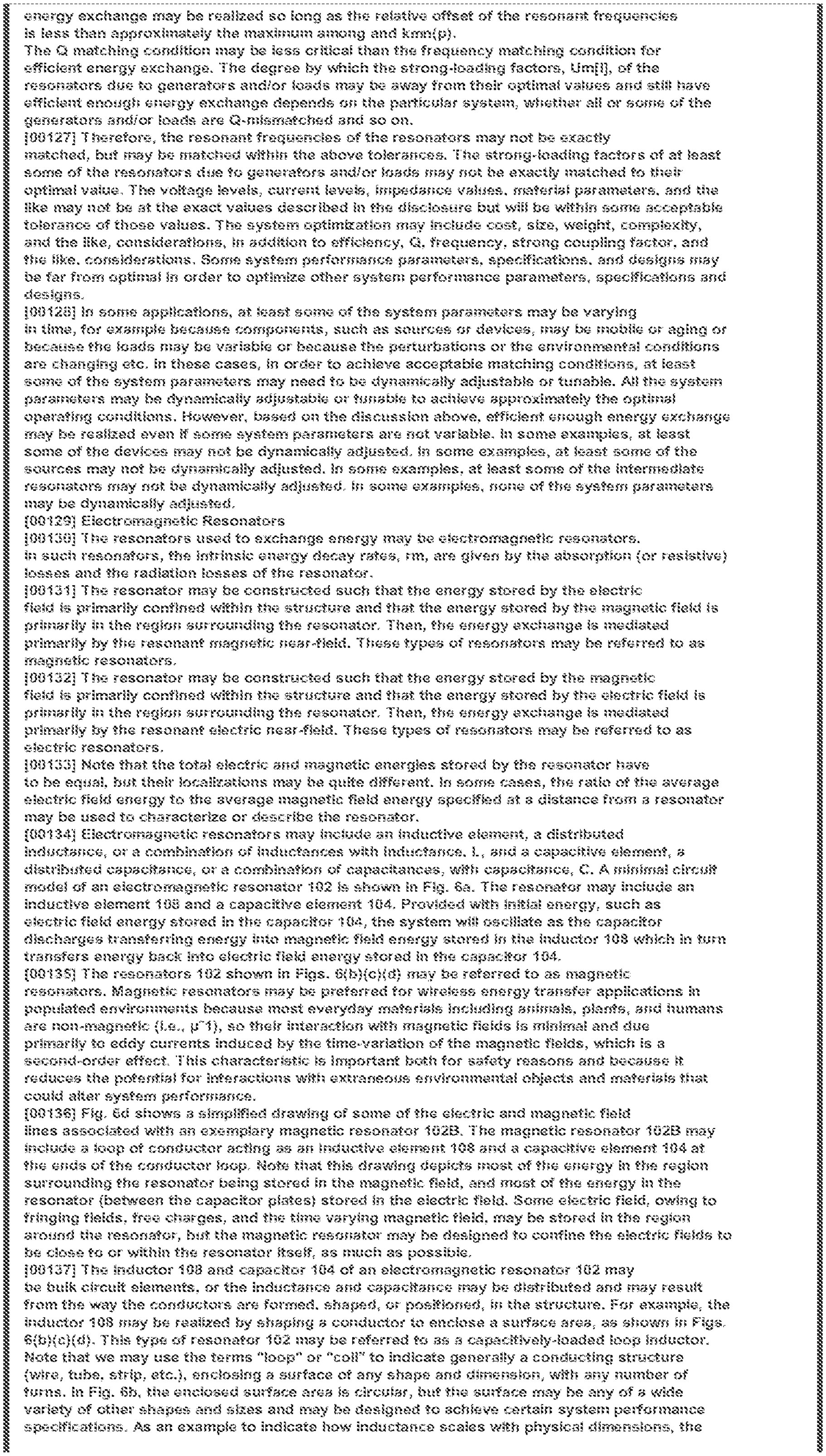
[00122] Some extraneous perturbations may sometimes be detrimental for the perturbed strong-coupling factors (via large perturbations on the coupling factors or the quality factors). Therefore, techniques may be used to reduce the effect of extraneous perturbations on the system and preserve large strong-coupling factor insensitivites.

[00123] Efficiency of Energy Exchange

[00124] The so-called "useful" energy in a useful energy exchange is the energy or power that must be delivered to a device (or devices) in order to power or charge the device. The transfer efficiency that corresponds to a useful energy exchange may be system or application dependent. For example, high power vehicle charging applications that transfer kilowatts of power may need to be at least 80% efficient in order to supply useful amounts of power resulting in a useful energy exchange sufficient to recharge a vehicle battery, without significantly heating up various components of the transfer system. In some consumer electronics applications, a useful energy exchange may include any energy transfer efficiencies greater than 10%, or any other amount acceptable to keep rechargeable batteries "topped off" and running for long periods of time. For some wireless sensor applications, transfer efficiencies that are much less than 1% may be adequate for powering multiple low power sensors from a single source located a significant distance from the sensors. For still other applications, where wired power transfer is either impossible or impractical, a wide range of transfer efficiencies may be acceptable for a useful energy exchange and may be said to supply useful power to devices in those applications. In general, an operating distance is any distance over which a useful energy exchange is or can be maintained according to the principles disclosed herein.

[00125] A useful energy exchange for a wireless energy transfer in a powering or recharging application may be efficient, highly efficient, or efficient enough, as long as the wasted energy levels, heat dissipation, and associated field strengths are within tolerable limits. The tolerable limits may depend on the application, the environment and the system location. Wireless energy transfer for powering or recharging applications may be efficient, highly efficient, or efficient enough, as long as the desired system performance may be attained for the reasonable cost restrictions, weight restrictions, size restrictions, and the like. Efficient energy transfer may be determined relative to that which could be achieved using traditional inductive techniques that are not high-Q systems. Then, the energy transfer may be defined as being efficient, highly efficient, or efficient enough, if more energy is delivered than could be delivered by similarly sized coil structures in traditional inductive schemes over similar distances or alignment offsets.

[00126] Note that, even though certain frequency and Q matching conditions may optimize the system efficiency of energy transfer, these conditions may not need to be exactly met in order to have efficient enough energy transfer for a useful energy exchange. Efficient



energy exchange may be realized so long as the relative offset of the resonant frequencies is less than approximately the maximum among and kmn(p).

The Q matching condition may be less critical than the frequency matching condition for efficient energy exchange. The degree by which the strong-loading factors, Um[l], of the resonators due to generators and/or loads may be away from their optimal values and still have efficient enough energy exchange depends on the particular system, whether all or some of the generators and/or loads are Q-mismatched and so on.

[00127] Therefore, the resonant frequencies of the resonators may not be exactly matched, but may be matched within the above tolerances. The strong-loading factors of at least some of the resonators due to generators and/or loads may not be exactly matched to their optimal value. The voltage levels, current levels, impedance values, material parameters, and the like may not be at the exact values described in the disclosure but will be within some acceptable tolerance of those values. The system optimization may include cost, size, weight, complexity, and the like, considerations, in addition to efficiency, Q, frequency, strong coupling factor, and the like, considerations. Some system performance parameters, specifications, and designs may be far from optimal in order to optimize other system performance parameters, specifications and designs.

[00128] In some applications, at least some of the system parameters may be varying in time, for example because components, such as sources or devices, may be mobile or aging or because the loads may be variable or because the perturbations or the environmental conditions are changing etc. In these cases, in order to achieve acceptable matching conditions, at least some of the system parameters may need to be dynamically adjustable or tunable. All the system parameters may be dynamically adjustable or tunable to achieve approximately the optimal operating conditions. However, based on the discussion above, efficient enough energy exchange may be realized even if some system parameters are not variable. In some examples, at least some of the devices may not be dynamically adjusted. In some examples, at least some of the sources may not be dynamically adjusted. In some examples, at least some of the intermediate resonators may not be dynamically adjusted. In some examples, none of the system parameters may be dynamically adjusted.

[00129] Electromagnetic Resonators

[00130] The resonators used to exchange energy may be electromagnetic resonators. In such resonators, the intrinsic energy decay rates, rm, are given by the absorption (or resistive) losses and the radiation losses of the resonator.

[00131] The resonator may be constructed such that the energy stored by the electric field is primarily confined within the structure and that the energy stored by the magnetic field is primarily in the region surrounding the resonator. Then, the energy exchange is mediated primarily by the resonant magnetic near-field. These types of resonators may be referred to as magnetic resonators.

[00132] The resonator may be constructed such that the energy stored by the magnetic field is primarily confined within the structure and that the energy stored by the electric field is primarily in the region surrounding the resonator. Then, the energy exchange is mediated primarily by the resonant electric near-field. These types of resonators may be referred to as electric resonators.

[00133] Note that the total electric and magnetic energies stored by the resonator have to be equal, but their localizations may be quite different. In some cases, the ratio of the average electric field energy to the average magnetic field energy specified at a distance from a resonator may be used to characterize or describe the resonator.

[00134] Electromagnetic resonators may include an inductive element, a distributed inductance, or a combination of inductances with inductance, L, and a capacitive element, a distributed capacitance, or a combination of capacitances, with capacitance, C. A minimal circuit model of an electromagnetic resonator 102 is shown in Fig. 6a. The resonator may include an inductive element 108 and a capacitive element 104. Provided with initial energy, such as electric field energy stored in the capacitor 104, the system will oscillate as the capacitor discharges transferring energy into magnetic field energy stored in the inductor 108 which in turn transfers energy back into electric field energy stored in the capacitor 104.

[00135] The resonators 102 shown in Figs. 6(b)(c)(d) may be referred to as magnetic resonators. Magnetic resonators may be preferred for wireless energy transfer applications in populated environments because most everyday materials including animals, plants, and humans are non-magnetic (i.e., μ˜1), so their interaction with magnetic fields is minimal and due primarily to eddy currents induced by the time-variation of the magnetic fields, which is a second-order effect. This characteristic is important both for safety reasons and because it reduces the potential for interactions with extraneous environmental objects and materials that could alter system performance.

[00136] Fig. 6d shows a simplified drawing of some of the electric and magnetic field lines associated with an exemplary magnetic resonator 102B. The magnetic resonator 102B may include a loop of conductor acting as an inductive element 108 and a capacitive element 104 at the ends of the conductor loop. Note that this drawing depicts most of the energy in the region surrounding the resonator being stored in the magnetic field, and most of the energy in the resonator (between the capacitor plates) stored in the electric field. Some electric field, owing to fringing fields, free charges, and the time varying magnetic field, may be stored in the region around the resonator, but the magnetic resonator may be designed to confine the electric fields to be close to or within the resonator itself, as much as possible.

[00137] The inductor 108 and capacitor 104 of an electromagnetic resonator 102 may be bulk circuit elements, or the inductance and capacitance may be distributed and may result from the way the conductors are formed, shaped, or positioned, in the structure. For example, the inductor 108 may be realized by shaping a conductor to enclose a surface area, as shown in Figs. 6(b)(c)(d). This type of resonator 102 may be referred to as a capacitively-loaded loop inductor. Note that we may use the terms "loop" or "coil" to indicate generally a conducting structure (wire, tube, strip, etc.), enclosing a surface of any shape and dimension, with any number of turns. In Fig. 6b, the enclosed surface area is circular, but the surface may be any of a wide variety of other shapes and sizes and may be designed to achieve certain system performance specifications. As an example to indicate how inductance scales with physical dimensions, the

inductance for a length of circular conductor arranged to form a circular single-turn loop is approximately,

where µ0 is the magnetic permeability of free space, x, is the radius of the enclosed circular surface area and, a, is the radius of the conductor used to form the inductor loop. A more precise value of the inductance of the loop may be calculated analytically or numerically.

[00138] The inductance for other cross-section conductors, arranged to form other enclosed surface shapes, areas, sizes, and the like, and of any number of wire turns, may be calculated analytically, numerically or it may be determined by measurement. The inductance may be realized using inductor elements, distributed inductance, networks, arrays, series and parallel combinations of inductors and inductances, and the like. The inductance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[00139] There are a variety of ways to realize the capacitance required to achieve the desired resonant frequency for a resonator structure. Capacitor plates 110 may be formed and utilized as shown in Fig. 6b, or the capacitance may be distributed and be realized between adjacent windings of a multi-loop conductor 114, as shown in Fig. 6c. The capacitance may be realized using capacitor elements, distributed capacitance, networks, arrays, series and parallel combinations of capacitances, and the like. The capacitance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[00140] It is to be understood that the inductance and capacitance in an electromagnetic resonator 102 may be lumped, distributed, or a combination of lumped and distributed inductance and capacitance and that electromagnetic resonators may be realized by combinations of the various elements, techniques and effects described herein.

[00141] Electromagnetic resonators 102 may be include inductors, inductances, capacitors, capacitances, as well as additional circuit elements such as resistors, diodes, switches, amplifiers, diodes, transistors, transformers, conductors, connectors and the like.

[00142] Resonant Frequency of an Electromagnetic Resonator

[00143] An electromagnetic resonator 102 may have a characteristic, natural, or resonant frequency determined by its physical properties. This resonant frequency is the frequency at which the energy stored by the resonator oscillates between that stored by the electric field, We, (WE=q2/2C, where q is the charge on the capacitor, C) and that stored by the magnetic field, Wb, (WB=Li2/2, where i is the current through the inductor, L) of the resonator. In the absence of any losses in the system, energy would continually be exchanged between the electric field in the capacitor 104 and the magnetic field in the inductor 108. The frequency at which this energy is exchanged may be called the characteristic frequency, the natural frequency, or the resonant frequency of the resonator, and is given by ?,

[00144] The resonant frequency of the resonator may be changed by tuning the inductance, L, and/or the capacitance, C, of the resonator. The resonator frequency may be design to operate at the so-called ISM (Industrial, Scientific and Medical) frequencies as specified by the FCC. The resonator frequency may be chosen to meet certain field limit specifications, specific absorption rate (SAR) limit specifications, electromagnetic compatibility (EMC) specifications, electromagnetic interference (EMI) specifications, component size, cost or performance specifications, and the like.

[00145] Quality Factor of an Electromagnetic Resonator

[00146] The energy in the resonators 102 shown in Fig. 6 may decay or be lost by intrinsic losses including absorptive losses (also called ohmic or resistive losses) and/or radiative losses. The Quality Factor, or Q, of the resonator, which characterizes the energy decay, is inversely proportional to these losses. Absorptive losses may be caused by the finite conductivity of the conductor used to form the inductor as well as by losses in other elements, components, connectors, and the like, in the resonator. An inductor formed from low loss materials may be referred to as a "high-Q inductive element" and elements, components, connectors and the like with low losses may be referred to as having "high resistive Q's". In general, the total absorptive loss for a resonator may be calculated as the appropriate series and/or parallel combination of resistive losses for the various elements and components that make up the resonator. That is, in the absence of any significant radiative or component/connection losses, the Q of the resonator may be given by Qabs,

where ?, is the resonant frequency, L, is the total inductance of the resonator and the resistance for the conductor used to form the inductor, for example, may be given by (/ is the length of the wire, ? is the resistivity of the conductor material, and A is the cross-sectional area over which current flows in the wire). For alternating currents, the cross-sectional area over which current flows may be less than the physical cross-sectional area of the conductor owing to the skin effect. Therefore, high-Q magnetic resonators may be composed of conductors with high conductivity, relatively large surface areas and/or with specially designed profiles (e.g. Litz wire) to minimize proximity effects and reduce the AC resistance.

[00147] The magnetic resonator structures may include high-Q inductive elements composed of high conductivity wire, coated wire, Litz wire, ribbon, strapping or plates, tubing, paint, gels, traces, and the like. The magnetic resonators may be self-resonant, or they may include external coupled elements such as capacitors, inductors, switches, diodes, transistors, transformers, and the like. The magnetic resonators may include distributed and lumped capacitance and inductance. In general, the Q of the resonators will be determined by the Q's of all the individual components of the resonator.

[00148] Because Q is proportional to inductance, L, resonators may be designed to increase L, within certain other constraints. One way to increase L, for example, is to use more than one turn of the conductor to form the inductor in the resonator. Design techniques and trade-offs may depend on the application, and a wide variety of structures, conductors, components, and resonant frequencies may be chosen in the design of high-Q magnetic resonators.

[00149] In the absence of significant absorption losses, the Q of the resonator may be determined primarily by the radiation losses, and given by, Qrnd = ?L\Rrad , where Rrad is the radiative loss of the resonator and may depend on the size of the resonator relative to the frequency, ?, or wavelength, ?, of operation. For the magnetic resonators discussed above, radiative losses may scale as Rrad ~ (x/?)4 (characteristic of magnetic dipole radiation), where x

is a characteristic dimension of the resonator, such as the radius of the inductive element shown in Fig. 6b, and where ? = c/f, where c is the speed of light and/is as defined above. The size of the magnetic resonator may be much less than the wavelength of operation so radiation losses may be very small. Such structures may be referred to as sub-wavelength resonators. Radiation may be a loss mechanism for non-radiative wireless energy transfer systems and designs may be chosen to reduce or minimize Rrad. Note that a high-Qrad may be desirable for non-radiative wireless energy transfer schemes.

[00150] Note too that the design of resonators for non-radiative wireless energy transfer differs from antennas designed for communication or far-field energy transmission purposes. Specifically, capacitively-loaded conductive loops may be used as resonant antennas (for example in cell phones), but those operate in the far-field regime where the radiation g's are intentionally designed to be small to make the antenna efficient at radiating energy. Such designs are not appropriate for the efficient near-field wireless energy transfer technique disclosed in this application.

[00151] The quality factor of a resonator including both radiative and absorption losses is Q = ?L/(Rabc +Rrad). Note that there may be a maximum Q value for a particular resonator and that resonators may be designed with special consideration given to the size of the resonator, the materials and elements used to construct the resonator, the operating frequency, the connection mechanisms, and the like, in order to achieve a high-Q resonator. Fig. 7 shows a plot of Q of an exemplary magnetic resonator (in this case a coil with a diameter of 60 cm made of copper pipe with an outside diameter (OD) of 4 cm) that may be used for wireless power transmission at MHz frequencies. The absorptive Q (dashed line) 702 increases with frequency, while the radiative Q (dotted line) 704 decreases with frequency, thus leading the overall Q to peak 708 at a particular frequency. Note that the Q of this exemplary resonator is greater than 100 over a wide frequency range. Magnetic resonators may be designed to have high-Q over a range of frequencies and system operating frequency may set to any frequency in that range.

[00152] When the resonator is being described in terms of loss rates, the Q may be defined using the intrinsic decay rate, 2?, as described previously. The intrinsic decay rate is the rate at which an uncoupled and undriven resonator loses energy. For the magnetic resonators described above, the intrinsic loss rate may be given by] , and the quality factor, Q, of the resonator is given by Q=?/2?.

[00153] Note that a quality factor related only to a specific loss mechanism may be denoted as Qmechanism, if the resonator is not specified, or as Q1,mechanism, if the resonator is specified (e.g. resonator 1). For example, Q1,rad is the quality factor for resonator 1 related to its radiation losses.

[00154] Electromagnetic Resonator Near-Fields

[00155] The high-Q electromagnetic resonators used in the near-field wireless energy transfer system disclosed here may be sub-wavelength objects. That is, the physical dimensions of the resonator may be much smaller than the wavelength corresponding to the resonant frequency. Sub-wavelength magnetic resonators may have most of the energy in the region surrounding the resonator stored in their magnetic near-fields, and these fields may also be described as stationary or non-propagating because they do not radiate away from the resonator. The extent of the near-field in the area surrounding the resonator is typically set by the wavelength, so it may extend well beyond the resonator itself for a sub-wavelength resonator. The limiting surface, where the field behavior changes from near-field behavior to far-field behavior may be called the "radiation caustic".

[00156] The strength of the near-field is reduced the farther one gets away from the resonator. While the field strength of the resonator near-fields decays away from the resonator, the fields may still interact with objects brought into the general vicinity of the resonator. The degree to which the fields interact depends on a variety of factors, some of which may be controlled and designed, and some of which may not. The wireless energy transfer schemes described herein may be realized when the distance between coupled resonators is such that one resonator lies within the radiation caustic of the other.

[00157] The near-field profiles of the electromagnetic resonators may be similar to those commonly associated with dipole resonators or oscillators. Such field profiles may be described as omni-directional, meaning the magnitudes of the fields are non-zero in all directions away from the object.

[00158] Characteristic Size of An Electromagnetic Resonator

[00159] Spatially separated and/or offset magnetic resonators of sufficient Q may achieve efficient wireless energy transfer over distances that are much larger than have been seen in the prior art, even if the sizes and shapes of the resonator structures are different. Such resonators may also be operated to achieve more efficient energy transfer than was achievable with previous techniques over shorter range distances. We describe such resonators as being capable of mid-range energy transfer.

[00160] Mid-range distances may be defined as distances that are larger than the characteristic dimension of the smallest of the resonators involved in the transfer, where the distance is measured from the center of one resonator structure to the center of a spatially separated second resonator structure. In this definition, two-dimensional resonators are spatially separated when the areas circumscribed by their inductive elements do not intersect and three-dimensional resonators are spatially separated when their volumes do not intersect. A two-dimensional resonator is spatially separated from a three-dimensional resonator when the area circumscribed by the former is outside the volume of the latter.

[00161] Fig. 8 shows some example resonators with their characteristic dimensions labeled. It is to be understood that the characteristic sizes 802 of resonators 102 may be defined in terms of the size of the conductor and the area circumscribed or enclosed by the inductive element in a magnetic resonator and the length of the conductor forming the capacitive element of an electric resonator. Then, the characteristic size 802 of a resonator 102, xchar, may be equal to the radius of the smallest sphere that can fit around the inductive or capacitive element of the magnetic or electric resonator respectively, and the center of the resonator structure is the center of the sphere. The characteristic thickness 804, tChar, of a resonator 102 may be the smallest possible height of the highest point of the inductive or capacitive element in the magnetic or capacitive resonator respectively, measured from a flat surface on which it is placed. The

characteristic width 808 of a resonator 102, wChar, may be the radius of the smallest possible circle through which the inductive or capacitive element of the magnetic or electric resonator respectively, may pass while traveling in a straight line. For example, the characteristic width 808 of a cylindrical resonator may be the radius of the cylinder.

[00162] In this inventive wireless energy transfer technique, energy may be exchanged efficiently over a wide range of distances, but the technique is distinguished by the ability to exchange useful energy for powering or recharging devices over mid-range distances and between resonators with different physical dimensions, components and orientations. Note that while k may be small in these circumstances, strong coupling and efficient energy transfer may be realized by using high-g resonators to achieve a high . That is, increases in Q may be used to at least partially overcome decreases in k, to maintain useful energy transfer efficiencies.

[00163] Note too that while the near-field of a single resonator may be described as omni-directional, the efficiency of the energy exchange between two resonators may depend on the relative position and orientation of the resonators. That is, the efficiency of the energy exchange may be maximized for particular relative orientations of the resonators. The sensitivity of the transfer efficiency to the relative position and orientation of two uncompensated resonators may be captured in the calculation of either k or k . While coupling may be achieved between resonators that are offset and/or rotated relative to each other, the efficiency of the exchange may depend on the details of the positioning and on any feedback, tuning, and compensation techniques implemented during operation.

[00164] High-Q Magnetic Resonators

[00165] In the near-field regime of a sub-wavelength capacitively-loaded loop magnetic resonator (x< composed of N turns of wire whose radius is larger than the skin depth, are approximately
where p is the resistivity of the conductor material and ?c ` 120p O is the impedance of free space. . The inductance, L, for such a N-turn loop is approximately N2 times the inductance of a single-turn loop given previously. The quality factor of such a resonator, , is highest for a particular frequency determined by the system parameters (Fig. 4). As described previously, at lower frequencies the Q is determined primarily by absorption losses and at higher frequencies the Q is determined primarily by radiation losses.

[001-66] Note that the formulas given above are approximate and intended to illustrate the functional dependence of Rabs, Rrad and L on the physical parameters of the structure. More accurate numerical calculations of these parameters that take into account deviations from the strict quasi-static limit, for example a non-uniform current/charge distribution along the conductor, may be useful for the precise design of a resonator structure.

[00167] Note that the absorptive losses may be minimized by using low loss conductors to form the inductive elements. The loss of the conductors may be minimized by using large surface area conductors such as conductive tubing, strapping, strips, machined objects, plates, and the like, by using specially designed conductors such as Litz wire, braided wires, wires of any cross-section, and other conductors with low proximity losses, in which case the frequency scaled behavior described above may be different, and by using low resistivity materials such as high-purity copper and silver, for example. One advantage of using conductive tubing as the conductor at higher operating frequencies is that it may be cheaper and lighter than a similar diameter solid conductor, and may have similar resistance because most of the current is traveling along the outer surface of the conductor owing to the skin effect.

[00168] To get a rough estimate of achievable resonator designs made from copper wire or copper tubing and appropriate for operation in the microwave regime, one may calculate the optimum Q and resonant frequency for a resonator composed of one circular inductive element (N=1) of copper wire (p=1.69-108 Om) with various cross sections. Then for an inductive element with characteristic size x=l cm and conductor diameter a=1 mm, appropriate for a cell phone for example, the quality factor peaks at g=1225 whenf=380 MHz. For x=50 cm and a=2 mm, an inductive element size that might be appropriate for a laptop or a household robot, Q=1103 at f=7 7 MHz. For a larger source inductive element that might be located in the ceiling for example, x=l m and a=4 mm, Q may be as high as Q=1315 at f=5 MHz. Note that a number of practical examples yield expected quality factors of Q`1000-1500 at ?/x`50-80. Measurements of a wider variety of coil shapes, sizes, materials and operating frequencies than described above show that Q's >100 may be realized for a variety of magnetic resonator structures using commonly available materials.

[00169] As described above, the rate for energy transfer between two resonators of characteristic size x1 and x2, and separated by a distance D between their centers, may be given by k . To give an example of how the defined parameters scale, consider the cell phone, laptop, and ceiling resonator examples from above, at three (3) distances; D/x=10, 8, 6. In the examples considered here, the source and device resonators are the same size, x1=x2, and shape, and are oriented as shown in Fig. 1(b). In the cell phone example, ?/2? =3033, 1553, 655 respectively. In the laptop example, ?/ 2? =7131, 3651, 1540 respectively and for the ceiling resonator example, ?/2? =6481,3318, 1400. The corresponding coupling-to-loss ratios peak at the frequency where the inductive element Q peaks and are ?/? =0.4, 0.79, 1.97 and 0.15,0.3, 0.72 and 0.2, 0.4, 0.94 for the three inductive element sizes and distances described above. An example using different sized inductive elements is that of an x1=1 m inductor (e.g. source in the ceiling) and an x2=30 cm inductor (e.g. household robot on the floor) at a distance D =3 m apart (e.g. room height). In this example, the strong-coupling figure of merit, for an efficiency of approximately 14%, at the optimal operating frequency of f =6.4 MHz. Here, the optimal system operating frequency lies between the peaks of the individual resonator Q's.

[00170] Inductive elements may be formed for use in high-Q magnetic resonators. We have demonstrated a variety of high-Q magnetic resonators based on copper conductors that are formed into inductive elements that enclose a surface. Inductive elements may be formed using a variety of conductors arranged in a variety of shapes, enclosing any size or shaped area, and they may be single turn or multiple turn elements. Drawings of exemplary inductive elements 900A-B are shown in Fig. 9. The inductive elements may be formed to enclose a circle, a rectangle, a square, a triangle, a shape with rounded corners, a shape that follows the contour of a particular

structure or device, a shape that follows, fills, or utilizes, a dedicated space within a structure or device, and the like. The designs may be optimized for size, cost, weight, appearance, performance, and the like.

[00171] These conductors may be bent or formed into the desired size, shape, and number of turns. However, it may be difficult to accurately reproduce conductor shapes and sizes using manual techniques. In addition, it may be difficult to maintain uniform or desired center-to-center spacings between the conductor segments in adjacent turns of the inductive elements. Accurate or uniform spacing may be important in determining the self capacitance of the structure as well as any proximity effect induced increases in AC resistance, for example.

[00172] Molds may be used to replicate inductor elements for high-Q resonator designs. In addition, molds may be used to accurately shape conductors into any kind of shape without creating kinks, buckles or other potentially deleterious effects in the conductor. Molds may be used to form the inductor elements and then the inductor elements may be removed from the forms. Once removed, these inductive elements may be built into enclosures or devices that may house the high-Q magnetic resonator. The formed elements may also or instead remain in the mold used to form them.

[00173] The molds may be formed using standard CNC (computer numerical control) routing or milling tools or any other known techniques for cutting or forming grooves in blocks. The molds may also or instead be formed using machining techniques, injection molding techniques, casting techniques, pouring techniques, vacuum techniques, thermoforming techniques, cut-in-place techniques, compression forming techniques and the like.

[00174] The formed element may be removed from the mold or it may remain in the mold. The mold may be altered with the inductive element inside. The mold may be covered, machined, attached, painted and the like. The mold and conductor combination may be integrated into another housing, structure or device. The grooves cut into the molds may be any dimension and may be designed to form conducting tubing, wire, strapping, strips, blocks, and the like into the desired inductor shapes and sizes.

[00175] The inductive elements used in magnetic resonators may contain more than one loop and may spiral inward or outward or up or down or in some combination of directions. In general, the magnetic resonators may have a variety of shapes, sizes and number of turns and they may be composed of a variety of conducing materials.

[00176] The magnetic resonators may be free standing or they may be enclosed in an enclosure, container, sleeve or housing. The magnetic resonators may include the form used to make the inductive element. These various forms and enclosures may be composed of almost any kind of material. Low loss materials such as Teflon, REXOLITE, styrene, and the like may be preferable for some applications. These enclosures may contain fixtures that hold the inductive elements.

[00177] Magnetic resonators may be composed of self-resonant coils of copper wire or copper tubing. Magnetic resonators composed of self resonant conductive wire coils may include a wire of length l, and cross section radius a, wound into a helical coil of radius x, height h, and number of turns N, which may for example be characterized as

[00178] A magnetic resonator structure may be configured so that x is about 30 cm, h is about 20 cm, a is about 3 mm and N is about 5.25, and, during operation, a power source coupled to the magnetic resonator may drive the resonator at a resonant frequency,f, where f is about 10.6 MHz. Where x is about 30 cm, h is about 20 cm, a is about 1 cm and N is about 4, the resonator may be driven at a frequency,f, where/is about 13.4 MHz. Where x is about 10 cm, h is about 3 cm, a is about 2 mm and N is about 6, the resonator may be driven at a frequency,f, where/is about 21.4 MHz.

[00179] High-Q inductive elements may be designed using printed circuit board traces. Printed circuit board traces may have a variety of advantages compared to mechanically formed inductive elements including that they may be accurately reproduced and easily integrated using established printed circuit board fabrication techniques, that their AC resistance may be lowered using custom designed conductor traces, and that the cost of mass-producing them may be significantly reduced.

[00180] High-Q inductive elements may be fabricated using standard PCB techniques on any PCB material such as FR-4 (epoxy E-glass), multi-functional epoxy, high performance epoxy, bismalaimide triazine/epoxy, polyimide, Cyanate Ester, polytetraflouroethylene (Teflon), FR-2, FR-3, CEM-1, CEM-2, Rogers, Resolute, and the like. The conductor traces may be formed on printed circuit board materials with lower loss tangents.

[00181] The conducting traces may be composed of copper, silver, gold, aluminum, nickel and the like, and they may be composed of paints, inks, or other cured materials. The circuit board may be flexible and it may be a flex-circuit. The conducting traces may be formed by chemical deposition, etching, lithography, spray deposition, cutting, and the like. The conducting traces may be applied to form the desired patterns and they may be formed using crystal and structure growth techniques.

[00182] The dimensions of the conducting traces, as well as the number of layers containing conducting traces, the position, size and shape of those traces and the architecture for interconnecting them may be designed to achieve or optimize certain system specifications such as resonator Q, $Q(p)$, resonator size, resonator material and fabrication costs, U, $U(p)$, and the like.

[00183] As an example, a three-turn high-Q inductive element 1001A was fabricated on a four-layer printed circuit board using the rectangular copper trace pattern as shown in Fig. 10(a). The copper trace is shown in black and the PCB in white. The width and thickness of the copper traces in this example was approximately 1 cm (400 mils) and 43 μ m (1.7 mils) respectively. The edge-to-edge spacing between turns of the conducting trace on a single layer was approximately 0.75 cm (300 mils) and each board layer thickness was approximately 100 μ m (4 mils). The pattern shown in Fig. 10(a) was repeated on each layer of the board and the conductors were connected in parallel. The outer dimensions of the 3-loop structure were approximately 30 cm by 20 cm. The measured inductance of this PCB loop was 5.3 μ H. A magnetic resonator using this inductor element and tunable capacitors had a quality factor, Q, of 550 at its designed resonance frequency of 6.78 MHz. The resonant frequency could be tuned by changing the inductance and capacitance values in the magnetic resonator.

[00184] As another example, a two-turn inductor 1001B was fabricated on a four-layer

printed circuit board using the rectangular copper trace pattern shown in Fig. 10(b). The copper trace is shown in black and the PCB in white. The width and height of the copper traces in this example were approximately 0.75 cm (300 mils) and 43 μ m (1.7 mils) respectively. The edge-to-edge spacing between turns of the conducting trace on a single layer was approximately 0.635 cm (250 mils) and each board layer thickness was approximately 100 μ m (4 mils). The pattern shown in Fig. 10(b) was repeated on each layer of the board and the conductors were connected in parallel. The outer dimensions of the two-loop structure were approximately 7.62 cm by 26.7 cm. The measured inductance of this PCB loop was 1.3 μ H. Stacking two boards together with a vertical separation of approximately 0.635 cm (250 mils) and connecting the two boards in series produced a PCB inductor with an inductance of approximately 3.4 μ H. A magnetic resonator using this stacked inductor loop and tunable capacitors had a quality factor, Q, of 390 at its designed resonance frequency of 6.78 MHz. The resonant frequency could be tuned by changing the inductance and capacitance values in the magnetic resonator.

[00185] The inductive elements may be formed using magnetic materials of any size, shape thickness, and the like, and of materials with a wide range of permeability and loss values. These magnetic materials may be solid blocks, they may enclose hollow volumes, they may be formed from many smaller pieces of magnetic material tiled and or stacked together, and they may be integrated with conducting sheets or enclosures made from highly conducting materials. Wires may be wrapped around the magnetic materials to generate the magnetic near-field. These wires may be wrapped around one or more than one axis of the structure. Multiple wires may be wrapped around the magnetic materials and combined in parallel, or in series, or via a switch to form customized near-field patterns.

[00186] The magnetic resonator may include 15 turns of Litz wire wound around a 19.2 cm x 10 cm x 5 mm tiled block of 3F3 ferrite material. The Litz wire may be wound around the ferrite material in any direction or combination of directions to achieve the desire resonator performance. The number of turns of wire, the spacing between the turns, the type of wire, the size and shape of the magnetic materials and the type of magnetic material are all design parameters that may be varied or optimized for different application scenarios.

[00187] High-Q Magnetic resonators using magnetic material structures

[00188] It may be possible to use magnetic materials assembled to form an open magnetic circuit, albeit one with an air gap on the order of the size of the whole structure, to realize a magnetic resonator structure. In these structures, high conductivity materials are wound around a structure made from magnetic material to form the inductive element of the magnetic resonator. Capacitive elements may be connected to the high conductivity materials, with the resonant frequency then determined as described above. These magnetic resonators have their dipole moment in the plane of the two dimensional resonator structures, rather than perpendicular to it, as is the case for the capacitively-loaded inductor loop resonators.

[00189] A diagram of a single planar resonator structure is shown in Fig. 11(a). The planar resonator structure is constructed of a core of magnetic material 1121, such as ferrite with a loop or loops of conducting material 1122 wrapped around the core 1121. The structure may be used as the source resonator that transfers power and the device resonator that captures energy. When used as a source, the ends of the conductor may be coupled to a power source. Alternating electrical current flowing through the conductor loops excites alternating magnetic fields. When the structure is being used to receive power, the ends of the conductor may be coupled to a power drain or load. Changing magnetic fields induce an electromotive force in the loop or loops of the conductor wound around the core magnetic material. The dipole moment of these types of structures is in the plane of the structures and is, for example, directed along the Y axis for the structure in Figure 11(a). Two such structures have strong coupling when placed substantially in the same plane (i.e. the X,Y plane of Figure 11). The structures of Figure 11(a) have the most favorable orientation when the resonators are aligned in the same plane along their Y axis.

[00190] The geometry and the coupling orientations of the described planar resonators may be preferable for some applications. The planar or flat resonator shape may be easier to integrate into many electronic devices that are relatively flat and planar. The planar resonators may be integrated into the whole back or side of a device without requiring a change in geometry of the device. Due to the flat shape of many devices, the natural position of the devices when placed on a surface is to lay with their largest dimension being parallel to the surface they are placed on. A planar resonator integrated into a flat device is naturally parallel to the plane of the surface and is in a favorable coupling orientation relative to the resonators of other devices or planar resonator sources placed on a flat surface.

[00191] As mentioned, the geometry of the planar resonators may allow easier integration into devices. Their low profile may allow a resonator to be integrated into or as part of a complete side of a device. When a whole side of a device is covered by the resonator, magnetic flux can flow through the resonator core without being obstructed by lossy material that may be part of the device or device circuitry.

[00192] The core of the planar resonator structure may be of a variety of shapes and thicknesses and may be flat or planar such that the minimum dimension does not exceed 30% of the largest dimension of the structure. The core may have complex geometries and may have indentations, notches, ridges, and the like. Geometric enhancements may be used to reduce the coupling dependence on orientation and they may be used to facilitate integration into devices, packaging, packages, enclosures, covers, skins, and the like. Two exemplary variations of core geometries are shown in Figure 11(b). For example, the planar core 1131 may be shaped such that the ends are substantially wider than the middle of the structure to create an indentation for the conductor winding. The core material may be of varying thickness with ends that are thicker and wider than the middle. The core material 1132 may have any number of notches or cutouts 1133 of various depths, width, and shapes to accommodate conductor loops, housing, packaging, and the like.

[00193] The shape and dimensions of the core may be further dictated by the dimensions and characteristics of the device that they are integrated into. The core material may curve to follow the contours of the device, or may require non-symmetric notches or cutouts to allow clearance for parts of the device. The core structure may be a single monolithic piece of magnetic material or may be composed of a plurality of tiles, blocks, or pieces that are arranged together to form the larger structure. The different layers, tiles, blocks, or pieces of the structure

may be of similar or may be of different materials. It may be desirable to use materials with different magnetic permeability in different locations of the structure. Core structures with different magnetic permeability may be useful for guiding the magnetic flux, improving coupling, and affecting the shape or extent of the active area of a system.

[00194] The conductor of the planar resonator structure may be wound at least once around the core. In certain circumstances, it may be preferred to wind at least three loops. The conductor can be any good conductor including conducting wire, Litz wire, conducting tubing, sheets, strips, gels, inks, traces and the like.

[00195] The size, shape, or dimensions of the active area of source may be further enhanced, altered, or modified with the use of materials that block, shield, or guide magnetic fields. To create non-symmetric active area around a source once side of the source may be covered with a magnetic shield to reduce the strength of the magnetic fields in a specific direction. The shield may be a conductor or a layered combination of conductor and magnetic material which can be used to guide magnetic fields away from a specific direction. Structures composed of layers of conductors and magnetic materials may be used to reduce energy losses that may occur due to shielding of the source.

[00196] The plurality of planar resonators may be integrated or combined into one planar resonator structure. A conductor or conductors may be wound around a core structure such that the loops formed by the two conductors are not coaxial. An example of such a structure is shown in Figure 12 where two conductors 1201,1202 are wrapped around a planar rectangular core 1203 at orthogonal angles. The core may be rectangular or it may have various geometries with several extensions or protrusions. The protrusions may be useful for wrapping of a conductor, reducing the weight, size, or mass of the core, or may be used to enhance the directionality or omni-directionality of the resonator. A multi wrapped planar resonator with four protrusions is shown by the inner structure 1310 in Figure ,13, where four conductors 1301, 1302, 1303,1304 are wrapped around the core. The core may have extensions 1305,1306,1307,1308 with one or more conductor loops. A single conductor may be wrapped around a core to form loops that are not coaxial. The four conductor loops of Figure 13, for example, may be formed with one continuous piece of conductor, or using two conductors where a single conductor is used to make all coaxial loops.

[00197] Non-uniform or asymmetric field profiles around the resonator comprising a plurality of conductor loops may be generated by driving some conductor loops with non-identical parameters. Some conductor loops of a source resonator with a plurality of conductor loops may be driven by a power source with a different frequency, voltage, power level, duty cycle, and the like all of which may be used to affect the strength of the magnetic field generated by each conductor.

[00198] The planar resonator structures may be combined with a capacitively-loaded inductor resonator coil to provide an omni-directional active area all around, including above and below the source while maintaining a flat resonator structure. As shown in Figure 13, an additional resonator loop coil 1309 comprising of a loop or loops of a conductor, may be placed in a common plane as the planar resonator structure 1310. The outer resonator coil provides an active area that is substantially above and below the source. The resonator coil can be arranged with any number of planar resonator structures and arrangements described herein.

[00199] The planar resonator structures may be enclosed in magnetically permeable packaging or integrated into other devices. The planar profile of the resonators within a single, common plane allows packaging and integration into flat devices. A diagram illustrating the application of the resonators is shown in Figure 14. A flat source 1411 comprising one or more planar resonators 1414 each with one or more conductor loops may transfer power to devices 1412,1413 that are integrated with other planar resonators 1415,1416 and placed within an active area 1417 of the source. The devices may comprise a plurality of planar resonators such that regardless of the orientation of the device with respect to the source the active area of the source does not change. In addition to invariance to rotational misalignment, a flat device comprising of planar resonators may be turned upside down without substantially affecting the active area since the planar resonator is still in the plane of the source.

[00200] Another diagram illustrating a possible use of a power transfer system using the planar resonator structures is shown in Figure 15. A planar source 1521 placed on top of a surface 1525 may create an active area that covers a substantial surface area creating an "energized surface" area. Devices such as computers 1524, mobile handsets 1522, games, and other electronics 1523 that are coupled to their respective planar device resonators may receive energy from the source when placed within the active area of the source, which may be anywhere on top of the surface. Several devices with different dimensions may be placed in the active area and used normally while charging or being powered from the source without having strict placement or alignment constraints. The source may be placed under the surface of a table, countertop, desk, cabinet, and the like, allowing it to be completely hidden while energizing the top surface of the table, countertop, desk, cabinet and the like, creating an active area on the surface that is much larger than the source.

[00201] The source may include a display or other visual, auditory, or vibration indicators to show the direction of charging devices or what devices are being charged, error or problems with charging, power levels, charging time, and the like.

[00202] The source resonators and circuitry may be integrated into any number of other devices. The source may be integrated into devices such as clocks, keyboards, monitors, picture frames, and the like. For example, a keyboard integrated with the planar resonators and appropriate power and control circuitry may be used as a source for devices placed around the keyboard such as computer mice, webcams, mobile handsets, and the like without occupying any additional desk space.

[00203] While the planar resonator structures have been described in the context of mobile devices it should be clear to those skilled in the art that a flat planar source for wireless power transfer with an active area that extends beyond its physical dimensions has many other consumer and industrial applications. The structures and configuration may be useful for a large number of applications where electronic or electric devices and a power source are typically located, positioned, or manipulated in substantially the same plane and alignment. Some of the possible application scenarios include devices on walls, floor, ceilings or any other substantially

planar surfaces.

[00204] Flat source resonators may be integrated into a picture frame or hung on a wall thereby providing an active area within the plane of the wall where other electronic devices such as digital picture frames, televisions, lights, and the like can be mounted and powered without wires. Planar resonators may be integrated into a floor resulting in an energized floor or active area on the floor on which devices can be placed to receive power. Audio speakers, lamps, heaters, and the like can be placed within the active are and receive power wirelessly.

[00205] The planar resonator may have additional components coupled to the conductor. Components such as capacitors, inductors, resistors, diodes, and the like may be coupled to the conductor and may be used to adjust or tune the resonant frequency and the impedance matching for the resonators.

[00206] A planar resonator structure of the type described above and shown in Fig. 11(a), may be created, for example, with a quality factor, Q, of 100 or higher and even Q of 1,000 or higher. Energy may be wirelessly transferred from one planar resonator structure to another over a distance larger than the characteristic size of the resonators, as shown in Fig. 11(c).

[00207] In addition to utilizing magnetic materials to realize a structure with properties similar to the inductive element in the magnetic resonators, it may be possible to use a combination of good conductor materials and magnetic material to realize such inductive structures. Fig. 16(a) shows a magnetic resonator structure 1602 that may include one or more enclosures made of high-conductivity materials (the inside of which would be shielded from AC electromagnetic fields generated outside) surrounded by at least one layer of magnetic material and linked by blocks of magnetic material 1604.

A structure may include a high-conductivity sheet of material covered on one side by a layer of magnetic material. The layered structure may instead be applied conformally to an electronic device, so that parts of the device may be covered by the high-conductivity and magnetic material layers, while other parts that need to be easily accessed (such as buttons or screens) may be left uncovered. The structure may also or instead include only layers or bulk pieces of magnetic material. Thus, a magnetic resonator may be incorporated into an existing device without significantly interfering with its existing functions and with little or no need for extensive redesign. Moreover, the layers of good conductor and/or magnetic material may be made thin enough (of the order of a millimeter or less) that they would add little extra weight and volume to the completed device. An oscillating current applied to a length of conductor wound around the structure, as shown by the square loop in the center of the structure in Figure 16 may be used to excite the electromagnetic fields associated with this structure.

[00208] Quality factor of the structure

[00209] A structure of the type described above may be created with a quality factor, Q, of the order of 1,000 or higher. This high-Q is possible even if the losses in the magnetic material are high, if the fraction of magnetic energy within the magnetic material is small compared to the total magnetic energy associated with the object. For structures composed of layers conducting materials and magnetic materials, the losses in the conducting materials may be reduced by the presence of the magnetic materials as described previously. In structures where the magnetic material layer's thickness is of the order of 1/100 of the largest dimension of the system (e.g., the magnetic material may be of the order of 1 mm thick, while the area of the structure is of the order of 10 cm x 10 cm), and the relative permeability is of the order of 1,000, it is possible to make the fraction of magnetic energy contained within the magnetic material only a few hundredths of the total magnetic energy associated with the object or resonator. To see how that comes about, note that the expression for the magnetic energy contained in a volume is so as long as B (rather than H) is the main field conserved across the magnetic material-air interface (which is typically the case in open magnetic circuits), the fraction of magnetic energy contained in the high-μr region may be significantly reduced compared to what it is in air.

[00210] If the fraction of magnetic energy in the magnetic material is denoted by frac, and the loss tangent of the material is tand, then the Q of the resonator, assuming the magnetic material is the only source of losses, is Q=1/(frac x tand). Thus, even for loss tangents as high as 0.1, it is possible to achieve Q 's of the order of 1,000 for these types of resonator structures.

[00211] If the structure is driven with 7V turns of wire wound around it, the losses in the excitation inductor loop can be ignored if N is sufficiently high. Fig. 17 shows an equivalent circuit 1700 schematic for these structures and the scaling of the loss mechanisms and inductance with the number of turns, N, wound around a structure made of conducting and magnetic material. If proximity effects can be neglected (by using an appropriate winding, or a wire designed to minimize proximity effects, such as Litz wire and the like), the resistance 1702 due to the wire in the looped conductor scales linearly with the length of the loop, which is in turn proportional to the number of turns. On the other hand, both the equivalent resistance 1708 and equivalent inductance 1704 of these special structures are proportional to the square of the magnetic field inside the structure. Since this magnetic field is proportional to TV, the equivalent resistance 1708 and equivalent inductance 1704 are both proportional to TV2. Thus, for large enough N, the resistance 1702 of the wire is much smaller than the equivalent resistance 1708 of the magnetic structure, and the Q of the resonator asymptotes to Qmax = ?Lp /Rμ .

[00212] Fig. 16 (a) shows a drawing of a copper and magnetic material structure 1602 driven by a square loop of current around the narrowed segment at the center of the structure 1604 and the magnetic field streamlines generated by this structure 1608. This exemplary structure includes two 20 cm x 8 cm x 2 cm hollow regions enclosed with copper and then completely covered with a 2 mm layer of magnetic material having the properties μ'r = 1,400, μ"r = 5, and s = 0.5 S/m. These two parallelepipeds are spaced 4 cm apart and are connected by a 2 cm x 4 cm x 2 cm block of the same magnetic material. The excitation loop is wound around the center of this block. At a frequency of 300 kHz, this structure has a calculated Q of 890. The conductor and magnetic material structure may be shaped to optimize certain system parameters. For example, the size of the structure enclosed by the excitation loop may be small to reduce the resistance of the excitation loop, or it may be large to mitigate losses in the magnetic material associated with large magnetic fields. Note that the magnetic streamlines and Q 's associated with the same structure composed of magnetic material only would be similar to the layer conductor

and magnetic material design shown here.

[00213] Electromagnetic Resonators Interacting with Other Objects

[00214] For electromagnetic resonators, extrinsic loss mechanisms that perturb the intrinsic Q may include absorption losses inside the materials of nearby extraneous objects and radiation losses related to scattering of the resonant fields from nearby extraneous objects. Absorption losses may be associated with materials that, over the frequency range of interest, have non-zero, but finite, conductivity, s , (or equivalently a non-zero and finite imaginary part of the dielectric permittivity), such that electromagnetic fields can penetrate it and induce * currents in it, which then dissipate energy through resistive losses. An object may be described as lossy if it at least partly includes lossy materials.

[00215] Consider an object including a homogeneous isotropic material of conductivity, s and magnetic permeability, µ. The penetration depth of electromagnetic fields inside this object is given by the skin depth, . The power dissipated inside the object, Pd, can be determined from where we made use of Ohm's law, $J = sE$, and where E is the electric field and J is the current density.

[00216] If over the frequency range of interest, the conductivity, s , of the material that composes the object is low enough that the material's skin depth, d, may be considered long, (i.e. d is longer than the objects' characteristic size, or d is longer than the characteristic size of the portion of the object that is lossy) then the electromagnetic fields, E and H, where H is the magnetic field, may penetrate significantly into the object. Then, these finite-valued fields may give rise to a dissipated power that scales as where Vol is the volume of the object that is lossy and is the spatial average of the electric-field squared, in the volume under consideration. Therefore, in the low-conductivity limit, the dissipated power scales proportionally to the conductivity and goes to zero in the limit of a non-conducting (purely dielectric) material.

[00217] If over the frequency range of interest, the conductivity, s , of the material that composes the object is high enough that the material's skin depth may be considered short, then the electromagnetic fields, E and H, may penetrate only a short distance into the object (namely they stay close to the 'skin' of the material, where d is smaller than the characteristic thickness of the portion of the object that is lossy). In this case, the currents induced inside me material may be concentrated very close to the material surface, approximately within a skin depth, and their magnitude may be approximated by the product of a surface current density (mostly determined by the shape of the incident electromagnetic fields and, as long as the thickness of the conductor is much larger than the skin-depth, independent of frequency and conductivity to first order) K(x, y) (where x and y are coordinates parameterizing the surface) and a function decaying exponentially into the surface: $exp(-x /d)/d$ (where x denotes the coordinate locally normal to the surface): Then, the dissipated power, Pd, may be estimated by,

[00218] Therefore, in the high-conductivity limit, the dissipated power scales inverse proportionally to the square-root of the conductivity and goes to zero in the limit of a perfectly-conducting material.

[00219] If over the frequency range of interest, the conductivity, s , of the material that composes the object is finite, then the material's skin depth, d , may penetrate some distance into the object and some amount of power may be dissipated inside the object, depending also on the size of the object and the strength of the electromagnetic fields. This description can be generalized to also describe the general case of an object including multiple different materials with different properties and conductivities, such as an object with an arbitrary inhomogeneous and anisotropic distribution of the conductivity inside the object.

[00220] Note that the magnitude of the loss mechanisms described above may depend on the location and orientation of the extraneous objects relative to the resonator fields as well as the material composition of the extraneous objects. For example, high-conductivity materials may shift the resonant frequency of a resonator and detune it from other resonant objects. This frequency shift may be fixed by applying a feedback mechanism to a resonator that corrects its frequency, such as through changes in the inductance and/or capacitance of the resonator. These changes may be realized using variable capacitors and inductors, in some cases achieved by changes in the geometry of components in the resonators. Other novel tuning mechanisms, described below, may also be used to change the resonator frequency.

[00221] Where external losses are high, the perturbed Q may be low and steps may be taken to limit the absorption of resonator energy inside such extraneous objects and materials. Because of the functional dependence of the dissipated power on the strength of the electric and magnetic fields, one might optimize system performance by designing a system so that the desired coupling is achieved with shorter evanescent resonant field tails at the source resonator and longer at the device resonator, so that the perturbed Q of the source in the presence of other objects is optimized (or vice versa if the perturbed Q of the device needs to be optimized).

[00222] Note that many common extraneous materials and objects such as people, animals, plants, building materials, and the like, may have low conductivities and therefore may have little impact on the wireless energy transfer scheme disclosed here. An important fact related to the magnetic resonator designs we describe is that their electric fields may be confined primarily within the resonator structure itself, so it should be possible to operate within the commonly accepted guidelines for human safety while providing wireless power exchange over mid range distances.

[00223] Electromagnetic Resonators with Reduced Interactions

[00224] One frequency range of interest for near-field wireless power transmission is between 10 kHz and 100 MHz. In this frequency range, a large variety of ordinary non-metallic materials, such as for example several types of wood and plastic may have relatively low conductivity, such that only small amounts of power may be dissipated inside them. In addition, materials with low loss tangents, tan?, where tan ? = e'' / e', and e'' and e' are the imaginary and real parts of the permittivity respectively, may also have only small amounts of power dissipated inside them. Metallic materials, such as copper, silver, gold, and the like, with relatively high conductivity, may also have little power dissipated in them, because electromagnetic fields are not able to significantly penetrate these materials, as discussed earlier.

These very high and very low conductivity materials, and low loss tangent materials and objects may have a negligible impact on the losses of a magnetic resonator.

[00225] However, in the frequency range of interest, there are materials and objects such as some electronic circuits and some lower-conductivity metals, which may have moderate (in general inhomogeneous and anisotropic) conductivity, and/or moderate to high loss tangents, and which may have relatively high dissipative losses. Relatively larger amounts of power may be dissipated inside them. These materials and objects may dissipate enough energy to reduce Q(p) by non-trivial amounts, and may be referred to as "lossy objects".

[00226] One way to reduce the impact of lossy materials on the Q(p) of a resonator is to use high-eonductivity materials to shape the resonator fields such that they avoid the lossy ***objects. The process of using high-conductivity materials to tailor electromagnetic fields so that they avoid lossy objects in their vicinity may be understood by visualizing high-conductivity materials as materials that deflect or reshape the fields. This picture is qualitatively correct as long as the thickness of the conductor is larger than the skin-depth because the boundary conditions for electromagnetic fields at the surface of a good conductor force the electric field to be nearly completely perpendicular to, and the magnetic field to be nearly completely tangential to, the conductor surface. Therefore, a perpendicular magnetic field or a tangential electric field will be "deflected away" from the conducting surface. Furthermore, even a tangential magnetic field or a perpendicular electric field may be forced to decrease in magnitude on one side and/or in particular locations of the conducting surface, depending on the relative position of the sources of the fields and the conductive surface.

[00227] As an example, Fig. 18 shows a finite element method (FEM) simulation of two high conductivity surfaces 1802 above and below a lossy dielectric material 1804 in an external, initially uniform, magnetic field of frequency f= 6.78 MHz. The system is azimuthally symmetric around the r=0 axis. In this simulation, the lossy dielectric material 1804 is sandwiched between two conductors 1802, shown as the white lines at approximately z = ±0.01m. In the absence of the conducting surfaces above and below the dielectric disk, the magnetic field (represented by the drawn magnetic field lines) would have remained essentially uniform (field lines straight and parallel with the z-axis), indicating that the magnetic field would have passed straight through the lossy dielectric material. In this case, power would have been dissipated in the lossy dielectric disk. In the presence of conducting surfaces, however, this simulation shows the magnetic field is reshaped. The magnetic field is forced to be tangential to surface of the conductor and so is deflected around those conducting surfaces 1802, minimizing the amount of power that may be dissipated in the lossy dielectric material 1804 behind or between the conducting surfaces. As used herein, an axis of electrical symmetry refers to any axis about which a fixed or time-varying electrical or magnetic field is substantially symmetric during an exchange of energy as disclosed herein.

[00228] A similar effect is observed even if only one conducting surface, above or below, the dielectric disk, is used. If the dielectric disk is thin, the fact that the electric field is essentially zero at the surface, and continuous and smooth close to it, means that the electric field is very low everywhere close to the surface (i.e. within the dielectric disk). A single surface implementation for deflecting resonator fields away from lossy objects may be preferred for applications where one is not allowed to cover both sides of the lossy material or object (e.g. an LCD screen). Note that even a very thin surface of conducting material, on the order of a few skin-depths, may be sufficient (the skin depth in pure copper at 6.78 MHz is ~20 μ m, and at 250 kHz is ~ 100 μ m) to significantly improve the Q(p) of a resonator in the presence of lossy materials.

[00229] Lossy extraneous materials and objects may be parts of an apparatus, in which a high-g resonator is to be integrated. The dissipation of energy in these lossy materials and objects may be reduced by a number of techniques including:

- by positioning the lossy materials and objects away from the resonator, or, in special positions and orientations relative to the resonator.
- by using a high conductivity material or structure to partly or entirely cover lossy materials and objects in the vicinity of a resonator
- by placing a closed surface (such as a sheet or a mesh) of high-conductivity material around a lossy object to completely cover the lossy object and shape the resonator fields such that they avoid the lossy object.
- by placing a surface (such as a sheet or a mesh) of a high-conductivity material around only a portion of a lossy object, such as along the top, the bottom, along the side, and the like, of an object or material.
- by placing even a single surface (such as a sheet or a mesh) of high-conductivity material above or below or on one side of a lossy object to reduce the strength of the fields at the location of the lossy object.

[00230] Fig. 19 shows a capacitively-loaded loop inductor forming a magnetic resonator 102 and a disk-shaped surface of high-conductivity material 1802 that completely surrounds a lossy object 1804 placed inside the loop inductor. Note that some lossy objects may be components, such as electronic circuits, that may need to interact with, communicate with, or be connected to the outside environment and thus cannot be completely electromagnetically isolated. Partially covering a lossy material with high conductivity materials may still reduce extraneous losses while enabling the lossy material or object to function properly.

[00231] Fig. 20 shows a capacitively-loaded loop inductor that is used as the resonator 102 and a surface of high-conductivity material 1802, surrounding only a portion of a lossy object 1804, that is placed inside the inductor loop.

[00232] Extraneous losses may be reduced, but may not be completely eliminated, by placing a single surface of high-conductivity material above, below, on the side, and the like, of a lossy object or material. An example is shown in Fig. 21, where a capacitively-loaded loop inductor is used as the resonator 102 and a surface of high-conductivity material 1802 is placed inside the inductor loop under a lossy object 1804 to reduce the strength of the fields at the location of the lossy object. It may be preferable to cover only one side of a material or object because of considerations of cost, weight, assembly complications, air flow, visual access, physical access, and the like.

[00233] A single surface of high-conductivity material may be used to avoid objects

that cannot or should not be covered from both sides (e.g. LCD or plasma screens). Such lossy objects may be avoided using optically transparent conductors. High-conductivity optically opaque materials may instead be placed on only a portion of the lossy object, instead of, or in addition to, optically transparent conductors. The adequacy of single-sided vs. multi-sided covering implementations, and the design trade-offs inherent therein may depend on the details of the wireless energy transfer scenario and the properties of the lossy materials and objects.

[00234] Below we describe an example using high-conductivity surfaces to improve the Q-insensitivity, T(p), of an integrated magnetic resonator used in a wireless energy-transfer system. Fig. 22 shows a wireless projector 2200. The wireless projector may include a device resonator 102C, a projector 2202, a wireless network/video adapter 2204, and power conversion circuits 2208, arranged as shown. The device resonator 102C may include a three-turn conductor loop, arranged to enclose a surface, and a capacitor network 2210. The conductor loop may be designed so that the device resonator 102C has a high Q (e.g., >100) at its operating resonant frequency. Prior to integration in the completely wireless projector 2200, this device resonator 102C has a Q of approximately 477 at the designed operating resonant frequency of 6.78 MHz. Upon integration, and placing the wireless network/video adapter card 2204 in the center of the resonator loop inductor, the resonator Q(integrated) was decreased to approximately 347. At least some of the reduction from Q to Q(integrated) was attributed to losses in the perturbing wireless network/video adapter card. As described above, electromagnetic fields associated with the magnetic resonator 102C may induce currents in and on the wireless network/video adapter card 2204, which may be dissipated in resistive losses in the lossy materials that compose the card. We observed that Q(integrated) of the resonator may be impacted differently depending on the composition, position, and orientation, of objects and materials placed in its vicinity.

[00235] In a completely wireless projector example, covering the network/video adapter card with a thin copper pocket (a folded sheet of copper that covered the top and the bottom of the wireless network/video adapter card, but not the communication antenna) improved the Q(integrated) of the magnetic resonator to a Q(integrated + copper pocket) of approximately 444. In other words, most of the reduction in Q(integrated) due to the perturbation caused by the extraneous network/video adapter card could be eliminated using a copper pocket to deflect the resonator fields away from the lossy materials.

[00236] In another completely wireless projector example, covering the network/video adapter card with a single copper sheet placed beneath the card provided a Q(integrated + copper sheet) approximately equal to Q(integrated + copper pocket). In that example, the high perturbed Q of the system could be maintained with a single high-conductivity sheet used to deflect the resonator fields away from the lossy adapter card.

[00237] It may be advantageous to position or orient lossy materials or objects, which are part of an apparatus including a high-Q electromagnetic resonator, in places where the fields produced by the resonator are relatively weak, so that little or no power may be dissipated in these objects and so that the Q-insensitivity, T(p), may be large. As was shown earlier, materials of different conductivity may respond differently to electric versus magnetic fields. Therefore, according to the conductivity of the extraneous object, the positioning technique may be specialized to one or the other field.

[00238] Fig. 23 shows the magnitude of the electric 2312 and magnetic fields 2314 along a line that contains the diameter of the circular loop inductor and the electric 2318 and magnetic fields 2320 along the axis of the loop inductor for a capacitively-loaded circular loop inductor of wire of radius 30 cm, resonant at 10 MHz. It can be seen that the amplitude of the resonant near-fields reach their maxima close to the wire and decay away from the loop, 2312 , 2314 . In the plane of the loop inductor 2318, 2320, the fields reach a local minimum at the center of the loop. Therefore, given the finite size of the apparatus, it may be that the fields are weakest at the extrema of the apparatus or it may be that the field magnitudes have local minima somewhere within the apparatus. This argument holds for any other type of electromagnetic resonator 102 and any type of apparatus. Examples are shown in Figs. 24a and 24b, where a capacitively-loaded inductor loop forms a magnetic resonator 102 and an extraneous lossy object 1804 is positioned where the electromagnetic fields have minimum magnitude.

[00239] In a demonstration example, a magnetic resonator was formed using a three-turn conductor loop, arranged to enclose a square surface (with rounded corners), and a capacitor network. The Q of the resonator was approximately 619 at the designed operating resonant frequency of 6.78 MHz. The perturbed Q of this resonator depended on the placement of the perturbing object, in this case a pocket projector, relative to the resonator. When the perturbing projector was located inside the inductor loop and at its center or oh top of the inductor wire hirns, Q(projector) was approximately 96, lower than when the perturbing projector was placed outside of the resonator, in which case Q(projector) was approximately 513. These measurements support the analysis that shows the fields inside the inductor loop may be larger than those outside it, so lossy objects placed inside such a loop inductor may yield lower perturbed Q 's for the system than when the lossy object is placed outside the loop inductor. Depending on the resonator designs and the material composition and orientation of the lossy object, the arrangement shown in Fig. 24b may yield a higher Q-insensitivity, T(projector), than the arrangement shown in Fig. 24a.

[00240] High-Q resonators may be integrated inside an apparatus. Extraneous materials and objects of high dielectric permittivity, magnetic permeability, or electric -conductivity may be part of the apparatus into which a high-Q resonator is to be integrated. For these extraneous materials and objects in the vicinity of a high-Q electromagnetic resonator, depending on their size, position and orientation relative to the resonator, the resonator field-profile may be distorted and deviate significantly from the original unperturbed field-profile of the resonator. Such a distortion of the unperturbed fields of the resonator may significantly decrease the Q to a lower Q(p), even if the extraneous objects and materials are lossless.

[00241] It may be advantageous to position high-conductivity objects, which are part of an apparatus including a high-Q electromagnetic resonator, at orientations such that the surfaces of these objects are, as much as possible, perpendicular to the electric field lines produced by the unperturbed resonator and parallel to the magnetic field lines produced by the unperturbed resonator, thus distorting the resonant field profiles by the smallest amount possible. Other common objects that may be positioned perpendicular to the plane of a magnetic resonator

loop include screens (LCD, plasma, etc), batteries, cases, connectors, radiative antennas, and the like. The Q-insensitivity, T(p), of the resonator may be much larger than if the objects were positioned at a different orientation with respect to the resonator fields.

[00242] Lossy extraneous materials and objects, which are not part of the integrated apparatus including a high-Q resonator, may be located or brought in the vicinity of the resonator, for example, during the use of the apparatus. It may be advantageous in certain circumstances to use high conductivity materials to tailor the resonator fields so that they avoid the regions where lossy extraneous objects may be located or introduced to reduce power dissipation in these materials and objects and to increase Q-insensitivity, T(p). An example is shown in Fig. 25, where a capacitively-loaded loop inductor and capacitor are used as the resonator 102 and a surface of high-conductivity material 1802 is placed above the inductor loop to reduce the magnitude of the fields in the region above the resonator, where lossy extraneous objects 1804 may be located or introduced.

[00243] Note that a high-conductivity surface brought in the vicinity of a resonator to reshape the fields may also lead to The reduction in the perturbed Q may be due to the dissipation of energy inside the lossy conductor or to the distortion of the unperturbed resonator field profiles associated with matching the field boundary conditions at the surface of the conductor. Therefore, while a high-conductivity surface may be used to reduce the extraneous losses due to dissipation inside an extraneous lossy object, in some cases, especially in some of those where this is achieved by significantly reshaping the electromagnetic fields, using such a high-conductivity surface so that the fields avoid the lossy object may result effectively in rather than the desired result

[00244] As described above, in the presence of loss inducing objects, the perturbed quality factor of a magnetic resonator may be improved if the electromagnetic fields associated with the magnetic resonator are reshaped to avoid the loss inducing objects. Another way to reshape the unperturbed resonator fields is to use high permeability materials to completely or partially enclose or cover the loss inducing objects, thereby reducing the interaction of the magnetic field with the loss inducing objects.

[00245] Magnetic field shielding has been described previously, for example in Electrodynamics 3rd Ed., Jackson, pp. 201-203. There, a spherical shell of magnetically permeable material was shown to shield its interior from external magnetic fields. For example, if a shell of inner radius a, outer radius b, and relative permeability µr, is placed in an initially uniform magnetic field Ho, then the field inside the shell will have a constant magnitude, which tends to This result shows that an incident magnetic field (but not necessarily an incident electric field) may be greatly attenuated inside the shell, even if the shell is quite thin, provided the magnetic permeability is high enough. It may be advantageous in certain circumstances to use high permeability materials to partly or entirely cover lossy materials and objects so that they are avoided by the resonator magnetic fields and so that little or no power is dissipated in these materials and objects. In such an approach, the Q-insensitivity, T(p), may be larger than if the materials and objects were not covered, possibly larger than 1.

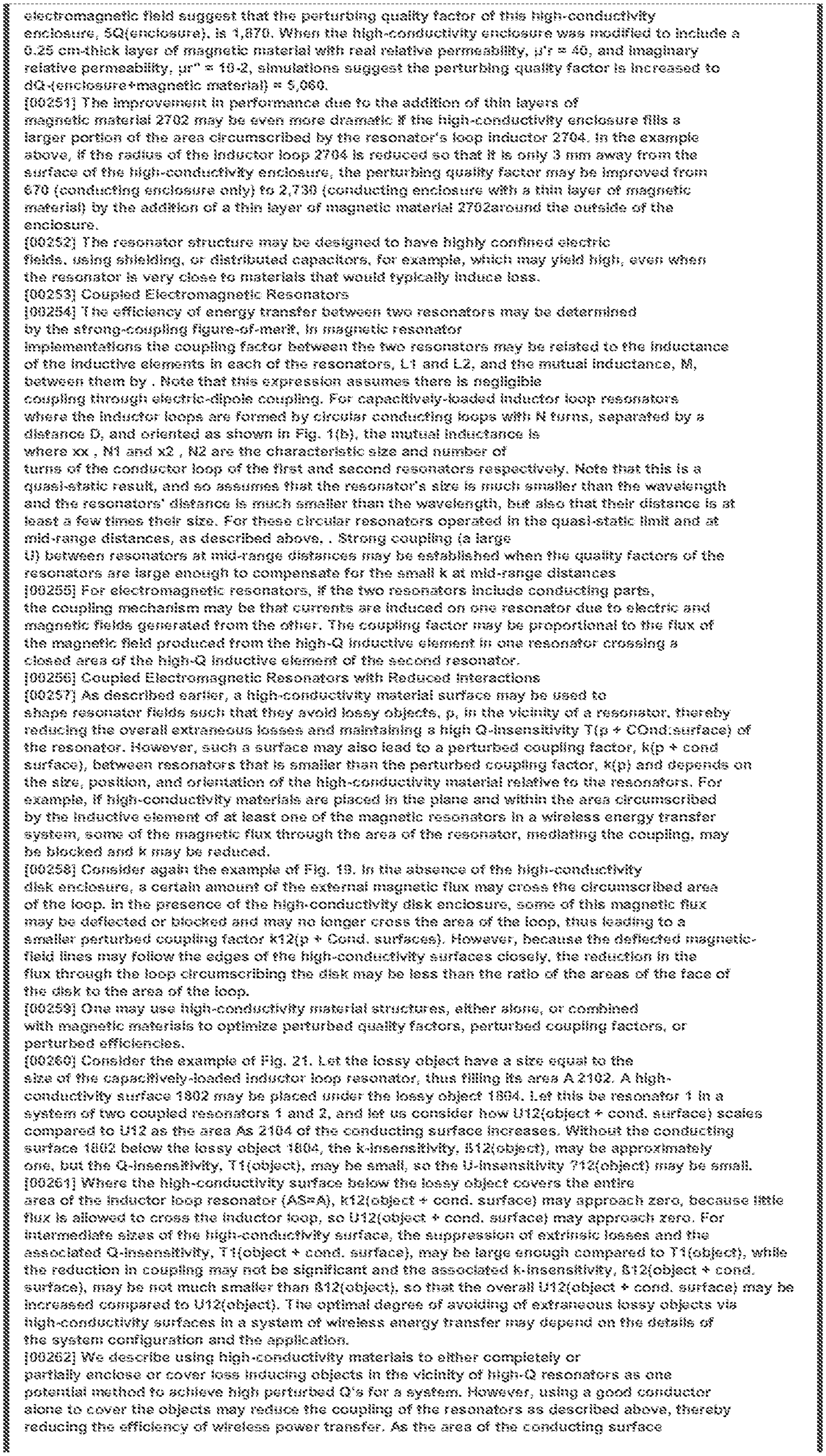
[00246] It may be desirable to keep both the electric and magnetic fields away from loss inducing objects. As described above, one way to shape the fields in such a manner is to use high-conductivity surfaces to either completely or partially enclose or cover the loss inducing objects. A layer of magnetically permeable material, also referred to as magnetic material, (any material or meta-material having a non-trivial magnetic permeability), may be placed on or around the high-conductivity surfaces. The additional layer of magnetic material may present a lower reluctance path (compared to free space) for the deflected magnetic field to follow and may partially shield the electric conductor underneath it from the incident magnetic flux. This arrangement may reduce the losses due to induced currents in the high-conductivity surface. Under some circumstances the lower reluctance path presented by the magnetic material may improve the perturbed Q of the structure.

[00247] Fig. 26a shows an axially symmetric FEM simulation of a thin conducting 2604 (copper) disk (20 cm in diameter, 2 cm in height) exposed to an initially uniform, externally applied magnetic field (gray flux lines) along the z-axis. The axis of symmetry is at r=0. The magnetic streamlines shown originate at z = -co, where they are spaced from r=3 cm to r=10 cm in intervals of 1 cm. The axes scales are in meters. Imagine, for example, that this conducing cylinder encloses loss-inducing objects within an area circumscribed by a magnetic resonator in a wireless energy transfer system such as shown in Fig. 19.

[00248] This high-conductivity enclosure may increase the perturbing Q of the lossy objects and therefore the overall perturbed Q of the system, but the perturbed Q may still be less than the unperturbed Q because of induced losses in the conducting surface and changes to the profile of the electromagnetic fields. Decreases in the perturbed Q associated with the high-conductivity enclosure may be at least partially recovered by including a layer of magnetic material along the outer surface or surfaces of the high-conductivity enclosure. Fig. 26b shows an axially symmetric FEM simulation of the thin conducting 2604A (copper) disk (20 cm in diameter, 2 cm in height) from Fig. 26a, but with an additional layer of magnetic material placed directly on the outer surface of the high-conductivity enclosure. Note that the presence of the magnetic material may provide a lower reluctance path for the magnetic field, thereby at least partially shielding the underlying conductor and reducing losses due to induced eddy currents in the conductor.

[00249] Fig. 27 depicts a variation (in axi-symmetric view) to the system shown in Fig. 26 where not all of the lossy material 2708 may be covered by a high-conductivity surface 2706. In certain circumstances it may be useful to cover only one side of a material or object, such as due to considerations of cost, weight, assembly complications, air flow, visual access, physical access, and the like. In the exemplary arrangement shown in Fig. 27, only one surface of the lossy material 2708 is covered and the resonator inductor loop is placed on the opposite side of the high-conductivity surface.

[00250] Mathematical models were used to simulate a high-conductivity enclosure made of copper and shaped like a 20 cm diameter by 2 cm high cylindrical disk placed within an area circumscribed by a magnetic resonator whose inductive element was a single-turn wire loop with loop radius r=l 1 cm and wire radius a= 1 mm. Simulations for. an applied 6.78 MHz



electromagnetic field suggest that the perturbing quality factor of this high-conductivity enclosure, 5Q(enclosure), is 1,870. When the high-conductivity enclosure was modified to include a 0.25 cm-thick layer of magnetic material with real relative permeability, μ'r = 40, and imaginary relative permeability, μr'' = 10-2, simulations suggest the perturbing quality factor is increased to dQ-(enclosure+magnetic material) = 5,060.

[00251] The improvement in performance due to the addition of thin layers of magnetic material 2702 may be even more dramatic if the high-conductivity enclosure fills a larger portion of the area circumscribed by the resonator's loop inductor 2704. In the example above, if the radius of the inductor loop 2704 is reduced so that it is only 3 mm away from the surface of the high-conductivity enclosure, the perturbing quality factor may be improved from 670 (conducting enclosure only) to 2,730 (conducting enclosure with a thin layer of magnetic material) by the addition of a thin layer of magnetic material 2702around the outside of the enclosure.

[00252] The resonator structure may be designed to have highly confined electric fields, using shielding, or distributed capacitors, for example, which may yield high, even when the resonator is very close to materials that would typically induce loss.

[00253] Coupled Electromagnetic Resonators

[00254] The efficiency of energy transfer between two resonators may be determined by the strong-coupling figure-of-merit, In magnetic resonator implementations the coupling factor between the two resonators may be related to the inductance of the inductive elements in each of the resonators, L1 and L2, and the mutual inductance, M, between them by . Note that this expression assumes there is negligible coupling through electric-dipole coupling. For capacitively-loaded inductor loop resonators where the inductor loops are formed by circular conducting loops with N turns, separated by a distance D, and oriented as shown in Fig. 1(b), the mutual inductance is where xx , N1 and x2 , N2 are the characteristic size and number of turns of the conductor loop of the first and second resonators respectively. Note that this is a quasi-static result, and so assumes that the resonator's size is much smaller than the wavelength and the resonators' distance is much smaller than the wavelength, but also that their distance is at least a few times their size. For these circular resonators operated in the quasi-static limit and at mid-range distances, as described above, . Strong coupling (a large U) between resonators at mid-range distances may be established when the quality factors of the resonators are large enough to compensate for the small k at mid-range distances

[00255] For electromagnetic resonators, if the two resonators include conducting parts, the coupling mechanism may be that currents are induced on one resonator due to electric and magnetic fields generated from the other. The coupling factor may be proportional to the flux of the magnetic field produced from the high-Q inductive element in one resonator crossing a closed area of the high-Q inductive element of the second resonator.

[00256] Coupled Electromagnetic Resonators with Reduced Interactions

[00257] As described earlier, a high-conductivity material surface may be used to shape resonator fields such that they avoid lossy objects, p, in the vicinity of a resonator, thereby reducing the overall extraneous losses and maintaining a high Q-insensitivity T(p + COnd:surface) of the resonator. However, such a surface may also lead to a perturbed coupling factor, k(p + cond surface), between resonators that is smaller than the perturbed coupling factor, k(p) and depends on the size, position, and orientation of the high-conductivity material relative to the resonators. For example, if high-conductivity materials are placed in the plane and within the area circumscribed by the inductive element of at least one of the magnetic resonators in a wireless energy transfer system, some of the magnetic flux through the area of the resonator, mediating the coupling, may be blocked and k may be reduced.

[00258] Consider again the example of Fig. 19. In the absence of the high-conductivity disk enclosure, a certain amount of the external magnetic flux may cross the circumscribed area of the loop. In the presence of the high-conductivity disk enclosure, some of this magnetic flux may be deflected or blocked and may no longer cross the area of the loop, thus leading to a smaller perturbed coupling factor k12(p + Cond. surfaces). However, because the deflected magnetic-field lines may follow the edges of the high-conductivity surfaces closely, the reduction in the flux through the loop circumscribing the disk may be less than the ratio of the areas of the face of the disk to the area of the loop.

[00259] One may use high-conductivity material structures, either alone, or combined with magnetic materials to optimize perturbed quality factors, perturbed coupling factors, or perturbed efficiencies.

[00260] Consider the example of Fig. 21. Let the lossy object have a size equal to the size of the capacitively-loaded inductor loop resonator, thus filling its area A 2102. A high-conductivity surface 1802 may be placed under the lossy object 1804. Let this be resonator 1 in a system of two coupled resonators 1 and 2, and let us consider how U12(object + cond. surface) scales compared to U12 as the area As 2104 of the conducting surface increases. Without the conducting surface 1802 below the lossy object 1804, the k-insensitivity, ß12(object), may be approximately one, but the Q-insensitivity, T1(object), may be small, so the U-insensitivity ?12(object) may be small.

[00261] Where the high-conductivity surface below the lossy object covers the entire area of the inductor loop resonator (AS=A), k12(object + cond. surface) may approach zero, because little flux is allowed to cross the inductor loop, so U12(object + cond. surface) may approach zero. For intermediate sizes of the high-conductivity surface, the suppression of extrinsic losses and the associated Q-insensitivity, T1(object + cond. surface), may be large enough compared to T1(object), while the reduction in coupling may not be significant and the associated k-insensitivity, ß12(object + cond. surface), may be not much smaller than ß12(object), so that the overall U12(object + cond. surface) may be increased compared to U12(object). The optimal degree of avoiding of extraneous lossy objects via high-conductivity surfaces in a system of wireless energy transfer may depend on the details of the system configuration and the application.

[00262] We describe using high-conductivity materials to either completely or partially enclose or cover loss inducing objects in the vicinity of high-Q resonators as one potential method to achieve high perturbed Q's for a system. However, using a good conductor alone to cover the objects may reduce the coupling of the resonators as described above, thereby reducing the efficiency of wireless power transfer. As the area of the conducting surface

approaches the area of the magnetic resonator, for example, the perturbed coupling factor, k(p), may approach zero, making the use of the conducting surface incompatible with efficient wireless power transfer.

[00263] One approach to addressing the aforementioned problem is to place a layer of magnetic material around the high-conductivity materials because the additional layer of permeable material may present a lower reluctance path (compared to free space) for the deflected magnetic field to follow and may partially shield the electric conductor underneath it from incident magnetic flux. Under some circumstances the lower reluctance path presented by the magnetic material may improve the electromagnetic coupling of the resonator to other resonators. Decreases in the perturbed coupling factor associated with using conducting materials to tailor resonator fields so that they avoid lossy objects in and around high-Q magnetic resonators may be at least partially recovered by including a layer of magnetic material along the outer surface or surfaces of the conducting materials. The magnetic materials may increase the perturbed coupling factor relative to its initial unperturbed value.

[00264] Note that the simulation results in Fig. 26 show that an incident magnetic field may be deflected less by a layered magnetic material and conducting structure than by a conducting structure alone. If a magnetic resonator loop with a radius only slightly larger than that of the disks shown in Figs. 26(a) and 26(b) circumscribed the disks, it is clear that more flux lines would be captured in the case illustrated in Fig. 26(b) than in Fig. 26(a), and therefore k(disk) would be larger for the case illustrated in Fig. 26(b). Therefore, including a layer of magnetic material on the conducting material may improve the overall system performance. System analyses may be performed to determine whether these materials should be partially, totally, or minimally integrated into the resonator.

[00265] As described above, Fig. 27 depicts a layered conductor 2706 and magnetic material 2702 structure that may be appropriate for use when not all of a lossy material 2708 may be covered by a conductor and/or magnetic material structure. It was shown earlier that for a copper conductor disk with a 20 cm diameter and a 2 cm height, circumscribed by a resonator with an inductor loop radius of 11 cm and a wire radius $a=1$ mm, the calculated perturbing Q for the copper cylinder was 1,870. If the resonator and the conducting disk shell are placed in a uniform magnetic field (aligned along theaxis of symmetry of the inductor loop), we calculate that the copper conductor has an associated coupling factor insensitivity of 0.34. For comparison, we model the same arrangement but include a 0.25 cm-thick layer of magnetic material with a real relative permeability, $\mu'r = 40$, and an imaginary relative permeability, $\mu r'' = 10-2$. Using the same model and parameters described above, we find that the coupling factor insensitivity is improved to 0.64 by the addition of the magnetic material to the surface of the conductor.

[00266] Magnetic materials may be placed within the area circumscribed by the magnetic resonator to increase the coupling in wireless energy transfer systems. Consider a solid sphere of a magnetic material with relative permeability, μr, placed in an initially uniform magnetic field. In this example, the lower reluctance path offered by the magnetic material may cause the magnetic field to concentrate in the volume of the sphere. We find that the magnetic flux through the area circumscribed by the equator of the sphere is enhanced by a factor of $3\mu r/(\mu r + 2)$, by the addition of the magnetic material. If $\mu r >> 1$, this enhancement factor may be close to 3.

[00267] One can also show that the dipole moment of a system comprising the magnetic sphere circumscribed by the inductive element in a magnetic resonator would have its magnetic dipole enhanced by the same factor. Thus, the magnetic sphere with high permeability practically triples the dipole magnetic coupling of the resonator. It is possible to keep most of this increase in coupling if we use a spherical shell of magnetic material with inner radius a, and outer radius b, even if this shell is on top of block or enclosure made from highly conducting materials. In this case, the enhancement in the flux through the equator is

For $\mu r=1,000$ and $(a/b)=0.99$, this enhancement factor is still 2.73, so it possible to significantly improve the coupling even with thin layers of magnetic material.

[00268] As described above, structures containing magnetic materials may be used to realize magnetic resonators. Fig. 16(a) shows a 3 dimensional model of a copper and magnetic material structure 1600 driven by a square loop of current around the choke point at its center. Fig. 16(b) shows the interaction, indicated by magnetic field streamlines , between two identical structures 1600A-B with the same properties as the one shown in Fig. 16(a). Because of symmetry, and to reduce computational complexity, only one half of the system is modeled. If we fix the relative orientation between the two objects and vary their center-to-center distance (the image shown is at a relative separation of 50 cm), we find that, at 300 kHz, the coupling efficiency varies from 87% to 55% as the separation between the structures varies from 30 cm to 60 cm. Each of the example structures shown 1600 A-B includes two 20 cm x 8 cm x 2cm parallelepipeds made of copper joined by a 4 cm x 4 cm x 2 cm block of magnetic material and entirely covered with a 2 mm layer of the same magnetic material (assumed to have $\mu r=1,400+j5$). Resistive losses in the driving loop are ignored. Each structure has a calculated Q of 815.

[00269] ELECTROMAGNETIC RESONATORS AND IMPEDANCE MATCHING

[00270] Impedance Matching Architectures for Low-Loss Inductive Elements

[00271] For purposes of the present discussion, an inductive element may be any coil or loop structure (the 'loop') of any conducting material, with or without a (gapped or ungapped) core made of magnetic material, which may also be coupled inductively or in any other contactless way to other systems. The element is inductive because its impedance, including both the impedance of the loop and the so-called 'reflected' impedances of any potentially coupled systems, has positive reactance, X, and resistance, R.

[00272] Consider an external circuit, such as a driving circuit or a driven load or a transmission line, to which an inductive element may be connected. The external circuit (e.g. a driving circuit) may be delivering power to the inductive element and the inductive element may be delivering power to the external circuit (e.g. a driven load). The efficiency and amount of power delivered between the inductive element and the external circuit at a desired frequency may depend on the impedance of the inductive element relative to the properties of the external circuit. Impedance-matching networks and external circuit control techniques may be used to

regulate the power delivery between the external circuit and the inductive element, at a desired frequency,/

[00273] The external circuit may be a driving circuit configured to form a amplifier of class A, B, C, D, DE, E, F and the like, and may deliver power at maximum efficiency (namely with minimum losses within the driving circuit) when it is driving a resonant network with specific impedance Z*o, where Z0 may be complex and * denotes complex conjugation. The external circuit may be a driven load configured to form a rectifier of class A, B, C, D, DE, E, F and the like, and may receive power at maximum efficiency (namely with minimum losses within the driven load) when it is driven by a resonant network with specific impedance Zo*, where Z0 may be complex. The external circuit may be a transmission line with characteristic impedance, Z0, and may exchange power at maximum efficiency (namely with zero reflections) when connected to an impedance Zo*. We will call the characteristic impedance Z0 of an external circuit the complex conjugate of the impedance that may be connected to it for power exchange at maximum efficiency.

[00274] Typically the impedance of an inductive element, R+jX, may be much different from Zo*. For example, if the inductive element has low loss (a high X/R), its resistance, R, may be much lower than the real part of the characteristic impedance, Zo, of the external circuit. Furthermore, an inductive element by itself may not be a resonant network. An impedance-matching network connected to an inductive element may typically create a resonant network, whose impedance may be regulated.

[00275] Therefore, an impedance-matching network may be designed to maximize the efficiency of the power delivered between the external circuit and the inductive element (including the reflected impedances of any coupled systems). The efficiency of delivered power may be maximized by matching the impedance of the combination of an impedance-matching network and an inductive element to the characteristic impedance of an external circuit (or transmission line) at the desired frequency.

[00276] An impedance-matching network may be designed to deliver a specified amount of power between the external circuit and the inductive element (including the reflected impedances of any coupled systems). The delivered power may be determined by adjusting the complex ratio of the impedance of the combination of the impedance-matching network and the inductive element to the impedance of the external circuit (or transmission line) at the desired frequency.

[00277] Impedance-matching networks connected to inductive elements may create magnetic resonators. For some applications, such as wireless power transmission using strongl) coupled magnetic resonators, a high Q may be desired for the resonators. Therefore, the inductive element may be chosen to have low losses (high X/R).

[00278] Since the matching circuit may typically include additional sources of loss inside the resonator, the components of the matching circuit may also be chosen to have low losses. Furthermore, in high-power applications and/or due to the high resonator Q, large currents may run in parts of the resonator circuit and large voltages may be present across some circuit elements within the resonator. Such currents and voltages may exceed the specified tolerances for particular circuit elements and may be too high for particular components to withstand. In some cases, it may be difficult to find or implement components, such as tunable capacitors for example, with size, cost and performance (loss and current/voltage-rating) specifications sufficient to realize high-Q and high-power resonator designs for certain applications. We disclose matching circuit designs, methods, implementations and techniques that may preserve the high Q for magnetic resonators, while reducing the component requirements for low loss and/or high current/voltage-rating.

[00279] Matching-circuit topologies may be designed that minimize the loss and current-rating requirements on some of the elements of the matching circuit. The topology of a circuit matching a low-loss inductive element to an impedance, Z0, may be chosen so that some of its components lie outside the associated high-Q resonator by being in series with the external circuit. The requirements for low series loss or high current-ratings for these components may be reduced. Relieving the low series loss and/or high-current-rating requirement on a circuit element may be particularly useful when the element needs to be variable and/or to have a large voltage-rating and/or low parallel loss.

[00280] Matching-circuit topologies may be designed that minimize the voltage rating requirements on some of the elements of the matching circuit. The topology of a circuit matching a low-loss inductive element to an impedance, Z0, may be chosen so that some of its components lie outside the associated high-Q resonator by being in parallel with Zo. The requirements for low parallel loss or high voltage-rating for these components may be reduced. Relieving the low parallel loss and/or high-voltage requirement on a circuit element may be particularly useful when the element needs to be variable and/or to have a large current-rating and/or low series loss.

[00281] The topology of the circuit matching a low-loss inductive element to an external characteristic impedance, Zo, may be chosen so that the field pattern of the associated resonant mode and thus its high Q are preserved upon coupling of the resonator to the external impedance. Otherwise inefficient coupling to the desired resonant mode may occur (potentially due to coupling to other undesired resonant modes), resulting in an effective lowering of the resonator Q.

[00282] For applications where the low-loss inductive element or the external circuit, may exhibit variations, the matching circuit may need to be adjusted dynamically to match the inductive element to the external circuit impedance, Zo, at the desired frequency,f. Since there may typically be two tuning objectives, matching or controlling both the real and imaginary part of the impedance level, Zo, at the desired frequency,f, there may be two variable elements in the matching circuit. For inductive elements, the matching circuit may need to include at least one variable capacitive element.

[00283] A low-loss inductive element may be matched by topologies using two variable capacitors, or two networks of variable capacitors. A variable capacitor may, for example, be a tunable butterfly-type capacitor having, e.g., a center terminal for connection to a ground or other lead of a power source or load, and at least one other terminal across which a capacitance of the tunable butterfly-type capacitor can be varied or tuned, or any other capacitor

having a user-configurable, variable capacitance.

[00284] A low-loss inductive element may be matched by topologies using one, or a network of, variable capacitor(s) and one, or a network of, variable inductor(s).

[00285] A low-loss inductive element may be matched by topologies using one, or a network of, variable capacitor(s) and one, or a network of, variable mutual inductance(s), which transformer-couple the inductive element either to an external circuit or to other systems.

[00286] In some cases, it may be difficult to find or implement tunable lumped elements with size, cost and performance specifications sufficient to realize high-Q, high-power, and potentially high-speed, tunable resonator designs. The topology of the circuit matching a variable inductive element to an external circuit may be designed so that some of the variability is assigned to the external circuit by varying the frequency, amplitude, phase, waveform, duty cycle, and the like, of the drive signals applied to transistors, diodes, switches and the like, in the external circuit.

[00287] The variations in resistance, R, and inductance, L, of an inductive element at the resonant frequency may be only partially compensated or not compensated at all. Adequate system performance may thus be preserved by tolerances designed into other system components or specifications. Partial adjustments, realized using fewer tunable components or less capable tunable components, may be sufficient.

[00288] Matching-circuit architectures may be designed that achieve the desired variability of the impedance matching circuit under high-power conditions, while minimizing the voltage/current rating requirements on its tunable elements and achieving a finer (i.e. more precise, with higher resolution) overall tunability. The topology of the circuit matching a variable inductive element to an impedance, Z0, may include appropriate combinations and placements of fixed and variable elements, so that the voltage/current requirements for the variable components may be reduced and the desired tuning range may be covered with finer tuning resolution. The voltage/current requirements may be reduced on components that are not variable.

[00289] The disclosed impedance matching architectures and techniques may be used to achieve the following:

- To maximize the power delivered to, or to minimize impedance mismatches between, the source low-loss inductive elements (and any other systems wirelessly coupled to them) from the power driving generators.
- To maximize the power delivered from, or to minimize impedance mismatches between, the device low-loss inductive elements (and any other systems wirelessly coupled to them) to the power driven loads.
- To deliver a controlled amount of power to, or to achieve a certain impedance relationship between, the source low-loss inductive elements (and any other systems wirelessly coupled to them) from the power driving generators.
- To deliver a controlled amount of power from, or to achieve a certain impedance relationship between, the device low-loss inductive elements (and any other systems wirelessly coupled to them) to the power driven loads.

[00290] TOPOLOGIES FOR PRESERVATION OF MODE PROFILE (HIGH-Q)

[00291] The resonator structure may be designed to be connected to the generator or the load wirelessly (indirectly) or with a hard-wired connection (directly).

[00292] Consider a general indirectly coupled matching topology such as that shown by the block diagram in Fig. 28(a). There, an inductive element 2802 , labeled as (R,L) and represented by the circuit symbol for an inductor, may be any of the inductive elements discussed in this disclosure or in the references provided herein, and where an impedance-matching circuit 2402 includes or consists of parts A and B. B may be the part of the matching circuit that connects the impedance 2804 , Z0, to the rest of the circuit (the combination of A and the inductive element (A+(R,L)) via a wireless connection (an inductive or capacitive coupling mechanism).

[00293] The combination of A and the inductive element 2802 may form a resonator 102, which in isolation may support a high-Q resonator electromagnetic mode, with an associated current and charge distribution. The lack of a wired connection between the external circuit, Zo and B, and the resonator, A + (R,L), may ensure that the high-Q resonator electromagnetic mode and its current/charge distributions may take the form of its intrinsic (in-isolation) profile, so long as the degree of wireless coupling is not too large. That is, the electromagnetic mode, current/charge distributions, and thus the high-Q of the resonator may be automatically maintained using an indirectly coupled matching topology.

[00294] This matching topology may be referred to as indirectly coupled, or transformer-coupled, or inductively-coupled, in the case where inductive coupling is used between the external circuit and the inductor loop. This type of coupling scenario was used to couple the power supply to the source resonator and the device resonator to the light bulb in the demonstration of wireless energy transfer over mid-range distances described in the referenced Science article.

[00295] Next consider examples in which the inductive element may include the inductive element and any indirectly coupled systems. In this case, as disclosed above, and again because of the lack of a wired connection between the external circuit or the coupled systems and the resonator, the coupled systems may not, with good approximation for not-too-large degree of indirect coupling, affect the resonator electromagnetic mode profile and the current/charge distributions of the resonator. Therefore, an indirectly-coupled matching circuit may work equally well for any general inductive element as part of a resonator as well as for inductive elements wirelessly-coupled to other systems, as defined herein. Throughout this disclosure, the matching topologies we disclose refer to matching topologies for a general inductive element of this type, that is, where any additional systems may be indirectly coupled to the low-loss inductive element, and it is to be understood that those additional systems do not greatly affect the resonator electromagnetic mode profile and the current/charge distributions of the resonator.

[00296] Based on the argument above, in a wireless power transmission system of any number of coupled source resonators, device resonators and intermediate resonators the wireless magnetic (inductive) coupling between resonators does not affect the electromagnetic mode profile and the current/charge distributions of each one of the resonators. Therefore, when these resonators have a high (unloaded and unperturbed) Q, their (unloaded and unperturbed) Q may

be preserved in the presence of the wireless coupling. (Note that the loaded Q of a resonator may be reduced in the presence of wireless coupling to another resonator, but we may be interested in preserving the unloaded Q, which relates only to loss mechanisms and not to coupling/loading mechanisms.)

[00297] Consider a matching topology such as is shown in Fig. 28(b). The capacitors shown in Fig. 28(b) may represent capacitor circuits or networks. The capacitors shown may be used to form the resonator 102 and to adjust the frequency and/or impedance of the source and device resonators. This resonator 102 may be directly coupled to an impedance, Zo, using the ports labeled "terminal connections" 2808. Fig. 28(c) shows a generalized directly coupled matching topology, where the impedance-matching circuit 2602 includes or consists of parts A, B and C. Here, circuit elements in A, B and C may be considered part of the resonator 102 as well as part of the impedance matching 2402 (and frequency tuning) topology. B and C may be the parts of the matching circuit 2402 that connect the impedance Z0 2804 (or the network terminals) to the rest of the circuit (A and the inductive element) via a single wire connection each. Note that B and C could be empty (short-circuits). If we disconnect or open circuit parts B and C (namely those single wire connections), then, the combination of A and the inductive element (R,L) may form the resonator.

[00298] The high-Q resonator electromagnetic mode may be such that the profile of the voltage distribution along the inductive element has nodes, namely positions where the voltage is zero. One node may be approximately at the center of the length of the inductive element, such as the center of the conductor used to form the inductive element, (with or without magnetic materials) and at least one other node may be within A. The voltage distribution may be approximately anti-symmetric along the inductive element with respect to its voltage node. A high Q may be maintained by designing the matching topology (A, B, C) and/or the terminal voltages (V1, V2) so that this high-Q resonator electromagnetic mode distribution may be approximately preserved on the inductive element. This high-Q resonator electromagnetic mode distribution may be approximately preserved on the inductive element by preserving the voltage node (approximately at the center) of the inductive element. Examples that achieve these design goals are provided herein.

[00299] A, B, and C may be arbitrary (namely not having any special symmetry), and V1 and V2 may be chosen so that the voltage across the inductive element is symmetric (voltage node at the center inductive). These results may be achieved using simple matching circuits but potentially complicated terminal voltages, because a topology-dependent common-mode signal (V1+V2)/2 may be required on both terminals.

[00300] Consider an 'axis' that connects all the voltage nodes of the resonator, where again one node is approximately at the center of the length of the inductive element and the others within A. (Note that the 'axis' is really a set of points (the voltage nodes) within the electric-circuit topology and may not necessarily correspond to a linear axis of the actual physical structure. The 'axis' may align with a physical axis in cases where the physical structure has symmetry.) Two points of the resonator are electrically symmetric with respect to the 'axis', if the impedances seen between each of the two points and a point on the 'axis', namely a voltage-node point of the resonator, are the same.

[00301] B and C may be the same (C=B), and the two terminals may be connected to any two points of the resonator (A + (R,L)) that are electrically symmetric with respect to the 'axis' defined above and driven with opposite voltages (V2=-V1) as shown in Fig. 28(d). The two electrically symmetric points of the resonator 102 may be two electrically symmetric points on the inductor loop. The two electrically symmetric points of the resonator may be two electrically symmetric points inside A. If the two electrically symmetric points, (to which each of the equal parts B and C is connected), are inside A, A may need to be designed so that these electrically-symmetric points are accessible as connection points within the circuit. This topology may be referred to as a 'balanced drive' topology. These balanced-drive examples may have the advantage that any common-mode signal that may be present on the ground line, due to perturbations at the external circuitry or the power network, for example, may be automatically rejected (and may not reach the resonator). In some balanced-drive examples, this topology may require more components than other topologies.

[00302] In other examples, C may be chosen to be a short-circuit and the corresponding terminal to be connected to ground (V=0) and to any point on the electric-symmetry (zero-voltage) 'axis' of the resonator, and B to be connected to any other point of the resonator not on the electric-symmetry 'axis', as shown in Fig. 28(e). The ground-connected point on the electric-symmetry 'axis' may be the voltage node on the inductive element, approximately at the center of its conductor length. The ground-connected point on the electric-symmetry 'axis' may be inside the circuit A. Where the ground-connected point on the electric-symmetry 'axis' is inside A, A may need to be designed to include one such point on the electrical-symmetric 'axis' that is electrically accessible, namely where connection is possible.

[00303] This topology may be referred to as an 'unbalanced drive' topology. The approximately anti-symmetric voltage distribution of the electromagnetic mode along the inductive element may be approximately preserved, even though the resonator may not be driven exactly symmetrically. The reason is that the high Q and the large associated R-vs.-Zo mismatch necessitate that a small current may run through B and ground, compared to the much larger current that may flow inside the resonator, (A+(R,L)). In this scenario, the perturbation on the resonator mode may be weak and the location of me voltage node may stay at approximately the center location of the inductive element. These unbalanced-drive examples may have the advantage that they may be achieved using simple matching circuits and that there is no restriction on the driving voltage at the V1 terminal. In some unbalanced-drive examples, additional designs may be required to reduce common-mode signals that may appear at the ground terminal.

[00304] The directly-coupled impedance-matching circuit, generally including or consisting of parts A, B and C, as shown in Fig. 28(c), may be designed so that the wires and components of the circuit do not perturb the electric and magnetic field profiles of the electromagnetic mode of the inductive element and/or the resonator and thus preserve the high resonator Q. The wires and metallic components of the circuit may be oriented to be perpendicular to the electric field lines of the electromagnetic mode. The wires and components

of the circuit may be placed in regions where the electric and magnetic field of the electromagnetic mode are weak.

[00305] TOPOLOGIES FOR ALLEVIATING LOW-SERIES-LOSS AND HIGH-CURRENT-RATING REQUIREMENTS ON ELEMENTS

[00306] If the matching circuit used to match a small resistance, R, of a low-loss inductive element to a larger characteristic impedance, Zo, of an external circuit may be considered lossless, then and the current flowing through the terminals is much smaller than the current flowing through the inductive element. Therefore, elements connected immediately in series with the terminals (such as in directly-coupled B, C (Fig. 28(c))) may not carry high currents. Then, even if the matching circuit has lossy elements, the resistive loss present in the elements in series with the terminals may not result in a significant reduction in the high-Q of the resonator. That is, resistive loss in those series elements may not significantly reduce the efficiency of power transmission from Zo to the inductive element or vice versa. Therefore, strict requirements for low-series-loss and/or high current-ratings may not be necessary for these components. In general, such reduced requirements may lead to a wider selection of components that may be designed into the high-Q and/or high-power impedance matching and resonator topologies. These reduced requirements may be especially helpful in expanding the variety of variable and/or high voltage and/or low-parallel-loss components that may be used in these high-Q and/or high-power impedance-matching circuits.

[00307] TOPOLOGIES FOR ALLEVIATING LOW-PARALLEL-LOSS AND HIGH-VOLTAGE-RATING REQUIREMENTS ON ELEMENTS

[00308] If, as above, the matching circuit used to match a small resistance, R, of a low-loss inductive element to a larger characteristic impedance, Zo, of an external circuit is lossless, then using the previous analysis,

and, for a low-loss (high-X/R) inductive element, the voltage across the terminals may be typically much smaller than the voltage across the inductive element. Therefore, elements connected immediately in parallel to the terminals may not need to withstand high voltages. Then, even if the matching circuit has lossy elements, the resistive loss present in the elements in parallel with the terminals may not result in a significant reduction in the high-Q of the resonator. That is, resistive loss in those parallel elements may not significantly reduce the efficiency of power transmission from Zo to the inductive element or vice versa. Therefore, strict requirements for low-parallel-loss and/or high voltage-ratings may not be necessary for these components. In general, such reduced requirements may lead to a wider selection of components that may be designed into the high-Q and/or high-power impedance matching and resonator topologies. These reduced requirements may be especially helpful in expanding the variety of variable and/or high current and/or low-series-loss components that may be used in these high-Q and/or high-power impedance-matching and resonator circuits.

[00309] Note that the design principles above may reduce currents and voltages on various elements differently, as they variously suggest the use of networks in series with Zo (such as directly-coupled B, C) or the use of networks in parallel with Z0. The preferred topology for a given application may depend on the availability of low-series-loss/high-current-rating or low-parallel-loss/high-voltage-rating elements.

[00310] COMBINATIONS OF FIXED AND VARIABLE ELEMENTS FOR ACHIEVING FINE TUNABILrrY AND ALLEVIATING HIGH-RATING REQUIREMENTS ON VARIABLE ELEMENTS

[00311] Circuit topologies

[00312] Variable circuit elements with satisfactory low-loss and high-voltage or current ratings may be difficult or expensive to obtain. In this disclosure, we describe impedance-matching topologies that may incorporate combinations of fixed and variable elements, such that large voltages or currents may be assigned to fixed elements in the circuit, which may be more likely to have adequate voltage and current ratings, and alleviating the voltage and current rating requirements on the variable elements in the circuit.

[00313] Variable circuit elements may have tuning ranges larger than those required by a given impedance-matching application and, in those cases, fine tuning resolution may be difficult to obtain using only such large-range elements. In this disclosure, we describe impedance-matching topologies that incorporate combinations of both fixed and variable elements, such that finer tuning resolution may be accomplished with the same variable elements.

[00314] Therefore, topologies using combinations of both fixed and variable elements may bring two kinds of advantages simultaneously: reduced voltage across, or current through, sensitive tuning components in the circuit and finer tuning resolution. Note that the maximum achievable tuning range may be related to the maximum reduction in voltage across, or current through, the tunable components in the circuit designs.

[00315] Element topologies

[00316] A single variable circuit-element (as opposed to the network of elements discussed above) may be implemented by a topology using a combination of fixed and variable components, connected in series or in parallel, to achieve a reduction in the rating requirements of the variable components and a finer tuning resolution. This can be demonstrated mathematically by the fact that:

where X|SubscriPt| is any element value (e.g. capacitance, inductance), X is voltage or current, and the "+ sign" denotes the appropriate (series-addition or parallel-addition) combination of elements. Note that the subscript format for X|subscript|, is chosen to easily distinguish it from the radius of the area enclosed by a circular inductive element (e.g. x, x1, etc.).

[00317] Furthermore, this principle may be used to implement a variable electric element of a certain type (e.g. a capacitance or inductance) by using a variable element of a different type, if the latter is combined appropriately with other fixed elements.

[00318] In conclusion, one may apply a topology optimization algorithm mat decides on the required number, placement, type and values of fixed and variable elements with the required tunable range as an optimization constraint and the minimization of the currents and/or voltages on the variable elements as the optimization objective.

[00319] EXAMPLES

[00320] In the following schematics, we show different specific topology implementations for impedance matching to and resonator designs for a low-loss inductive element. In addition, we indicate for each topology: which of the principles described above are used, the equations giving the values of the variable elements that may be used to achieve the matching, and the range of the complex impedances that may be matched (using both inequalities and a Smith-chart description). For these examples, we assume that Z0 is real, but an extension to a characteristic impedance with a non-zero imaginary part is straightforward, as it implies only a small adjustment in the required values of the components of the matching network. We will use the convention that the subscript, n, on a quantity implies normalization to (division by) Z0.

[00321] Fig. 29 shows two examples of a transformer-coupled impedance-matching circuit, where the two tunable elements are a capacitor and the mutual inductance between two inductive elements. If we define respectively X2=?L2 for Fig. 29(a) and X2=?L2-1/?C2 for Fig. 29(b), and X = ?L, then the required values of the tunable elements are:

For the topology of Fig. 29(b), an especially straightforward design may be to choose X2=0. In that case, these topologies may match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 29(c).

[00322] Given a well pre-chosen fixed M, one can also use the above matching topologies with a tunable C2 instead.

[00323] Fig. 30 shows six examples (a)-(f) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and six examples (h)-(m) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 30(a),(b),(c),(h),(i),(j), a common-mode signal may be required at the two terminals to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(c). For the symmetric topologies of Figs. 30(d),(e),(f),(k),(l),(m), the two terminals may need to be driven anti-symmetrically (balanced drive) to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(d). It will be appreciated that a network of capacitors, as used herein, may in general refer to any circuit topology including one or more capacitors, including without limitation any of the circuits specifically disclosed herein using capacitors, or any other equivalent or different circuit structure(s), unless another meaning is explicitly provided or otherwise clear from the context.

[00324] Let us define respectively Z=R+j?L for Figs. 30(a),(d),(h),(k), Z=R+j?L+l/j?C3 for Figs. 30(b),(e),(i),(l), and Z=(R+j?L)||(l/j?C3) for Figs. 30(c),(f),(j),(m), where the symbol "||" means "the parallel combination of, and then R = Re{Z}, X = Im{Z}. Then, for Figs.30(a)-(f) the required values of the tunable elements may be given by:

and these topologies can match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 30(g). For Figs,30(h)-(m) the required values of the tunable elements may be given by:

[00325] Fig. 31 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 31(a),(b),(c),(e),(f),(g), the ground terminal is connected between two equal-value capacitors, 2C1, (namely on the axis of symmetry of the main resonator) to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00326] Let us define respectively Z=R+j?L for Figs. 3 l(a),(e), Z=R+j?L+l/j?C3 for Figs. 31(b),(f), and Z=(R+j?L)||(1/j?C3) for Fig. 31(c),(g), and then R = Re{Z}, X = Im{Z}. Then, for Figs.31(a)-(c) the required values of the tunable elements may be given by:

and these topologies can match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 31 (d). For Figs.31(e)-(g) the required values of the tunable elements may be given by:

[00327] Fig. 32 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 32(a),(b),(c),(e),(f),(g), the ground terminal may be connected at the center of the inductive element to preserve the voltage node of the resonator at that point and thus the high Q. Note that these example may be described as implementations of the general topology shown in Fig. 28(e).

[00328] Let us define respectively Z=R+j?L for Fig. 32(a), Z=R+j?L+1/j?C3 for Fig. 32(b), and Z=(R+j?L)??(1/j?C3) for Fig. 32(c), and then R = Re{Z}, X = Im{Z}. Then, for Figs.32(a)-(c) the required values of the tunable elements may be given by:

where k is defined by M' = -kL', where V is the inductance of each half of the inductor loop and M' is the mutual inductance between the two halves, and these topologies can match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 32(d). For Figs.32(e)-(g) the required values of the tunable elements may be given by:

[00329] In the circuits of Figs. 30, 31, 32, the capacitor, C2, or the inductor, L2, is (or

the two capacitors, 2C2, or the two inductors, L2/2, are) in series with the terminals and may not need to have very low series-loss or withstand a large current.

[00330] Fig. 33 shows six examples (a)-(f) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and six examples (h)-(m) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 33(a),(b),(c),(h),(i),(j), a common-mode signal may be required at the two terminals to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(c), where B and C are short-circuits and A is not balanced. For the symmetric topologies of Figs. 33(d),(e),(f),(k),(l),(m), the two terminals may need to be driven anti-symmetrically (balanced drive) to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(d), where B and C are short-circuits and A is balanced.

[00331] Let us define respectively Z=R+j?L for Figs. 33(a),(d),(h),(k), Z=R+j?L+1/j?C3 for Figs. 33(b),(e),(i),(1), and Z=(R+j?L)||(1/j?C3) for Figs. 33(c),(f),(j),(m), and then R = Re{Z}, X = Im{Z}. Then, for Figs.33(a)-(f) the required values of the tunable elements may be given by:

and these topologies can match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 33(g). For Figs.35(h)-(m) the required values of the tunable elements may be given by:

[00332] Fig. 34 shows three examples (a)-(c) of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors, and three examples (e)-(g) of directly-coupled impedance-matching circuits, where the two tunable elements are one capacitor and one inductor. For the topologies of Figs. 34(a),(b),(c),(e),(f),(g), the ground terminal is connected between two equal-value capacitors, 2C2, (namely on the axis of symmetry of the main resonator) to preserve the voltage node of the resonator at the center of the inductive element and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00333] Let us define respectively Z=R+j?L for Fig. 34(a),(e), Z=R+j?L+1/j?C3 for Fig. 34(b),(f), and Z=(R+j?L)||(1/j?C3) for Fig. 34(c),(g), and then R = Re{Z}, X = Im{Z} . Then, for Figs.34(a)-(c) the required values of the tunable elements may be given by:

and these topologies can match the impedances satisfying the inequalities:

which are shown by the area enclosed by the bold lines on the Smith chart of Fig. 34(d). For Figs.34(e)-(g) the required values of the tunable elements may be given by:

[00334] Fig. 35 shows three examples of directly-coupled impedance-matching circuits, where the two tunable elements are capacitors. For the topologies of Figs. 35, the ground terminal may be connected at the center of the inductive element to preserve the voltage node of the resonator at that point and thus the high Q. Note that these examples may be described as implementations of the general topology shown in Fig. 28(e).

[00335] Let us define respectively Z=R+j?L for Fig. 35(a), Z=R+j?L+l/j?C3 for Fig. 35(b), and Z=(R+j?L)||(1/j?C3) for Fig. 35(c), and then R = Re{Z}, X = Im{Z} . Then, the required values of the tunable elements may be given by:

where and k is defined by M' = -kL', where L' is the inductance of each half of the inductive element and M' is the mutual inductance between the two halves. These topologies can match the impedances satisfying the inequalities:

f

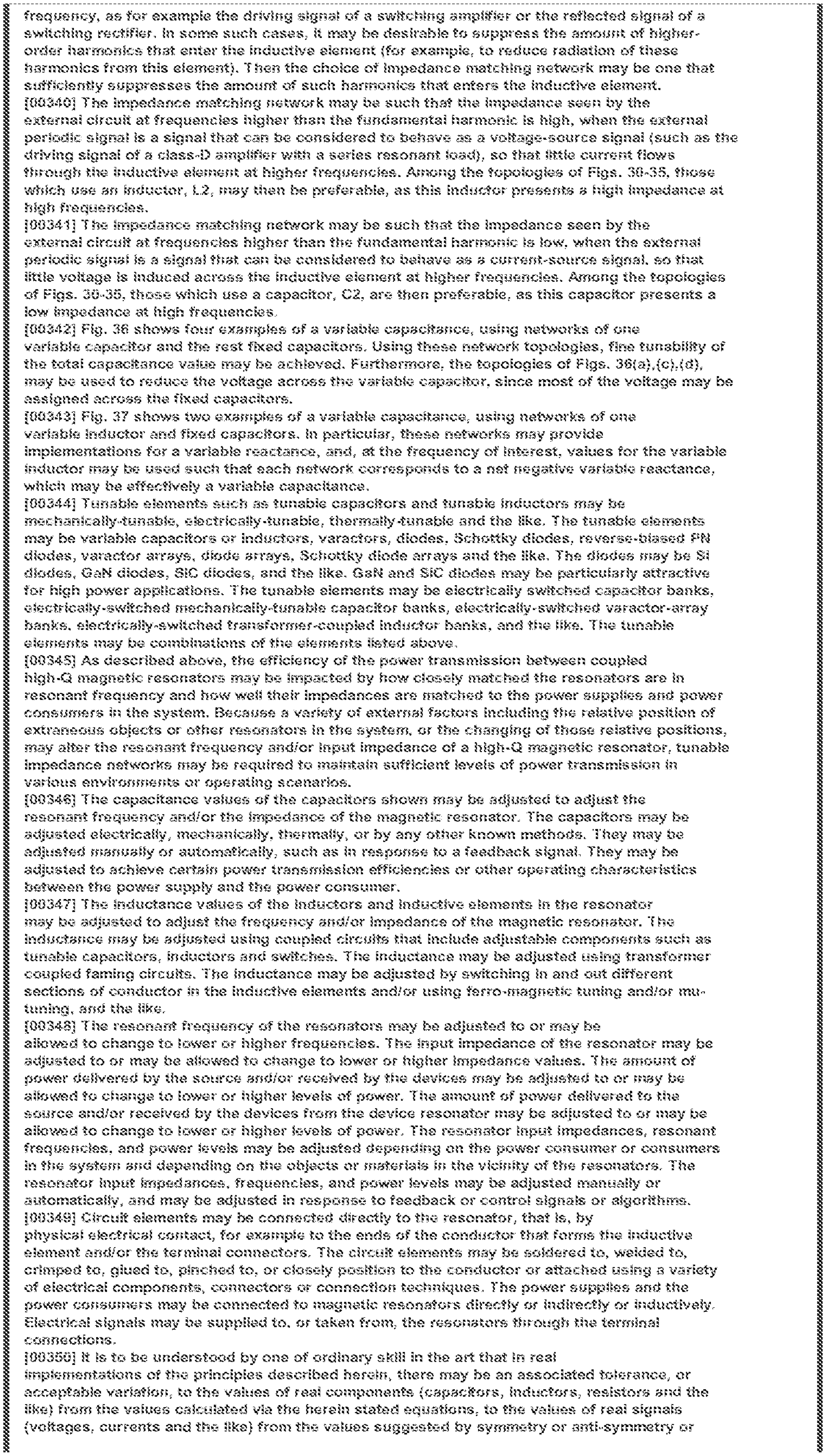
which are shown by the area enclosed by the bold lines on the three Smith charts shown in Fig. 35(d) for k=0, Fig. 35(e) for k=0.05, and Fig. 35(f) for k=1. Note that for 0<1 there are two disconnected regions of the Smith chart that this topology can match.

[00336] In the circuits of Figs.33, 34, 35, the capacitor, C2, or the inductor, L2, is (or one of the two capacitors, 2C2, or one of the two inductors, 2L2, are) in parallel with the terminals and thus may not need to have a high voltage-rating. In the case of two capacitors, 2C2, or two inductors, 2L2, both may not need to have a high voltage-rating, since approximately the same current flows through them and thus they experience approximately the same voltage across them.

[00337] For the topologies of Figs. 30-35, where a capacitor, C3, is used, the use of the capacitor, C3, may lead to finer tuning of the frequency and the impedance. For the topologies of Figs. 30-35, the use of the fixed capacitor, C3, in series with the inductive element may ensure that a large percentage of the high inductive-element voltage will be across this fixed capacitor, C3, thus potentially alleviating the voltage rating requirements for the other elements of the impedance matching circuit, some of which may be variable. Whether or not such topologies are preferred depends on the availability, cost and specifications of appropriate fixed and tunable components.

[00338] In all the above examples, a pair of equal-value variable capacitors without a common terminal may be implemented using ganged-type capacitors or groups or arrays of varactors or diodes biased and controlled to tune their values as an ensemble. A pair of equal-value variable capacitors with one common terminal can be implemented using a tunable butterfly-type capacitor or any other tunable or variable capacitor or group or array of varactors or diodes biased and controlled to tune their capacitance values as an ensemble.

[00339] Another criterion which may be considered upon the choice of the impedance matching network is the response of the network to different frequencies than the desired operating frequency. The signals generated in the external circuit, to which the inductive element is coupled, may not be monochromatic at the desired frequency but periodic with the desired



frequency, as for example the driving signal of a switching amplifier or the reflected signal of a switching rectifier. In some such cases, it may be desirable to suppress the amount of higher-order harmonics that enter the inductive element (for example, to reduce radiation of these harmonics from this element). Then the choice of impedance matching network may be one that sufficiently suppresses the amount of such harmonics that enters the inductive element.

[00340] The impedance matching network may be such that the impedance seen by the external circuit at frequencies higher than the fundamental harmonic is high, when the external periodic signal is a signal that can be considered to behave as a voltage-source signal (such as the driving signal of a class-D amplifier with a series resonant load), so that little current flows through the inductive element at higher frequencies. Among the topologies of Figs. 30-35, those which use an inductor, L2, may then be preferable, as this inductor presents a high impedance at high frequencies.

[00341] The impedance matching network may be such that the impedance seen by the external circuit at frequencies higher than the fundamental harmonic is low, when the external periodic signal is a signal that can be considered to behave as a current-source signal, so that little voltage is induced across the inductive element at higher frequencies. Among the topologies of Figs. 30-35, those which use a capacitor, C2, are then preferable, as this capacitor presents a low impedance at high frequencies.

[00342] Fig. 36 shows four examples of a variable capacitance, using networks of one variable capacitor and the rest fixed capacitors. Using these network topologies, fine tunability of the total capacitance value may be achieved. Furthermore, the topologies of Figs. 36(a),(c),(d), may be used to reduce the voltage across the variable capacitor, since most of the voltage may be assigned across the fixed capacitors.

[00343] Fig. 37 shows two examples of a variable capacitance, using networks of one variable inductor and fixed capacitors. In particular, these networks may provide implementations for a variable reactance, and, at the frequency of interest, values for the variable inductor may be used such that each network corresponds to a net negative variable reactance, which may be effectively a variable capacitance.

[00344] Tunable elements such as tunable capacitors and tunable inductors may be mechanically-tunable, electrically-tunable, thermally-tunable and the like. The tunable elements may be variable capacitors or inductors, varactors, diodes, Schottky diodes, reverse-biased PN diodes, varactor arrays, diode arrays, Schottky diode arrays and the like. The diodes may be Si diodes, GaN diodes, SiC diodes, and the like. GaN and SiC diodes may be particularly attractive for high power applications. The tunable elements may be electrically switched capacitor banks, electrically-switched mechanically-tunable capacitor banks, electrically-switched varactor-array banks, electrically-switched transformer-coupled inductor banks, and the like. The tunable elements may be combinations of the elements listed above.

[00345] As described above, the efficiency of the power transmission between coupled high-Q magnetic resonators may be impacted by how closely matched the resonators are in resonant frequency and how well their impedances are matched to the power supplies and power consumers in the system. Because a variety of external factors including the relative position of extraneous objects or other resonators in the system, or the changing of those relative positions, may alter the resonant frequency and/or input impedance of a high-Q magnetic resonator, tunable impedance networks may be required to maintain sufficient levels of power transmission in various environments or operating scenarios.

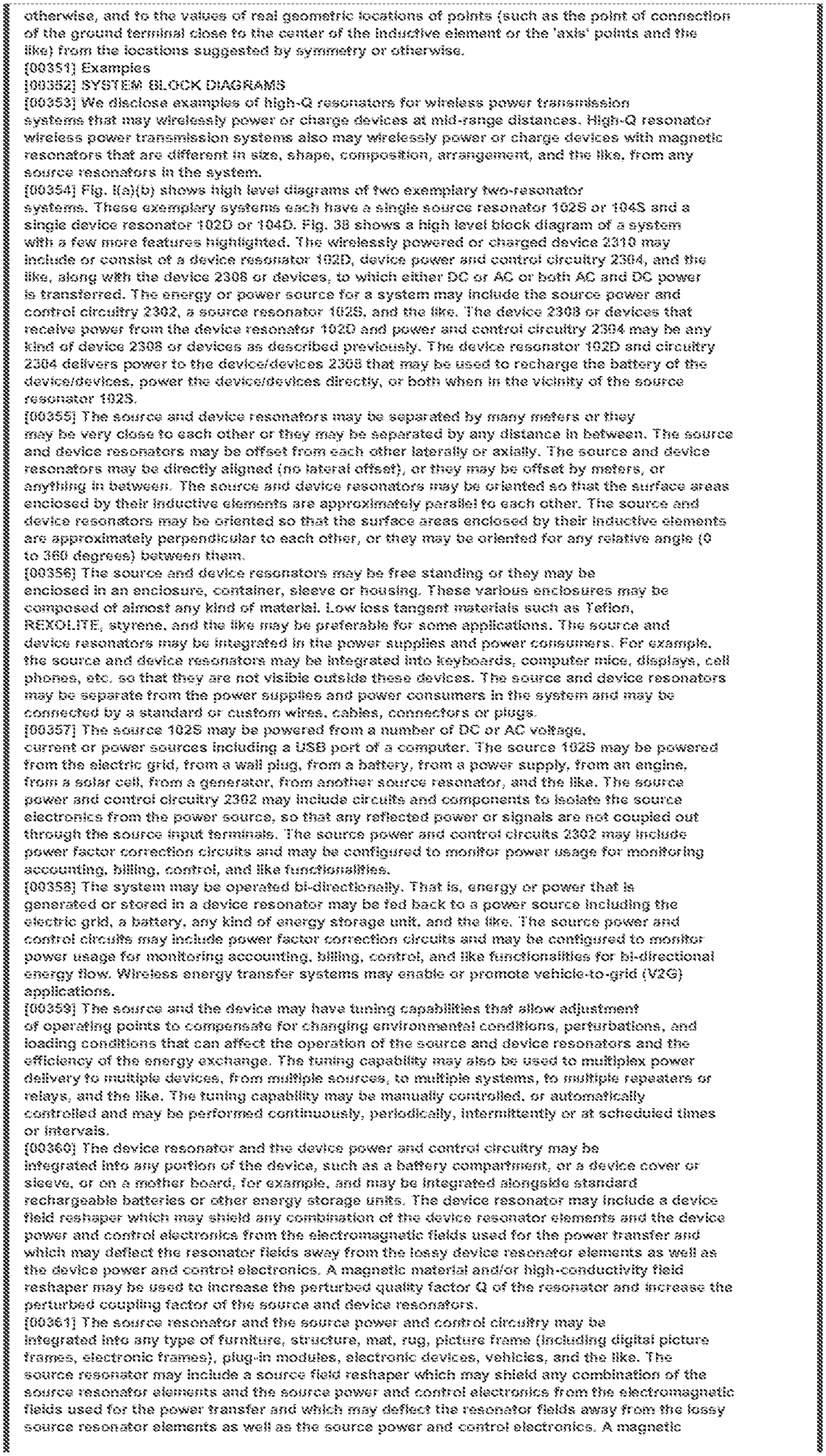
[00346] The capacitance values of the capacitors shown may be adjusted to adjust the resonant frequency and/or the impedance of the magnetic resonator. The capacitors may be adjusted electrically, mechanically, thermally, or by any other known methods. They may be adjusted manually or automatically, such as in response to a feedback signal. They may be adjusted to achieve certain power transmission efficiencies or other operating characteristics between the power supply and the power consumer.

[00347] The inductance values of the inductors and inductive elements in the resonator may be adjusted to adjust the frequency and/or impedance of the magnetic resonator. The inductance may be adjusted using coupled circuits that include adjustable components such as tunable capacitors, inductors and switches. The inductance may be adjusted using transformer coupled faming circuits. The inductance may be adjusted by switching in and out different sections of conductor in the inductive elements and/or using ferro-magnetic tuning and/or mu-tuning, and the like.

[00348] The resonant frequency of the resonators may be adjusted to or may be allowed to change to lower or higher frequencies. The input impedance of the resonator may be adjusted to or may be allowed to change to lower or higher impedance values. The amount of power delivered by the source and/or received by the devices may be adjusted to or may be allowed to change to lower or higher levels of power. The amount of power delivered to the source and/or received by the devices from the device resonator may be adjusted to or may be allowed to change to lower or higher levels of power. The resonator input impedances, resonant frequencies, and power levels may be adjusted depending on the power consumer or consumers in the system and depending on the objects or materials in the vicinity of the resonators. The resonator input impedances, frequencies, and power levels may be adjusted manually or automatically, and may be adjusted in response to feedback or control signals or algorithms.

[00349] Circuit elements may be connected directly to the resonator, that is, by physical electrical contact, for example to the ends of the conductor that forms the inductive element and/or the terminal connectors. The circuit elements may be soldered to, welded to, crimped to, glued to, pinched to, or closely position to the conductor or attached using a variety of electrical components, connectors or connection techniques. The power supplies and the power consumers may be connected to magnetic resonators directly or indirectly or inductively. Electrical signals may be supplied to, or taken from, the resonators through the terminal connections.

[00350] It is to be understood by one of ordinary skill in the art that in real implementations of the principles described herein, there may be an associated tolerance, or acceptable variation, to the values of real components (capacitors, inductors, resistors and the like) from the values calculated via the herein stated equations, to the values of real signals (voltages, currents and the like) from the values suggested by symmetry or anti-symmetry or



otherwise, and to the values of real geometric locations of points (such as the point of connection of the ground terminal close to the center of the inductive element or the 'axis' points and the like) from the locations suggested by symmetry or otherwise.

[00351] Examples

[00352] SYSTEM BLOCK DIAGRAMS

[00353] We disclose examples of high-Q resonators for wireless power transmission systems that may wirelessly power or charge devices at mid-range distances. High-Q resonator wireless power transmission systems also may wirelessly power or charge devices with magnetic resonators that are different in size, shape, composition, arrangement, and the like, from any source resonators in the system.

[00354] Fig. l(a)(b) shows high level diagrams of two exemplary two-resonator systems. These exemplary systems each have a single source resonator 102S or 104S and a single device resonator 102D or 104D. Fig. 38 shows a high level block diagram of a system with a few more features highlighted. The wirelessly powered or charged device 2310 may include or consist of a device resonator 102D, device power and control circuitry 2304, and the like, along with the device 2308 or devices, to which either DC or AC or both AC and DC power is transferred. The energy or power source for a system may include the source power and control circuitry 2302, a source resonator 102S, and the like. The device 2308 or devices that receive power from the device resonator 102D and power and control circuitry 2304 may be any kind of device 2308 or devices as described previously. The device resonator 102D and circuitry 2304 delivers power to the device/devices 2308 that may be used to recharge the battery of the device/devices, power the device/devices directly, or both when in the vicinity of the source resonator 102S.

[00355] The source and device resonators may be separated by many meters or they may be very close to each other or they may be separated by any distance in between. The source and device resonators may be offset from each other laterally or axially. The source and device resonators may be directly aligned (no lateral offset), or they may be offset by meters, or anything in between. The source and device resonators may be oriented so that the surface areas enclosed by their inductive elements are approximately parallel to each other. The source and device resonators may be oriented so that the surface areas enclosed by their inductive elements are approximately perpendicular to each other, or they may be oriented for any relative angle (0 to 360 degrees) between them.

[00356] The source and device resonators may be free standing or they may be enclosed in an enclosure, container, sleeve or housing. These various enclosures may be composed of almost any kind of material. Low loss tangent materials such as Teflon, REXOLITE, styrene, and the like may be preferable for some applications. The source and device resonators may be integrated in the power supplies and power consumers. For example, the source and device resonators may be integrated into keyboards, computer mice, displays, cell phones, etc. so that they are not visible outside these devices. The source and device resonators may be separate from the power supplies and power consumers in the system and may be connected by a standard or custom wires, cables, connectors or plugs.

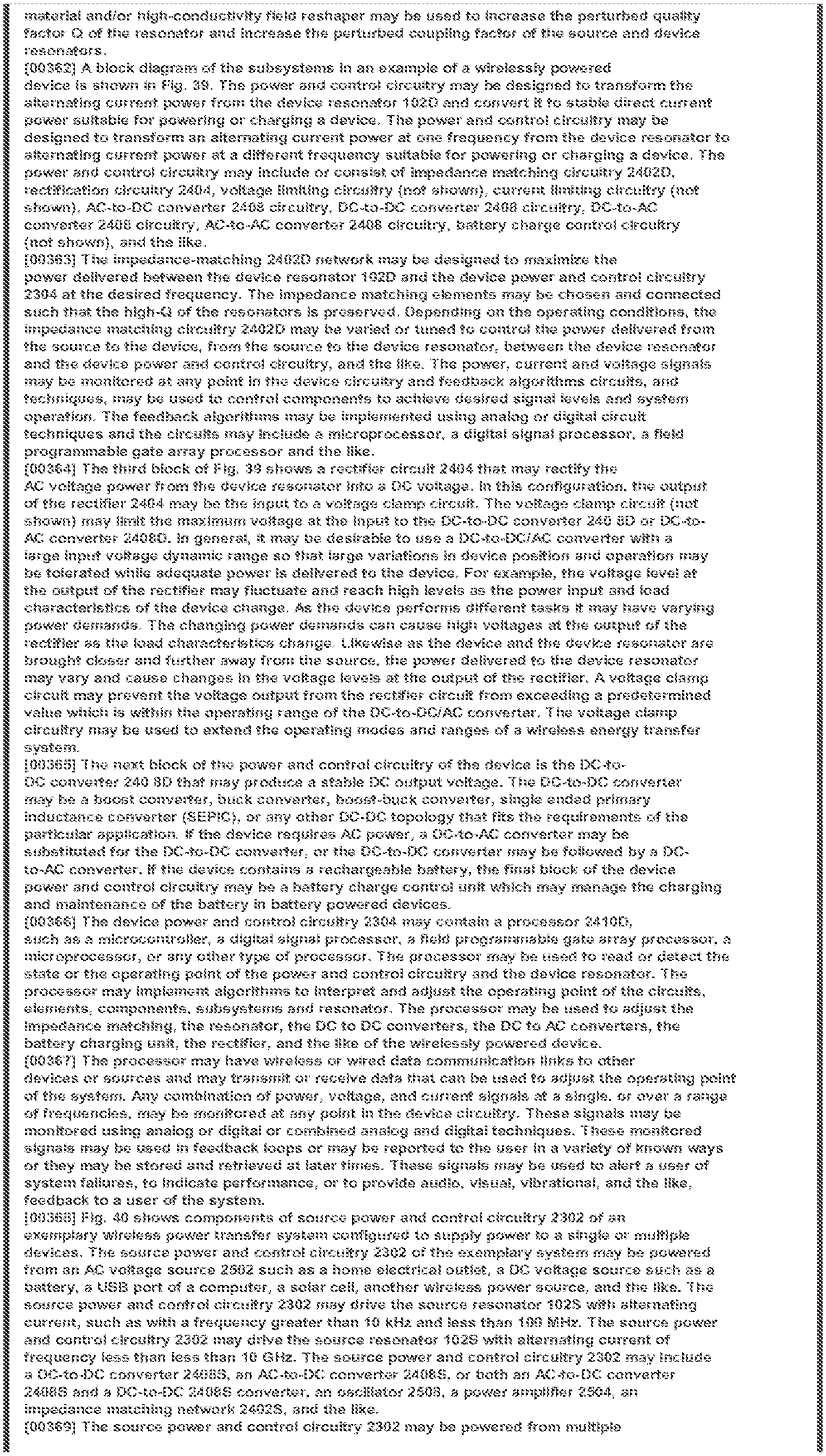
[00357] The source 102S may be powered from a number of DC or AC voltage, current or power sources including a USB port of a computer. The source 102S may be powered from the electric grid, from a wall plug, from a battery, from a power supply, from an engine, from a solar cell, from a generator, from another source resonator, and the like. The source power and control circuitry 2302 may include circuits and components to isolate the source electronics from the power source, so that any reflected power or signals are not coupled out through the source input terminals. The source power and control circuits 2302 may include power factor correction circuits and may be configured to monitor power usage for monitoring accounting, billing, control, and like functionalities.

[00358] The system may be operated bi-directionally. That is, energy or power that is generated or stored in a device resonator may be fed back to a power source including the electric grid, a battery, any kind of energy storage unit, and the like. The source power and control circuits may include power factor correction circuits and may be configured to monitor power usage for monitoring accounting, billing, control, and like functionalities for bi-directional energy flow. Wireless energy transfer systems may enable or promote vehicle-to-grid (V2G) applications.

[00359] The source and the device may have tuning capabilities that allow adjustment of operating points to compensate for changing environmental conditions, perturbations, and loading conditions that can affect the operation of the source and device resonators and the efficiency of the energy exchange. The tuning capability may also be used to multiplex power delivery to multiple devices, from multiple sources, to multiple systems, to multiple repeaters or relays, and the like. The tuning capability may be manually controlled, or automatically controlled and may be performed continuously, periodically, intermittently or at scheduled times or intervals.

[00360] The device resonator and the device power and control circuitry may be integrated into any portion of the device, such as a battery compartment, or a device cover or sleeve, or on a mother board, for example, and may be integrated alongside standard rechargeable batteries or other energy storage units. The device resonator may include a device field reshaper which may shield any combination of the device resonator elements and the device power and control electronics from the electromagnetic fields used for the power transfer and which may deflect the resonator fields away from the lossy device resonator elements as well as the device power and control electronics. A magnetic material and/or high-conductivity field reshaper may be used to increase the perturbed quality factor Q of the resonator and increase the perturbed coupling factor of the source and device resonators.

[00361] The source resonator and the source power and control circuitry may be integrated into any type of furniture, structure, mat, rug, picture frame (including digital picture frames, electronic frames), plug-in modules, electronic devices, vehicles, and the like. The source resonator may include a source field reshaper which may shield any combination of the source resonator elements and the source power and control electronics from the electromagnetic fields used for the power transfer and which may deflect the resonator fields away from the lossy source resonator elements as well as the source power and control electronics. A magnetic



material and/or high-conductivity field reshaper may be used to increase the perturbed quality factor Q of the resonator and increase the perturbed coupling factor of the source and device resonators.

[00362] A block diagram of the subsystems in an example of a wirelessly powered device is shown in Fig. 39. The power and control circuitry may be designed to transform the alternating current power from the device resonator 102D and convert it to stable direct current power suitable for powering or charging a device. The power and control circuitry may be designed to transform an alternating current power at one frequency from the device resonator to alternating current power at a different frequency suitable for powering or charging a device. The power and control circuitry may include or consist of impedance matching circuitry 2402D, rectification circuitry 2404, voltage limiting circuitry (not shown), current limiting circuitry (not shown), AC-to-DC converter 2408 circuitry, DC-to-DC converter 2408 circuitry, DC-to-AC converter 2408 circuitry, AC-to-AC converter 2408 circuitry, battery charge control circuitry (not shown), and the like.

[00363] The impedance-matching 2402D network may be designed to maximize the power delivered between the device resonator 102D and the device power and control circuitry 2304 at the desired frequency. The impedance matching elements may be chosen and connected such that the high-Q of the resonators is preserved. Depending on the operating conditions, the impedance matching circuitry 2402D may be varied or tuned to control the power delivered from the source to the device, from the source to the device resonator, between the device resonator and the device power and control circuitry, and the like. The power, current and voltage signals may be monitored at any point in the device circuitry and feedback algorithms circuits, and techniques, may be used to control components to achieve desired signal levels and system operation. The feedback algorithms may be implemented using analog or digital circuit techniques and the circuits may include a microprocessor, a digital signal processor, a field programmable gate array processor and the like.

[00364] The third block of Fig. 39 shows a rectifier circuit 2404 that may rectify the AC voltage power from the device resonator into a DC voltage. In this configuration, the output of the rectifier 2404 may be the input to a voltage clamp circuit. The voltage clamp circuit (not shown) may limit the maximum voltage at the input to the DC-to-DC converter 240 8D or DC-to-AC converter 2408D. In general, it may be desirable to use a DC-to-DC/AC converter with a large input voltage dynamic range so that large variations in device position and operation may be tolerated while adequate power is delivered to the device. For example, the voltage level at the output of the rectifier may fluctuate and reach high levels as the power input and load characteristics of the device change. As the device performs different tasks it may have varying power demands. The changing power demands can cause high voltages at the output of the rectifier as the load characteristics change. Likewise as the device and the device resonator are brought closer and further away from the source, the power delivered to the device resonator may vary and cause changes in the voltage levels at the output of the rectifier. A voltage clamp circuit may prevent the voltage output from the rectifier circuit from exceeding a predetermined value which is within the operating range of the DC-to-DC/AC converter. The voltage clamp circuitry may be used to extend the operating modes and ranges of a wireless energy transfer system.

[00365] The next block of the power and control circuitry of the device is the DC-to-DC converter 240 8D that may produce a stable DC output voltage. The DC-to-DC converter may be a boost converter, buck converter, boost-buck converter, single ended primary inductance converter (SEPIC), or any other DC-DC topology that fits the requirements of the particular application. If the device requires AC power, a DC-to-AC converter may be substituted for the DC-to-DC converter, or the DC-to-DC converter may be followed by a DC-to-AC converter. If the device contains a rechargeable battery, the final block of the device power and control circuitry may be a battery charge control unit which may manage the charging and maintenance of the battery in battery powered devices.

[00366] The device power and control circuitry 2304 may contain a processor 2410D, such as a microcontroller, a digital signal processor, a field programmable gate array processor, a microprocessor, or any other type of processor. The processor may be used to read or detect the state or the operating point of the power and control circuitry and the device resonator. The processor may implement algorithms to interpret and adjust the operating point of the circuits, elements, components, subsystems and resonator. The processor may be used to adjust the impedance matching, the resonator, the DC to DC converters, the DC to AC converters, the battery charging unit, the rectifier, and the like of the wirelessly powered device.

[00367] The processor may have wireless or wired data communication links to other devices or sources and may transmit or receive data that can be used to adjust the operating point of the system. Any combination of power, voltage, and current signals at a single, or over a range of frequencies, may be monitored at any point in the device circuitry. These signals may be monitored using analog or digital or combined analog and digital techniques. These monitored signals may be used in feedback loops or may be reported to the user in a variety of known ways or they may be stored and retrieved at later times. These signals may be used to alert a user of system failures, to indicate performance, or to provide audio, visual, vibrational, and the like, feedback to a user of the system.

[00368] Fig. 40 shows components of source power and control circuitry 2302 of an exemplary wireless power transfer system configured to supply power to a single or multiple devices. The source power and control circuitry 2302 of the exemplary system may be powered from an AC voltage source 2502 such as a home electrical outlet, a DC voltage source such as a battery, a USB port of a computer, a solar cell, another wireless power source, and the like. The source power and control circuitry 2302 may drive the source resonator 102S with alternating current, such as with a frequency greater than 10 kHz and less than 100 MHz. The source power and control circuitry 2302 may drive the source resonator 102S with alternating current of frequency less than less than 10 GHz. The source power and control circuitry 2302 may include a DC-to-DC converter 2408S, an AC-to-DC converter 2408S, or both an AC-to-DC converter 2408S and a DC-to-DC 2408S converter, an oscillator 2508, a power amplifier 2504, an impedance matching network 2402S, and the like.

[00369] The source power and control circuitry 2302 may be powered from multiple

AC-or-DC voltage sources 2502 and may contain AC-to-DC and DC-to-DC converters 2408S to provide necessary voltage levels for the circuit components as well as DC voltages for the power amplifiers that may be used to drive the source resonator. The DC voltages may be adjustable and may be used to control the output power level of the power amplifier. The source may contain power factor correction circuitry.

[00370] The oscillator 2508 output may be used as the input to a power amplifier 2504 that drives the source resonator 102S. The oscillator frequency may be tunable and the amplitude of the oscillator signal may be varied as one means to control the output power level from the power amplifier. The frequency, amplitude, phase, waveform, and duty cycle of the oscillator signal may be controlled by analog circuitry, by digital circuitry or by a combination of analog and digital circuitry. The control circuitry may include a processor 241 OS, such as a microprocessor, a digital signal processor, a field programmable gate array processor, and the like.

[00371] The impedance matching blocks 2402 of the source and device resonators may be used to tune the power and control circuits and the source and device resonators. For example, tuning of these circuits may adjust for perturbation of the quality factor Q of the source or device resonators due to extraneous objects or changes in distance between the source and device in a system. Tuning of these circuits may also be used to sense the operating environment, control power flow to one or more devices, to control power to a wireless power network, to reduce power when unsafe or failure mode conditions are detected, and the like.

[00372] Any combination of power, voltage, and current signals may be monitored at any point in the source circuitry. These signals may be monitored using analog or digital or combined analog and digital techniques. These monitored signals may be used in feedback circuits or may be reported to the user in a variety of known ways or they may be stored and retrieved at later times. These signals may be used to alert a user to system failures, to alert a user to exceeded safety thresholds, to indicate performance, or to provide audio, visual, vibrational, and the like, feedback to a user of the system.

[00373] The source power and control circuitry may contain a processor. The processor may be used to read the state or the operating point of the power and control circuitry and the source resonator. The processor may implement algorithms to interpret and adjust the operating point of the circuits, elements, components, subsystems and resonator. The processor may be used to adjust the impedance matching, the resonator, the DC-to-DC converters, the AC-to-DC converters, the oscillator, the power amplifier of the source, and the like. The processor and adjustable components of the system may be used to implement frequency and/or time power delivery multiplexing schemes. The processor may have wireless or wired data communication links to devices and other sources and may transmit or receive data that can be used to adjust the operating point of the system.

[00374] Although detailed and specific designs are shown in these block diagrams, it should be clear to those skilled in the art that many different modifications and rearrangements of the components and building blocks are possible within the spirit of the exemplary system. The division of the circuitry was outlined for illustrative purposes and it should be clear to those skilled in the art that the components of each block may be further divided into smaller blocks or merged or shared. In equivalent examples the power and control circuitry may be composed of individual discrete components or larger integrated circuits. For example, the rectifier circuitry may be composed of discrete diodes, or use diodes integrated on a single chip. A multitude of other circuits and integrated devices can be substituted in the design depending on design criteria such as power or size or cost or application. The whole of the power and control circuitry or any portion of the source or device circuitry may be integrated into one chip.

[00375] The impedance matching network of the device and or source may include a capacitor or networks of capacitors, an inductor or networks of inductors, or any combination of capacitors, inductors, diodes, switches, resistors, and the like. The components of the impedance matching network may be adjustable and variable and may be controlled to affect the efficiency and operating point of the system. The impedance matching may be performed by controlling the connection point of the resonator, adjusting the permeability of a magnetic material, controlling a bias field, adjusting the frequency of excitation, and the like. The impedance matching may use or include any number or combination of varactors, varactor arrays, switched elements, capacitor banks, switched and tunable elements, reverse bias diodes, air gap capacitors, compression capacitors, BZT electrically tuned capacitors, MEMS-tunable capacitors, voltage variable dielectrics, transformer coupled tuning circuits, and the like. The variable components may be mechanically tuned, thermally tuned, electrically tuned, piezo-electrically tuned, and the like. Elements of the impedance matching may be silicon devices, gallium nitride devices, silicon carbide devices and the like. The elements may be chosen to withstand high currents, high voltages, high powers, or any combination of current, voltage and power. The elements may be chosen to be high-Q elements.

[00376] The matching and tuning calculations of the source may be performed on an external device through a USB port that powers the device. The device may be a computer a PDA or other computational platform.

[00377] A demonstration system used a source resonator, coupled to a device resonator, to wirelessly power/recharge multiple electronic consumer devices including, but not limited to, a laptop, a DVD player, a projector, a cell-phone, a display, a television, a projector, a digital picture frame, a light, a TV/DVD player, a portable music player, a circuit breaker, a hand-held tool, a personal digital assistant, an external battery charger, a mouse, a keyboard, a camera, an active load, and the like. A variety of devices may be powered simultaneously from a single device resonator. Device resonators may be operated simultaneously as source resonators. The power supplied to a device resonator may pass through additional resonators before being delivered to its intended device resonator.

[00378] Monitoring, Feedback and Control

[00379] So-called port parameter measurement circuitry may measure or monitor certain power, voltage, and current, signals in the system and processors or control circuits may adjust certain settings or operating parameters based on those measurements. In addition to these port parameter measurements, the magnitude and phase of voltage and current signals, and the magnitude of the power signals, throughout the system may be accessed to measure or monitor

the system performance. The measured signals referred to throughout this disclosure may be any combination of the port parameter signals, as well as voltage signals, current signals, power signals, and the like. These parameters may be measured using analog or digital signals, they may be sampled and processed, and they may be digitized or converted using a number of known analog and digital processing techniques. Measured or monitored signals may be used in feedback circuits or systems to control the operation of the resonators and/or the system. In general, we refer to these monitored or measured signals as reference signals, or port parameter measurements or signals, although they are sometimes also referred to as error signals, monitor signals, feedback signals, and the like. We will refer to the signals that are used to control circuit elements such as the voltages used to drive voltage controlled capacitors as the control signals.

[00380] In some cases the circuit elements may be adjusted to achieve a specified or predetermined impedance value for the source and device resonators. In other cases the impedance may be adjusted to achieve a desired impedance value for the source and device resonators when the device resonator is connected to a power consumer or consumers. In other cases the impedance may be adjusted to mitigate changes in the resonant frequency, or impedance or power level changes owing to movement of the source and/or device resonators, or changes in the environment (such as the movement of interacting materials or objects) in the vicinity of the resonators. In other cases the impedance of the source and device resonators may be adjusted to different impedance values.

[00381] The coupled resonators may be made of different materials and may include different circuits, components and structural designs or they may be the same. The coupled resonators may include performance monitoring and measurement circuitry, signal processing and control circuitry or a combination of measurement and control circuitry. Some or all of the high-Q magnetic resonators may include tunable impedance circuits. Some or all of the high-Q magnetic resonators may include automatically controlled tunable impedance circuits.

[00382] Fig. 41 shows a magnetic resonator with port parameter measurement circuitry 3802 configured to measure certain parameters of the resonator. The port parameter measurement circuitry may measure the input impedance of the structure, or the reflected power. Port parameter measurement circuits may be included in the source and/or device resonator designs and may be used to measure two port circuit parameters such as S-parameters (scattering parameters), Z-parameters (impedance parameters), Y-parameters (admittance parameters), T-parameters (transmission parameters), H-parameters (hybrid parameters), ABCD-parameters (chain, cascade or transmission parameters), and the like. These parameters may be used to describe the electrical behavior of linear electrical networks when various types of signals are applied.

[00383] Different parameters may be used to characterize the electrical network under different operating or coupling scenarios. For example, S-parameters may be used to measure matched and unmatched loads. In addition, the magnitude and phase of voltage and current signals within the magnetic resonators and/or within the sources and devices themselves may be monitored at a variety of points to yield system performance information. This information may be presented to users of the system via a user interface such as a light, a read-out, a beep, a noise, a vibration or the like, or it may be presented as a digital signal or it may be provided to a processor in the system and used in the automatic control of the system. This information may be logged, stored, or may be used by higher level monitoring and control systems.

[00384] Fig. 42 shows a circuit diagram of a magnetic resonator where the tunable impedance network may be realized with voltage controlled capacitors 3902 or capacitor networks. Such an implementation may be adjusted, tuned or controlled by electrical circuits and/or computer processors, such as a programmable voltage source 3908, and the like. For example, the voltage controlled capacitors may be adjusted in response to data acquired by the port parameter measurement circuitry 3802 and processed by a measurement analysis and control algorithm subsystem 3904. Reference signals may be derived from the port parameter measurement circuitry or other monitoring circuitry designed to measure the degree of deviation from a desired system operating point. The measured reference signals may include voltage, current, complex-impedance, reflection coefficient, power levels and the like, at one or several points in the system and at a single frequency or at multiple frequencies.

[00385] The reference signals may be fed to measurement analysis and control algorithm subsystem modules that may generate control signals to change the values of various components in a tunable impedance matching network. The control signals may vary the resonant frequency and/or the input impedance of the magnetic resonator, or the power level supplied by the source, or the power level drawn by the device, to achieve the desired power exchange between power supplies/generators and power drains/loads.

[00386] Adjustment algorithms may be used to adjust the frequency and/or impedance of the magnetic resonators. The algorithms may take in reference signals related to the degree of deviation from a desired operating point for the system and output correction or control signals related to that deviation that control variable or tunable elements of the system to bring the system back towards the desired operating point or points. The reference signals for the magnetic resonators may be acquired while the resonators are exchanging power in a wireless power transmission system, or they may be switched out of the circuit during system operation. Corrections to the system may be applied or performed continuously, periodically, upon a threshold crossing, digitally, using analog methods, and the like.

[00387] Fig. 43 shows an end-to-end wireless power transmission system. Both the source and the device may include port measurement circuitry 3802 and a processor 2410. The box labeled "coupler/switch" 4002 indicates that the port measurement circuitry 3802 may be connected to the resonator 102 by a directional coupler or a switch, enabling the measurement, adjustment and control of the source and device resonators to take place in conjunction with, or separate from, the power transfer functionality.

[00388] The port parameter measurement and/or processing circuitry may reside with some, any, or all resonators in a system. The port parameter measurement circuitry may utilize portions of the power transmission signal or may utilize excitation signals over a range of frequencies to measure the source/device resonator response (i.e. transmission and reflection between any two ports in the system), and may contain amplitude and/or phase information. Such measurements may be achieved with a swept single frequency signal or a multi-frequency

signal. The signals used to measure and monitor the resonators and the wireless power transmission system may be generated by a processor or processors and standard input/output (I/O) circuitry including digital to analog converters (DACs), analog to digital converters (ADCs), amplifiers, signal generation chips, passive components and the like. Measurements may be achieved using test equipment such as a network analyzer or using customized circuitry. The measured reference signals may be digitized by ADCs and processed using customized algorithms running on a computer, a microprocessor, a DSP chip, an ASIC, and the like. The measured reference signals may be processed in an analog control loop.

[00389] The measurement circuitry may measure any set of two port parameters such as S-parameters, Y-parameters, Z-parameters, H-parameters, G-parameters, T-parameters, ABCD-parameters, and the like. Measurement circuitry may be used to characterize current and voltage signals at various points in the drive and resonator circuitry, the impedance and/or admittance of the source and device resonators at opposite ends of the system, i.e. looking into the source resonator matching network ("port 1" in Fig. 43) towards the device and vice versa.

[00390] The device may measure relevant signals and/or port parameters, interpret the measurement data, and adjust its matching network to optimize the impedance looking into the coupled system independently of the actions of the source. The source may measure relevant port parameters, interpret the measurement data, and adjust its matching network to optimize the impedance looking into the coupled system independently of the actions of the device.

[00391] - Fig. 43 shows a block diagram of a source and device in a wireless power transmission system. The system may be configured to execute a control algorithm that actively adjusts the tuning/matching networks in either of or both the source and device resonators to optimize performance in the coupled system. Port measurement circuitry 3802S may measure signals in the source and communicate those signals to a processor 2410. A processor 2410 may use the measured signals in a performance optimization or stabilization algorithm and generate control signals based on the outputs of those algorithms. Control signals may be applied to variable circuit elements in the tuning/impedance matching circuits 2402S to adjust the source's operating characteristics, such as power in the resonator and coupling to devices. Control signals may be applied to the power supply or generator to turn the supply on or off, to increase or decrease the power level, to modulate the supply signal and the like.

[00392] The power exchanged between sources and devices may depend on a variety of factors. These factors may include the effective impedance of the sources and devices, the Q's of the sources and devices, the resonant frequencies of the sources and devices, the distances between sources and devices, the interaction of materials and objects in the vicinity of sources and devices and the like. The port measurement circuitry and processing algorithms may work in concert to adjust the resonator parameters to maximize power transfer, to hold the power transfer constant, to controllably adjust the power transfer, and the like, under both dynamic and steady state operating conditions.

[00393] Some, all or none of the sources and devices in a system implementation may include port measurement circuitry 3802S and processing 2410 capabilities. Fig. 44 shows an end-to-end wireless power transmission system in which only the source 102S contains port measurement circuitry 3802 and a processor 2410S. In this case, the device resonator 102D operating characteristics may be fixed or may be adjusted by analog control circuitry and without the need for control signals generated by a processor.

[00394] Fig. 45 shows an end-to-end wireless power transmission system. Both the source and the device may include port measurement circuitry 3802 but in the system of Fig. 45, only the source contains a processor 2410S. The source and device may be in communication with each other and the adjustment of certain system parameters may be in response to control signals that have been wirelessly communicated, such as though wireless communications circuitry 4202, between the source and the device. The wireless communication channel 4204 may be separate from the wireless power transfer channel 4208, or it may be the same. That is, the resonators 102 used for power exchange may also be used to exchange information. In some cases, information may be exchanged by modulating a component a source or device circuit and sensing that change with port parameter or other monitoring equipment.

[00395] Implementations where only the source contains a processor 2410 may be beneficial for multi-device systems where the source can handle all of the tuning and adjustment "decisions" and simply communicate the control signals back to the device(s). This implementation may make the device smaller and cheaper because it may eliminate the need for, or reduce the required functionality of, a processor in the device. A portion of or an entire data set from each port measurement at each device may be sent back to the source microprocessor for analysis, and the control instructions may be sent back to the devices. These communications may be wireless communications.

[00396] Fig. 46 shows an end-to-end wireless power transmission system. In this example, only the source contains port measurement circuitry 3802 and a processor 2410S. The source and device may be in communication, such as via wireless communication circuitry 4202, with each other and the adjustment of certain system parameters may be in response to control signals that have been wirelessly communicated between the source and the device.

[00397] Fig. 47 shows coupled electromagnetic resonators 102 whose frequency and impedance may be automatically adjusted using a processor or a computer. Resonant frequency tuning and continuous impedance adjustment of the source and device resonators may be implemented with reverse biased diodes, Schottky diodes and/or varactor elements contained within the capacitor networks shown as C1, C2, and C3 in Fig. 47. The circuit topology that was built and demonstrated and is described here is exemplary and is not meant to limit the discussion of automatic system tuning and control in any way. Other circuit topologies could be utilized with the measurement and control architectures discussed in this disclosure.

[00398] Device and source resonator impedances and resonant frequencies may be measured with a network analyzer 4402A-B, or by other means described above, and implemented with a controller, such as with Lab View 4404. The measurement circuitry or equipment may output data to a computer or a processor that implements feedback algorithms and dynamically adjusts the frequencies and impedances via a programmable DC voltage source.

[00399] In one arrangement, the reverse biased diodes (Schottky, semiconductor junction, and the like) used to realize the tunable capacitance drew very little DC current and

could be reverse biased by amplifiers having large series output resistances. This implementation may enable DC control signals to be applied directly to the controllable circuit elements in the resonator circuit while maintaining a very high-Q in the magnetic resonator.

[00400] C2 biasing signals may be isolated from C1 and/or C3 biasing signals with a DC blocking capacitor as shown in Fig. 47, if the required DC biasing voltages are different. The output of the biasing amplifiers may be bypassed to circuit ground to isolate RF voltages from the biasing amplifiers, and to keep non-fundamental RF voltages from being injected into the resonator. The reverse bias voltages for some of the capacitors may instead be applied through the inductive element in the resonator itself, because the inductive element acts as a short circuit at DC.

[00401] The port parameter measurement circuitry may exchange signals with a processor (including any required ADCs and D ACs) as part of a feedback or control system that is used to automatically adjust the resonant frequency, input impedance, energy stored or captured by the resonator or power delivered by a source or to a device load. The processor may also send control signals to tuning or adjustment circuitry in or attached to the magnetic resonator.

[00402] When utilizing varactors or diodes as tunable capacitors, it may be beneficial to place fixed capacitors in parallel and in series with the tunable capacitors operating at high reverse bias voltages in the tuning/matching circuits. This arrangement may yield improvements in circuit and system stability and in power handling capability by optimizing the operating voltages on the tunable capacitors.

[00403] Varactors or other reverse biased diodes may be used as a voltage controlled capacitor. Arrays of varactors may be used when higher voltage compliance or different capacitance is required than that of a single varactor component. Varactors may be arranged in an N by M array connected serially and in parallel and treated as a single two terminal component with different characteristics than the individual varactors in the array. For example, an N by N array of equal varactors where components in each row are connected in parallel and components in each column are connected in series may be used as a two terminal device with the same capacitance as any single varactor in the array but with a voltage compliance that is N . times that of a single varactor in the array. Depending on the variability and differences of parameters of the individual varactors in the array additional biasing circuits composed of resistors, inductors, and the like may be needed. A schematic of a four by four array of unbiased varactors 4502 that may be suitable for magnetic resonator applications is shown in Fig. 48.

[00404] Further improvements in system performance may be realized by careful selection of the fixed value capacitor(s) that are placed in parallel and/or in series with the tunable (varactor/diode/capacitor) elements. Multiple fixed capacitors that are switched in or out of the circuit may be able to compensate for changes in resonator Q's, impedances, resonant frequencies, power levels, coupling strengths, and the like, that might be encountered in test, development and operational wireless power transfer systems. Switched capacitor banks and other switched element banks may be used to assure the convergence to the operating frequencies and impedance values required by the system design.

[00405] An exemplary control algorithm for isolated and coupled magnetic resonators may be described for the circuit and system elements shown in Fig. 47. One control algorithm first adjusts each of the source and device resonator loops "in isolation", that is, with the other resonators in the system "shorted out" or "removed" from the system. For practical purposes, a resonator can be "shorted out" by making it resonant at a much lower frequency such as by maximizing the value of C1 and/or C3. This step effectively reduces the coupling between the resonators, thereby effectively reducing the system to a single resonator at a particular frequency and impedance.

[00406] Tuning a magnetic resonator in isolation includes varying the tunable elements in the tuning and matching circuits until the values measured by the port parameter measurement circuitry are at their predetermined, calculated or measured relative values. The desired values for the quantities measured by the port parameter measurement circuitry may be chosen based on the desired matching impedance, frequency, strong coupling parameter, and the like. For the exemplary algorithms disclosed below, the port parameter measurement circuitry measures S-parameters over a range of frequencies. The range of frequencies used to characterize the resonators may be a compromise between the system performance information obtained and computation/measurement speed. For the algorithms described below the frequency range may be approximately +/- 20% of the operating resonant frequency.

[00407] Each isolated resonator may be tuned as follows. First, short out the resonator not being adjusted. Next minimize C1, C2, and C3, in the resonator that is being characterized and adjusted. In most cases there will be fixed circuit elements in parallel with C1, C2, and C3, so this step does not reduce the capacitance values to zero. Next, start increasing C2 until the resonator impedance is matched to the "target" real impedance at any frequency in the range of measurement frequencies described above. The initial "target" impedance may be less than the expected operating impedance for the coupled system.

[00408] C2 may be adjusted until the initial "target" impedance is realized for a frequency in the measurement range. Then C1 and/or C3 may be adjusted until the loop is resonant at the desired operating frequency.

[00409] Each resonator may be adjusted according to the above algorithm. After tuning each resonator in isolation, a second feedback algorithm may be applied to optimize the resonant frequencies and/or input impedances for wirelessly transferring power in the coupled system.

[00410] The required adjustments to C1 and/or C2 and/or C3 in each resonator in the coupled system may be determined by measuring and processing the values of the real and imaginary parts of the input impedance from either and/or both "port(s)" shown in Fig. 43. For coupled resonators, changing the input impedance of one resonator may change the input impedance of the other resonator. Control and tracking algorithms may adjust one port to a desired operating point based on measurements at that port, and then adjust the other port based on measurements at that other port. These steps may be repeated until both sides converge to the desired operating point.

[00411] S-parameters may be measured at both the source and device ports and the

following series of measurements and adjustments may be made. In the description that follows, Z0 is an input impedance and may be the target impedance. In some cases Z0 is 50 ohms or is near 50 ohms. Z1 and Z2 are intermediate impedance values that may be the same value as Zo or may be different than Zo. Re{value} means the real part of a value and Im{value} means the imaginary part of a value.

[00412] An algorithm that may be used to adjust the input impedance and resonant frequency of two coupled resonators is set forth below:

1) Adjust each resonator "in isolation" as described above.
2) Adjust source C1/C3 until, at ?0, Re{S11} = (Z1 +/- eRe) as follows:
- If Re{Sll @?0 } > (Z1 + eRe), decrease C1/C3. If Re{S11 @?o } < (Zo - eRe), increase C1/C3.

3) Adjust source C2 until, at ?o, Im{S11} = (+/- e1m) as follows:
- If Im{S11 @ ?o} > e1m, decrease C2. If Im{S11 @ ?o} < - e1m , increase C2.

4) Adjust device C1/C3 until, at ?o, Re{S22} = (Z2 +/- eRe) as follows:
- If Re{S22 @ ?o} > (Z2 + eRe), decrease C1/C3. If Re{S22 @ ?o} < (Zo - eRe), increase C1/C3.

5) Adjust device C2 until, at ?o, Im{S22} = 0 as follows:
- If Im{S22 @ ?o} > e1m, decrease C2. If Im{S22 @ ?o } < -e1m, increase C2.

[00413] We have achieved a working system by repeating steps 1 -4 until both (Re{S11}, Im{S11}) and (Re{S22}, Im{S22}) converge-to ((Z0 +/- eRe), (+/- e1m)) at ?0, where Z0 is the desired matching impedance and ?0 is the desired operating frequency. Here, e1m represents the maximum deviation of the imaginary part, at , from the desired value of 0, and eRe represents the maximum deviation of the real part from the desired value of Z0. It is understood that e1m and eRe can be adjusted to increase or decrease the number of steps to convergence at the potential cost of system performance (efficiency). It is also understood that steps 1-4 can be performed in a variety of sequences and a variety of ways other than that outlined above (i.e. first adjust the source imaginary part, then the source real part; or first adjust the device real part, then the device imaginary part, etc.) The intermediate impedances Z1 and Z2 may be adjusted during steps 1-4 to reduce the number of steps required for convergence. The desire or target impedance value may be complex, and may vary in time or under different operating scenarios.

[00414] Steps 1-4 may be performed in any order, in any combination and any number of times. Having described the above algorithm, variations to the steps or the described implementation may be apparent to one of ordinary skill in the art. The algorithm outlined above may be implemented with any equivalent linear network port parameter measurements (i.e., Z-parameters, Y-parameters, T-parameters, H-parameters, ABCD-parameters, etc.) or other monitor signals described above, in the same way that impedance or admittance can be alternatively used to analyze a linear circuit to derive the same result.

[00415] The resonators may need to be retuned owing to changes in the "loaded" resistances, Rs and Rd, caused by changes in the mutual inductance M (coupling) between the source and device resonators. Changes in the inductances, Ls and Ld, of the inductive elements themselves may be caused by the influence of external objects, as discussed earlier, and may also require compensation. Such variations may be mitigated by the adjustment algorithm described above.

[00416] A directional coupler or a switch may be used to connect the port parameter measurement circuitry to the source resonator and tuning/adjustment circuitry. The port parameter measurement circuitry may measure properties of the magnetic resonator while it is exchanging power in a wireless power transmission system, or it may be switched out of the circuit during system operation. The port parameter measurement circuitry may measure the parameters and the processor may control certain tunable elements of the magnetic resonator at start-up, or at certain intervals, or in response to changes in certain system operating parameters.

[00417] A wireless power transmission system may include circuitry to vary or tune the impedance and/or resonant frequency of source and device resonators. Note that while tuning circuitry is shown in both the source and device resonators, the circuitry may instead be included in only the source or the device resonators, or the circuitry may be included in only some of the source and/or device resonators. Note too that while we may refer to the circuitry as "tuning" the impedance and or resonant frequency of the resonators, this tuning operation simply means that various electrical parameters such as the inductance or capacitance of the structure are being varied. In some cases, these parameters may be varied to achieve a specific predetermined value, in other cases they may be varied in response to a control algorithm or to stabilize a target performance value that is changing. In some cases, the parameters are varied as a function of temperature, of other sources or devices in the area, of the environment, at the like.

[00418] Applications

[00419] For each listed application, it will be understood by one of ordinary skill-in-the-art that there are a variety of ways that the resonator structures used to enable wireless power transmission may be connected or integrated with the objects that are supplying or being powered. The resonator may be physically separate from the source and device objects. The resonator may supply or remove power from an object using traditional inductive techniques or through direct electrical connection, with a wire or cable for example. The electrical connection may be from the resonator output to the AC or DC power input port on the object. The electrical connection may be from the output power port of an object to the resonator input.

[00420] FIG. 49 shows a source resonator 4904 that is physically separated from a power supply and a device resonator 4902 that is physically separated from the device 4900, in this illustration a laptop computer. Power may be supplied to the source resonator, and power may be taken from the device resonator directly, by an electrical connection. One of ordinary skill in the art will understand from the materials incorporated by reference that the shape, size, material composition, arrangement, position and orientation of the resonators above are provided by way of non-limiting example, and that a wide variation in any and all of these parameters could be supported by the disclosed technology for a variety of applications.

[00421] Continuing with the example of the laptop, and without limitation, the device resonator may be physically connected to the device it is powering or charging. For example, as shown in FIG. 50a and FIG. 50b, the device resonator 5002 may be (a) integrated into the

housing of the device 5000 or (b) it may be attached by an adapter. The resonator 5002 may (FIG. 50b-d) or may not (FIG. 50a) be visible on the device. The resonator may be affixed to the device, integrated into the device, plugged into the device, and the like.

[00422] The source resonator may be physically connected to the source supplying the power to the system. As described above for the devices and device resonators, there are a variety of ways the resonators may be attached to, connected to or integrated with the power supply. One of ordinary skill in the art will understand that there are a variety of ways the resonators may be integrated in the wireless power transmission system, and that the sources and devices may utilize similar or different integration techniques.

[00423] Continuing again with the example of the laptop computer, and without limitation, the laptop computer may be powered, charged or recharged by a wireless power transmission system. A source resonator may be used to supply wireless power and a device resonator may be used to capture the wireless power. A device resonator 5002 may be integrated into the edge of the screen (display) as illustrated in FIG. 50d, and/or into the base of the laptop as illustrated in FIG. 50c. The source resonator 5002 may be integrated into the base of the laptop and the device resonator may be integrated into the edge of the screen. The resonators may also or instead be affixed to the power source and/or the laptop. The source and device resonators may also or instead be physically separated from the power supply and the laptop and may be electrically connected by a cable. The source and device resonators may also or instead be physically separated from the power supply and the laptop and may be electrically coupled using a traditional inductive technique. One of ordinary skill in the art will understand that, while the preceding examples relate to wireless power transmission to a laptop, that the methods and systems disclosed for this application may be suitably adapted for use with other electrical or electronic devices. In general, the source resonator may be external to the source and supplying power to a device resonator that in turn supplies power the device, or the Source resonator may be connected to the source and supplying power to a device resonator that in turn supplies power to a portion of the device, or the source resonator may internal to the source and supplying power to a device resonator that in turn supplies power to a portion of the device, as well as any combination of these.

[00424] A system or method disclosed herein may provide power to an electrical or electronics device, such as, and not limited to, phones, cell phones, cordless phones, smart phones, PDAs, audio devices, music players, MP3 players, radios, portable radios and players, wireless headphones, wireless headsets, computers, laptop computers, wireless keyboards, wireless mouse, televisions, displays, flat screen displays, computer displays, displays embedded . in furniture, digital picture frames, electronic books, (e.g. the Kindle, e-ink books, magazines, and the like), remote control units (also referred to as controllers, game controllers, commanders, clickers, and the like, and used for the remote control of a plurality of electronics devices, such as televisions, video games, displays, computers, audio visual equipment, lights, and the like), lighting devices, cooling devices, air circulation devices, purification devices, personal hearing aids, power tools, security systems, alarms, bells, flashing lights, sirens, sensors, loudspeakers, electronic locks, electronic keypads, light switches, other electrical switches, and the like. Here the term electronic lock is used to indicate a door lock which operates electronically (e.g. with electronic combo-key, magnetic card, RFID card, and the like) which is placed on a door instead of a mechanical key-lock. Such locks are often battery operated, risking the possibility that the lock might stop working when a battery dies, leaving the user locked-out. This may be avoided where the battery is either charged or completely replaced by a wireless power transmission implementation as described herein.

[00425] Here, the term light switch (or other electrical switch) is meant to indicate any switch (e.g. on a wall of a room) in one part of the room that turns on/off a device (e.g. light fixture at the center of the ceiling) in another part of the room. To install such a switch by direct connection, one would have to run a wire all the way from the device to the switch. Once such a switch is installed at a particular spot, it may be very difficult to move. Alternately, one can envision a 'wireless switch', where "wireless" means the switching (on/off) commands are communicated wirelessly, but such a switch has traditionally required a battery for operation. In general, having too many battery operated switches around a house may be impractical, because those many batteries will need to be replaced periodically. So, a wirelessly communicating switch may be more convenient, provided it is also wirelessly powered. For example, there already exist communications wireless door-bells that are battery powered, but where one still has to replace the battery in them periodically. The remote doorbell button may be made to be completely wireless, where there may be no need to ever replace the battery again. Note that here, the term 'cordless' or 'wireless' or 'communications wireless' is used to indicate that there is a cordless or wireless communications facility between the device and another electrical component, such as the base station for a cordless phone, the computer for a wireless keyboard, and the like. One skilled in the art will recognize that any electrical or electronics device may include a wireless communications facility, and that the systems and methods described herein may be used to add wireless power transmission to the device. As described herein, power to the electrical or electronics device may be delivered from an external or internal source resonator, and to the device or portion of the device. Wireless power transmission may significantly reduce the need to charge and/or replace batteries for devices that enter the near vicinity of the source resonator and thereby may reduce the downtime, cost and disposal issues often associated with batteries.

[00426] The systems and methods described herein may provide power to lights - without the need for either wired power or batteries. That is, the systems and methods described herein may provide power to lights without wired connection to any power source, and provide the energy to the light non-radiatively across mid-range distances, such as across a distance of a quarter of a meter, one meter, three meters, and the like. A 'light' as used herein may refer to the light source itself, such as an incandescent light bulb, florescent light bulb lamps, Halogen lamps, gas discharge lamps, fluorescent lamps, neon lamps, high-intensity discharge lamps, sodium vapor lamps, Mercury-vapor lamps, electroluminescent lamps, light emitting diodes (LED) lamps, and the like; the light as part of a light fixture, such as a table lamp, a floor lamp, a ceiling lamp, track lighting, recessed light fixtures, and the like; light fixtures integrated with other functions, such as a light/ceiling fan fixture, and illuminated picture frame, and the like. As

such, the systems and methods described herein may reduce the complexity for installing a light, such as by minimizing the installation of electrical wiring, and allowing the user to place or mount the light with minimal regard to sources of wired power. For instance, a light may be placed anywhere in the vicinity of a source resonator, where the source resonator may be mounted in a plurality of different places with respect to the location of the light, such as on the floor of the room above, (e.g. as in the case of a ceiling light and especially when the room above is the attic); on the wall of the next room, on the ceiling of the room below, (e.g. as in the case of a floor lamp); in a component within the room or in the infrastructure of the room as described herein; and the like. For example, a light/ceiling fan combination is often installed in a master bedroom, and the master bedroom often has the attic above it. In this instance a user may more easily install the light/ceiling fan combination in the master bedroom, such as by simply mounting the light/ceiling fan combination to the ceiling, and placing a source coil (plugged into the house wired AC power) in the attic above the mounted fixture. In another example, the light may be an external light, such as a flood light or security light, and the source resonator mounted inside the structure. This way of installing lighting may be particularly beneficial to users who rent their homes, because now they may be able to mount lights and such other electrical components without the need to install new electrical wiring. The control for the light may also be communicated by near-field communications as described herein, or by traditional wireless communications methods.

[00427] The systems and methods described herein may provide power from a source resonator to a device resonator that is either embedded into the device component, or outside the device component, such that the device component may be a traditional electrical component or fixture. For instance, a ceiling lamp may be designed or retrofitted with a device resonator integrated into the fixture, or the ceiling lamp may be a traditional wired fixture, and plugged into a separate electrical facility equipped with the device resonator. In an example, the electrical facility may be a wireless junction box designed to have a device resonator for receiving wireless power, say from a source resonator placed on the floor of the room above (e.g. the attic), and which contains a number of traditional outlets that are powered from the device resonator. The wireless junction box, mounted on the ceiling, may now provide power to traditional wired electrical components on the ceiling (e.g. a ceiling light, track lighting, a ceiling fan). Thus, the ceiling lamp may now be mounted to the ceiling without the need to run wires through the infrastructure of the building. This type of device resonator to traditional outlet junction box may be used in a plurality of applications, including being designed for the interior or exterior of a building, to be made portable, made for a vehicle, and the like. Wireless power may be transferred through common building materials, such as wood, wall board, insulation, glass, brick, stone, concrete, and the like. The benefits of reduced installation cost, re-configurability, and increased application flexibility may provide the user significant benefits over traditional wired installations. The device resonator for a traditional outlet junction box may include a plurality of electrical components for facilitating the transfer of power from the device resonator to the traditional outlets, such as power source electronics which convert the specific frequencies needed to implement efficient power transfer to line voltage, power capture electronics which may convert high frequency AC to usable voltage and frequencies (AC and/or DC), controls which synchronize the capture device and the power output and which ensure consistent, safe, and maximally efficient power transfer, and the like.

[00428] The systems and methods described herein may provide advantages to lights or electrical components that operate in environments that are wet, harsh, controlled, and the like, such has outside and exposed to the rain, in a pool/sauna/shower, in a maritime application, in hermetically sealed components, in an explosive-proofroom, on outside signage, a harsh industrial environment in a volatile environment (e.g. from volatile vapors or airborne organics, such as in a grain silo or bakery) , and the like. For example, a light mounted under the water level of a pool is normally difficult to wire up, and is required to be water-sealed despite the need for external wires. But a pool light using the principles disclosed herein may more easily be made water sealed, as there may be no external wires needed. In another example, an explosion proofroom, such as containing volatile vapors, may not only need to be hermetically sealed, but may need to have all electrical contacts (that could create a spark) sealed. Again, the principles disclosed herein may provide a convenient way to supply sealed electrical components for such applications.

[00429] The systems and methods disclosed herein may provide power to game controller applications, such as to a remote handheld game controller. These game controllers may have been traditionally powered solely by batteries, where the game controller's use and power profile caused frequent changing of the battery, battery pack, rechargeable batteries, and the like, that may not have been ideal for the consistent use to the game controller, such as during extended game play. A device resonator may be placed into the game controller, and a source resonator, connected to a power source, may be placed in the vicinity. Further, the device resonator in the game controller may provide power directly to the game controller electronics without a battery; provide power to a battery, battery pack, rechargeable battery, and the like, which then provides power to the game controller electronics; and the like. The game controller may utilize multiple battery packs, where each battery pack is equipped with a device resonator, and thus may be constantly recharging while in the vicinity of the source resonator, whether plugged into the game controller or not. The source resonator may be resident in a main game controller facility for the game, where the main game controller facility and source resonator are supplied power from AC 'house' power; resident in an extension facility form AC power, such as in a source resonator integrated into an 'extension cord'; resident in a game chair, which is at least one of plugged into the wall AC, plugged into the main game controller facility, powered by a battery pack in the game chair; and the like. The source resonator may be placed and implemented in any of the configurations described herein.

[00430] The systems and methods disclosed herein may integrate device resonators into battery packs, such as battery packs that are interchangeable with other battery packs. For instance, some portable devices may use up electrical energy at a high rate such that a user may need to have multiple interchangeable battery packs on hand for use, or the user may operate the device out of range of a source resonator and need additional battery packs to continue operation, such as for power tools, portable lights, remote control vehicles, and the like. The use of the

principles disclosed herein may not only provide a way for device resonator enabled battery packs to be recharged while in use and in range, but also for the recharging of battery packs not currently in use and placed in range of a source resonator. In this way, battery packs may always be ready to use when a user runs down the charge of a battery pack being used. For example, a user may be working with a wireless power tool, where the current requirements may be greater than can be realized through direct powering from a source resonator. In this case, despite the fact that the systems and methods described herein may be providing charging power to the in-use battery pack while in range, the battery pack may still run down, as the power usage may have exceeded the recharge rate. Further, the user may simply be moving in and out of range, or be completely out of range while using the device. However, the user may have placed additional battery packs in the vicinity of the source resonator, which have been recharged while not in use, and are now charged sufficiently for use. In another example, the user may be working with the power tool away from the vicinity of the source resonator, but leave the supplemental battery packs to charge in the vicinity of the source resonator, such as in a room with a portable source resonator or extension cord source resonator, in the user's vehicle, in user's tool box, and the like. In this way, the user may not have to worry about taking the time to, and/or remembering to plug in their battery packs for future use. The user may only have to change out the used battery pack for the charged battery pack and place the used one in the vicinity of the source resonator for recharging. Device resonators may be built into enclosures with known battery form factors and footprints and may replace traditional chemical batteries in known devices and applications. For example, device resonators may be built into enclosures with mechanical dimensions equivalent to AA batteries, AAA batteries, D batteries, 9V batteries, laptop batteries, cell phone batteries, and the like. The enclosures may include a smaller "button battery" in addition to the device resonator to store charge and provide extended operation, either in terms of time or distance. Other energy storage devices in addition to or instead of button batteries may be integrated with the device resonators and any associated power conversion circuitry. These new energy packs may provide similar voltage and current levels as provided by traditional batteries, but may be composed of device resonators, power conversion electronics, a small battery, and the like. These new energy packs may last longer than traditional batteries because they may be more easily recharged and may be recharging constantly when they are located in a wireless power zone. In addition, such energy packs may be lighter than traditional batteries, may be safer to use and store, may operate over wider temperature and humidity ranges, may be less harmful to the environment when thrown away, and the like. As described herein, these energy packs may last beyond the life of the product when used in wireless power zones as described herein.

[00431] The systems and methods described herein may be used to power visual displays, such as in the case of the laptop screen, but more generally to include the great variety and diversity of displays utilized in today's electrical and electronics components, such as in televisions, computer monitors, desktop monitors, laptop displays, digital photo frames, electronic books, mobile device displays (e.g. on phones, PDAs, games, navigation devices, DVD players), and the like. Displays that may be powered through one or more of the wireless power transmission systems described herein may also include embedded displays, such as embedded in electronic components (e.g. audio equipment, home appliances, automotive displays, entertainment devices, cash registers, remote controls), in furniture, in building infrastructure, in a vehicle, on the surface of an object (e.g. on the surface of a vehicle, building, clothing, signs, transportation), and the like. Displays may be very small with tiny resonant devices, such as in a smart card as described herein, or very large, such as in an advertisement sign. Displays powered using the principles disclosed herein may also be any one of a plurality of imaging technologies, such as liquid crystal display (LCD), thin film transistor LCD, passive LCD, cathode ray tube (CRT), plasma display, projector display (e.g. LCD, DLP, LCOS), surface-conduction electron-emitter display (SED), organic light-emitting diode (OLED), and the like. Source coil configurations may include attaching to a primary power source, such as building power, vehicle power, from a wireless extension cord as described herein, and the like; attached to component power, such as the base of an electrical component (e.g. the base of a computer, a cable box for a TV); an intermediate relay source coil; and the like. For example, hanging a digital display on the wall may be very appealing, such as in the case of a digital photo frame that receives its information signals wirelessly or through a portable memory device, but the need for an unsightly power cord may make it aesthetically unpleasant. However, with a device coil embedded in the digital photo frame, such as wrapped within the frame portion, may allow the digital photo frame to be hung with no wires at all. The source resonator may then be placed in the vicinity of the digital photo frame, such as in the next room on the other side of the wall, plugged directly into a traditional power outlet, from a wireless extension cord as described herein, from a central source resonator for the room, and the like.

[00432] The systems and methods described herein may provide wireless power transmission between different portions of an electronics facility. Continuing with the example of the laptop computer, and without limitation, the screen of the laptop computer may require power from the base of the laptop. In this instance, the electrical power has been traditionally routed via direct electrical connection from the base of the laptop to the screen over a hinged portion of the laptop between the screen and the base. When a wired connection is utilized, the wired connection may tend to wear out and break, the design functionality of the laptop computer may be limited by the required direct electrical connection, the design aesthetics of the laptop computer may be limited by the required direct electrical connection, and the like. However, a wireless connection may be made between the base and the screen. In this instance, the device resonator may be placed in the screen portion to power the display, and the base may be either powered by a second device resonator, by traditional wired connections, by a hybrid of resonator-battery- direct electrical connection, and the like. This may not only improve the reliability of the power connection due to the removal of the physical wired connection, but may also allow designers to improve the functional and/or aesthetic design of the hinge portion of the laptop in light of the absence of physical wires associated with the hinge. Again, the laptop computer has been used here to illustrate how the principles disclosed herein may improve the design of an electric or electronic device, and should not be taken as limiting in any way. For instance, many other electrical devices with separated physical portions could benefit from the systems and methods described herein, such as a refrigerator with electrical functions on the

door, including an ice maker, a sensor system, a light, and the like; a robot with movable portions, separated by joints; a car's power system and a component in the car's door; and the like. The ability to provide power to a device via a device resonator from an external source resonator, or to a portion of the device via a device resonator from either external or internal source resonators, will be recognized by someone skilled in the art to be widely applicable across the range of electric and electronic devices.

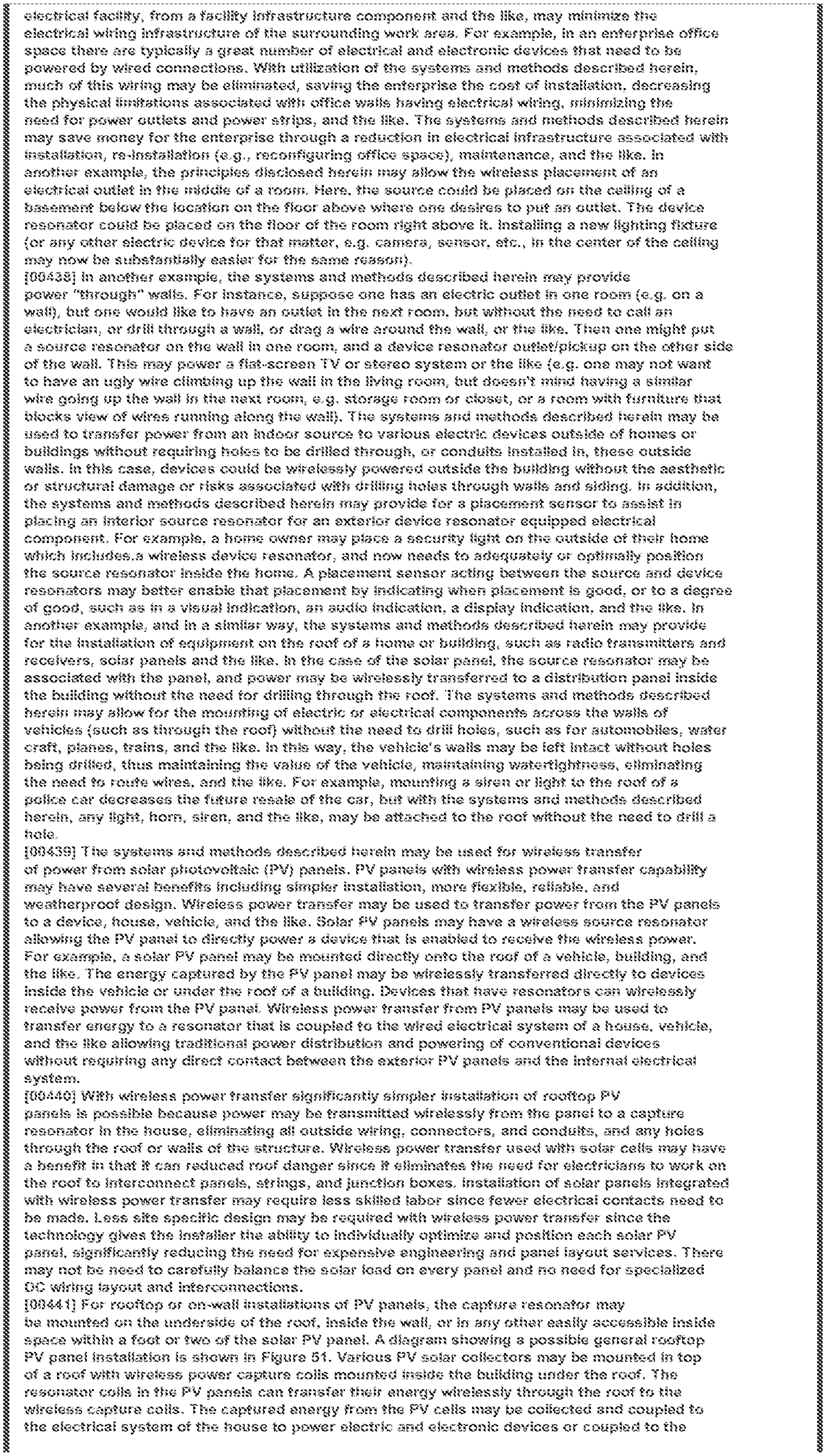
[00433] The systems and methods disclosed herein may provide for a sharing of electrical power between devices, such as between charged devices and uncharged devices. For instance a charged up device or appliance may act like a source and send a predetermined amount of energy, dialed in amount of energy, requested and approved amount of energy, and the like, to a nearby device or appliance. For example, a user may have a cell phone and a digital camera that are both capable of transmitting and receiving power through embedded source and device resonators, and one of the devices, say the cell phone, is found to be low on charge. The user may then transfer charge from the digital camera to the cell phone. The source and device resonators in these devices may utilize the same physical resonator for both transmission and reception, utilize separate source and device resonators, one device may be designed to receive and transmit while the other is designed to receive only, one device may be designed to transmit only and the other to receive only, and the like.

[00434] To prevent complete draining the battery of a device it may have a setting allowing a user to specify how much of the power resource the receiving device is entitled to. It may be useful, for example, to put a limit on the amount of power available to external devices and to have the ability to shut down power transmission when battery power falls below a threshold.

[00435] The systems and methods described herein may provide wireless power transfer to a nearby electrical or electronics component in association with an electrical facility, where the source resonator is in the electrical facility and the device resonator is in the electronics component. The source resonator may also be connected to, plugged into, attached to the electrical facility, such as through a universal interface (e.g. a USB interface, PC card interface), supplemental electrical outlet, universal attachment point, and the like, of the electrical facility. For example, the source resonator may be inside the structure of a computer on a desk, or be integrated into some object, pad, and the like, that is connected to the computer, such as into one of the computer's USB interfaces. In the example of the source resonator embedded in the object, pad, and the like, and powered through a USB interface, the source resonator may then be easily added to a user's desktop without the need for being integrated into any other electronics device, thus conveniently providing a wireless energy zone around which a plurality of electric and/or electronics devices may be powered. The electrical facility may be a computer, a light fixture, a dedicated source resonator electrical facility, and the like, and the nearby components may be computer peripherals, surrounding electronics components, infrastructure devices, and the like, such as computer keyboards, computer mouse, fax machine, printer, speaker system, cell phone, audio device, intercom, music player, PDA, lights, electric pencil sharpener, fan, digital picture frame, calculator, electronic games, and the like. For example, a computer system may be the electrical facility with an integrated source resonator that utilizes a 'wireless keyboard' and 'wireless mouse', where the use of the term wireless here is meant to indicate that there is wireless communication facility between each device and the computer, and where each device must still contain a separate battery power source. As a result, batteries would need to be replaced periodically, and in a large company, may result in a substantial burden for support personnel for replacement of batteries, cost of batteries, and proper disposal of batteries. Alternatively, the systems and methods described herein may provide wireless power transmission from the main body of the computer to each of these peripheral devices, including not only power to the keyboard and mouse, but to other peripheral components such as a fax, printer, speaker system, and the like, as described herein. A source resonator integrated into the electrical facility may provide wireless power transmission to a plurality of peripheral devices, user devices, and the like, such that there is a significant reduction in the need to charge and/or replace batteries for devices in the near vicinity of the source resonator integrated electrical facility. The electrical facility may also provide tuning or auto-tuning software, algorithms, facilities, and the like, for adjusting the power transfer parameters between the electrical facility and the wirelessly powered device. For example, the electrical facility may be a computer on a user's desktop, and the source resonator may be either integrated into the computer or plugged into the computer (e.g. through a USB connection), where the computer provides a facility for providing the tuning algorithm (e.g. through a software program running on the computer).

[00436] The systems and methods disclosed herein may provide wireless power transfer to a nearby electrical or electronics component in association with a facility infrastructure component, where the source resonator is in, or mounted on, the facility infrastructure component and the device resonator is in the electronics component. For instance, the facility infrastructure component may be a piece of furniture, a fixed wall, a movable wall or partition, the ceiling, the floor, and the source resonator attached or integrated into a table or desk (e.g. just below/above the surface, on the side, integrated into a table top or table leg), a mat placed on the floor (e.g. below a desk, placed on a desk), a mat on the garage floor (e.g. to charge the car and/or devices in the car), in a parking lot/garage (e.g. on a post near where the car is parked), a television (e.g. for charging a remote control), a computer monitor (e.g. to power/charge a wireless keyboard, wireless mouse, cell phone), a chair (e.g. for powering electric blankets, medical devices, personal health monitors), a painting, office furniture, common household appliances, and the like. For example, the facility infrastructure component may be a lighting fixture in an office cubical, where the source resonator and light within the lighting fixture are both directly connected to the facility's wired electrical power. However, with the source resonator now provided in the lighting fixture, there would be no need to have any additional wired connections for those nearby electrical or electronics components that are connected to, or integrated with, a device resonator. In addition, there may be a reduced need for the replacement of batteries for devices with device resonators, as described herein.

[00437] The use of the systems and methods described herein to supply power to electrical and electronic devices from a central location, such as from a source resonator in an



electrical facility, from a facility infrastructure component and the like, may minimize the electrical wiring infrastructure of the surrounding work area. For example, in an enterprise office space there are typically a great number of electrical and electronic devices that need to be powered by wired connections. With utilization of the systems and methods described herein, much of this wiring may be eliminated, saving the enterprise the cost of installation, decreasing the physical limitations associated with office walls having electrical wiring, minimizing the need for power outlets and power strips, and the like. The systems and methods described herein may save money for the enterprise through a reduction in electrical infrastructure associated with installation, re-installation (e.g., reconfiguring office space), maintenance, and the like. In another example, the principles disclosed herein may allow the wireless placement of an electrical outlet in the middle of a room. Here, the source could be placed on the ceiling of a basement below the location on the floor above where one desires to put an outlet. The device resonator could be placed on the floor of the room right above it. Installing a new lighting fixture (or any other electric device for that matter, e.g. camera, sensor, etc., in the center of the ceiling may now be substantially easier for the same reason).

[00438] In another example, the systems and methods described herein may provide power "through" walls. For instance, suppose one has an electric outlet in one room (e.g. on a wall), but one would like to have an outlet in the next room, but without the need to call an electrician, or drill through a wall, or drag a wire around the wall, or the like. Then one might put a source resonator on the wall in one room, and a device resonator outlet/pickup on the other side of the wall. This may power a flat-screen TV or stereo system or the like (e.g. one may not want to have an ugly wire climbing up the wall in the living room, but doesn't mind having a similar wire going up the wall in the next room, e.g. storage room or closet, or a room with furniture that blocks view of wires running along the wall). The systems and methods described herein may be used to transfer power from an indoor source to various electric devices outside of homes or buildings without requiring holes to be drilled through, or conduits installed in, these outside walls. In this case, devices could be wirelessly powered outside the building without the aesthetic or structural damage or risks associated with drilling holes through walls and siding. In addition, the systems and methods described herein may provide for a placement sensor to assist in placing an interior source resonator for an exterior device resonator equipped electrical component. For example, a home owner may place a security light on the outside of their home which includes.a wireless device resonator, and now needs to adequately or optimally position the source resonator inside the home. A placement sensor acting between the source and device resonators may better enable that placement by indicating when placement is good, or to a degree of good, such as in a visual indication, an audio indication, a display indication, and the like. In another example, and in a similar way, the systems and methods described herein may provide for the installation of equipment on the roof of a home or building, such as radio transmitters and receivers, solar panels and the like. In the case of the solar panel, the source resonator may be associated with the panel, and power may be wirelessly transferred to a distribution panel inside the building without the need for drilling through the roof. The systems and methods described herein may allow for the mounting of electric or electrical components across the walls of vehicles (such as through the roof) without the need to drill holes, such as for automobiles, water craft, planes, trains, and the like. In this way, the vehicle's walls may be left intact without holes being drilled, thus maintaining the value of the vehicle, maintaining watertightness, eliminating the need to route wires, and the like. For example, mounting a siren or light to the roof of a police car decreases the future resale of the car, but with the systems and methods described herein, any light, horn, siren, and the like, may be attached to the roof without the need to drill a hole.

[00439] The systems and methods described herein may be used for wireless transfer of power from solar photovoltaic (PV) panels. PV panels with wireless power transfer capability may have several benefits including simpler installation, more flexible, reliable, and weatherproof design. Wireless power transfer may be used to transfer power from the PV panels to a device, house, vehicle, and the like. Solar PV panels may have a wireless source resonator allowing the PV panel to directly power a device that is enabled to receive the wireless power. For example, a solar PV panel may be mounted directly onto the roof of a vehicle, building, and the like. The energy captured by the PV panel may be wirelessly transferred directly to devices inside the vehicle or under the roof of a building. Devices that have resonators can wirelessly receive power from the PV panel. Wireless power transfer from PV panels may be used to transfer energy to a resonator that is coupled to the wired electrical system of a house, vehicle, and the like allowing traditional power distribution and powering of conventional devices without requiring any direct contact between the exterior PV panels and the internal electrical system.

[00440] With wireless power transfer significantly simpler installation of rooftop PV panels is possible because power may be transmitted wirelessly from the panel to a capture resonator in the house, eliminating all outside wiring, connectors, and conduits, and any holes through the roof or walls of the structure. Wireless power transfer used with solar cells may have a benefit in that it can reduced roof danger since it eliminates the need for electricians to work on the roof to interconnect panels, strings, and junction boxes. Installation of solar panels integrated with wireless power transfer may require less skilled labor since fewer electrical contacts need to be made. Less site specific design may be required with wireless power transfer since the technology gives the installer the ability to individually optimize and position each solar PV panel, significantly reducing the need for expensive engineering and panel layout services. There may not be need to carefully balance the solar load on every panel and no need for specialized DC wiring layout and interconnections.

[00441] For rooftop or on-wall installations of PV panels, the capture resonator may be mounted on the underside of the roof, inside the wall, or in any other easily accessible inside space within a foot or two of the solar PV panel. A diagram showing a possible general rooftop PV panel installation is shown in Figure 51. Various PV solar collectors may be mounted in top of a roof with wireless power capture coils mounted inside the building under the roof. The resonator coils in the PV panels can transfer their energy wirelessly through the roof to the wireless capture coils. The captured energy from the PV cells may be collected and coupled to the electrical system of the house to power electric and electronic devices or coupled to the

power grid when more power than needed is generated. Energy is captured from the PV cells without requiring holes or wires that penetrate the roof or the walls of the building. Each PV panel may have a resonator that is coupled to a corresponding resonator on the interior of the vehicle or building. Multiple panels may utilize wireless power transfer between each other to transfer or collect power to one or a couple of designated panels that are coupled to resonators on the interior of the vehicle of house. Panels may have wireless power resonators on their sides or in their perimeter that can couple to resonators located in other like panels allowing transfer of power from panel to panel. An additional bus or connection structure may be provided that wirelessly couples the power from multiple panels on the exterior of a building or vehicle and transfers power to one or a more resonators on the interior of building or vehicle.

[00442] For example, as shown in Fig. 51, a source resonator 5102 may be coupled to a PV cell 5100 mounted on top of roof 5104 of a building. A corresponding capture resonator 5106 is placed inside the building. The solar energy captured by the PV cells can then be transferred between the source resonators 5102 outside to the device resonators 5106 inside the building without having direct holes and connections through the building.

[00443] Each solar PV panel with wireless power transfer may have its own inverter, significantly improving the economics of these solar systems by individually optimizing the power production efficiency of each panel, supporting a mix of panel sizes and types in a single installation, including single panel "pay-as-you-grow" system expansions. Reduction of installation costs may make a single panel economical for installation. Eliminating the need for panel string designs and careful positioning and orienting of multiple panels, and eliminating a single point of failure for the system.

[00444] Wireless power transfer in PV solar panels may enable more solar deployment scenarios because the weather-sealed solar PV panels eliminate the need to drill holes for wiring through sealed surfaces such as car roofs and ship decks, and eliminate the requirement that the panels be installed in fixed locations. With wireless power transfer, PV panels may be deployed temporarily, and then moved or removed, without leaving behind permanent alterations to the surrounding structures. They may be placed out in a yard on sunny days, and moved around to follow the sun, or brought inside for cleaning or storage, for example. For backyard or mobile solar PV applications, an extension cord with a wireless energy capture device may be thrown on the ground or placed near the solar unit. The capture extension cord can be completely sealed from the elements and electrically isolated, so that it may be used in any indoor or outdoor environment.

[00445] With wireless power transfer no wires or external connections may be necessary and the PV solar panels can be completely weather sealed. Significantly improved reliability and lifetime of electrical components in the solar PV power generation and transmission circuitry can be expected since the weather-sealed enclosures can protect components from UV radiation, humidity, weather, and the like. With wireless power transfer and weather-sealed enclosures it may be possible to use less expensive components since they will no longer be directly exposed to external factors and weather elements and it may reduce the cost of PV panels.

[00446] Power transfer between the PV panels and the capture resonators inside a building or a vehicle may be bidirectional. Energy may be transmitted from the house grid to the PV panels to provide power when the panels do not have enough energy to perform certain tasks such. Reverse power flow can be used to melt snow from the panels, or power motors that will position the panels in a more favorable positions with respect to the sun energy. Once the snow is melted or the panels are repositioned and the PV panels can generate their own energy the direction of power transfer can be returned to normal delivering power from the PV panels to buildings, vehicles, or devices.

[00447] PV panels with wireless power transfer may include auto-tuning on installation to ensure maximum and efficient power transfer to the wireless collector. Variations in roofing materials or variations in distances between the PV panels and the wireless power collector in different installations may affect the performance or perturb the properties of the resonators of the wireless power transfer. To reduce the installation complexity the wireless power transfer components may include a tuning capability to automatically adjust their operating point to compensate for any effects due to materials or distance. Frequency, impedance, capacitance, inductance, duty cycle, voltage levels and the like may be adjusted to ensure efficient and safe power transfer

[00448] The systems and methods described herein may be used to provide a wireless power zone on a temporary basis or in extension of traditional electrical outlets to wireless power zones, such as through the use of a wireless power extension cord. For example, a wireless power extension cord may be configured as a plug for connecting into a traditional power outlet, a long wire such as in a traditional power extension cord, and a resonant source coil on the other end (e.g. in place of, or in addition to, the traditional socket end of the extension The wireless extension cord may also be configured where there are source resonators at a plurality of locations along the wireless extension cord. This configuration may then replace any traditional extension cord where there are wireless power configured devices, such as providing wireless power to a location where there is no convenient power outlet (e.g. a location in the living room where there's no outlet), for temporary wireless power where there is no wired power infrastructure (e.g. a construction site), out into the yard where there are no outlets (e.g. for parties or for yard grooming equipment that is wirelessly powered to decrease the chances of cutting the traditional electrical cord), and the like. The wireless extension cord may also be used as a drop within a wall or structure to provide wireless power zones within the vicinity of the drop. For example, a wireless extension cord could be run within a wall of a new or renovated room to provide wireless power zones without the need for the installation of traditional electrical wiring and outlets.

[00449] The systems and methods, described herein may be utilized to provide power between moving parts or rotating assemblies of a vehicle, a robot, a mechanical device, a wind turbine, or any other type of rotating device or structure with moving parts such as robot arms, construction vehicles, movable platforms and the like. Traditionally, power in such systems may have been provided by slip rings or by rotary joints for example. Using wireless power transfer as described herein, the design simplicity, reliability and longevity of these devices may be

significantly improved because power can be transferred over a range of distances without any physical connections or contact points that may wear down or out with time. In particular, the preferred coaxial and parallel alignment of the source and device coils may provide wireless power transmission that is not severely modulated by the relative rotational motion of the two coils.

[00450] The systems and methods described herein may be utilized to extend power needs beyond the reach of a single source resonator by providing a series of source-device-source-device resonators. For instance, suppose an existing detached garage has no electrical power and the owner now wants to install a new power service. However, the owner may not want to run wires all over the garage, or have to break into the walls to wire electrical outlets throughout the structure. In this instance, the owner may elect to connect a source resonator to the new power service, enabling wireless power to be supplied to device resonator outlets throughout the back of the garage. The owner may then install a device-source 'relay' to supply wireless power to device resonator outlets in the front of the garage. That is, the power relay may now receive wireless power from the primary source resonator, and then supply available power to a second source resonator to supply power to a second set of device resonators in the front of the garage. This configuration may be repeated again and again to extend the effective range of the supplied wireless power.

[00451] Multiple resonators may be used to extend power needs around an energy blocking material. For instance, it may be desirable to integrate a source resonator into a computer or computer monitor such that the resonator may power devices placed around and especially in front of the monitor or computer such as keyboards, computer mice, telephones , and the like. Due to aesthetics, space constraints, and the like an energy source that may be used for the source resonator may only be located or connected to in the back of the monitor or computer. In many designs of computer or monitors metal components and metal containing circuits are used in the design and packaging which may limit and prevent power transfer from source resonator in the back of the monitor or computer to the front of the monitor or computer. An additional repeater resonator may be integrated into the base or pedestal of the monitor or computer that couples to the source resonator in the back of the monitor or computer and allows power transfer to the space in front of the monitor or computer. The intermediate resonator integrated into the base or pedestal of the monitor or computer does not require an additional power source, it captures power from the source resonator and transfers power to the front around the blocking or power shielding metal components of the monitor or computer.

[00452] The systems and methods described herein may be built-into, placed on, hung from, embedded into, integrated into, and the like, the structural portions of a space, such as a vehicle, office, home, room, building, outdoor structure, road infrastructure, and the like. For instance, one or more sources may be built into, placed on, hung from, embedded or integrated into a wall, a ceiling or ceiling panel, a floor, a divider, a doorway, a stairwell, a compartment, a road surface, a sidewalk, a ramp, a fence, an exterior structure, and the like. One or more sources may be built into an entity within or around a structure, for instance a bed, a desk, a chair, a rug, a mirror, a clock, a display, a television, an electronic device, a counter, a table, a piece of furniture, a piece of artwork, an enclosure, a compartment, a ceiling panel, a floor or door panel, a dashboard, a trunk, a wheel well, a post, a beam, a support or any like entity. For example, a source resonator may be integrated into the dashboard of a user's car so that any device that is equipped with or connected to a device resonator may be supplied with power from the dashboard source resonator. In this way, devices brought into or integrated into the car may be constantly charged or powered while in the car.

[00453] The systems and methods described herein may provide power through the walls of vehicles, such as boats, cars, trucks, busses, trains, planes, satellites and the like. For instance, a user may not want to drill through the wall of the vehicle in order to provide power to an electric device on the outside of the vehicle. A source resonator may be placed inside the vehicle and a device resonator may be placed outside the vehicle (e.g. on the opposite side of a window, wall or structure). In this way the user may achieve greater flexibility in optimizing the placement, positioning and attachment of the external device to the vehicle, (such as without regard to supplying or routing electrical connections to the device). In addition, with the electrical power supplied wirelessly, the external device may be sealed such that it is water tight, making it safe if the electric device is exposed to weather (e.g. rain), or even submerged under water. Similar techniques may be employed in a variety of applications, such as in charging or powering hybrid vehicles, navigation and communications equipment, construction equipment, remote controlled or robotic equipment and the like, where electrical risks exist because of exposed conductors. The systems and methods described herein may provide power through the walls of vacuum chambers or other enclosed spaces such as those used in semiconductor growth and processing, material coating systems, aquariums, hazardous materials handling systems and the like. Power may be provided to translation stages, robotic arms, rotating stages, manipulation and collection devices, cleaning devices and the like.

[00454] The systems and methods described herein may provide wireless power to a kitchen environment, such as to counter-top appliances, including mixers, coffee makers, toasters, toaster ovens, grills, griddles, electric skillets, electric pots, electric woks, waffle makers, blenders, food processors, crock pots, warming trays, induction cooktops, lights, computers, displays, and the like. This technology may improve the mobility and/or positioning flexibility of devices, reduce the number of power cords stored on and strewn across the counter-top, improve the washability of the devices, and the like. For example, an electric skillet may traditionally have separate portions, such as one that is submersible for washing and one that is not submersible because it includes an external electrical connection (e.g. a cord or a socket for a removable cord). However, with a device resonator integrated into the unit, all electrical connections may be sealed, and so the entire device may now be submersed for cleaning. In addition, the absence of an external cord may eliminate the need for an available electrical wall outlet, and there is no longer a need for a power cord to be placed across the counter or for the location of the electric griddle to be limited to the location of an available electrical wall outlet.

[00455] The systems and methods described herein may provide continuous power/charging to devices equipped with a device resonator because the device doesn't leave the proximity of a source resonator, such as fixed electrical devices, personal computers, intercom

systems, security systems, household robots, lighting, remote control units, televisions, cordless phones, and the like. For example, a household robot (e.g. ROOMBA) could be powered/charged via wireless power, and thus work arbitrarily long without recharging. In this way, the power supply design for the household robot may be changed to take advantage of this continuous source of wireless power, such as to design the robot to only use power from the source resonator without the need for batteries, use power from the source resonator to recharge the robot's batteries, use the power from the source resonator to trickle charge the robot's batteries, use the power from the source resonator to charge a capacitive energy storage unit, and the like. Similar optimizations of the power supplies and power circuits may be enabled, designed, and realized, for any and all of the devices disclosed herein.

[00456] The systems and methods described herein may be able to provide wireless power to electrically heated blankets, heating pads/patches, and the like. These electrically heated devices may find a variety of indoor and outdoor uses. For example, hand and foot warmers supplied to outdoor workers such as guards, policemen, construction workers and the like might be remotely powered from a source resonator associated with or built into a nearby vehicle, building, utility pole, traffic light, portable power unit, and the like.

[00457] The systems and methods described herein may be used to power a portable information device that contains a device resonator and that may be powered up when the information device is near an information source containing a source resonator. For instance, the information device may be a card (e.g. credit card, smart card, electronic card, and the like) carried in a user's pocket, wallet, purse, vehicle, bike, and the like. The portable information device may be powered up when it is in the vicinity of an information source that then transmits information to the portable information device that may contain electronic logic, electronic processors, memory, a display, an LCD display, LEDs, RFID tags, and the like. For example, the portable information device may be a credit card with a display that "turns on" when it is near an information source, and provide the user with some information such as, "You just received a coupon for 50% off your next Coca Cola purchase". The information device may store information such as coupon or discount information that could be used on subsequent purchases. The portable information device may be programmed by the user to contain tasks, calendar appointments, to-do lists, alarms and reminders, and the like. The information device may receive up-to-date price information and inform the user of the location and price of previously selected or identified items.

[00458] The systems and methods described herein may provide wireless power transmission to directly power or recharge the batteries in sensors, such as environmental sensors, security sensors, agriculture sensors, appliance sensors, food spoilage sensors, power sensors, and the like, which may be mounted internal to a structure, external to a structure, buried underground, installed in walls, and the like. For example, this capability may replace the need to dig out old sensors to physically replace the battery, or to bury a new sensor because the old sensor is out of power and no longer operational. These sensors may be charged up periodically through the use of a portable sensor source resonator charging unit. For instance, a truck carrying a source resonator equipped power source, say providing ~kW of power, may provide enough power to a ~mW sensor in a few minutes to extend the duration of operation of the sensor for more than a year. Sensors may also be directly powered, such as powering sensors that are in places where it is difficult to connect to them with a wire but they are still within the vicinity of a source resonator, such as devices outside of a house (security camera), on the other side of a wall, on an electric lock on a door, and the like. In another example, sensors that may need to be otherwise supplied with a wired power connection may be powered through the systems and methods described herein. For example, a ground fault interrupter breaker combines residual current and over-current protection in one device for installation into a service panel. However, the sensor traditionally has to be independently wired for power, and this may complicate the installation. However, with the systems and methods described herein the sensor may be powered with a device resonator, where a single source resonator is provided within the service panel, thus simplifying the installation and wiring configuration within the service panel. In addition, the single source resonator may power device resonators mounted on either side of the source resonator mounted within the service panel, throughout the service panel, to additional nearby service panels, and the like. The systems and methods described herein may be employed to provide wireless power to any electrical component associated with electrical panels, electrical rooms, power distribution and the like, such as in electric switchboards, distribution boards, circuit breakers, transformers, backup batteries, fire alarm control panels, and the like. Through the use of the systems and methods described herein, it may be easier to install, maintain, and modify electrical distribution and protection components and system installations.

[00459] In another example, sensors that are powered by batteries may run continuously, without the need to change the batteries, because wireless power may be supplied to periodically or continuously recharge or trickle charge the battery. In such applications, even low levels of power may adequately recharge or maintain the charge in batteries, significantly extending their lifetime and usefulness. In some cases, the battery life may be extended to be longer than the lifetime of the device it is powering, making it essentially a battery that "lasts forever".

[00460] The systems and methods described herein may be used for charging implanted medical device batteries, such as in an artificial heart, pacemaker, heart pump, insulin pump, implanted coils for nerve or acupressure/acupuncture point stimulation, and the like. For instance, it may not be convenient or safe to have wires sticking out of a patient because the wires may be a constant source of possible infection and may generally be very unpleasant for the patient. The systems and methods described herein may also be used to charge or power medical devices in or on a patient from an external source, such as from a bed or a hospital wall or ceiling with a source resonator. Such medical devices may be easier to attach, read, use and monitor the patient. The systems and methods described herein may ease the need for attaching wires to the patient and the patient's bed or bedside, making it more convenient for the patient to move around and get up out of bed without the risk of inadvertently disconnecting a medical device. This may, for example, be usefully employed with patients that have multiple sensors monitoring them, such as for measuring pulse, blood pressure, glucose, and the like. For medical and monitoring devices that utilize batteries, the batteries may need to be replaced quite often,

perhaps multiple times a week. This may present risks associated with people forgetting to replace batteries, not noticing that the devices or monitors are not working because the batteries have died, infection associated with improper cleaning of the battery covers and compartments, and the like.

[00461] The systems and methods described herein may reduce the risk and complexity of medical device implantation procedures. Today many implantable medical devices such as ventricular assist devices, pacemakers, defibrillators and the like, require surgical implantation due to their device form factor, which is heavily influenced by the volume and shape of the long-life battery that is integrated in the device. In one aspect, there is described herein a non-invasive method of recharging the batteries so that the battery size may be dramatically reduced, and the entire device may be implanted, such as via a catheter. A catheter implantable device may include an integrated capture or device coil. A catheter implantable capture or device coil may be designed so that it may be wired internally, such as after implantation. The capture or device coil may be deployed via a catheter as a rolled up flexible coil (e.g. rolled up like two scrolls, easily unrolled internally with a simple spreader mechanism). The power source coil may be worn in a vest or article of clothing that is tailored to fit in such a way that places the source in proper position, may be placed in a chair cushion or bed cushion, may be integrated into a bed or piece of furniture, and the like.

[00462] The systems and methods described herein may enable patients to have a 'sensor vest', sensor patch, and the like, that may include at least one of a plurality of medical sensors and a device resonator that may be powered or charged when it is in the vicinity of a source resonator. Traditionally, this type of medical monitoring facility may have required batteries, thus making the vest, patch, and the like, heavy, and potentially impractical. But using the principles disclosed herein, no batteries (or a lighter rechargeable battery) may be required, thus making such a device more convenient and practical, especially in the case where such a medical device could be held in place without straps, such as by adhesive, in the absence of batteries or with substantially lighter batteries. A medical facility may be able to read the sensor data remotely with the aim of anticipating (e.g. a few minutes ahead of) a stroke, a heart-attack, or the like. When the vest is used by a person in a location remote from the medical facility, such as in their home, the vest may then be integrated with a cell-phone or communications device to call an ambulance in case of an accident or a medical event. The systems and methods described herein may be of particular value in the instance when the vest is to be used by an elderly person, where traditional non-wireless recharging practices (e.g. replacing batteries, plugging in at night, and the like) may not be followed as required. The systems and methods described herein may also be used for charging devices that are used by or mat aid handicapped or disabled people who may have difficulty replacing or recharging batteries, or reliably supplying power to devices they enjoy or rely on.

[00463] The systems and methods described herein may be used for the charging and powering of artificial limbs. Artificial limbs have become very capable in terms of replacing the functionality of original limbs, such as arms, legs, hands and feet. However, an electrically powered artificial limb may require substantial power, (such as 10-20W) which may translate into a substantial battery. In that case, the amputee may be left with a choice between a light battery that doesn't last very long, and a heavy battery that lasts much longer, but is more difficult to 'carry' around. The systems and methods described herein may enable the artificial limb to be powered with a device resonator, where the source resonator is either carried by the user and attached to a part of the body that may more easily support the weight (such as on a belt around the waist, for example) or located in an external location where the user will spend an adequate amount of time to keep the device charged or powered, such as at their desk, in then-car, in their bed, and the like.

[00464] The systems and methods described herein may be used for charging and powering of electrically powered exo-skeletons, such as those used in industrial and military applications, and for elderly/weak/sick people. An electrically powered exo-skeleton may provide up to a 10-to-20 times increase in "strength" to a person, enabling the person to perform physically strenuous tasks repeatedly without much fatigue. However, exo-skeletons may require more than 100W of power under certain use scenarios, so battery powered operation may be limited to 30 minutes or less. The delivery of wireless power as described herein may provide a user of an exo-skeleton with a continuous supply of power both for powering the structural movements of the exo-skeleton and for powering various monitors and sensors distributed throughout the structure. For instance, an exo-skeleton with an embedded device resonator(s) may be supplied with power from a local source resonator. For an industrial exo-skeleton, the source resonator may be placed in the walls of the facility. For a military exo-skeleton, the source resonator may be carried by an armored vehicle. For an exo-skeleton employed to assist a caretaker of the elderly, the source resonator(s) may be installed or placed in or the room(s) of a person's home.

[00465] The systems and methods described herein may be used for the powering/charging of portable medical equipment, such as oxygen systems, ventilators, defibrillators, medication pumps, monitors, and equipment in ambulances or mobile medical units, and the like. Being able to transport a patient from an accident scene to the hospital, or to move patients in their beds to other rooms or areas, and bring all the equipment that is attached with them and have it powered the whole time offers great benefits to the patients' health and eventual well-being. Certainly one can understand the risks and problems caused by medical devices that stop working because their battery dies or because they must be unplugged while a patient is transported or moved in any way. For example, an emergency medical team on the scene of an automotive accident might need to utilize portable medical equipment in the emergency care of patients in the field. Such portable medical equipment must be properly maintained so that there is sufficient battery life to power the equipment for the duration of the emergency. However, it is too often the case that the equipment is not properly maintained so that batteries are not fully charged and in some cases, necessary equipment is not available to the first responders. The systems and methods described herein may provide for wireless power to portable medical equipment (and associated sensor inputs on the patient) in such a way that the charging and maintaining of batteries and power packs is provided automatically and without human intervention. Such a system also benefits from the improved mobility of a patient

unencumbered by a variety of power cords attached to the many medical monitors and devices used in their treatment.

[00466] The systems and methods described herein may be used to for the powering/charging of personal hearing aids. Personal hearing aids need to be small and light to fit into or around the ear of a person. The size and weight restrictions limit the size of batteries that can be used. Likewise, the size and weight restrictions of the device make battery replacement difficult due to the delicacy of the components. The dimensions of the devices and hygiene concerns make it difficult to integrate additional charging ports to allow recharging of the batteries. The systems and methods described herein may be integrated into the hearing aid and may reduce the size of the necessary batteries which may allow even smaller hearing aids. Using the principles disclosed herein, the batteries of the hearing aid may be recharged without requiring external connections or charging ports. Charging and device circuitry and a small rechargeable battery may be integrated into a form factor of a conventional hearing aid battery allowing retrofit into existing hearing aids. The hearing aid may be recharged while it is used and worn by a person. The energy source may be integrated into a pad or a cup allowing recharging when the hearing is placed on such a structure. The charging source may be integrated into a hearing aid dryer box allowing wireless recharging while the hearing aid is drying or being sterilized. The source and device resonator may be used to also heat the device reducing or eliminating the need for an additional heating element. Portable charging cases powered by batteries or AC adaptors may be used as storage and charging stations.

[00467] The source resonator for the medical systems described above may be in the main body of some or all of the medical equipment, with device resonators on the patient's sensors and devices; the source resonator may be in the ambulance with device resonators on the patient's sensors and the main body of some or all of the equipment; a primary source resonator may be in the ambulance for transferring wireless power to a device resonator on the medical equipment while the medical equipment is in the ambulance and a second source resonator is in the main body of the medical equipment and a second device resonator on the patient sensors when the equipment is away from the ambulance; and the like. The systems and methods described herein may significantly improve the ease with which medical personnel are able to transport patients from one location to another, where power wires and the need to replace or manually charge associated batteries may now be reduced.

[00468] The systems and methods described herein may be used for the charging of devices inside a military vehicle or facility, such as a tank, armored carrier, mobile shelter, and the like. For instance, when soldiers come back into a vehicle after "action" or a mission, they may typically start charging their electronic devices. If their electronic devices were equipped with device resonators, and there was a source resonator inside the vehicle, (e.g. integrated in the seats or on the ceiling of the vehicle), their devices would start charging immediately. In fact, the same vehicle could provide power to soldiers/robots (e.g. packbot from iRobot) standing outside or walking beside the vehicle. This capability may be useful in minimizing accidental battery-swapping with someone else (this may be a significant issue, as soldiers tend to trust only their own batteries); in enabling quicker exits from a vehicle under attack; in powering or charging laptops or other electronic devices inside a tank, as too many wires inside the tank may present a hazard in terms of reduced ability to move around fast in case of "trouble" and/or decreased visibility; and the like. The systems and methods described herein may provide a significant improvement in association with powering portable power equipment in a military environment.

[00469] The systems and methods described herein may provide wireless powering or charging capabilities to mobile vehicles such as golf carts or other types of carts, all-terrain vehicles, electric bikes, scooters, cars, mowers, bobcats and other vehicles typically used for construction and landscaping and the like. The systems and methods described herein may provide wireless powering or charging capabilities to miniature mobile vehicles, such as mini-helicopters, airborne drones, remote control planes, remote control boats, remote controlled or robotic rovers, remote controlled or robotic lawn mowers or equipment, bomb detection robots, and the like. For instance, mini-helicopter flying above a military vehicle to increase its field of view can fly for a few minutes on standard batteries. If these mini-helicopters were fitted with a device resonator, and the control vehicle had a source resonator, the mini-helicopter might be able to fly indefinitely. The systems and methods described herein may provide an effective alternative to recharging or replacing the batteries for use in miniature mobile vehicles. In addition, the systems and methods described herein may provide power/charging to even smaller devices, such as microelectromechanical systems (MEMS), nano-robots, nano devices, and the like. In addition, the systems and methods described herein may be implemented by installing a source device in a mobile vehicle or flying device to enable it to serve as an in-field or in-flight re-charger, that may position itself autonomously in proximity to a mobile vehicle that is equipped with a device resonator.

[00470] The systems and methods described herein may be used to provide power networks for temporary facilities, such as military camps, oil drilling setups, remote filming locations, and the like, where electrical power is required, such as for power generators, and where power cables are typically run around the temporary facility. There are many instances when it is necessary to set up temporary facilities that require power. The systems and methods described herein may enable a more efficient way to rapidly set up and tear down these facilities, and may reduce the number of wires that must be run throughout the faculties to supply power. For instance, when Special Forces move into an area, they may erect tents and drag many wires around the camp to provide the required electricity. Instead, the systems and methods described herein may enable an army vehicle, outfitted with a power supply and a source resonator, to park in the center of the camp, and provide all the power to nearby tents where the device resonator may be integrated into the tents, or some other piece of equipment associated with each tent or area. A series of source-device-source-device resonators may be used to extend the power to tents that are farther away. That is, the tents closest to the vehicle could then provide power to tents behind them. The systems and methods described herein may provide a significant improvement to the efficiency with which temporary installations may be set up and torn down, thus improving the mobility of the associated facility.

[00471] The systems and methods described herein may be used in vehicles, such as for replacing wires, installing new equipment, powering devices brought into the vehicle,

charging the battery of a vehicle (e.g. for a traditional gas powered engine, for a hybrid car, for an electric car, and the like), powering devices mounted to the interior or exterior of the vehicle, powering devices in the vicinity of the vehicle, and the like. For example, the systems and methods described herein may be used to replace wires such as those are used to power lights, fans and sensors distributed throughout a vehicle. As an example, a typical car may have 50kg of wires associated with it, and the use of the systems and methods described herein may enable the elimination of a substantial amount of this wiring. The performance of larger and more weight sensitive vehicles such as airplanes or satellites could benefit greatly from having the number of cables that must be run throughout the vehicle reduced. The systems and methods described herein may allow the accommodation of removable or supplemental portions of a vehicle with electric and electrical devices without the need for electrical harnessing. For example, a motorcycle may have removable side boxes that act as a temporary trunk space for when the cyclist is going on a long trip. These side boxes may have exterior lights, interior lights, sensors, auto equipment, and the like, and if not for being equipped with the systems and methods described herein might require electrical connections and harnessing.

[00472] An in-vehicle wireless power transmission system may charge or power one or more mobile devices used in a car: mobile phone handset, Bluetooth headset, blue tooth hands free speaker phone, GPS, MP3 player, wireless audio transceiver for streaming MP3 audio through car stereo via FM, Bluetooth, and the like. The in vehicle wireless power source may utilize source resonators that are arranged in any of several possible configurations including charging pad on dash, charging pad otherwise mounted on floor, or between seat and center console, charging "cup" or receptacle that fits in cup holder or on dash, and the like.

[00473] The wireless power transmission source may utilize a rechargeable battery system such that said supply battery gets charged whenever the vehicle power is on such that when the vehicle is turned off the wireless supply can draw power from the supply battery and can continue to wirelessly charge or power mobile devices that are still in the car.

[00474] The plug-in electric cars, hybrid cars, and the like, of the future need to be charged, and the user may need to plug in to an electrical supply when they get home or to a . charging station. Based on a single over-night recharging, the user may be able to drive up to 50 miles the next day. Therefore, in the instance of a hybrid car, if a person drives less than 50 miles on most days, they will be driving mostly on electricity. However, it would be beneficial if they didn't have to remember to plug in the car at night. That is, it would be nice to simply drive into a garage, and have the car take care of its own charging. To this end, a source resonator may be built into the garage floor and/or garage side-wall, and the device resonator may be built into the bottom (or side) of the car. Even a few kW transfer may be sufficient to recharge the car over-night. The in-vehicle device resonator may measure magnetic field properties to provide feedback to assist in vehicle (or any similar device) alignment to a stationary resonating source. The vehicle may use this positional feedback to automatically position itself to achieve optimum alignment, thus optimum power transmission efficiency. Another method may be to use the positional feedback to help the human operator to properly position the vehicle or device, such as by making LED's light up, providing noises, and the like when it is well positioned. In such cases where the amount of power being transmitted could present a safety hazard to a person or animal that intrudes into the active field volume, the source or receiver device may be equipped with an active light curtain or some other external device capable of sensing intrusion into the active field volume, and capable of shutting off the source device and alert a human operator. In addition, the source device may be equipped with self-sensing capability such that it may detect that its expected power transmission rate has been interrupted by an intruding element, and in such case shut off the source device and alert a human operator. Physical or mechanical structures such as hinged doors or inflatable bladder shields may be incorporated as a physical barrier to prevent unwanted intrusions. Sensors such as optical, magnetic, capacitive, inductive, and the like may also be used to detect foreign structures or interference between the source and device resonators. The shape of the source resonator may be shaped such to prevent water or debris accumulation. The source resonator may be placed in a cone shaped enclosure or may have an enclosure with an angled top to allow water and debris to roll off. The source of the system may use battery power of the vehicle or its own battery power to transmit its presence to the source to initiate power transmission.

[00475] The source resonator may be mounted on an embedded or hanging post, on a wall, on a stand, and the like for coupling to a device resonator mounted on the bumper, hood, body panel, and the like, of an electric vehicle. The source resonator may be enclosed or embedded into a flexible enclosure such as a pillow, a pad, a bellows, a spring loaded enclosure and the like so that the electric vehicle may make contact with the structure containing the source coil without damaging the car in any way. The structure containing the source may prevent objects from getting between the source and device resonators. Because the wireless power transfer may be relatively insensitive to misalignments between the source and device coils, a variety of flexible source structures and parking procedures may be appropriate for this application.

[00476] The systems and methods described herein may be used to trickle charge batteries of electric, hybrid or combustion engine vehicles. Vehicles may require small amounts of power to maintain or replenish battery power. The power may be transferred wirelessly from a source to a device resonator that may be incorporated into the front grill, roof, bottom, or other parts of the vehicle. The device resonator may be designed to fit into a shape of a logo on the front of a vehicle or around the grill as not to obstruct air flow through the radiator. The device or source resonator may have additional modes of operation that allow the resonator to be used as a heating element which can be used to melt of snow or ice from the vehicle.

[00477] An electric vehicle or hybrid vehicle may require multiple device resonators, such as to increase the ease with which the vehicle may come in proximity with a source resonator for charging (i.e. the greater the number and varied position of device resonators are, the greater the chances that the vehicle can pull in and interface with a diversity of charging stations), to increase the amount of power that can be delivered in a period of time (e.g. additional device resonators may be required to keep the local heating due to charging currents to acceptable levels), to aid in automatic parking/docking the vehicle with the charging station, and the like. For example, the vehicle may have multiple resonators (or a single resonator) with a

feedback system that provides guidance to either the driver or an automated parking/docking facility in the parking of the vehicle for optimized charging conditions (i.e., the optimum positioning of the vehicle's device resonator to the charging station's source resonator may provide greater power transfer efficiency). An automated parking/docking facility may allow for the automatic parking of the vehicle based on how well the vehicle is coupled.

[00478] The power transmission system may be used to power devices and peripherals of a vehicle. Power to peripherals may be provided while a vehicle is charging, or while not charging, or power may be delivered to conventional vehicles that do not need charging. For example, power may be transferred wirelessly to conventional non-electric cars to power air conditioning, refrigeration units, heaters, lights, and the like while parked to avoid running the engine which may be important to avoid exhaust build up in garage parking lots or loading docks. Power may for example be wirelessly transferred to a bus while it is parked to allow powering of lights, peripherals, passenger devices, and the like avoiding the use of onboard engines or power sources. Power may be wirelessly transferred to an airplane while parked on the tarmac or in a hanger to power instrumentation, climate control, de-icing equipment, and the like without having to use onboard engines or power sources.

[00479] Wireless power transmission on vehicles may be used to enable the concept of Vehicle to Grid (V2G). Vehicle to grid is based on utilizing electric vehicles and plug-in hybrid electric vehicles (PHEV) as distributed energy storage devices, charged at night when the electric grid is underutilized, and available to discharge back into the grid during episodes of peak demand that occur during the day. The wireless power transmission system on a vehicle and the respective infrastructure may be implemented in such a way as to enable bidirectional energy flow—so that energy can flow back into the grid from the vehicle—without requiring a plug in connection. Vast fleets of vehicles, parked at factories, offices, parking lots, can be viewed as "peaking power capacity" by the smart grid. Wireless power transmission on vehicles can make such a V2G vision a reality. By simplifying the process of connecting a vehicle to the grid, (i.e. by simply parking it in a wireless charging enabled parking spot), it becomes much more likely that a certain number of vehicles will be "dispatchable" when the grid needs to tap their power. Without wireless charging, electric and PHEV owners will likely charge their vehicles at home, and park them at work in conventional parking spots. Who will want to plug their vehicle in at work, if they do not need charging? With wireless charging systems capable of handling 3 kW, 100,000 vehicles can provide 300 Megawatts back to the grid—using energy generated the night before by cost effective base load generating capacity. It is the streamlined ergonomics of the cordless self charging PHEV and electric vehicles that make it a viable V2G energy source.

[00480] The systems and methods described herein may be used to power sensors on the vehicle, such as sensors in tires to measure air-pressure, or to run peripheral devices in the vehicle, such as cell phones, GPS devices, navigation devices, game players, audio or video players, DVD players, wireless routers, communications equipment, anti-theft devices, radar devices, and the like. For example, source resonators described herein may be built into the main compartment of the car in order to supply power to a variety of devices located both inside and outside of the main compartment of the car. Where the vehicle is a motorcycle or the like, devices described herein may be integrated into the body of the motorcycle, such as under the seat, and device resonators may be provided in a user's helmet, such as for communications, entertainment, signaling, and the like, or device resonators may be provided in the user's jacket, such as for displaying signals to other drivers for safety, and the like.

[00481] The systems and methods described herein may be used in conjunction with transportation infrastructure, such as roads, trains, planes, shipping, and the like. For example, source resonators may be built into roads, parking lots, rail-lines, and the like. Source resonators may be built into traffic lights, signs, and the like. For example, with source resonators embedded into a road, and device resonators built into vehicles, the vehicles may be provided power as they drive along the road or as they are parked in lots or on the side of the road. The systems and methods described herein may provide an effective way for electrical systems in vehicles to be powered and/or charged while the vehicle traverses a road network, or a portion of a road network. In this way, the systems and methods described herein may contribute to the powering/charging of autonomous vehicles, automatic guided vehicles, and the like. The systems and methods described herein may provide power to vehicles in places where they typically idle or stop, such as in the vicinity of traffic lights or signs, on highway ramps, or in parking lots.

[00482] The systems and methods described herein may be used in an industrial environment, such as inside a factory for powering machinery, powering/charging robots, powering and/or charging wireless sensors on robot arms, powering/charging tools and the like. For example, using the systems and methods described herein to supply power to devices on the arms of robots may help eliminate direct wire connections across the joints of the robot arm. In this way, the wearing out of such direct wire connections may be reduced, and the reliability of the robot increased. In this case, the device resonator may be out on the arm of the robot, and the source resonator may be at the base of the robot, in a central location near the robot, integrated into the industrial facility in which the robot is providing service, and the like. The use of the systems and methods described herein may help eliminate wiring otherwise associated with power distribution within the industrial facility, and thus benefit the overall reliability of the facility.

[00483] The systems and methods described herein may be used for underground applications, such as drilling, mining, digging, and the like. For example, electrical components and sensors associated with drilling or excavation may utilize the systems and methods described herein to eliminate cabling associated with a digging mechanism, a drilling bit, and the like, thus eliminating or minimizing cabling near the excavation point. In another example, the systems and methods described herein may be used to provide power to excavation equipment in a mining application where the power requirements for the equipment may be high and the distances large, but where there are no people to be subjected to the associated required fields. For instance, the excavation area may have device resonator powered digging equipment that has high power requirements and may be digging relatively far from the source resonator. As a result the source resonator may need to provide high field intensities to satisfy these requirements, but personnel are far enough away to be outside these high intensity fields. This high power, no personnel, scenario may be applicable to a plurality of industrial applications.

[00484] The systems and methods described herein may also use the near-field non-radiative resonant scheme for information transfer rather than, or in addition to, power transfer. For instance, information being transferred by near-field non-radiative resonance techniques may not be susceptible to eavesdropping and so may provide an increased level of security compared to traditional wireless communication schemes. In addition, information being transferred by near-field non-radiative resonance techniques may not interfere with the EM radiative spectrum and so may not be a source of EM interference, thereby allowing communications in an extended frequency range and well within the limits set by any regulatory bodies. Communication services may be provided between remote, inaccessible or hard-to-reach places such as between remote sensors, between sections of a device or vehicle, in tunnels, caves and wells (e.g. oil wells, other drill sites) and between underwater or underground devices, and the like. Communications services may be provided in places where magnetic fields experience less loss than electric fields.

[00485] The systems and methods described herein may enable the simultaneous transmission of power and communication signals between sources and devices in wireless power transmission systems, or it may enable the transmission of power and communication signals during different time periods or at different frequencies. The performance characteristics of the resonator may be controllably varied to preferentially support or limit the efficiency or range of either energy or information transfer. The performance characteristics of the resonators may be controlled to improve the security by reducing the range of information transfer, for example. The performance characteristics of the resonators may be varied continuously, periodically, or according to a predetermined, computed or automatically adjusted algorithm. For example, the power and information transfer enabled by the systems and methods described herein may be provided in a time multiplexed or frequency multiplexed manner. A source and device may signal each other by tuning, changing, varying, dithering, and the like, the resonator impedance which may affect the reflected impedance of other resonators that can be detected. The information transferred as described herein may include information regarding device identification, device power requirements, handshaking protocols, and the like.

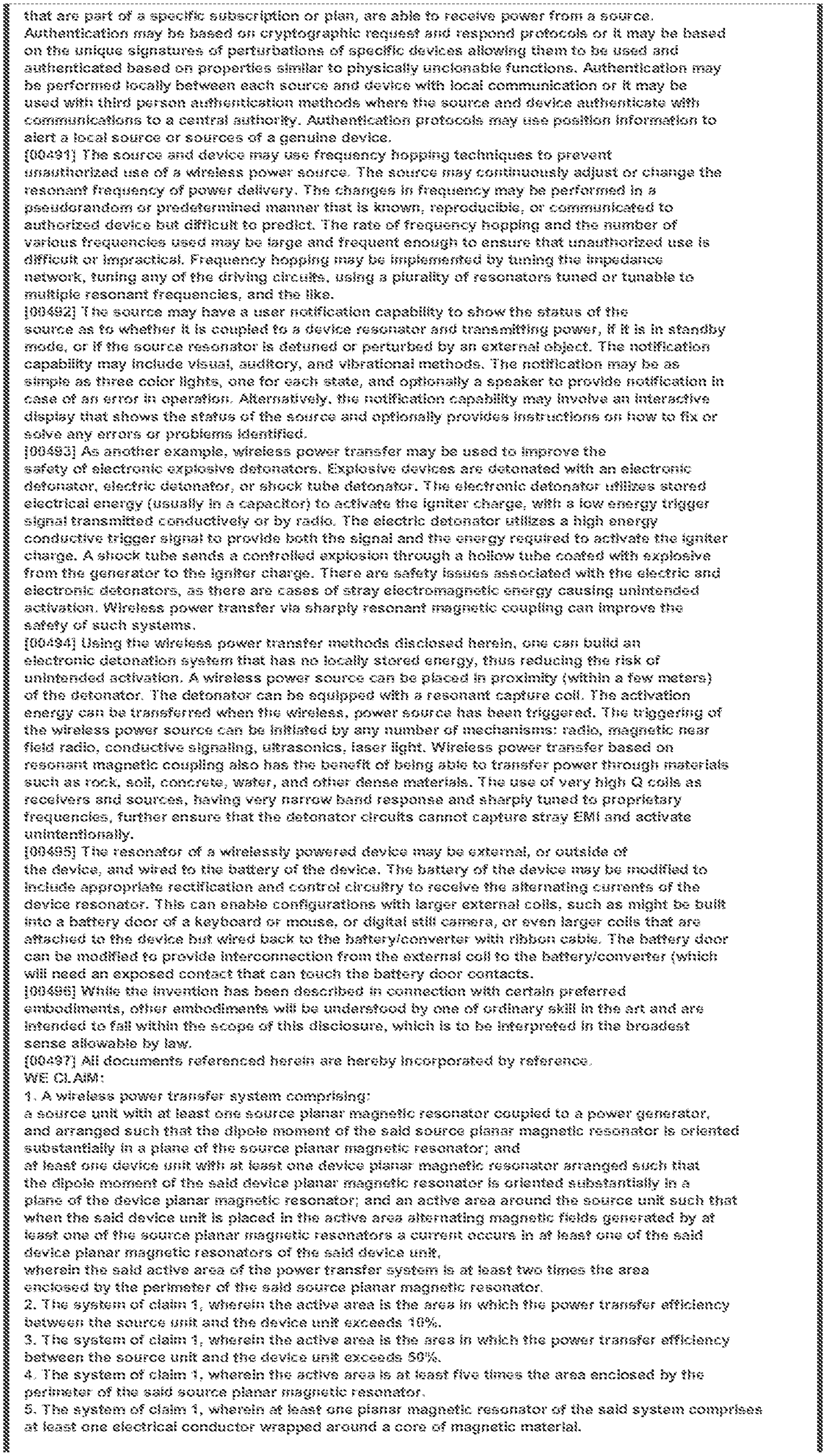
[00486] The source and device may sense, transmit, process and utilize position and location information on any other sources and/or devices in a power network. The source and device may capture or use information such as elevation, tilt, latitude and longitude, and the like from a variety of sensors and sources that may be built into the source and device or may be part of a component the source or device connect. The positioning and orientation information may include sources such as global positioning sensors (GPS), compasses, accelerometers, pressure sensors, atmospheric barometric sensors, positioning systems which use Wi-Fi or cellular network signals, and the like. The source and device may use the position and location information to find nearby wireless power transmission sources. A source may broadcast or communicate with a central station or database identifying its location. A device may obtain the source location information from the central station or database or from the local broadcast and guide a user or an operator to the source with the aid of visual, vibrational, or auditory signals. Sources and devices may be nodes in a power network, in a communications network, in a sensor network, in a navigational network, and the like or in kind of combined functionality network.

[00487] The position and location information may also be used to optimize or coordinate power delivery. Additional information about the relative position of a source and a device may be used to optimize magnetic field direction and resonator alignment. The orientation of a device and a source which may be obtained from accelerometers and magnetic sensors, and the like, for example, may be used to identify the orientation of resonators and the most favorable direction of a magnetic field such that the magnetic flux is not blocked by the device circuitry. With such information a source with the most favorable orientation, or a combination of sources, may be used. Likewise, position and orientation information may be used to move or provide feedback to a user or operator of a device to place a device in a favorable orientation or location to maximize power transmission efficiency, minimize losses, and the like.

[00488] The source and device may include power metering and measuring circuitry and capability. The power metering may be used to track how much power was delivered to a device or how much power was transferred by a source. The power metering and power usage information may be used in fee based power delivery arrangements for billing purposes. Power metering may be also be used to enable power delivery policies to ensure power is distributed to multiple devices according to specific criteria. For example, the power metering may be used to categorize devices based on the amount of power they received and priority in power delivery may be given to those having received the least power. Power metering may be used to provide tiered delivery services such as "guaranteed power" and "best effort power" which may be billed at separate rates. Power metering may be used to institute and enforce hierarchical power delivery structures and may enable priority devices to demand and receive- more power under certain circumstances or use scenarios.

[00489] Power metering may be used to optimize power delivery efficiency and minimize absorption and radiation losses. Information related to the power received by devices may be used by a source in conjunction with information about the power output of the source to identify unfavorable operating environments or frequencies. For example, a source may compare the amount of power which was received by the devices and the amount of power which it transmitted to determine if the transmission losses may be unusually or unacceptably large. Large transmission losses may be due to an unauthorized device receiving power from the source and the source and other devices may initiate frequency hopping of the resonance frequency or other defensive measures to prevent or deter unauthorized use. Large transmission losses may be due to absorption losses for example, and the device and source may tune to alternate resonance frequencies to minimize such losses. Large transmission losses may also indicate the presence of unwanted or unknown objects or materials and the source may turn down or off its power level until the unwanted or unknown object is removed or identified, at which point the source may resume powering remote devices.

[00490] The source and device may include authentication capability. Authentication may be used to ensure that only compatible sources and devices are able to transmit and receive power. Authentication may be used to ensure that only authentic devices that are of a specific manufacturer and not clones or devices and sources from other manufacturers, or only devices



that are part of a specific subscription or plan, are able to receive power from a source. Authentication may be based on cryptographic request and respond protocols or it may be based on the unique signatures of perturbations of specific devices allowing them to be used and authenticated based on properties similar to physically unclonable functions. Authentication may be performed locally between each source and device with local communication or it may be used with third person authentication methods where the source and device authenticate with communications to a central authority. Authentication protocols may use position information to alert a local source or sources of a genuine device.

[00491] The source and device may use frequency hopping techniques to prevent unauthorized use of a wireless power source. The source may continuously adjust or change the resonant frequency of power delivery. The changes in frequency may be performed in a pseudorandom or predetermined manner that is known, reproducible, or communicated to authorized device but difficult to predict. The rate of frequency hopping and the number of various frequencies used may be large and frequent enough to ensure that unauthorized use is difficult or impractical. Frequency hopping may be implemented by tuning the impedance network, tuning any of the driving circuits, using a plurality of resonators tuned or tunable to multiple resonant frequencies, and the like.

[00492] The source may have a user notification capability to show the status of the source as to whether it is coupled to a device resonator and transmitting power, if it is in standby mode, or if the source resonator is detuned or perturbed by an external object. The notification capability may include visual, auditory, and vibrational methods. The notification may be as simple as three color lights, one for each state, and optionally a speaker to provide notification in case of an error in operation. Alternatively, the notification capability may involve an interactive display that shows the status of the source and optionally provides instructions on how to fix or solve any errors or problems identified.

[00493] As another example, wireless power transfer may be used to improve the safety of electronic explosive detonators. Explosive devices are detonated with an electronic detonator, electric detonator, or shock tube detonator. The electronic detonator utilizes stored electrical energy (usually in a capacitor) to activate the igniter charge, with a low energy trigger signal transmitted conductively or by radio. The electric detonator utilizes a high energy conductive trigger signal to provide both the signal and the energy required to activate the igniter charge. A shock tube sends a controlled explosion through a hollow tube coated with explosive from the generator to the igniter charge. There are safety issues associated with the electric and electronic detonators, as there are cases of stray electromagnetic energy causing unintended activation. Wireless power transfer via sharply resonant magnetic coupling can improve the safety of such systems.

[00494] Using the wireless power transfer methods disclosed herein, one can build an electronic detonation system that has no locally stored energy, thus reducing the risk of unintended activation. A wireless power source can be placed in proximity (within a few meters) of the detonator. The detonator can be equipped with a resonant capture coil. The activation energy can be transferred when the wireless, power source has been triggered. The triggering of the wireless power source can be initiated by any number of mechanisms: radio, magnetic near field radio, conductive signaling, ultrasonics, laser light. Wireless power transfer based on resonant magnetic coupling also has the benefit of being able to transfer power through materials such as rock, soil, concrete, water, and other dense materials. The use of very high Q coils as receivers and sources, having very narrow band response and sharply tuned to proprietary frequencies, further ensure that the detonator circuits cannot capture stray EMI and activate unintentionally.

[00495] The resonator of a wirelessly powered device may be external, or outside of the device, and wired to the battery of the device. The battery of the device may be modified to include appropriate rectification and control circuitry to receive the alternating currents of the device resonator. This can enable configurations with larger external coils, such as might be built into a battery door of a keyboard or mouse, or digital still camera, or even larger coils that are attached to the device but wired back to the battery/converter with ribbon cable. The battery door can be modified to provide interconnection from the external coil to the battery/converter (which will need an exposed contact that can touch the battery door contacts.

[00496] While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law.

[00497] All documents referenced herein are hereby incorporated by reference.

WE CLAIM:

1. A wireless power transfer system comprising:

a source unit with at least one source planar magnetic resonator coupled to a power generator, and arranged such that the dipole moment of the said source planar magnetic resonator is oriented substantially in a plane of the source planar magnetic resonator; and

at least one device unit with at least one device planar magnetic resonator arranged such that the dipole moment of the said device planar magnetic resonator is oriented substantially in a plane of the device planar magnetic resonator; and an active area around the source unit such that when the said device unit is placed in the active area alternating magnetic fields generated by at least one of the source planar magnetic resonators a current occurs in at least one of the said device planar magnetic resonators of the said device unit,

wherein the said active area of the power transfer system is at least two times the area enclosed by the perimeter of the said source planar magnetic resonator.

2. The system of claim 1, wherein the active area is the area in which the power transfer efficiency between the source unit and the device unit exceeds 10%.

3. The system of claim 1, wherein the active area is the area in which the power transfer efficiency between the source unit and the device unit exceeds 50%.

4. The system of claim 1, wherein the active area is at least five times the area enclosed by the perimeter of the said source planar magnetic resonator.

5. The system of claim 1, wherein at least one planar magnetic resonator of the said system comprises at least one electrical conductor wrapped around a core of magnetic material.

6. The system of claim 5, further comprising at least one tunable electrical component network, wherein the said electrical component network is coupled to the at least one electrical conductor.

7. The system of claim 6, wherein at least one electrical component network comprises at least one capacitor.

8. The system of claim 6, wherein at least one electrical component network comprises at least one inductor.

9. The system of claim 6, wherein at least one electrical component network comprises at least one tunablecomponent.

10. The system of claim 6, wherein the electrical component network is connected to the at least one electrical conductor using a direct physical connection.

11. The system of claim 5, wherein the electrical conductor is wrapped around the core of magnetic material forming loops of which some are not coaxial.

12. The system of claim 5, wherein at least one planar magnetic resonator has a quality factor Q>100.

13. The system of claim 5, wherein the smallest dimension of the core is at most 30% of the largest dimension.

14. The system of claim 5, wherein the electrical conductor comprises printed conductor traces.

15. The system of claim 1, wherein at least one source planar magnetic resonator comprises two conductors wrapped around orthogonal axes of a core of magnetic material.

16. The system of claim 5, wherein the source unit is integrated with an electronic device.

17. The system of claim 1, further comprising a repeater resonator configured to improve coupling between the source resonator and the device resonator.

18. The system of claim 5, wherein at least one resonator further comprises a metallic shield positioned to reduce the effects of a lossy object on the parameters of the resonator.

19. A wireless power transfer method comprising the steps of:

providing a source unit with at least one source planar magnetic resonator coupled to a power generator and arranged such that the dipole moment of the said planar source magnetic resonator is oriented substantially in a plane of the source planar magnetic resonator;

providing at least one device unit with at least one device planar magnetic resonator and arranged such that the dipole moment of the said device planar magnetic resonator is oriented substantially in the plane of the device planar magnetic resonator;

providing power to at least one of the said source planar magnetic resonators through the power generator to generate an active area of alternating electromagnetic field around the source unit; and

positioning the at least one device unity in the active area around the source unit to receive useful power from the source.

wherein the said active area is at least two times the area enclosed by the perimeter of the said source planar magnetic resonator.

20. The method of claim 18 wherein the active area is the area in which the power transfer efficiency between the source unit and the device unit exceeds 1%.

21. The method of claim 18, wherein at least one planar magnetic resonator of the said method comprises at least one electrical conductor wrapped around a core of magnetic material.

22. The method of claim 18, wherein at least one planar magnetic resonator has a quality factor greater than 100.

23. A wireless power transfer system comprising:

a source unit with at least one source planar magnetic resonator coupled to a power generator, and arranged such that the dipole moment of the said source planar magnetic resonator is oriented substantially in a plane of the source planar magnetic resonator; and

at least one device unit with at least one device planar magnetic resonator arranged such that the dipole moment of the said device planar magnetic resonator is oriented substantially in a plane of the device planar magnetic resonator,

wherein source and device resonators are positioned to point the dipole moments of the resonators in a substantially parallel direction and the source and device resonators are substantially on different planes.

24. The system of claim 23, wherein at least one planar magnetic resonator of the said system comprises at least one electrical conductor wrapped around a core of magnetic material.

25. The system of claim 23, wherein at least one planar magnetic resonator has a quality factor greater than 100.

26. The system of claim 23 wherein the dipole moments are aligned to achieve useful energy transfer.

27. The system of claim 23 wherein the direction of at least one of the dipole moments may be varied to maximize the coupling between the source unit resonator and the device unit resonator.

28. A wireless power transfer apparatus comprising:

a first planar magnetic resonator, having an active area around the resonator, the resonator arranged such that the dipole moment of said first planar magnetic resonator is oriented substantially in a plane of the first planar magnetic resonator,

wherein the first planar magnetic resonator is configured for energy transfer with a second planar magnetic resonator structure when the second planar magnetic resonator structure is positioned inside the active area of the first magnetic resonator, and

wherein the said active area of the first planar magnetic resonator is at least two times the area enclosed by the perimeter of the first planar magnetic resonator.

29. The apparatus of claim 28, wherein the active area is the area in which the power transfer efficiency exceeds 1%.

30. The apparatus of claim 28, wherein the active area is the area in which the power transfer efficiency exceeds 10%.

31. The apparatus of claim 29, wherein the active area is at least five times the area enclosed by the perimeter of the first planar magnetic resonator.

32. The apparatus of claim 29, wherein the first planar magnetic resonator comprises at least one electrical conductor wrapped around a core of magnetic material.

33. A wireless power transfer source comprising:

a source unit having an active area around the unit, the source unit comprising at least one source planar magnetic resonator coupled to a power generator, and arranged such that the dipole moment of the said source planar magnetic resonator is oriented substantially in a plane of the

source planar magnetic resonator,
wherein the source unit is adapted for energy transfer with at least one device unit with at least one device planar magnetic resonator arranged such that the dipole moment of the said device planar magnetic resonator is oriented substantially in a plane of the device planar magnetic resonator,
wherein the said active area of the source unit is at least two times the area enclosed by the perimeter of the source planar magnetic resonators of the source unit.
34. The source of claim 33, wherein the active area is the area in which the power transfer efficiency exceeds 1%.
35. The source of claim 33, wherein the active area is the area in which the power transfer efficiency exceeds 10%.
36. The source of claim 33, wherein the active area is at least five times the area enclosed by the perimeter of the first planar magnetic resonator.
37. The source of claim 33, wherein the first planar magnetic resonator comprises at least one electrical conductor wrapped around a core of magnetic material.

Described herein are improved capabilities for a source resonator having a Q- factor Q1>100 and a characteristic
size x1 coupled to an energy source, and a second resonator having a Q-factor Q2>100 and a characteristic size x2 coupled to an
energy drain located a distance D from the source resonator, where the source resonator and the second resonator are coupled to
exchange energy wirelessly among the source resonator and the second resonator.

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Bibliographic data: JP2002097005 (A) — 2002-04-02

SILICON NITRIDE-BASED POWDER AND ITS MANUFACTURING METHOD, SILICON NITRIDE-BASED SINTERED COMPACT AND ITS MANUFACTURING METHOD, AND CIRCUIT BOARD

Inventor(s):	IMAMURA TOSHIYUKI; SOFUE MASAHISA; HAMAYOSHI SHIGEYUKI +	
Applicant(s):	HITACHI METALS LTD +	
Classification:	**- international:**	***C01B21/068; C04B35/626;*** (IPC1-7): C01B21/068; C04B35/626
	- European:	
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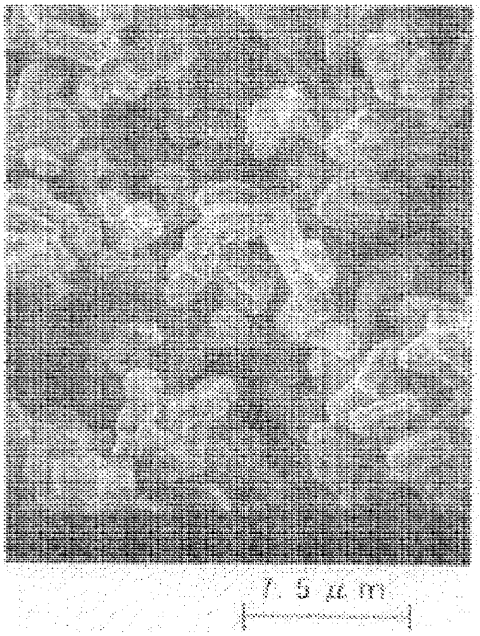
Priority number (s):	JP20000284957 20000920	
Also published as:	JP3565425 (B2)	

Abstract of JP2002097005 (A)

PROBLEM TO BE SOLVED: To provide a highly thermal conductive-type silicon nitride-based sintered compact having an excellent mechanical strength and the enhanced thermal conductivity more than before without the anisotropy in the direction of thermal conduction.
SOLUTION: For the method for manufacturing a silicon nitride-based power, the raw material contains oxygen in the range of >=0.02 wt.%, <2 wt.% in SiO2 conversion and has a specific surface area of >=0.5 m2/g, is characteristically heated above 1,400 degree C in the non-acidic atmosphere of nitrogen or nitrogen/hydrogen.



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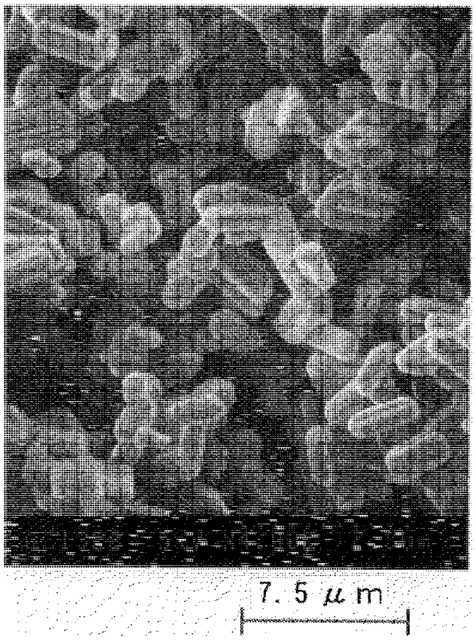
最終頁に続く

(54)【発明の名称】 窒化ケイ素質粉末、窒化ケイ素質粉末の製造方法、窒化ケイ素質焼結体、窒化ケイ素質焼結体の製造方法および回路基板

(57)【要約】

【課題】 機械的強度に優れ、熱伝導の方向に異方性を持たずに従来に比べて熱伝導率を高めた高熱伝導型窒化ケイ素質焼結体を提供する。

【解決手段】 SiO_2換算として0.02wt％以上、２wt％未満の酸素を含み、比表面積が0.5m^2/g以上である窒化ケイ素質粉末原料を窒素あるいは窒素/水素の非酸性雰囲気下にて、温度1400℃以上で熱処理することを特徴とする窒化ケイ素質粉末の製造方法。



【特許請求の範囲】

【請求項１】　ＳｉＯ$_2$換算として0.02ｗｔ％以上、２ｗｔ％未満の酸素を含み、比表面積が0.5m^2/g以上である窒化ケイ素質粉末原料を窒素あるいは窒素/水素の非酸性雰囲気下にて、温度1400℃以上で熱処理することを特徴とする窒化ケイ素質粉末の製造方法。

【請求項２】　β分率が30～100％であり、酸素量が0.5ｗｔ％以下であり、平均粒子径が0.2～10μmであり、アスペクト比が10以下であることを特徴とする窒化ケイ素質粉末。

【請求項３】　Ｆｅ含有量およびＡｌ含有量がそれぞれ100ppm以下である請求項２に記載の窒化ケイ素質粉末。

【請求項４】　β分率が30～100％であり、酸素量が0.5ｗｔ％以下であり、平均粒子径が0.2～10μmであり、アスペクト比が10以下である窒化ケイ素質粉末１～50重量部と、平均粒子径が0.2～４μmのα型窒化ケイ素粉末99～50重量部とを配合し、焼結することを特徴とする窒化ケイ素質焼結体の製造方法。

【請求項５】　含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（ＲＥ$_x$Ｏ$_y$）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％であることを特徴とする窒化ケイ素質焼結体。

【請求項６】　常温における熱伝導率が100～300W/（m・K）であり、常温における３点曲げ強度が600～1500MPaである高強度・高熱伝導性に富んだ請求項５に記載の窒化ケイ素質焼結体。

【請求項７】　含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（ＲＥ$_x$Ｏ$_y$）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％であり、かつ（ＭｇＯ／ＲＥ$_x$Ｏ$_y$）で表される重量比が１～70である請求項５または６に記載の窒化ケイ素質焼結体。

【請求項８】　含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（ＲＥ$_x$Ｏ$_y$）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％である窒化ケイ素質焼結体を用いて構成されることを特徴とする高強度・高熱伝導性に富んだ回路基板。

【発明の詳細な説明】

【０００１】

【発明の属する技術分野】本発明は、半導体用基板や発熱素子用ヒートシンク等の電子部品用部材、あるいは一般機械器具用部材、溶融金属用部材、または熱機関用部材等の構造用部材として好適な高強度・高熱伝導性に富んだ窒化ケイ素質焼結体およびその製造方法、その製造に用いる好適な窒化ケイ素質粉末およびその製造方法、ならびに前記窒化ケイ素質焼結体を用いて構成される回路基板に関する。

【０００２】

【従来の技術】窒化ケイ素質焼結体は、高温強度特性および耐摩耗性等の機械的特性に加え、耐熱性、低熱膨張性、耐熱衝撃性、および金属に対する耐食性に優れているので、従来からガスタービン用部材、エンジン用部材、製鋼用機械部材、あるいは溶融金属の耐溶部材等の各種構造用部材に用いられている。また、高い絶縁性を利用して電気絶縁材料として使用されている。

【０００３】近年、高周波トランジスタ、パワーＩＣ等の発熱量の大きい半導体素子の発展に伴い、電気絶縁性に加えて良好な放熱特性を得るために高い熱伝導率を有するセラミックス基板の需要が増加している。このようなセラミックス基板として、窒化アルミニウム基板が用いられているが、機械的強度や破壊靭性等が低く、基板ユニットの組立て工程での締め付けによって割れを生じるという問題がある。また、Ｓｉ半導体素子を窒化アルミニウム基板に実装した回路基板では、Ｓｉと窒化アルミニウム基板との熱膨張差が大きいため、熱サイクルにより窒化アルミニウム基板にクラックや割れを発生し実装信頼性が低下するという問題がある。

【０００４】そこで、窒化アルミニウム基板より熱伝導率は劣るものの、熱膨張率がＳｉに近く、かつ機械的強度、破壊靭性および耐熱疲労特性に優れる高熱伝導窒化ケイ素質焼結体からなる基板が注目され、種々の提案が行われている。

【０００５】例えば、特開平４－１７５２６８号公報には、実質的に窒化ケイ素からなり、不純物として含有されるＡｌおよび酸素が共に3.5重量％以下であり、密度が3.15Mg/m3（3.15g/cm3）以上であり、40W/(m・K)以上の熱伝導率を有する窒化ケイ素質焼結体が記載されている。

【０００６】また、特開平９－３０８６６号公報には、85～99重量％のβ型窒化ケイ素粒と残部が酸化物または酸窒化物の粒界相とから構成され、粒界相中にＭｇ，Ｃａ，Ｓｒ，Ｂａ，Ｙ，Ｌａ，Ｃｅ，Ｐｒ，Ｎｄ，Ｓｍ，Ｇｄ，Ｄｙ，Ｈｏ，ＥｒおよびＹｂのうちから選ばれる少なくとも１種の元素を0.5～10重量％含有し、粒界相中のＡｌ元素含有量が１重量％以下であり、気孔率が５％以下であり、かつβ型窒化ケイ素粒のうちで短軸径５μm以上を持つものの割合が10～60体積％である窒化ケイ素質焼結体が記載されている。

【０００７】また、日本セラミックス協会1996年年会講演予稿集１Ｇ１１、同１Ｇ１２、および特開平１０－１９４８４２号公報には、原料粉末に柱状の窒化ケイ素粒子またはウイスカーを予め添加し、ドクターブレード法あるいは押出成形法を用いて、この粒子を２次元的に配向させた成形体を得た後、焼成することにより熱伝導に異方性を付与して特定方向の熱伝導率を高めた窒化ケイ

素質焼結体が記載されている。

【０００８】窒化ケイ素の熱伝導率の向上あるいは曲げ強度と破壊靭性を両立させる微構造の構築のために用いられるβ粉末の作製方法として、窒化ケイ素原料粉末を所定量のY_2O_3およびSiO_2と混合し、混合物を窒素等の非酸化性雰囲気中で焼成して得る方法が、J．Ceram. Soc. Japan., 101[9] 1078-80(1993)に記載されている。

【０００９】さらに、窒化ケイ素粉末のβ分率を向上させる方法として、比表面積が１m^2/g以上、SiO_2換算として２～５重量%の酸素を含んだ窒化ケイ素質原料粉末を窒素等の非酸化性雰囲気中で熱処理する方法が特開平６－２６３４１０号公報に記載されている。

【００１０】

【発明が解決しようとする課題】前述の特開平４－１７５２６８号公報では40W/(m・K)以上の熱伝導率が得られているが、さらに熱伝導率を高めた、機械的強度に優れる材料が望まれている。また、特開平９－３０８６６号公報、特開平１０－１９４８４２号等公報に記載の方法では、窒化ケイ素質焼結体中に巨大な柱状粒子を得るために、成長核となる種結晶あるいはウィスカーを予め添加し、2000℃以上および10.1MPa（100気圧）以上の窒素雰囲気下での焼成が不可欠である。したがって、ホットプレスあるいはHIP等の特殊な高温・高圧設備が必要となりコストアップを招来する。また、窒化ケイ素粒子を配向させた成形体を得るための成形プロセスが複雑であるため、生産性性が著しく低下するという問題がある。

【００１１】また、前述のJ．Ceram. Soc. Japan, 101[9] 1078-80(1993)に記載されている手法では、スラグとして使用するY_2O_3量およびSiO_2量が多いため、得られる処理粉末の凝集が強くなり、粉砕乳鉢等で破砕することが必須となる。また、粒子表面に付着した酸化物除去ための酸による溶解処理、さらに粒度調整のための分級処理が必要であり、プロセスが煩雑になる。また、得られた処理粉末中には使用した助剤成分が固溶するといった難点がある。

【００１２】さらに、前述の特開平６－２６３４１０号公報に記載される手法は、β分率が95%以上の窒化ケイ素質粉末を工業的に安価に製造することを可能にしている。これによるとβ分率を向上させる手法として、SiO_2換算として２～５重量%の酸素を含み、比表面積が1m^2/g以上である窒化ケイ素質粉末を、非酸性雰囲気下、温度1500℃以上で熱処理することを特徴としている。当該発明で使用される窒化ケイ素質粉末に含まれる酸素量をSiO_2換算で２～５wt%と規定する理由には、該値が２wt%未満では、窒化ケイ素質粉末のβ分率の増大効果が小さく、また、β分率にばらつきが生じやすいこと。一方、該値が５wt%を超えると、熱処理後の窒化ケイ素質粉末にSiO_2が残留し窒化ケイ素質粉末の粉末特性が悪くなるとしている。また、粒度については、当該発明の処理を均一かつ短時間に行うために、比表面積が1m^2/g以上の微粉であることが好ましいとしている。しかしながら、実施例には、β分率が９５%以上の処理粉末が得られているものの、低温・短時間にて処理を完了させることを目的として、SiO_2換算で２～５wt%の酸素量である窒化ケイ素質原料粉末を用いているために、得られる粉末の酸素量はいずれも1.2wt%以上である。また、原料粉末の酸素量を所定量に調整するために予めSiO_2粉末を添加したり、あるいは酸素雰囲気中での熱処理を必要とするといった難点がある。さらに、当該発明の方法によって得られる窒化ケイ素質粉末は、熱処理によって凝集しているので、使用に際しては、例えばボールミル、ロールークラッシャー等を用いて解砕する工程を要するといった難点がある。

【００１３】本発明は上記従来の問題に鑑みてなされたものであり、2000℃以上でかつ10.1MPa（100気圧）以上の高温・高圧焼成といったコストの高い焼成法を必要とせず、機械的強度に優れ、熱伝導の方向に異方性を持たずに従来に比べて熱伝導率を高めた高熱伝導型窒化ケイ素質焼結体を提供することを課題とする。また本発明の課題は、窒化ケイ素質粉末のβ分率、含有酸素量、不純物量およびα型窒化ケイ素質粉末との混合比等を規定することにより、高い熱伝導率および高い強度を有する窒化ケイ素質焼結体およびその製造方法を提供することである。また本発明の課題は、高強度・高熱伝導性の発現のために用いる窒化ケイ素質粉末およびその製造方法を提供することである。また本発明の課題は前記高強度・高熱伝導性に富んだ窒化ケイ素質焼結体用いて構成される放熱性の良好な回路基板を提供することである。

【００１４】

【課題を解決するための手段】本発明者らは上記課題を達成するため、用いる窒化ケイ素質粉末のβ分率、含有酸素量、不純物およびα粉末との混合比等の粉末特性を規定することにより、安定して100W/(m K)以上の熱伝導率と十分な曲げ強度を有する窒化ケイ素質焼結体が得られることを発見した。また、焼結助剤をMgO基として焼結性を向上させ、かつLa，YおよびYbを含む希土類元素（RE）から選択される少なくとも１種の元素を特定量含有させることが有効なことを発見し、本発明に至った。

【００１５】本発明の窒化ケイ素質粉末は、例えば、金属シリコン直接窒化法、シリカ還元法またはシリコンイミド分解法による原料の窒化ケイ素質粉末を用い、窒素または窒素/水素の混合雰囲気中で1400℃～1950℃×５～20時間熱処理することにより製造できる。高いβ分率および低酸素化を実現するために、熱処理条件を1800℃～1900℃×５～20時間にすることがより好ましい。なお、1800℃以上の熱処理では窒化ケイ素の分解を避けるために1.0MPa（10気圧）以上の窒素あるいは窒素/水素

雰囲気中で行うことが望ましい。熱処理後の含有酸素量を0.5ｗｔ％以下にするために、初期含有酸素量をSiO_2量換算で２ｗｔ％未満とすることが好ましい。またＦｅ，Ａｌ等の不純物量を極力少なく抑える目的からイミド分解法による高純度原料の窒化ケイ素質粉末の使用がより好ましい。原料粉末充填に共する容器はカーボン製またはＢＮ製のいずれでもよいが、カーボン製ヒーターおよびカーボン製断熱材仕様の熱処理炉を使用する場合は過度のＣＯ還元性雰囲気の作用を抑制するためにＢＮ製のものが望ましい。

【００１６】本発明の窒化ケイ素質粉末は、含有酸素量の少ない原料粉末を用いるため助剤として作用するSiO_2成分が少なく、さらにα型窒化ケイ素質粉末からβ型窒化ケイ素質粉末への相転移は気相を介しているため、結果として低酸素含有量になり、熱処理後も凝集がなく、粉砕ならびに表面酸化物除去のための酸処理工程を必要としない。また、Y_2O_3等の酸化物を粒子成長のための焼結助剤として用いないため、これら助剤成分の窒化ケイ素質粉末内への固溶を避けることができる。すなわち、本発明の窒化ケイ素質粉末はβ分率が30～100％であり、酸素量が0.5wt％以下であり、平均粒子径が0.2～10μmであり、アスペクト比が10以下であることを特徴とする。さらにＦｅ含有量およびＡｌ含有量がそれぞれ100ppm以下であることを特徴とする。

【００１７】また本発明の窒化ケイ素質焼結体の製造方法は、β分率が30～100％であり、酸素量が０．５ｗｔ％以下であり、平均粒子径が0.2～10μｍであり、アスペクト比が10以下である窒化ケイ素質粉末１～59重量部と、平均粒子径が0.2～４μmのα型窒化ケイ素質粉末99～50重量部とを配合し、焼結することを特徴とする。前記窒化ケイ素質粉末のβ分率が30％未満では成長核としての効果はあるものの部分的に核として作用するため、異常粒成長が起こり、最終的に得られる窒化ケイ素質焼結体のミクロ組織中に大きな粒子を均一分散できなくなり曲げ強度が低下する。したがって、窒化ケイ素質粉末のβ分率は30％以上が望ましい。また前記窒化ケイ素質粉末の平均粒子径が0.2μm未満では前記同様に柱状粒子が均一に発達したミクロ組織を呈する窒化ケイ素質焼結体を得られず、熱伝導率および曲げ強度を高めることが困難である。前記窒化ケイ素質粉末の平均粒子径が10μmより大きいと焼結体の窒化ケイ素質緻密化が阻害される。したがって、窒化ケイ素質粉末の平均粒子径は0.2～10μmが好ましい。また、アスペクト比が10超の場合は窒化ケイ素質焼結体の緻密化が阻害され、結果として、常温における３点曲げ強度は600MPa未満になる。したがって、窒化ケイ素質粉末のアスペクト比を10以下とすることが好ましい。

【００１８】本発明の窒化ケイ素質焼結体は、含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（RE_xO_y）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％であることを特徴とする。前記酸化物換算含有量の合計が0.6ｗｔ％未満では焼結時の緻密化作用が不十分となり相対密度が95％未満となり好ましくなく、７ｗｔ％超では窒化ケイ素質焼結体の第２のミクロ組織成分である熱伝導率の低い粒界相の量が過剰となり焼結体の熱伝導率が100W/(m・K)未満になる。これら窒化ケイ素質含有量の合計は0.6～４ｗｔ％がより好ましい。前記窒化ケイ素質焼結体は、常温における熱伝導率が100～300W/（m・K）であり、常温における３点曲げ強度が600～1500MPaであり高強度・高熱伝導性に富んでいる。また前記窒化ケイ素質焼結体が、含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（RE_xO_y）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％であり、かつＭｇＯ／ＲＥxOyで表される重量比が１～70である場合に特に高強度・高熱伝導性が向上する。（ＭｇＯ／RE_xO_y）（重量比）が１未満では粒界相中の希土類酸化物の割合が増大するため焼結過程で液相線温度が上昇し難焼結性となり緻密な焼結体が得られない。（ＭｇＯ／RE_xO_y）（重量比）が70超では焼成時におけるＭｇの拡散を抑制することができず焼結体表面に色むらの発生を生じる。ＭｇＯ／ＲＥxOy（重量比）が１～70の範囲にある場合、1650～1850℃の焼結温度で成形体を予備焼成し、次いで1850～1900℃の熱処理を行うと高熱伝導化が顕著になり120w/(m・K)を超える窒化ケイ素質焼結体を得られ特に好ましい。この熱処理による高熱伝導化は窒化ケイ素粒子の成長と、蒸気圧の高いＭｇＯ基とした粒界相成分が効率よく窒化ケイ素質焼結体外へ揮発することの複合効果による。

【００１９】また本発明の回路基板は、含有するＭｇを酸化マグネシウム（ＭｇＯ）換算し、また含有するＬａ，ＹおよびＹｂを含む希土類元素（ＲＥ）から選択される少なくとも１種の元素を酸化物（RE_xO_y）換算し、それら酸化物換算含有量の合計が0.6～７ｗｔ％である窒化ケイ素質焼結体を用いて構成され、従来に比べて耐熱抵抗性および放熱性が優れたものを提供できる。

【００２０】

【発明の実施の形態】前記窒化ケイ素質粉末の酸素量を0.5ｗｔ％以下としたのは、前記窒化ケイ素質粉末を成長核として作用させて窒化ケイ素質焼結体を形成した場合、窒化ケイ素質焼結体を構成する窒化ケイ素質粒子内に固溶する酸素量は、成長核として用いる前記化ケイ素質粉末の酸素量に強く依存し、前記窒化ケイ素質粉末の酸素量が高い程、前記窒化ケイ素質粒子内に固溶する酸素量が高くなる。窒化ケイ素質粒子中に含有される酸素により熱伝導媒体であるフォノンの散乱が発生し、窒化ケイ素質焼結体の熱伝導率が低下する。100W/m.K以上と

いう従来の窒化ケイ素質焼結体では得られなかった高い熱伝導率を発現するには、窒化ケイ素質粉末の含有酸素量を0.5wt%以下に抑えて、最終的に得られる窒化ケイ素質焼結体の酸素量を低減することが必要不可欠である。

【００２１】窒化ケイ素質粉末中のＦｅ含有量およびＡｌ含有量がそれぞれ100ppm超では窒化ケイ素粒子内にＦｅまたはＡｌが顕著に固溶し、この固溶部分で熱伝導媒体であるフォノンの散乱を生じ、窒化ケイ素質焼結体の熱伝導率を低下させる。したがって100W/m・K以上の熱伝導率を得るには窒化ケイ素質粉末中のＦｅ含有量およびＡｌ含有量をそれぞれ100ppm以下に制御することが肝要である。

【００２２】前記β分率が30～100%の窒化ケイ素質粉末とα型窒化ケイ素質粉末との比率は１～50ｗｔ％：99～50ｗｔ％が好ましい。前記β分率が30～100%の窒化ケイ素質粉末の比率が１ｗｔ％未満では成長核としての効果はあるものの、添加量が少ないために作用する成長核の数が少なく、異常粒成長が起こりミクロ組織中に大きな粒子を均一分散できなくなり、曲げ強度が低下する。また、50ｗｔ％超では成長核の数が多くなり、粒成長の過程で、粒子同士が互いに衝突するため成長阻害が起こり、強度は維持できるが、発達した柱状粒子からなる窒化ケイ素質焼結体のミクロ組織を得られず、従来に比べて高い熱伝導率を実現困難になる。

【００２３】ＭｇおよびＹは焼結助剤として有用であり、窒化ケイ素質原料粉末の緻密化に有効である。これらの元素は窒化ケイ素質焼結体を構成する第１ミクロ組織成分である窒化ケイ素質粒子に対する固溶度が小さいので、窒化ケイ素粒子、ひいては窒化ケイ素質焼結体の熱伝導率を高い水準に保つことができる。

【００２４】Ｙと同様に窒化ケイ素質粒子に対する固溶度が小さく、焼結助剤として有用な元素として、Ｌａ，Ｃｅ，Ｎｄ，Ｐｍ，Ｓｍ，Ｅｕ，Ｇｄ，Ｄｙ，Ｈｏ，Ｅｒ，Ｔｍ，ＹｂおよびＬｕの群から選択される少なくとも１種の希土類元素が挙げられる。そのうち、温度および圧力が高くなり過ぎずに焼成ができる点でＬａ，Ｃｅ，Ｇｄ，ＤｙおよびＹｂの群から選択される少なくとも１種の希土類元素が好ましい。

【００２５】本発明の窒化ケイ素質焼結体からなる基板は高強度、高靭性ならびに高熱伝導率の特性を生かして、パワー半導体用基板またはマルチチップモジュール用基板などの各種基板、あるいはペルチェ素子用熱伝板、または各種発熱素子用ヒートシンクなどの電子部品用部材に好適である。

【００２６】本発明の窒化ケイ素質焼結体を半導体素子用基板として用いた場合、半導体素子の作動に伴う繰り返しの熱サイクルを受けたときの前記基板のクラックの発生が抑えられ、耐熱衝撃性ならびに耐熱サイクル性が著しく向上し、信頼性に優れたものとなる。また、高出力化および高集積化を指向する半導体素子を搭載した場合でも、熱抵抗特性の劣化が少なく、優れた放熱特性を発揮する。さらに、優れた機械的特性により本来の基板材料としての機能だけでなく、それ自体が構造部材を兼ねることができるため、基板ユニット自体の構造を簡略化できる。

【００２７】また、本発明の窒化ケイ素質焼結体は、上述の電子部品用部材以外に熱衝撃および熱疲労の耐熱抵抗特性が要求される材料に幅広く利用できる。構造用部材として、各種の熱交換器部品や熱機関用部品、アルミニウムや亜鉛等の金属溶解の分野で用いられるヒーターチューブ、ストークス、ダイカストスリーブ、溶湯攪拌用プロペラ、ラドル、あるいは熱電対保護管等に適用できる。また、アルミニウム、亜鉛等の溶融金属めっきラインで用いられるシンクロール、サポートロール、軸受、あるいは軸等に適用することにより、急激な加熱や冷却に対して耐割れ性に富んだ部材となり得る。また、鉄鋼あるいは非鉄の加工分野では、圧延ロール、スキーズロール、ガイドローラ、線引きダイス、あるいは工具用チップ等に用いれば、被加工物との接触時の放熱性が良好なため、耐熱疲労性および耐熱衝撃性を改善することができ、これにより摩耗が少なく、熱応力割れを生じにくくできる。

【００２８】さらに、スパッタターゲット部材にも適用でき、例えば磁気記録装置のＭＲヘッド、ＧＭＲヘッド、またはＴＭＲヘッドなどに用いられる電気絶縁膜の形成や、熱転写プリンターのサーマルヘッドなどに用いられる耐摩耗性皮膜の形成に好適である。スパッタして得られる被膜は、本質的に高熱伝導特性を持つとともに、スパッタレートも十分高くでき、被膜の電気的絶縁耐圧が高いものとなる。このため、このスパッタターゲットで形成したＭＲヘッド、ＧＭＲヘッド、またはＴＭＲヘッド用の電気絶縁性被膜は高熱伝導ならびに高耐電圧の特性を有するので、素子の高発熱密度化や絶縁性被膜の薄膜化が図れる。また、このスパッタターゲットで形成したサーマルヘッド用の耐摩耗性被膜は、窒化ケイ素本来の特性により耐摩耗性が良好であることはもとより、高熱伝導性のため熱抵抗が小さくできるので印字速度を高めることができる。

【００２９】

【実施例】以下、実施例により本発明を説明するが、それら実施例により本発明が限定されるものではない。

（実施例１）含有酸素量がＳｉＯ$_2$換算で2.0ｗｔ％未満、平均粒子径0.2～2.0μmのイミド分解法による窒化ケイ素質粉末をＢＮ製るつぼに充填し、次いで常圧～1.0MPa（10気圧）のＮ$_2$雰囲気中にて1400℃～1950℃で１～20時間加熱する熱処理を施し、次いで室温まで冷却した。得られた窒化ケイ素質粉末のβ分率は90～100%であり、酸素含有量は0.2～0.4ｗｔ％であった。図1に得られた窒化ケイ素質粉末例のＳＥＭ観察像を示す。当該粉末のβ分率は１００％、酸素量は0.2ｗｔ％、Ｆｅお

よびＡｌ量はそれぞれ、５０ｐｐｍおよび４０ｐｐｍである。当該粉末には粒子の長軸方向と平行に溝部が形成されており、これは気相を介して粒成長が起こる場合の特徴で、特に酸素量が微量であるほど顕著となることが実証された。当該粉末の次いで、得られたβ型Ｓｉ$_3$Ｎ$_4$を主体とする粉末窒化ケイ素質粉末５～３０重量部と、酸素含有量が0.3～1.5ｗｔ％であり平均粒子径0.5μmのα型窒化ケイ素（Ｓｉ3N4）粉末９９．５～６６重量部とを配合し、さらに焼結助剤として平均粒子径0.2μmのＭｇＯ粉末、および平均粒子径0.2～2.0μmの表１に記載されるＲＥ$_x$Ｏ$_y$粉末（焼結助剤）を配合し、さらに2wt%の分散剤（　　－　GP）を配合し、エタノールを満たしたボールミル容器中に投入し、次いで混合した。得られた混合物を真空乾燥し、次いで目開き150?mの篩を通して造粒した。次に、プレス機により直径20mm×厚さ10mmおよび直径100mm×厚さ15mmのディスク状の成形体を圧力3tonのCIP成形により得た。次いで1750～1900℃，0.9MPa（９気圧）の窒素ガス雰囲気中で５時間焼成した。得られた窒化ケイ素質粉末のＦｅ，Ａｌの不純物分析はプラズマ発光分析（ICP）法により行った。また、酸素含有量は赤外線加熱吸収法により測定した。また得られた窒化ケイ素質粉末のβ分率はＣｕ－Ｋα線を用いたX線回折強度比から式(1)により求めた。

β分率（％）＝$\{(I_{\beta(101)}+I_{\beta(210)})/(I_{\beta(101)}+I_{\beta(210)}+I_{\alpha(102)}+I_{\alpha(201)})\}\times 100$　(1)

$I_{\beta(101)}$　：β型Ｓｉ$_3$Ｎ$_4$の(101)面回折　－強度，

$I_{\beta(210)}$　：β型Ｓｉ$_3$Ｎ$_4$の(210)面回折　－強度，

$I_{\alpha(102)}$　：α型Ｓｉ$_3$Ｎ$_4$の(102)面回折　－強度，

$I_{\alpha(210)}$　：α型Ｓｉ$_3$Ｎ$_4$の(210)面回折　－強度。

また、得られた窒化ケイ素質粉末の平均粒子径および平均アスペクト比は、SEM観察にて観察倍率×2000倍で得られたSEM写真を用い、200μm×500μm視野面積内にある計500個の窒化ケイ素質粒子を無作為に選定して画像解析装置により最小径と最大径を測定し、その平均値を求めて評価した。次に得られた窒化ケイ素質焼結体から、直径10mm×厚さ３mmの熱伝導率および密度測定用の試験片、ならびに縦３mm×横４mm×長さ40mmの曲げ試験片を採取した。密度はマイクロメータにより寸法を測定し、また重量を測定し、算出した。熱伝導率はレーザーフラッシュ法により常温での比熱および熱拡散率を測定し熱伝導率を算出した。３点曲げ強度は常温にてＪＩＳ　Ｒ１６０６に準拠して測定を行った。以上の製造条件の概略および評価結果を、表１，２の試料No.１～11に示す。

【００３０】（比較例１）表１に記載の製造条件とした以外は実施例１と同様にしてβ分率の異なる窒化ケイ素質粉末を作製した。次いで得られた窒化ケイ素質粉末を用いて窒化ケイ素質焼結体を作製し、評価した。以上の製造条件の概略および評価結果を、表１，２の試料No.３１～41に示す。

【００３１】

【表１】

試料No	焼結助剤の含有量（ｗｔ％）			ＭｇＯ／ＲＥ$_x$Ｏ$_y$	温度（℃）	時間（Hr）	窒素圧（MPa）
	ＭｇＯ	Ｒ$_x$Ｏ$_y$					
		Ｙ$_2$Ｏ$_3$					
１	１．０	－	－	－	１７５０	５	０．９
２	７．０	－	－	－	１８５０	５	０．９
３	３．０	０．１	－	３０	１８５０	５	０．９
４	３．０	１．０	－	３．０	１８５０	５	０．９
５	３．０	－	1.0La$_2$O$_3$	３．０	１８５０	５	０．９
６	３．０	－	1.0CeO$_2$	３．０	１８５０	５	０．９
７	３．０	－	1.0Dy$_2$O$_3$	３．０	１８５０	５	０．９
８	３．０	－	1.0Gd$_2$O$_3$	３．０	１８５０	５	０．９
９	３．０	－	1.0Yb$_2$O$_3$	３．０	１８５０	５	０．９
１０	３．０	１．０	1.0La$_2$O$_3$	１．５	１８５０	５	０．９
１１	３．０	１．０	1.0Yb$_2$O$_3$	１．５	１８５０	５	０．９
３１	３．０	－	1.0Yb$_2$O$_3$	３．０	１８５０	５	０．９
３２	３．０	１．０	－	３．０	１８５０	５	０．９
３３	３．０	１．０	－	３．０	１８５０	５	０．９
３４	３．０	１．０	－	３．０	１８５０	５	０．９
３５	３．０	１．０	－	３．０	１９００	５	０．９
３６	３．０	１．０	－	３．０	１８５０	５	０．９
３７	３．０	１．０	－	３．０	１８５０	５	０．９
３８	３．０	１．０	－	３．０	１９００	５	０．９
３９	３．０	１．０	－	３．０	１８５０	５	０．９
４０	０．５	－	－	－	１９００	５	０．９
４１	８．０	－	－	－	１８５０	５	０．９

【００３２】

【表２】

試料No	窒化ケイ素粉末							密度(%)	熱伝導率(W/m.K)	曲げ強度(MPa)
	β分率(%)	不純物量			平均粒子径(μm)	ｱｽﾍﾟｸﾄ比	添加量(wt%)			
		O (wt%)	Fe (ppm)	Al (ppm)						
1	90	0.3	30	50	2	5	10	99.1	110	850
2	90	0.3	30	50	2	5	10	99.0	115	820
3	90	0.3	30	50	2	5	10	99.2	120	810
4	90	0.3	50	70	5	6	15	99.1	125	790
5	100	0.4	50	70	5	6	15	98.6	130	780
6	100	0.4	50	70	5	6	15	99.0	140	765
7	100	0.4	70	50	3	6	30	98.9	155	720
8	100	0.4	70	50	3	4	30	98.7	150	710
9	100	0.4	70	50	2	4	30	98.8	145	720
10	100	0.3	50	50	2	4	30	99.0	140	705
11	100	0.3	50	50	2	5	30	98.9	125	710
31	25	0.3	30	50	2	5	10	99.5	70	520
32	90	1.0	30	50	2	5	10	99.6	70	700
33	90	0.3	500	50	2	5	10	99.0	65	680
34	100	0.3	30	500	2	5	10	99.1	55	680
35	100	0.3	30	30	0.1	5	10	99.2	60	700
36	100	0.2	30	20	12.0	5	10	85.0	60	560
37	100	0.2	50	20	3	15	10	86.0	75	550
38	100	0.2	50	20	3	5	0.5	99.3	77	580
39	100	0.2	50	40	3	5	60	85.0	70	580
40	90	0.4	50	50	2	5	5	81.0	40	500
41	90	0.4	50	50	2	5	5	99.0	55	620

【００３３】表１および表２の試料No.１～11から、以下の知見が得られた。成長核として添加する窒化ケイ素質粉末のβ分率が30％以上、不純物としての酸素含有量が0.5ｗｔ％以下，Ｆｅ含有量が100ppm以下、およびＡｌ含有量が100ppm以下であり、平均粒子径が0.2～10μm、アスペクト比が10以下、およびβ化率が30％以上の前記窒化ケイ素質粉末の配合量を１～50ｗｔ％とし得られた窒化ケイ素質焼結体は、常温における熱伝導率が100w/(m・K)以上になり、かつ常温における３点曲げ強度が600MPa以上になる。従来技術による窒化ケイ素質焼結体の熱伝導率40 w/(m・K)程度であり、熱伝導率を飛躍的に高めることができた。また、焼結助剤として、Ｍｇを酸化マグネシウム（ＭｇＯ）換算し、Ｙ，Ｌａ，Ｃｅ，Ｄｙ，ＧｄおよびＹｂを酸化物（$\mathrm{RE_xO_y}$）換算して、それら酸化物換算含有量の合計が0.6～7.0ｗｔ％であり、かつ（$\mathrm{MgO/RE_xO_y}$）（重量比）が１～70のものは熱伝導率が100w/(m K) 以上でかつ曲げ強度が600MPa以上を得られた。

【００３４】これに対し、表１，２の比較例１の試料No.31～41から以下の知見が得られた。No.31では、窒化ケイ素質粒子のβ分率が30％未満では曲げ強度が顕著に低下し500MPa程度になる。またNo.32では、窒化ケイ素質粉末中に不可避に含有する酸素量が0.5ｗｔ超では熱伝導率が70 w/(m・K)以下に劣化する。またNo.33およびNo.34では、窒化ケイ素質粉末中に含有する不純物のＦｅおよびＡｌの含有量がそれぞれ100ppmを超えると熱伝導率が65 w/(m・K)以下に低下する。またNo.35およびNo.36では、窒化ケイ素質粉末の平均粒子径が0.2μm未満では熱伝導率は60 w/(m・K)以下に低下し、10μmより大きい場合には緻密な焼結体が得られず熱伝導率は60 w/(m・K)以下になり曲げ強度は600MPa以下に低下する。またNo.37では、窒化ケイ素質粉末のアスペクト比が10以上では、緻密な焼結体が得られず、曲げ強度は600MPa以下に低下した。またNo.38およびNo.39では、窒化ケイ素質粉末の添加量が1.0ｗｔ％未満では曲げ強度は600MPa以下に低下し、50ｗｔ％より大きい場合には熱伝導率は70 w/(m K)以下に低下した。またNo.40およびNo.41では、焼結助剤成分が0.6ｗｔ％未満では焼結体の密度が低下し、このために熱伝導率および曲げ強度は著しく低下した。また焼結助剤成分が7.0ｗｔ％を超えると焼成過程で充分なガラス相が生成するので焼結体の緻密化は達成されたが、その反面、低熱伝導相である粒界相の増加により熱伝導率は60 w/(m・K)以下に低下した。

【００３５】（実施例２）実施例１で作製したβ化率が30％以上の窒化ケイ素質粉末に３ｗｔ％ＭｇＯ、1ｗｔ％$\mathrm{Y_2O_3}$の焼結助剤を添加した混合粉末を作製した。次いで、アミン系の分散剤を２ｗｔ％添加したトルエン・ブタノール溶液を満たしたボールミルの樹脂製ポット中に作製した混合粉末および粉砕媒体の窒化ケイ素製ボールを投入し、48時間湿式混合した。次いで、前記ポット中の混合粉末100重量部に対しポリビニル系の有機バインダーを１５重量部および可塑剤（ジメチルフタレート）を５重量部添加し、次いで48時間湿式混合しシート成形用スラリーを得た。この成形用スラリーを調整後、ドクターブレード法によりグリーンシート成形した。次いで、成形したグリーンシートを空気中400～600℃で２～５時間加熱することにより、予め添加し有機バインダー成分を十分に脱脂（除去）した。次いで脱脂体を0.9MPa（９気圧）の窒素雰囲気中で1850℃×５時間の焼成を行い、次いで同窒素雰囲気中で1900℃×24時間の熱処理

を行い、その後室温に冷却した、得られた窒化ケイ素質焼結体シートに機械加工を施し縦50mm×横50mm×厚さ0.6mmの半導体装置用の基板を製造した。この窒化ケイ素質焼結体製基板を用いて図2に示す回路基板を作製した。図2において、回路基板１は作製した前記縦50mm×横50mm×厚さ0.6mmの寸法の窒化ケイ素質焼結体製基板２の表面に銅製回路板３を設け、前記基板２の裏面に銅板４をろう材５により接合して構成されている。この回路基板１に対し、３点曲げ強度の評価および耐熱サイクル試験を行った。その結果、曲げ強度が600MPa以上と大きく、回路基板１の実装工程における締め付け割れおよびはんだ付け工程時の熱応力に起因するクラックの発生する頻度がほぼ見られなくなり、回路基板を使用した半導体装置の製造歩留まりを大幅に改善できることが実証された。また、耐熱サイクル試験は、−40での冷却を20分、室温での保持を10分および180℃における加熱を20分とする昇温/降温サイクルを１サイクルとし、これを繰り返し付与し、基板部にクラック等が発生するまでのサイクル数を測定した。その結果、1000サイクル経過後においても窒化ケイ素質焼結体製基板２の割れや銅製回路板２の剥離はなく、優れた耐久性と信頼性を兼備することが確認された。また、1000サイクル経過後においても耐電圧特性の低下は発生しなかった。

【００３６】

【発明の効果】以上記述の通り、本発明の窒化ケイ素質焼結体は、本来有する高強度/高靭性に加えて高い熱伝導率を具備するので、半導体素子用基板として用いた場合に半導体素子の作動に伴う繰り返しの熱サイクルによって基板にクラックが発生することが少なく、耐熱衝撃性ならびに耐熱サイクル性を著しく向上することができる。

【図面の簡単な説明】

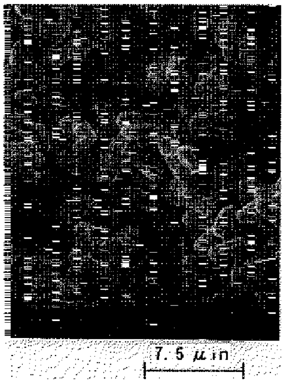
【図１】本発明の代表的な窒化ケイ素質粉末を走査型電子顕微鏡により撮影した写真である。

【図２】本発明の回路基板の要部断面図を示す。

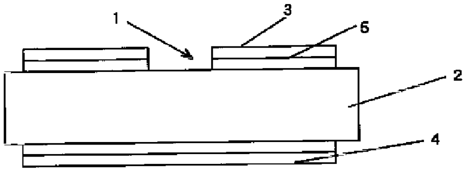
【符号の説明】

１　回路基板、　２　基板、　３　銅製回路板、　４　銅板、　５　ろう材。

【図１】



【図２】



フロントページの続き

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WIRELESS ENERGY TRANSFER SYSTEMS

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Applicant(s):		
Classification:	**- international:**	***H01F38/14; H02J17/00; H04B5/02***
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Abstract not available for JP2012504387 (A)
Abstract of corresponding document: WO2010036980 (A1)

Described herein are improved capabilities for a source resonator having a Q- factor Q1>100 and a characteristic size x1 coupled to an energy source, and a second resonator having a Q-factor Q2>100 and a characteristic size x2 coupled to an energy drain located a distance D from the source resonator, where the source resonator and the second resonator are coupled to exchange energy wirelessly among the source resonator and the second resonator.

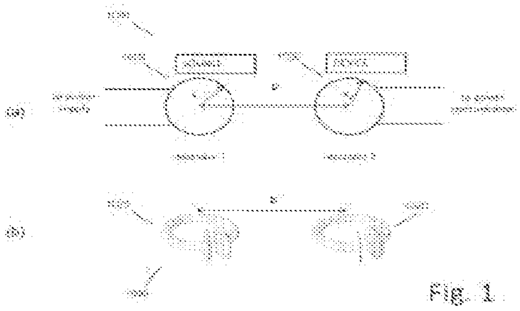

Fig. 1

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最終頁に続く

(54)【発明の名称】無線エネルギー伝達システム

(57)【要約】

エネルギー源に結合され、ＱファクタQ_1＞１００及び特有サイズx_1を有する供給源共振器と、供給源共振器から距離Ｄに位置するエネルギードレインに結合され、ＱファクタQ_2＞１００及び特有サイズx_2を有する第２の共振器とのための改善された能力が説明され、この場合、供給源共振器および第２の共振器が、供給源共振器と第２の共振器との間でワイヤレスでエネルギーを交換するように結合される。

【選択図】図１

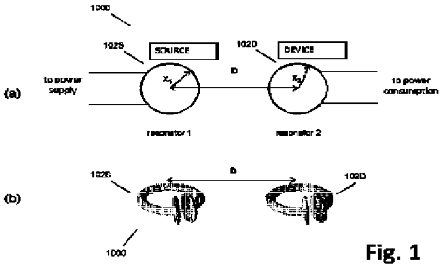


Fig. 1

【特許請求の範囲】

【請求項１】

電力発生装置に結合され、ＱファクタQ_1及び特有サイズx_1を有する供給源共振器と、前記供給源共振器から距離Ｄに位置する負荷に結合され、ＱファクタQ_2及び特有サイズx_2を有する第２の共振器とを含み、前記供給源共振器および前記第２の共振器が、前記供給源共振器と前記第２の共振器との間でワイヤレスでエネルギーを交換するように結合され、$(Q_1 Q_2)^{1/2}>100$である、システム。

【請求項２】

$Q_1<100$である、請求項１に記載のシステム。

【請求項３】

$Q_2<100$である、請求項１に記載のシステム。

【請求項４】

前記供給源共振器および前記第２の共振器と非放射的にエネルギーを伝送するように構成された、ＱファクタQ_3を有する第３の共振器を更に含み、$(Q_1 Q_3)^{1/2}>100$及び$(Q_2 Q_3)^{1/2}>100$である、請求項１に記載のシステム。

【請求項５】

$Q_3<100$である、請求項４に記載のシステム。

【請求項６】

前記供給源共振器が直接的な電気接続で前記電力発生装置に結合される、請求項１に記載のシステム。

【請求項７】

インピーダンスマッチング回路網を更に含み、前記供給源共振器が、直接的な電気接続で前記電力発生装置に結合され及びインピーダンスマッチングされる、請求項１に記載のシステム。

【請求項８】

調整可能な回路を更に含み、前記供給源共振器が、直接的な電気接続でもって、前記調整可能な回路を介して前記電力発生装置に結合される、請求項１に記載のシステム。

【請求項９】

前記直接的な電気接続の少なくとも１つが、前記供給源共振器の共振モードを実質的に保持するように構成されている、請求項６、７、又は８に記載のシステム。

【請求項１０】

前記供給源共振器が、第１の端子、第２の端子、及び中央端子を有し、前記第１の端子と前記中央端子との間のインピーダンス、及び前記第２の端子と前記中央端子との間のインピーダンスが実質的に等しい、請求項６に記載のシステム。

【請求項１１】

前記供給源共振器は、第１の端子、第２の端子、及び中央端子を有する、容量的に装荷されたループを含み、前記第１の端子と前記中央端子との間のインピーダンス、及び前記第２の端子と前記中央端子との間のインピーダンスが実質的に等しい、請求項６に記載のシステム。

【請求項１２】

前記供給源共振器が、インピーダンスマッチング回路網に結合され、前記インピーダンスマッチング回路網が更に、第１の端子、第２の端子、及び中央端子を含み、前記第１の端子と前記中央端子との間のインピーダンス、及び前記第２の端子と前記中央端子との間のインピーダンスが実質的に等しい、請求項６に記載のシステム。

【請求項１３】

前記第１の端子および前記第２の端子が、前記電力発生装置に直接的に結合され、ほぼ１８０度位相がずれている発振信号で駆動される、請求項１０、１１、又は１２に記載のシステム。

【請求項１４】

前記供給源共振器が、共振周波数ω_1を有し、前記第１の端子および前記第２の端子が

、前記電力発生装置に直接的に結合され、前記共振周波数ω_1に実質的に等しい発振信号で駆動される、請求項１０、１１、又は１２に記載のシステム。

【請求項１５】

前記中央端子が、電気接地に接続される、請求項１０、１１、又は１２に記載のシステム。

【請求項１６】

前記供給源共振器が、共振周波数ω_1を有し、前記第１の端子および前記第２の端子が、前記電力発生装置に直接的に結合され、前記共振周波数ω_1に実質的に等しい周波数で駆動される、請求項１５に記載のシステム。

【請求項１７】

前記電力発生装置および前記負荷に結合された複数のコンデンサを含む、請求項２に記載のシステム。

【請求項１８】

前記供給源共振器および前記第２の共振器がそれぞれ、低い損失正接の材料内に収容される、請求項１に記載のシステム。

【請求項１９】

電力変換回路を更に含み、前記第２の共振器が、前記電力変換回路に結合されて、ＤＣ電力を前記負荷に伝える、請求項１に記載のシステム。

【請求項２０】

電力変換回路を更に含み、前記第２の共振器が、前記電力変換回路に結合されて、ＡＣ電力を前記負荷に伝える、請求項１に記載のシステム。

【請求項２１】

電力変換回路を更に含み、前記第２の共振器が、前記電力変換回路に結合されて、ＡＣ及びＤＣ電力を前記負荷に伝える、請求項１に記載のシステム。

【請求項２２】

電力変換回路および複数の負荷を更に含み、前記第２の共振器が、前記電力変換回路に結合され、前記電力変換回路が前記複数の負荷に結合される、請求項１に記載のシステム。

【請求項２３】

前記インピーダンスマッチング回路網がコンデンサを含む、請求項７に記載のシステム。

【請求項２４】

前記インピーダンスマッチング回路網がインダクタを含む、請求項７に記載のシステム。

【請求項２５】

前記調整可能な回路が、可変コンデンサを含む、請求項８に記載のシステム。

【請求項２６】

前記調整可能な回路が、可変インダクタを含む、請求項８に記載のシステム。

【発明の詳細な説明】

【技術分野】

【０００１】

関連出願に対する相互参照

本出願は、以下の米国特許出願の優先権を主張しており、それら特許出願のそれぞれは、参照により全体として本明細書に組み込まれる。即ち、２００８年９月２７日に出願された米国特許出願第６１／１００７２１号、２００８年１０月２７日に出願された米国特許出願第６１／１０８７４３号、２００９年１月２６日に出願された米国特許出願第６１／１４７３８６号、２００９年２月１２日に出願された米国特許出願第６１／１５２０８６号、２００９年５月１５日に出願された米国特許出願第６１／１７８５０８号、２００９年６月１日に出願された米国特許出願第６１／１８２７６８号、２００８年１２月９日に出願された米国特許出願第６１／１２１１５９号、２００９年１月７日に出願された米

国特許出願第６１／１４２９７７号、２００９年１月６日に出願された米国特許出願第６１／１４２８８５号、２００９年１月６日に出願された米国特許出願第６１／１４２７９６号、２００９年１月６日に出願された米国特許出願第６１／１４２８８９号、２００９年１月６日に出願された米国特許出願第６１／１４２８８０号、２００９年１月６日に出願された米国特許出願第６１／１４２８１８号、２００９年１月６日に出願された米国特許出願第６１／１４２８８７号、２００９年３月２日に出願された米国特許出願第６１／１５６７６４号、２００９年１月７日に出願された米国特許出願第６１／１４３０５８号、２００９年２月１３日に出願された米国特許出願第６１／１５２３９０号、２００９年３月２６日に出願された米国特許出願第６１／１６３６９５号、２００９年４月２４日に出願された米国特許出願第６１／１７２６３３号、２００９年４月１４日に出願された米国特許出願第６１／１６９２４０号、及び２００９年４月２９日に出願された米国特許出願第６１／１７３７４７号である。

【０００２】

背景

分野

本発明は、無線（ワイヤレス）電力伝送とも呼ばれる無線エネルギー伝達に関する。

【０００３】

関連技術の説明

エネルギー又は電力は、様々な良く知られた放射技術または遠距離場技術、及び非放射技術または近接場技術を用いてワイヤレスで伝送され得る。例えば、無線および移動体通信システム、及び家庭用コンピュータネットワークで使用されるような低指向性アンテナを用いる放射型無線情報伝送は、無線エネルギー伝送と考えられ得る。しかしながら、このタイプの放射型伝送は非常に非効率的であり、その理由は、受信器が獲得するのは、供給される電力または放射される電力のわずかな部分、即ちその方向の一部であり、それらは部分的に重なっているからである。電力の大部分は、他の全方向に放散されて自由空間で失われる。係る非効率的な電力伝送は、データ送信に受け入れ可能であるが、電気装置の電力供給または充電のような仕事を行うために、有用な量の電気エネルギーを伝送するには実用的ではない。幾つかの放射型エネルギー伝送方法の伝送効率を改善するための１つの方法は、放射されたエネルギーを受信器の方に限定する及び優先的に向けるために指向性アンテナを使用することである。しかしながら、これらの方向を持った（有向）放射方法は、中断されない見通し線を必要とする場合があり、移動できる送信器および／または受信器の場合には潜在的に複雑なトラッキング（追跡）及びステアリング（操向）機構を必要とする場合がある。更に、係る方法は、適度な量から大きな量の電力が伝送されている際に、ビームを横切る又はビームと交差する物体または人々に危害を及ぼす可能性がある。誘導または従来の誘導と呼ばれることが多い、既知の非放射型または近接場無線エネルギー伝送方法は、電力を（意図的に）放射しないが、一次コイルを通過する振動電流を用いて、近接受信または二次コイルで電流を誘導する振動近傍磁界を生成する。従来の誘導方法は、適度な量から大量の電力の伝送を実証したが、非常に短い距離にわたるだけであり、一次電源ユニットと二次受信器ユニットとの間の非常に小さいオフセット量の許容範囲を有する。変圧器および近接充電器は、この既知の短距離の近接場エネルギー伝送方法を利用する装置の例である。

【０００４】

従って、中距離にわたって、又は中程度の位置合わせオフセット量で有用な量の電力を伝送することができる無線電力伝送方法が必要とされている。係る無線電力伝送方法は、従来の誘導方法で実現されたものと比べてより大きい距離にわたる、及びより大きい位置合わせオフセット量での有用なエネルギー伝送を可能にするべきであり、放射型送信方法に固有の制限および危険性なしで可能にするべきである。

【０００５】

概要

本明細書において、中距離にわたって、及び中程度の位置合わせオフセット量で有用な

量の電力を伝送することができる非放射型または近接場無線エネルギー伝送方法が開示される。本発明の技術は、長寿命振動性共振モードで結合された電磁共振器を使用して、電源からの電力を電力ドレインに伝送する。当該技術は一般的であり、本明細書で開示された具体例が電磁共振器に関係する場合でも、広範囲の共振器に適用され得る。共振器が設計される場合、電界によって蓄積されたエネルギーが主として構造体内に閉じ込められ、及び磁界により蓄積されたエネルギーが主として共振器の周囲の領域にあるようにされる。そして、エネルギー交換は共振近傍磁界により主として実現される。これらタイプの共振器は、磁気共振器と呼ばれ得る。共振器が設計される場合、磁界により蓄積されたエネルギーが主として構造体内に閉じ込められ、及び電界により蓄積されたエネルギーが主として共振器の周囲の領域にあるようにされる。そして、エネルギー交換は共振近傍電界により主として実現される。これらタイプの共振器は、電気共振器と呼ばれ得る。また、共振器のどちらかのタイプは、電磁共振器とも呼ばれ得る。共振器の双方のタイプが本明細書で開示される。

【０００６】

開示される共振器の近接場に関して、全方向であるが変化しない（非損失性）特徴は、様々な電子デバイス（電子装置、電子機器）の充電、電力供給、又は同時の電力供給と充電に適した、中距離にわたる、広範囲の方向および共振器の位置関係にわたる、効率的な無線エネルギー伝送を可能にする。結果として、システムは、広範囲の様々な考えられる応用形態を有することができ、この場合、電源に接続された第１の共振器が１つの場所にあり、電気／電子デバイス、バッテリー、電力供給または充電回路などに潜在的に接続された第２の共振器は、第２の場所にあり、第１の共振器から第２共振器までの距離は、センチメートルからメートルのオーダーである。例えば、有線電気送電系統に接続された第１の共振器は、部屋の天井に配置され得るが、ロボット、車両、コンピュータ、通信装置、医療機器などのようなデバイスに接続された他の共振器は、部屋の中を動き回り、この場合、これらのデバイスは常に又は断続的に、供給源共振器からワイヤレスで電力を受け取っている。この一例から、本明細書で開示されたシステム及び方法が中距離にわたって無線電力を供給することができる多くの応用形態を考えることができ、係る応用形態には、家庭用電化製品、工業的応用形態、電力および照明のインフラ、運搬用車両、コンピュータゲーム、軍事的応用形態などが含まれる。

【０００７】

２つの電磁共振器間のエネルギー交換は、共振器が実質的に同じ周波数にチューニングされ、システムの損失が最小限である場合に、最適化され得る。無線エネルギー伝送システムは、共振器間の「結合時間」が共振器の「損失時間」より大幅に短いように設計され得る。従って、本明細書で説明されたシステム及び方法は、低い固有損失率を有する高いＱファクタ（高Ｑ）の共振器を利用することができる。更に、本明細書で説明されたシステム及び方法は、共振器の特有サイズより大幅に長く延在する近接場を有するサブ波長共振器を使用することができ、そのためエネルギーを交換する共振器の近接場は、中距離で部分的に重なる。これは、以前に実施されていなかった、且つ従来の誘導設計とは大幅に異なる動作の状況である。

【０００８】

本明細書で開示された高Ｑ磁気共振器の方式と既知の近距離または近接型誘導方式との違いを理解することは重要であり、即ちこれら既知の方式は従来、高Ｑ共振器を利用していない。結合モード理論（ＣＭＴ）（例えば、H.A. Haus著「Waves and Fields in Optoelectronics」、Prentice Hall、1984年を参照）を用いることにより、高Ｑ共振器の結合メカニズムが、中距離だけ離間された共振器間において、従来の誘導方式により可能にされたものよりも数桁大きい効率的な電力供給を可能にすることができることが示される。結合された高Ｑ共振器は、中距離にわたる効率的なエネルギー伝送を実証し、短距離エネルギー伝送の応用形態における効率性およびオフセット量の許容範囲を改善した。

【０００９】

本明細書で説明されたシステム及び方法は、強く結合された高Ｑ共振器を介した近接場

無線エネルギー伝送を提供し、安全に且つ従来の誘導技術を用いて達成されたものよりもはるかに長い距離にわたって、ピコワットからキロワットまでの電力レベルを伝送するための可能性を有する技術を提供することができる。効率的なエネルギー伝送は、強く結合された共振器の様々な一般的なシステム、例えば、強く結合された音響共振器、核共振器、機械共振器などのシステムに関して実現されることができ、係る一般的なシステムは、M.I.T.の研究者により彼らの文献で最初に説明されており、係る文献は、「Efficinet wireless non-radiative mid-range energy transfer」、Annals of Physics、Vol 323、Issue 1、p.34、2008年、及び「Wireless Power Transfer via Strongly Coupled Magnetic Resonances」、Science、vol.317、no.5834、p.83、2007年である。また、本明細書で開示された電磁共振器および結合された電磁共振器のシステムは、より具体的には、１０ＧＨｚ未満の動作周波数を有する、結合された磁気共振器および結合された電気共振器と呼ばれる。

【００１０】

本開示は、無線電力送信技術とも呼ばれる無線エネルギー伝送技術を説明する。本開示の全体にわたって、用語の無線エネルギー伝送、無線電力伝送、無線電力送信などは、区別なく使用され得る。本発明者は、供給源、ＡＣ又はＤＣ供給源、バッテリー、供給源共振器、電源、電力発生装置、ソーラーパネル、及び熱吸収装置などからのエネルギー又は電力を、デバイス、遠隔デバイス、複数の遠隔デバイス、デバイス共振器（単数または複数）などに供給することに言及する。本発明者は、無線エネルギー伝送システムの有効範囲を拡張する中間共振器を説明し、その拡張は、供給源共振器から他のデバイス及び中間共振器の任意の組合せまで、エネルギーを跳ばす、通過伝送する、一時期的に蓄積する、部分的に消散することを可能にすることにより行われ、又は形はどうあれ仲介されるべき伝送のために行われ、その結果、エネルギー伝送ネットワーク又は一続きのもの、又は延長経路が実現され得る。デバイス共振器は、供給源共振器からのエネルギーを受け取り、デバイスに電力供給またはデバイスを充電するための電力にそのエネルギーの一部を変換し、同時に受け取ったエネルギーの一部を他のデバイス又はモバイル機器の共振器に送ることができる。エネルギーは、供給源共振器から複数のデバイス共振器まで伝送されることができ、エネルギーがワイヤレスで伝送され得る距離は大幅に延ばされる。無線電力伝送システムは、様々なシステムアーキテクチャ及び共振器の設計を用いて実現され得る。システムは、電力を単一のデバイス又は複数のデバイスに送信する単一の供給源または複数の供給源を含むことができる。共振器は、供給源共振器またはデバイス共振器となるように設計され得るか、或いは中継器となるように設計され得る。場合によっては、共振器は、同時にデバイス及び供給源共振器になることができ、又は供給源としての動作からデバイス又は中継器としての動作に切り換えられ得る。当業者には理解されるように、様々なシステムアーキテクチャは、本明細書で説明された広範囲の共振器設計および機能によりサポートされ得る。

【００１１】

説明される無線エネルギー伝送システムにおいて、遠隔デバイスは、ワイヤレスで供給される電力またはエネルギーを用いて直接的に電力供給され得るか、又はバッテリー、スーパーコンデンサ、ウルトラコンデンサなどのようなエネルギー蓄積ユニット（又は他の種類の電力ドレイン）に結合されることができ、この場合、エネルギー蓄積ユニットは、ワイヤレスで充電または再充電されることができ、及び／又は無線電力伝送機構は、デバイスの主電源に対する単なる補助的なものになる。デバイスは、一体型蓄積キャパシタなどを備えるバッテリーのような、ハイブリッドのバッテリー／エネルギー蓄積装置により電力供給され得る。更に、新規なバッテリー及びエネルギー蓄積装置が、無線電力送信システムにより可能にされる動作上の改善を利用するように設計され得る。

【００１２】

他の電力管理状況は、デバイスがアイドル状態、スリープモードなどで電源がオフされている間に、バッテリーを再充電またはエネルギー蓄積ユニットを充電するためにワイヤレスで供給される電力を用いることを含む。バッテリー又はエネルギー蓄積ユニットは、

高速（急速）又は低速（遅い）で充電または再充電され得る。バッテリー又はエネルギー蓄積ユニットは、トリクル充電またはフロート充電され得る。複数のデバイスは、同時に並行して充電または電力供給され得るか、又は複数のデバイスへの電力供給は、他の電力供給が他のデバイスに切り換えられた後の時間期間に、１つ又は複数のデバイスが電力を受け取るように、シリアル化され得る。複数のデバイスは、１つ又は複数の供給源からの電力を、１つ又は複数の他のデバイスと同時に、又は時分割多重化方法で、又は周波数分割多重化方法で、又は空間的多重化方法で、又は配向的多重化方法で、又は時分割、周波数分割、空間的、及び配向的多重化の任意の組合せで、共用することができる。複数のデバイスは、無線電力供給源として動作するために、互いに電力を共用する、或いは連続的に、断続的に、周期的に、時折に、又は一時的に再構成され得る少なくとも１つのデバイスと電力を共用する。当業者には理解されるように、デバイスの電力供給および／または充電のための様々な態様が存在し、様々な態様は、本明細書で説明された技術および応用形態に適用され得る。

【００１３】

無線エネルギー伝送は、様々な考えられる応用形態を有することができ、係る応用形態には例えば、天井に、床の下に、又は部屋の壁に供給源（例えば、有線電気送電系統に接続された供給源）を配置すると同時に、ロボット、車両、コンピュータ、ＰＤＡ又は類似物のようなデバイスが部屋の内部に配置されて自由に移動することが含まれる。他の応用形態には、バス及び／又はハイブリッド車のような電気エンジン車両、及び装着型または埋込み型装置のような医療機器の電力供給または再充電が含まれ得る。更なる例の応用形態には、自律電子機器（例えば、ラップトップコンピュータ、携帯電話、携帯型音楽プレイヤ、家庭用ロボット、ＧＰＳナビゲーションシステム、ディスプレイなど）、センサ、工業および製造装置、医療機器およびモニタ、家庭用電気製品および工具（例えば、照明、送風機、ドリル、鋸、ヒータ、ディスプレイ、テレビ、調理台の電化製品など）、軍事用機器、加熱または照明付き衣類、通信およびナビゲーション機器（車両、衣類および防護服（例えば、ヘルメット、防弾チョッキ及びベストなど）に組み込まれた機器を含む）に対する電力供給または再充電する能力、並びに物理的に分離されたデバイス（例えば、埋め込まれた医療機器、隠された、埋設された、埋没した、又は埋め込まれたセンサ又はタグ、屋根のソーラーパネルから屋内の分電盤まで及び／又は屋内の分電盤から屋根のソーラーパネルまでなど）に電力を送信する能力が含まれる。

【００１４】

一態様において、本明細書で開示されたシステムは、電力発生装置に結合され、ＱファクタＱ$_{1}$及び特有サイズｘ$_{1}$を有する供給源共振器、供給源共振器から距離Ｄに位置する負荷に結合され、ＱファクタＱ$_{2}$及び特有サイズｘ$_{2}$を有する第２の共振器を含み、供給源共振器および第２の共振器が、供給源共振器と第２の共振器との間でワイヤレスでエネルギーを交換するように結合され、$(Q_{1}Q_{2})^{1/2}>100$である。

【００１５】

Ｑ$_{1}$は１００未満とすることができる。Ｑ$_{2}$は１００未満とすることができる。システムは、供給源共振器および第２の共振器と非放射的にエネルギーを伝送するように構成された、ＱファクタＱ$_{3}$を有する第３の共振器を含むことができ、$(Q_{1}Q_{3})^{1/2}>100$及び$(Q_{2}Q_{3})^{1/2}>100$である。Ｑ$_{3}$は１００未満とすることができる。

【００１６】

供給源共振器は、直接的な電気接続で電力発生装置に結合され得る。システムは、インピーダンスマッチング回路網を含むことができ、供給源共振器は、直接的な電気接続で電力発生装置に結合され及びインピーダンスマッチングされる。システムは、調整可能な回路を含むことができ、供給源共振器は、直接的な電気接続でもって、調整可能な回路を介して電力発生装置に結合される。調整可能な回路は、可変コンデンサを含むことができる。調整可能な回路は、可変インダクタを含むことができる。直接的な電気接続の少なくとも１つは、供給源共振器の共振モードを実質的に保持するように構成され得る。供給源共振器は、第１の端子、第２の端子、及び中央端子を有し、第１の端子と中央端子との間の

インピーダンス、及び第２の端子と中央端子との間のインピーダンスは実質的に等しくすることができる。供給源共振器は、第１の端子、第２の端子、及び中央端子を有する、容量的に装荷されたループを含むことができ、第１の端子と中央端子との間のインピーダンス、及び第２の端子と中央端子との間のインピーダンスは実質的に等しい。供給源共振器は、インピーダンスマッチング回路網に結合されることができ、インピーダンスマッチング回路網は更に、第１の端子、第２の端子、及び中央端子を含み、第１の端子と中央端子との間のインピーダンス、及び第２の端子と中央端子との間のインピーダンスは実質的に等しい。

【００１７】

第１の端子および第２の端子は、電力発生装置に直接的に結合され、ほぼ１８０度位相がずれている発振信号で駆動され得る。供給源共振器は、共振周波数ω_1を有し、第１の端子および第２の端子は、電力発生装置に直接的に結合され、共振周波数ω_1に実質的に等しい発振信号で駆動され得る。中央端子は、電気接地に接続され得る。供給源共振器は、共振周波数ω_1を有し、第１の端子および第２の端子は、電力発生装置に直接的に結合され、共振周波数ω_1に実質的に等しい周波数で駆動され得る。システムは、電力発生装置および負荷に結合された複数のコンデンサを含むことができる。供給源共振器および第２の共振器はそれぞれ、低い損失正接の材料内に収容され得る。システムは、電力変換回路を含むことができ、第２の共振器は、電力変換回路に結合されて、ＤＣ電力を負荷に伝える。システムは、電力変換回路を含むことができ、第２の共振器は、電力変換回路に結合されて、ＡＣ電力を負荷に伝える。システムは、電力変換回路を含むことができ、第２の共振器は、電力変換回路に結合されて、ＡＣ及びＤＣ電力を負荷に伝える。システムは、電力変換回路および複数の負荷を含むことができ、第２の共振器は、電力変換回路に結合され、電力変換回路は複数の負荷に結合される。インピーダンスマッチング回路網はコンデンサを含むことができる。インピーダンスマッチング回路網はインダクタを含むことができる。

【００１８】

本開示の全体にわたって、本発明者は、回路部品または回路素子として、コンデンサ、インダクタ、抵抗、ダイオード、スイッチなどのような特定の回路部品に言及する。また、本発明者は、素子、回路網、接続形態（トポロジー）、回路などとして、これら部品の直列および並列の組合せにも言及する。本発明者は、調整可能なインピーダンス回路網、チューニング回路網、マッチング回路網、調整素子などとして、コンデンサ、ダイオード、バラクタ、トランジスタ、及び／又はスイッチの組合せを説明する。また、本発明者は、全物体の全体にわたって分布された（又は単に集中されるとは対照的に、部分的に分布された）キャパシタンス及びインダクタンスを有する「自己共振」物体に言及する。当業者ならば理解されるように、回路または回路網内の調整および制御する可変構成要素は、その回路または回路網の性能を調整することができ、それらの調整は概して、チューニング、調整、マッチング、補正などとして説明され得る。無線電力伝送システムの動作点をチューニング又は調整するための他の方法は、単独で、或いはインダクタ及びコンデンサ、又はインダクタ及びコンデンサのバンクのような、調整可能な構成要素を調整することに加えて使用され得る。

【００１９】

特に定義されない限り、本明細書で使用される全ての技術用語および科学用語は、本開示が属する技術の当業者により一般に理解されるような同じ意味を有する。本明細書で言及された又は参照により本明細書に組み込まれる刊行物、特許出願、特許、及び他の文献と食い違う場合には、定義を含む本明細書が支配する。

【００２０】

上記で説明された任意の特徴は、本発明の範囲から逸脱せずに、単独で又は組み合わせて使用され得る。本明細書で開示されたシステム及び方法に関する他の特徴、目的、及び利点は、以下の詳細な説明および図面から明らかになるであろう。

【図面の簡単な説明】

【００２１】

【図１】（ａ）と（ｂ）は、距離Ｄだけ離れた供給源の共振器１及びデバイスの共振器２を含む例示的な無線電力システムを示す。

【図２】本開示で説明された表記規則に従って表記された例示的な共振器を示す。留意すべきは、共振器１の近傍には、外部物体または追加の共振器が示されていない。

【図３】本開示で説明された表記規則に従って表記された「ローディング」物体の存在する状態での例示的な共振器を示す。

【図４】本開示で説明された表記規則に従って表記された「パータービング」物体の存在する状態での例示的な共振器を示す。

【図５】効率η対強結合率$U=\kappa/(\Gamma_s\Gamma_d)^{1/2}=k(Q_s Q_d)^{1/2}$のグラフである。

【図６】（ａ）は共振器の一例の回路図を示し、（ｂ）は容量的に装荷されたインダクタループの磁気共振器の一例の図を示し、（ｃ）は分布キャパシタンス及びインダクタンスを有する自己共振コイルの図を示し、（ｄ）は本開示の例示的な磁気共振器に関連した電界および磁界の力線の簡易図を示し、（ｅ）は電気共振器の一例の図を示す。

【図７】ＭＨｚ周波数での無線電力伝送に使用され得る例示的な共振器の周波数の関数として「Ｑファクタ」Ｑ（実線）のグラフを示す。吸収Ｑ（波線）は周波数と共に増加するが、放射Ｑ（点線）は周波数と共に減少し、かくして全体のＱが特定の周波数でピークということになる。

【図８】表示された特有サイズ、厚さ、及び幅を有する共振器構造の図である。

【図９】例示的な誘導性ループ素子の図である。

【図１０】（ａ）と（ｂ）は、プリント回路基板上に形成され、且つ磁気共振器構造で誘導性素子を実現するために使用されるトレース構造の例を示す。

【図１１】（ａ）は、平面磁気共振器の斜視図であり、（ｂ）は様々な幾何学的形状を有する２つの平面磁気共振器の斜視図であり、（ｃ）は距離Ｄだけ離れた２つの平面磁気共振器の斜視図である。

【図１２】平面磁気共振器の例の斜視図である。

【図１３】円形共振器コイルを有する平面磁気共振器の構成の斜視図である。

【図１４】平面磁気共振器の活性領域の斜視図である。

【図１５】供給源の周りに配置された、テーブル電力供給している幾つかのデバイスの中心に供給源を有する、無線電力伝送システムの応用形態の斜視図である。

【図１６】（ａ）は、中央における絞り箇所の周りの正方形ループの電流により駆動される銅および磁性材料構造の３Ｄ有限要素モデルを示す。この例において、構造体は、銅のような導電材料から作成され、磁性材料の層により覆われ、磁性材料のブロックにより接続された２つのボックスから構成され得る。この例における２つの導電ボックスの内部は、ボックスの外部で生じたＡＣ電磁界から遮蔽され、ＡＣ電磁界により悪影響を及ぼされる共振器またはデリケートな構成要素のＱを低下させる損失性物体を収容することができる。また、この構造体により生成される、計算された磁界の流線が示され、係る流線は、磁力線が磁性材料のより低い磁気抵抗の経路をたどる傾向があることを示す。（ｂ）は、（ａ）に示されたような２つの同一の構造体間での、計算された磁界の流線により示されるような相互作用を示す。対称性の故に、及び計算の複雑性を低減するために、システムの半分だけがモデル化されている（しかし、計算は、残りの半分の対称配置を推測する）。

【図１７】場合によっては磁気的に透過性の材料を含む、構造体の周りにＮ回巻き付けられた導電ワイヤを含む磁気共振器の等価回路図である。インダクタンスは、磁性材料を含む構造体の周りに巻き付けられた導電ループを用いて実現され、抵抗は、システムの損失機構を表す（R_{wire}はループの抵抗損失、R_{μ}はループにより取り囲まれた構造体の等価直列抵抗を示す）。損失は、高Ｑ共振器を実現するために最小限にされ得る。

【図１８】周波数６．７８ＭＨｚの外部磁界において、損失性誘電体材料からなるディスクの上下の２つの高い導電率表面に関する有限要素法（ＦＥＭ）のシミュレーションを示

す図である。留意すべきは、磁界は、ディスクの前で均一であり、導電材料がシミュレートされる環境に導入された。このシミュレーションは円筒座標で行われた。画像は、ｒ＝０の軸の周りに方位対称である。損失性誘電体ディスクは、ε_r＝１及びσ＝１０Ｓ／ｍを有する。

【図１９】高導電率表面により完全に覆われた損失性物体を近傍に有する磁気共振器の図である。

【図２０】高導電率表面により部分的に覆われた損失性物体を近傍に有する磁気共振器の図である。

【図２１】高導電率表面の上面に配置された損失性物体を近傍に有する磁気共振器の図である。

【図２２】完全なワイヤレスプロジェクタの図である。

【図２３】円形ループインダクタの直径を含むラインに沿った電界および磁界の大きさ、並びにループインダクタの軸に沿った電界および磁界の大きさを示す図である。

【図２４】磁気共振器および必要であるが損失性の物体を伴うその筐体の図であり、係る損失性物体は、（ａ）共振器構造体からできる限り遠く離れて筐体の角に配置されているか、又は（ｂ）磁気共振器の誘導性素子により包囲された表面の中央に配置されている。

【図２５】磁気共振器の上に高導電率表面を有する磁気共振器と損失性物体の図であり、係る損失性物体は、共振器の近傍に持って来られるが、高導電率シートの上に持って来られる。

【図２６】（ａ）は、ｚ軸に沿って最初は均一に外部から印加された磁界（灰色の力線）にさらされた、薄い導電（銅）円筒またはディスク（直径２０ｃｍ、高さ２ｃｍ）の軸対称ＦＥＭシミュレーションを示す。対称軸は、ｒ＝０にある。示された磁気的流線は、ｚ＝－∞で発し、この場合、それらはｒ＝３ｃｍからｒ＝１０ｃｍまで１ｃｍの間隔で配置される。軸の目盛りはメートルである。（ｂ）は、外面にμ'_r＝４０の磁性材料からなる０．２５ｍｍの層（非可視）を含むように、導電円筒が変更されていることを除いて、（ａ）と同じ構造および外部から印加された磁界を示す。留意すべきは、磁気的流線は、（ａ）においてよりも大幅に少なく円筒から離れるように偏向されている。

【図２７】図２６に示されたシステムに基づいた変形形態の軸対称の図である。損失性材料の１つの表面のみが銅および磁性材料の層状構造により覆われる。図示されたように、インダクタループが損失性材料の反対側の銅および磁性材料構造の側に配置されている。

【図２８】（ａ）は、高Ｑ誘導性素子に対する間接的結合を含むマッチング回路の一般的な接続形態を示し、（ｂ）は、導体ループインダクタ及び調整可能なインピーダンス回路網を含む磁気共振器のブロック図を示す。この共振器に対する物理的電気接続は端子接続部に行われ得る。（ｃ）は、高Ｑ誘導性素子に直接的に結合されたマッチング回路の一般的な接続形態を示す。（ｄ）は、高Ｑ誘導性素子に直接的に結合され、反対称的に駆動された対称性マッチング回路の一般的な接続形態を示す（平衡駆動）。（ｅ）は、高Ｑ誘導性素子に直接的に結合され、主共振器の対称点で接地に接続されたマッチング回路の一般的な接続形態を示す（不平衡駆動）。

【図２９】（ａ）と（ｂ）はそれぞれ、高Ｑ誘導性素子にトランス結合された（即ち、間接的に又は誘導的に）マッチング回路の接続形態を示す。（ｃ）におけるスミスチャートの強調表示部分は、$\omega L_2 = 1/\omega C_2$の場合における図３１の（ｂ）の接続形態により任意の実インピーダンスZ_0にマッチングされ得る複素インピーダンス（誘導性素子のＬ及びＲから生じる）を示す。

【図３０】（ａ）、（ｂ）、（ｃ）、（ｄ）、（ｅ）、（ｆ）は、高Ｑ誘導性素子に直接的に結合され、Z_0に直列接続されたコンデンサを含むマッチング回路の６つの接続形態を示す。（ａ）、（ｂ）、（ｃ）に示された接続形態は、入力端子でコモンモード信号で駆動されるが、（ｄ）、（ｅ）、（ｆ）に示された接続形態は、対称であり、平衡駆動を受け取る。（ｇ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。（ｈ）、（ｉ）、（ｊ）、（ｋ）、（ｌ）、（ｍ）は、高Ｑ誘導性素子に直接的に結合され、Z_0に直列接続されたインダクタを含むマッチ

ング回路の６つの接続形態を示す。

【図３１】（ａ）、（ｂ）、（ｃ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に直列接続されたコンデンサを含むマッチング回路の３つの接続形態を示す。それらは、コンデンサの中心点で接地に接続され、不平衡駆動を受け取る。（ｄ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。（ｅ）、（ｆ）、（ｇ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に直列接続されたインダクタを含むマッチング回路の３つの接続形態を示す。

【図３２】（ａ）、（ｂ）、（ｃ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に直列接続されたコンデンサを含むマッチング回路の３つの接続形態を示す。それらは、インダクタループの中心点でタップ接続することにより接地に接続され、不平衡駆動を受け取る。（ｄ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。（ｅ）、（ｆ）、（ｇ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に直列接続されたインダクタを含むマッチング回路の３つの接続形態を示す。

【図３３】（ａ）、（ｂ）、（ｃ）、（ｄ）、（ｅ）、（ｆ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に並列接続されたコンデンサを含むマッチング回路の６つの接続形態を示す。（ａ）、（ｂ）、（ｃ）に示された接続形態は、入力端子でコモンモード信号で駆動されるが、（ｄ）、（ｅ）、（ｆ）に示された接続形態は、対称であり、平衡駆動を受け取る。（ｇ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。（ｈ）、（ｉ）、（ｊ）、（ｋ）、（ｌ）、（ｍ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に並列接続されたインダクタを含むマッチング回路の６つの接続形態を示す。

【図３４】（ａ）、（ｂ）、（ｃ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に並列接続されたコンデンサを含むマッチング回路の３つの接続形態を示す。それらは、コンデンサの中心点で接地に接続され、不平衡駆動を受け取る。（ｄ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。（ｅ）、（ｆ）、（ｇ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に並列接続されたインダクタを含むマッチング回路の３つの接続形態を示す。

【図３５】（ａ）、（ｂ）、（ｃ）は、高Ｑ誘導性素子に直接的に結合され、Ｚ$_0$に並列接続されたコンデンサを含むマッチング回路の３つの接続形態を示す。それらは、インダクタループの中心点でタップ接続することにより接地に接続され、不平衡駆動を受け取る。（ｄ）、（ｅ）及び（ｆ）のスミスチャートの強調表示部分は、これら接続形態によりマッチングされ得る複素インピーダンスを示す。

【図３６】（ａ）、（ｂ）、（ｃ）、（ｄ）は、微細な調整分解能を有し、可変コンデンサでの電圧が或る量低減される、可変コンデンサ全体を作成するために設計された固定および可変コンデンサの回路網に関する４つの接続形態を示す。

【図３７】（ａ）及び（ｂ）は、可変コンデンサ全体を作成するために設計された固定コンデンサ及び可変インダクタの回路網に関する２つの接続形態を示す。

【図３８】無線電力伝送システムの高レベルブロック図である。

【図３９】例示的な無線電力供給されるデバイスのブロック図である。

【図４０】例示的な無線電力伝送システムの供給源のブロック図である。

【図４１】磁気共振器の等価回路図である。コンデンサの記号を通る斜線は、表されたコンデンサが固定または可変とすることができることを示す。ポートパラメータ測定回路は、特定の電気信号を測定するように構成され、信号の大きさ及び位相を測定することができる。

【図４２】調整可能なインピーダンス回路網が電圧制御コンデンサで実現されている、磁気共振器の回路図である。係る具現化形態は、プログラム可能または制御可能電圧源および／またはコンピュータプロセッサを含む電気回路により調整、チューニング、又は制御され得る。電圧制御コンデンサは、ポートパラメータ測定回路により測定され、測定値分析および制御アルゴリズム及びハードウェアにより処理されたデータに応じて調整され得る。電圧制御コンデンサは、コンデンサの切り換えられるバンクとすることができる。

【図４３】エンドツーエンド無線電力送信システムの図である。この例において、供給源およびデバイスは、ポート測定回路およびプロセッサを含む。「カプラー／スイッチ」と表示されたボックスは、ポート測定回路が方向性カプラー又はスイッチにより共振器に接続され、供給源共振器およびデバイス共振器の測定、調整、及び制御が、電力伝送の機能と共に、又は係る機能から離れて行われることを可能にすることを示す。
【図４４】エンドツーエンド無線電力送信システムの図である。この例において、供給源だけが、ポート測定回路およびプロセッサを含む。この場合、デバイス共振器の動作特性は、固定され得るか、又はアナログ制御回路により、且つプロセッサにより生成された制御信号を必要とせずに調整され得る。
【図４５】エンドツーエンド無線電力送信システムの図である。この例において、供給源およびデバイスは、ポート測定回路を含むが、供給源のみがプロセッサを含む。デバイスからのデータは、別個のアンテナで、又は供給源駆動信号の何らかの変調を通じて実現され得る無線通信チャネルを介して送信される。
【図４６】エンドツーエンド無線電力送信システムの図である。この例において、供給源だけが、ポート測定回路およびプロセッサを含む。デバイスからのデータは、別個のアンテナで、又は供給源駆動信号の何らかの変調を通じて実現され得る無線通信チャネルを介して送信される。
【図４７】周波数およびインピーダンスがプロセッサ又はコンピュータを用いて実現されたアルゴリズムを用いて、自動的に調整され得る、結合された電磁共振器の図である。
【図４８】バラクタアレイの図である。
【図４９】供給源によりワイヤレスで電力供給または充電されているデバイス（ラップトップコンピュータ）の図であり、この場合、供給源共振器およびデバイス共振器は、供給源およびデバイスから物理的に分離されるが、供給源およびデバイスに電気接続される。
【図５０】（ａ）は、ワイヤレスで電力供給または充電されるラップトップコンピュータの応用形態の図であり、この場合、デバイス共振器がラップトップコンピュータのケース内にあり且つ見ることができない。（ｂ）は、ワイヤレスで電力供給または充電されるラップトップコンピュータの応用形態の図であり、この場合、共振器はラップトップコンピュータの基部の下にあり、電気ケーブルによりラップトップコンピュータの電力入力に電気接続される。（ｃ）は、ワイヤレスで電力供給または充電されるラップトップコンピュータの応用形態の図であり、この場合、共振器は、ラップトップコンピュータの基部に取り付けられる。（ｄ）は、ワイヤレスで電力供給または充電されるラップトップコンピュータの応用形態の図であり、この場合、共振器は、ラップトップコンピュータのディスプレイに取り付けられる。
【図５１】無線電力伝送を有する、屋根のＰＶパネルの図である。
【００２２】
　詳細な説明
　上述したように、本開示は、電源からの電力を電力ドレイン（drain：消費元）にワイヤレス（無線）で伝送することができる、長寿命振動性共振モード（long-lived oscillatory resonant mode）で結合された電磁共振器に関する。しかしながら、当該技術は、電磁共振器に限定されず、全般的であり、多種多様の共振器および共振物体に適用され得る。従って、最初に一般的な技術が説明され、次いで無線エネルギー伝送の電磁的例が開示される。
【００２３】
　共振器
　共振器は、少なくとも２つの異なる形態でエネルギーを蓄積することができるシステムとして定義されることができ、この場合、蓄積されたエネルギーは、２つの形態間で振動している。共振は、共振（モード）周波数ｆ、及び共振（モード）場を有する特定の振動モードを有する。共振角周波数ωは、ω＝２πｆとして定義されることができ、共振波長λは、λ＝ｃ／ｆとして定義されることができ、ここでｃは光の速度であり、及び共振周器Ｔは、Ｔ＝１／ｆ＝２π／ωとして定義され得る。損失機構、結合機構または外部エネ

ルギー供給機構またはドレイン機構がない場合、共振器の蓄積された全エネルギーＷは、一定のままであり、且つ２つの形態のエネルギーが振動し、この場合、他方が最小である場合に、一方が最大であり、逆もまた同じである。

【００２４】

外部材料または外部物体がない場合、図１に示された共振器１０２のエネルギーは、固有損失により減衰または失われ得る。そして、共振器場は、以下の一次方程式に従う。即ち、

$$da(t)/dt=-i(\omega-i\Gamma)a(t)$$

ここで、変数ａ（ｔ）は、共振器内に包含されるエネルギーが$|a(t)|^2$により与えられるように定義された共振場の振幅である。Γは、固有エネルギー減衰または損失率（例えば、吸収損失および放射損失に起因）である。

【００２５】

エネルギー減衰の特性を表す、共振器のQuality Factor、又はＱファクタ、又はＱは、これらエネルギー損失に反比例する。それは、$Q=\omega*W/P$として定義されることができ、ここでＰは、定常状態での時間平均電力損失である。即ち、高いＱを有する共振器１０２は比較的低い固有損失を有し、比較的長い時間にわたってエネルギーを蓄積することができる。共振器がその固有減衰率２Γでエネルギーを失うので、その固有Ｑ（intrinsic Q）とも呼ばれるそのＱは、$Q=\omega/2\Gamma$により与えられる。また、Ｑファクタは、振動周期Ｔの数も表し、共振器のエネルギーがｅの倍数で減衰するのに要するのがＴである。

【００２６】

上述したように、本発明者は、固有の損失機構のみに起因するものとして共振器のＱファクタ又はＱを定義する。Q_1のような下付き文字は、Ｑが関係する共振器（この場合、共振器１）を示す。図２は、この規則に従って表記された電磁共振器１０２を示す。留意すべきは、この図において、共振器１の近傍には、外部物体または追加の共振器は存在していない。

【００２７】

第１の共振器の近傍の外部物体および／または追加の共振器は、第１の共振器に摂動を与え又は第１の共振器に負荷をかけ、それにより共振器と物体または他の共振器との間の距離、物体または他の共振器の材料組成、第１の共振器の構造、第１の共振器の電力などのような様々な因子に応じて、第１の共振器のＱに摂動を与える又は負荷をかける。共振器の近傍の外部材料および外部物体に対する意図しない外部エネルギー損失または結合機構は、共振器のＱに「摂動を与える（perturbing：パータービング）」と呼ばれることができ、丸い括弧（）内の下付き文字により示され得る。他の共振器、及び電力発生装置に対する結合を介したエネルギー伝送に関連した意図された外部エネルギー損失、及び無線エネルギー伝送システムの負荷は、共振器のＱに「負荷をかける（loading：ローディング）」と呼ばれることができ、角括弧［ ］内の下付き文字により示され得る。

【００２８】

電力発生装置ｇ、又は負荷３０２、ｌに接続または結合された共振器１０２のＱは、「ローデッドＱファクタ」又は「ローデッド（loaded：負荷をかけられた）Ｑ」と呼ばれることができ、図３に示されたように$Q_{[g]}$又は$Q_{[l]}$により示され得る。一般に、共振器１０２に接続された２つ以上の電力発生装置または負荷３０２が存在することができる。しかしながら、それらの電力発生装置または負荷は別々に列挙されないで、電力発生装置および負荷の組合せによりもたらされる等価な回路負荷を表すために「ｇ」及び「ｌ」が使用される。全般的な説明において、共振器に接続された電力発生装置または負荷を表すために下付き文字「ｌ」が使用され得る。

【００２９】

本明細書の一部の説明において、共振器に接続された電力発生装置または負荷に起因した「ローディングＱファクタ」又は「ローディング（loading：負荷をかける）Ｑ」が、$\delta Q_{[l]}$として定義され、ここで、$1/\delta Q_{[l]}=1/Q_{[l]}-1/Q$である。留意すべき

は、電力発生装置または負荷のより大きなローディングＱ、δＱ$_{[l]}$、より少ないローデッドＱ、Ｑ$_{[l]}$は、共振器の無負荷時のＱから導出される。

【００３０】

エネルギー伝送システムの一部であると意図されていない、外部物体４０２、ｐが存在する状態の共振器のＱは、「パーターブドＱファクタ」又は「パーターブド（perturbed：摂動を与えられた（摂動された））Ｑ」と呼ばれることができ、図４に示されるように、Ｑ$_{(p)}$により示され得る。一般に、ｐ１、ｐ２等として示される多くの外部物体、又は共振器１０２のＱに摂動を与える一組の外部物体｛ｐ｝が存在することができる。この場合、パーターブドＱは、Ｑ$_{(p1+p2+\cdots)}$又はＱ$_{(\{p\})}$で示され得る。例えば、Ｑ$_{1(brick+wood)}$は、れんが及び木片の存在する状態での無線電力交換のシステムにおける第１の共振器のパーターブドＱファクタを示すことができ、Ｑ$_{2(\{office\})}$は、オフィス環境での無線電力交換のシステムにおける第２の共振器のパーターブドＱファクタを示すことができる。

【００３１】

本明細書の一部の説明において、外部物体ｐに起因した「パータービングＱファクタ」又は「パータービングＱ」は、δＱ$_{(p)}$として定義され、ここで、$1/\delta Q_{(p)} \equiv 1/Q_{(p)} - 1/Q$である。前述したように、パータービングＱファクタは、複数の外部物体ｐ１、ｐ２など、又は一組の外部物体｛ｐ｝に依存することができる。物体のより大きな、パータービングＱ、δＱ$_{(p)}$、より小さいパーターブドＱ、Ｑ$_{(p)}$は、共振器の摂動されていないＱから導出される。

【００３２】

本明細書の一部の説明において、$\Theta_{(p)} \equiv Q_{(p)}/Q$も定義され、それは、外部物体の存在する状態での共振器の「Ｑファクタの無感受性」又は「Ｑ無感受性」と呼ばれる。Θ$_{1(p)}$のような下付き文字は、摂動される及び摂動されないＱファクタが表している共振器を示し、即ち$\Theta_{1(p)} = Q_{1(p)}/Q_1$である。

【００３３】

留意すべきは、ＱファクタＱは、パーターブドＱファクタＱ$_{(p)}$と区別することが必要な場合には、「アンパーターブド（unperturbed：摂動されない）」としても特徴付けられることができ、ローデッドＱファクタＱ$_{[l]}$と区別することが必要な場合には、「アンローデッド（unloaded：負荷をかけられていない）」として特徴付けられる。同様に、パーターブドＱファクタＱ$_{(p)}$は、ローデッド・パーターブドＱファクタＱ$_{(p)[l]}$と区別することが必要な場合には、「アンローデッド」としても特徴付けられ得る。

【００３４】

結合された共振器

実質的に同じ共振周波数を有し、近接場の任意の部分を介して結合された共振器は、相互作用してエネルギーを交換することができる。このエネルギー交換を理解する、設計する、最適化する、及び特徴付けるために採用され得る様々な物理的画像およびモデルが存在する。２つの結合された共振器間のエネルギー交換を説明する及びモデル化するための１つの方法は、結合モード理論（ＣＭＴ）を用いている。

【００３５】

結合モード理論において、共振器の場は、以下の一次方程式の組に従う。

【００３６】

【数１】

$$\frac{da_m(t)}{dt} = -i\left(\omega_m - i\Gamma_m\right)a_m(t) + i\sum_{n\neq m}\kappa_{mn}a_n(t)$$

【００３７】

ここで、添え字は異なる共振器を示し、κ$_{mn}$は共振器間の結合係数である。相反系の場合、結合係数は、関係$\kappa_{mn} = \kappa_{nm}$に従うことができる。留意すべきは、本明細書の

ために、遠距離場放射線干渉の影響は無視され、かくして結合係数が実数とみなされる。更に、本明細書でのシステム性能の以後の計算の全てにおいて、結合係数は、それらの二乗、$(\kappa_{mn})^2$でのみ現れ、κ_{mn}を用いて、実結合係数の絶対値が示される。

【００３８】

留意すべきは、上述したＣＭＴからの結合係数κ_{mn}は、$k_{mn}=2\kappa_{mn}/(\omega_m\omega_n)^{1/2}$により、共振器ｍとｎとの間のいわゆる結合率$k_{mn}$に関係づけられる。「強い結合率（強結合率と称す）」U_{mn}は、$U_{mn}=\kappa_{mn}/(\Gamma_m\Gamma_n)^{1/2}=k_{mn}(Q_mQ_n)^{1/2}$により、共振器ｍとｎとの間の結合および損失率の比として定義される。

【００３９】

同様の周波数共振器ｎ又は追加の共振器の存在する状態で、共振器ｍのＱファクタは、接続された電力発生装置または電力消費装置により負荷をかけられている共振器に類似するように、その共振器ｎ又は追加の共振器により負荷をかけられ得る。共振器ｍが共振器ｎにより負荷をかけられ得る（逆もまた同じ）という事実は、共振器が結合されることを確認するための単に異なる方法である。

【００４０】

これらの場合での共振器のローデッドＱは、$Q_{m[n]}$及び$Q_{n[m]}$として示され得る。多数の共振器または負荷供給器またはデバイスの場合、共振器の全負荷は、各負荷を抵抗損失としてモデル化することにより、及び集合体の等価負荷を求めるために適切な並列および／または直列の組合せで、多数の負荷を追加することにより求められ得る。

【００４１】

本明細書の一部の説明において、共振器ｎに起因して共振器ｍの「ローディングＱファクタ」又は「ローディングQ_m」が、$\delta Q_{m[n]}$として定義され、ここで、$1/\delta Q_{m[n]}=1/Q_{m[n]}-1/Q_m$である。留意すべきは、共振器ｎも共振器ｍにより負荷をかけられ、その「ローディングQ_n」は、$1/\delta Q_{n[m]}=1/Q_{n[m]}-1/Q_n$により与えられる。

【００４２】

１つ又は複数の共振器が電力発生装置または負荷に接続される場合、一次方程式の組は次のように変更される。

【００４３】

【数２】

$$\frac{da_m(t)}{dt}=-i\left(\omega_m-i\Gamma_m\right)a_m(t)+i\sum_{n\neq m}\kappa_{mn}a_n(t)-\kappa_m a_m(t)+\sqrt{2\kappa_m}s_{+m}(t)$$

$$s_{-m}(t)=\sqrt{2\kappa_m}a_m(t)-s_{+m}(t)$$

【００４４】

ここで、$s_{+m}(t)$及び$s_{-m}(t)$はそれぞれ、電力発生装置から共振器ｍに入る場の振幅、及び共振器ｍから電力発生装置の方へ戻る又は負荷へ入る場の振幅であり、それらが伝える電力が$|s_{+m}(t)|^2$及び$|s_{-m}(t)|^2$により与えられるように定義される。負荷係数κ_mは、エネルギーが共振器ｍと電力発生装置またはそれに接続された負荷との間で交換される割合（rate：率、速度）に関係する。

【００４５】

留意すべきは、上述したＣＭＴからの負荷係数κ_mは、$\delta Q_{m[l]}=\omega_m/2\kappa_m$により前に定義されたローディングＱファクタ$\delta Q_{m[l]}$に関係づけられる。

【００４６】

共振器ｍの負荷および損失率の比として、「強ローディング率」$U_{m[l]}$が定義され、$U_{m[l]}=\kappa_m/\Gamma_m=Q_m/\delta Q_{m[l]}$である。

【００４７】

図１の（ａ）は、２つの結合された共振器１０００の例を示し、第１の共振器１０２Ｓは供給源の共振器（以降、供給源共振器と称す）として構成され、第２の共振器１０２Ｄはデバイスの共振器（以降、デバイス共振器と称す）として構成される。エネルギーは共振器間の距離Ｄにわたって伝送され得る。供給源共振器１０２Ｓは、電源または電力発生装置（図示せず）により駆動され得る。仕事は、電力消費ドレイン又は負荷（例えば、負荷抵抗器、図示せず）により、デバイス共振器１０２Ｄから取り出され得る。供給源に対して下付き文字「ｓ」を使用し、デバイスに対して「ｄ」を使用し、電力発生装置に対して「ｇ」を使用し、負荷に対して「ｌ」を使用し、この例において、２つの共振器のみが存在し、$\kappa_{sd}=\kappa_{ds}$であるので、κ_{sd}、k_{sd}、及びU_{sd}の添え字を省き、それらをそれぞれκ、ｋ及びＵとして示す。

【００４８】

電力発生装置は、角駆動周波数ωに対応する一定の駆動周波数ｆで供給源共振器を絶えず駆動することができ、ここで、$\omega=2\pi f$である。

【００４９】

この場合、（供給源共振器及びデバイス共振器を介した）電力発生装置から負荷への電力伝送の効率、$\eta=|s_{-d}|^2/|s_{+s}|^2$は、以下の条件の下で最大にされる。即ち、供給源共振器の周波数、デバイス共振器の周波数、及び電力発生装置の駆動周波数は一致される必要があり、即ち、

$\omega_s=\omega_d=\omega$

更に、電力発生装置に起因した供給源共振器のローディングＱ、$\delta Q_{s[g]}$は、デバイス共振器及び負荷に起因した供給源共振器のローデッドＱ、$Q_{s[dl]}$にマッチング（等しく）される必要があり、逆に負荷に起因したデバイス共振器のローディングＱ、$\delta Q_{d[l]}$は、供給源共振器および電力発生装置に起因したデバイス共振器のローデッドＱ、$Q_{d[sg]}$にマッチング（等しく）される必要があり、即ち、

$\delta Q_{s[g]}=Q_{s[dl]}$及び$\delta Q_{d[l]}=Q_{d[sg]}$

これらの方程式は、電力発生装置による供給源共振器の、及び負荷によるデバイス共振器の最適な負荷率を以下のように求める。

【００５０】

【数３】

$$U_{d[l]}=\kappa_d/\Gamma_d=Q_d/\delta Q_{d[l]}=\sqrt{1+U^2}=\sqrt{1+\left(\kappa/\sqrt{\Gamma_s\Gamma_d}\right)^2}=Q_s/\delta Q_{s[g]}=\kappa_s/\Gamma_s=U_{s[g]}$$

【００５１】

留意すべきは、上記の周波数マッチング及びＱマッチングの条件は、電気工学において「インピーダンスマッチング」として共に知られている。

【００５２】

上記の条件の下で、最大化効率は、図５に示されるように、供給源共振器とデバイス共振器との間の強結合率$U=\kappa/(\Gamma_s\Gamma_d)^{1/2}=k(Q_sQ_d)^{1/2}$の関数のみを単調に増加させ、$\eta=U^2/(1+(1+U^2)^{1/2})^2$により与えられる。留意すべきは、結合効率$\eta$は、Ｕが０．２より大きい場合に１％より大きく、Ｕが０．７より大きい場合に１０％より大きく、Ｕが１より大きい場合に１７％より大きく、Ｕが３より大きい場合に５２％より大きく、Ｕが９より大きい場合に８０％より大きく、Ｕが１９より大きい場合に９０％より大きく、Ｕが４５より大きい場合に９５％より大きい。幾つかの応用形態において、$U>1$の場合の動作状況は、「強い結合（強結合）」の状況と呼ばれ得る。

【００５３】

特定の環境において、大きな$U=\kappa/(\Gamma_s\Gamma_d)^{1/2}=(2\kappa/(\omega_s\omega_d)^{1/2})(Q_sQ_d)^{1/2}$が望ましいので、高いＱ（以降、高Ｑと称する）である共振器が使用され得る。各共振器のＱは、高くすることができる。共振器のＱの幾何平均（Q_sQ

${}_d)^{1/2}$も又はむしろ高くするとができる。

【００５４】

結合率ｋは、０≦ｋ≦１の間の数であり、供給源共振器およびデバイス共振器の共振周波数に無関係（又はほぼ無関係）とすることができ、むしろそれらの相対的な幾何学的形状およびそれらの結合に介在する場の物理的な減衰法則により主として求められ得る。対照的に、結合係数$\kappa = k(\omega_s \omega_d)^{1/2}/2$は、共振周波数の強い関数とすることができる。共振器の共振周波数は好適には、低いΓを達成するよりも、高いＱを達成するために選択されることができ、その理由は、これら２つの目標が２つの別個の共振周波数の状況で達成可能であるからである。

【００５５】

高Ｑの共振器（以降、高Ｑ共振器と称す）は、Ｑ＞１００を有するものとして定義され得る。２つの結合された共振器は、各共振器が１００より大きいＱ（$Q_s > 100$及び$Q_d > 100$）を有する場合に、高Ｑ共振器のシステムと呼ばれ得る。他の具現化形態において、２つの結合された共振器は、共振器のＱの幾何平均が１００より大きい場合（$(Q_s Q_d)^{1/2} > 100$）に、高Ｑ共振器のシステムと呼ばれ得る。

【００５６】

共振器は命名または番号付けされ得る。それらは、供給源共振器、デバイス共振器、第１の共振器、第２の共振器、中継共振器などと呼ばれ得る。理解されるべきは、２つの共振器が図１に示されるが、以下の例の多くにおいて、他の具現化形態は３つ以上の共振器を含むことができる。例えば、単一の供給源共振器１０２Ｓは、多数のデバイス共振器１０２Ｄ又は多数のデバイスにエネルギーを伝送することができる。エネルギーは、第１のデバイスから第２のデバイスへ、次いで第２のデバイスから第３のデバイスへ以下同様に伝送され得る。多数の供給源がエネルギーを単一のデバイスへ、又は単一のデバイス共振器に接続された多数のデバイスへ、又は多数のデバイス共振器に接続された多数のデバイスへ伝送することができる。共振器１０２は、交互に又は同時に供給源、デバイスとしての機能を果たすことができ、又は１つの場所の供給源からの電力を別の場所のデバイスに中継するために使用され得る。中間の電磁共振器１０２は、無線エネルギー伝送システムの距離範囲を広げるために使用され得る。多数の共振器１０２は、相互にデイジーチェーン接続されて、延長された距離にわたって、広範囲の供給源およびデバイスとエネルギーを交換することができる。多数のデバイスに伝送される高い電力レベルが、多数の供給源１０２Ｓ間で分割されて、遠くの場所で再結合され得る。

【００５７】

単一の供給源および単一のデバイス共振器の分析は、多数の供給源共振器および／または多数のデバイス共振器および／または多数の中間共振器に拡張され得る。係る分析において、結論は、多数の共振器の少なくとも幾つか又は全ての間の大きな強結合率U_{mn}が、無線エネルギー伝送での高いシステム効率に好適であるということである。また、具現化形態は、高いＱを有する供給源共振器、デバイス共振器、及び中間共振器を使用することができる。各共振器のＱは高くすることができる。一対の共振器ｍとｎ（大きなU_{mn}が望ましい）のＱの幾何平均（$(Q_s Q_d)^{1/2}$）も又はむしろ高くすることができる。

【００５８】

留意すべきは、２つの共振器の強結合率が、各共振器の損失機構および２つの共振器間の結合機構の相対的大きさにより求められることができ、これら機構の何れかまたは全ての強さは、上述したように共振器の近傍の外部物体の存在する状態で摂動され得る。

【００５９】

前のセクションから表記に関する規則を続けると、外部物体または材料が存在しない状態での結合率としてｋが説明される。外部物体ｐの存在する状態での結合率は$k_{(p)}$として示され、それを「パーターブド（perturbed：摂動される）結合率」又は「パーターブドｋ」と呼ぶ。留意すべきは、結合率ｋも、パーターブド結合率$k_{(p)}$から区別する必要がある場合に、「アンパーターブド（unperturbed：摂動されない）」として特徴付けられ得る。

【００６０】

$\delta k_{(p)} \equiv k_{(p)} - k$を定義し、それは、外部物体ｐに起因した「結合率に対する摂動」又は「ｋに対する摂動」と呼ばれる。

【００６１】

また、$\beta_{(p)} \equiv k_{(p)} / k$も定義し、それは、「結合率無感受性」又は「ｋ無感受性」と呼ばれる。$\beta_{12(p)}$のような、下部の添え字は、パーターブド及びアンパーターブド結合率が関連する共振器を示し、即ち$\beta_{12(p)} \equiv k_{12(p)} / k_{12}$である。

【００６２】

同様に、外部物体の存在しない状態での強結合率としてＵを説明する。外部物体ｐの存在する状態での強結合率が$U_{(p)}$、$U_{(p)} = k_{(p)} (Q_{1(p)} Q_{2(p)})^{1/2}$として示され、それは「パーターブド強結合率」又は「パーターブドＵ」と呼ばれる。留意すべきは、強結合率Ｕも、パーターブド強結合率$U_{(p)}$から区別する必要がある場合に、「アンパーターブド（unperturbed：摂動されない）」として特徴付けられ得る。

【００６３】

$\delta U_{(p)} \equiv U_{(p)} - U$を定義し、それは、外部物体ｐに起因した「結合率に対する摂動」又は「Ｕに対する摂動」と呼ばれる。

【００６４】

$\Xi_{(p)} = U_{(p)} / U$も定義し、それは、「強結合率の無感受性」又は「Ｕ無感受性」と呼ばれる。$\Xi_{12(p)}$のような、下部の添え字は、パーターブド及びアンパーターブド結合率が関連する共振器を示し、即ち$\Xi_{12(p)} \equiv U_{12(p)} / U_{12}$である。

【００６５】

摂動されるシステムにおけるエネルギー交換の効率は、摂動されないシステムの効率を与える同じ式により与えられることができ、この場合、強結合率、結合率、及びＱファクタのような全パラメータは、それらの摂動される（パーターブド）同等物により置き換えられる。例えば、１つの供給源および１つのデバイス共振器を含む無線エネルギー伝送のシステムにおいて、最適な効率は、以下のように計算され得る。

【００６６】

【数４】

$$\eta_{(p)} = \left[U_{(p)} \Big/ \left(1 + \sqrt{1 + U_{(p)}^{2}} \right) \right]^{2}$$

【００６７】

従って、外部物体により摂動される無線エネルギー交換のシステムにおいて、多数の共振器の少なくとも幾つか又は全ての間の大きいパーターブド強結合率$U_{mn(p)}$は、無線エネルギー伝送の高いシステム効率に望ましい。供給源共振器、デバイス共振器、及び／又は中間共振器は高い$Q_{(p)}$を有することができる。

【００６８】

幾つかの外因性摂動は、（結合率またはＱファクタに対する大きな摂動を介して）パーターブド強結合率に時として弊害をもたらす場合がある。従って、システムに対する外因性摂動の影響を低減するための技術が使用され、大きな強結合率無感受性が維持され得る。

【００６９】

エネルギー交換の効率

有用なエネルギー交換でのいわゆる「有用な」エネルギーは、デバイスに電力を供給する又はデバイスを充電するためにデバイス（単数または複数）に伝えられる必要があるエネルギー又は電力である。有用なエネルギー交換に対応する伝送効率は、システム依存または用途依存とすることができる。例えば、数キロワットの電力を伝送する高い電力の車両充電用途は、伝送システムの様々な構成要素が大幅に加熱せずに、車両のバッテリーを再充電するのに十分なように、有用なエネルギー交換で生じる有用な量の電力を供給する

ために少なくとも８０％の効率である必要がある。幾つかの家庭用電化製品の用途では、有用なエネルギー交換は、１０％よりも大きい任意のエネルギー伝送効率、又は再充電可能なバッテリーを「満タン状態」に保つ及び長期間の動作を保つために許容できる他の量を含むことができる。幾つかの無線センサ用途の場合、１％よりも大幅に少ない伝送効率が、センサからかなりの距離に配置された単一の供給源から多数の低電力センサに電力供給するために適切であるかもしれない。更に他の用途について、有線の電力伝送が不可能または実用的でない場合、広範囲の伝送効率が有用なエネルギー交換に受け入れ可能であり、これらの用途において有用な電力がデバイスに供給されると考えられ得る。一般に、動作距離は、有用なエネルギー交換が本明細書で開示された原理に従って維持される又は維持され得る任意の距離である。

【００７０】

電力供給または再充電の用途における無線エネルギー伝送の有用なエネルギー交換は、無駄なエネルギーレベル、熱放散、及び関連する電界強度が許容限界内である限り、効率的、非常に効率的、又は十分に効率的とすることができる。許容限界は、用途、環境、システムの場所に依存する場合がある。電力供給または再充電の用途の無線エネルギー伝送は、所望のシステム性能が適度なコスト的制限、重量制限、サイズ制限などに対して達せられ得る限り、効率的、非常に効率的、又は十分に効率的とすることができる。効率的なエネルギー伝送は、高いＱシステムでない従来の誘導技術を用いて達成され得るものに対して決定され得る。次いで、エネルギー伝送は、同様の距離にわたって又は位置合わせオフセット量で従来の誘導方法での同様なサイズのコイル構造により伝えられ得るエネルギーよりも多くのエネルギーが伝えられた場合に、効率的、非常に効率的、又は十分に効率的であるとして定義され得る。

【００７１】

留意すべきは、たとえ特定の周波数およびＱマッチング条件がエネルギー伝送のシステム効率を最適化できるとしても、これら条件は、有用なエネルギー交換に関して効率的で十分なエネルギー伝送を有するために厳密に満たされる必要はないかもしれない。効率的なエネルギー交換は、共振周波数の相対的なオフセット量（$|\omega_m-\omega_n|/(\omega_m\omega_n)^{1/2}$）が、$1/Q_{m(p)}$、$1/Q_{n(p)}$、及び$k_{mn(p)}$の中のほぼ最大値より小さい限り、実現され得る。Ｑマッチング条件は、効率的なエネルギー交換の周波数マッチング条件よりもあまり重要でない。電力発生装置および／または負荷に起因した共振器の強ローディング率$U_{m[l]}$がそれらの最適な値から離れることができる、及び依然として効率的で十分なエネルギー交換を有する程度は、特定のシステムに依存し、電力発生装置および／または負荷の全て又は幾つかがＱのミスマッチングであるか否かなどに依存する。

【００７２】

従って、共振器の共振周波数は厳密にマッチングされることができないが、上記の許容範囲内でマッチングされ得る。電力発生装置および／または負荷に起因した少なくとも幾つかの共振器の強ローディング率は、それらの最適な値に厳密にマッチングされなくてもよい。電圧レベル、電流レベル、インピーダンス値、材料パラメータなどは、本開示で説明された厳密な値にいなくてもよいが、これらの値の何らかの許容できる許容範囲内にある。システムの最適化には、効率、Ｑ、周波数、強結合率など、考慮事項に加えて、コスト、サイズ、重量、複雑性など、考慮事項が含まれ得る。幾つかのシステム性能パラメータ、仕様、及び設計は、他のシステム性能パラメータ、仕様、及び設計を最適化するために、決して最適ではないかもしれない。

【００７３】

幾つかの用途において、少なくとも幾つかのシステムパラメータは、例えば、供給源またはデバイスのような構成要素が移動できる又は経年劣化するという理由で、又は負荷が変化しやすいという理由で、又は摂動または環境条件が変化しているなどの理由で、時間的に変化する可能性がある。これらの場合において、許容できるマッチング条件を達成するために、少なくとも幾つかのシステムパラメータは、動的に調整可能またはチューナブルである必要がある。全システムパラメータは、ほぼ最適な動作状態を達成するために動

的に調整可能またはチューナブルとすることができる。しかしながら、上述したことに基づいて、効率的で十分なエネルギー交換は、たとえ幾つかのシステムパラメータが可変でなくても、実現され得る。幾つかの例において、少なくとも幾つかのデバイスは動的に調整されなくてもよい。幾つかの例において、少なくとも幾つかの供給源は動的に調整されなくてもよい。幾つかの例において、少なくとも幾つかの中間の共振器は動的に調整されなくてもよい。幾つかの例において、システムパラメータはどれも動的に調整されなくてもよい。

【００７４】

電磁共振器

エネルギーを交換するために使用される共振器は電磁共振器とすることができる。係る共振器において、固有のエネルギー減衰率Γ_mは、共振器の吸収（又は抵抗）損失および放射損失により与えられる。

【００７５】

共振器は、電界により蓄積されるエネルギーが主として構造体内に閉じ込められるように、及び磁界により蓄積されたエネルギーが主として共振器の周囲の領域にあるように構成され得る。そして、エネルギー交換は共振近傍磁界により主として実現される。これらタイプの共振器は、磁気共振器と呼ばれ得る。

【００７６】

共振器は、磁界により蓄積されたエネルギーが主として構造体内に閉じ込められるように、及び電界により蓄積されたエネルギーが主として共振器の周囲の領域にあるように構成され得る。そして、エネルギー交換は共振近傍電界により主として実現される。これらタイプの共振器は、電気共振器と呼ばれ得る。

【００７７】

留意すべきは、共振器により蓄積される電気的エネルギー及び磁気エネルギーは等しい必要があるが、それらの局在性は、全く違う場合がある。場合によっては、共振器から或る距離を離れて特定された平均電界エネルギーと平均磁界エネルギーの比は、共振器を特徴づける又は説明するために使用され得る。

【００７８】

電磁共振器は、誘導性素子、分布インダクタンス、又はインダクタンスＬを有するインダクタンスの組合せ、及び容量性素子、分布キャパシタンス、又はキャパシタンスＣを有するキャパシタンスの組合せを含むことができる。電磁共振器１０２の最小回路モデルが図６ａに示される。共振器は、誘導性素子１０８及び容量性素子１０４を含むことができる。コンデンサ１０４に蓄電された電界エネルギーのような初期エネルギーが提供されると、システムは、コンデンサが伝送エネルギーをインダクタ１０８に蓄積される磁場エネルギーへ放電し、次いでインダクタ１０８がコンデンサ１０４に蓄電される電界エネルギーへエネルギーを戻すように振動する。

【００７９】

図６の（ｂ）、（ｃ）、（ｄ）に示された共振器１０２は、磁気共振器と呼ばれ得る。磁気共振器は、人口の多い環境において無線エネルギー伝送用途に好適であり、その理由は、動物、植物、及び人間を含むほぼ日常の構成物質が非磁性（即ち、$\mu_r \fallingdotseq 1$）であり、そのためそれらの磁界との相互作用が最小であるからであり、係る相互作用は、二次効果である、磁界の時間変化により誘導される渦電流に主として起因する。この特徴は、安全上の理由で、及びそれが、システム性能を変化させる可能性がある外部環境物体および材料との相互作用の可能性を低減するという理由で重要である。

【００８０】

図６の（ｄ）は、例示的な磁気共振器１０２Ｂに関連した電界および磁界の力線の幾つかの簡易図を示す。磁気共振器１０２Ｂは、誘導性素子１０８として働くコンダクタのループ、及びコンダクタループの両端に容量性素子１０４を含むことができる。留意すべきは、この図面は、磁界に蓄積されている共振器の周囲の領域でのエネルギーの大部分、及び電界に蓄積された共振器（蓄電板の間）のエネルギーの大部分を示す。フリンジ電界、

自由電荷、及び時間変動磁界に起因した或る電界は、共振器の周りの領域に蓄積され得るが、磁気共振器は、できる限り多くの電界を共振器自体に接近して又は共振器自体内に閉じ込めるように設計され得る。

【００８１】

電磁共振器１０２のインダクタ１０８及びコンデンサ１０４は、バルク回路素子とすることができるか、又はインダクタンス及びキャパシタンスは分布（分散）されることができ、結果としてその態様から構造内に導体が形成され、形作られ、又は配置され得る。例えば、インダクタ１０８は、図６の（ｂ）、（ｃ）、（ｄ）に示されるように、表面積を包囲するように導体を形作ることにより実現され得る。このタイプの共振器１０２は、容量的に装荷されたループインダクタと呼ばれ得る。留意すべきは、用語「ループ」又は「コイル」は、任意の形状および寸法の表面を包囲し、任意のターン数を有する導電構造（ワイヤ、管、ストリップなど）を概して示すために使用される。図６の（ｂ）において、包囲された表面積は円形であるが、表面は任意の多種多様な他の形状およびサイズとすることができ、特定のシステム性能の仕様を達成するために設計され得る。インダクタンスが如何にして物理的寸法に対応するかを示すための例として、一巻きの円形ループを形成するように構成された円形導体の長さに対するインダクタンスは、ほぼ以下の通りである。

【００８２】

【数５】

$$L=\mu_0 x(\ln\frac{8x}{a}-2)$$

【００８３】

ここで、μ０は自由空間の透磁率であり、ｘは包囲された円形の表面積の半径であり、ａはインダクタループを形成するために使用される導体の半径である。ループのインダクタンスのより正確な値は、分析的に又は数値的に計算され得る。

【００８４】

他の包囲される表面形状、領域、サイズなどを形成するために構成された、及び任意のターン数のワイヤの、他の断面の導体に関するインダクタンスは、分析的、数値的に計算され得るか、又は測定により求められ得る。インダクタンスは、インダクタ素子、分布インダクタンス、回路網、アレイ、インダクタ及びインダクタンスの直列および並列の組合せなどを用いて実現され得る。インダクタンスは、固定または可変とすることができ、インピーダンスマッチング並びに共振周波数の動作条件を変更するために使用され得る。

【００８５】

共振器構造の所望の共振周波数を達成するために必要なキャパシタンスを実現するための様々な方法が存在する。蓄電板１１０が、図６の（ｂ）に示されるように形成されて利用され得るか、又はキャパシタンスが、図６の（ｃ）に示されるように、複数ループの導体１１４の隣接する巻線間に分布されて実現され得る。キャパシタンスは、コンデンサ素子、分布キャパシタンス、回路網、アレイ、キャパシタンスの直列および並列の組合せなどを用いて実現され得る。キャパシタンスは固定または可変とすることができ、インピーダンスマッチング並びに共振周波数の動作条件を変更するために使用され得る。

【００８６】

理解されるべきは、電磁共振器１０２のインダクタンス及びキャパシタンスは、集中され得るか、分布され得るか、又は集中および分布インダクタンス及びキャパシタンスの組合せとすることができ、電磁共振器は、様々な素子、技術、及び本明細書で説明される効果の組合せにより実現され得る。

【００８７】

電磁共振器１０２は、インダクタ、インダクタンス、コンデンサ、キャパシタンス、及び追加の回路素子（例えば、抵抗、ダイオード、スイッチ、増幅器、ダイオード、トラン

ジスタ、変圧器、導体、コネクタなど）を含むことができる。

【００８８】

電磁共振器の共振周波数

電磁共振器１０２は、特有の共振周波数、固有の共振周波数、又はその物理的特性により求められる共振周波数を有することができる。この共振周波数は、共振器の電界W_E（$W_E = q^2 / 2C$、ここでｑはコンデンサＣの電荷である）により蓄積されたエネルギーと、磁界W_B（$W_B = Li^2 / 2$、ここでｉはインダクタＬを流れる電流である）により蓄積されたエネルギーとの間で、共振器により蓄積されたエネルギーが振動する周波数である。システム（系）において任意の損失がない場合、エネルギーはコンデンサ１０４の電界とインダクタ１０８の磁界との間で継続的に交換される。エネルギーが交換される周波数は、共振器の特有周波数、固有周波数、又は共振周波数と呼ばれることができ、それは、ω、$\omega = 2\pi f = (1/LC)^{1/2}$により与えられる。

【００８９】

共振器の共振周波数は、共振器のインダクタンスＬ、及び／又はキャパシタンスＣをチューニング（調整）することにより変更され得る。共振器の周波数は、ＦＣＣにより規定されるような、いわゆるＩＳＭ（Industrial（工業）、Scientific（科学）、Medical（医療））周波数で動作するように設計され得る。共振器の周波数は、特定の領域制限の仕様、比吸収率（ＳＡＲ）制限の仕様、電磁両立性（ＥＭＣ）の仕様、電磁妨害（ＥＭＩ）の仕様、構成要素のサイズ、コスト、又は性能仕様などを満たすように選択され得る。

【００９０】

電磁共振器のＱファクタ

図６に示された共振器１０２のエネルギーは、吸収損失（抵抗損または抵抗損失とも呼ぶ）及び／又は放射損失を含む固有損失により減衰または失われ得る。エネルギー減衰を特徴付ける、共振器のＱファクタ又はＱは、それらの損失に反比例する。吸収損失は、インダクタを形成するために使用される導体の有限導電率により、並びに共振器の他の素子、構成要素、コネクタなどの損失によりもたらされる可能性がある。低損失材料から形成されたインダクタは、「高Ｑ誘導性素子」と呼ばれることができ、低い損失を有する素子、構成要素、コネクタなどは、「高い抵抗性Ｑ」を有すると呼ばれ得る。一般に、共振器の全吸収損失は、共振器を構成する様々な素子および構成要素の抵抗損失の適切な直列および／または並列の組合せとして計算され得る。即ち、任意の顕著な放射損失または構成要素／接続の損失がない状態において、共振器のＱは、Q_{abs}、$Q_{abs} = \omega L / R_{abs}$により与えられ得る。ここで、ωは共振周波数であり、Ｌは共振器の全インダクタンスであり、例えば、インダクタを形成するために使用される導体の抵抗は、$R_{abs} = l\rho / A$により与えられる（ｌはワイヤの長さであり、ρは導体材料の抵抗率であり、Ａは電流がワイヤに流れる断面積である）。交流電流の場合、電流が流れる断面積は、表皮効果に起因して導体の物理的な断面積より小さくすることができる。従って、高Ｑ磁気共振器は、高い導電率、比較的大きな表面積を有する導体、及び／又は近接効果を最小限にする及びＡＣ抵抗を低減するために特別に設計された断面（プロファイル）（例えば、リッツ線）を有する導体から構成され得る。

【００９１】

磁気共振器の構造は、高い導電率のワイヤ、被覆線、リッツ線、リボン、ストラップ又はプレート、管、塗料、ゲル、トレースなどから構成された高Ｑ誘導性素子を含むことができる。磁気共振器は、自己共振とすることができ、コンデンサ、インダクタ、スイッチ、ダイオード、トランジスタ、変圧器などのような外部結合素子を含むことができる。磁気共振器は、分布および集中キャパシタンス及びインダクタンスを含むことができる。一般に、共振器のＱは、共振器の個々の構成要素の全てのＱにより求められ得る。

【００９２】

Ｑはインダクタンスに比例するので、共振器は、特定の他の制約の範囲内でＬを増加させるように設計され得る。例えば、Ｌを増加させるための１つの方法は、共振器のインダクタを形成するために２つ以上のターン数の導体を使用することである。設計技術およ

びトレードオフは用途に依存し、多種多様な構造、導体、構成要素、及び共振周波数は、高Ｑ磁気共振器の設計で選択され得る。

【００９３】

顕著な吸収損失がない状態で、共振器のＱは、主として放射損失により求められることができ、$Q_{rad}=\omega L/R_{rad}$により与えられ、ここで、R_{rad}は共振器の放射損失であり、動作の周波数ω又は波長λに対する共振器のサイズに依存する。上述した磁気共振器の場合、放射損失は、$R_{rad}\sim(x/\lambda)^4$（磁気双極子放射の特性）としてスケーリングされることができ、ここで、ｘは図６の（ｂ）に示された誘導性素子の半径のような、共振器の特有寸法であり、$\lambda=c/f$であり、ｃは光速であり、ｆは上記で定義されたものと同じである。磁気共振器のサイズは、動作の波長よりも非常に小さくすることができ、そのため放射損失が非常に小さくなることができる。係る構造は、副波長共振器と呼ばれ得る。放射は、非放射型無線エネルギー伝送システムの損失機構とすることができ、設計は、R_{rad}を低減または最小化するように選択され得る。留意すべきは、高Q_{rad}は、非放射型無線エネルギー伝送方法に望ましい。

【００９４】

また、留意すべきは、非放射型無線エネルギー伝送用の共振器の設計は、通信または遠距離場エネルギー伝送目的に設計されたアンテナとは異なる。特に、容量的に装荷された導電性ループは共振アンテナ（例えば、セル方式の携帯電話で）として使用され得るが、それらは、放射Ｑが放射エネルギーにおいてアンテナ効率を小さくするように意図的に設計されている遠距離場の状況で動作する。係る設計は、本明細書で開示された効率的な近接場無線エネルギー伝送技術に適切ではない。

【００９５】

放射損失および吸収損失を含む共振器のＱファクタは、$Q=\omega L/(R_{abs}+R_{rad})$である。留意すべきは、特定の共振器に対する最大Ｑ値が存在し、その共振器は、高Ｑ共振器を達成するために、共振器、動作周波数、接続機構などを構成するために使用される共振器のサイズ、材料、及び素子に特別に配慮して設計され得る。図７は、ＭＨｚ周波数での無線電力送信に使用され得る例示的な磁気共振器（この場合、４ｃｍの外径（ＯＤ）を有する銅管から作成された６０ｃｍの直径を有するコイル）のＱのグラフを示す。吸収Ｑ（波線）７０２は周波数と共に増加するが、放射Ｑ（点線）７０４は周波数と共に減少し、かくして全体のＱが特定の周波数でピーク７０８ということになる。留意すべきは、この例示的な共振器のＱは、広い周波数範囲にわたって１００より大きい。磁気共振器は、周波数範囲にわたって高Ｑを有するように設計されることができ、システムの動作周波数はその範囲の任意の周波数に設定され得る。

【００９６】

共振器が損失率の点で記述されている場合、そのＱは、前述されたように、固有の減衰率２Γを用いて定義され得る。固有の減衰率は、非結合および非駆動の共振器がエネルギーを失う率である。上述した磁気共振器の場合、固有の損失率は、$\Gamma=(R_{abs}+R_{rad})/2L$により与えられることができ、共振器のＱファクタＱは、$Q=\omega/2\Gamma$により与えられる。

【００９７】

留意すべきは、特定の損失機構にのみ関連したＱファクタは、共振器が特定されていない場合、$Q_{mechanism}$として示され、共振器が特定されている場合（例えば、共振器１）、$Q_{1,mechanism}$として示される。例えば、$Q_{1,rad}$は、放射損失に関連した共振器１のＱファクタである。

【００９８】

電磁共振器の近接場

本明細書で開示された近接場無線エネルギー伝送システムで使用される高Ｑ電磁共振器は、副波長物体とすることができる。即ち、共振器の物理的寸法は、共振周波数に対応する波長よりもはるかに小さくすることができる。副波長磁気共振器は、それらの近傍磁界に蓄積されたエネルギーの大部分を共振器の周囲の領域に有することができ、これらの場

は、共振器から離れて放射しないので、変化しないもの又は非伝搬としても記述され得る。共振器を取り囲む領域の近接場の範囲は一般に、波長により設定され、そのため、近接場は、副波長共振器の共振器自体を越えて適切に広がることができる。場の振る舞いが近接場の振る舞いから遠距離場の振る舞いに変化する制限表面は、「放射コーステック（caustic：火面、腐食性）」と呼ばれ得る。

【００９９】

近接場の強さは、共振器から遠ざかるほど低減される。共振器近接場の場の強さは、共振器から離れるように減衰するが、場は、共振器の全般的な近傍に持ってこられた物体と依然として相互作用することができる。場が相互作用する程度は、様々な因子に依存し、当該因子の幾つかは制御および設計されることができ、及び当該因子の幾つかは制御および設計されることができない。本明細書で説明される無線エネルギー伝送方法は、結合された共振器間の距離が、１つの共振器が他の共振器の放射コーステックの範囲内に位置する場合に実現され得る。

【０１００】

電磁共振器の近接場のプロファイルは、双極子（ダイポール）共振器または振動子に一般に関連したものに類似する。係る場のプロファイルは、全方向として記述されることができ、場の大きさを意味することは、物体から離れる全方向において非ゼロである。

【０１０１】

電磁共振器の特有サイズ

空間的に分離および／またはオフセットした、十分なＱの磁気共振器は、たとえ共振器構造のサイズ及び形状が異なっても、従来技術で見られたものよりはるかに長い距離にわたって効率的な無線エネルギー伝送を達成することができる。また、係る共振器は、より短い範囲の距離にわたって、従来技術で達成可能であったものよりも効率的なエネルギー伝送を達成するように動作され得る。係る共振器が中距離エネルギー伝送をできるものとして説明される。

【０１０２】

中距離は、伝送に含まれる最も小さい共振器の特有寸法よりも大きい距離として定義されることができ、この場合、距離は、１つの共振器構造の中心から、空間的に離れた第２の共振器構造の中心までを測定される。この定義において、二次元共振器は、それらの誘導性素子によって外接した領域が交差しない場合に空間的に分離されており、三次元共振器は、それらの体積が交差しない場合に空間的に分離されている。二次元共振器は、二次元共振器により外接した領域が三次元共振器の体積の外側にある場合に、三次元共振器から空間的に分離されている。

【０１０３】

図８は、特有寸法を表記された幾つかの共振器の例を示す。理解されるべきは、共振器１０２の特有サイズ８０２は、導体のサイズ、磁気共振器の誘導性素子により外接または包囲された領域、電気共振器の容量性素子を形成する導体の長さの点で定義され得る。そして、共振器１０２の特有サイズ８０２、x_{char}は、磁気または電気共振器のそれぞれの誘導性素子または容量性素子の周りに適合することができる最も小さい球の半径に等しくすることができ、共振器構造の中心が球の中心である。共振器１０２の特有厚さ８０４、t_{char}は、磁気または電気共振器のそれぞれの誘導性素子または容量性素子の、それが配置された平面から測定された最も高い点の最も小さい可能な高さとすることができる。共振器１０２の特有幅８０８、w_{char}は、磁気または電気共振器のそれぞれの誘導性素子または容量性素子が通過ることができるが、直線で進む最も小さい可能な円の半径とすることができる。例えば、円柱状共振器の特有幅８０８は、円柱の半径とすることができる。

【０１０４】

本発明の無線エネルギー伝送技術において、エネルギーは、広範囲の距離にわたって効率的に交換され得るが、当該技術は、中間距離にわたって、及び異なる物理的寸法、構成要素、及び位置関係（orientation：幾何学的配置、方向性、配向性）を有する共振器間で、デバイスに電力供給またはデバイスを再充電するための有用なエネルギーを交換する

ための能力により区別される。留意すべきは、ｋはこれらの環境で小さくすることができるが、強い結合および効率的なエネルギー伝送は、高いＵ、$U=k(Q_sQ_d)^{1/2}$を達成するために高Ｑ共振器を用いることにより実現され得る。即ち、Ｑの増加は、有用なエネルギー伝送効率を維持するために、少なくとも部分的にｋの減少を克服するために使用され得る。

【０１０５】

また、留意すべきは、単一の共振器の近接場が全方向として説明され得るが、２つの共振器間のエネルギー交換の効率は、共振器の相対的な位置および方向性に依存する可能性がある。即ち、エネルギー交換の効率は、共振器の特定の相対的な方向性に対して最大化され得る。２つの補償されていない共振器の相対位置および方向性に対する伝送効率の感度は、ｋ又はκの計算で捕らえられ得る。結合は、互いに対してオフセットされた及び／又は回転された共振器間で達成され得るが、交換の効率は、位置決めの細部に依存する、及び動作中に実施される任意のフィードバック、チューニング、及び補償技術に依存する可能性がある。

【０１０６】

高Ｑ磁気共振器

副波長の容量的に装荷されたループ磁気共振器（ｘ≪λ）の近接場の状況において、半径が浸透厚（skin depth：表皮厚さ）より大きい、Ｎターンのワイヤから構成された円形導電性ループインダクタに関連した抵抗は、ほぼ以下の通りである。

【０１０７】

【数６】

$$R_{abs}=\sqrt{\mu_o\rho\omega/2}\cdot Nx/a \quad \text{及び} \quad R_{rad}=\pi/6\cdot\eta_o N^2\left(\omega x/c\right)^4$$

【０１０８】

ここで、ρは、導電材料の抵抗率であり、η_0≒１２０πΩは自由空間のインピーダンスである。係るＮターンのループのインダクタンスＬは、予め与えられる単一ターンのループのインダクタンスのほぼN^2倍である。係る共振器のＱファクタ、$Q=\omega L/(R_{abs}+R_{rad})$は、システムパラメータ（図４）により求められた特定の周波数に対して最も高い。前述されたように、より低い周波数において、Ｑは主として吸収損失により求められ、より高い周波数において、Ｑは、主として放射損失により求められる。

【０１０９】

留意すべきは、上記で与えられた式は、近似であり、構造の物理的パラメータにおけるR_{abs}、R_{rad}及びＬの関数依存性を示すことが意図されている。厳密な準静的制限からの偏移、例えば、導体に沿った不均一な電流／電荷分布を考慮する、これらパラメータのより正確な数値計算は、共振器構造の精密な設計に役立つことができる。

【０１１０】

留意すべきは、吸収損失は、誘導性素子を形成するために低損失導体を用いることにより最小化され得る。導体の損失は、導電性管、ストラップ、ストリップ、機械加工物体、プレートなどのような大きな表面積の導体を用いることにより、リッツ線、編組線、任意の断面のワイヤ、及び低い近接損失を有する他の導体のような特別に設計された導体（この場合、上述した周波数スケーリングされた振る舞いは異なる可能性がある）を用いることにより、及び例えば、高純度銅および銀のような低い抵抗率の材料を用いることにより、最小限にされ得る。より高い動作周波数において導体として導電性管を用いる１つの利点は、同様の直径の中空でない導体よりも安く及び軽くでき、大部分の電流が表皮効果に起因して導体の外面に沿って伝わるので同様の抵抗を有することができるということである。

【０１１１】

銅線または銅管から作成され、マイクロ波領域での動作に適した実現可能な共振器の設計のおおよその推定を得るために、様々な断面を有する銅線（$\rho=1.69\cdot10^{-8}$Ω ｍ）からなる１つの円形誘導性素子（Ｎ＝１）から構成された共振器の最適なＱ及び共振周波数が計算され得る。そして、例えば、セル式携帯電話に適した、特有サイズｘ＝１ｃｍ、及び導体直径ａ＝１ｍｍの誘導性素子については、Ｑファクタは、ｆ＝３８０ＭＨｚの場合に、Ｑ＝１２２５でピークに達する。ｘ＝３０ｃｍ、及びａ＝２ｍｍの場合、誘導性素子のサイズがラップトップコンピュータ又は家庭用ロボットに適しており、ｆ＝１７ＭＨｚでＱ＝１１０３である。例えば、天井に配置され得る、より大きな供給源の誘導性素子の場合、ｘ＝１ｍ、及びａ＝４ｍｍであり、Ｑは、ｆ＝５ＭＨｚでＱ＝１３１５までなることができる。留意すべきは、多数の実際的な例は、λ／ｘ≒５０～８０で、Ｑ≒１０００～１５００の予想されるＱファクタを生じる。上述したものよりも多種多様のコイル形状、サイズ、材料、及び動作周波数の測定値は、Ｑ＞１００が、一般に入手可能な材料を用いた様々な磁気共振器構造に実現され得ることを示す。

【０１１２】

上述したように、特有サイズx_{1}及びx_{2}、中心間の距離Ｄだけ離れた２つの共振器間でのエネルギー伝送の割合（rate：率）は、κにより与えられ得る。定義されたパラメータが如何にしてスケーリングされるかに関する例を与えるために、３つの距離Ｄ／ｘ＝１０、８、６において、上記からのセル式携帯電話、ラップトップコンピュータ、及び天井の共振器の例を考察する。ここで考察される例において、供給源およびデバイスの共振器は同じサイズ$x_{1}=x_{2}$と形状であり、図１の（ｂ）に示されるように配置される。セル式携帯電話の例において、それぞれω／２κ＝３０３３、１５５３、６５５である。ラップトップコンピュータの例では、それぞれω／２κ＝７１３１、３６５１、１５４０であり、天井の共振器の例については、それぞれω／２κ＝６４８１、３３１８、１４００である。誘導性素子のＱがピークに達する周波数での対応する結合対損失率のピークは、上述した３つの誘導性素子のサイズと距離の場合、κ／Γ＝０．４、０．７９、１．９７及び０．１５、０．３、０．７２及び０．２、０．４、０．９４である。異なるサイズの誘導性素子を用いる例は、距離Ｄ＝３ｍ離れて（例えば、部屋の高さ）、x_{1}＝１ｍのインダクタ（例えば、天井の供給源）、及びx_{2}＝３０ｃｍのインダクタ（例えば、床上の家庭用ロボット）である。この例において、最適な動作周波数ｆ＝６．４ＭＨｚにおいて、約１４％の効率について、強い結合の性能指数$U=\kappa/(\Gamma_{1}\Gamma_{2})^{1/2}$＝０．８８である。ここで、最適なシステムの動作周波数は、個々の共振器のＱのピーク間にある。

【０１１３】

誘導性素子は、高Ｑの磁気共振器用に形成され得る。本発明者は、表面を包囲する誘導性素子へ形成される、銅導体を用いた様々な高Ｑ磁気共振器を実証した。誘導性素子は、様々な形状に構成された様々な導体を用いて形成されることができ、任意のサイズ又は形状の領域を包囲し、単一のターン数又は複数のターン数の素子とすることができる。例示的な誘導性素子９００Ａ～９００Ｂの図面が図９に示される。誘導性素子は、円形、長方形、正方形、三角形、丸みを帯びたかど（すみ）を有する形状、特定の構造またはデバイスの輪郭をたどる形状、構造またはデバイス内の専用空間をたどる、満たす、又は利用する形状などを包囲するように形成され得る。設計は、サイズ、コスト、重量、体裁、性能などに最適化され得る。

【０１１４】

これらの導体は、所望のサイズ、形状、及びターン数へ曲げられ又は形成され得る。しかしながら、手動の技術を用いて正確に導体の形状およびサイズを複製することは困難である可能性がある。更に、誘導性素子の隣接するターンの導体セグメント間での均一な又は所望の中心間の間隔を維持することは困難である可能性がある。正確または均一な間隔は、例えば、構造の自己キャパシタンス、並びにＡＣ抵抗における任意の近接効果の誘導的増加を決定する際に重要である。

【０１１５】

高Ｑ共振器の設計のためのインダクタ素子を複製するために、金型（モールド）が使用され得る。更に、金型は、導体にねじれ、よじれ、又は場合によっては他の有害な影響を生じることなく、導体を任意の種類の形状へと正確に形作るために使用され得る。金型は

、インダクタ素子を形成するために使用されることができ、次いでインダクタ素子は、型から取り外され得る。ひとたび取り外されれば、これらの誘導性素子は、高Ｑ磁気共振器を収容することができる筐体またはデバイスへ組み込まれ得る。また又は代わりとして、形成された素子は、それらを形成するために使用された金型に残存してもよい。

【０１１６】

金型は、標準的なＣＮＣ（コンピュータ数値制御）のルーティング又はフライス加工のツール、或いは切断またはブロックに溝を形成するための任意の他の知られた技術を用いて形成され得る。また又は代わりとして、金型は、機械加工技術、射出成形技術、鋳造技術、鋳込み技術、真空技術、熱成形技術、カットインプレイス（cut-in-place）技術、圧縮成型技術などを用いて形成され得る。

【０１１７】

形成された素子は、金型から取り外されるか、又は金型に残存してもよい。金型は、誘導性素子の内側で変更され得る。金型は、被覆され、機械加工され、取り付けられ、塗装などされ得る。金型および導体の組合せは、別のハウジング、構造、デバイスに組み込まれ得る。金型に切り込まれた溝は、任意の寸法とすることができ、導電管、ワイヤ、ストラップ、ストリップ、ブロックなどを所望の導体形状とサイズに形成するために設計され得る。

【０１１８】

磁気共振器に使用される誘導性素子は、２つ以上のループを含むことができ、内側に又は外側に螺旋状に、又は螺旋状に上昇又は下降、又は幾つかの方向の組合せで螺旋状になることができる。一般に、磁気共振器は、様々な形状、サイズ、及びターン数を有することができ、様々な導電材料から構成され得る。

【０１１９】

磁気共振器は、自立型とすることができるか、又は筐体、容器、スリーブ又はハウジング内に収容され得る。磁気共振器は、誘導性素子を作成するために使用された型を含むことができる。これらの様々な型および筐体は、ほぼ任意の種類の材料から構成され得る。テフロン（登録商標）、REXOLITE（登録商標）、スチレンなどのような低損失材料は、幾つかの用途に好適とすることができる。これらの筐体は、誘導性素子を保持する固定具を含むことができる。

【０１２０】

磁気共振器は、銅ワイヤ又は銅管の自己共振コイルから構成され得る。自己共振導電性ワイヤコイルから構成された磁気共振器は、長さｌ、及び断面半径ａのワイヤを含み、そのワイヤは、半径ｘ、高さｈ、及びターン数Ｎの螺旋コイルへ巻かれ、それは例えば、$N=(l^{2}-h^{2})^{1/2}/2\pi x$として特徴づけられ得る。

【０１２１】

磁気共振器の構造は、ｘが約３０ｃｍ、ｈが約２０ｃｍ、ａが約３ｍｍ、及びＮが約５．２５であるように構成されることができ、動作中、磁気共振器に結合された電源が共振周波数ｆ（この場合、ｆは約１０．６ＭＨｚ）で共振器を駆動することができる。ｘが約３０ｃｍ、ｈが約２０ｃｍ、ａが約１ｃｍ、Ｎが約４である場合、共振器は周波数ｆ（この場合、ｆは約１３．４ＭＨｚ）で駆動され得る。ｘが約１０ｃｍ、ｈが約３ｃｍ、ａが約２ｍｍ、Ｎが約６である場合、共振器は周波数ｆ（この場合、ｆは約２１．４ＭＨｚ）で駆動され得る。

【０１２２】

高Ｑ誘導性素子は、プリント回路基板のトレースを用いて設計され得る。プリント回路基板のトレースは、機械的に形成された誘導性素子に比べて、確立されたプリント回路基板の製作技術を用いて正確に複製され且つ容易に集積化され得ること、それらのＡＣ抵抗が特注設計された導体トレースを用いて低くされ得ること、及びそれらを大量生産するコストが大幅に低減され得ることを含む様々な利点を有することができる。

【０１２３】

高Ｑ誘導性素子は、ＦＲ－４（エポキシＥガラス）、多機能エポキシ、高性能エポキシ

、ビスマレイミドトリアジン／エポキシ、ポリイミド、シアネートエステル、ポリテトラフルオロエチレン（Teflon（登録商標））、ＦＲ－２、ＦＲ－３、ＣＥＭ－１、ＣＥＭ－２、Rogers（登録商標）、Resolute（登録商標）などのような任意のＰＣＢ材料に関する標準的なＰＣＢ技術を用いて製作され得る。導体トレースは、より低い損失正接を有するプリント回路基板材料で形成され得る。

【０１２４】

導電トレースは、銅、銀、金、アルミニウム、ニッケルなどから構成されることができ、塗料、インク又は他の硬化材料から構成されてもよい。回路基板は、フレキシブルとすることができ、フレックス回路とすることができる。導電トレースは、化学蒸着、エッチング、リソグラフィ、スプレー蒸着、切断加工（cutting）などにより形成され得る。導電トレースは、所望のパターンを形成するように付着されることができ、結晶および構造成長技術を用いて形成され得る。

【０１２５】

導電トレースの寸法、並びに導電トレースを含む層の数、位置、係るトレースのサイズと形状、及びトレースを相互接続するための構造は、共振器のＱ、$Q_{(p)}$、共振器のサイズ、共振器の材料および製作コスト、Ｕ、$U_{(p)}$などのような特定のシステム仕様を達成または最適化するために設計され得る。

【０１２６】

一例として、図１０の（ａ）に示されるように、３ターンの高Ｑ誘導性素子１００１Ａが、長方形の銅トレースパターンを用いて４層プリント回路基板に製作された。銅トレースは黒色で示され、ＰＣＢは白色で示される。この例における銅トレースの幅と厚さはそれぞれ、約1ｃｍ（４００ミル）及び４３μｍ（１．７ミル）である。単一層上の導電トレースのターン間のエッジ間距離は、約０．７５ｃｍ（３００ミル）であり、基板の各層の厚さは、約１００μｍ（４ミル）である。図１０の（ａ）に示されたパターンは、基板の各層で繰り返され、導体は並列に接続される。３ループ構造の外側の寸法は、約３０ｃｍ×２０ｃｍである。このＰＣＢループの測定されたインダクタンスは、５．３μＨである。この誘導性素子および調整可能なコンデンサを用いる磁気共振器は、その設計された６．７８ＭＨｚの共振周波数において５５０のＱファクタＱを有する。共振周波数は、磁気共振器のインダクタンス及びキャパシタンスの値を変更することによりチューニング（調整）され得る。

【０１２７】

別の例として、２ターンのインダクタ１００１Ｂが、図１０の（ｂ）に示された長方形の銅トレースパターンを用いて４層のプリント回路基板上に製作された。銅トレースは黒色で示され、ＰＣＢは白色で示される。この例における銅トレースの幅と高さはそれぞれ、約０．７５ｃｍ（３００ミル）及び４３μｍ（１．７ミル）である。単一層上の導電トレースのターン間のエッジ間距離は、約０．６３５ｃｍ（２５０ミル）であり、基板の各層の厚さは、約１００μｍ（４ミル）である。図１０の（ｂ）に示されたパターンは、基板の各層で繰り返され、導体は並列に接続される。２ループ構造の外側の寸法は、約７．６２ｃｍ×２６．７ｃｍである。このＰＣＢループの測定されたインダクタンスは、１．３μＨである。約０．６３５ｃｍ（２５０ミル）の垂直離隔距離で２つの基板を互いに積み重ね、直列に２つの基板を接続することにより、約３．４μＨのインダクタンスを有するＰＣＢインダクタが作成された。このスタック型インダクタループ及び調整可能なコンデンサを用いる磁気共振器は、その設計された６．７８ＭＨｚの共振周波数において３９０のＱファクタＱを有する。共振周波数は、磁気共振器のインダクタンス及びキャパシタンスの値を変更することによりチューニング（調整）され得る。

【０１２８】

誘導性素子は、任意のサイズ、形状、厚さなどの磁性材料、及び広範囲の透磁率および損失の値を有する材料の磁性材料を用いて形成され得る。これら磁性材料は、中実のブロックとすることができ、中空の体積を包囲することができ、多くの小さい磁性材料のタイル片から形成または互いに積み重ねられることができ、高い導電材料から作成された導電

シート又は筐体と一体化され得る。ワイヤは、近傍磁界を生成するために、磁性材料に巻き付けられ得る。これらのワイヤは、構造の１つの軸又は２つ以上の軸に巻き付けられ得る。複数のワイヤが、並列または直列で組み合わされて、又はカスタマイズされた近接場のパターンを形成するためにスイッチを介して、磁性材料に巻き付けられ得る。

【０１２９】

磁気共振器は、３Ｆ３フェライト材料の１９．２ｃｍ×１０ｃｍ×５ｍｍのタイル状ブロックに１５ターン巻き付けられたリッツ線を含むことができる。リッツ線は、所望の共振器性能を達成するために、任意の方向または方向の組合せでフェライト材料に巻き付けられる。ワイヤのターン数、ターン間の間隔、ワイヤの種類、磁性材料のサイズと形状、及び磁性材料の種類は全て、様々な用途の状況に関して変化または最適化され得る設計パラメータである。

【０１３０】

磁性材料構造を用いる高Ｑ磁気共振器

たとえ構造全体の或る程度のサイズの空隙を有するとしても、開磁路を形成するために組み立てられた磁性材料を用いて、磁気共振器構造を実現することができる。これらの構造において、高い導電性材料が、磁性材料から作成された構造体に巻き付けられて、磁気共振器の誘導性素子を形成する。コンデンサ素子は、高い導電性材料に接続され、次いで共振周波数が上述したように決定され得る。これら磁気共振器は、容量的に装荷されたインダクタループの共振器の場合のように、垂直でなくて二次元共振器構造の平面において双極子モーメントを有する。

【０１３１】

単一の平面共振器構造の図が図１１の（ａ）に示される。平面共振器構造は、フェライトのような磁性材料のコア１１２１から構築され、コア１１２１に巻き付けられた導電材料１１２２のループ（単数または複数）を有する。構造は、電力を伝送する供給源共振器として、及びエネルギーを捕らえるデバイス共振器として使用され得る。供給源として使用される場合、導体の両端部は電源に結合され得る。導体ループを流れる交流電流が交番磁界を生じさせる。構造が電力を受け取るために使用される場合、導体の両端部は、電力ドレイン又は負荷に結合され得る。変化する磁界が、コアの磁性材料に巻き付けられた導体のループ（単数または複数）に起電力を誘導する。これらタイプの構造の双極子モーメントは、構造体の平面内にあり、例えば、図１１の（ａ）の構造体のＹ軸に沿って方向付けられる。２つの係る構造体は、実質的に同じ平面内に配置される場合（即ち、図１１のＸ、Ｙ平面）、強い結合を有する。図１１の（ａ）の構造体は、共振器がＹ軸に沿って同じ平面に整列された場合に最も好適な位置関係を有する。

【０１３２】

説明された平面共振器の幾何学的形状および結合の位置関係は、幾つかの用途に好適とすることができる。平面または平坦な共振器形状は、比較的平坦および平面である多くの電気デバイスに容易に組み込まれ得る。平面共振器は、デバイスの幾何学的形状の変更を必要とせずに、デバイスの全裏面または側面に組み込まれ得る。多くのデバイスの平坦な形状に起因して、表面上に配置されたデバイスの自然の位置は、それらが配置された表面に平行である最も大きい寸法で横たわることである。平坦なデバイスに組み込まれた平面共振器は、表面の平面に自然に平行であり、他のデバイスの共振器または平坦な表面に配置された平面共振器の供給源に対して好適な結合の位置関係にある。

【０１３３】

前述したように、平面共振器の幾何学的形状は、デバイスへのより容易な組み込みを可能にすることができる。これらの薄型により、共振器がデバイスの全側面へ又は全側面の一部として組み込まれることが可能になる。デバイスの全側面が共振器により覆われる場合、磁束は、デバイス又はデバイスの回路の一部である可能性がある損失性材料により妨害されずに、共振器のコアを流れることができる。

【０１３４】

平面共振器構造のコアは、様々な形状および厚さからなることができ、最小寸法が構造

の最も大きい寸法の３０％を超えないないように、平坦または平面にすることができる。コアは、複雑な幾何学的形状を有することができ、くぼみ、切欠き、隆起部などを有することができる。幾何学的な増強が、位置関係への結合依存性を低減するために使用されることができ、デバイス、パッケージング、パッケージ、筐体、カバー、外板などへの組み込みを容易にするために使用され得る。コアの幾何学的形状の２つの例示的な変形形態が、図１１の（ｂ）に示される。例えば、平面コア１１３１は、導体の巻線のくぼみを形成するために、端部が構造体の中央部よりもかなり広くなるように形作られ得る。コア材料は、変化する厚さからなることができ、端部は、中央部よりも厚く且つ広い。コア材料１１３２は、導体ループ、ハウジング、パッケージングなどに適合するための様々な深さ、幅、及び形状の任意の数の切欠きまたは切開部１１３３を有することができる。

【０１３５】

コアの形状および寸法は、組み込まれるデバイスの寸法および特徴により更に影響され得る。コア材料は、デバイスの輪郭に追従するように湾曲することができ、又はデバイスの部品の隙間（クリアランス）を可能にするために、非対称の切欠きまたは切開部を必要とする場合がある。コアの構造は、磁性材料の単一のモノリシック片とすることができるか、又は大きな構造を形成するために互いに構成された複数のタイル、ブロック、又は部片から構成され得る。構造体の異なる層、タイル、ブロック、又は部片は同様のものからなることができ、又は異なる材料からなることができる。構造体の異なる場所には、異なる透磁率を有する材料を使用することが望ましい。異なる透磁率を有するコアの構造体は、磁束を誘導するために、結合を改善するために、システムの活性領域の形状または範囲に影響を及ぼすために役に立つことができる。

【０１３６】

平面共振器構造体の導体は、コアに少なくとも１回巻き付けられ得る。或る特定の状況では、少なくとも３つのループで巻き付けることが好ましい場合がある。導体は、導電ワイヤ、リッツ線、導電管、シート、ストリップ、ゲル、インク、トレースなどを含む任意の適切な導体とすることができる。

【０１３７】

供給源の活性領域のサイズ、形状、又は寸法は、磁界を阻止、遮蔽、又は誘導する材料を使用することにより、更に強化、変更、又は改良され得る。供給源の周りに非対称活性領域を生成するために、供給源の一方の側面が、磁気シールドで覆われて、特定の方向の磁界の強度を低減することができる。シールドは、導体することができるか、又は特定方向から離れるように磁界を誘導するために使用され得る磁性材料と導体の層状の組合せとすることができる。導体および磁性材料の層から構成された構造は、供給源の遮蔽に起因して生じる可能性があるエネルギー損失を低減するために使用され得る。

【０１３８】

複数の平面共振器は、１つの平面共振器構造に一体化または組み合わされ得る。導体（単数または複数）は、２つの導体により形成されたループが同軸でないように、コア構造体に巻き付けられ得る。係る構造体の例が図１２に示され、この場合、２つの導体１２０１、１２０２が平面長方形コア１２０３に直交角度で巻き付けられている。コアは、長方形とすることができるか、又は幾つかの延長部分または突出部を有する様々な幾何学的形状を有することができる。突出部は、導体の巻き付け、重量、サイズ又はコアの質量の低減に役立つことができるか、又は共振器の指向性または全方向性を強化するために使用され得る。図１３において、４つの突出部を有する、複数の巻き付けられた平面共振器が、内部構造１３１０により示され、この場合、４つの導体１３０１、１３０２、１３０３、１３０４がコアに巻き付けられる。コアは、１つ又は複数の導体ループを有する、延長部分１３０５、１３０６、１３０７、１３０８を有することができる。単一の導体が、コアに巻き付けられて、同軸でないループを形成することができる。例えば、図１３の４つの導体ループは、連続した１本の導体で、又は２つの導体を用いて（この場合、単一の導体を用いて全て同軸のループを作成する）形成されることができる。

【０１３９】

複数の導体ループを含む共振器の周りの不均一な又は非対称の場のプロファイルは、同一でないパラメータで幾つかの導体ループを駆動することにより生成され得る。複数の導体ループを有する供給源共振器の幾つかの導体ループは、異なる周波数、電圧、電力レベル、デューティサイクル、及び各導体により生成される磁界強度に影響を及ぼすために使用され得る全ての同様のもので、電源により駆動され得る。

【０１４０】

平面共振器構造体は、平坦共振器構造を維持しながら供給源の上および下を含む、辺り一面に全方向性活性領域を提供するために、容量的に装荷されたインダクタ共振器コイルと組み合わせられ得る。図１３に示されるように、導体のループ（単数または複数）からなる追加の共振器ループコイル１３０９が、平面共振器構造体１３１０としての共通平面に配置され得る。外側共振器コイルは、供給源のほぼ上および下にある活性領域を提供する。共振器コイルは、本明細書で説明された任意の数の平面共振器構造体および構成で構成され得る。

【０１４１】

平面共振器構造体は、磁気的に透過性のパッケージングに収容され得るか、又は他のデバイスに組み込まれ得る。単一の共通平面内の共振器の平面形状は、平坦なデバイスへのパッケージング及び組み込みを可能にする。共振器の応用形態を示す図が図１４に示される。それぞれが１つ又は複数の導体ループを有する１つ又は複数の平面共振器１４１４からなる平坦な供給源１４１１が、他の平面共振器１４１５、１４１６と一体化され、且つ供給源の活性領域１４１７内に配置されたデバイス１４１２、１４１３へ電力を伝送することができる。デバイスは、供給源に対するデバイスの位置関係に関係なく、供給源の活性領域が変化しないように、複数の平面共振器を含むことができる。回転の位置合わせ不良に対する不変性に加えて、平面共振器からなる平坦なデバイスは、平面共振器が供給源の平面内に依然として存在するという理由で、活性領域に実質的に影響を与えずに、裏返されることができる。

【０１４２】

平面共振器構造体を用いた電力伝送システムの可能な用途を示す別の図が、図１５に示される。表面１５２５の上に配置された平面供給源１５２１は、「付勢表面」の領域を生じる実質的な表面積に及ぶ活性領域を生成することができる。コンピュータ１５２４、携帯電話機１５２２、ゲーム、及びそれぞれの平面デバイス共振器に結合される他の電子装置１５２３のようなデバイスは、供給源の活性領域内に配置された場合に供給源からエネルギーを受け取ることができ、係るデバイスは表面の上のどこにでもいてもよい。異なる寸法を有する幾つかのデバイスが、活性領域内に配置されることができ、厳格な配置または位置合わせの制約を有せずに、供給源から充電または電力供給されながら普通に使用され得る。供給源は、テーブル、カウンタ、机、キャビネットなどの表面の下に配置されることができ、それにより供給源は、テーブル、カウンタ、机、キャビネットなどの表面の上を付勢し、供給源よりも非常に大きな表面に活性領域を生成しながら、完全に隠されることが可能になる。

【０１４３】

供給源は、充電しているデバイスの方向またはどのデバイスが充電中であるか、充電に伴うエラー又は問題、電力レベル、充電時間などを示すために、ディスプレイ、又は他の可視的、聴覚的、又は振動的インジケータを含むことができる。

【０１４４】

供給源共振器および回路は、任意の数の他のデバイスに組み込まれ得る。供給源は、時計、キーボード、モニタ、絵画用額縁などのようなデバイスに組み込まれ得る。例えば、平面共振器並びに適切な電力および制御回路と一体化されたキーボードは、任意の追加のデスクスペースを占有することなく、コンピュータマウス、ウェブカメラ、携帯電話機などのような、キーボードの周りに配置されたデバイスに対する供給源として使用され得る。

【０１４５】

平面共振器構造体がモバイル機器に関連して説明されたが、当業者には明らかなように、物理的な寸法を超えて延在する活性領域を有する無線電力伝送用の平坦な平面供給源は、多くの他の民生用および産業用の応用形態を有する。構造体および構成は、電子または電気装置および電源が一般に、実質的に同じ平面および位置合わせで、位置する、配置される、又は操作される非常に多数の応用形態に役に立つことができる。可能な応用形態の状況の幾つかは、壁、床、天井、又は任意の他の実質的に平坦な表面上にデバイスを含む。

【０１４６】

平坦な供給源共振器は、絵画用額縁に組み込まれ、又は壁に掛けられることができ、それによりデジタルピクチャーフレーム、テレビ、照明などのような他の電子デバイスが取り付けられて、ワイヤなしで電力供給され得る壁の平面内に活性領域を提供する。平面共振器は、床に組み込まれることができ、結果として、付勢されている床または装置が電力を受け取るために配置され得る床上に活性領域を生じる。音声スピーカ、照明、ヒータなどは、活性領域内に配置されて、ワイヤレスで電力を受け取ることができる。

【０１４７】

平面共振器は、導体に結合された追加の構成要素を有することができる。コンデンサ、インダクタ、抵抗、ダイオードなどのような構成要素は、導体に結合されることができ、共振周波数および共振器のインピーダンスマッチングを調整または同調するために使用され得る。

【０１４８】

図１１の（ａ）に示された、上述したタイプの平面共振器構造体は、例えば、１００のＱファクタＱ、又はより高い１０００以上のＱさえも有するように作成され得る。図１１の（ｃ）に示されるように、エネルギーは、１つの平面共振器構造体から別の共振器構造体へ、共振器の特有サイズより大きい距離にわたってワイヤレスで伝送され得る。

【０１４９】

磁気共振器の誘導性素子に類似した特性を有する構造体を実現するために磁性材料を利用することに加えて、係る誘導性構造を実現するために良好な導体材料および磁性材料の組合せを使用することが可能である。図１６の（ａ）は、磁性材料の少なくとも１つの層により包囲され、磁性材料のブロック１６０４により連結された高い導電率の材料から作成された１つ又は複数の筐体（その内部は、外側で生じたＡＣ電磁界から遮蔽される）を含むことができる磁気共振器構造体１６０２を示す。

【０１５０】

構造体は、磁性材料の層により一面に覆われた高い導電率の材料のシートを含むことができる。層状構造体は代わりに、電子デバイスの部品が高い導電率の磁性材料層により覆われることができると同時に、容易にアクセスされる必要がある他の部品（ボタン又は画面など）が覆われていない状態にされ得るように、電子デバイスに共形的（conformally）に適用され得る。また又は代わりとして、構造体は、磁性材料の層またはバルク片のみを含むことができる。かくして、磁気共振器は、既存の機能を大幅に妨げることなく、且つ大規模な再設計を殆ど又は全く必要とせずに、既存のデバイスに組み込まれ得る。更に、良好な導体および／または磁性材料の層は、それらが完成したデバイスに余計な重量および体積を殆ど加えないほど十分に薄く（ミリメータ以下のオーダー）作成され得る。図１６において、構造体の中央の正方形ループにより示されるように、構造体に巻き付けられた一本の導体に印加される振動電流は、この構造体に関連した電磁界を生じさせるために使用され得る。

【０１５１】

構造体のＱファクタ

上述したタイプの構造体は、約１０００以上のＱファクタＱを有するように作成され得る。この高Ｑは、たとえ磁性材料の損失が高くても、磁性材料内の磁気エネルギーの割合が、物体に関連した全磁気エネルギーに比べて小さい場合に、可能である。導電材料および磁性材料の層からなる構造体の場合、導電材料の損失は、前述したように、磁性材料の

存在により低減され得る。磁性材料の層の厚さがシステムの最も大きな寸法の１／１００のオーダーであり（例えば、磁性材料が約１ｍｍの厚さからなることができると同時に、構造体の面積が約１０ｃｍ×１０ｃｍである）、且つ相対透磁率が約１０００である構造体において、磁性材料内に含まれる磁気エネルギーの割合を、物体または共振器に関連した全磁気エネルギーの数１００分の１だけにすることが可能である。それが如何にして生じるかを見るために、留意すべきは、体積に含まれる磁気エネルギーの式が、以下の通りであり、

【０１５２】

【数７】

$$U_m = \int_V d\mathbf{r}\,\mathbf{B}(\mathbf{r})^2 / (2\mu_r\mu_0)$$

【０１５３】

そのため、Ｂ（Ｈではなく）が磁性材料－空気の界面を横切って保存される主磁界であり（一般に開磁路での場合）、高μ_rの領域に含まれた磁気エネルギーの割合は、空気中にあるものと比べて大幅に低減され得る。

【０１５４】

磁性材料の磁気エネルギーの割合がfracにより示され、材料の損失正接がtanδである場合、共振器のＱは、磁性材料が損失の唯一の原因であると仮定すれば、Ｑ＝１／（frac x tanδ）である。かくして、損失正接が０．１と大きくても、これらタイプの共振器構造体に対して約１０００のＱを達成することが可能である。

【０１５５】

構造体がそれに巻き付けられたＮターンのワイヤで駆動される場合、励磁導体ループの損失は、Ｎが十分に大きい場合に無視され得る。図１７は、これら構造体の等価回路１７００の図、及び導電および磁性材料から作成された構造体にＮターン数巻き付けられた状態での、損失機構およびインダクタンスのスケーリングを示す。近接効果が無視され得る（適切な巻線または近接効果を最小限にするように設計されたワイヤ、例えばリッツ線などを用いることにより）場合、ループ導体のワイヤに起因した抵抗１７０２は、ターン数に比例する１ターンであるループの長さに線形的に比例する。他方では、これら特別の構造体の等価抵抗１７０８及び等価インダクタンス１７０４は、構造体の内部の磁界の二乗に比例する。磁界はＮに比例するので、等価抵抗１７０８及び等価インダクタンス１７０４は、N^2に比例する。かくして、Ｎが十分に大きい場合、ワイヤの抵抗１７０２は、磁気構造体の等価抵抗１７０８よりも非常に小さくなり、共振器のＱは$Q_{max}=\omega L_\mu / R_\mu$に漸近する。

【０１５６】

図１６の（ａ）は、構造体１６０４の中央の狭くなった部分の周りの正方形ループの電流により駆動された銅および磁性材料構造体１６０２の図、及びこの構造体１６０８により生成される磁界の流線を示す。この例示的な構造体は、銅で包囲され、次いでμ'_r＝１４００、μ''_r＝５、及びσ＝０．５Ｓ／ｍの特性を有する磁性材料の２ｍｍの層で完全に覆われた２つの２０ｃｍ×８ｃｍ×２ｃｍの中空領域を含む。これら２つの平行六面体は、４ｃｍ離れて配置され、同じ磁性材料の２ｃｍ×４ｃｍ×２ｃｍのブロックにより接続される。励磁ループは、このブロックの中央に巻き付けられる。３００ＫＨｚの周波数において、この構造体は、計算された８９０のＱを有する。導体および磁性材料の構造体は、特定のシステムパラメータを最適化するように形作られ得る。例えば、励磁ループにより包囲された構造体のサイズは、励磁ループの抵抗を低減するために小さくすることができるか、又は大きな磁界に関連した磁性材料の損失を軽減するように大きくすることができる。留意すべきは、磁性材料のみからなる同じ構造体に関連した磁界の流線およびＱは、本明細書で示された層導体および磁性材料の設計に類似する。

【０１５７】

他の物体と相互作用する電磁共振器

電磁共振器の場合、固有Ｑに摂動を与える外因性損失機構は、近くの外部物体の材料内部の吸収損失、及び近くの外部物体からの共振場の散乱に関連した放射損失を含むことができる。吸収損失は、対象となる周波数範囲にわたって非ゼロであるが、有限の導電率σ（又は同様に、誘電体誘電率の非ゼロで有限の虚数部）を有する材料に関連付けられることができ、そのため電磁界は、その材料に入り込むことができ、その材料内に電流を生じさせることができ、次いで抵抗損失を介してエネルギーが放散される。物体が少なくとも部分的に損失性材料を含む場合、それは損失性として記述され得る。

【０１５８】

導電率σ、及び透磁率μの均質等方材料を含む物体を考察する。この物体の内部の電磁界の侵入深さは、浸透厚により与えられ、$\delta=(2/\omega\mu\sigma)^{1/2}$である。物体の内部で消散される電力$P_d$は、以下の式により求められる。

【０１５９】

【数８】

$$P_d = \int_V d\mathbf{r}\,\sigma\,|\mathbf{E}|^2 = \int_V d\mathbf{r}\,|\mathbf{J}|^2/\sigma$$

【０１６０】

ここで、本発明者は、オームの法則を使用し、$J=\sigma E$であり、Ｅは電界であり、Ｊは電流密度である。

【０１６１】

対象となる周波数にわたって、物体を構成する材料の導電率σが、材料の浸透厚δが長いと考えられ得るほど十分に低い場合（即ち、δが物体の特有サイズよりも長い、又はδが損失性である物体の一部の特有サイズより長い）、電磁界Ｅ及びＨ（ここでＨは磁界である）は、物体内へ大幅に入り込むことができる。次いで、これら有限値の場は、$P_d \sim \sigma V_{01}\langle|E|^2\rangle$として、スケーリングされる消散電力を生じさせることができ、ここで、V_{01}は損失性である物体の体積であり、$\langle|E|^2\rangle$は、検討中の体積における電界の二乗の空間平均値である。従って、低い導電率の制限において、消散電力は、導電率に比例し、非導電（純粋に誘電体）材料の制限においてゼロに達する。

【０１６２】

対象となる周波数にわたって、物体を構成する材料の導電率σが、材料の浸透厚が短いと考えられ得るほど十分に高い場合、電磁界Ｅ及びＨは、物体内へほんの短い距離だけ入り込むことができる（即ち、電磁界は材料の「表皮」の近くにとどまり、ここでδは損失性である物体の一部の特有厚さより小さい）。この場合、材料内に生じる電流は、材料の表面に非常に接近して、ほぼ浸透厚内に集中されることができ、それらの大きさは、表面電流密度（大部分は、入射電磁界の形状により求められ、導体の厚さが浸透厚より大幅に大きい限り、周波数に無関係であり、一次までの導電率）$K(x, y)$（ここで、ｘとｙは表面をパラメータ化する座標である）と表面内への指数関数的に減衰する関数、即ち$\exp(-z/\delta)/\delta$（ここで、ｚは、表面に局所的に垂直な座標を示す）の積により近似されることができ、即ち$J(x, y, z)=K(x, y)\exp(-z/\delta)/\delta$である。次いで、消散電力$P_d$は、以下の式により概算され得る。

【０１６３】

【数９】

$$P_d = {}^{V} d\mathbf{r}\,|\mathbf{J}(\mathbf{r})|^2/\sigma \simeq \left({}^{S}\mathbf{dxdy}\,|\mathbf{K}(\mathbf{x},\mathbf{y})|^2\right)\left({}_{0}^{\infty}\mathbf{dz}\,\mathbf{exp}(\mathbf{2z}/\delta)/(\sigma\delta^2)\right) = \sqrt{\mu\omega/8\sigma}\left({}^{S} dxdy\,|K(x,y)|^2\right)$$

【０１６４】

従って、高い導電率の限界において、消散電力は、導電率の平方根に反比例し、完全に導電する材料の限界においてゼロに達する。

【０１６５】

対象となる周波数にわたって、物体を構成する材料の導電率σが有限である場合、材料

の浸透厚δが物体内へ或る距離だけ入り込み、電力の或る量が、物体のサイズおよび電磁界の強度にも依存して物体内で消散され得る。また、この説明は、物体内の導電率の任意の不均一で異方性の分布を有する物体のような、異なる特性および導電率を有する多数の異なる材料を含む物体の一般的な場合を説明するためにも一般化され得る。

【０１６６】

留意すべきは、上述した損失機構の大きさは、共振器の場に対する外部物体の場所および位置関係、並びに外部物体の材料組成に依存する可能性がある。例えば、高導電率の材料は、共振器の共振周波数をシフトし、他の共振物体からそれを同調ずれさせる可能性がある。この周波数シフトは、共振器のインダクタンス及び／又はキャパシタンスの変化を通じてのように、周波数を補正するフィードバック機構を共振器に適用することにより固定され得る。これらの変化は、可変コンデンサ及びインダクタを用いて実現されることができ、場合によっては共振器の構成要素の幾何学的形状の変化により達成され得る。また、以下で説明される他の新規なチューニング機構を用いて、共振器の周波数を変更することもできる。

【０１６７】

外因性損失が高い場合、パーターブドＱは低くなることができ、係る外部物体および材料の内部の共振器エネルギーの吸収を制限するために措置が講じられ得る。電界および磁界の強度に対する消散電力の関数依存性の故に、システム性能は、所望の結合が供給源共振器においてより短い及びデバイス共振器においてより長いエバネセント共振場の末端で達成されるようにシステムを設計することにより最適化されることができ、その結果、他の物体の存在する状態での供給源のパーターブドＱが最適化される（又はデバイスのパーターブドＱが最適化される必要がある場合には逆もまた同じである）。

【０１６８】

留意すべきは、人々、動物、植物、建築材料などのような多くの一般的な外部材料および物体は、低い導電率を有することができ、それ故に本明細書で開示された無線エネルギー伝送方法に殆ど影響を及ぼさない。本発明者が説明する磁気共振器設計に関連した重要な事実は、それらの電界が共振器構造自体内に主として閉じ込められることができ、そのため中距離にわたって無線電力交換を提供しながら、人の安全に関する一般に認められた指針内で動作することが可能である。

【０１６９】

低減された相互作用を有する電磁共振器

近接場無線電力送信の対象となる１つの周波数範囲は、１０ｋＨｚ～１００ＭＨｚである。この周波数範囲において、例えば幾つかのタイプの木材およびプラスチックのような多種多様の通常の非金属材料は、比較的低い導電率を有することができ、そのため電力の僅かな量しかそれらの内部で消散されない。更に、低い損失正接tanΔを有する材料（ここで、tanΔ＝ε”／ε’、ε”及びε’はそれぞれ誘電率の虚数部と実数部である）でも、それらの内部で消散される電力は僅かな量でしかない。銅、銀、金などのような、比較的高い導電率を有する金属材料でも、それらの内部で消散される電力は僅かであり、その理由は、前述したように、電磁界がこれらの材料に大幅に入り込むことができないからである。これら非常に高い及び非常に低い導電率材料、並びに低い損失正接の材料および物体では、磁気共振器の損失に対する影響は無視しても構わない。

【０１７０】

しかしながら、対象となる周波数範囲において、適度な（一般に不均一で異方性）導電率、及び／又は適度から高い損失正接を有することができ、比較的高い消散的損失を有することができる、幾つかの電子回路および幾つかのより低い導電率の金属のような材料および物体が存在する。比較的大きな量の電力がそれらの内部で消散され得る。これら材料および物体は、かなりの量だけ$Q_{(p)}$を低減するのに十分なエネルギーを消散することができ、「損失性物体」と呼ばれ得る。

【０１７１】

共振器の$Q_{(p)}$に関して損失性材料の影響を低減するための１つの方法は、共振器の場

が損失性物体を避けるように、共振器の場を形作るために高い導電率材料を使用することである。電磁界がそれらの近傍において損失性物体を避けるように電磁界を調整するために高い導電率の材料を使用することに関するプロセスは、電磁界を偏向させる又はその形を作り直す材料として高い導電率の材料を視覚化することにより理解され得る。この画像は、導体の厚さが浸透厚より大きい限り定性的に正しく、その理由は、良好な導体の表面における電磁界の境界条件が、電界を強制的にほぼ完全に導体表面に垂直にさせ、磁界を強制的に導体表面にほぼ完全に正接させるからである。従って、垂直な磁界または正接の電界は導体表面から「離れるように偏向」する。更に、正接の磁界または垂直な電界でさえも、場の供給源および導電性表面の相対位置に依存して、一面および／または導電表面の特定の場所での大きさが強制的に減少され得る。

【０１７２】

一例として、図１８は、周波数ｆ＝６．７８ＭＨｚの外部の初期均一磁界において、損失性誘電体材料１８０４の上下の２つの高い導電率表面１８０２に関する有限要素法（ＦＥＭ）のシミュレーションを示す。系は、ｒ＝０軸の周りに方位角的に対称である。このシミュレーションにおいて、損失性誘電体材料１８０４が、約ｚ＝±０．０１ｍにおいて白線として示された２つの導体１８０２の間に挟まれている。誘電体ディスクの上下に導電表面がない状態では、磁界（磁力線を描くことにより表される）は、本質的に均一の状態のままであり（磁力線は直線であり、ｚ軸に平行）、磁界が損失性誘電体材料を真っ直ぐに通過することが示される。この場合、電力は、損失性誘電体ディスクで消散される。しかしながら、導電表面の存在する状態では、このシミュレーションは、磁界の形が作り直されることを示す。磁界は、強制的に導体の表面に正接するようにされ、そのためこれらの導電表面１８０２の周りに偏向し、導電表面の裏、又は導電表面間の損失性誘電体材料１８０４に消散され得る電力の量が最小限にされる。本明細書で使用される場合、電気的対称性の軸は、一定または時間変化する電界または磁界が、本明細書で開示されたようなエネルギーの交換中に実質的に対称である任意の軸を意味する。

【０１７３】

同様な効果は、誘電体ディスクの上または下に１つの導電表面だけが使用された場合でも観測される。誘電体ディスクが薄い場合、電界が表面において実質的にゼロであり、それに接近して連続的で平滑であるという事実は、電界が表面の近くのどこででも（即ち、誘電体ディスク内で）非常に低いことを意味する。損失性物体から離れるように共振器の場を偏向するための単一表面の具現化形態は、損失性材料または物体（例えば、ＬＣＤ画面）の両面を覆うことができない応用形態に好適とすることができる。留意すべきは、多少の浸透厚のオーダーでの導電材料の非常に薄い表面でさえも、損失性材料の存在する状態での共振器の$Q_{(p)}$を大幅に改善するのには十分とすることができる（６．７８ＭＨｚでの純銅の浸透厚は～２０μｍ、２５０ｋＨｚでは～１００μｍ）。

【０１７４】

損失性外部材料および物体は、高Ｑ共振器が一体化されるべき装置の部品とすることができる。これら損失性材料および物体におけるエネルギーの消散は、以下を含む多数の技術により、即ち、

・損失性材料および物体を共振器から離して、又は共振器に対する特別な位置および位置関係に配置することにより、

・共振器の近傍の損失性材料および物体を部分的または完全に覆うために高導電率の材料または構造を用いることにより、

・損失性物体を完全に覆うために、及び共振器の場が損失性物体を避けるように共振器の場を形作るために損失性物体の周りに高導電率の材料の閉曲面（例えば、シート又はメッシュなど）を配置することにより、

・物体または材料の上面、底面に沿って、側面に沿ってなどのように、損失性物体の一部のみの周りに高導電率の材料の表面（例えば、シート又はメッシュなど）を配置することにより、

・損失性物体の場所において場の強度を低減するために損失性物体の上または下または一

面に高導電率の材料の単一表面（例えば、シート又はメッシュなど）でさえも配置することにより、
低減され得る。

【０１７５】

図１９は、磁気共振器１０２を形成する容量的に装荷されたループインダクタ、及びループインダクタの内部に配置された損失性物体１８０４を完全に取り囲む高導電率材料のディスク状表面１８０２を示す。留意すべきは、幾つかの損失性物体は、外部環境と相互作用、外部環境と通信、又は外部環境に接続される必要があり、ひいては電磁的に完全に分離されることができない電子回路のような構成要素とすることができる。高導電率材料で損失性材料を部分的に覆うことは、損失性材料または物体が適切に機能することを可能にしながら、依然として外因性損失を低減することができる。

【０１７６】

図２０は、共振器１０２として使用される容量的に装荷されたループインダクタ、及びインダクタループの内部に配置され、損失性物体１８０４の一部のみを取り囲む高導電率材料の表面１８０２を示す。

【０１７７】

損失性物体または材料の上に、下に、又は側面などに高導電率材料の単一表面を配置することにより、外因性損失は低減され得るが、完全には除去されることができない。一例が図２１に示され、この場合、容量的に装荷されたループインダクタが共振器１０２として使用され、高導電率材料の表面１８０２がインダクタループの内部で損失性物体１８０４の下に配置され、損失性物体の場所において場の強度を低減する。コスト、重量、組立の複雑化、空気の流れ、視覚的アクセス、物理的アクセスなどを考慮するという理由で、材料または物体の一面のみを覆うことが好適である。

【０１７８】

高導電率材料の単一表面を用いて、両面から覆われることができない又は覆われるべきでない物体（例えば、ＬＣＤ画面またはプラズマ画面）を避けることができる。係る損失性物体は、光学的に透明な導体を用いて避けられ得る。光学的に透明な導体の代わりに、又はそれに加えて、高導電率の光学的に不透明な材料が損失性物体の一部のみに代わりとして配置されてもよい。片面対複数面の覆いの具現化形態の妥当性、及び内部固有の設計のトレードオフは、無線エネルギー伝送状況の細部、及び損失性材料および物体の特性に依存する可能性がある。

【０１７９】

以下において、無線エネルギー伝送システムで使用される集積磁気共振器のＱ無感受性$\Theta_{(p)}$を改善するために、高導電率表面を用いる例が説明される。図２２はワイヤレスプロジェクタ２２００を示す。ワイヤレスプロジェクタは、図示されたように構成されたデバイス共振器１０２Ｃ、プロジェクタ２２０２、無線ネットワーク／ビデオアダプタ２２０４、及び電力変換回路２２０８を含むことができる。デバイス共振器１０２Ｃは、表面を包囲するように構成された３ターンの導体ループ、及びコンデンサ回路２２１０を含むことができる。導体ループは、デバイス共振器１０２Ｃがその動作共振周波数において高いＱ（例えば、＞１００）を有するように設計され得る。完全なワイヤレスプロジェクタ２２００に集積化（一体化）する前に、このデバイス共振器１０２Ｃは、設計された６．７８ＭＨｚの動作共振周波数で約４７７のＱを有する。集積化、及び共振器ループインダクタの中央に無線ネットワーク／ビデオアダプタカード２２０４を配置した後で、共振器の$Q_{(integrated)}$は約３４７まで減少する。Ｑから$Q_{(integrated)}$までの少なくとも幾つかの減少は、摂動を与える（パータービング）無線ネットワーク／ビデオアダプタカードの損失に起因すると考えられる。上述したように、磁気共振器１０２Ｃに関連した電磁界は、無線ネットワーク／ビデオアダプタカード２２０４に電流を生じさせる可能性があり、係る電流は当該カードを構成する損失性材料の抵抗損失で消散され得る。共振器の$Q_{(integrated)}$が、共振器の近傍に配置された物体および材料の組成、位置、及び位置関係に依存して、異なるように影響されることを、本発明者は観測した。

【０１８０】
完全なワイヤレスプロジェクタの例において、ネットワーク／ビデオアダプタカードを薄い銅のポケット（無線ネットワーク／ビデオアダプタカードの上面と底面を覆うが、通信アンテナを覆わない銅の折り畳まれたシート）で覆うことは、磁気共振器の$Q_{(integrated)}$を約４４４の$Q_{(integrated+copper\ pocket)}$まで改善する。言い換えれば、外部ネットワーク／ビデオアダプタカードにより生じた摂動に起因した$Q_{(integrated)}$の減少の大部分は、損失性材料から離れるように共振器の場を偏向するために銅ポケットを用いて防止され得る。

【０１８１】
別の完全なワイヤレスプロジェクタの例において、ネットワーク／ビデオアダプタカードの下に配置された単一の銅シートでネットワーク／ビデオアダプタカードを覆うことにより、$Q_{(integrated+copper\ sheet)}$はほぼ$Q_{(integrated+copper\ pocket)}$に等しくされる。この例において、システムの高いパーターブドＱは、損失性アダプタカードから離れるように共振器の場を偏向するために使用される単一の高導電率シートで維持され得る。

【０１８２】
高Ｑ電磁共振器を含む装置の一部である損失性材料または物体を、共振器により生じた場が比較的弱く、そのため電力がこれら物体で殆ど又は全く消散されず、Ｑ無感受性$\Theta_{(p)}$を大きくすることができる場所に配置することは有利であるかもしれない。前に示されたように、異なる導電率の材料は、電界対磁界に異なるように応答することができる。従って、外部物体の導電率によれば、位置決め技術は、一方または他方の場に限定され得る。

【０１８３】
図２３は、円形ループインダクタの直径を含むラインに沿った電界２３１２及び磁界２３１４、並びに１０ＭＨｚの共振で半径３０ｃｍの容量的に装荷された円形ループインダクタのワイヤのループインダクタの軸に沿った電界２３１８及び磁界２３２０の大きさを示す。共振近接場の振幅が、ワイヤの近くでそれらの最大値に達し、ループから離れるように減衰すること（２３１２、２３１４）が看取され得る。ループインダクタの平面において、場２３１８、２３２０がループの中央で極小に到達する。従って、装置の有限サイズを考えると、場は装置の極値で最も弱くなるかもしれない、又は場の大きさは、装置内のどこかで極小を有するかもしれない。この議論は、任意の他のタイプの電磁共振器１０２及び任意のタイプの装置に当てはまる。例が、図２４の（ａ）と（ｂ）に示され、この場合、容量的に装荷されたインダクタループが磁気共振器１０２を形成し、外因性損失性物体１８０４は、電磁界が最小限の大きさを有する場所に配置される。

【０１８４】
実証例において、磁気共振器は、正方形表面（丸みを帯びた角を有する）を包囲するように構成された３ターンの導体ループおよびコンデンサ回路を用いて形成された。共振器のＱは、所望の動作共振周波数６．７８ＭＨｚで約６１９であった。この共振器のパーターブドＱは、摂動を与える（パータービング）物体の配置（この場合、共振器に対するポケットプロジェクタ）に依存した。摂動を与える（パータービング）プロジェクタがインダクタループの内部およびその中央に、又はインダクタワイヤの巻線の上に位置する場合、$Q_{(projector)}$は約９６であり、それは、摂動を与えるプロジェクタが共振器の外側に配置された場合（$Q_{(projector)}$は約５１３である）より低い。これらの測定値は、インダクタループの内側の場がその外側の場より大きく、そのため係るループインダクタの内部に配置された損失性物体は、損失性物体がループインダクタの外側に配置された場合に比べて、システムのより低いパーターブドＱを生じることができることを示す分析をサポートする。共振器設計および材料組成および損失性物体の位置関係に依存して、図２４の（ｂ）に示された構成は、図２４の（ａ）に示された構成に比べて、より高いＱ無感受性$\Theta_{(projector)}$を生じることができる。

【０１８５】
高Ｑ共振器は、装置の内部に組み込まれ得る。高い誘電体誘電率、透磁率、又は導電率

の外部材料および物体は、高Ｑ共振器が組み込まれるべき装置の一部とすることができる。高Ｑ電磁共振器の近傍のこれら外部材料および物体については、それらのサイズ、共振器に対する位置と位置関係に依存して、共振器の場のプロファイルは、共振器の摂動を与えられていない元の場のプロファイルから大幅に歪まされ逸脱され得る。共振器の摂動を与えられていない（アンパーターブド）場の係る歪みは、外部物体および材料が無損失であっても、Ｑをより低い$Q_{(p)}$まで大幅に低減する可能性がある。

【０１８６】

高Ｑ電磁共振器を含む装置の一部である高導電率物体を、これら物体の表面ができる限り、摂動を与えられていない共振器により生じる電気力線に垂直になり、且つ摂動を与えられていない共振器により生じる磁力線に平行になるような位置関係に配置し、かくして実現可能な最も少ない量だけ共振器の場のプロファイルを歪ませることが有利である。磁気共振器の平面に垂直に配置され得る他の一般的な物体は、スクリーン（ＬＣＤ、プラズマ等）、バッテリー、ケース、コネクタ、放射アンテナなどを含む。共振器のＱ無感受性$\Theta_{(p)}$は、物体が共振器の場に対して異なる位置関係に配置される場合よりも非常に大きくすることができる。

【０１８７】

高Ｑ電磁共振器を含む集積化装置の一部でない損失性外部材料および物体は、例えば、装置の使用中に共振器の近傍に配置され得るか、又は持って来られ得る。特定の状況において、損失性外部物体が位置する又は導入される領域を、共振器の場が避けるように共振器の場を調整するために高導電率材料を使用することが有利であり、それによりこれら材料および物体の電力消散が低減され、Ｑ無感受性$\Theta_{(p)}$が増加される。一例が図２５に示され、この場合、容量的に装荷されたループインダクタ及びコンデンサが共振器１０２として使用され、高導電率材料の表面１８０２がインダクタループの上に配置されて、損失性外部物体１８０４が配置または導入され得る、共振器上の領域の場の大きさが低減される。

【０１８８】

留意すべきは、場の形を作り直すために共振器の近傍にもたらされた高導電率表面も、$Q_{(cond.surface)}<Q$につながることができる。パーターブドＱの減少は、損失性導体の内部のエネルギーの消散、又は導体の表面における場の境界条件のマッチングに関連した、摂動を与えられていない共振器の場のプロファイルの歪みに起因する。従って、高導電率表面を用いて、外因性損失性物体の内部の消散に起因した外因性損失を低減する、場合によっては、特に、電磁界の形を大幅に作り直すことにより、これが達成される外因性損失の一部において低減することができるが、場が損失性物体を避けるように係る高導電率表面を用いることは、所望の結果$Q_{(p+cond.surface)}>Q_{(p)}$ではなくて、事実上$Q_{(p+cond.surface)}<Q_{(p)}$という結果になる。

【０１８９】

上述したように、損失誘発物体の存在する状態で、磁気共振器のパーターブドＱファクタは、電磁共振器に関連した電磁界の形が損失誘発物体を避けるために作り直される場合に、改善され得る。摂動を与えられていない共振器の場の形を作り直すための別の方法は、高透磁率材料を用いて損失誘発物体を完全に又は部分的に包囲または覆い、それにより損失誘発物体と磁界の相互作用を低減することである。

【０１９０】

磁界遮蔽は、例えば、Jackson著、「Electrodynamics 3^{rd} Ed.」pp.201-203に従来説明されている。そこでは、磁気的透過性材料の球状シェルが示され、外部磁界からその内部が遮蔽される。例えば、内側半径ａ、外側半径ｂ、及び相対的透磁率μ_rのシェルが最初は均一な磁界H_0に配置される場合、シェルの内部の場は、一定の大きさ、$9\mu_r H_0/[(2\mu_r+1)(\mu_r+2)-2(a/b)^3(\mu_r-1)^2]$を有し、それは、$\mu_r\gg 1$の場合、$9H_0/2\mu_r(1-(a/b)^3)$に向かう。この結果は、シェルが極めて薄い場合でさえも、透磁率が十分に高い場合には、入射磁界（必ずしも入射磁界ではないが）がシェルの内部で著しく減衰され得ることを示す。特定の状況において、損失性材

料および物体が共振器の磁界により避けられるように、及び電力がこれらの材料よび物体で殆ど又は全く消散されないように、損失性材料および物体を部分的に又は完全に覆うために高い透磁率材料を用いることは有利である。係る手法において、Ｑ無感受性$\Theta_{(p)}$は、材料および物体が覆われていない場合に比べて、大きくなることができ、場合によっては１より大きい。

【０１９１】

損失誘発物体から離れるように電界および磁界を保持することが望ましい。上述されたように、係る態様において場を形作るための１つの方法は、損失誘発物体を完全に又は部分的に包囲または覆うために高導電率表面を使用することである。磁性材料（ゼロでない透磁率を有する任意の材料またはメタマテリアル）とも呼ばれる磁気的透過性材料の層は、高導電率表面の上に又はその周りに配置され得る。磁性材料の追加の層は、偏向した磁界が追従する、より低い磁気抵抗経路（自由空間に比べて）を提供することができ、その下の導体を入射磁束から部分的に遮蔽することができる。この構成は、高導電率表面に生じた電流に起因する損失を低減することができる。ある状況下では、磁性材料により提供される、より低い磁気抵抗経路は、構造体のパーターブドＱを改善することができる。

【０１９２】

図２６の（ａ）は、ｚ軸に沿って最初は均一に外部から印加された磁界（灰色の力線）にさらされた、薄い導電（銅）ディスク２６０４（直径２０ｃｍ、高さ２ｃｍ）の軸対称ＦＥＭシミュレーションを示す。対称軸は、ｒ＝０にある。示された磁気的流線は、ｚ＝－∞で発し、この場合、これらはｒ＝３ｃｍからｒ＝１０ｃｍまで１ｃｍの間隔で配置される。軸の目盛りはメートルである。例えば、図１９に示されたような無線エネルギー伝送システムにおいて、この導電円筒が、磁気共振器により閉じ込められた領域内に損失誘発物体を包囲することを想像されたい。

【０１９３】

この高導電率筐体は、損失性物体のパーターピングＱ、それ故にシステムの全体のパーターブドＱを増大させせるが、導電表面に生じた損失および電磁界のプロファイルに対する変化故に、当該パーターブドＱは、依然としてアンパーターブドＱ未満であることができる。高導電率筐体に関連したパーターブドＱの減少は、高導電率筐体の外面または表面に沿って磁性材料の層を含むことにより少なくとも部分的に回復され得る。図２６の（ｂ）は、図２６の（ａ）から薄い導電（銅）ディスク２６０４（直径２０ｃｍ、高さ２ｃｍ）の軸対称ＦＥＭシミュレーションを示すが、磁性材料の追加の層が高導電率筐体の外面に直に配置されている。留意すべきは、磁性材料の存在は、より低い磁気抵抗の経路を磁界に提供することができ、それにより下にある導体を少なくとも部分的に遮蔽し、導体に生じた渦電流に起因した損失を低減する。

【０１９４】

図２７は、図２６に示されたシステムに対する変形形態（軸対称の図において）を示し、この場合、損失性材料２７０８の全てが高導電率表面２７０６により覆われているとは限らない。特定の状況において、コスト、重量、組立の複雑化、空気の流れ、視覚的アクセス、物理的アクセスなどの考慮事項に起因するように、材料または物体の一面のみを覆うことが有用であるかもしれない。図２７に示された例示的な構成において、損失性材料２７０８の１つの表面のみが覆われて、共振器のインダクタループが高導電率表面の反対側に配置される。

【０１９５】

数学的モデルを用いて、磁気共振器により閉じ込められた領域内に配置された、銅から作成され、直径２０ｃｍ、高さ２ｃｍの円筒形ディスクのように形作られた高導電率筐体をシミュレートし、当該磁気共振器は、ループ半径ｒ＝１１ｃｍ、ワイヤの半径ａ＝１ｍｍの単一ターンのワイヤループである誘導性素子を有する。適用される６．７８ＭＨｚの電磁界のシミュレーションは、この高導電率筐体のパーターピングＱファクタ$\delta Q_{(enclosure)}$が１８７０であることを示す。高導電率筐体が、実数の相対透磁率$\mu'_{r}=40$、及び虚数の相対透磁率$\mu''_{r}=10^{-2}$を有する磁性材料の０．２５ｃｍ厚の層を含むよ

うに変更された場合、シミュレーションは、パータービングＱファクタが$\delta Q_{(enclosure+magnetic\ material)}$＝５０６０まで増加することを示す。

【０１９６】

磁性材料２７０２の薄い層の追加に起因した性能の改善は、高導電率筐体が共振器のループインダクタ２７０４により閉じ込められた領域のより大きい部分を占める場合には、更に劇的である。上記の例において、インダクタループ２７０４の半径が低減され、そのためそれが高導電率筐体の表面から３ｍｍだけ離れる場合、パータービングＱファクタは、筐体の外側の周りに磁性材料２７０２の薄い層を追加することにより、６７０（導電筐体のみ）から２７３０（磁性材料の薄い層を有する導電筐体）まで改善され得る。

【０１９７】

共振器構造体は、一般に損失を生じさせる材料に共振器が非常に接近している場合でさえも、例えば、高い水準をもたらすことができる遮蔽または分布コンデンサを用いて高度に閉じ込められた電界を有するように設計され得る。

【０１９８】

結合電磁共振器

２つの共振器間のエネルギー伝送の効率は、強い結合の性能指数、$U=\kappa/(\Gamma_s\Gamma_d)^{1/2}=(2\kappa/(\omega_s\omega_d)^{1/2})(Q_sQ_d)^{1/2}$により求められ得る。磁気共振器の具現化形態において、２つの共振器間の結合率は、共振器のそれぞれの誘導性素子のインダクタンスL_1及びL_2、及びそれらの間の相互インダクタンスＭに、$\kappa_{12}=\omega M/2(L_1L_2)^{1/2}$により関連付けられ得る。留意すべきは、この式は、電気双極子結合を介した無視できる結合が存在すると仮定する。インダクタが円形導電ループによりＮターンで形成され、図１の（ｂ）に示されたように距離Ｄだけ離されて配向されている、容量的に装荷されたインダクタループの共振器の場合、相互インダクタンスは、$M=\pi/4\cdot\mu_0N_1N_2(x_1x_2)^2/D^3$であり、ここで$x_1$、$N_1$及び$x_2$、$N_2$はそれぞれ、第１及び第２の共振器の導体ループの特有サイズ及びターン数である。留意すべきは、これは準静的な結果であり、そのため共振器のサイズが波長よりも非常に小さく、共振器の距離が波長よりも非常に小さいが、それらの距離が少なくともそれらのサイズの数倍であることが仮定される。上述されたように、準静的制限で及び中距離で動作されたこれら円形共振器の場合、$k=2\kappa/(\omega_1\omega_2)^{1/2}\sim((x_1x_2)^{1/2}/D)^3$である。中距離における共振器間の強い結合（大きいＵ）は、共振器のＱファクタが中距離において小さいｋを補償するほど十分に大きい場合に確立され得る。

【０１９９】

磁気共振器に関して、２つの共振器が導電部品を含む場合、結合機構は、他方から生じた電界と磁界に起因して電流が一方の共振器に生じることができる。結合率は、第２の共振器の高Ｑ誘導性素子の囲まれた領域を横切る、第１の共振器の高Ｑ誘導性素子から生じた磁界の磁束に比例することができる。

【０２００】

低減された相互作用を有する結合電磁共振器

前述されたように、高導電率材料の表面は、共振器の場が共振器の近傍の損失性物体ｐを避けることにより、共振器の全体的な外因性損失を低減および高いＱ無感受性$\Theta_{(p+cond.surface)}$を維持するように、共振器の場を形作るために使用され得る。しかしながら、係る表面は、パーターブド結合率$k_{(p)}$より小さく、且つサイズ、位置、及び共振器に対する高導電率材料の位置関係に依存する、共振器間のパーターブド結合率$k_{(p+cond.surface)}$もまねく可能性がある。例えば、高導電率材料が平面内に配置され、且つ無線エネルギー伝送システムにおける少なくとも１つの磁気共振器の誘導性素子により閉じ込められた領域内に配置される場合、結合に介在する共振器の領域を通る磁束の一部が阻止され、ｋが低減され得る。

【０２０１】

再び図１９の例を考察する。高導電率のディスク筐体のない状態では、外部磁束の特定量は、ループの閉じ込められた領域を横切ることができる。高導電率のディスク筐体の存

在する状態では、この磁束の一部は、偏向または阻止され、もはやループの領域を横切ることはできず、かくしてより小さいパーターブド結合率$k_{12(p+cond.surface)}$をまねく。しかしながら、偏向された磁力線が高導電率表面のエッジに沿って接近して進むことができるので、ディスクを閉じ込めるループを通る磁束の減少は、ディスクの面の領域とループの領域の比より小さい。

【０２０２】

単独で又は磁性材料との組合せで高導電率材料の構造体を使用することにより、パーターブドＱファクタ、パーターブド結合率、又はパーターブド効率を最適化することができる。

【０２０３】

図２１の例を考察する。損失性物体が容量的に装荷されたインダクタループ共振器のサイズに等しいサイズを有するように、かくしてその領域Ａ２１０２を満たすようにする。高導電率表面１８０２が損失性物体１８０４の下に配置され得る。これが２つの結合された共振器１と２のシステムにおける共振器１とし、導電表面の領域（面積）A_s ２１０４が増加するにつれて$U_{12(object+cond.surface)}$が$U_{12}$に比べて如何にしてスケーリングされるかを考察しよう。損失性物体１８０４の下に導電表面１８０２がない場合、ｋ無感受性$\beta_{12(object)}$は約１になることができるが、Ｑ無感受性$\Theta_{1(object)}$は小さくなり、そのためＵ無感受性$\Xi_{12(object)}$は小さくなる。

【０２０４】

損失性物体の下の高導電率表面がインダクタループ共振器の全領域を覆う（$A_s = A$）場合、$k_{12(object+cond.surface)}$がゼロに近づくことができ、その理由は、インダクタループを横切ることができる磁束が殆どなく、そのため$U_{12(object+cond.surface)}$がゼロに近づくからである。高導電率表面の中間のサイズの場合、外因性損失および関連したＱ無感受性$\Theta_{1(object+cond.surface)}$の抑制は、$\Theta_{1(object)}$に比べて十分に大きくなることができるが、結合の減少は著しくなく、関連するｋ無感受性$\beta_{12(object+cond.surface)}$は、$\beta_{12(object)}$よりあまり小さくなく、そのため全体的な$U_{12(object+cond.surface)}$は$U_{12(object)}$に比べて増大することができる。無線エネルギー伝送システムにおける高導電率表面を介して外部損失性物体を回避する最適な程度は、システム構成の細部および用途に依存する可能性がある。

【０２０５】

本発明者は、システムの高いパーターブドＱを達成するための１つの可能な方法として、高Ｑ共振器の近傍における損失を含む物体を完全に又は部分的に包囲する又は覆うために、高導電率材料を用いることを説明した。しかしながら、物体を覆うために良好な導体だけを用いることは、上述したように共振器の結合を低減する可能性があり、それにより無線電力伝送の効率が低減される。導電表面の面積が磁気共振器の面積に近づくにつれて、例えば、パーターブド結合率$k_{(p)}$はゼロに近づくことができ、それにより導電表面の使用は効率的な無線電力伝送と相反する。

【０２０６】

前述した問題に対処するための１つの手法は、高導電率材料の周りに磁性材料の層を配置することであり、その理由は、透磁性材料の追加の層が、偏向された磁界が追従するより低い磁気抵抗経路（自由空間に比べて）を提供することができ、その下にある導体を入射磁束から部分的に遮蔽することができるからである。ある状況下では、磁性材料により提供される、より低い磁気抵抗経路は、他の共振器に対する共振器の電磁結合を改善することができる。共振器の場が高Ｑ磁気共振器内またはその周りの損失性物体を避けるように共振器の場を調整するために導電材料を用いることに関連したパーターブド結合率の減少は、導電材料の外面（単数または複数）に沿って磁性材料の層を含むことにより少なくとも部分的に回復され得る。磁性材料は、その初期の摂動を与えられていない（アンパーターブド）値に対してパーターブド結合率を増加させることができる。

【０２０７】

留意すべきは、図２６のシミュレーション結果は、入射磁界が導電構造体だけによるも

のに比べて、層状磁性材料および導電構造体によるものにより少なく偏向され得ることを示す。図２６の（ａ）と（ｂ）に示されたディスクの半径よりもほんの僅かに大きい半径を有する磁気共振器ループが、当該ディスクを閉じ込める場合、より多くの磁束線が図２６の（ａ）に示された場合に比べて図２６の（ｂ）に示された場合で捕捉されることが明らかであり、それ故に$k_{(disk)}$は図２６の（ｂ）に示された場合にはより大きくなる。従って、導電材料に磁性材料の層を含むことは、全体的なシステム性能を改善することができる。システムの分析は、これら材料が部分的に、全体的に、又は最小限に共振器に組み込まれるべきであるか否かを判定するために行われ得る。

【０２０８】

上述したように、図２７は、損失性材料２７０８の全てが導体および／または磁性材料の構造により覆われることができるとは限らない場合に使用するのに適切とすることができる、層状の導体２７０６及び磁性材料２７０２の構造を示す。１１ｃｍの半径のインダクタループ及びワイヤ半径ａ＝１ｍｍの共振器により閉じ込められた、２０ｃｍの直径および２ｃｍの高さを有する銅導体ディスクについて、当該銅円筒の計算されたパータービングＱは１８７０であることが上記で示された。共振器および導電ディスクシェルが均一な磁界内に配置（インダクタループの対称軸に沿って位置合わせされて）される場合、本発明者は、銅導体が関連した結合率の無感受性０．３４を有すると計算した。比較のために、本発明者は、実数の相対透磁率μ'_{r}＝４０、及び虚数の相対透磁率μ''_{r}＝１０$^{-2}$を有する磁性材料の０．２５ｃｍ厚の層を含むことを除いて同じ構造をモデル化した。上述した同じモデル及びパラメータを用いて、本発明者は、結合率の無感受性が、導体の表面に磁性材料を追加することにより、０．６４まで改善されることを見出した。

【０２０９】

磁性材料は、無線エネルギー伝送システムでの結合を増大させるために、磁気共振器により閉じ込められた領域内に配置され得る。最初は均一な磁界に配置された、相対透磁率μ_{r}を有する磁性材料の中実の球体を考察する。この例において、磁性材料により提供される、より低い磁気抵抗経路は、磁界を球体の体積に集中させ得る。本発明者は、球体の赤道（均分円）により囲まれた領域を通る磁束が、磁性材料の追加により、３μ_{r}／（μ_{r}＋２）倍で強化されることを見出した。$\mu_{r}\gg 1$の場合、この強化係数は、３に近づくことができる。

【０２１０】

誘導性素子により囲まれた磁気球体を磁気共振器に含むシステムの双極子モーメントが、同じ係数により強化されたその磁気双極子を有することも示されるであろう。かくして、高い透磁率を有する磁気球体は、共振器の双極子磁気結合を実質的に３倍にする。内側半径ａ及び外側半径ｂを有する磁性材料の球体シェルを使用する場合、このシェルが高い導電材料から作成されたブロック又は筐体の上にある場合でさえも、結合におけるこの増加の大部分を保持することが可能である。この場合、赤道を通る磁束の強化（増大）は、以下の通りである。

【０２１１】

【数１０】

$$\frac{3\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)}{\mu_r\left(1-\left(\frac{a}{b}\right)^3\right)+2\left(1+\frac{1}{2}\left(\frac{a}{b}\right)^3\right)}$$

【０２１２】

μ_{r}＝１０００、及び（ａ／ｂ）＝０．９９の場合、この強化係数は依然として２．７３であり、そのため、磁性材料の薄い層を有していても、結合を大幅に改善することが可

能である。

【０２１３】

上述されたように、磁性材料を含む構造体を用いて、磁気共振器を実現することができる。図１６の（ａ）は、銅および磁性材料構造体１６００の三次元モデルを示し、当該構造体は、その中央における絞り箇所の周りの正方形ループの電流により駆動される。図１６の（ｂ）は、図１６の（ａ）に示されたような、同じ特性を有する２つの同一の構造体１６００Ａ、１６００Ｂ間での、磁界の流線により示されるような相互作用を示す。対称性の故に、及び計算の複雑性を低減するために、システムの半分だけがモデル化されている。２つの物体間の相対的な位置関係を固定し、それらの中心間距離を変化させる場合（図は、５０ｃｍの相対的な離隔距離で示された）、本発明者は、３００ｋＨｚにおいて、結合効率は、構造体間の離隔距離が３０ｃｍから６０ｃｍまで変化するにつれて、８７％から５５％まで変化することを見出した。図示された構造体１６００Ａ、１６００Ｂの例の各々は、４ｃｍ×４ｃｍ×２ｃｍの磁性材料のブロックにより結合され、且つ同じ磁性材料の２ｍｍの層で完全に覆われた、銅製の２つの２０ｃｍ×８ｃｍ×２ｃｍの平行六面体を含む（μ_r＝１４００＋ｊ５を有すると考えられる）。駆動ループの抵抗損失は無視される。各構造体は、８１５の計算されたＱを有する。

【０２１４】

電磁共振器およびインピーダンスマッチング

低損失誘導性素子のインピーダンスマッチングのアーキテクチャ

本説明のために、誘導性素子は、磁性材料から作成された（ギャップ付き又はギャップ無し）コアを備える又は備えない、任意の導電材料の任意のコイル又はループ構造（「ループ」）とすることができ、それはまた、他のシステムに誘導的に又は任意の他の非接触方法で結合され得る。素子は、ループのインピーダンス及び任意に潜在的に結合されたシステムのいわゆる「反射」インピーダンスを含むそのインピーダンスが、正のリアクタンスＸ、及び抵抗Ｒを有するので、誘導性である。

【０２１５】

誘導性素子が接続され得る駆動回路または駆動される負荷または伝送ラインのような外部回路を考察する。外部回路（例えば、駆動回路）は、電力を誘導性素子に伝えることができ、及び誘導性素子は外部回路に電力を伝えることができる（例えば、駆動される負荷）。所望の周波数において誘導性素子と外部回路との間で伝えられる電力の効率およびその量は、外部回路の特性に対する誘導性素子のインピーダンスに依存する可能性がある。インピーダンスマッチングの回路網および外部回路制御技術を用いて、所望の周波数ｆにおいて、外部回路と誘導性素子との間の電力伝送を調整することができる。

【０２１６】

外部回路は、クラスＡ、Ｂ、Ｃ、Ｄ、ＤＥ、Ｅ、Ｆなどの増幅器を形成するように構成された駆動回路とすることができ、それが固有インピーダンス$Z_0{}^*$を有する共振回路網を駆動する場合に、最大の効率で（即ち、駆動回路内で最小の損失で）電力を伝えることができ、ここでZ_0は複素数とすることができ、＊は複素共役を示す。外部回路は、クラスＡ、Ｂ、Ｃ、Ｄ、ＤＥ、Ｅ、Ｆなどの整流装置を形成するように構成された、駆動される負荷とすることができ、それが固有インピーダンス$Z_0{}^*$を有する共振回路網により駆動される場合に、最大の効率で（即ち、駆動される負荷内で最小の損失で）電力を受け取ることができ、ここでZ_0は複素数とすることができる。外部回路は、特性インピーダンスZ_0を有する伝送ラインとすることができ、インピーダンス$Z_0{}^*$に接続される場合に、最大の効率で（即ち、ゼロ反射で）電力をやりとりすることができる。本発明者は、外部回路の特性インピーダンスZ_0を最大の効率で電力交換するためにそれに接続され得るインピーダンスの複素共役と呼ぶ。

【０２１７】

誘導性素子の一般的なインピーダンスＲ＋ｊＸは、$Z_0{}^*$とは非常に異なる可能性がある。例えば、誘導性素子が低い損失（高いＸ／Ｒ）を有する場合、その抵抗Ｒは外部回路の特性インピーダンスZ_0の実数部より非常に小さくなることができる。更に、誘導性素

子はそれ自体により、共振回路網となることができない。誘導性素子に接続されたインピーダンスマッチング回路網は一般に、共振回路網を形成することができ、そのインピーダンスは調整され得る。

【０２１８】

従って、インピーダンスマッチング回路網は、外部回路と誘導性素子（任意の結合されたシステムの反射インピーダンスを含む）との間で伝えられる電力の効率を最大化するように設計され得る。伝えられる電力の効率は、所望の周波数において、インピーダンスマッチング回路網と誘導性素子の組合せのインピーダンスを外部回路（又は伝送ライン）の特性インピーダンスにマッチングすることにより最大化され得る。

【０２１９】

インピーダンスマッチング回路網は、外部回路と誘導性素子（任意の結合されたシステムの反射インピーダンスを含む）との間で所定量の電力を伝えるように設計され得る。伝えられる電力は、所望の周波数において、インピーダンスマッチング回路網および誘導性素子の組合せのインピーダンスと外部回路（又は伝送ライン）のインピーダンスの複素数比を調整することにより決定され得る。

【０２２０】

誘導性素子に接続されたインピーダンスマッチング回路網は、磁気共振器を形成することができる。強く結合された磁気共振器を用いる無線電力伝送のような幾つかの用途の場合、高いＱは共振器に望ましい。従って、誘導性素子は、低い損失（高いＸ／Ｒ）を有するように選択され得る。

【０２２１】

マッチング回路が一般に共振器の内部に追加の損失源を含む可能性があるので、マッチング回路の構成要素は、低い損失を有するようにも選択され得る。更に、高い電力用途において及び／又は高い共振器のＱに起因して、大きな電流が共振器回路の部品に流れる可能性があり、大きい電圧が共振器内の幾つかの回路素子の両端に存在するかもしれない。係る電流および電圧は、特定の回路素子の所定の許容範囲を越える可能性があり、特定の構成要素については非常に高いので耐えることができないかもしれない。場合によっては、例えば、特定の用途のために高Ｑおよび高い電力共振器の設計を実現するために十分なサイズ、コスト、及び性能（損失および電流／電圧の定格）の仕様に関して、調整可能なコンデンサのような構成要素を得る又は実装することが困難であるかもしれない。本発明者は、低い損失および／または高い電流／電圧の定格に関する構成要素の要件を低減しながら、磁気共振器の高いＱを保持することができるマッチング回路の設計、方法、具現化形態および技術を開示する。

【０２２２】

マッチング回路の幾つかの素子に対する損失および電流定格の要件を最小化する、マッチング回路の接続形態が設計され得る。低損失誘導性素子をインピーダンスZ_0にマッチングする回路の接続形態は、その構成要素の幾つかが外部回路と直列にすることにより、関連した高Ｑ共振器の外側にあるように選択され得る。これら構成要素の低い直列損失または高い電流定格の要件は、低減され得る。回路素子に対する低い直列損失および／または高い電流定格の要件を軽減することは、素子が可変である必要があり、及び／又は大きい電圧定格および／または低い並列損失を有する必要がある場合に特に有用であるかもしれない。

【０２２３】

マッチング回路の幾つかの素子に対する電圧定格の要件を最小限にするマッチング回路の接続形態が、設計され得る。低損失誘導性素子をインピーダンスZ_0にマッチングする回路の接続形態は、その構成要素の幾つかがZ_0と並列にすることにより、関連した高Ｑ共振器の外側にあるように選択され得る。これら構成要素の低い並列損失または高い電圧定格の要件は、低減され得る。回路素子に対する低い並列損失および／または高い電圧の要件を軽減することは、素子が可変である必要があり、及び／又は大きい電流定格および／または低い直列損失を有する必要がある場合に特に有用であるかもしれない。

【０２２４】

低損失誘導性素子を外部特性インピーダンスZ_0にマッチングする回路の接続形態は、関連した共振モードの電磁界パターン、ひいてはその高いＱが、外部インピーダンスに共振器を結合する際に保持されるように、選択され得る。もしそうでなければ、所望の共振モードに対する非効率的な結合が生じる可能性があり（場合によっては、他の不要共振モードへの結合に起因して）、結果として共振器のＱを事実上、低くすることになる。

【０２２５】

低損失誘導性素子または外部回路が変化を呈することができる応用形態の場合、マッチング回路は、所望の周波数ｆにおいて、誘導性素子を外部回路のインピーダンスZ_0にマッチングするために動的に調整される必要があるかもしれない。２つのチューニング目標、即ち所望の周波数ｆにおいてインピーダンスレベルZ_0の実数部と虚数部をマッチング又は制御することが一般に存在するので、マッチング回路に２つの可変素子が存在することができる。誘導性素子の場合、マッチング回路は、少なくとも１つの可変容量性素子を含む必要があるかもしれない。

【０２２６】

低損失誘導性素子は、２つの可変コンデンサ又は可変コンデンサの２つの回路網を用いる接続形態によりマッチングされ得る。例えば、可変コンデンサは、調整可能なバタフライ型コンデンサとすることができるか、又はユーザ設定できる可変キャパシタンスを有する任意の他のコンデンサとすることができ、当該調整可能なバタフライ型コンデンサは、例えば接地、或いは電源または負荷の他のリード線に接続するための中央端子、及び当該調整可能なバタフライ型コンデンサのキャパシタンスが変更または調整され得る少なくとも１つの他の端子を有する。

【０２２７】

低損失誘導性素子は、可変コンデンサ（単数または複数）の１つ又は係る可変コンデンサの回路網、及び可変インダクタ（単数または複数）の１つ又は係る可変インダクタの回路網を用いる接続形態によりマッチングされ得る。

【０２２８】

低損失誘導性素子は、外部回路または他のシステムに誘導性素子をトランス結合する、可変コンデンサ（単数または複数）の１つ又は係る可変コンデンサの回路網、及び可変相互インダクタンス（単数または複数）の１つ又は係る可変相互インダクタンスの回路網を用いる接続形態によりマッチングされ得る。

【０２２９】

場合によっては、サイズ、コスト及び高Ｑを実現するために十分な性能仕様、高い電力、及び場合によっては高速で同調可能な共振器設計に関して、調整可能な集中素子を得る又は実装することが困難であるかもしれない。可変誘導性素子を外部回路にマッチングする回路の接続形態は、幾つかの可変性が、外部回路のトランジスタ、ダイオード、スイッチなどに印加される駆動信号の周波数、振幅、位相、波形、デューティサイクルなどを変更することにより外部回路に割り当てられるように設計され得る。

【０２３０】

共振周波数における誘導性素子の抵抗ＲおよびインダクタンスＬのばらつきは、部分的にのみ補償され得るか、又は全然補償されない。かくして、適切なシステム性能は、他のシステム構成要素または仕様へと設計された許容範囲により保持され得る。より少ない調整可能な構成要素または調整可能能力の低い構成要素を用いて実現される部分的な調整は十分とすることができる。

【０２３１】

マッチング回路のアーキテクチャは、その調整可能な素子の電圧／電流定格要件を最小限にし且つより微細な（即ち、より高い分解能でより精密な）全体的な調整可能性を達成しながら、高電力条件下でインピーダンスマッチング回路の所望の可変性を達成するように設計され得る。可変誘導性素子をインピーダンスZ_0にマッチングする回路の接続形態は、可変構成要素の電圧／電流要件が低減されることができ、且つ所望の調整範囲がより

微細な調整分解能でカバーされ得るように、固定および可変素子の適切な組合せ及び配置を含むことができる。電圧／電流要件は、可変でない構成要素で低減され得る。

【０２３２】

開示されたインピーダンスマッチングのアーキテクチャ及び技術は、以下のことを達成するために使用され得る。即ち、

・電力駆動発生装置から供給源の低損失誘導性素子（及び低損失誘導性素子にワイヤレスで結合された任意の他のシステム）に伝えられる電力を最大化する、又は係る低損失誘導性素子間のインピーダンス不整合を最小限にするために、

・デバイスの低損失誘導性素子（及び低損失誘導性素子にワイヤレスで結合された任意の他のシステム）から電力駆動される負荷へ伝えられる電力を最大化する、又は係る低損失誘導性素子間のインピーダンス不整合を最小限にするために、

・電力駆動発生装置から供給源の低損失誘導性素子（及び低損失誘導性素子にワイヤレスで結合された任意の他のシステム）に制御された電力量を伝える、又は係る低損失誘導性素子間の特定のインピーダンス関係を達成するために、

・デバイスの低損失誘導性素子（及び低損失誘導性素子にワイヤレスで結合された任意の他のシステム）から電力駆動される負荷へ制御された電力量を伝える、又は係る低損失誘導性素子間の特定のインピーダンス関係を達成するために。

【０２３３】

モードプロファイルの保存の接続形態（高いＱ）

共振器構造体は、電力発生装置または負荷にワイヤレスで（間接的に）又は有線接続で（直接的に）接続されるように設計され得る。

【０２３４】

図２８の（ａ）のブロック図により示されるような、一般的に間接的に結合されたマッチング接続形態を考察する。そこで、（Ｒ、Ｌ）として表示され、インダクタの回路記号により表された誘導性素子２８０２が、本明細書または本明細書で提供される文献に説明された任意の誘導性素子とすることができ、この場合、インピーダンスマッチング回路２４０２は、部品Ａ及びＢを含む、又は部品Ａ及びＢからなる。Ｂは、インピーダンス２８０４、Z_0を残りの回路（Ａと誘導性素子の組合せ（Ａ＋（Ｒ、Ｌ）））に、ワイヤレス接続（誘導性または容量性結合機構）を介して接続するマッチング回路の一部とすることができる。

【０２３５】

Ａと誘導性素子２８０２の組合せは、共振器１０２を形成することができ、それは孤立して、関連した電流および電荷分布で高Ｑ共振器電磁モードをサポートすることができる。外部回路Z_0とＢ、共振器Ａ＋（Ｒ、Ｌ）との間に有線接続がないことは、高Ｑ共振器電磁モード及びその電流／電荷分布が、ワイヤレス結合の程度があまり大きくない限り、その固有の（孤立した）プロファイルの形態をとることができることを保証することができる。即ち、電磁モード、電流／電荷分布、ひいては共振器の高Ｑは、間接的に結合されるマッチング接続形態を用いて自動的に維持され得る。

【０２３６】

このマッチング接続形態は、誘導性結合が外部回路とインダクタループとの間に使用される場合に、間接的に結合された、又はトランス結合された、又は誘導性結合されたと呼ばれ得る。このタイプの結合状況は、参照されるScienceの論文で説明された中距離にわたる無線エネルギー伝送の実証において、電源を供給源共振器に結合する、及びデバイス共振器をライトバルブに結合するために使用された。

【０２３７】

次に、誘導性素子が、誘導性素子および任意の間接的に結合されたシステムを含むことができる例を考察する。この場合、上述されたように、やはり外部回路または結合されたシステムと共振器との間に有線接続がないという理由で、結合されたシステムは、あまり大きくない程度の間接結合の良好な接近で、共振器の電磁モードプロファイル及び共振器の電流／電荷分布に影響を与えることはない。従って、間接的に結合されたマッチング回

路は、本明細書で定義されるような、共振器の一部としての任意の一般的な誘導性素子、並びに他のシステムにワイヤレスで結合された誘導性素子に同様にうまく機能することができる。本明細書の全体にわたって、本発明者が開示するマッチング接続形態は、このタイプの一般的な誘導性素子に関するマッチング接続形態を意味し、即ち、この場合、任意の追加のシステムが低損失誘導性素子に間接的に結合されることができ、理解されるべきは、これらの追加のシステムが共振器の電磁モードプロファイル及び共振器の電流／電荷分布に大した影響を与えることはない。

【０２３８】

上記の議論に基づいて、任意の数の結合された供給源共振器、デバイス共振器、及び中間の共振器からなる無線電力伝送システムにおいて、共振器間のワイヤレス磁気（誘導性）結合は、共振器のそれぞれの電磁モードプロファイル及び電流／電荷分布に影響を与えない。従って、これら共振器が高い（アンローデッド及びアンパーターブド）Ｑを有する場合、それらの（アンローデッド及びアンパーターブド）Ｑは、ワイヤレス結合の存在する状態で保持される（留意すべきは、共振器のローデッドＱは、別の共振器へのワイヤレス結合が存在する状態で低減され得るが、本発明者は、損失機構のみに関連し、結合／装荷（ローディング）機構に関連しないアンローデッドＱを保持することに興味がある）。

【０２３９】

図２８の（ｂ）に示されたようなマッチング接続形態を考察する。図２８の（ｂ）に示されたコンデンサは、コンデンサ回路または回路網を表すことができる。図示されたコンデンサを用いて、共振器１０２を形成することができ、且つ供給源共振器およびデバイス共振器の周波数および／またはインピーダンスを調整することができる。この共振器１０２は、「端子接続」２８０８と表示されたポートを用いて、インピーダンス$Ｚ_0$に直接的に結合され得る。図２８の（ｃ）は、一般化された直接結合されたマッチング接続形態を示し、この場合、インピーダンスマッチング回路２４０２は、部品Ａ、Ｂ、及びＣを含む又はそれらからなる。ここで、Ａ、Ｂ、及びＣの回路素子は、共振器１０２の一部、並びにインピーダンスマッチング２４０２（及び周波数調整）接続形態の一部と考えられ得る。Ｂ及びＣは、インピーダンス$Ｚ_0$ ２８０４（又は回路網の端子）を残りの回路（Ａ及び誘導性素子）に、各単一ワイヤ接続を介して接続するマッチング回路２４０２の部品とすることができる。留意すべきは、Ｂ及びＣは無くてもよい（短絡）。回路部品Ｂ及びＣ（即ちこれら単一のワイヤ接続）を切断する又は開く場合、Ａ及び誘導性素子（Ｒ、Ｌ）の組合せは、共振器を形成することができる。

【０２４０】

高Ｑ共振器の電磁モードは、誘導性素子に沿った電圧分布のプロファイルがノード、即ち電圧がゼロである位置を有するようになるかもしれない。１つのノードは、（磁性材料を備える又は備えない）誘導性素子を形成するために使用される導体の中心のような、誘導性素子の長さのほぼ中心にあることができ、少なくとも１つの他のノードはＡ内にあることができる。電圧分布は、その電圧ノードに対して誘導性素子に沿ってほぼ反対称になることができる。高いＱは、マッチング接続形態（Ａ、Ｂ、Ｃ）及び／又は端子電圧（Ｖ１、Ｖ２）を設計することにより維持されることができ、そのためこの高Ｑ共振器の電磁モードの分布は、誘導性素子上にほぼ保持され得る。この高Ｑ共振器の電磁モードの分布は、誘導性素子の電圧ノードを（ほぼ中心に）保持することにより、誘導性素子上にほぼ保持され得る。これら設計の目標を達成する例が本明細書で提供される。

【０２４１】

Ａ、Ｂ、及びＣは任意（即ち、任意の特別な対称性を備えない）とすることができ、Ｖ１及びＶ２は、誘導性素子の両端の電圧が対称性（誘導性素子の中央にある電圧ノード）であるように選択され得る。これらの結果は、接続形態に依存するコモンモード信号（Ｖ１＋Ｖ２）／２が双方の端子で要求され得るので、潜在的に複雑な端子電圧を除いて、簡単なマッチング回路を用いて達成されることができる。

【０２４２】

共振器の電圧ノード全てを接続する「軸」を考察し、この場合、やはり１つのノードが

誘導性素子の長さのほぼ中心にあり、他のノードがＡ内にある（留意すべきは、「軸」は、電気回路接続形態内で実際に一組の点（電圧ノード）であり、実際の物理的構造の線形軸に必ずしも対応するとは限らない。「軸」は、物理的構造が対称性を有する場合に物理的軸とそろうかもしれない。）。共振器の２つの点は、インピーダンスが２つの点のそれぞれとの間で見出され、「軸」上の点、即ち共振器の電圧ノードの点が同じである場合、「軸」に対して電気的に対称である。

【０２４３】

Ｂ及びＣは同じ（Ｃ＝Ｂ）であり、２つの端子は、図２８の（ｄ）に示されるように、上記で定義された「軸」に対して電気的に対称であり、対向する電圧（Ｖ２＝－Ｖ１）で駆動される、共振器（Ａ＋（Ｒ、Ｌ））の任意の２つの点に接続され得る。共振器１０２の２つの電気的に対称の点は、インダクタループ上の２つの電気的に対称の点とすることができる。共振器の２つの電気的に対称の点は、Ａの内部の２つの電気的に対称の点とすることができる。２つの電気的に対称の点（等しい部品Ｂ及びＣのそれぞれが接続される）がＡの内部にある場合、Ａは、これらの電気的に対称の点が回路内の接続点としてアクセス可能であるように設計される必要がある。この接続形態は、「平衡駆動」の接続形態と呼ばれ得る。これら平衡駆動の例は、外部回路または電力回路網における摂動に起因して接地線上に存在することができる任意のコモンモード信号が、例えば、自動的に除去され得る（及び共振器に到達できない）という利点を有することができる。幾つかの平衡駆動の例において、この接続形態は他の接続形態よりも多くの構成要素を必要とするかもしれない。

【０２４４】

他の例において、図２８の（ｅ）に示されるように、Ｃは短絡するように選択され、対応する端子が接地（Ｖ＝０）、及び共振器の電気対称（ゼロ電圧）の「軸」上の任意の点に接続され、Ｂが電気対称の「軸」上にない共振器の任意の他の点に接続されるように選択される。電気対称の「軸」上の接地接続された点は、誘導性素子上の、その導体長さのほぼ中心にある電圧ノードとすることができる。電気対称の「軸」上の接地接続された点は、回路Ａの内部にあることができる。電気対称の「軸」上の接地接続された点がＡの内部にある場合、Ａは、電気的にアクセス可能な、即ち接続が可能な、電気対称の「軸」上に係る１つの点を含むように設計される必要がある。

【０２４５】

この接続形態は、「不平衡駆動」の接続形態と呼ばれ得る。誘導性素子に沿った電磁モードのほぼ反対称の電圧分布は、共振器が正確に対称的に駆動されることができなくても、ほぼ保持され得る。その理由は、高いＱ及び大きな関連したＲ対Z_0の不整合は、共振器（Ａ＋（Ｒ、Ｌ））の内部を流れることができる非常に大きな電流に比べて、少ない電流がＢ及び接地を通って流れることができることを必要とするということである。この状況において、共振器モード上の摂動は、弱くなることができ、電圧ノードの場所は、誘導性素子のほぼ中央の場所にとどまることができる。これら不平衡駆動の例は、それらが簡単なマッチング回路を用いて達成されることができ、Ｖ１端子の駆動電圧に制限がないという利点を有することができる。幾つかの不平衡駆動の例において、接地端子に生じるかもしれないコモンモード信号を低減するために、追加の設計が必要とされるかもしれない。

【０２４６】

図２８の（ｃ）に示されるように、概して部品Ａ、Ｂ及びＣを含む又はそれらからなる直接的に結合されたインピーダンスマッチング回路は、ワイヤ及び回路の構成要素が誘導性素子および／または抵抗の電磁モードの電界および磁界のプロファイルに摂動を与えず、ひいては共振器の高いＱを保持するように設計され得る。回路のワイヤ及び金属の構成要素は、電磁モードの電気力線に垂直になるように配向され得る。回路のワイヤ及び構成要素は、電磁モードの電界および磁界が弱い領域に配置され得る。

【０２４７】

素子の低直列損失および高電流定格の要件を軽減するための接続形態

低い損失の誘導性素子の小さい抵抗Ｒを外部回路のより大きな特性インピーダンスＺ$_0$にマッチングするために使用されるマッチング回路が無損失であると考えられる場合、

$$I_{Z_o}^2 Z_o = I_R^2 R \leftrightarrow I_{Z_o} / I_R = \sqrt{R / Z_o}$$

及び端子を流れる電流は、誘導性素子を流れる電流よりも非常に小さい。従って、端子と直に直列接続された素子（例えば、直接的に結合されたＢ、Ｃ（図２８（ｃ）））は、大きい電流を伝えることができない。従って、たとえマッチング回路が損失性素子を有するとしても、端子に直列接続された素子に存在する抵抗損失は、共振器の高Ｑにおける著しい減少という結果にならない。即ち、それら直列素子の抵抗損失は、Ｚ$_0$から誘導性素子への（または逆もまた同じ）電力伝送の効率を著しく低減しない。従って、低直列損失および／または高電流定格の厳密な要件は、これら構成要素に必要ないかもしれない。一般に、係る低減された要件は、高Ｑ及び／又は高電力インピーダンスマッチング及び共振器の接続形態へと設計され得る構成要素のより広い選択をもたらすことができる。これら低減された要件は特に、これら高Ｑ及び／又は高電力インピーダンスマッチング回路で使用され得る、可変および／または高電圧および／または低並列損失の構成要素の種類を広げることに有用となることができる。

【０２４８】

素子の低並列損失および高電圧定格の要件を軽減するための接続形態

上記のように、低い損失の誘導性素子の小さい抵抗Ｒを外部回路のより大きな特性インピーダンスＺ$_0$にマッチングするために使用されるマッチング回路が無損失であると考えられる場合、前の分析を用いて、

$$|V_{Z_o} / V_{load}| = |I_{Z_o} Z_o / I_R (R + jX)| \approx \sqrt{R / Z_o} \cdot Z_o / X = \sqrt{Z_o / R} / (X / R)$$

及び低損失（高いＸ／Ｒ）誘導性素子の場合、端子にわたる電圧は一般に、誘導性素子の両端の電圧より非常に小さい。従って、端子に直に並列接続された素子は、高電圧に耐える必要がない。従って、たとえマッチング回路が損失性素子を有するとしても、端子に並列接続された素子に存在する抵抗損失は、共振器の高Ｑにおける著しい減少という結果にならない。即ち、それら並列素子の抵抗損失は、Ｚ$_0$から誘導性素子への（または逆もまた同じ）電力伝送の効率を著しく低減しない。従って、低並列損失および／または高電圧定格の厳密な要件は、これら構成要素に必要ないかもしれない。一般に、係る低減された要件は、高Ｑ及び／又は高電力インピーダンスマッチング及び共振器の接続形態へと設計され得る構成要素のより広い選択をもたらすことができる。これら低減された要件は特に、これら高Ｑ及び／又は高電力インピーダンスマッチング及び共振器回路で使用され得る、可変および／または高電流および／または低直列損失の構成要素の種類を広げることに有用となることができる。

【０２４９】

留意すべきは、上記の設計原理は、Ｚ$_0$と直列接続された回路網の使用（直接的に結合されたＢ、Ｃのような）、又はＺ$_0$と並列接続された回路網の使用を様々に提案するように、様々な素子における電流および電圧を異なるように低減することができる。所与の用途に好適な接続形態は、低直列損失／高電流定格、又は低並列損失／高電圧定格の素子の入手のしやすさに依存する可能性がある。

【０２５０】

微細な調整可能性を達成し、及び可変素子の高い定格要件を軽減するための固定および可変素子の組合せ

回路の接続形態

満足な低損失および高電圧または高電流定格を有する可変回路素子は、入手するのに困

難または高価である可能性がある。本明細書において、本発明者は、適切な電圧および電流定格を有する可能性がより高い、回路の固定素子に大きな電圧または電流が割り当てられ、且つ回路の可変素子に対する電圧および電流定格要件を軽減するように、固定素子および可変素子の組合せを組み込むことができるインピーダンスマッチング接続形態を説明する。

【０２５１】

可変回路素子は、所与のインピーダンスマッチングの用途により必要されるものよりも大きな調整（チューニング）範囲を有することができ、これらの場合、微細調整の分解能は、係る大きな範囲の素子だけを用いて得ることは困難である可能性がある。本明細書において、本発明者は、より微細な調整分解能が同じ可変素子で達成され得るように、固定素子および可変素子の組合せを組み込むインピーダンスマッチング接続形態を説明する。

【０２５２】

従って、固定素子および可変素子の組合せを用いる接続形態は、同時に２種類の利点をもたらすことができ、即ち回路の敏感なチューニング構成要素にわたる電圧またはそれを流れる電流の低減、及びより微細な調整分解能である。留意すべきは、最大の達成可能な調整範囲は、回路設計における調整可能な構成要素にわたる電圧またはそれを流れる電流の最大限の減少に関係付けられ得る。

【０２５３】

素子の接続形態

単一の可変回路素子（上述した素子の回路網とは対照的に）は、可変構成要素の定格要件の減少およびより微細な調整分解能を達成するために、直列または並列に接続された固定および可変構成要素の組合せを用いた接続形態により実現され得る。これは、以下の事実により数学的に実証され得る。

【０２５４】

【数１１】

$$x_{|total|} = x_{|fixed|} + x_{|variable|} \quad \text{の場合}$$

$$\Delta x_{|total|} / x_{|total|} = \Delta x_{|\mathrm{variable}|} / (x_{|fixed|} + x_{|\mathrm{variable}|})$$

$$\text{及び} \quad X_{\mathrm{variable}} / X_{total} = X_{\mathrm{variable}} / (X_{fixed} + X_{\mathrm{variable}})$$

【０２５５】

ここで、$x_{|subscript|}$は任意の素子の値（例えば、キャパシタンス、インダクタンス）であり、Ｘは電圧または電流であり、「＋符号」は、素子の適切な（直列追加または並列追加）組合せを示す。留意すべきは、$x_{|subscript|}$の下付き文字の形式は、円形誘導性素子（例えば、x、x_1など）により包囲される面積の半径からそれを容易に区別ために選択される。

【０２５６】

更に、この原理は、可変素子が他の固定素子と適切に組み合わされる場合、異なるタイプの可変素子を用いることにより、特定のタイプ（例えば、キャパシタンス又はインダクタンス）の可変電気素子を実現するために使用され得る。

【０２５７】

結論として、最適化の制約として必要な調整範囲を有する固定および可変素子の必要な数、配置、タイプ、及び値、並びに最適化の目的として可変素子の電流および／または電圧の最小化を決定する接続形態最適化のアルゴリズムが適用され得る。

【０２５８】

例

以下の回路図において、本発明者は、低損失誘導性素子に対するインピーダンスマッチ

ング及び係る誘導性素子の共振器設計の異なる特定の接続形態の具現化形態を示す。更に、本発明者は、各接続形態について、上述されたどの原理が使用されているか、マッチングを達成するために使用され得る可変素子の値を与える式、及びマッチングされ得る複素インピーダンスの範囲（不等式およびスミスチャートの表現を用いて）を示す。これらの例の場合、本発明者は、Ｚ$_0$が実数であるが、非ゼロの虚数部を有する特性インピーダンスまでの拡張が真っ直ぐであると仮定し、その理由は、それがマッチング回路網の構成要素の必要な値における小さな調整だけを意味するからである。本発明者は、量に関する下付き文字ｎがＺ$_0$（除算した）に対する正規化を意味する取り決めを使用する。

【０２５９】

図２９は、トランス結合されたインピーダンスマッチング回路の２つの例を示し、この場合、２つの調整可能な素子（要素）は、コンデンサ及び２つの誘導性素子間の相互インダクタンスである。本発明者が、図２９の（ａ）に関して、Ｘ$_2$＝ωＬ$_2$、及び図２９の（ｂ）に関して、Ｘ$_2$＝ωＬ$_2$－１／ωＣ$_2$、及びＸ＝ωＬを定義する場合、調整可能な素子の必要な値は、以下の通りである。

【０２６０】

【数１２】

$$\omega C_1 = \frac{1}{X + RX_{2n}}$$

$$\omega M = \sqrt{Z_o R(1+X_{2n}^2)}$$

【０２６１】

図２９の（ｂ）の接続形態の場合、特に簡単な設計は、Ｘ$_2$＝０を選択することである。この場合、これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。即ち、

Ｒ$_n$＞０、Ｘ$_n$＞０

それらは、図２９の（ｃ）のスミスチャートの実線により包囲された領域によって示される。

【０２６２】

良好に予め選択された固定Ｍが与えられる場合、調整可能なＣ$_2$を有する上記マッチング接続形態を代わりに使用することもできる。

【０２６３】

図３０は、直接的に結合されたインピーダンスマッチング回路の６つの例（ａ）～（ｆ）（この場合２つの調整可能な素子はコンデンサである）、及び直接的に結合されたインピーダンスマッチング回路の６つの例（ｈ）～（ｍ）（この場合２つの調整可能な素子は１つのコンデンサと１つのインダクタである）を示す。図３０の（ａ）、（ｂ）、（ｃ）、（ｈ）、（ｉ）、（ｊ）の接続形態の場合、コモンモード信号は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために２つの端子に必要とされ得る。留意すべきは、これらの例は、図２８の（ｃ）に示された一般的な接続形態の具現化形態として説明され得る。図３０の（ｄ）、（ｅ）、（ｆ）、（ｋ）、（ｌ）、（ｍ）の対称の接続形態の場合、２つの端子は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために反対称的に駆動される必要があるかもしれない。留意すべきは、これらの例は、図２８の（ｄ）に示された一般的な接続形態の具現化形態として説明され得る。理解されるべきは、本明細書で使用されるようなコンデンサの回路網は、別の意味が明確に提供される又は文脈から明らかであることを除いて、１つ又は複数のコンデンサを含む任意の回路接続形態を一般に意味し、コンデンサ、又は任意の他の等価物または異なる回路構造（単数または複数）を用いる特に本明細書で開示された任

意の回路を制限しないことを含む。

【０２６４】

図３０の（ａ）、（ｄ）、（ｈ）、（ｋ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬを定義し、図３０の（ｂ）、（ｅ）、（ｉ）、（ｌ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬ＋１／ｊωC_3を定義し、図３０の（ｃ）、（ｆ）、（ｊ）、（ｍ）についてそれぞれ、Ｚ＝（Ｒ＋ｊωＬ）‖（１／ｊωC_3）を定義しよう。ここで記号「‖」は、「～の並列組合せ」を意味し、Ｒ≡Ｒｅ｛Ｚ｝、Ｘ≡Ｉｍ｛Ｚ｝である。図３０の（ａ）～（ｆ）について、調整可能な素子の必要な値は、以下により与えられる。

【０２６５】

【数１３】

$$\omega C_1 = \frac{X - \sqrt{X^2 R_n - R^2(1-R_n)}}{X^2 + R^2},$$

$$\omega C_2 = \frac{R_n \omega C_1}{1 - X\omega C_1 - R_n}$$

【０２６６】

これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。即ち、

$R_n \leqq 1$、$X_n \geqq (R_n(1-R_n))^{1/2}$

それらは、図３０の（ｇ）のスミスチャートの実線により包囲された領域によって示される。図３０の（ｈ）～（ｍ）の場合、調整可能な素子の必要な値は、以下により与えられ得る。

【０２６７】

【数１４】

$$\omega C_1 = \frac{X + \sqrt{X^2 R_n - R^2(1-R_n)}}{X^2 + R^2},$$

$$\omega L_2 = -\frac{1 - X\omega C_1 - R_n}{R_n \omega C_1}$$

【０２６８】

図３１は、直接的に結合されたインピーダンスマッチング回路の３つの例（ａ）～（ｃ）（この場合２つの調整可能な素子はコンデンサである）、及び直接的に結合されたインピーダンスマッチング回路の３つの例（ｅ）～（ｇ）（この場合２つの調整可能な素子は１つのコンデンサと１つのインダクタである）を示す。図３１の（ａ）、（ｂ）、（ｃ）、（ｅ）、（ｆ）、（ｇ）の接続形態の場合、接地端子は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために、２つの等しい値のコンデンサ２C_1の間（即ち、主共振器の対称軸上）に接続される。留意すべきは、これらの例は、図２８の（ｅ）に示された一般的な接続形態の具現化形態として説明され得る。

【０２６９】

図３１の（ａ）、（ｅ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬを定義し、図３１の（ｂ）、（ｆ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬ＋１／ｊωC_3を定義し、図３１の（ｃ）、（ｇ）についてそれぞれ、Ｚ＝（Ｒ＋ｊωＬ）‖（１／ｊωC_3）を定義し、及びＲ≡Ｒ e｛Z｝、X≡Im｛Z｝を定義しよう。図３１の（ａ）～（ｃ）について、調整可能な素子の必要な値は、以下により与えられる。

【０２７０】

【数１５】

$$\omega C_1 = \frac{X - \frac{1}{2}\sqrt{X^2 R_n - R^2(4 - R_n)}}{X^2 + R^2},$$

$$\omega C_2 = \frac{R_n \omega C_1}{1 - X\omega C_1 - \frac{R_n}{2}}$$

【０２７１】

これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。

【０２７２】

【数１６】

$$R_n \leq 1,\ \ X_n \geq \sqrt{\frac{R_n}{1 - R_n}(2 - R_n)}$$

【０２７３】

それらは、図３１の（ｄ）のスミスチャートの実線により包囲された領域によって示される。図３１の（ｅ）～（ｇ）の場合、調整可能な素子の必要な値は、以下により与えられ得る。

【０２７４】

【数１７】

$$\omega C_1 = \frac{X + \frac{1}{2}\sqrt{X^2 R_n - R^2(4 - R_n)}}{X^2 + R^2},$$

$$\omega L_2 = -\frac{1 - X\omega C_1 - \frac{R_n}{2}}{R_n \omega C_1}$$

【０２７５】

図３２は、直接的に結合されたインピーダンスマッチング回路の３つの例（ａ）～（ｃ）（この場合２つの調整可能な素子はコンデンサである）、及び直接的に結合されたインピーダンスマッチング回路の３つの例（ｅ）～（ｇ）（この場合２つの調整可能な素子は１つのコンデンサと１つのインダクタである）を示す。図３２の（ａ）、（ｂ）、（ｃ）、（ｅ）、（ｆ）、（ｇ）の接続形態の場合、接地端子は、誘導性素子の中央に接続され、その点に共振器の電圧ノードを保持する、ひいては高いＱを保持することができる。留意すべきは、これらの例は、図２８の（ｅ）に示された一般的な接続形態の具現化形態と

して説明され得る。

【０２７６】

図３２の（ａ）について、$Z=R+j\omega L$を定義し、図３２の（ｂ）について、$Z=R+j\omega L+1/j\omega C_3$を定義し、図３２の（ｃ）について、$Z=(R+j\omega L)\parallel(1/j\omega C_3)$を定義し、及び$R\equiv\mathrm{Re}\{Z\}$、$X\equiv\mathrm{Im}\{Z\}$を定義しよう。図３２の（ａ）～（ｃ）について、調整可能な素子の必要な値は、以下により与えられる。

【０２７７】

【数１８】

$$\omega C_1=\frac{X-\sqrt{\dfrac{X^2R_n-2R^2(2-R_n)}{4-R_n}}}{X^2+R^2},$$

$$\omega C_2=\frac{R_n\omega C_1}{1-X\omega C_1-\dfrac{R_n}{2}+\dfrac{R_nX\omega C_1}{2(1+k)}}$$

【０２７８】

ここで、ｋは$M'=-kL'$により定義され、ここでL'は、インダクタループの各半分のインダクタンスであり、M'は係る２つの半分間の相互インダクタンスであり、これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。即ち、

$R_n\leqq 2$、$X_n\geqq(2R_n(2-R_n))^{1/2}$

それらは、図３２の（ｄ）のスミスチャートの実線により包囲された領域によって示される。図３２の（ｅ）～（ｇ）の場合、調整可能な素子の必要な値は、以下により与えられ得る。

【０２７９】

【数１９】

$$\omega C_1=\frac{X+\sqrt{\dfrac{X^2R_n-2R^2(2-R_n)}{4-R_n}}}{X^2+R^2}$$

【０２８０】

図３０、図３１、図３２の回路において、コンデンサC_2又はインダクタL_2（又は２つのコンデンサ$2C_2$又は２つのインダクタ$L_2/2$）は、端子に直列に接続され、非常に低い直列損失を有するか、又は大きい電流に耐える必要はないかもしれない。

【０２８１】

図３３は、直接的に結合されたインピーダンスマッチング回路の６つの例（ａ）～（ｆ）（この場合２つの調整可能な素子はコンデンサである）、及び直接的に結合されたインピーダンスマッチング回路の６つの例（ｈ）～（ｍ）（この場合２つの調整可能な素子は１つのコンデンサと１つのインダクタである）を示す。図３３の（ａ）、（ｂ）、（ｃ）、（ｈ）、（ｉ）、（ｊ）の接続形態の場合、コモンモード信号は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために２つの端子に必要とされ得る。留意すべきは、これらの例は、図２８の（ｃ）に示された一般的な接続形態の具現化形態として説明されることができ、ここでＢ及びＣは短絡であり、Ａは平衡されてい

ない。図３３の（ｄ）、（ｅ）、（ｆ）、（ｋ）、（ｌ）、（ｍ）の対称の接続形態の場合、２つの端子は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために反対称的に駆動（平衡駆動）される必要があるかもしれない。留意すべきは、これらの例は、図２８の（ｄ）に示された一般的な接続形態の具現化形態として説明されることができ、ここでＢ及びＣは短絡であり、Ａは平衡されている。

【０２８２】

図３３の（ａ）、（ｄ）、（ｈ）、（ｋ）についてそれぞれ、$Z=R+j\omega L$を定義し、図３３の（ｂ）、（ｅ）、（ｉ）、（ｌ）についてそれぞれ、$Z=R+j\omega L+1/j\omega C_3$を定義し、図３３の（ｃ）、（ｆ）、（ｊ）、（ｍ）についてそれぞれ、$Z=(R+j\omega L)\parallel(1/j\omega C_3)$を定義し、及び$R\equiv \mathrm{Re}\{Z\}$、$X\equiv \mathrm{Im}\{Z\}$を定義しよう。図３３の（ａ）～（ｆ）について、調整可能な素子の必要な値は、以下により与えられる。

【０２８３】

【数２０】

$$\omega C_1=\frac{1}{X-Z_o\sqrt{R_n(1-R_n)}},$$

$$\omega C_2=\frac{1}{Z_o}\sqrt{\frac{1}{R_n}-1}$$

【０２８４】

これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。即ち、

$R_n\leqq 1$、$X_n\geqq (R_n(1-R_n))^{1/2}$

それらは、図３３の（ｇ）のスミスチャートの実線により包囲された領域によって示される。図３３の（ｈ）～（ｍ）の場合、調整可能な素子の必要な値は、以下により与えられ得る。

【０２８５】

【数２１】

$$\omega C_1=\frac{1}{X+Z_o\sqrt{R_n(1-R_n)}},$$

$$\omega L_2=\frac{Z_o}{\sqrt{\frac{1}{R_n}-1}}$$

【０２８６】

図３４は、直接的に結合されたインピーダンスマッチング回路の３つの例（ａ）～（ｃ）（この場合２つの調整可能な素子はコンデンサである）、及び直接的に結合されたインピーダンスマッチング回路の３つの例（ｅ）～（ｇ）（この場合２つの調整可能な素子は１つのコンデンサと１つのインダクタである）を示す。図３４の（ａ）、（ｂ）、（ｃ）、（ｅ）、（ｆ）、（ｇ）の接続形態の場合、接地端子は、誘導性素子の中央に共振器の電圧ノードを保持する、ひいては高いＱを保持するために、２つの等しい値のコンデンサ$2C_2$の間（即ち、主共振器の対称軸上）に接続される。留意すべきは、これらの例は、

図２８の（ｅ）に示された一般的な接続形態の具現化形態として説明され得る。

【０２８７】

図３４の（ａ）、（ｅ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬを定義し、図３４の（ｂ）、（ｆ）についてそれぞれ、Ｚ＝Ｒ＋ｊωＬ＋１／ｊωＣ$_3$を定義し、図３４の（ｃ）、（ｇ）についてそれぞれ、Ｚ＝（Ｒ＋ｊωＬ）‖（１／ｊωＣ$_3$）を定義し、及びＲ≡Ｒｅ｛Ｚ｝、Ｘ＝Ｉｍ｛Ｚ｝を定義しよう。図３４の（ａ）～（ｃ）について、調整可能な素子の必要な値は、以下により与えられる。

【０２８８】

【数２２】

$$\omega C_1 = \frac{1}{X - Z_o\sqrt{\frac{1-R_n}{R_n}}(2-R_n)},$$

$$\omega C_2 = \frac{1}{2Z_o}\sqrt{\frac{1}{R_n}-1}$$

【０２８９】

これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。

【０２９０】

【数２３】

$$R_n \le 1,\ X_n \ge \sqrt{\frac{R_n}{1-R_n}}(2-R_n)$$

【０２９１】

それらは、図３４の（ｄ）のスミスチャートの実線により包囲された領域によって示される。図３４の（ｅ）～（ｇ）の場合、調整可能な素子の必要な値は、以下により与えられ得る。

【０２９２】

【数２４】

$$\omega C_1 = \frac{1}{X + Z_o\sqrt{\frac{1-R_n}{R_n}}(2-R_n)},$$

$$\omega L_2 = \frac{2Z_o}{\sqrt{\frac{1}{R_n}-1}}$$

【０２９３】

図３５は、直接的に結合されたインピーダンスマッチング回路の３つの例を示し、この場合２つの調整可能な素子はコンデンサである。図３５の接続形態の場合、接地端子は、

誘導性素子の中央に接続され、その点に共振器の電圧ノードを保持する、ひいては高いＱを保持することができる。留意すべきは、これらの例は、図２８の（ｅ）に示された一般的な接続形態の具現化形態として説明され得る。

【０２９４】

図３５の（ａ）について、Ｚ＝Ｒ＋ｊωＬを定義し、図３５の（ｂ）について、Ｚ＝Ｒ＋ｊωＬ＋１／ｊωＣ$_3$を定義し、図３５の（ｃ）について、Ｚ＝（Ｒ＋ｊωＬ）‖（１／ｊωＣ$_3$）を定義し、及びＲ≡Ｒｅ｛Ｚ｝、Ｘ≡Ｉｍ｛Ｚ｝を定義しよう。調整可能な素子の必要な値は、以下により与えられる。

【０２９５】

【数２５】

$$\omega C_1 = \frac{2}{X(1+a)-\sqrt{Z_o R(4-R_n)(1+a^2)}} ,$$

$$\omega C_2 = \frac{2}{X(1+a)+\sqrt{Z_o R(4-R_n)(1+a^2)}}$$

【０２９６】

ここで、ａ＝Ｒ／（２Ｚ$_0$－Ｒ）・ｋ／（１＋ｋ）、ｋはＭ’＝－ｋＬ’により定義され、ここでＬ’は、誘導性素子の各半分のインダクタンスであり、Ｍ’は係る２つの半分間の相互インダクタンスである。これらの接続形態は、以下の不等式を満たすインピーダンスをマッチングすることができる。

【０２９７】

【数２６】

$$R_n \le 2 \,\&\, \frac{2}{\gamma} \le R_n \le 4,$$

$$X_n \ge \sqrt{\frac{R_n(4-R_n)(2-R_n)}{2-\gamma R_n}}$$

この場合

$$\gamma = \frac{1-6k+k^2}{1+2k+k^2} \le 1$$

【０２９８】

それらは、ｋ＝０の場合の図３５の（ｄ）に示された、ｋ＝０．０５の場合の図３５の（ｅ）に示された、及びｋ＝１の場合の図３５の（ｆ）に示された３つのスミスチャートの実線により包囲された領域によって示される。留意すべきは、０＜ｋ＜１の場合、この接続形態がマッチングすることができる、スミスチャートの２つの分離された領域が存在する。

【０２９９】

図３３、図３４、図３５の回路において、コンデンサＣ$_2$又はインダクタＬ$_2$（又は２つのコンデンサ２Ｃ$_2$の一方、又は２つのインダクタ２Ｌ$_2$の一方）は、端子に並列に接続され、ひいては高い電圧定格を有する必要はないかもしれない。２つのコンデンサ２Ｃ$_2$又は２つのインダクタ２Ｌ$_2$の場合、双方は高い電圧定格を有する必要はないかもしれない。その理由は、ほぼ同じ電流がそれらを流れ、かくしてそれらが、それらにわたるほ

ぼ同じ電圧を蒙るからである。

【０３００】

図３０～図３５の接続形態に関して、コンデンサＣ$_3$が使用される場合、コンデンサＣ$_3$の使用は、周波数およびインピーダンスの微細な調整をもたらすことができる。図３０～図３５の接続形態に関して、誘導性素子に直列接続された固定コンデンサＣ$_3$の使用は、高い誘導性素子の電圧の大部分がこの固定コンデンサＣ$_3$を横切り、かくして幾つかを可変とすることができるインピーダンスマッチング回路の他の素子に対する電圧定格要件を潜在的に軽減する。係る接続形態が好適か否かは、適切な固定および調整可能な構成要素の入手可能性、コスト、及び仕様に依存する。

【０３０１】

上記の例において、共通端子を備えない一対の等しい値の可変コンデンサは、連動型コンデンサ、又は集合体として値を調整するためにバイアスされる及び制御されるバラクタ又はダイオードのグループ又はアレイを用いて実現され得る。１つの共通端子を備える一対の等しい値の可変コンデンサは、調整可能なバタフライ型コンデンサ、又は任意の他の調整可能な又は可変コンデンサ、又は集合体としてキャパシタンス値を調整するためにバイアスされる及び制御されるバラクタ又はダイオードのグループ又はアレイを用いて実現され得る。

【０３０２】

インピーダンスマッチング回路網の選択の際に考慮され得る別の基準は、所望の動作周波数以外の異なる周波数に対する回路網の応答である。誘導性素子が結合される外部回路で生成される信号は、所望の周波数において単一波長でないが、例えば、スイッチングアンプの駆動信号、又はスイッチング整流装置の反射信号のような、所望の周波数で周期的とすることができる。係る場合によっては、誘導性素子に入力する高次の高調波の量を抑制することが望ましかもしれない（例えば、この素子からこれらの高調波の放射を低減するために）。従って、インピーダンスマッチング回路網の選択は、誘導性素子に入力する係る高調波の量を十分に抑制するものとすることができる。

【０３０３】

外部の周期信号が電圧供給源信号（直列共振負荷でクラスＤ増幅器の駆動信号のような）として挙動すると考えられることができる信号であり、そのため、より高い周波数で誘導性素子を流れる電流が殆どない場合に、インピーダンスマッチング回路網は、基本波より高い周波数において外部回路により見出されるインピーダンスが高いようにするこができる。図３０～図３５の接続形態の中で、インダクタＬ$_2$を使用するものは、このインダクタが高い周波数において高いインピーダンスを提供するので、好適とすることができる。

【０３０４】

外部の周期信号が電流供給源信号として挙動すると考えられることができる信号であり、そのため、より高い周波数で誘導性素子の両端に生じる電圧が殆どない場合に、インピーダンスマッチング回路網は、基本波より高い周波数において外部回路により見出されるインピーダンスが低いようにするこができる。図３０～図３５の接続形態の中で、コンデンサＣ$_2$を使用するものは、このコンデンサが高い周波数において低いインピーダンスを提供するので、好適とすることができる。

【０３０５】

図３６は、１つの可変コンデンサ、及び残りの固定コンデンサの回路網を使用する可変コンデンサの４つの例を示す。これらの回路網の接続形態を用いると、全キャパシタンス値の微細な調整可能性が達成され得る。更に、図３６の（ａ）、（ｃ）、（ｄ）の接続形態は、電圧の大部分が固定コンデンサにわたって割り当てられ得るので、可変コンデンサの両端の電圧を低減するために使用され得る。

【０３０６】

図３７は、１つの可変インダクタ及び固定コンデンサの回路網を使用する可変コンデンサの２つの例を示す。特に、これら回路網は、可変リアクタンスの具現化形態を提供し、

及び関心のある周波数において、各回路網が、実質的に可変キャパシタンスとすることができる正味の負の可変リアクタンスに対応するように、可変インダクタが使用され得る値を提供することができる。

【０３０７】

調整可能なコンデンサ及び調整可能なインダクタのような調整可能な素子は、機械的に調整可能、電気的に調整可能、熱的に調整可能などとすることができる。調整可能な素子は、可変コンデンサ又はインダクタ、バラクタ、ダイオード、ショットキーダイオード、逆バイアスＰＮダイオード、バラクタアレイ、ダイオードアレイ、ショットキーダイオードアレイなどとすることができる。ダイオードは、Siダイオード、GaNダイオード、SiCダイオードなどとすることができる。GaN及びSiCダイオードは特に、高電力用途には魅力的とすることができる。調整可能な素子は、電気的に切り換えられるコンデンサバンク、電気的に切り換えられ機械的に調整可能なコンデンサバンク、電気的に切り換えられるバラクタアレイバンク、電気的に切り換えられるトランス結合されたインダクタバンクなどとすることができる。調整可能な素子は、上記で列挙された素子の組合せとすることができる。

【０３０８】

上述したように、結合された高Ｑ磁気共振器間の電力伝送の効率は、共振器が共振周波数に如何に接近してマッチングされるか、及びそれらのインピーダンスがシステムの電源および電力消費装置に如何に良好にマッチングされるかにより、影響を受ける。システムにおける外部物体または他の共振器の相対位置、又はそれら相対位置の変更を含む様々な外部要因が、共振周波数および／または高Ｑ磁気共振器の入力インピーダンスを変更する可能性があるので、調整可能なインピーダンス回路網は、様々な環境または動作状況において、十分な電力伝送のレベルを維持するために必要であるかもしれない。

【０３０９】

図示されたコンデンサのキャパシタンス値は、磁気共振器の共振周波数および／またはインピーダンスを調整するために調整され得る。コンデンサは、電気的、機械的、熱的に、又は任意の他の知られた方法により調整され得る。コンデンサは、フィードバック信号に応じてのように、手動で又は自動的に調整され得る。コンデンサは、特定の電力伝送効率、又は電源と電力消費装置との間の他の動作特性を達成するために調整され得る。

【０３１０】

共振器のインダクタ及び誘導性素子のインダクタンス値は、磁気共振器の周波数および／またはインピーダンスを調整するために調整され得る。インダクタンスは、調整可能なコンデンサ、インダクタ、及びスイッチのような調整可能な構成要素を含む結合回路を用いて調整され得る。インダクタンスは、トランス結合されたチューニング回路を用いて調整され得る。インダクタンスは、誘導性素子の導体の異なるセクションの出入りを切り換えることにより、及び／又は強磁性同調（チューニング）及び／又はミュー同調などを用いて調整され得る。

【０３１１】

共振器の共振周波数は、より低い又はより高い周波数に調整され得るか、又は変更することを可能にすることができる。共振器の入力インピーダンスは、より低い又はより高い入力インピーダンス値に調整され得るか、又は変更することを可能にすることができる。供給源により伝えられる及び／又はデバイスにより受け取られる電力の量は、より低い又はより高いレベルの電力に調整され得るか、又は変更することを可能にすることができる。供給源に伝えられる及び／又はデバイス共振器からデバイスにより受け取られる電力の量は、より低い又はより高いレベルの電力に調整され得るか、又は変更することを可能にすることができる。共振器の入力インピーダンス、共振周波数、及び電力レベルは、システムの電力消費装置（単数または複数）に依存して、及び共振器の近傍の物体または材料に依存して調整され得る。共振器の入力インピーダンス、周波数、及び電力レベルは、手動または自動的に調整されることができ、フィードバック又は制御信号、又はアルゴリズムに応じて調整され得る。

【０３１２】

回路素子は、共振器に直接的に接続され得る、即ち、物理的な電気コンタクトにより、例えば、誘導性素子を形成する導体の両端部に及び／又は端子接続に直接的に接続され得る。回路素子は、導体にはんだ付けされ、溶接され、圧着され、接着され、挟まれ、又は接近して配置され、或いは様々な電気構成要素、コネクタ又は接続技術を用いて取り付けられ得る。電源および電力消費装置は、磁気共振器に直接的に又は間接的に又は誘導的に接続され得る。電気信号は、端子接続を介して共振器に供給、又は当該共振器から取られることができる。

【０３１３】

当業者には理解されるように、本明細書で説明された原理の実際の具現化形態において、本明細書で記載された方程式を介して計算された値から実際の構成要素（コンデンサ、インダクタ、抵抗など）の値まで、対称性または反対称性またはその他により示された値から実際の信号（電圧、電流など）の値まで、及び対称性またはその他により示された場所から点（例えば、誘導性素子の中央または「軸」の点などに接近した接地端子の接続点）の実際の幾何学的場所の値まで、関連した許容範囲または許容変動が存在してもよい。

【０３１４】

例

システムブロック図

本発明者は、中距離でワイヤレスでデバイスに電力供給またはデバイスを充電することができる無線電力伝送システム用の高Ｑ共振器の例を開示する。また、高Ｑ共振器の無線電力伝送システムは、システムの任意の供給源共振器とは異なるサイズ、形状、組成、構成などである磁気共振器でもってワイヤレスでデバイスに電力を供給またはデバイスを充電することもできる。

【０３１５】

図１の（ａ）、（ｂ）は、２つの例示的な２共振器システムの高レベルブロック図を示す。これら例示的なシステムはそれぞれ、単一の供給源共振器１０２Ｓ又は１０４Ｓ、及び単一のデバイス共振器１０２Ｄ又は１０４Ｄを有する。図３８は、さらに幾つかの特徴が浮き彫りにされたシステムの高レベルブロック図を示す。ワイヤレスで電力供給される又は充電されるデバイス２３１０は、ＤＣ又はＡＣ、或いはＤＣ及びＡＣの電力が伝送されるデバイス（単数または複数）２３０８と共に、デバイス共振器１０２Ｄ、デバイス電力および制御回路２３０４などを含む又はからなることができる。システムのエネルギー源又は電源は、電源および制御回路２３０２、供給源共振器１０２Ｓなどを含むことができる。デバイス共振器１０２Ｄ、並びに電力および制御回路２３０４から電力を受け取るデバイス（単数または複数）２３０８は、前述されたように任意の種類のデバイス（単数または複数）２３０８とすることができる。デバイス共振器１０２Ｄ及び回路２３０４は、デバイス（単数または複数）のバッテリーを再充電する、デバイス（単数または複数）に直接的に電力を供給する、又は供給源共振器１０２Ｓの近傍にある場合に双方を行うために使用され得るデバイス（単数または複数）２３０８に電力を供給する。

【０３１６】

供給源共振器およびデバイス共振器は、数メートルだけ離され得るか、又は互いに非常に接近することができるか、又はそれらの間の任意の距離だけ離され得る。供給源共振器およびデバイス共振器は、互いから水平方向に又は軸方向にオフセットされて（ずらされて）もよい。供給源共振器およびデバイス共振器は、直線的に整列されるか（水平方向のオフセットなし）、或いは数メートル又はそれらの間の任意の距離だけオフセットされてもよい。供給源共振器およびデバイス共振器は、それらの誘導性素子により包囲された表面領域（表面積）が互いにほぼ平行になるように配向され得る。供給源共振器およびデバイス共振器は、それらの誘導性素子により包囲された表面領域が互いにほぼ垂直になるように配向され得るか、又はそれらの間の任意の相対角度（０度～３６０度）に配向され得る。

【０３１７】

供給源共振器およびデバイス共振器は、自立型とすることができるか、又は筐体、容器、スリーブ、又はハウジングに収容され得る。これら様々な筐体は、ほぼ任意の種類の材料から構成され得る。Teflon（登録商標）、REXOLITE（登録商標）、スチレンなどのような低い損失正接の材料が、幾つかの用途に好適とすることができる。供給源共振器およびデバイス共振器は、電源および電力消費装置に一体化され得る。例えば、供給源共振器およびデバイス共振器は、キーボード、コンピュータマウス、ディスプレイ、携帯電話などに組み込まれることができ、そのためそれらはこれらデバイスの外側で見ることができない。供給源共振器およびデバイス共振器は、システムにおいて電源および電力消費装置から分離されることができ、及び標準的な又は特注のワイヤ、ケーブル、コネクタ又はプラグにより接続されてもよい。

【０３１８】

供給源１０２Ｓは、コンピュータのＵＳＢポートを含む、多数のＤＣ又はＡＣ電圧源、電流源、又は電源から電力供給され得る。供給源１０２Ｓは、配電網から、壁コンセントから、バッテリーから、電源から、エンジンから、太陽電池から、電力発生装置から、別の供給源共振器などから、電力供給され得る。供給源電力および制御回路２３０２は、電源から供給源電子回路を分離するための回路および構成要素を含むことができ、そのため任意の反射された電力または信号が供給源の入力端子を通じて結合されない。供給源電力および制御回路２３０２は、力率補正回路を含むことができ、監視、課金、請求書作成、制御、及び類似した機能のために電力使用量を監視するように構成され得る。

【０３１９】

システムは、双方向で動作され得る。即ち、デバイス共振器で生成される又はデバイス共振器に蓄積されるエネルギー又は電力は、配電網、バッテリー、任意の種類のエネルギー蓄積ユニットなどを含む電源にフィードバックされ（返され）得る。供給源電力および制御回路は、力率補正回路を含むことができ、双方向のエネルギーの流れに関して、監視、課金、請求書作成、制御、及び類似した機能のために電力使用量を監視するように構成され得る。無線エネルギー伝送システムは、ビークルトゥグリッド（Ｖ２Ｇ）の応用形態を可能にする又は推進することができる。

【０３２０】

供給源およびデバイスは、供給源およびデバイスの共振器の動作、及びエネルギー交換の効率に影響を与える可能性がある環境条件、摂動、及びローディング（装荷）条件の変更を、動作点の調整が補償することを可能にするチューニング能力を有することができる。また、チューニング能力は、多数の供給源から、多数のデバイスへの、多数のシステムへの、多数の中継器などへの電力供給を多重伝送するためにも使用され得る。チューニング能力は、手動で制御され得るか、又は自動で制御されることができ、連続的に、周期的に、断続的に、又は計画的な時間または間隔で実行され得る。

【０３２１】

デバイス共振器、及びデバイス電力および制御回路は、バッテリー室、又はデバイスのカバー又はスリーブ、又はマザーボードのような、デバイスの任意の部分に組み込まれることができ、例えば標準的な再充電可能なバッテリー又は他のエネルギー蓄積ユニットと共に一体化され得る。デバイス共振器は、デバイス共振器素子、及びデバイス電力および制御電子回路の任意の組合せを電力伝送に使用される電磁界から遮蔽することができる、且つ損失性デバイス共振器素子、並びにデバイス電力および制御電子回路から離れるように共振器の場を偏向させることができる、デバイスの場の再整形回路（場－再整形回路と称する）を含むことができる。磁性材料および／または高導電率の場－再整形回路を用いて、共振器のパーターブドＱファクタＱを増加させ、供給源共振器およびデバイス共振器のパーターブド結合率を増加させることができる。

【０３２２】

供給源共振器、及び供給源電力および制御回路は、任意のタイプの家具、構造体、マット、ラグマット、額縁（デジタルピクチャフレーム、電子フレームを含む）、プラグインモジュール、電子デバイス、車両などに組み込まれ得る。供給源共振器は、供給源共振器

素子、及び供給源電力および制御電子回路の任意の組合せを電力伝送に使用される電磁界から遮蔽することができる、且つ損失性供給源共振器素子、並びに供給源電力および制御電子回路から離れるように共振器の場を偏向させることができる、供給源の場－再整形回路を含むことができる。磁性材料および／または高導電率の場－再整形回路を用いて、共振器のパーターブドＱファクタＱを増加させ、供給源共振器およびデバイス共振器のパーターブド結合率を増加させることができる。

【０３２３】

ワイヤレスで電力供給されるデバイスの例におけるサブシステムのブロック図が図３９に示される。電力および制御回路は、デバイス共振器１０２Ｄからの交流電流電力を変換するように、及びデバイスに電力供給またはデバイスを充電するのに適した安定した直流電力にそれを変換するように設計され得る。電力および制御回路は、デバイス共振器からの一周波数の交流電流電力を、デバイスに電力供給またはデバイスを充電するのに適した異なる周波数の交流電流電力に変換するように設計され得る。電力および制御回路は、インピーダンスマッチング回路２４０２Ｄ、整流回路２４０４、電圧制限回路（図示せず）、電流制限回路（図示せず）、ＡＣ／ＤＣ変換器２４０８回路、ＤＣ／ＤＣ変換器２４０８回路、ＤＣ／ＡＣ変換器２４０８回路、ＡＣ／ＡＣ変換器２４０８回路、バッテリー充電制御回路（図示せず）などを含む、又はからなることができる。

【０３２４】

インピーダンスマッチング２４０２Ｄ回路網は、所望の周波数において、デバイス共振器１０２Ｄとデバイス電力および制御回路２３０４との間で伝えられる電力を最大にするように設計され得る。インピーダンスマッチング素子は、共振器の高いＱが保持されるように、選択および接続され得る。動作条件に応じて、インピーダンスマッチング回路２４０２Ｄは、供給源からデバイスへ、供給源からデバイス共振器へ、デバイス共振器とデバイス電力および制御回路との間などで伝えられる電力を制御するために変更または調整され得る。電力信号、電流信号、及び電圧信号は、デバイス回路およびフィードバックアルゴリズム回路および技術の任意の点で監視されることができ、所望の信号レベル及びシステム動作を達成するために構成要素を制御するために使用され得る。フィードバックアルゴリズムは、アナログ又はデジタル回路技術を用いて実現されることができ、回路はマイクロプロセッサ、デジタルシグナルプロセッサ、フィールドプログラマブルゲートアレイのプロセッサなどを含むことができる。

【０３２５】

図３９の３番目のブロックは、デバイス共振器からのＡＣ電圧電力をＤＣ電圧に整流することができる整流器回路２４０４を示す。この構成において、整流器２４０４の出力は、電圧クランプ回路への入力することができる。電圧クランプ回路（図示せず）は、ＤＣ／ＤＣ変換器２４０８Ｄ又はＤＣ／ＡＣ変換器２４０８Ｄに対する入力において最大電圧を制限することができる。一般に、デバイスの位置および動作の大きなばらつきが許容され得ると同時に、最適な電力がデバイスに伝えられるように、大きな入力電圧のダイナミックレンジを有するＤＣ対ＤＣ／ＡＣ変換器を使用することが望ましいかもしれない。例えば、整流器の出力における電圧レベルは、デバイスの電源入力および負荷の特性が変化するにつれて、変動し、高レベルに到達する可能性がある。デバイスが異なる仕事（タスク）を実行する場合、電力需要が変動するかもしれない。変化する電力需要は、負荷特性が変化する際に整流器の出力において高い電圧を生じる可能性がある。同様に、デバイス及びデバイス共振器は、供給源の近くに及び供給源から更に離れて持って来られるので、デバイス共振器に伝えられる電力は変動し、整流器の出力において電圧レベルの変化を生じるかもしれない。電圧クランプ回路は、整流器回路からの電圧出力が、ＤＣ対ＤＣ／ＡＣ変換器の動作範囲内にある所定値を超えないようにすることができる。電圧クランプ回路を用いて、無線エネルギー伝送システムの動作モード及び範囲を拡張することができる。

【０３２６】

デバイスの電力および制御回路の次のブロックは、安定したＤＣ出力電圧を生成するこ

とができるＤＣ／ＤＣ変換器２４０８Ｄである。ＤＣ／ＤＣ変換器（コンバータ）は、ブーストコンバータ、バックコンバータ、ブーストバックコンバータ、セピック（Single ended primary inductance converter：ＳＥＰＩＣ）、又は特定の用途の要件に適した任意の他のＤＣ／ＤＣ接続形態（トポロジー）とすることができる。デバイスがＡＣ電力を必要とする場合、ＤＣ／ＡＣ変換器がＤＣ／ＤＣ変換器の代わりに使用され得るか、又はＤＣ／ＤＣ変換器の後に、ＤＣ／ＡＣ変換器が続く。デバイスが再充電可能バッテリーを含む場合、デバイス電力および制御回路の最後のブロックは、バッテリー駆動デバイスのバッテリーの充電およびメンテナンスを管理することができるバッテリー充電制御ユニットとすることができる。

【０３２７】

デバイス電力および制御回路２３０４は、マイクロコントローラ、デジタルシグナルプロセッサ、フィールドプログラマブルゲートアレイのプロセッサ、マイクロプロセッサ、又は任意の他のタイプのプロセッサのような、プロセッサ２４１０Ｄを含むことができる。プロセッサを用いて、電力および制御回路、及びデバイス共振器の状態または動作点を読み出す又は検出することができる。プロセッサは、回路、素子、構成要素、サブシステム、及び共振器の動作点を解釈する及び調整するためのアルゴリズムを実施することができる。ワイヤレスで電力供給されるデバイスのインピーダンスマッチング、共振器、ＤＣ／ＤＣ変換器、ＤＣ／ＡＣ変換器、バッテリー充電ユニット、整流器などを調整するために、プロセッサが使用され得る。

【０３２８】

プロセッサは、他のデバイス又は供給源への無線または有線のデータ通信リンクを有することができ、システムの動作点を調整するために使用され得るデータを送受信することができる。単一の周波数における又は周波数範囲にわたる電力信号、電圧信号、及び電流信号の任意の組合せは、デバイス回路の任意の点で監視され得る。これら信号は、アナログ技術またはデジタル技術、又は組み合わされたアナログ及びデジタル技術を用いて監視され得る。これら監視される信号は、フィードバックループで使用されることができ、又は様々な既知の態様でユーザに伝えられることができ、又は格納されて後で検索され得る。これら信号を用いて、システムのユーザに故障を警告する、性能を示す、又は音声、視覚、振動などを提供し、システムのユーザにフィードバックすることができる。

【０３２９】

図４０は、電力を単一又は複数のデバイスに供給するように構成された例示的な無線電力伝送システムの供給源電力および制御回路２３０２の構成要素を示す。例示的なシステムの供給源電力および制御回路２３０２は、家庭用コンセントのようなＡＣ電圧源２５０２、バッテリー、コンピュータのＵＳＢポート、太陽電池、別のワイヤレス電源などのようなＤＣ電圧源から電力供給され得る。供給源電力および制御回路２３０２は、例えば１０ｋＨｚより大きく且つ１００ＭＨｚ未満の周波数を有する交流電流で供給源共振器１０２Ｓを駆動することができる。供給源電力および制御回路２３０２は、１０ＧＨｚ未満の周波数の交流電流で供給源共振器１０２Ｓを駆動することができる。供給源電力および制御回路２３０２は、ＤＣ／ＤＣ変換器２４０８Ｓ、ＡＣ／ＤＣ変換器２４０８Ｓ、又はＡＣ／ＤＣ変換器２４０８Ｓ及びＤＣ／ＤＣ変換器２４０８Ｓ、発振器２５０８、電力増幅器２５０４、インピーダンスマッチング回路網２４０２Ｓなどを含むことができる。

【０３３０】

供給源電力および制御回路２３０２は、複数のＡＣ又はＤＣ電圧源２５０２から電力供給されることができ、必要な電圧レベルを回路構成要素に提供する、並びに供給源共振器を駆動するために使用され得る電力増幅器にＤＣ電圧を提供するために、ＡＣ／ＤＣ及びＤＣ／ＤＣ変換器２４０８Ｓを含むことができる。ＤＣ電圧は、調整可能とすることができ、電力増幅器の出力電力レベルを制御するために使用され得る。供給源は力率補正回路を含むことができる。

【０３３１】

発振器２５０８の出力は、供給源共振器１０２Ｓを駆動する電力増幅器２５０４に対す

る入力として使用され得る。発振器の周波数は、同調可能とすることができ、発振器信号の振幅は、電力増幅器からの出力電力レベルを制御するという意味で変更され得る。発振器信号の周波数、振幅、位相、波形、及びデューティサイクルは、アナログ回路により、デジタル回路により、又はアナログ及びデジタル回路の組合せにより制御され得る。制御回路は、マイクロプロセッサ、デジタルシグナルプロセッサ、フィールドプログラマブルゲートアレイのプロセッサなどのような、プロセッサ２４１０Ｓを含むことができる。

【０３３２】

供給源共振器およびデバイス共振器のインピーダンスマッチングのブロック２４０２は、電力を調整、並びに回路および供給源共振器およびデバイス共振器を制御するために使用され得る。例えば、これら回路のチューニングは、外部物体またはシステムの供給源とデバイスとの間の距離の変化に起因して、供給源共振器またはデバイス共振器のＱファクタＱの摂動を調整することができる。また、これら回路のチューニングは、動作環境を検出するために、１つ又は複数のデバイスに流れる電力を制御するために、無線電力回路網への電力を制御するために、危険又は故障モードの条件が検出された場合に電力を低減するなどのために使用され得る。

【０３３３】

電力信号、電圧信号、及び電流信号の任意の組合せは、供給源回路の任意の点で監視され得る。これら信号は、アナログ技術、又はデジタル技術、又は組み合わされたアナログ技術とデジタル技術を用いて監視され得る。これら監視される信号は、フィードバック回路で使用されることができ、又は様々な既知の態様でユーザに伝えられることができ、又は格納されて後で検索され得る。これら信号を用いて、ユーザにシステム故障を警告する、ユーザに安全性の限界値を超えていることを警告する、性能を示す、又は音声、視覚、振動などを提供し、システムのユーザにフィードバックすることができる。

【０３３４】

供給源電力および制御回路は、プロセッサを含むことができる。プロセッサを用いて、電力および制御回路、及び供給源共振器の状態または動作点を読み出すことができる。プロセッサは、回路、素子、構成要素、サブシステム、及び共振器の動作点を解釈する及び調整するためのアルゴリズムを実施することができる。供給源のインピーダンスマッチング、共振器、ＤＣ／ＤＣ変換器、ＡＣ／ＤＣ変換器、発振器、電力増幅器などを調整するために、プロセッサが使用され得る。システムのプロセッサ及び調整可能な構成要素は、周波数および／または時間電力多重化供給の方式を実現するために使用され得る。プロセッサは、デバイス及び他の供給源への無線または有線のデータ通信リンクを有することができ、システムの動作点を調整するために使用され得るデータを送受信することができる。

【０３３５】

詳細な及び特定の設計がこれらのブロック図に示されるが、当業者には明らかなように、コンポーネント及び構成要素の多くの様々な変形および再構成は、例示的なシステムの思想の範囲内にあることができる。回路の部分は、例証目的のために概略的に示され、当業者には明らかなように、各ブロックの構成要素は、より小さいブロックに更に分割、結合または共用されてもよい。同等の例において、電力および制御回路は、個々のディスクリート部品、又はより大きな集積回路から構成され得る。例えば、整流器回路は、ディスクリートのダイオードから構成されることができ、又は単一チップ上に集積されたダイオードを使用することができる。多数の他の回路および集積デバイスは、電力またはサイズ又はコスト又は用途のような設計基準に依存して、設計において置き換えられ得る。電力および制御回路の全部、又は供給源またはデバイス回路の任意の一部は、１つのチップへと集積化され得る。

【０３３６】

デバイス及び／又は供給源のインピーダンスマッチング回路網は、コンデンサ又はコンデンサの回路網、インダクタ又はインダクタの回路網、或いはコンデンサ、インダクタ、ダイオード、スイッチ、抵抗などの任意の組合せを含むことができる。インピーダンスマ

ッチング回路網の構成要素は、調整可能および可変とすることができ、システムの効率および動作点に影響を及ぼすように制御され得る。インピーダンスマッチングは、共振器の接続点を制御することにより、磁性材料の透磁率を調整することにより、バイアス磁場を制御することにより、励起の周波数を調整することなどにより、実行され得る。インピーダンスマッチングは、任意の数または組合せのバラクタ、バラクタのアレイ、切り換えられる素子、コンデンサバンク、切り換えられて調整可能な素子、逆バイアスダイオード、空隙コンデンサ、圧縮コンデンサ、ＢＺＴ電気調整コンデンサ、ＭＥＭＳ調整可能コンデンサ、電圧可変誘電体、トランス結合されたチューニング回路などを使用する又は含むことができる。可変構成要素は、機械的に調整され、熱的に調整され、電気的に調整され、圧電的に調整されるなどされ得る。インピーダンスマッチングの素子は、シリコンデバイス、窒化ガリウムデバイス、炭化ケイ素デバイスなどとすることができる。素子は、高い電流、高い電圧、高い電力、或いは電流、電圧および電力の任意の組合せに耐えるように選択され得る。素子は、高Ｑ素子となるように選択され得る。

【０３３７】

供給源のマッチング及びチューニングの計算は、デバイスに電力供給するＵＳＢポートを介して外部デバイスで実行され得る。デバイスは、コンピュータ、ＰＤＡ、又は他のコンピュータプラットフォームとすることができる。

【０３３８】

複数の電子消費者装置をワイヤレスで電力供給／再充電するために、デバイス共振器に結合された供給源共振器を使用した実演例は、以下に限定されないが、ラップトップコンピュータ、ＤＶＤプレイヤ、プロジェクタ、携帯電話、ディスプレイ、テレビ、プロジェクタ、デジタルピクチャフレーム、ライト（照明）、ＴＶ／ＤＶＤプレイヤ、携帯音楽プレイヤ、回路遮断器、ハンドヘルドツール、携帯情報端末、外部バッテリー充電器、マウス、キーボード、カメラ、能動負荷などを含む。様々なデバイスが単一のデバイス共振器から同時に電力供給され得る。デバイス共振器は、供給源共振器として同時に動作され得る。デバイス共振器に供給される電力は、その意図されたデバイス共振器に伝えられる前に、追加の共振器を通過することができる。

【０３３９】

監視、フィードバック及び制御

いわゆるポートパラメータ測定回路は、システムの特定の電力、電圧、及び電流信号を測定または監視することができ、プロセッサ又は制御回路は、それら測定値に基づいて特定の設定値または動作パラメータを調整することができる。これらポートパラメータの測定値に加えて、システムの全体にわたる電圧および電流信号の大きさ及び位相、並びに電力信号の大きさは、システム性能を測定または監視するためにアクセスされ得る。本明細書の全体にわたって言及される測定信号は、ポートパラメータの信号、並びに電圧信号、電流信号、電力信号などの任意の組合せとすることができる。これらパラメータは、アナログ又はデジタル信号を用いて測定されることができ、それらはサンプリング及び処理されることができ、それらは多数の既知のアナログ及びデジタル処理技術を用いてデジタル化または変換され得る。測定信号または監視信号は、フィードバック回路またはシステムで使用されて、共振器および／またはシステムの動作が制御され得る。一般に、本発明者は、これら監視信号または測定信号を、基準信号、又はポートパラメータ測定値または信号と呼ぶが、それらは時として、エラー信号、監視信号、フィードバック信号などとも呼ばれる。本発明者は、電圧制御コンデンサを駆動するために使用される電圧のような、回路素子を制御するために使用される信号を、制御信号と呼ぶ。

【０３４０】

場合によっては、回路素子が、供給源共振器およびデバイス共振器の規定の又は所定のインピーダンス値を達成するために調整され得る。別の場合では、インピーダンスは、デバイス共振器が電力消費装置（単数または複数）に接続された場合に、供給源共振器およびデバイス共振器の所望のインピーダンス値を達成するために調整され得る。別の場合では、インピーダンスは、共振周波数の変化、又は供給源共振器および／またはデバイス共

振器の移動に起因したインピーダンス又は電力レベルの変化、又は共振器の近傍における環境の変化（例えば、相互作用する材料または物体の移動など）を軽減するために調整され得る。別の場合では、供給源共振器およびデバイス共振器のインピーダンスは、異なるインピーダンス値に調整され得る。

【０３４１】

結合された共振器は、異なる材料から作成されることができ、異なる回路、構成要素、及び構造的な設計を含むことができ、又はそれらは同じとすることができる。結合された共振器は、性能監視および測定回路、信号処理および制御回路、又は測定および制御回路の組合せを含むことができる。高Ｑ磁気共振器の幾つか又は全ては、調整可能なインピーダンス回路を含むことができる。高Ｑ磁気共振器の幾つか又は全ては、自動的に制御される調整可能なインピーダンス回路を含むことができる。

【０３４２】

図４１は、共振器の特定のパラメータを測定するように構成されたポートパラメータ測定回路３８０２を有する磁気共振器を示す。ポートパラメータ測定回路は、構造体の入力インピーダンス、又は反射電力を測定することができる。ポートパラメータ測定回路は、供給源および／またはデバイス共振器の設計に含められることができ、Ｓパラメータ（散乱パラメータ）、Ｚパラメータ（インピーダンスパラメータ）、Ｙパラメータ（アドミタンスパラメータ）、Ｔパラメータ（伝送パラメータ）、Ｈパラメータ（ハイブリッドパラメータ）、ＡＢＣＤパラメータ（鎖、カスケード又は伝送パラメータ）などのような２ポート回路パラメータを測定するために使用され得る。これらパラメータは、様々なタイプの信号が印加される場合に、線形電気回路網の電気的挙動を記述するために使用され得る。

【０３４３】

異なる動作状況または結合状況の下で電気回路網を特徴付けるために、異なるパラメータが使用され得る。例えば、Ｓパラメータは、マッチングされた及びマッチングされていない負荷を測定するために使用され得る。更に、磁気共振器内の及び／又は供給源およびデバイス自体内の電圧信号および電流信号の大きさ及び位相は、システム性能の情報を生成するために、様々な点で監視され得る。この情報は、光、読み上げ、ビープ音、ノイズ、振動などのようなユーザインターフェースを介してシステムのユーザに提供され得るか、又はデジタル信号として提供され得るか、又はシステムのプロセッサに提供されてシステムの自動制御に使用され得る。この情報は、ログ記録され、格納されることができ、又はより高いレベルの監視および制御システムにより使用され得る。

【０３４４】

図４２は、磁気共振器の回路図を示し、この場合、調整可能なインピーダンス回路網は、電圧制御コンデンサ３９０２又はコンデンサ回路網で実現され得る。係る具現化形態は、プログラム可能電圧源３９０８などのような電気回路および／またはコンピュータプロセッサにより、調整され、チューニングされ、又は制御され得る。例えば、電圧制御コンデンサは、ポートパラメータ測定回路３８０２により取得され、測定分析および制御アルゴリズムサブシステム３９０４により処理されたデータに応じて調整され得る。基準信号は、ポートパラメータ測定回路または所望のシステム動作点からの偏移の程度を測定するように設計された他の監視回路から導出され得る。測定された基準信号は、システムの１つ又は幾つかの点における、及び単一の周波数または複数の周波数における電圧、電流、複素インピーダンス、反射係数、電力レベルなどを含むことができる。

【０３４５】

基準信号は、調整可能インピーダンスマッチング回路網の様々な構成要素の値を変更するための制御信号を生成することができる、測定値分析および制御アルゴリズムサブシステムモジュールに供給される。制御信号は、共振周波数および／または磁気共振器の入力インピーダンス、又は供給源により供給される電力レベル、又はデバイスにより引き出される電力レベルを変更して、電源／電力発生装置と電力ドレイン／負荷との間の所望の電力交換を達成することができる。

【０３４６】
調整アルゴリズムを用いて、磁気共振器の周波数および／またはインピーダンスを調整することができる。アルゴリズムは、システムの所望の動作点および出力補正からの偏移の程度に関連した基準信号、又は所望の動作点（単数または複数）の方へシステムを戻すためにシステムの可変または調整可能素子を制御するその偏移に関連した制御信号を取り込むことができる。共振器が無線電力送信システムにおいて電力を交換している間に、磁気共振器の基準信号が取得され得るか、又はそれらはシステム動作中に回路から切り換えられ得る。システムに対する補正は、閾値を超える際に、デジタル的に、アナログ方法などを用いて、連続的に、周期的に適用または実行され得る。

【０３４７】
図４３は、エンドツーエンド無線電力送信システムを示す。供給源およびデバイスは、ポート測定回路３８０２およびプロセッサ２４１０を含むことができる。「カプラー／スイッチ」と表示されたボックス４００２は、ポート測定回路３８０２が方向性カプラー又はスイッチにより共振器１０２に接続され、供給源共振器およびデバイス共振器の測定、調整、及び制御が、電力伝送の機能と共に、又は係る機能から離れて行われることを可能にすることを示す。

【０３４８】
ポートパラメータ測定および／または処理回路は、システムの幾つかの、任意の、又は全ての共振器と共に存在することができる。ポートパラメータ測定回路は、供給源／デバイス共振器の応答（即ち、システムの任意の２つのポート間の伝送および反射）を測定するために、電力送信信号の一部を利用することができ、又は周波数の範囲にわたって励起信号を利用することができ、振幅および／または位相情報を含むことができる。係る測定は、掃引信号周波数の信号で、又は多重周波数信号で達成され得る。共振器および無線電力送信システムを測定および監視するために使用される信号は、プロセッサ（単数または複数）及び標準入出力（Ｉ／Ｏ）回路により生成されることができ、係る標準入出力（Ｉ／Ｏ）回路は、デジタル／アナログ変換器（ＤＡＣ）、アナログ／デジタル変換器（ＡＤＣ）、増幅器、信号生成チップ、受動素子などを含む。測定は、ネットワーク分析器のような試験装置を用いて、又は専用回路を用いて達成され得る。測定された基準信号は、ＡＤＣによりデジタル化され、コンピュータ、マイクロプロセッサ、ＤＳＰチップ、ＡＳＩＣなどで実行する専用アルゴリズムを用いて処理され得る。測定された基準信号は、アナログ制御ループで処理されてもよい。

【０３４９】
測定回路は、Ｓパラメータ、Ｙパラメータ、Ｚパラメータ、Ｈパラメータ、Ｇパラメータ、Ｔパラメータ、ＡＢＣＤパラメータなどのような、２つのポートパラメータの任意の組を測定することができる。測定回路は、駆動回路および共振器回路の様々な点での電流および電圧信号、システムの対向する端部（即ちデバイスに向かって供給源共振器のマッチング回路（図４３の「ポート１」）を調査する及びその逆もまた同じ）における供給源共振器およびデバイス共振器のインピーダンス及び／又はアドミタンスの特性を表すために使用され得る。

【０３５０】
デバイスは、関連した信号および／またはポートパラメータを測定し、測定データを解釈し、供給源の動作とは無関係に、結合されたシステムを調査してインピーダンスを最適化するためにそのマッチング回路網を調整することができる。供給源は、関連したポートパラメータを測定し、測定データを解釈し、デバイスの動作とは無関係に、結合されたシステムを調査してインピーダンスを最適化するためにそのマッチング回路網を調整することができる。

【０３５１】
図４３は、無線電力送信システムにおける供給源およびデバイスのブロック図を示す。システムは、結合されたシステムでの性能を最適化するために、供給源共振器およびデバイス共振器の何れか又は双方のチューニング／マッチング回路網を能動的に調整する制御

アルゴリズムを実行するように構成され得る。ポート測定回路３８０２Ｓは、供給源の信号を測定し、これら信号をプロセッサ２４１０に伝える。プロセッサ２４１０は、測定された信号を性能最適化または安定化アルゴリズムで使用し、これらアルゴリズムの出力に基づいて制御信号を生成することができる。制御信号は、チューニング／インピーダンスマッチング回路２４０２Ｓの可変回路素子に印加されて、共振器の電力およびデバイスに対する結合のような、供給源の動作特性を調整することができる。制御信号は、電源または電力発生装置に印加されて、供給をオン又はオフする、電力レベルを増減する、供給信号を変調するなどすることができる。

【０３５２】

供給源とデバイスとの間で交換される電力は、様々な要因に依存する可能性がある。これら要因には、供給源およびデバイスの実効インピーダンス、供給源およびデバイスのＱ、供給源およびデバイスの共振周波数、供給源とデバイスとの間の距離、供給源およびデバイスの近傍の材料および物体の相互作用などが含まれ得る。ポート測定回路および処理アルゴリズムは、動的状態および定常状態の動作条件下で、一致協力して共振器パラメータを調整して、電力伝送を最大化する、電力伝送を一定に保持する、電力伝送を制御可能に調整するなどすることができる。

【０３５３】

システムの具現化形態における供給源およびデバイスの幾つか、又は全ては、ポート測定回路３８０２Ｓ及び処理２４１０能力を含む、又はそれらのどれも係るポート測定回路３８０２Ｓ及び処理２４１０能力を含まなくてもよい。図４４は、供給源１０２Ｓだけがポート測定回路３８０２及びプロセッサ２４１０Ｓを含む、エンドツーエンド無線電力送信システムを示す。この場合、デバイス共振器１０２Ｄの動作特性は、固定され得るか、又はアナログ制御回路により、且つプロセッサにより生成された制御信号を必要とせずに調整され得る。

【０３５４】

図４５は、エンドツーエンド無線電力送信システムを示す。供給源およびデバイスは、ポート測定回路３８０２を含むが、図４５のシステムにおいて、供給源のみがプロセッサ２４１０Ｓを含む。供給源およびデバイスは、互いに通信して、特定のシステムパラメータの調整は、供給源とデバイスとの間の無線通信回路４２０２を介してのように、ワイヤレスで伝えられた制御信号に応答することができる。無線通信チャネル４２０４は、無線電力伝送チャネル４２０８から分離され得るか、又は同じとすることができる。即ち、電力交換に使用される共振器１０２は、情報交換にも使用され得る。場合によっては、情報は、構成要素、供給源またはデバイス回路を変調し、ポートパラメータ又は他の監視装置でその変化を検知することにより交換され得る。

【０３５５】

供給源のみがプロセッサ２４１０を含む具現化形態は、供給源がチューニング及び調整の全ての「決定」を処理し、デバイス（単数または複数）に制御信号を単に戻すように伝えることができるマルチデバイスシステムに有用であるかもしれない。この具現化形態は、デバイスのプロセッサの必要性を取り除き、又は係るプロセッサの必要な機能を低減することができるので、デバイスをより小さく且つより安くすることができる。各デバイスにおける各ポート測定からのデータセットの一部または全部は、分析のために供給源のマイクロプロセッサに返信されることができ、制御命令は、デバイスに返信され得る。これら通信は、無線通信とすることができる。

【０３５６】

図４６は、エンドツーエンド無線電力送信システムを示す。この例において、供給源だけが、ポート測定回路３８０２及びプロセッサ２４１０Ｓを含む。供給源およびデバイスは、無線通信回路４２０２を介してのように、互いに通信することができ、特定のシステムパラメータの調整は、供給源とデバイスとの間でワイヤレスで伝えられた制御信号に応答することができる。

【０３５７】

図４７は、周波数およびインピーダンスがプロセッサ又はコンピュータを用いて自動的に調整され得る、結合された電磁共振器１０２を示す。供給源共振器およびデバイス共振器の共振周波数のチューニング及び連続したインピーダンス調整は、図４７のＣ１、Ｃ２、Ｃ３として示されたコンデンサ回路網内に包含された逆バイアスダイオード、ショットキーダイオード、及び／又はバラクタ素子で実現され得る。本明細書で構築および実証された、及び説明された回路接続形態は、例示であり、自動システムチューニング及び制御の説明を制限することは決して意図されていない。他の回路接続形態が、本明細書で説明された測定および制御のアーキテクチャで利用され得る。

【０３５８】

デバイス共振器および供給源共振器のインピーダンス及び共振周波数は、Lab View（登録商標）４４０４のようなコントローラで実現された、ネットワーク分析器４４０２Ａ、４４０２Ｂで、又は上述した他の手段により測定され得る。測定回路または装置は、フィードバックアルゴリズムを実現する、及びプログラム可能ＤＣ電圧源を介して周波数およびインピーダンスを動的に調整するコンピュータ又はプロセッサにデータを出力することができる。

【０３５９】

一構成において、逆バイアスされたダイオード（ショットキー、半導体接合部など）は、非常に少ないＤＣ電流を引き出す調整可能コンデンサを実現するために使用され、大きな直列出力抵抗を有する増幅器により逆バイアスされ得る。この具現化形態は、磁気共振器の非常に高いＱを維持しながら、ＤＣ制御信号が共振器回路の制御可能な回路素子に直接的に印加されることを可能にすることができる。

【０３６０】

図４７に示されるように、必要なＤＣバイアス電圧が異なる場合に、Ｃ２バイアス信号は、ＤＣ阻止コンデンサでＣ１及び／又はＣ３バイアス信号から絶縁され得る。バイアス増幅器の出力は、バイアス増幅器からのＲＦ電圧を絶縁するために回路接地にバイパスされ、基本でないＲＦ電圧が共振器へ導入されることを避けることができる。幾つかのコンデンサに対する逆バイアス電圧は、代わりに共振器自体の誘導性素子を介して印加されてもよく、その理由は誘導性素子がＤＣにおいて短絡として働くからである。

【０３６１】

ポートパラメータ測定回路は、共振周波数、入力インピーダンス、共振器により蓄積または捕捉されるエネルギー、或いは供給源により伝えられる又はデバイス負荷に伝えられる電力を自動的に調整するために使用されるフィードバック又は制御システムの一部として、プロセッサ（任意の必要なＡＤＣ及びＤＡＣを含む）と信号を交換することができる。また、プロセッサは、磁気共振器内の、又は磁気共振器に取り付けられたチューニング回路または調整回路に制御信号を送信することができる。

【０３６２】

調整可能なコンデンサとしてバラクタ又はダイオードを利用する場合、チューニング／マッチング回路において高い逆バイアス電圧で動作する調整可能なコンデンサに並列および直列に固定コンデンサを配置することが有利であるかもしれない。この構成は、回路およびシステムの安定性の改善、及び調整可能なコンデンサの動作電圧を最適化することにより電力処理能力の改善をもたらすことができる。

【０３６３】

バラクタ又は他の逆バイアスダイオードは、電圧制御コンデンサとして使用され得る。バラクタのアレイは、より高い電圧適合性または異なるキャパシタンスが単一のバラクタ構成要素のもの以外に必要とされる場合に、使用され得る。バラクタは、直列に、及び並列に接続されたＮ×Ｍアレイで構成され、アレイの個々のバラクタとは異なる特性を有する単一の２端子構成要素として扱われ得る。例えば、各行の構成要素が並列に接続され、各列の構成要素が直列に接続された同等のバラクタからなるＮ×Ｍアレイは、アレイにおける任意の単一のバラクタと同じキャパシタンスを有する２端子デバイスとして使用され得るが、電圧適合性は、アレイにおける単一のバラクタのＮ倍である。アレイにおける個

々のバラクタのパラメータに関するばらつき及び差異に応じて、抵抗、インダクタなどからなる追加のバイアス回路が必要とされるかもしれない。磁気共振器の用途に適することができる、バイアスされていないバラクタの４×４アレイ４５０２の回路図が、図４８に示される。

【０３６４】

システム性能の更なる改善は、調整可能な（バラクタ／ダイオード／コンデンサ）素子と並列に及び／又は直列に配置される固定値のコンデンサ（単数または複数）の慎重な選択により実現され得る。回路の出入りを切り換えられる複数の固定コンデンサは、試験、開発、及び稼働中の無線電力伝送システムで遭遇するかもしれない共振器のＱ、インピーダンス、共振周波数、電力レベル、結合強度などの変化を補償することができる。切り換えられるコンデンサバンク及び他の切り換えられる素子バンクは、システム設計により必要とされる動作周波数およびインピーダンス値に収束することを確実にするために使用され得る。

【０３６５】

分離された及び結合された磁気共振器の例示的な制御アルゴリズムは、図４７に示された回路およびシステムの素子に関して説明され得る。制御アルゴリズムは最初、供給源共振器およびデバイス共振器のループのそれぞれを「分離して」、即ちシステムの他の共振器がシステムから「短絡された」又は「取り外された」状態で、調整する。事実上、共振器は、例えばＣ１及び／又はＣ３の値を最大化することにより、非常に低い周波数で共振させることにより、「短絡され」得る。このステップは、共振器間の結合を実質的に低減し、それにより特定の周波数およびインピーダンスにおいてシステムを単一の共振器に実質的に低減する。

【０３６６】

分離して磁気共振器をチューニングすることは、ポートパラメータ測定回路により測定された値がそれらの所定の相対値、計算された相対値、または測定された相対値になるまで、チューニング及びマッチング回路の調整可能な素子を変更することを含む。ポートパラメータ測定回路により測定された量の所望の値は、所望のマッチングインピーダンス、周波数、強い結合パラメータなどに基づいて選択され得る。以下で開示される例示的なアルゴリズムの場合、ポートパラメータ測定回路は、周波数の範囲にわたってＳパラメータを測定する。共振器の特性を表すために使用される周波数の範囲は、得られるシステム性能情報と計算／測定速度との間の折衷したものとすることができる。以下で説明されるアルゴリズムの場合、周波数範囲は、動作共振周波数の約±２０％とすることができる。

【０３６７】

各分離された共振器は、以下のようにチューニングされ得る。最初に、調整されない共振器を短絡する。次に、特徴付けられている及び調整されている共振器のＣ１、Ｃ２、及びＣ３を最小化する。ほとんどの場合、Ｃ１、Ｃ２、及びＣ３に並列に接続された固定回路素子が存在し、そのためこのステップはキャパシタンス値をゼロまで低減しない。次に、上述した測定周波数の範囲の任意の周波数において、共振器のインピーダンスが「目標（ターゲット）」の実インピーダンスにマッチングされるまで、Ｃ２を増加させることを開始する。最初の「目標」インピーダンスは、結合されたシステムの予想される動作インピーダンス未満とすることができる。

【０３６８】

Ｃ２は、最初の「目標」インピーダンスが測定範囲の周波数に対して実現されるまで調整され得る。次いで、Ｃ１及び／又はＣ３は、ループが所望の動作周波数で共振するまで調整され得る。

【０３６９】

各共振器は、上記のアルゴリズムに従って調整され得る。分離して各共振器をチューニングした後、第２のフィードバックアルゴリズムが適用されて、結合されたシステムにおける無線送信電力に対して共振周波数および／または入力インピーダンスが最適化され得る。

【０３７０】

結合されたシステムにおける各共振器のＣ１及び／又はＣ２及び／又はＣ３に対する必要な調整は、図４３に示された何れかの「ポート（単数または複数）」及び／又は双方の「ポート（単数または複数）」から入力インピーダンスの実数部および虚数部の値を測定および処理することにより求められ得る。結合された共振器の場合、１つの共振器の入力インピーダンスの変更は、他の共振器の入力インピーダンスを変更することができる。制御および追跡アルゴリズムは、１つのポートの測定値に基づいて所望の動作点までそのポートを調整することができ、次いで他のポートの測定値に基づいて係る他のポートを調整することができる。これらステップは、両側が所望の動作点に収束するまで繰り返され得る。

【０３７１】

Ｓパラメータが供給源のポート及びデバイスのポートで測定され、次の一連の測定および調整が行われ得る。以下の説明において、$Ｚ_0$は入力インピーダンスであり、目標インピーダンスとすることができる。場合によっては、$Ｚ_0$は５０オーム、又はほぼ５０オームである。$Ｚ_1$及び$Ｚ_2$は、$Ｚ_0$と同じ値とすることができるか、又は$Ｚ_0$と異なることができる中間インピーダンス値である。Ｒｅ｛値｝は、値の実数部を意味し、Ｉｍ｛値｝は値の虚数部を意味する。

【０３７２】

２つの結合された共振器の入力インピーダンス及び共振周波数を調整するために使用され得るアルゴリズムは以下に記載される。即ち、

1) Adjust each resonator "in isolation" as described above.

2) Adjust source C1/C3 until, at ω_o , Re{S11} = (Z_1 +/- ε_{Re}) as follows:

  - If Re{S11 @ ω_o } > (Z_1 + ε_{Re}), decrease C1/C3. If Re{S11 @ ω_o } < (Z_0 - ε_{Re}), increase C1/C3.

3) Adjust source C2 until, at ω_o, Im{S11} = (+/- ε_{Im}) as follows:

  - If Im{S11 @ ω_o } > ε_{Im}, decrease C2. If Im{S11 @ ω_o } < $-\varepsilon_{Im}$, increase C2.

4) Adjust device C1/C3 until, at ω_0, Re{S22} = (Z_2 +/- ε_{Re}) as follows:

  - If Re{S22 @ ω_o } > (Z_2 + ε_{Re}), decrease C1/C3. If Re{S22 @ ω_o} < (Z_0 - ε_{Re}), increase C1/C3.

5) Adjust device C2 until, at ω_o, Im{S22} = 0 as follows:

  - If Im{S22 @ ω_o } > ε_{Im}, decrease C2. If Im{S22 @ ω_o } < $-\varepsilon_{Im}$, increase C2。

【０３７３】

本発明者は、（Re{S11}、Im{S11}）及び（Re{S22}、Im{S22}）が、ω_0において、（（$Ｚ_0$＋／－ε_{Re}）、（＋／－ε_{Im}））に収束するまで、ステップ１～４を繰り返すことにより、実際に役立つシステムを達成した。この場合、$Ｚ_0$は所望のマッチングインピーダンスであり、ω_0は所望の動作周波数である。ここで、ε_{Im}は、ω_0において０の所望の値からの虚数部の最大の偏移（偏差）を表し、ε_{Re}は$Ｚ_0$の所望の値からの実数部の最大の偏移を表す。理解されるべきは、ε_{Im}とε_{Re}は、システム性能の可能なコスト（効率）において、収束までのステップの数を増減するために調整され得る。また、理解されるべきは、ステップ１～４は様々なシーケンスで、及び上記で概説されたもの以外の様々な方法（即ち、最初に供給源の虚数部を調整し、次いで供給源の実数部、又は最初にデバイスの実数部を調整し、次いでデバイスの虚数部など）で実行され得る。中間インピーダンス$Ｚ_1$及び$Ｚ_2$は、収束するために必要なステップの数を低減するために、ステップ１～４の間に調整され得る。所望の又は目標のインピーダンス値は、複素数とすることができ、時間的に、又は異なる動作状況の下で変化してもよい。

【０３７４】

ステップ１～４は、任意の順序で、任意の組み合わせで、及び任意の回数で実行され得る。説明した上記のアルゴリズムに関して、ステップ又は説明された具現化形態に対する

変形形態は、当業者には明らかになるであろう。上記で概説されたアルゴリズムは、任意の同等の線形回路網のポートパラメータ測定（即ち、Ｚパラメータ、Ｙパラメータ、Ｔパラメータ、Ｈパラメータ、ＡＢＣＤパラメータなど）で、又は上述された他の監視信号でもって実現されることができ、同様に代案としてインピーダンス又はアドミタンスが、同じ結果を導出するために線形回路を分析するために使用され得る。

【０３７５】

共振器は、供給源共振器とデバイス共振器との間の相互インダクタンスＭ（結合）の変化により生じる、「負荷をかけられた（ローデッド）」抵抗Ｒｓ及びＲｄの変化に起因して、再チューニングされる必要があるかもしれない。誘導性素子自体のインダクタンスＬｓ及びＬｄの変化は、前述したように外部物体の影響により生じる可能性があり、また補償を必要とするかもしれない。係る変動は、上述された調整アルゴリズムにより軽減され得る。

【０３７６】

方向性カプラー又はスイッチを用いて、ポートパラメータ測定回路を供給源共振器およびチューニング／調整回路に接続することができる。ポートパラメータ測定回路は、磁気共振器の特性を測定することができる限り、それは無線電力送信システムの交換電力であり、又はポートパラメータ測定回路はシステム動作中に回路から外へ切り換えられ得る。ポートパラメータ測定回路はパラメータを測定することができ、プロセッサは、起動時に、又は特定の間隔で、或いは特定のシステム動作パラメータの変化に応じて、磁気共振器の特定の調整可能な素子を制御することができる。

【０３７７】

無線電力送信システムは、供給源共振器およびデバイス共振器のインピーダンス及び／又は共振周波数を変更または調整するための回路を含むことができる。留意すべきは、チューニング回路が供給源共振器およびデバイス共振器に示されているが、回路は代わりに、供給源共振器またはデバイス共振器のみに含まれてもよく、又は回路は、供給源共振器および／またはデバイス共振器の幾つかのみに含まれてもよい。また、留意すべきは、本発明者は、回路が共振器のインピーダンス及び／又は共振周波数を「チューニング」すると言っているが、このチューニング動作は、構造体のインダクタンス又はキャパシタンスのような様々な電気パラメータが変動していることを単に意味する。場合によっては、これらパラメータは、特定の所定値を達成するために変更されることができ、別の場合では、それらは、制御アルゴリズムに応答して、又は変化している目標の性能値を安定化するために変更され得る。場合によっては、パラメータは、環境の温度、領域内の他の供給源またはデバイスの温度などの関数として変更される。

【０３７８】

応用形態

各列挙される応用形態に関して、当業者には理解されるように、無線電力送信を可能にするために使用される共振器構造体が、給電している又は電力供給されている物体と接続または一体化され得る様々な態様が存在する。共振器は、供給源の物体およびデバイスの物体から物理的に分離され得る。共振器は、従来の誘導性技術を用いて、又は例えばワイヤ又はケーブルを用いた直接的な電気接続を介して、物体に給電する又は物体から電力を取り出すことができる。電気接続は、共振器出力から物体のＡＣ又はＤＣ電力入力ポートまでとすることができる。電気接続は、物体の出力電力ポートから共振器ユニットまでとすることができる。

【０３７９】

図４９は、電源から物理的に分離されている供給源共振器４９０４、及びこの例においてラップトップコンピュータであるデバイス４９００から物理的に分離されているデバイス共振器４９０２を示す。電力は、供給源共振器に供給されることができ、電力は、電気接続により、直接的にデバイス共振器から引き出され得る。当業者ならば参照により組み込まれる資料から理解されるように、上記の共振器の形状、サイズ、材料組成、構成、位置、及び位置関係が、制限しない例として提供されており、これらパラメータの任意また

は全てにおける幅広いバリエーションは、様々な応用形態に関して開示された技術によりサポートされ得る。

【０３８０】

制限せずに、ラップトップコンピュータの例を続けると、デバイス共振器は、それが電力供給する又は充電するデバイスに物理的に接続され得る。例えば、図５０の（ａ）及び（ｂ）に示されるように、デバイス共振器５００２は、ａ）デバイス５０００ハウジングに組み込まれ得るか、又はｂ）それはアダプターにより取り付けられ得る。共振器５００２は、デバイス上で見ることができる（図５０の（ｂ）～（ｄ））か、又は見ることができない（図５０の（ａ））。共振器はデバイスに固定され得るか、デバイスに組み込まれ得るか、デバイスにプラグ接続されるなどされ得る。

【０３８１】

供給源共振器は、システムに電力を供給する供給源に物理的に接続され得る。デバイス及びデバイス共振器に関して上述されたように、共振器が電源に取り付けられ得る、接続され得る、又は一体化され得る様々な態様が存在する。当業者ならば理解されるように、共振器が無線電力送信システムに組み込まれることができ、供給源およびデバイスが類似した又は異なる組み込み技術を利用することができる様々な態様が存在する。

【０３８２】

制限せずに、ラップトップコンピュータの例を続けると、ラップトップコンピュータは、無線電力送信システムにより電力供給、充電、又は再充電され得る。供給源共振器は無線電力を供給するために使用され、デバイス共振器は無線電力を捕捉するために使用され得る。デバイス共振器５００２は、図５０の（ｄ）に示されるように画面（ディスプレイ）の縁部に、及び／又は図５０の（ｃ）に示されるようにラップトップコンピュータの基部に組み込まれ得る。供給源共振器５００２は、ラップトップコンピュータの基部に組み込まれることができ、デバイス共振器は画面の縁部に組み込まれ得る。また又は代わりとして、共振器は、電源および／またはラップトップコンピュータに取り付けられ得る。また又は代わりとして、供給源共振器およびデバイス共振器は、電源およびラップトップコンピュータから物理的に分離され、ケーブルにより電気接続され得る。また又は代わりとして、供給源共振器およびデバイス共振器は、電源およびラップトップコンピュータから物理的に分離され、従来の誘導的技術を用いて電気結合され得る。当業者には理解されるように、前述の例は、ラップトップコンピュータに対する無線電力送信に関係するが、この応用形態に関して開示された方法およびシステムは、他の電気または電子デバイスと使用するために適切に適合され得る。一般に、供給源共振器は、供給源の外部にあり、デバイスに電力を供給するデバイス共振器に電力を供給することができ、又は供給源共振器は供給源に接続され、デバイスの一部に電力を供給するデバイス共振器に電力を供給することができ、又は供給源共振器は、供給源の内部にあり、デバイスの一部に電力を供給するデバイス共振器に電力を供給することができ、並びにこれらの任意の組合せである。

【０３８３】

本明細書で開示されたシステム又は方法は、以下に限定されないが、電話、携帯電話、コードレス電話、スマートフォン、ＰＤＡ、オーディオ装置、音楽プレイヤ、ＭＰ３プレイヤ、ラジオ、携帯型ラジオ及びプレイヤ、ワイヤレスヘッドフォン、ワイヤレスヘッドセット、コンピュータ、ラップトップコンピュータ、ワイヤレスキーボード、ワイヤレスマウス、テレビ、ディスプレイ、平面ディスプレイ、コンピュータディスプレイ、家具に埋め込まれたディスプレイ、デジタルピクチャフレーム、電子書籍（例えば、Kindle（登録商標）、電子インク書籍、雑誌など）、遠隔制御ユニット（コントローラ、ゲームコントローラ、リモコン、クリッカ等とも呼ばれ、テレビ、ビデオゲーム、ディスプレイ、コンピュータ、視聴覚装置、照明などのような複数の電子機器装置の遠隔制御のために使用される）、照明装置、冷却装置、空気循環装置、浄化装置、補聴器、動力工具、セキュリティシステム、アラーム、ベル、閃光灯、サイレン、センサ、拡声器、電子ロック、電子キーパッド、照明スイッチ、他の電気スイッチなどのような電気または電子デバイスに電力を提供することができる。ここで、用語の電子ロックは、機械的なキーロックの代わり

にドアに配置される電子的に動作する（例えば、電子コンボキー、磁気カード、ＲＦＩＤカードなどを用いて）ドアロックを示すために使用される。係るロックは、バッテリー動作される場合が多く、バッテリーが消耗した場合に、ロックが動作を止める可能性の危険にさらされ、ユーザが締め出されたままになる。これは、バッテリーが、本明細書で説明されたような無線電力送信の具現化形態により充電または完全に置き換えられる場合に、回避され得る。

【０３８４】

ここで、用語の照明スイッチ（又は他の電気スイッチ）は、部屋の別の部分のデバイス（例えば、天井の中央にある照明器具）をオン／オフする、部屋の一部の任意のスイッチ（例えば、部屋の壁上の）を示すことが意図されている。係るスイッチを直接的な接続により設置するために、デバイスからスイッチまでどこでもワイヤを延ばす必要がある。ひとたび係るスイッチが特定の場所に設置されると、それは移動するのが非常に困難である。代わりに、「ワイヤレススイッチ」を想定することができ、この場合、「ワイヤレス」は、スイッチング（オン／オフ）コマンドがワイヤレスで伝えられるが、係るスイッチが従来のように、動作のために電池（バッテリー）を必要とすることを意味する。一般に、家の周りに非常に多くの電池式スイッチを有することは、これら多くの電池が定期的に交換される必要があるので、実際的でない。そのため、ワイヤレス通信スイッチがワイヤレスで電力供給もされる場合、ワイヤレス通信スイッチが非常に好都合である。例えば、電池式である通信用ワイヤレス呼び鈴が既に存在するが、それらの電池を定期的に交換することが依然として必要とされている。遠隔の呼び鈴ボタンは、完全にワイヤレスになるように作成されることができ、この場合、電池を再び交換することは永久に必要ない。留意すべきは、ここで、用語「コードレス」又は「ワイヤレス（無線）」又は「通信用ワイヤレス」は、デバイスと別の電気コンポーネント（例えば、コードレス電話の基地局、ワイヤレスキーボードのコンピュータなど）との間にコードレス又はワイヤレス通信設備が存在することを示すために使用される。当業者ならば認識されるように、任意の電気または電子機器装置は、ワイヤレス通信設備を含み、本明細書で説明されたシステム及び方法を用いて、当該装置に無線電力送信を追加することができる。本明細書で説明されたように、電気または電子機器装置への電力は、外部または内部供給源共振器から、当該装置または当該装置の一部に伝えられ得る。無線電力送信は、供給源共振器のほぼ近傍に入る装置（デバイス）のバッテリー（電池）を充電および／または交換する必要性を大幅に低減することができ、これによりバッテリーに関連することが多い休止時間、コスト、及び廃棄の問題が低減され得る。

【０３８５】

本明細書で説明されたシステム及び方法は、有線の電源またはバッテリーを必要とせずに、照明に電力を供給することができる。即ち、本明細書で説明されたシステム及び方法は、任意の電源に対する有線接続なしで電力を照明に供給することができ、１／４メートル、１メートル、３メートルなどの距離にわたってのように、中距離にわたって非放射的に照明にエネルギーを供給することができる。本明細書で使用される「照明」は、白熱電球、蛍光電球ランプ、ハロゲンランプ、ガス放電灯、蛍光灯、ネオン放電灯、高輝度放電ランプ、ナトリウム灯、水銀灯、エレクトロルミネセントランプ、発光ダイオード（ＬＥＤ）ランプなどのような光源自体、又は電気スタンド、フロアランプ、天井灯、レール式可動照明、埋め込み式ライトの器具のような照明器具の一部としての照明、又はライト／天井送風器具、及び照明付き額縁などのような他の機能と一体化された照明器具を意味する。そのようなものとして、本明細書で説明されたシステム及び方法は、例えば電気配線の設置を最小限にし、ユーザが有線の電力の供給源に最小限に関連して照明を配置または取り付けることを可能にすることにより、照明を設置するための複雑性を低減することができる。例えば、照明は、供給源共振器の近傍のどこにでも配置されることができ、この場合、供給源共振器は、部屋の上の床に（例えば、特に部屋の上が屋根裏部屋である場合に天井灯の場合でのように）、隣の部屋の壁に、部屋の下の天井に（例えば、フロアランプの場合のように）、又は本明細書で説明されたように部屋内の装置に又は部屋のインフ

ラになどのような、照明の場所に対して複数の異なる場所に取り付けられ得る。例えば、ライト／天井送風器の組合せは、主寝室に設置されることが多く、主寝室はその上に屋根裏部屋を有することが多い。この場合、ユーザは、例えばライト／天井送風器の組合せを単に天井に取り付け、取り付けられた器具の上の屋根裏部屋に供給源コイル（家の有線ＡＣ電源にプラグ接続された）を配置することにより、主寝室にライト／天井送風器の組合せをより容易に設置することができる。別の例において、照明は、フラッドライト又は保安灯のような外部ライトとすることができ、供給源共振器は、構造体の内部に取り付けられる。この照明の設置の態様は特に、家を賃借するユーザに有用であり、その理由は、今ユーザが新たな電気配線を設置する必要なしに照明および係る他の電気装置を取り付けることができるからである。また、照明の制御は、本明細書で説明されたような近接場通信により、又は従来のワイヤレス通信方法により伝えられ得る。

【０３８６】

本明細書で説明されたシステム及び方法は、デバイスの構成要素に組み込まれた、又はデバイスの構成要素の外側にあるデバイス共振器に供給源共振器から電力を供給することができ、そのため、デバイスの構成要素は、従来の電気構成要素または取付具とすることができる。例えば、天井灯は、デバイス共振器が取付具に組み込まれた状態で設計または係る状態に改造されることができ、或いは天井灯は、従来の配線された取付具とすることができ、デバイス共振器を備えた別個の電気設備にプラグ接続され得る。一例において、電気設備は、例えば部屋の上（例えば、屋根裏部屋）の床に配置された供給源共振器から無線電力を受け取るためにデバイス共振器を有するように設計されたワイヤレス接続箱とすることができ、係る箱は、デバイス共振器から電力供給される多数の従来のコンセントを含む。これで、天井の上に取り付けられたワイヤレス接続箱は、天井の従来の配線された電気構成要素（例えば、天井灯、レール式可動照明、天井ファン）に電力を供給することができる。かくして、天井灯は、建物のインフラを介してワイヤを延ばす必要なしに、天井に取り付けられ得る。従来のコンセント接続箱用のこのタイプのデバイス共振器は、建物の室内または外装のために設計される、携帯型にするために設計される、車両のために作成されることなどを含む、複数の応用形態で使用され得る。無線電力は、木材、板壁、断熱材、ガラス、れんが、石、コンクリートなどのような一般的な建築材料を通って伝送され得る。低減された設置コスト、再構成の可能性、及び増大した適用の柔軟性の利点は、従来の配線による設置よりも優れた顕著な利点をユーザに提供することができる。従来のコンセント接続箱用のデバイス共振器は、効率的な電力伝送を実現するのに必要な特定の周波数を線間電圧に変換する電源電子機器、高い周波数のＡＣを使用可能な電圧および周波数（ＡＣ及び／又はＤＣ）に変換することができる電力捕捉電子機器、電力捕捉装置と電力出力を同期させ且つ一貫性、安全性、及び最大の効率的な電力伝送などを保証する制御装置のような、デバイス共振器から従来のコンセントへの電力伝送を容易にするための複数の電気構成要素を含むことができる。

【０３８７】

本明細書で説明されたシステム及び方法は、屋外にあり雨にさらされる、プール／サウナ／シャワーにおいて、海事用途において、気密封止された構成要素内において、防爆室内において、屋外看板に、揮発性な環境における苛酷な産業環境（例えば、穀物サイロ又は製パン所においてのような、揮発性蒸気または空中の有機体から）などのような、濡れる、苛酷な、管理されるなどの環境において動作する照明または電気構成要素に利点を提供することができる。例えば、プールの水位の下に取り付けられた照明は一般に、配線をつなぐことが困難であり、外部ワイヤの必要性にも関わらず、水で密閉される必要がある。しかし、本明細書で開示された原理を使用するプール照明は、外部ワイヤが必要とされないので、より容易に水で密閉され得る。別の例において、揮発性蒸気を含むような、防爆室は、気密封止される必要があることのみならず、全ての電気コンタクト（火花を生じる可能性がある）もシールされる必要がある。やはり、本明細書で開示された原理は、係る応用形態に対してシールされた電気構成要素を供給するための好都合な方法を提供することができる。

【０３８８】

本明細書で説明されたシステム及び方法は、遠隔の手持ち式ゲームコントローラのような、ゲームコントローラの応用形態に電力を供給することができる。これらゲームコントローラは従来、バッテリーだけにより電力供給されており、この場合、延長されたゲームプレイ中のように、バッテリー、バッテリーパック、再充電可能バッテリーなどの頻繁な交換により生じるゲームコントローラの使用状態および電力プロファイルは、ゲームコントローラに対する一貫した使用に理想的でないかもしれない。デバイス共振器がゲームコントローラ内に配置されることができ、電源に接続された供給源共振器が近傍に配置され得る。更に、ゲームコントローラ内のデバイス共振器は、バッテリーを使用せずにゲームコントローラの電子機器に直接的に電力を供給し、又はバッテリー、バッテリーパック、再充電可能なバッテリーなどに電力を供給し、次いでゲームコントローラの電子機器に電力が供給されるなどである。ゲームコントローラは、複数のバッテリーパックを利用することができ、この場合、各バッテリーパックは、デバイス共振器を備え、かくしてゲームコントローラにプラグ接続されるか否かに関わらず、供給源共振器の近傍にいる間に常に再充電され得る。供給源共振器は、ゲームの主ゲームコントローラ設備に存在することができ、この場合、主ゲームコントローラ設備および供給源共振器は、ＡＣ「家庭用」電力から電力を供給される、又は供給源共振器は、「延長コード」に組み込まれた供給源共振器においてのような、ＡＣ電力を発生する延長設備に存在する、又は供給源共振器はゲームの椅子に存在し、係る椅子は、壁のＡＣにプラグ接続される、主ゲームコントローラ設備にプラグ接続される、ゲームの椅子のバッテリーパックにより電力供給されるなどの少なくとも１つである。供給源共振器は、本明細書で説明された任意の構成に配置および実現され得る。

【０３８９】

本明細書で説明されたシステム及び方法は、他のバッテリーパックと取り換え可能なバッテリーパックのような、バッテリーパックにデバイス共振器を組み込むことができる。例えば、幾つかの携帯機器は、ユーザが複数の取り換え可能なバッテリーパックを使用するために手元に持っている必要がある、又は動力工具、携帯型ライト、遠隔制御車両などのように、ユーザが供給源共振器の範囲外でデバイスを動作させて、動作を続けるために追加のバッテリーパックを必要とするような、高速で電気エネルギーを使い尽くす可能性がある。本明細書で開示された原理を使用することにより、使用中および範囲内にある間に、バッテリーパックが再充電されることを可能にするデバイス共振器の方法が提供されることのみならず、供給源共振器の範囲内に配置されて、現在使用中でないバッテリーパックの再充電の方法も提供する。このように、使用されているバッテリーパックの充電を、ユーザが使い切る場合に、バッテリーパックは常に、すぐに使用できる。例えば、ユーザは、ワイヤレス動力工具で作業していることができ、この場合、電流要件は、供給源共振器からの直接的な電力供給を通じて実現され得るものよりも大きい可能性がある。この場合、本明細書で説明されたシステム及び方法が、範囲内にある間に使用中のバッテリーパックに充電電力を提供することができるという事実にも関わらず、電力使用率が再充電率を超えているので、バッテリーパックを依然として使い切る可能性がある。更に、ユーザは、単に範囲の内外に移動することができ、又はデバイスを使用している間に、完全に範囲の外にいるかもしれない。しかしながら、ユーザは、使用中でない間に再充電される、追加のバッテリーパックを供給源共振器の近傍に配置しておくことができ、係る追加のバッテリーパックは現在、使用のために十分に充電されている。別の例において、ユーザは、供給源共振器の近傍から離れて動力工具で作業していることができるが、携帯型供給源共振器または延長コード供給源共振器を有する部屋に、ユーザの車両に、ユーザの工具箱などにのように、充電するための追加のバッテリーパックを供給源共振器の近傍に残しておくことができる。このように、ユーザは、今後の利用のためにバッテリーパックにプラグ接続する時間を取ること及び／又は係るプラグ接続することを覚えていることを心配する必要はない。ユーザは、使用済みバッテリーパックを充電済みバッテリーパックに交換し、使用済みバッテリーパックを再充電のために供給源共振器の近傍に配置するだけで

よい。デバイス共振器は、既知のバッテリーのフォームファクタ及び底面積を有する筐体に組み込まれ、既知のデバイス及び用途における従来の化学電池に取って代わることができる。例えば、デバイス共振器は、単三バッテリー、単四バッテリー、単一バッテリー、９Ｖバッテリー、ラップトップコンピュータのバッテリー、携帯電話のバッテリーなどに等しい機械的寸法を有する筐体に組み込まれ得る。筐体は、時間または距離に関して、充電を記憶し且つ延長動作を提供するために、デバイス共振器に加えてより小さい「ボタン電池」を含むことができる。ボタン電池に加えて又はその代わりに、他のエネルギー蓄積デバイスが、デバイス共振器および任意の関連した電力変換回路と一体化され得る。これらの新しいエネルギーパックは、従来のバッテリーにより提供されるような類似の電圧および電流レベルを提供するが、デバイス共振器、電力変換回路、小さいバッテリーなどから構成され得る。これらの新しいエネルギーパックは、それらがより容易に再充電されることができ、それらが無線電力区域に位置する場合に常に再充電され得るので、従来のバッテリーよりも長く存続することができる。更に、係るエネルギーパックは、従来のバッテリーよりも軽くでき、使用および保管するのにより安全であり、より広い温度および湿度の範囲にわたって動作でき、廃棄される場合に環境にあまり有害でないなどである。本明細書で説明されたように、これらエネルギーパックは、本明細書で説明されたように無線電力区域で使用される場合に、製品寿命を超えて存続することができる。

【０３９０】

本明細書で説明されたシステム及び方法は、ラップトップコンピュータの画面においてのような、しかしより一般的には、テレビ、コンピュータのモニタ、デスクトップコンピュータのモニタ、ラップトップコンピュータのディスプレイ、デジタルフォトフレーム、電子書籍、携帯機器のディスプレイ（例えば、電話、ＰＤＡ、ゲーム、ナビゲーション機器、ＤＶＤプレイヤ）などにおいてのような、今日の電気および電子機器の構成要素で利用される多種多様のディスプレイを含む、視覚ディスプレイに電力供給するために使用され得る。また、本明細書で説明された１つ又は複数の無線電力送信システムを介して電力供給され得るディスプレイは、電子構成要素（例えば、音響機器、家庭用電気製品、自動車用ディスプレイ、娯楽端末、レジ、リモコン装置）、家具、建物のインフラ、車両、物体の表面（例えば、車両、建物、衣類、看板、移動体の表面）などに埋め込まれるような、埋め込み式ディスプレイを含むことができる。ディスプレイは、本明細書で説明されたようなスマートカードにおいてのような極めて小さい共振デバイスでもって非常に小さくすることができ、又は広告看板においてのように非常に大きくすることができる。また、本明細書で開示された原理を用いて電力供給されるディスプレイは、液晶ディスプレイ（ＬＣＤ）、薄膜トランジスタＬＣＤ、受動型ＬＣＤ、ブラウン管（ＣＲＴ）、プラズマディスプレイ、プロジェクターディスプレイ（例えば、ＬＣＤ、ＤＬＰ、ＬＣＯＳ）、表面電界ディスプレイ（ＳＥＤ）、有機発光ダイオード（ＯＬＥＤ）などのような、複数のイメージング技術の任意の１つとすることができる。供給源のコイル構成は、本明細書で説明されたような無線延長コードなどから、建物の電力、車両の電力のような主電源に取り付けること、電気構成要素の基部（例えば、コンピュータの基部、ＴＶ用のケーブル箱）のような構成要素の電源に取り付けること、中間の中継供給源コイルなどを含むことができる。例えば、壁にデジタルディスプレイを掛けることは、ワイヤレスで又は携帯型メモリ装置を介して情報信号を受信するデジタルフォトフレームの場合のように、非常に魅力的とすることができるが、目障りな電源コードの必要性が、それを美的に不愉快にさせる可能性がある。しかしながら、フレーム部分内に包まれるように、デバイスコイルがデジタルフォトフレームに埋め込まれていることにより、デジタルフォトフレームは、全くワイヤを備えずに掛けられることが可能になる。そして、例えば、壁の向こう側の隣の部屋において、従来の電源コンセントに直接的にプラグ接続される、本明細書で説明されたような無線延長コードからの、部屋の中央供給源共振器などからの、供給源共振器が、デジタルフォトフレームの近傍に配置され得る。

【０３９１】

本明細書で説明されたシステム及び方法は、電子機器設備の異なる部分間で無線電力送

信を行うことができる。制限せずに、ラップトップコンピュータの例を続けると、ラップトップコンピュータの画面は、ラップトップコンピュータの基部からの電力を必要とする。この場合、電力は従来、画面と基部との間のラップトップコンピュータのヒンジ部分を介したラップトップコンピュータの基部から画面までの直接的な電気接続を介して送られていた。有線接続が利用される場合、有線接続は、擦り切れる及び切断する傾向があり、ラップトップコンピュータの設計の機能性は、必要な直接的な電気接続（直接電気接続と称す）により制限され、ラップトップコンピュータの設計美学は、必要な直接電気接続などにより制限され得る。しかしながら、無線接続が基部と画面との間で行われ得る。この場合、デバイス共振器は、ディスプレイに電力供給するために画面部分に配置され、基部は、第２のデバイス共振器により、従来の有線接続により、共振器－バッテリー－直接電気接続のハイブリッドなどにより、電力供給され得る。これは、物理的な有線接続の除去によって電力接続の信頼性を改善するだけでなく、設計者が、ヒンジに関連した物理的なワイヤの無いことを考慮して、ラップトップコンピュータのヒンジ部分の機能性および／または美観設計を改善することも可能にする。やはり、ラップトップコンピュータは、本明細書で開示された原理が電気または電子デバイスの設計を如何にして改善することができるかを示すために使用されたが、決して制限として解釈されるべきでない。例えば、ドアに電気的機能（製氷器、センサシステム、ライトなどを含む）を備えた冷蔵庫、ジョイント（関節）により分離された可動部分を有するロボット、車の電力システム及び車のドア内の構成要素などのような、分離した物理的な部分を有する多くの他の電気装置が、本明細書で説明されたシステム及び方法から利益を得ることができる。外部供給源共振器からデバイス共振器を介してデバイスに、或いは外部または内部の供給源共振器からデバイス共振器を介してデバイスの一部に電力を供給するための能力が、電気および電子デバイスの範囲にわたって幅広く適用可能であることは、当業者には認識されるであろう。

【０３９２】

本明細書で説明されたシステム及び方法は、充電済みのデバイスと充電されていないデバイスとの間のような、デバイス間の電力の共用を提供することができる。例えば、充電されるデバイス又は電化製品は、供給源のように作動し、所定の量のエネルギー、ダイヤル調整された量のエネルギー、要求および承認された量のエネルギーなどを近くのデバイス又は電化製品に送ることができる。例えば、ユーザは、埋め込まれた供給源共振器およびデバイス共振器を介して電力を送受信することができる携帯電話およびデジタルカメラを有することができ、デバイスの一方、例えば携帯電話は、充電が低いレベルであると判明している。次いで、ユーザはデジタルカメラから携帯電話に電荷を移すことができる。これらデバイスの供給源供給源およびデバイス共振器は、送受信のために同じ物理的共振器を利用することできる、別個の供給源共振器およびデバイス共振器を利用することができる、一方のデバイスが送受信するように設計され得るが、他方が受信だけするように設計される、一方のデバイスが送信だけするように設計され、他方が受信だけするように設計され得るなどである。

【０３９３】

デバイスのバッテリーを完全に枯渇させることを防止するために、受け取るデバイスがどれぐらいのバッテリー容量の権利を与えられるかを指定することをユーザに可能にする設定を有することができる。例えば、外部デバイスに利用可能な電力量を制限する、及びバッテリー電力が閾値を下回る場合に電力送信を停止する能力を有することは有用であるかもしれない。

【０３９４】

本明細書で説明されたシステム及び方法は、電気設備に関連して、近くの電気または電子機器構成要素に対する無線電力伝送を行うことができ、この場合、供給源共振器は、電気設備内にあり、デバイス共振器は、電子機器構成要素内にある。また、供給源共振器は、例えば、電気設備の万能インターフェース（例えば、ＵＳＢインターフェース、ＰＣカードインターフェース）、追加の電気コンセント、万能接続ポイントなどを介して、電気設備に対して接続、プラグ接続、取り付けられ得る。例えば、供給源共振器は、机の上の

コンピュータの構造体の内部にあるか、又はコンピュータに、例えばコンピュータのＵＳＢインターフェースの１つへ接続される何からの物体、パッドなどに組み込まれ得る。物体、パッドなどに埋め込まれ、ＵＳＢインターフェースを介して電力供給される供給源共振器の例において、供給源共振器は、任意の他の電子機器デバイスに組み込まれる必要なしに、ユーザのデスクトップに容易に追加されることができ、かくして複数の電気および／または電子機器デバイスが電力供給され得る無線エネルギー区域が、好都合に提供される。電気設備は、コンピュータ、照明器具、専用供給源共振器の電気設備などとすることができ、近くの構成要素は、コンピュータ周辺機器、周囲の電子機器構成要素、インフラ装置などとすることができ、例えば、コンピュータのキーボード、コンピュータのマウス、ファクシミリ、プリンタ、スピーカシステム、携帯電話、オーディオ装置、インターコム、音楽プレイヤ、ＰＤＡ、照明、電気鉛筆削り、送風機、デジタルピクチャフレーム、計算機、コンピュータゲームなどである。例えば、コンピュータシステムは、「ワイヤレスキーボード」及び「ワイヤレスマウス」を利用する、組み込まれた供給源共振器を備える電気設備とすることができ、この場合、用語のワイヤレスの使用は、各デバイスとコンピュータとの間に無線通信設備が存在することを示すことが意図されており、各デバイスは依然として別個のバッテリー電源を含む必要がある。この結果、バッテリーは周期的に交換される必要があり、大企業では、バッテリー交換のサポート要員、バッテリーのコスト、及び適切なバッテリーの廃棄にかなりの負担という結果になる。代わりに、本明細書で説明されたシステム及び方法は、コンピュータの本体からこれら周辺装置のそれぞれへの無線電力送信を行うことができ、本明細書で説明されるように、キーボード及びマウスに電力供給するだけでなく、ファクシミリ、プリンタ、スピーカシステムなどのような他の周辺機器の構成要素にも電力供給することを含む。電気設備に組み込まれた供給源共振器は、複数の周辺装置、ユーザデバイスなどに対する無線電力送信を行うことができ、そのため電気設備に組み込まれた供給源共振器の近傍にあるデバイスのバッテリーを充電および／または交換する必要性が大幅に低減される。また、電気設備は、電気設備と無線電力供給デバイスとの間の電力伝送パラメータを調整するために、チューニング又は自動チューニングのソフトウェア、アルゴリズム、機能などを提供することもできる。例えば、電気設備は、ユーザのデスクトップ上のコンピュータとすることができ、供給源共振器は、コンピュータに組み込まれ得るか、又はコンピュータにプラグ接続されることができ（ＵＳＢ接続を介して）、この場合、コンピュータはチューニングアルゴリズムを提供するための機能を提供する（例えば、コンピュータで実行されているソフトウェアプログラムを介して）。

【０３９５】

本明細書で説明されたシステム及び方法は、設備のインフラの構成要素に関連して近くの電気または電子機器構成要素に対する無線電力伝送を行うことができ、この場合、供給源共振器は、設備のインフラの構成要素内にあるか、又は係る構成要素に装着され、デバイス共振器は電子機器構成要素内にある。例えば、設備のインフラの構成要素は、１個の家具、固定壁、可動式間仕切り又はパーティション、天井、床、及びテーブル又は机に取り付けられた又は組み込まれた供給源共振器（例えば、その表面の直ぐ下／上に、側面に、テーブルの上面またはテーブルの脚に組み込まれた）、床の上に配置されたマット（例えば、机の下、机の上に配置された）、ガレージの床のマット（例えば、車および／または車内のデバイスを充電するために）、駐車場／ガレージ内のもの（例えば、駐車される場所の近くの支柱に）、テレビ（例えば、リモコンを充電するために）、コンピュータのモニタ（例えば、ワイヤレスキーボード、ワイヤレスマウス、携帯電話に対する電力供給／充電のために）、椅子（例えば、電気毛布、医療機器、個人の健康監視装置に電力供給するために）、絵画、オフィス家具、一般的な家庭電化製品などとすることができる。例えば、設備のインフラの構成要素は、立方体のオフィスの照明器具とすることができ、この場合、照明器具内の供給源共振器およびライトは、設備の有線電源に直接的に接続される。しかしながら、ここで照明器具に供給源共振器が設けられた場合、デバイス共振器に接続される又はデバイス共振器と一体化されるこれら近くの電気または電子機器構成要素

に対する任意の追加の有線接続を備える必要はない。更に、本明細書で説明されたように、デバイス共振器を備えるデバイスのバッテリーを交換する必要性も低減され得る。

【０３９６】

中心の位置から、例えば電気設備の供給源共振器から、設備のインフラの構成要素などから、電気および電子デバイスに電力を供給するために、本明細書で説明されたシステム及び方法を使用することは、周囲の作業領域の電気配線インフラを最小限にするこができる。例えば、企業のオフィス空間には、有線接続により電力供給される必要がある電気および電子デバイスが一般に非常に多く存在する。本明細書で説明されたシステム及び方法を利用することにより、これら配線の大部分が取り除かれ、企業の出費が減じられ、設置コストが節約され、電気配線を有するオフィスの壁に関連した物理的な制限が低減され、電源コンセント及び電源コードなどの必要性が最小限にされる。本明細書で説明されたシステム及び方法は、設置、再設置（例えば、オフィス空間の再構成）、メンテナンスなどに関連した電気インフラの低減を通じて企業のコストを削減することができる。別の例において、本明細書で開示された原理は、部屋の中央に電気コンセントをワイヤレスで配置することを可能にする。ここで、供給源は、コンセントを置くことを望む床の場所の下にある地下室の天井に配置され得る。デバイス共振器は、そのすぐ上の部屋の床に配置され得る。天井の中央に新しい照明器具（又は、その事項に関して任意の他の電気デバイス、例えばカメラ、センサなど）を設置することは、今や同じ理由で著しく容易になる。

【０３９７】

別の例において、本明細書で説明されたシステム及び方法は、壁を「通して」電力を供給することができる。例えば、１つの部屋に（例えば、壁に）電気コンセントを有するが、電気技術者を呼ぶ、又は壁にドリルで穴を開ける、又は壁の周りにワイヤを引くなどする必要なしに、隣の部屋にコンセントを設けたいことを仮定する。１つの部屋の壁に供給源共振器を置き、壁の向こう側にデバイス共振器のコンセント／ピックアップを置くことができる。これは、平面型ＴＶまたはステレオシステムなどに電力供給することができる（例えば、リビングルームの壁をはう醜いワイヤを設けることを望まないが、隣の部屋、例えば収納室またはクローゼット、又は壁に沿って延びているワイヤを見えないようにする家具を備えた部屋の壁を類似したワイヤがはうことを気にしないかもしれない）。本明細書で説明されたシステム及び方法は、屋内の供給源から家または建物の外の様々な電気デバイスに、これら外壁を貫通してドリル開けされた穴、又はこれら外壁に設置されたコンジットを必要とせずに、電力を伝送するために使用され得る。この場合、デバイスは、壁およびサイディングを貫通するドリル穴に関連した美的または構造的損傷または危険性なしに、建物の外でワイヤレスで電力供給され得る。更に、本明細書で説明されたシステム及び方法は、電気構成要素を備えた屋外用のデバイス共振器に対して、屋内の供給源共振器を配置することに役立つ配置センサを提供することができる。例えば、自宅の所有者は、無線デバイス共振器を含む保安灯をその家の外にに配置することができ、そして今、家の内部に供給源共振器を適切に又は最適に配置する必要がある。供給源共振器とデバイス共振器との間で働く配置センサは、配置が良好、又は或る程度まで良好になる時に、例えば視覚表示、音声指示、ディスプレイ表示などで示すことにより、その配置をより良好に可能にすることができる。別の例において、同様に、本明細書で説明されたシステム及び方法は、家または建物の屋根に、機器、例えば無線送信器および受信器、太陽電池パネルなどを設置することを行うことができる。太陽電池パネルの場合、供給源共振器は、パネルに関連付けられることができ、電力は、屋根に穴を開ける必要なしに、建物の内部の配電パネルにワイヤレスで伝送され得る。本明細書で説明されたシステム及び方法は、車両、例えば自動車、船、飛行機、列車などの壁の向こう側に（例えば、屋根などを介して）、ドリルで穴を開ける必要性なしに、電気または電子構成要素の装着を可能にすることができる。このように、車両の壁は、ドリルで開けられた穴を備えずに、損傷を受けていないままとすることができ、かくして車両の価値が維持され、水密性が維持され、ワイヤを配線する必要性などが取り除かれる。例えば、サイレン又はライトを警察車の屋根に取り付けることは、車の将来的な転売価格を低減させるが、本明細書で説明されたシステム

及び方法を用いる場合、任意のライト、ホーン、サイレンなどは、ドリルで穴を開ける必要性なしに屋根に取り付けられ得る。

【０３９８】

本明細書で説明されたシステム及び方法は、太陽光発電（ＰＶ）パネルからの電力の無線伝送に使用され得る。無線電力伝送能力を備えるＰＶパネルは、より簡単な取り付け、より大きな柔軟性、信頼性、及び全天候型設計を含む幾つかの利点を有することができる。無線電力伝送は、ＰＶパネルからデバイス、家、車両などへ電力を伝送するために使用され得る。太陽ＰＶパネルは、そのＰＶパネルが無線電力を受け取ることを可能にされたデバイスに直接的に電力供給することを可能にする無線供給源共振器を有することができる。例えば、太陽ＰＶパネルは、車両、建物などの屋根の上へ直接的に取り付けられ得る。ＰＶパネルにより捕捉されたエネルギーは、車両の内側または建物の屋根の下のデバイスに直接的にワイヤレスで伝送され得る。共振器を有するデバイスは、ＰＶパネルからの電力をワイヤレスで受け取ることができる。ＰＶパネルからの無線電力伝送は、家、車両などの有線電気システムに結合された共振器にエネルギーを伝送するために使用され、外部のＰＶパネルと内部の電気システムとの間の任意の直接的な接触を必要とせずに、従来の配電および従来のデバイスの電力供給を可能にする。

【０３９９】

無線電力伝送を用いることにより、ＰＶパネルの屋根の取り付けを著しく簡単にすることができ、その理由は、電力がパネルから家の捕捉共振器にワイヤレスで送信されることができ、全ての外部の配線、コネクタ及びコンジット、及び構造体の屋根または壁を貫通する任意の穴が除外されるからである。太陽電池で使用される無線電力伝送は、パネル、ひも状のもの、及び接続箱を相互接続するために、電気技術者が屋根で作業する必要性をなくすので、屋根の危険性を低減できるという利益を有することができる。無線電力伝送と一体化された太陽電池パネルの取り付けは、電気接触が行われる必要性がほとんどないので、熟練労働者をさほど必要としない。場所の詳細な設計は、無線電力伝送であまり必要とされず、その理由は、当該技術が、各太陽ＰＶパネルを別個に最適化および配置するための能力を設置者に与え、高価なエンジニアリング及びパネルレイアウトの点検の必要性が著しく低減されるからである。全てのパネルで太陽の負荷を入念に平衡させる必要はなく、特殊化したＤＣ配線レイアウト及び相互接続も必要ない。

【０４００】

ＰＶパネルの屋根または壁上の設置に関して、捕捉共振器は、屋根の下側、壁の内側、或いは１フィート（３０．４８ｃｍ）又は２つの太陽ＰＶパネル以内の容易にアクセス可能な任意の他の内部空間に取り付けられ得る。一般的な屋根の上面のＰＶパネルの可能な設置を示す図が、図５１に示される。様々なＰＶソーラーコレクターが、屋根の下の建物の内部に取り付けられた無線電力捕捉コイルと共に、屋根の上に取り付けられ得る。ＰＶパネルの共振器コイルは、屋根を介して無線捕捉コイルにワイヤレスでそれらのエネルギーを伝送することができる。ＰＶセルからの捕捉されたエネルギーは、集められ、家の電気システムに結合されて電気および電子デバイスに電力供給するか、又は必要とされるものよりも多くの電力が生成される場合には、電力網に結合される。エネルギーは、建物の屋根または壁を貫通する穴またはワイヤを必要とせずに、ＰＶセルから捕捉される。各ＰＶパネルは、車両または建物の内部の対応する共振器に結合される共振器を有することができる。複数のパネルは、互いの間で無線電力伝送を利用し、車両または家の内部の共振器に結合される１つ又は２つの指定パネルに電力を伝送または集めることができる。パネルは、他の同様のパネルに配置された共振器に結合することができる無線電力共振器をそれらの側面または周辺部に有することができ、それによりパネル間の電力の伝送を可能にする。建物または車両の外部の複数のパネルからの電力をワイヤレスで結合する、及び建物または車両の内部の１つ以上の共振器に電力を伝送する追加のバス又は接続構造が、設けられてもよい。

【０４０１】

例えば、図５１に示されるように、供給源共振器５１０２は、建物の屋根５１０４の上

に取り付けられたＰＶセル５１００に結合され得る。対応する捕捉共振器５１０６が、建物の内部に配置される。次いで、ＰＶセルにより捕捉された太陽エネルギーは、建物を貫通する真っ直ぐな穴および接続を備えていない建物の外部の供給源共振器５１０２と係る建物の内部のデバイス共振器５１０６との間で伝送され得る。

【０４０２】

無線電力伝送を備える各太陽ＰＶパネルは、それ自体のインバータを有することができ、各パネルの電力生成効率を別個に最適化すること、１回の設置においてパネルのサイズとタイプの混合をサポートすること、単一のパネルの「成長に合わせて投資」のシステム拡張を含むことにより、これらソーラーシステムの経済性が著しく改善される。設置コストの低減は、設置に関して単一パネルを安価にする。パネルの一続きの設計および複数のパネルの慎重な配置と配向の必要性が除去され、システムの単一点障害が除去される。

【０４０３】

ＰＶソーラーパネルにおける無線電力伝送は、より多くのソーラーの配置の計画を可能にすることができ、その理由は、防塵防滴（weather-sealed）のソーラーＰＶパネルが、車の屋根や船の甲板のようなシールされた表面を通して配線するためにドリルで穴を開ける必要性を無くし、パネルが固定場所に設置される要件を無くすからである。無線電力伝送を用いることにより、ＰＶパネルは、一時的に配置され、その後、周囲の構造体に永久的な変更を残さずに移動され又は除去されることができる。例えば、それらは、明るく晴れた日に構内の外に配置されて、太陽に追従するようにあちこち移動され、或いは掃除または保管のために中へ運ばれ得る。裏庭または移動できるソーラーＰＶの応用形態の場合、無線エネルギー捕捉デバイスを備えた延長コードが地面に投げられるか、又はソーラーユニットの近くに配置され得る。捕捉延長コードは、完全に素子から密封されて絶縁されており、そのためそれは、任意の屋内または屋外の環境で使用され得る。

【０４０４】

無線電力伝送を用いることにより、ワイヤ又は外部接続の必要性がなく、ＰＶソーラーパネルは、完全に防塵防滴とすることができる。ソーラーＰＶ発電および送信回路における電気構成要素の著しく改善された信頼性と寿命は、防塵防滴の筐体がＵＶ放射、湿度、風雨などから構成要素を保護することができるので、期待され得る。無線電力伝送および防塵防滴の筐体を用いることにより、構成要素がもはや外部要因および気象要素に直接的にさらされないので、安価な構成要素を使用することが可能であり、ＰＶパネルのコストが低減され得る。

【０４０５】

ＰＶパネルと建物または車両の内部の捕捉共振器との間の電力伝送は、双方向性とすることができる。エネルギーは、ＰＶパネルが特定の仕事（タスク）を行うための十分なエネルギーを備えていない場合に電力を供給するために、家の配電網からＰＶパネルに伝えられ得る。電力の逆の流れは、パネルから雪を溶かすために、又は太陽エネルギーに対してより好適な位置にパネルを配置するモーターに電力供給するために使用され得る。ひとたび雪が溶ければ、又はパネルが再配置されれば、ＰＶパネルはそれ自体のエネルギーを生成することができ、電力伝送の方向は、ＰＶパネルから建物、車両、又はデバイスへ電力を伝える正常に戻され得る。

【０４０６】

無線電力伝送を備えるＰＶパネルは、無線コレクターへの最大の及び効率的な電力伝送を保証するために、設置の自動チューニングを含むことができる。様々な設置における屋根材の違い又はＰＶパネルと無線電力コレクターとの間の距離のばらつきは、性能に影響を及ぼし、無線電力伝送の共振器の特性に摂動を与える可能性がある。設置の複雑性を低減するために、無線電力伝送の構成要素は、材料または距離に起因した任意の影響を補償するために、それらの動作点を自動的に調整するためのチューニング能力を含むことができる。周波数、インピーダンス、キャパシタンス、インダクタンス、デューティサイクル、電圧レベルなどは、効率的で安全な電力伝送を確実にするために調整され得る。

【０４０７】

本明細書で説明されたシステム及び方法は、一時的に無線電力区域を提供するために、又は従来の電気コンセントを無線電力区域まで延長するために使用され得る（例えば、無線電力延長コードの使用を通じて）。例えば、無線電力延長コードは、従来の電源コンセントに接続するためのプラグ、従来の電源延長コードのような長いワイヤ、及び他方の端部の共振器供給源コイル（例えば、従来の延長コードのソケット端部の代わりに、又は係るソケットに加えて）として構成され得る。また、無線延長コードに沿って複数の場所に供給源共振器が存在する無線延長コードも構成され得る。この構成は、便利な電源コンセントが存在しない場所（例えば、コンセントの無いリビングルームの場所）に無線電力を供給する、並びに配線された電源インフラが存在しない所（例えば、工事現場）で、及びコンセントが存在しない構内（例えば、パーティのために、又は従来の電気コードを切断する可能性を低減するためにワイヤレスで電力供給される庭手入れ用道具のために）に出て一時的に無線電力を供給するなどのような、無線電力供給の構成されたデバイスが存在する場合に、任意の従来の延長コードを置き換えることができる。また、無線延長コードは、壁または構造体内の引き込み線としても使用され、当該引き込み線の近傍内に無線電力区域を提供することができる。例えば、無線延長コードは、新しい又はリフォームされた部屋の壁内に引かれて、従来の電気配線およびコンセントの設置を必要とせずに、無線電力区域を提供することができる。

【０４０８】

本明細書で説明されたシステム及び方法は、車両の可動部品または回転組立体、ロボット、機械装置、風力タービン、或いはロボットアーム、建設車両、可動プラットフォームなどのような可動部品を備える任意の他のタイプの回転装置または構造体の間で、電力を供給するために利用され得る。従来、係るシステムの電力は、例えば、スリップリングにより、又はロータリージョイントにより提供されていた。本明細書で説明されたような無線電力伝送を使用することにより、これらデバイスの設計の簡略化、信頼性、及び寿命が著しく改善されることができ、その理由は、時間の経過につれてすり減る又は摩滅する可能性がある任意の物理的接続または接点を用いずに、或る距離範囲にわたって電力が伝送され得るからである。特に、供給源コイル及びデバイスコイルの好適な同軸および平行の位置合わせは、２つのコイルの相対的な回転運動により激しく変調されない無線電力伝送を行うことができる。

【０４０９】

本明細書で説明されたシステム及び方法は、一連の供給源共振器－デバイス共振器－供給源共振器－デバイス共振器を提供することにより、単一の供給源共振器の届く距離を超えて、電力ニーズを広げるために利用され得る。例えば、既存の一戸建てのガレージが電力を備えておらず、所有者が今、新しい電力サービスを設置することを望んでいると仮定する。しかしながら、所有者は、ガレージの全体にわたってワイヤを引くことを望まないかもしれないし、又は構造体の全体にわたって電気コンセントを配線するために壁に侵入する必要があるかもしれない。この場合、所有者は、供給源共振器を新しい電力サービスに接続することを選択することができ、それにより、無線電力が、ガレージの裏の全体にわたるデバイス共振器コンセントに供給されることが可能になる。次いで、所有者は、デバイス－供給源「中継器」を設置して、ガレージの表のデバイス共振器コンセントに無線電力を供給することができる。即ち、電力中継器は今、主供給源共振器から無線電力を受け取り、次いで利用可能な電力を、ガレージの表の第２の組のデバイス共振器に電力を供給するために第２の供給源共振器に供給する。この構成は、何度も繰り返されて、供給される無線電力の有効範囲を延ばすことができる。

【０４１０】

複数の共振器を用いて、エネルギー遮断材料の周りに電力ニーズを広げることができる。例えば、供給源共振器をコンピュータ又はコンピュータのモニタに組み込むことが望ましく、そのため当該共振器は、モニタ又はコンピュータの周りに、特に前に配置されたデバイス、例えば、キーボード、コンピュータのマウス、電話などに電力を供給することができる。美観、スペースの制約などに起因して、供給源共振器に使用され得るエネルギー

供給源は、モニタ又はコンピュータの後ろのみに配置または接続され得る。コンピュータ又はモニタの多くの設計において、金属構成要素および金属を含む回路が、設計およびパッケージングに使用され、それらは、モニタ又はコンピュータの後ろの供給源共振器からモニタ又はコンピュータの前への電力伝送を制限および妨げる可能性がある。追加の中継器共振器は、モニタ又はコンピュータの基部または台に組み込まれ、モニタ又はコンピュータの裏の供給源共振器に結合し、モニタ又はコンピュータの前の空間への電力伝送を可能にする。モニタ又はコンピュータの基部または台に組み込まれた中間共振器は、追加の電源を必要とせず、供給源共振器からの電力を捕捉して、モニタ又はコンピュータの遮断または電力遮蔽する金属構成要素の周りの前面まで電力を伝送する。

【０４１１】

本明細書で説明されたシステム及び方法は、車両、オフィス、家、部屋、建物、屋外構築物、道路施設などのような、空間の構造部分に内蔵され、配置され、つり下げられ、埋め込まれ、組み込まれるなどされ得る。例えば、１つ又は複数の供給源は、壁、天井または天井パネル、床、仕切り、戸口、階段の吹き抜け、小部屋（コンパートメント）、路面、歩道、（高速道路への）出入道路、フェンス、屋外構築物などに内蔵され、配置され、つり下げられ、埋め込まれ、又は組み込まれ得る。１つ又は複数の供給源は、構造体の内部または周りの実在物、例えばベッド、机、椅子、ラグマット、鏡、時計、ディスプレイ、テレビ、電子デバイス、カウンター（調理台）、テーブル、１個の家具、１個の芸術作品、囲い込むもの、小部屋、天井パネル、床またはドアパネル、ダッシュボード、トランク、ホイールウエル、支柱、ビーム、支持体、又は任意の同様な実在物に組み込まれ得る。例えば、供給源共振器は、ユーザの車のダッシュボードに組み込まれ、そのため、デバイス共振器を備えた又はデバイス共振器に接続された任意のデバイスが、ダッシュボードの供給源共振器から電力を供給され得る。このように、車に持ち込まれた又は組み込まれたデバイスは、車の中にある間に、常に充電または電力供給され得る。

【０４１２】

本明細書で説明されたシステム及び方法は、車両、例えばボート、車、トラック、バス、列車、飛行機、人工衛星などの壁を通して電力を供給することができる。例えば、ユーザは、車両の外の電子デバイスに電力を供給するために、車両の壁に穴を開けることを望まないかもしれない。供給源共振器は車両の内側に配置されることができ、デバイス共振器は、車両の外側に配置され得る（例えば、窓、壁または構造体の両側に）。このように、ユーザは、車両に対する外部デバイスの配置、位置決め、及び取り付けを最適化する際により大きな柔軟性を達成することができる（例えば、デバイスに対する電気接続を与える又は配線することを気にせずに）。更に、ワイヤレスで供給される電力を使用することにより、外部デバイスは、防水であるように密封絶縁され、その外部デバイスが風雨（例えば、雨）にさらされる場合に、又は水面下に沈んでも、安全にされる。類似した技術は、様々な応用形態、例えば、ハブリッド車、ナビゲーション及び通信機器、建設機器、被遠隔制御またはロボット設備などに対する充電または電力供給（露出導体のせいで電気的危険性が存在する）に利用され得る。本明細書で説明されたシステム及び方法は、半導体成長および処理、材料コーティングシステム、水槽、危険物処理システムなどで使用されるような、真空チャンバ又は他の密閉空間の壁を通して電力を供給することができる。電力は、並進ステージ、ロボットアーム、回転ステージ、操作および収集装置、クリーニング装置などに供給され得る。

【０４１３】

本明細書で説明されたシステム及び方法は、台所環境に、例えば、ミキサ、コーヒーメーカー、トースター、オーブントースター、ホットプレート、グリドル、電気フライパン、電気ポット、電気動作装置、ワッフルメーカー、ブレンダー、フードプロセッサ、クロックポット、加温トレイ、誘導式レンジ台、ライト、コンピュータ、ディスプレイなどを含むカウンタ上面の電化製品に、無線電力を供給することができる。この技術は、デバイスの移動性および／または配置の柔軟性を改善し、カウンタ上面に蓄積およびカウンタ上面にわたって散乱した多数の電源コードを低減し、デバイスの洗浄可能性なども改善する

ことができる。例えば、電気フライパン（electric skillet）は従来、別個の部分を備え、例えば、洗うために水の中に入ることができる部分と、外部電気接続（例えば、コード、又は取り外し可能なコード用のソケット）を含むので水の中に入ることができない部分である。しかしながら、そのユニットにデバイス共振器が組み込まれる場合、全ての電気接続は密封絶縁されることができ、そのためデバイス全体は今や清浄にするために水の中に入れられ得る。更に、外部コードが無いことは、利用可能な壁の電気コンセントの必要性を無くし、もはやカウンタを横切って配置されるべき電気コードの必要性、又は電気グリドルの場所を利用可能な壁の電気コンセントの場所に制限する必要性がなくなる。

【０４１４】

本明細書で説明されたシステム及び方法は、デバイス共振器を備えたデバイスに対して連続的な電力供給／充電を行うことでき、その理由は、デバイスが、固定電気デバイス、パーソナルコンピュータ、インターコムシステム、セキュリティシステム、家庭用ロボット、照明、リモコンユニット、テレビ、コードレス電話などのように、供給源共振器の近傍を離れないからである。例えば、家庭用ロボット（例えば、ROOMBA（登録商標））は、無線電力を介して電力供給／充電されることができ、ひいては再充電されずに任意の長時間、動作する。このように、家庭用ロボットに対する電源設計は、バッテリーを必要とせずに供給源共振器からの電力のみを使用するようにロボットを設計する、供給源共振器からの電力を用いてロボットのバッテリーを再充電するようにロボットを設計する、供給源共振器からの電力を使用してロボットのバッテリーをトリクル充電するようにロボットを設計する、供給源共振器の電力を用いて容量性エネルギー蓄積ユニットを充電するようにロボットを設計するなどのように、無線電力のこの連続的な供給源を利用するように変更され得る。電源および電源回路の類似した最適化は、本明細書で開示された任意および全てのデバイスに対して、可能にされる、設計される、及び実現され得る。

【０４１５】

本明細書で説明されたシステム及び方法は、電気加熱毛布、加温パッド／パッチなどに無線電力を供給することができる。これら電気加熱デバイスは、様々な屋内用途および屋外用途を見出すことができる。例えば、守衛、警察官、建設作業員などのような屋外労働者に支給される手足の加温器は、車両、建物、電柱、信号機、ポータブル電源ユニットなどの近くに関連付けられた又は組み込まれた供給源共振器から遠隔的に電力供給され得る。

【０４１６】

本明細書で説明されたシステム及び方法は、デバイス共振器を含む携帯型情報デバイスに電力供給するために使用されることができ、係る携帯型情報デバイスは、供給源共振器を含む情報供給源の近くにいる場合に、電源を入れられ得る。例えば、情報デバイスは、ユーザのポケット、財布、ハンドバック、車両、バイクなどに保持されたカード（例えば、クレジットカード、スマートカード、電子カードなど）とすることができる。携帯型情報デバイスは、情報供給源の近傍にいる場合に電源を入れられることができ、次いで電子ロジック、電子プロセッサ、メモリ、ディスプレイ、ＬＣＤディスプレイ、ＬＥＤ、ＲＦＩＤタグなどを含むことができる携帯型情報デバイスに、情報が送信される。例えば、携帯型情報デバイスは、それが情報供給源の近くにいる場合に「オン」になるディスプレイを備えたクレジットカードとすることができ、「You just received a coupon for 50% off your next Coca Cola purchase」のような何らかの情報をユーザに提供することができる。情報デバイスは、その後の購入で使用され得るクーポン又は値引き情報のような情報を格納することができる。携帯型情報デバイスは、タスク、スケジュール表、やることリスト、アラーム及びリマインダーなどを含むように、ユーザによりプログラムされ得る。情報デバイスは、最新の価格情報を受け取り、以前に選択または特定された商品の場所および価格の情報をユーザに知らせることができる。

【０４１７】

本明細書で説明されたシステム及び方法は、構造体の内部に取り付けられ得る、構造体の外部に取り付けられ得る、地中に埋設され得る、壁に取り付けられ得るなどの環境セン

サ、セキュリティセンサ、農業センサ、機器センサ、食品損傷センサ、電力センサなどのようなセンサのバッテリーに直接的に電力供給または係るバッテリーを再充電するために無線電力伝送を行うことができる。例えば、この能力は、バッテリーを物理的に交換するために古いセンサを掘り出す必要性、又は古いセンサの充電が切れて、もはや動作しないので新しいセンサを埋める必要性に取って代わることができる。これらセンサは、ユニットを充電する携帯型センサ供給源共振器の使用を通じて、周期的に充電され得る。例えば、電源（例えば～ｋＷの電力を供給する）を備えた、供給源共振器を携えるトラックは、～ｍＷセンサに数分で十分な電力を提供し、センサの動作の持続時間を１年以上にわたって延ばすことができる。また、センサは直接的に電力供給されることもでき、例えば、ワイヤで接続することが困難であるが、供給源共振器の近傍内に依然としてある所定位置のセンサ（例えば、家の外のデバイス（セキュリティカメラ）、壁の向こう側にあるデバイス、ドアの電気ロック上のデバイスなど）に電力供給する。別の例において、そうでなければ有線電力接続で供給される必要があるセンサが、本明細書で説明されたシステム及び方法を通じて電力供給され得る。例えば、漏電ブレーカは、配電盤への設置のために、残留電流および過電流保護を１つのデバイスに組み合わせる。しかしながら、センサは従来、電源のために別個に配線される必要があり、これは設置を複雑にする可能性がある。しかしながら、本明細書で説明されたシステム及び方法を用いることにより、センサは、デバイス共振器で電力供給されることができ、この場合、単一の供給源共振器は配電盤内に設けられ、かくして配電盤内の設置と配線条件が簡略化される。更に、単一の供給源共振器は、配電盤内に取り付けられた供給源共振器の両側に取り付けられたデバイス共振器に、配電盤の全体にわたって取り付けられたデバイス共振器に、近くの追加の配電盤に取り付けられたデバイス共振器などに電力供給することができる。本明細書で説明されたシステム及び方法は、電気配電盤、分電盤、回路遮断器、変圧器、予備バッテリー、火災警報制御パネルなどにおいてのように、電気パネル、電気室、配電などに関連した任意の電気構成要素に無線電力を供給するために利用され得る。本明細書で説明されたシステム及び方法の使用を通じて、配電および保護構成要素およびシステム設備を設置、維持、及び変更することが、より容易になる。

【０４１８】

別の例において、バッテリーで動くセンサは、無線電力が周期的に又は連続的にバッテリーを再充電またはトリクル充電するために供給され得るので、バッテリーを充電する必要なしに連続的に動作することができる。係る用途において、電力レベルが低くても、バッテリーの電荷を適切に再充電または維持することができ、バッテリーの寿命および有用性が著しく延ばされる。場合によっては、バッテリー寿命は、それが電力供給されているデバイスの寿命よりも長くするように延ばされることができ、本質的に「永遠に続く」バッテリーにする。

【０４１９】

本明細書で説明されたシステム及び方法は、人工心臓、ペースメーカー、心臓ポンプ、インスリンポンプ、神経または指圧療法／針治療のつぼ刺激などのための埋め込まれたコイルなどのような埋込み型医療装置のバッテリーを充電するために使用され得る。例えば、ワイヤが考えられる一定の感染源であり、一般に患者にとって非常に不愉快になるので、患者にワイヤを突き刺しておくことは好都合ではなく、又は安全ではない。また、本明細書で説明されたシステム及び方法は、供給源共振器を有するベッド又は病院の壁または天井のような、外部供給源から患者の医療装置に対して充電または電力供給するためにも使用され得る。係る医療装置は、患者に対する取り付け、読み出し、使用、及びモニタをより容易にすることができる。本明細書で説明されたシステム及び方法は、患者および患者のベッド又はベッドのそばにワイヤを取り付ける必要性を容易化し、患者が、不注意による医療装置の切断という危険を冒さずに、ベッドの周りに移動またはベッドから出ることをより便利にすることができる。例えば、これは、脈、血圧、ブドウ糖などの測定のような、患者をモニタする複数のセンサを有する患者と共に有用に利用され得る。バッテリーを利用する医療装置およびモニタ装置の場合、バッテリーは極めて頻繁に、恐らく週に

数回、交換される必要があるかもしれない。これは、バッテリーを交換することを忘れている人々に関連して、バッテリーが消耗したことにより装置またはモニタが動作していないことに気付かないこと、並びにバッテリーカバー及びバッテリー室などの不適切なクリーニングに関連した感染症などの危険を与える可能性がある。

【０４２０】

本明細書で説明されたシステム及び方法は、医療装置の埋め込み方法の危険性および複雑性を低減することができる。今日、心室補助装置、ペースメーカー、除細動器などのような多くの埋込み型医療装置は、当該装置に組み込まれる長寿命バッテリーの体積および形状によりかなり影響を受ける、それら装置のフォームファクタに起因して、外科的な埋め込みを必要とする。一態様において、本明細書においてバッテリーを再充電する非侵襲性の方法が説明され、そのためバッテリーサイズは劇的に低減され、装置全体は、例えばカテーテルを介して、埋め込まれ得る。カテーテル埋込み型装置は、一体化された捕捉またはデバイスコイルを含むことができる。カテーテル埋込み型捕捉またはデバイスコイルは、例えば埋め込み後に、それが内部で配線され得るように設計され得る。捕捉またはデバイスコイルは、クルクルと巻いたフレキシブルなコイル（例えば、２つの巻物のように巻かれ、単一のスプレッダ機構で内部で容易に広げられる）として、カテーテルを介して配置され得る。電源コイルは、電源が適切な位置に配置されるように適合するように仕立てられたベスト又は衣類に着けられ得るか、椅子のクッション又はベッドのクッションに配置され得るか、ベッド又は１個の家具に組み込まれるなどされ得る。

【０４２１】

本明細書で説明されたシステム及び方法により、供給源共振器の近傍にある場合に電力供給または充電され得るデバイス共振器、及び複数の医療センサの少なくとも１つを含むことができる「センサベスト」、センサパッチなどを、患者が備えることを可能にする。従来、このタイプの医療モニタ設備は、バッテリーを必要とし、それによりベスト、パッチなどを重くし、潜在的に実用的でなくしていた。しかし、本明細書で開示された原理を用いることにより、バッテリー（又はより軽い再充電可能バッテリー）は必要なく、かくして係る装置は、特にバッテリーが無いので、又はバッテリーが大幅に軽いので、ストラップを用いずに、例えば接着剤により、係る医療装置が所定位置に保持され得る場合には、より便利および実用的にされる。医療設備は、発作、または心臓発作などを予想（例えば、それより数分前に）するために、遠隔的にセンサデータを読み取ることができる。当該ベストが、医療設備から遠く離れた場所にいる、例えば家にいる人により使用される場合、ベストは、携帯電話または通信装置と一体化されて、事故または医療事象の場合に救急車を呼ぶことができる。本明細書で説明されたシステム及び方法は、当該ベストが高齢者により使用されるべきである場合の例において特に価値が高く、この場合、従来のワイヤレスでない再充電の手法（例えば、バッテリーの交換、及び夜にプラグ接続など）は要求事項として不随されない。また、本明細書で説明されたシステム及び方法は、バッテリーの交換または再充電が困難である身体障害者により使用される又は係る身体障害者を支援する充電装置、又は身体障害者が享受する又は頼りにする装置に電力を確実に供給することが困難である充電装置に使用され得る。

【０４２２】

本明細書で説明されたシステム及び方法は、義肢の充電および電力供給に使用され得る。義肢は、腕、脚、手、及び足のような元の肢の機能を置き換えるという点で、非常に有能になる。しかしながら、電動義肢は、結果として多大なバッテリーになる、かなりの電力（例えば１０～２０Ｗ）を必要とする。その場合、切断手術を受けた人は、あまり長く存続しない軽いバッテリーとかなり長く存続する重いバッテリーのどちらかを選択して帰路に付くことができるが、「持ち歩く」ことはより困難である。本明細書で説明されたシステム及び方法により、義肢は、デバイス共振器で電力供給されることが可能になり、この場合、供給源共振器は、ユーザにより携えられ重量をより容易に支えることができる体の一部に取り付けられるか（例えば、腰の周りのベルトに）、又はデバイスが充電または電力供給される状態を保つように適切な時間をユーザが過ごす外部場所（例えば、ユーザ

の机に、ユーザの車内に、及びユーザのベッドの中など）に配置される。

【０４２３】

本明細書で説明されたシステム及び方法は、工業的および軍事的応用形態で、及び高齢者／弱者／病人に使用されるような、電動エグゾスケルトン（exo-skeleton：外骨格）の充電および電力供給に使用され得る。電動エグゾスケルトンは、人に１０～２０倍までの「強さ」の増加を提供し、それにより人が、大きな疲れを伴わずに身体的に非常に骨が折れる作業を繰り返し行うことが可能になる。しかしながら、エグゾスケルトンは、特定の使用状況の下で１００Ｗを超える電力を必要とし、そのためバッテリー駆動動作は、３０分以下に制限され得る。本明細書で説明された無線電力の供給により、エグゾスケルトンのユーザに、エグゾスケルトンの構造運動に電力供給する、及び構造体の全体にわたって分散された様々なモニタ及びセンサに電力供給するための電力の連続的な供給を行うことができる。例えば、埋め込まれたデバイス共振器（単数または複数）を有するエグゾスケルトンは、局所的な供給源共振器から電力を供給され得る。工業用エグゾスケルトンの場合、供給源共振器は、施設の壁に配置され得る。軍事用エグゾスケルトンの場合、供給源共振器は、装甲車両により備えられ得る。高齢者のヘルパーを助けるために利用されるエグゾスケルトンの場合、供給源共振器（単数または複数）は、人の家の部屋（単数または複数）に設置または配置され得る。

【０４２４】

本明細書で説明されたシステム及び方法は、酸素システム、人工呼吸器、投薬ポンプ、モニタ、及び救急車の機器または携帯型医療ユニットなどのような、携帯型医療機器の電力供給／充電に使用され得る。患者を事故現場から病院に輸送できること、又はベッドの患者を他の部屋または領域に移動し、且つ患者に取り付けられて常に電力供給されている全機器を持っていくことができることは、患者の健康に大きな利益をもたらし、結果として幸せをもたらす。確かに、医療機器のバッテリーが消耗することにより、又は患者が多少なりとも輸送または移動される間に医療機器のプラグが抜かれる必要があることにより、動作を停止する医療機器によって生じる危険性および問題は理解され得る。例えば、自動車事故の現場の緊急医療チームは、現場での患者の救急治療で携帯型医療機器を利用する必要がある。係る携帯型医療機器は、緊急事態の持続期間に機器に電力供給するために十分なバッテリー寿命が存在するように適切に維持されなければならない。しかしながら、バッテリーが完全に充電されていない、場合によっては必要な機器が初動要員に利用可能でないように、機器が適切に維持されていない場合があまりにも頻繁にある。本明細書で説明されたシステム及び方法は、バッテリー及び電源パックの充電および維持が人間の介在なしで自動的に行われるように、携帯型医療機器（及び患者の関連したセンサ入力）に無線電力を供給することができる。また、係るシステムは、治療で使用される多くの医療モニタ及び装置に取り付けられた様々な電源コードによる邪魔を取り除いた、患者の改善された動きやすさから恩恵を受ける。

【０４２５】

本明細書で説明されたシステム及び方法は、個人の補聴器の電力供給／充電に使用され得る。個人の補聴器は、人の耳に嵌る又は当該耳の周りに装着するように小さくて軽い必要がある。サイズ及び重量の制約は、使用され得るバッテリーのサイズを制限する。同様に、デバイスのサイズ及び重量の制約は、構成要素の精巧さに起因してバッテリー交換を困難にする。デバイスの寸法および衛生状態の懸念事項は、バッテリーの再充電を可能にする追加の充電ポートを組み込むことを困難にする。本明細書で説明されたシステム及び方法は、補聴器に組み込まれることができ、必要なバッテリーのサイズを低減して更に小さい補聴器を可能にすることができる。本明細書で開示された原理を使用することにより、補聴器のバッテリーは、外部接続または充電ポートを必要とせずに再充電され得る。充電およびデバイス回路および小さい再充電可能バッテリーは、既存の補聴器に組み込むことを可能にする従来の補聴器のバッテリーのフォームファクタに組み込まれ得る。補聴器は、人により使用および着用されている間に再充電され得る。エネルギー供給源は、パッド又はカップに組み込まれることができ、それにより補聴器が係る構造体に配置された場

合に再充電されることが可能になる。充電供給源は、補聴器が乾燥または殺菌されている間にワイヤレス再充電を可能にする補聴器乾燥箱に組み込まれ得る。また、供給源共振器およびデバイス共振器はデバイスを加熱するためにも使用されることができ、追加の加熱素子の必要性を低減または取り除く。バッテリー又はＡＣアダプターにより電力供給される携帯型充電ケースは、保管および充電ステーションとして使用され得る。

【０４２６】

上記で説明された医療システム用の供給源共振器は、患者のセンサ及びデバイスのデバイス共振器と共に、医療機器の一部または全ての本体内にあることができ、又は供給源共振器は、患者のセンサ及び機器の一部または全ての本体のデバイス共振器と共に、救急車内にあることができ、又は医療機器が救急車内にある間に、第一の供給源共振器が医療機器のデバイス共振器に無線電力を伝送するために救急車内にあり、医療機器が救急車から離れる場合に、患者のセンサの第２のデバイス共振器に無線電力を伝送するために第二の供給源共振器が医療機器の本体内にあるなどである。本明細書で説明されたシステム及び方法は、医療関係者が患者を或る場所から別の場所に輸送することができる容易さを大幅に改善することができ、この場合、電源ワイヤ、及び関連したバッテリーを交換または手動で充電する必要性が直ちに低減され得る。

【０４２７】

本明細書で説明されたシステム及び方法は、戦車、装甲輸送車、可動式シェルターなどのような軍用車両または軍事施設内のデバイスの充電のために使用され得る。例えば、兵士が「戦闘」または作戦の後で車両に戻る場合、彼らは一般に電子デバイスを充電し始める。彼らの電子デバイスがデバイス共振器を備えており、供給源共振器が車両の内部にある場合（例えば、車両の座席または天井に組み込まれた）、彼らのデバイスは即座に充電を始める。実際には、同じ車両が、車両の外に立っている又は車両のそばを歩いている兵士／ロボット（iRobot（登録商標）からのPackBot（登録商標））に電力を供給することができる。この能力は、他の誰かとの偶発的なバッテリー交換を最小限にすることに（これは、兵士が自分のバッテリーだけを信用する傾向があるので、重要な問題である）、又は攻撃を受ける車両からのより迅速な退去を可能にすることに、又は「困難な状況」および／または減少した可視性の場合に、速くあちこち移動するための能力が低減されるという点で、戦車内の非常に多くのワイヤは危険を及ぼす可能性があるので、戦車の内部でラップトップコンピュータ又は他の電子デバイスに対して電力供給または充電することなどに有用である。本明細書で説明されたシステム及び方法は、軍事環境において携帯型電力機器に電力供給することに関連して著しい改善を提供することができる。

【０４２８】

本明細書で説明されたシステム及び方法は、ゴルフカート又は他のタイプのカート、オフロード車両、電気バイク、スクータ、車、芝刈り機、Bobcat（登録商標）及び建設および造園に一般に使用される他の車両などのような移動車両に、無線電力供給または充電の能力を提供することができる。本明細書で説明されたシステム及び方法は、小型のヘリコプター、空中の無人飛行機、遠隔制御飛行機、遠隔制御ボート、遠隔制御またはロボット探査車、遠隔制御またはロボット芝刈り機または機器、爆弾検出ロボットなどのような小型移動車両に、無線電力供給または充電の能力を提供することができる。例えば、視界を増加させるために軍用車両の上を飛行する小型のヘリコプターは、標準のバッテリーで数分間、飛行することができる。これら小型のヘリコプターがデバイス共振器を取り付けられ、制御車両が供給源共振器を有する場合、小型のヘリコプターは、いつまでも飛行することができる。本明細書で説明されたシステム及び方法は、小型の移動車両で使用するためのバッテリーを再充電または交換するための有効な代替案を提供することができる。更に、本明細書で説明されたシステム及び方法は、微小電気機械システム（ＭＥＭＳ）、ナノロボット、ナノデバイスなどのような更に小さいデバイスに電力供給／充電を行うことができる。更に、本明細書で説明されたシステム及び方法は、デバイス共振器を備えた移動車両の近傍に自発的に自身を配置することができる、出張または飛行中再充電器としての機能を果たすことを可能にするために移動車両または飛行するデバイスに供給源共振器

を設置することにより、実現され得る。

【０４２９】

本明細書で説明されたシステム及び方法は、電力発生装置のような電源が必要とされ、電源ケーブルが一般に仮設設備のあちこちに引かれる、軍事キャンプ、石油採掘設備、人里離れた映画撮影の場所などのような仮設設備に電力網を提供するために使用され得る。電力を必要とする仮設設備を設ける必要がある場合の多くの例が存在する。本明細書で説明されたシステム及び方法は、これら設備を迅速に設けて解体するためのより効率的な方法を可能にすることができ、施設の全体にわたって電源まで引かれる必要があるワイヤの数を低減することができる。例えば、特殊部隊が或る領域に移る場合、彼らはテントを建てて、必要な電力を提供するためにキャンプのあちこちに多くのワイヤを引く。代わりに、本明細書で説明されたシステム及び方法により、電源および供給源共振器を取り付けた軍用車両がキャンプの中央に駐車して、近くのテントに全ての電力を供給することが可能になり、この場合、デバイス共振器はテントに、又は各テント又は領域に関連した何らかの他の機器の一部に組み込まれ得る。一連の供給源共振器－デバイス共振器－供給源共振器－デバイス共振器を用いて、更に遠くに離れたテントに電力を延ばすことができる。即ち、車両に最も近いテントが、それらの背後のテントに電力を供給することができる。本明細書で説明されたシステム及び方法は、仮設物が設けられて解体され得る効率性に著しい改善を提供することができ、かくして関連した設備の動きやすさが改善される。

【０４３０】

本明細書で説明されたシステム及び方法は、車両で使用されることができ、例えば、ワイヤの交換のために、新しい機器の設置に、車両に持ち込まれるデバイスの電力供給に、車両（例えば、従来のガソリンエンジン、ハイブリッド車、電気自動車など）のバッテリーの充電に、車両の室内または室外に取り付けられたデバイスの電力供給に、車両の近傍にあるデバイスの電力供給などに使用され得る。例えば、本明細書で説明されたシステム及び方法は、車両の全体にわたって分散されたライト、送風機、及びセンサに電力供給するために使用されるようなワイヤを置き換えるために使用され得る。一例として、一般的な車は、それに関連した５０Ｋｇのワイヤを有する場合があり、本明細書で説明されたシステム及び方法を使用することにより、この配線のかなりの量を取り除くことを可能にすることができる。飛行機または人工衛星のような、より大きくてより重量に敏感な車両の性能は、車両の全体にわたって引かれる必要があるケーブルの数を低減することから著しく恩恵を受けることができる。本明細書で説明されたシステム及び方法は、電気ハーネスを必要とせずに、車両の取り外し可能な又は追加の部分を電気および電子デバイスと適合させることを可能にすることができる。例えば、オートバイは、長旅を続ける場合に一時的なトランク空間としての役割を果たす取り外し可能なサイドボックスを有することができる。これらサイドボックスは、外部ライト、内部ライト、センサ、自動車用品などを有することができ、本明細書で説明されたシステム及び方法を備えていない場合には、電気接続およびハーネスを必要とする。

【０４３１】

車載の無線電力送信システムは、車で使用される１つ又は複数のモバイル機器、即ち携帯電話機、ブルートゥースヘッドセット、ブルートゥースのハンズフリースピーカーフォン、ＧＰＳ、ＭＰ３プレイヤ、ＦＭおよびブルートゥースを介したカーステレオを通してＭＰ３オーディオをストリーミングするための無線オーディオトランシーバなどに対して充電または電力供給を行うことができる。車載の無線電力供給源は、ダッシュボード上のパッドを充電、もしそうでなければ床、又はシートとセンターコンソールの間に装着されたパッドを充電、及びカップホルダー内に又はダッシュボード上に適合する「カップ」又はレセプタクルを充電することを含む、任意の幾つかの可能な構成で構成され得る供給源共振器を利用することができる。

【０４３２】

無線電力送信供給源は、再充電可能なバッテリーシステムを利用することができ、そのため当該供給バッテリーは、車両の電源がオンであるときはいつでも充電され、そのため

車両がオフにされた場合に、無線電源が供給バッテリーから電力を引き出すことができ、車内に依然としてあるモバイル機器に対してワイヤレスで充電または電力供給することを続けることができる。

【０４３３】

未来のプラグイン電気自動車、及びハイブリッド車などは、充電される必要があり、ユーザは、ユーザが家または充電ステーションに着く場合に、電源にプラグ接続する必要がある。単一の夜間の再充電に基づいて、ユーザは、翌日、８０．４５Ｋｍ（５０マイル）まで運転することができる。従って、ハイブリッド車の例において、人が大半の日において８０．４５Ｋｍ（５０マイル）未満を運転する場合、それは主として電気で駆動されている。しかしながら、人が夜に車のプラグ接続を行うことを記憶に留める必要がない場合には、有益になるであろう。即ち、車を単にガレージに入れるだけで良く、車自体の充電の面倒を車に見させる。この目的を達成するために、供給源共振器は、ガレージの床および／またはガレージの側壁に組み込まれ、デバイス共振器は車の底面（又は側面）に組み込まれ得る。数ｋＷの伝送でも夜間の車の再充電には十分とすることができる。車載のデバイス共振器は、固定された共振供給源に対する車両（又は任意の類似したデバイス）の位置合わせを支援するように、フィードバックを提供するために磁界特性を測定することができる。車両は、この位置のフィードバックを用いて、自動的にそれ自体を位置決めし、最適な位置合わせを達成し、かくして最適な電力送信効率を達成することができる。別の方法は、車両が良好に位置決めされた場合に、例えばＬＥＤを点灯させる、ノイズを提供するなどにより、車両またはデバイスを適切に位置決めするように人間の操作者を支援するために当該位置のフィードバックを使用することとすることができる。そのような場合に、送信されている電力量が活性領域の体積に侵入する人または動物に対して安全上の問題をもたらす可能性がある場合、供給源または受信器デバイスは、活性光のカーテン、又は当該活性領域の体積への侵入を検知することができ、且つ供給源デバイスを止めることができる何からの他の外部デバイスを備えて、人間の操作者に警告することができる。更に、供給源デバイスは、自己検知能力を備えることができ、そのためそれは、その予想される電力送信率が侵入要素により妨害されているかを検知し、その場合は供給源デバイスを止めて人間の操作者に警告することができる。開き戸または空気注入式ブラダー保護物のような物理的または機械的構造体が、望まれていない侵入を防止するために物理的なバリアとして組み込まれ得る。また、光学的、磁気的、容量性、誘導的などのようなセンサは、無関係な構造体、又は供給源共振器とデバイス共振器との間の干渉を検出するために使用され得る。供給源共振器の形状は、水またはゴミの蓄積を防ぐように形作られ得る。供給源共振器は、円錐形の筐体内に配置され得るか、或いは水およびゴミが転がって落ちることを可能にするように傾斜した上面を備える筐体を有することができる。システムの供給源は、車両のバッテリー電力またはそれ自体のバッテリー電力を使用して、その存在を供給源に伝え、電力送信を開始することができる。

【０４３４】

供給源共振器は、電気自動車のバンパー、ボンネット、車体パネルなどに取り付けられたデバイス共振器に結合するために、壁、台などに埋め込まれた又はぶら下がったポスト（柱）に取り付けられ得る。供給源共振器は、クッション、パッド、ベロー、バネで留められた筐体などのようなフレキシブルな筐体に収容される又は埋め込まれることができ、そのため電気自動車は、決して車を損傷せずに、供給源コイルを包含する構造体と接触することができる。供給源を包含する構造体は、供給源共振器とデバイス共振器との間に物体が入ることを防止することができる。無線電力伝送は、供給源コイルとデバイスコイルとの間の位置合わせ不良に比較的影響を受けないので、様々なフレキシブルな供給源構造体および駐車手順は、この応用形態に適切とすることができる。

【０４３５】

本明細書で説明されたシステム及び方法は、電気自動車、ハイブリッド車、燃焼機関自動車のバッテリーをトリクル充電するために使用され得る。車両は、バッテリーの電力を維持または補充するために小量の電力を必要とする。電力は、車両のフロントグリル、屋

根、底面、又は他の部品に組み込まれ得るデバイス共振器に、供給源からワイヤレスで伝送され得る。デバイス共振器は、ラジエータを流れる空気を妨害しないように、車両の前面、又はグリルの周りのロゴの形状に適合するように設計され得る。デバイス共振器または供給源共振器は、車両から雪または氷を溶かすために使用され得る加熱素子として共振器が使用されることを可能にする追加の動作モードを有することができる。

【０４３６】

電気自動車またはハイブリッド車は、当該車両が充電のために供給源共振器の近傍に到達できる容易性を増加するように（即ち、より大きな数およびより大きく多様な位置のデバイス共振器は、車両が多種多様の充電ステーションに停車して、当該充電ステーションに接続して機能する可能性がより大きい）、或る時間期間に伝えられ得る電力量を増加するように（例えば、追加のデバイス共振器が許容可能なレベルまで電流を充電することに起因した局所的な加熱を防ぐために必要とされ得る）、及び充電ステーションに自動的に車両を止める（駐車）／結合させる際に支援するなどのように、多数のデバイス共振器を必要とする場合がある。例えば、車両は、最適化された充電状態（即ち、充電ステーションの供給源共振器に対する車両のデバイス共振器の最適な位置決めは、より大きな電力伝送効率を提供する）に関して運転者、又は車両の駐車場の自動駐車／結合設備に案内を提供するフィードバックシステムを備えた多数の共振器（又は単一の共振器）を有することができる。自動駐車／結合設備は、車両が如何に良く結合されるかに基づいて、車両の自動駐車を可能にすることができる。

【０４３７】

電力送信システムは、車両のデバイス及び周辺機器に電力供給するために使用され得る。周辺機器に対する電力供給は、車両が充電されている間に、又は充電されていない間に行われることができ、或いは電力は、充電をしなくてもよい従来の車両に伝えられ得る。例えば、電力は、ガレージの駐車場またはローディングドックで排ガスが蓄積するのを避けるために重要である、エンジンの動作を回避するように駐車されている間に、空調、冷凍ユニット、ヒータ、ライトなどに電力供給するために、従来の非電気自動車にワイヤレスで伝送され得る。電力は、例えば、駐車されている間にバスにワイヤレスで伝送され、搭載されたエンジン又は電源の使用を避けて、ライト、周辺機器、乗客のデバイスなどに電力供給することを可能にすることができる。電力は、駐機場またはハンガーに駐機されている間に航空機にワイヤレスで伝送され、搭載されたエンジン又は電源を使用する必要なしに、計器装備、温度調節器、防氷装置などに電力供給することができる。

【０４３８】

車両での無線電力送信は、ビークルトゥグリッド（Ｖ２Ｇ）の概念を可能にするために使用され得る。ビークルトゥグリッドは、分散されたエネルギー蓄積デバイスとして電気自動車およびプラグインハイブリッド電気自動車（ＰＨＥＶ）を利用することに基づいており、当該電気自動車およびプラグインハイブリッド電気自動車（ＰＨＥＶ）は、配電網が活用されていない夜に充電され、昼間に生じるピーク需要の出現の間に配電網へ戻すように放電するために利用可能である。車両および個々のインフラでの無線電力伝送システムは、プラグイン接続を必要とせずに、双方向のエネルギーの流れを可能にするように（その結果、エネルギーは車両から配電網へ逆流することができる）、実現され得る。工場、オフィス、駐車場に駐車された膨大な全車両は、スマートグリッドによって「ピーク電力能力（peaking power capacity）」とみなされ得る。車両での無線電力送信は、係るＶ２Ｇビジョンを現実のものにすることができる。配電網に車両を接続するプロセスを簡略化することにより（即ち、無線充電可能な駐車場に単に車両を止めることにより）、配電網が電力を利用する必要がある場合に特定数の車両が「派遣され得る」という可能性がより高くなる。無線充電を用いない場合、電気自動車および（ＰＨＥＶ）の所有者は、恐らく家で車両を充電し、職場で従来の駐車場に車両を止める。充電をする必要がない場合に、だれが職場で車両をプラグ接続することを望むであろうか？３ｋＷを取り扱うことができる無線充電システムの場合、１００，０００台の車両が３００メガワットを配電網に戻すことができる（コスト効率の良いベースロード発電能力により、以前に夜に生成された

エネルギーを用いて）。それは、実行可能なＶ２Ｇエネルギー源にする、ＰＨＥＶ車両および電気自動車のコードレス自己充電の合理化された人間工学である。

【０４３９】

本明細書で説明されたシステム及び方法は、空気圧を測定するためのタイヤ内のセンサのような車両のセンサに電力供給するために、又は携帯電話、ＧＰＳ装置、ナビゲーション装置、ゲーム機、オーディオ又はビデオプレイヤ、ＤＶＤプレイヤ、無線方式ルータ、通信機器、盗難防止装置、レーダー装置などのような、車両内の周辺機器を動作させるために使用され得る。例えば、本明細書で説明された供給源共振器は、車のメインコンパートメントに組み込まれて、車のメインコンパートメントの内側と外側に位置する様々なデバイスに電力を供給することができる。車両がオートバイなどである場合、本明細書で説明されたデバイスは、オートバイの本体、例えばシートの下に組み込まれることができ、デバイス共振器は、例えば通信、娯楽、信号を発するなどのために、ユーザのヘルメットに設けられ得るか、又はデバイス共振器は、例えば安全のために他の運転者に信号を表示するなどのために、ユーザのジャケットに設けられ得る。

【０４４０】

本明細書で説明されたシステム及び方法は、道路、列車、航空機、船舶輸送などのような交通インフラと連係して使用され得る。例えば、供給源共振器は、道路、駐車場、鉄道線路などに組み込まれ得る。供給源共振器は、信号機、標識などに組み込まれ得る。例えば、供給源共振器が道路に埋め込まれ、デバイス共振器が車両に組み込まれる場合、車両は、道路に沿って走行する際に、又は道路の区画または道路脇に駐車される際に電力を供給され得る。本明細書で説明されたシステム及び方法は、車両が道路網または道路網の一部を通過する間に電力供給および／または充電されるべき、車両の電気システムに効果的な方法を提供することができる。このように、本明細書で説明されたシステム及び方法は、自律走行車、無人搬送車などの電力供給／充電に寄与することができる。本明細書で説明されたシステム及び方法は、車両が一般にアイドリング又は停止する所々で、例えば、信号機または標識の近傍で、高速道路の出入道路で、又は駐車場などで、車両に電力を供給することができる。

【０４４１】

本明細書で説明されたシステム及び方法は、産業環境で、例えば機械装置に電力供給するために、ロボットの電力供給／充電のために、ロボットアームの無線センサの電力供給および／または充電のために、工具の電力供給／充電などのために工場の内部で、使用され得る。例えば、ロボットのアームのデバイスに電力を供給するために本明細書で説明されたシステム及び方法を用いることは、ロボットアームのジョイント（関節）を横切る直接的なワイヤ接続を取り除くことに役立つことができる。このように、係る直接的なワイヤ接続からの摩耗が低減され、ロボットの信頼性が向上することができる。この場合、デバイス共振器はロボットのアーム上の外にあり、供給源共振器は、ロボットの基部にあることができ、ロボットの近くの中心位置にあることができ、ロボットがサービスを提供している産業施設に組み込まれ得るなどである。本明細書で説明されたシステム及び方法の使用は、産業施設内での配電に関連した配線を取り除くことに役立ち、ひいては当該施設の総合的な信頼性に利することができる。

【０４４２】

本明細書で説明されたシステム及び方法は、掘削、採鉱、採掘などのような地下の応用形態に使用され得る。例えばボーリング又は掘削に関連した電気構成要素およびセンサは、本明細書で説明されたシステム及び方法を利用して、掘削機構、掘削ビットなどに関連したケーブル敷設をなくし、かくして掘削点の近くのケーブル敷設がなくなる又は最小限にされる。別の例において、本明細書で説明されたシステム及び方法は、採鉱の応用形態において掘削機器に電力を供給するために使用されることができ、この場合、当該機器の電力要件は高く且つ距離は大きいが、関連した必要な場にさらされる人は存在しない。例えば、掘削領域は、高い電力要件を有する掘削機器に電力供給するデバイス共振器を有することができ、供給源共振器から比較的遠くで掘削することができる。結果として、供給

源共振器は、これら要件を満たすために高い磁界強度を提供する必要があるが、職員はこれら高い強度の場の外側にいるように十分に遠く離れている。職員のいないこの高電力の状況は、複数の工業的応用形態に適用可能である。

【０４４３】

また、本明細書で説明されたシステム及び方法は、電力伝送の代わりに、又は電力伝送に加えて、情報伝送のために近接場の非放射共振方法を使用することができる。例えば、近接場の非放射共振技術により伝送されている情報は盗聴されにくく、そのため従来の無線通信方法に比べてセキュリティのレベルを上げることができる。更に、近接場の非放射共振技術により伝送されている情報は、ＥＭ放射スペクトルと干渉せず、そのためＥＭ干渉源になることができないことにより、拡大された周波数範囲内で且つ任意の規制機関により設定された制限の十分な範囲内で通信が可能になる。通信サービスは、例えば遠く離れたセンサ間、トンネル、洞窟および井戸（例えば、油井、他の掘削地点）におけるデバイス又は車両のセクション間、及び水中または地下のデバイス間などのような、遠く離れてアクセスできない又は到達しづらい場所間で提供され得る。通信サービスは、磁界が電界より少ない損失を蒙る所々で提供され得る。

【０４４４】

本明細書で説明されたシステム及び方法は、無線電力送信システムにおいて、供給源とデバイスとの間で電力および通信信号の同時送信を可能にすることができる、或いは異なる時間期間の間に又は異なる周波数で電力および通信信号の送信を可能にすることができる。共振器の性能特性は、エネルギー又は情報伝送の効率性または範囲を優先的にサポート又は制限するように制御可能に変更され得る。例えば、共振器の性能特性は、情報伝送の範囲を低減することにより、セキュリティを改善するために制御され得る。共振器の性能特性は、連続的に、周期的に、或いは所定のアルゴリズム、計算されたアルゴリズム又は自動調整されるアルゴリズムに従って変更され得る。例えば、本明細書で説明されたシステム及び方法により可能にされる電力および情報の伝送は、時分割または周波数分割の方法で行われ得る。供給源およびデバイスは、チューニング、変化、変更、ディザリングなどにより互いに信号を送ることができ、共振器のインピーダンスは、検出され得る他の共振器の反射インピーダンスに影響を及ぼすことができる。本明細書で説明されたように伝送される情報は、デバイスの識別、デバイス電力要件、ハンドシェーキングプロトコルなどに関連した情報を含むことができる。

【０４４５】

供給源およびデバイスは、電力網において任意の他の供給源および／またはデバイスに関する位置および場所の情報を検知、送信、処理および利用することができる。供給源およびデバイスは、供給源およびデバイスに組み込まれ得る、又は供給源およびデバイスが接続する構成要素の一部とすることができる様々なセンサおよび情報源からの、高度、傾き、緯度および経度などのような情報を捕捉または使用することができる。位置決め及び方向付けの情報は、全地球測位システム（ＧＰＳ）、コンパス、加速度計、圧力センサ、大気圧センサ、Wi-Fi又は携帯電話のネットワーク信号を使用する位置決めシステムなどのような情報源を含むことができる。供給源およびデバイスは、当該位置および場所の情報を使用して、近くの無線電力送信供給源を見つけることができる。供給源は一斉送信するか、或いは中央ステーション又はその場所を特定するデータベースと通信することができる。デバイスは、中央ステーション又はデータベースから、或いは局所的な放送から供給源の場所の情報を得ることができ、視覚的信号、振動的信号、又は聴覚的信号を利用して、ユーザ又は操作者を供給源に案内することができる。供給源およびデバイスは、電力網の、通信ネットワークの、センサネットワークの、ナビゲーションネットワークなどのノード、又は組み合わされた機能性ネットワークの類のノードとすることができる。

【０４４６】

また、当該位置および場所の情報は、電力供給を最適化または調整するために使用され得る。供給源およびデバイスの相対位置に関する追加情報は、磁場方向および共振器の位置合わせを最適化するために使用され得る。例えば、加速度計および磁気センサなどから

得られることができるデバイス及び供給源の位置関係は、磁束がデバイスの回路により阻止されないように、磁界の最も好適な方向と共振器の位置関係を特定するために使用され得る。係る情報を用いて、最も好適な位置関係を有する供給源、又は供給源の組合せが使用され得る。同様に、位置および位置関係の情報は、電力送信効率を最大化するために、損失を最小限にするなどのために好適な位置関係または場所にデバイスを配置するように、デバイスのユーザ又は操作者を動かす、又はデバイスのユーザ又は操作者にフィードバックを提供するために使用され得る。

【０４４７】

供給源およびデバイスは、電力計量および測定の回路および能力を含むことができる。電力計量は、どれぐらいの量の電力がデバイスに伝えられたか、又はどれぐらいの量の電力が供給源により伝送されたかを追跡するために使用され得る。電力計量および電力使用量の情報は、課金の目的のために、有料電力供給設備で使用され得る。また、電力計量は、電力が特定の基準に従って多数のデバイスに配電されることを確実にするように電力供給方針を可能にするために使用され得る。例えば、電力計量は、デバイスが受け取った電力量、及び電力供給において最も少ない電力を受け取ったデバイスに与えられ得る優先順位に基づいて、デバイスを分類するために使用され得る。電力計量は、別個の料率で課金され得る、「保証された電力」および「ベストエフォート型電力」のような段階的供給サービスを提供するために使用され得る。電力計量は、階層的電力供給構造を実施および実行するために使用されることができ、優先デバイスが、特定の状況または使用状況下で、より多くの電力を要求および受け取ることを可能にすることができる。

【０４４８】

電力計量は、電力供給の効率を最適化する、並びに吸収および放射損失を最小限にするために使用され得る。デバイスにより受け取られた電力に関連している情報は、望ましくない動作環境または周波数を識別するために、供給源の電力出力に関する情報と共に供給源により使用され得る。例えば、供給源は、デバイスにより受け取られた電力量と供給源が送信した電力量を比較し、送信損失が異常に又は許容できないくらい大きいかを判定する。大きな送信損失は、供給源からの電力を受け取る許可されていないデバイスに起因する可能性があり、供給源および他のデバイスは、許可されていない使用を防止または阻止するために、共振周波数の周波数ホッピング又は他の防御的測定を開始することができる。大きな送信損失は、例えば吸収損失に起因する可能性があり、デバイス及び供給源は、係る損失を最小限にするために共振周波数を変更するように調整することができる。また、大きな送信損失は、望まれていない又は未知の物体または材料の存在を示し、供給源は、その望まれていない又は未知の物体が除去される又は特定されるまで、その電力レベルを下げる又は止めることができ、係る物体が除去される又は特定された時に、供給源は遠隔デバイスの電力供給を再開することができる。

【０４４９】

供給源およびデバイスは、認証能力を含むことができる。認証は、相性が良い供給源とデバイスのみが電力を送受信することができることを確実にするために使用され得る。認証は、特定のメーカー製であり且つ他のメーカーからの複製品またはデバイス及び供給源でない真のデバイスのみ、或いは特定の予約申し込み又はプランの不可欠な要素であるデバイスのみが、供給源からの電力を受け取ることができることを確実にするために使用され得る。認証は、要求と応答の暗号プロトコルに基づくことができるか、又は特定のデバイスを使用可能にする当該特定のデバイスの摂動からなる一意の特徴（シグネチャ）に基づくことができ、物理的にコピー不可能な機能に類似した特性に基づいて認証される。認証は、局所的な通信を用いて各供給源とデバイスとの間で局所的に実行され得るか、又は第三者の認証方法と共に使用されることができ、この場合、供給源およびデバイスは中央権力部との通信で認証する。認証プロトコルは、位置情報を用いて、真のデバイスの局所的供給源（単数または複数）に警告することができる。

【０４５０】

供給源およびデバイスは、周波数ホッピング技術を用いて、無線電力供給源の許可され

ていない使用を防止することができる。供給源は、電力供給の共振周波数を連続的に調整または変更することができる。周波数の変更は、擬似ランダムの方法、又は再現可能であるが予測することが困難であると知られている所定の方法で実行され得るか、或いは許可されたデバイスに伝えられ得る。使用される周波数ホッピングのレート及び様々な周波数の数は、許可されていない使用が困難または実行不可能であることを十分に確実にするために大きく且つ頻繁にすることができる。周波数ホッピングは、インピーダンス回路網をチューニングすることにより、任意の駆動回路をチューニングすることにより、複数の共振周波数にチューニングされる又はチューナブルである複数の共振器を用いることなどにより実現され得る。

【０４５１】

供給源は、供給源がデバイス共振器に結合されて電力を送信しているか否か、供給源がスタンバイモードにあるか否か、又は供給源共振器が外部物体によりデチューンされている又は摂動を与えられているか否かに関して、供給源のステータスを示すためのユーザ通知能力を有することができる。当該通知能力は、視覚的方法、聴覚的方法、及び振動的方法を含むことができる。通知は、三色ライト（それぞれの色が各状態に対応）のように簡単にすることができ、オプションとして動作中のエラーの場合に通知を提供ためのスピーカとすることができる。代案として、通知能力は、供給源のステータスを示す、及びオプションとして特定された任意のエラー又は問題を如何にして修繕または解決するかに関する指示を提供する対話型ディスプレイを含むことができる。

【０４５２】

別の例として、無線電力伝送は、爆発物の電子雷管の安全性を改善するために使用され得る。爆破装置は、電子雷管、電気雷管、又は衝撃波管の起爆装置で爆発する。電子雷管は、導電的に又は無線により送信された低いエネルギーのトリガ信号でもって、イグナイター電荷を活性化するために、蓄電された電気エネルギー（通常、コンデンサに）を利用する。電気雷管は、イグナイター電荷を活性化するために必要な信号およびエネルギーを供給するために、高いエネルギーの導電性トリガ信号を利用する。衝撃波管は、爆発物でコーティングされた中空管を介して制御された爆発を発生器からイグナイター電荷まで送る。意図されない活性化（起動）を生じる漂遊電磁エネルギーが存在するので、電気雷管および電子雷管に関連した安全性の問題が存在する。鋭い共振磁気結合を介した無線電力伝送は、係るシステムの安全性を改善することができる。

【０４５３】

本明細書で開示された無線電力伝送の方法を用いることにより、局所的に蓄電されたエネルギーを備えない電子起爆システムが構築されることができ、かくして意図されない活性化の危険性が低減される。無線電力供給源は、起爆装置の近傍（数メートル以内）に配置され得る。起爆装置は、共振捕捉コイルを備えることができる。活性化エネルギーは、無線電力供給源がトリガされた場合に伝送され得る。無線電力供給源のトリガは、任意の数の機構、即ち無線、磁気近接場無線、導電性信号伝送、超音波、レーザ光により起動され得る。また、共振磁気結合に基づいた無線電力伝送は、岩、土、コンクリート、水、及び他の高密度物質のような構成物質を介して電力を伝送することができる利点を有する。受信器および供給源として、非常に狭い帯域応答を有し且つ専用周波数に鋭くチューニングされた非常に高いＱのコイルを使用することは、起爆装置の回路が漂遊ＥＭＩを捕捉することができず、且つ意図していない起動を行うことができないことを更に確実にする。

【０４５４】

ワイヤレスで電力供給されるデバイスの共振器は、外部またはデバイスの外側にあることができ、デバイスのバッテリーに配線され得る。デバイスのバッテリーは、デバイス共振器の交流電流を受け取るために、適切な整流および制御回路を含むように変更され得る。これは、キーボード又はマウスの電池蓋、又はデジタルスチルカメラに組み込まれ得るように、或いは更に大きなコイルがデバイスに取り付けられるが、リボンケーブルでバッテリー／コンバータに戻るように配線されるように、より大きな外部コイルを有する構成を可能にすることができる。電池蓋は、外部コイルからバッテリー／コンバータへの相互

接続（電池蓋のコンタクトに触れることができる露出されたコンタクトを必要とする）を提供するように変更され得る。

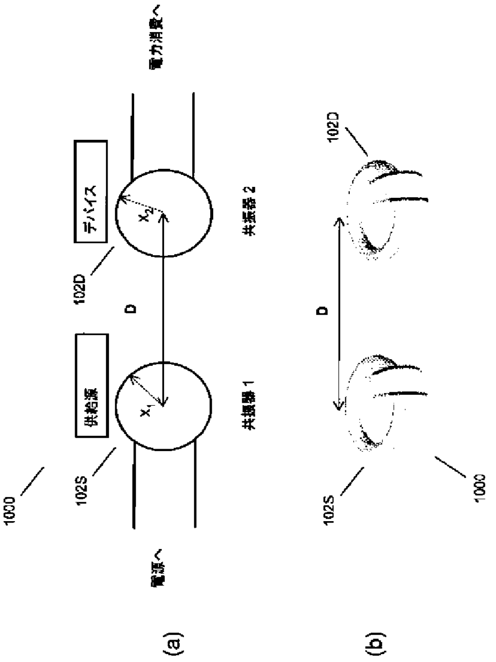
【０４５５】

本発明は、特定の好適な実施形態に関連して説明されたが、他の実施形態は、当業者により理解され、本発明の範囲内に入ることが意図され、法律によって許容可能な最も広い意味で解釈されるべきである。

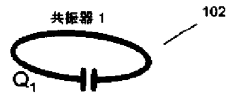
【０４５６】

本明細書で参照された全文献は、参照により本明細書に組み込まれる。

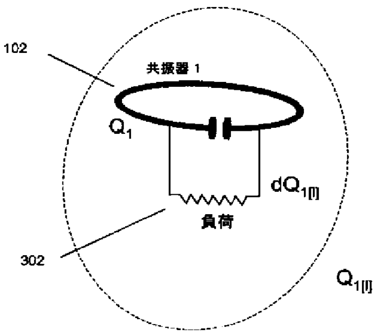
【図１】



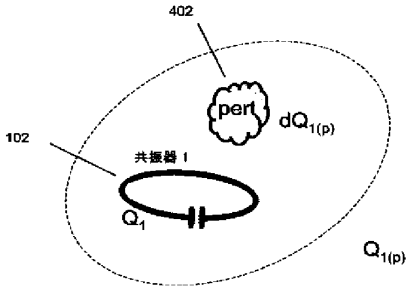
【図２】



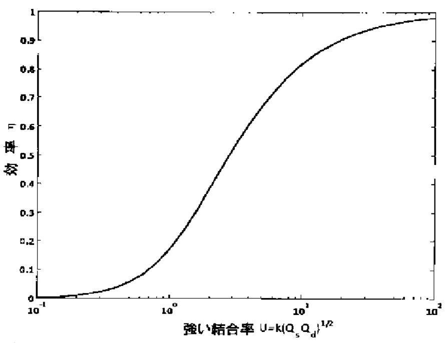
【図３】



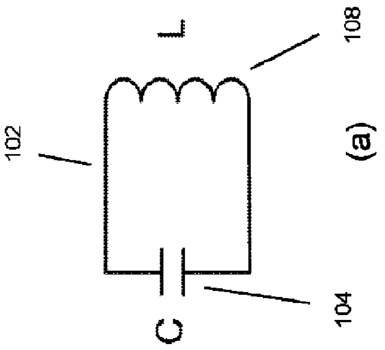
【図４】



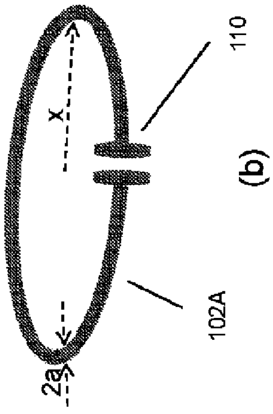
【図５】



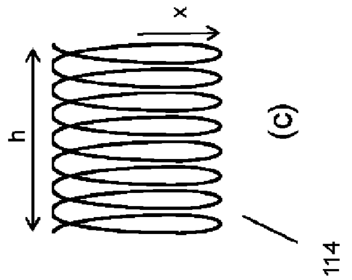
【図６（ａ）】



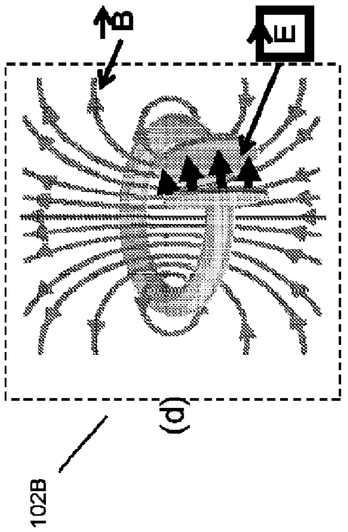
【図６（ｂ）】



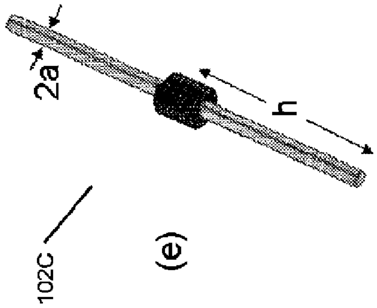
【図６（ｃ）】



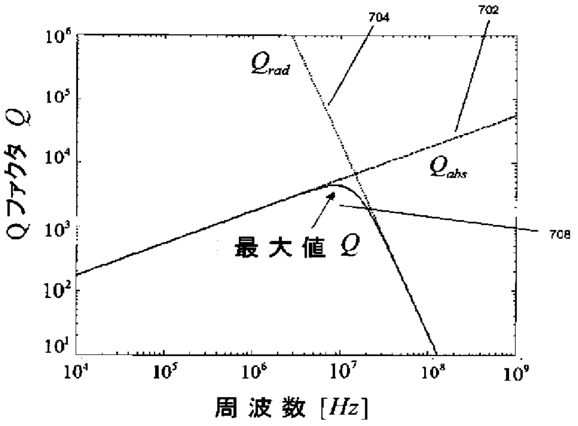
【図６（ｄ）】


B
E
(d)
102B

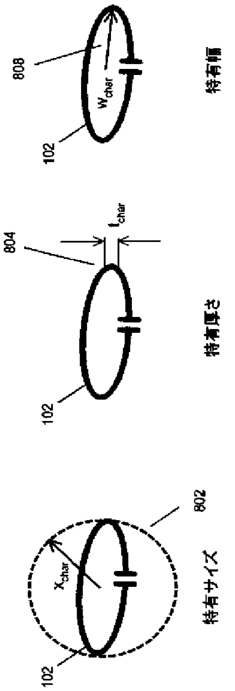
【図６（ｅ）】


2a
h
102C
(e)

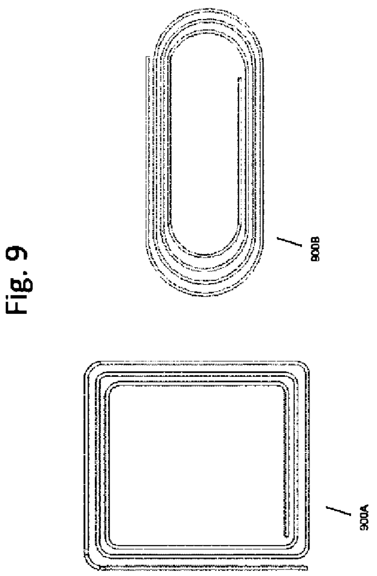
【図７】


704
702
Q_{rad}
Q_{abs}
最大値 Q
708
Qファクタ Q
10^6
10^5
10^4
10^3
10^2
10^1
10^4
10^5
10^6
10^7
10^8
10^9
周波数 [Hz]

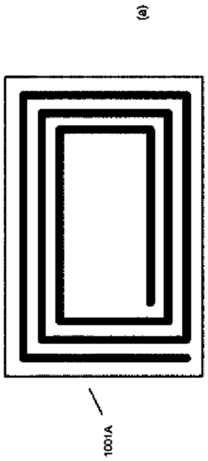
【図８】


808
w_{char}
102
特有幅
804
t_{char}
102
特有厚さ
802
x_{char}
102
特有サイズ

【図９】

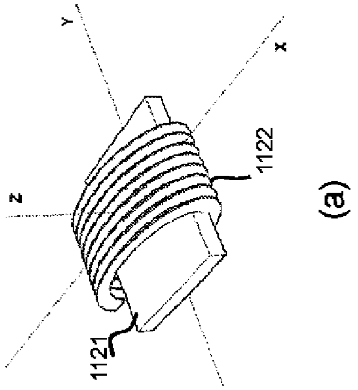


【図１０（ａ）】

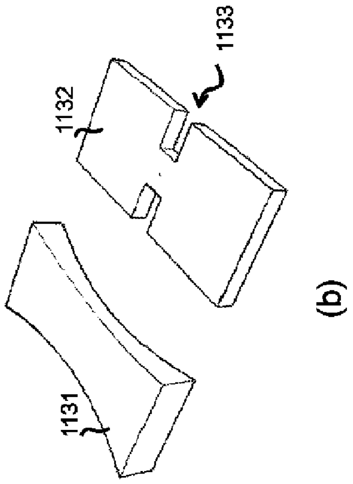


【図１０（ｂ）】

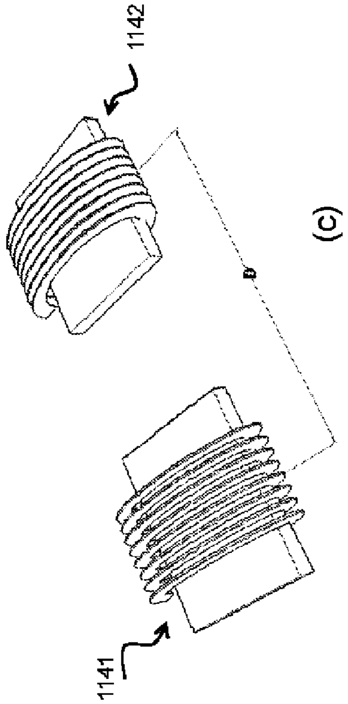
【図１１（ａ）】



【図１１（ｂ）】



【図１１（ｃ）】



【図１２】

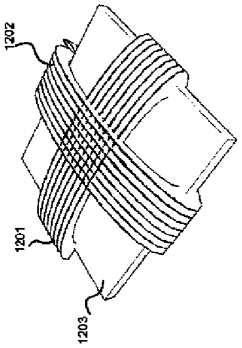


Fig. 12

【図１３】

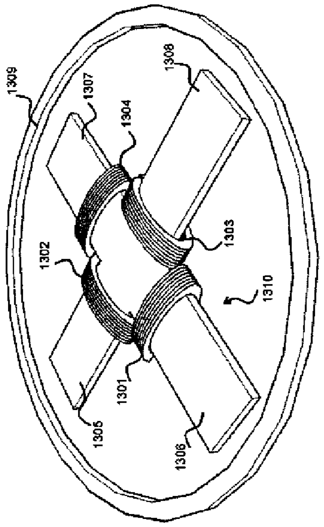


Fig. 13

【図１４】

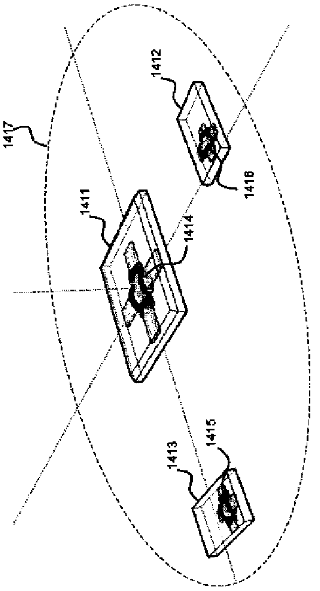


Fig. 14

【図１５】

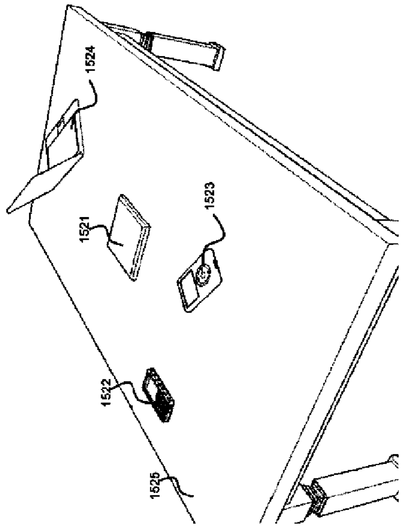
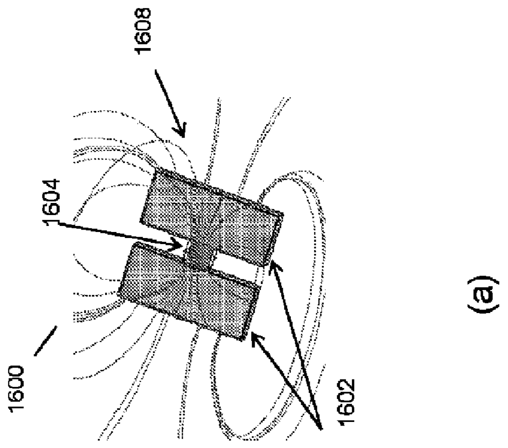
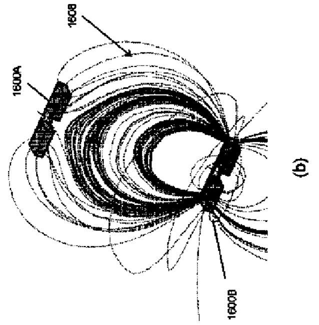


Fig. 15

【図１６（ａ）】

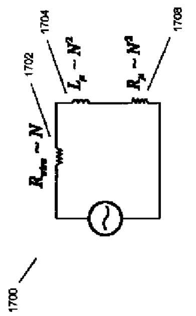


【図１６（ｂ）】

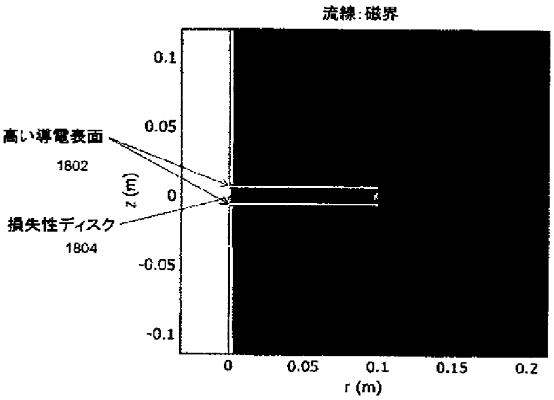


【図１７】

Fig. 17

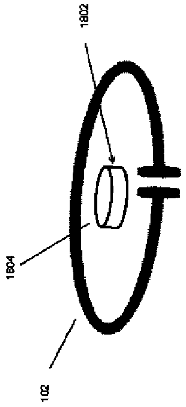


【図１８】



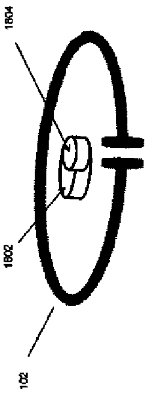
【図１９】

Fig. 19



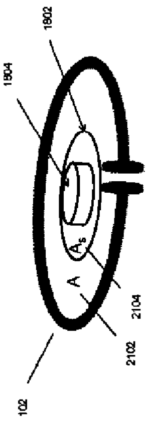
【図２０】

Fig. 20

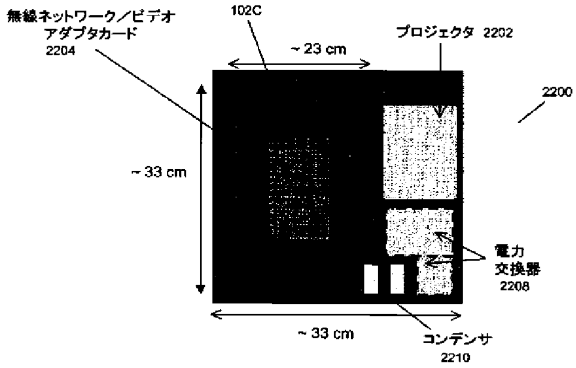


【図２１】

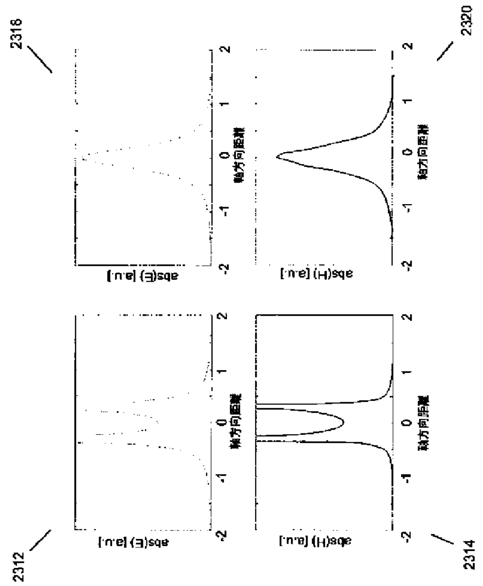
Fig. 21



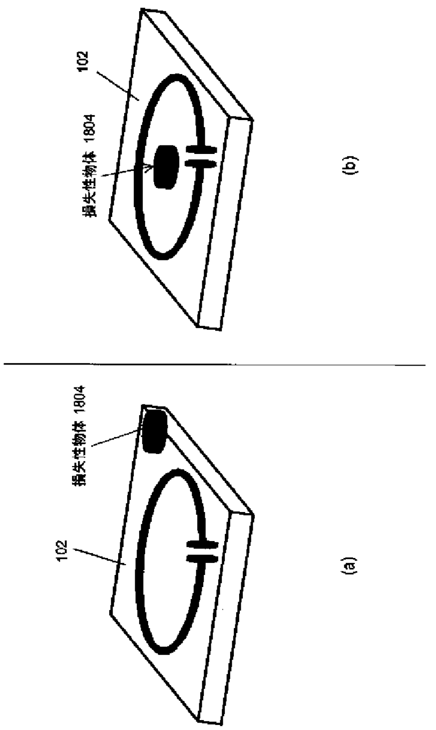
【図２２】



【図２３】

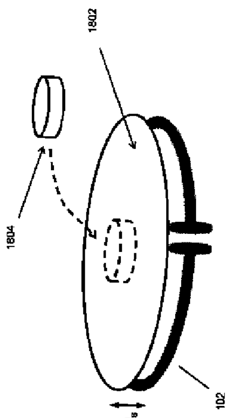


【図２４】



【図２５】

Fig. 25



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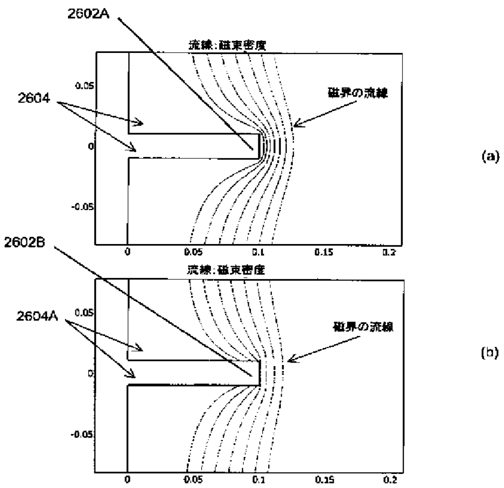

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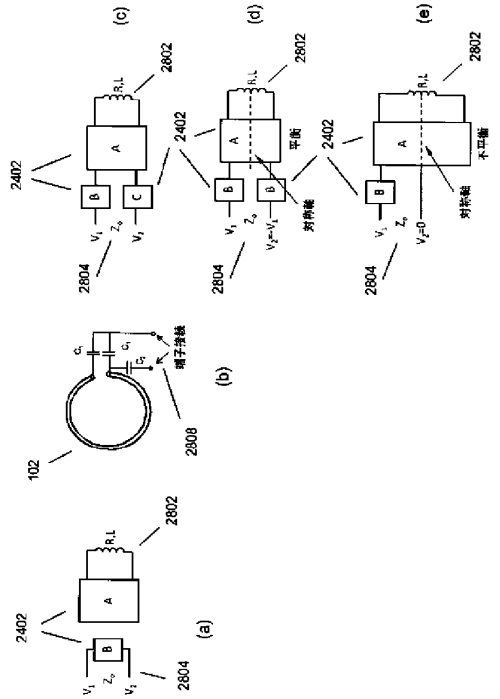
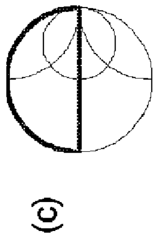


【図２９（ａ）】

【図２９（ｂ）】

【図２９（ｃ）】



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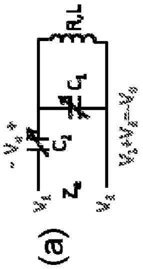

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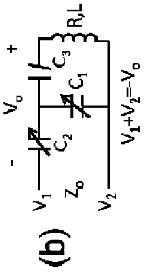

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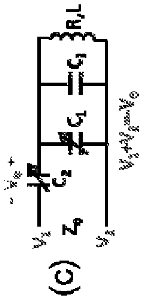

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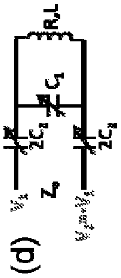

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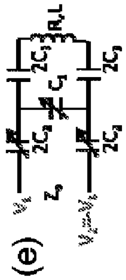

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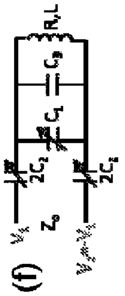

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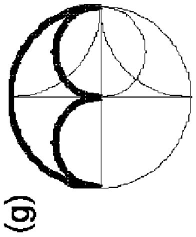

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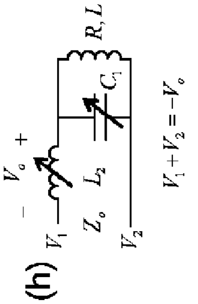

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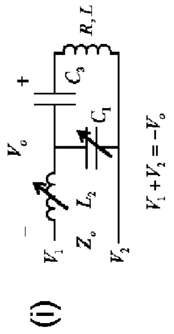

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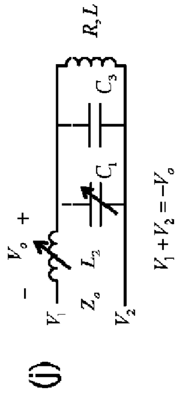

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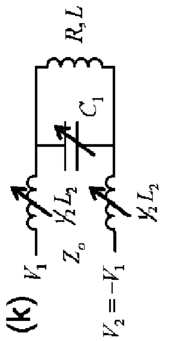

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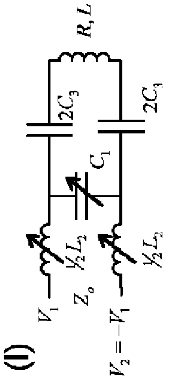

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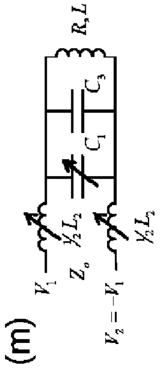

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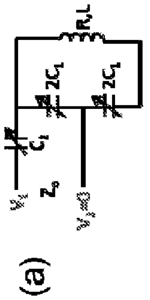

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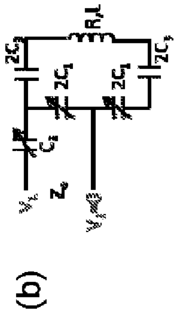

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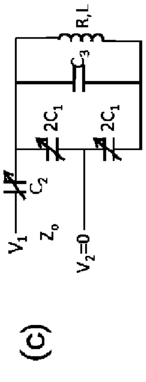

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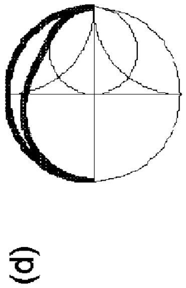

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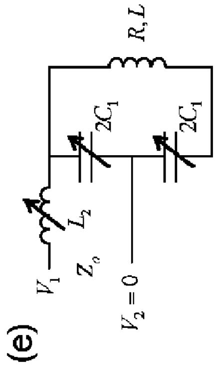

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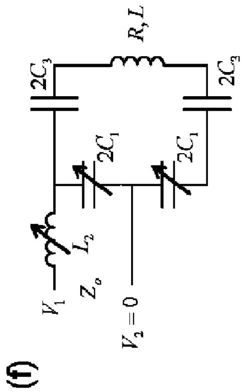

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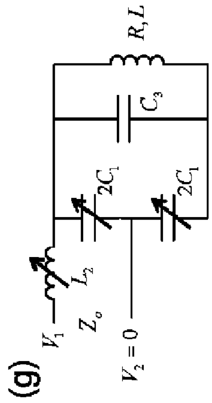

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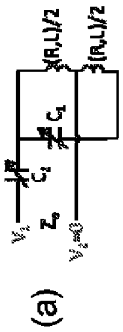

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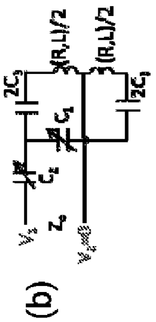

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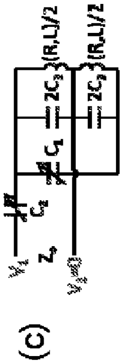

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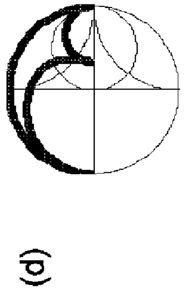

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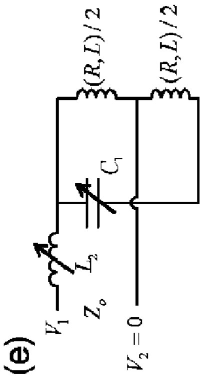

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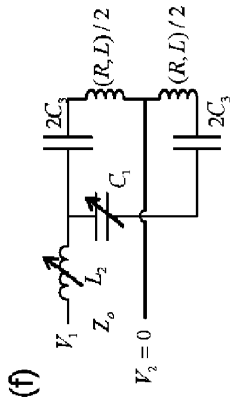

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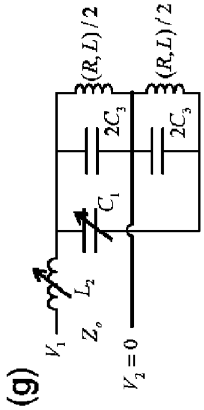

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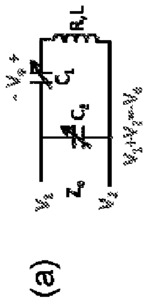

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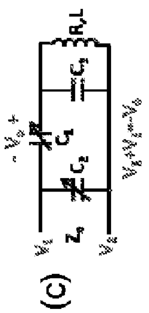

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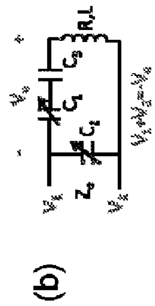

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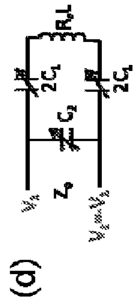

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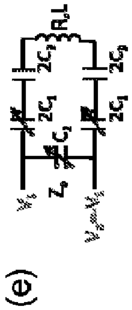

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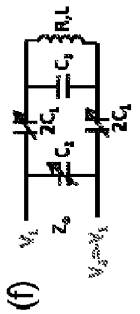

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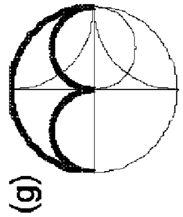

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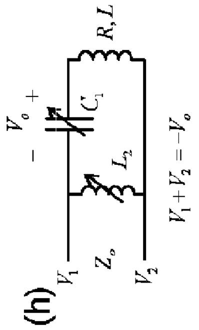

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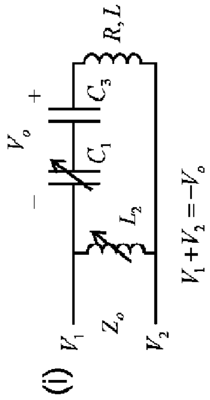

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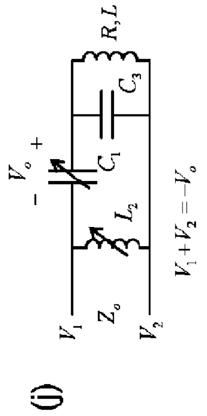

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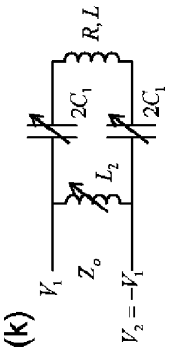

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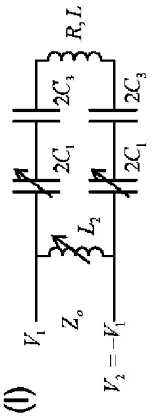

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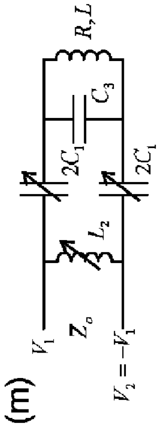

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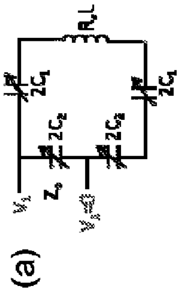

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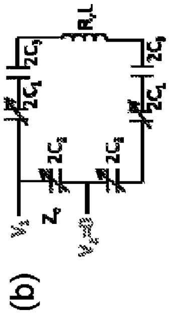

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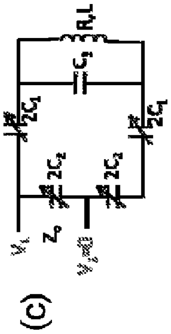

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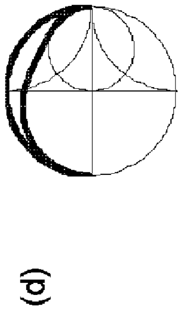

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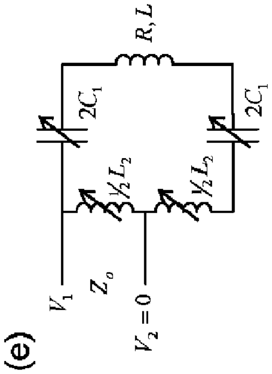

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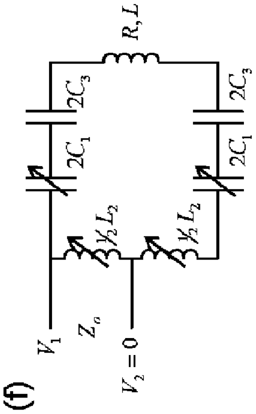

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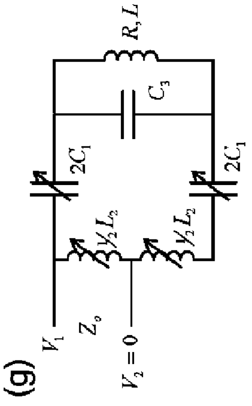

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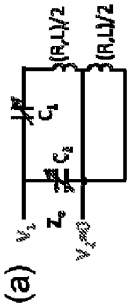

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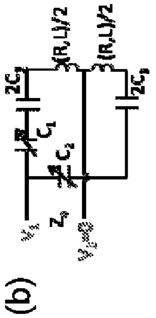

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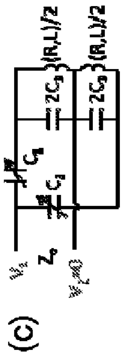

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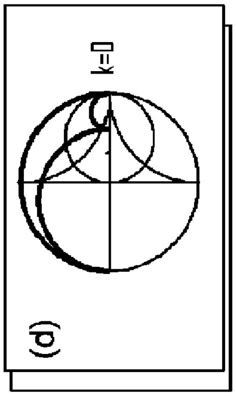

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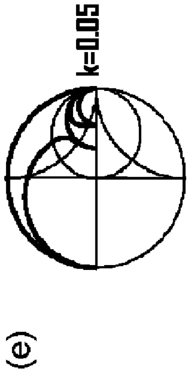

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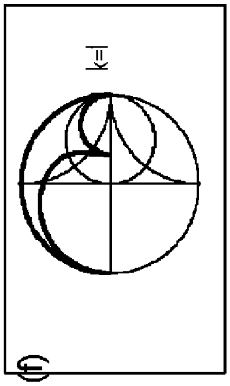

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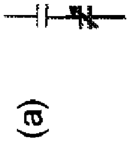

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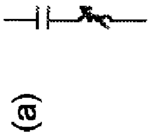

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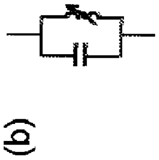

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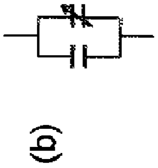

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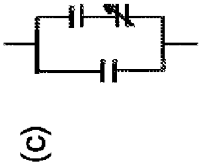

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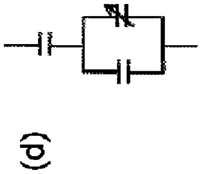

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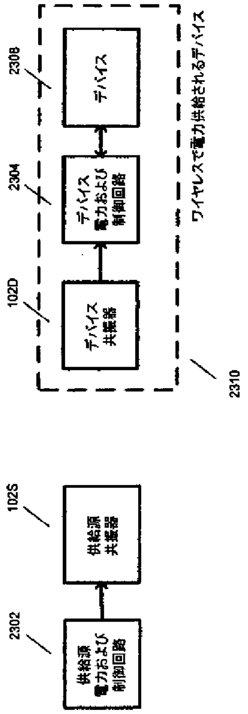
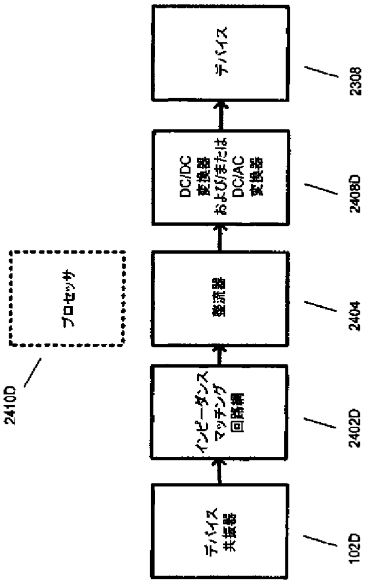
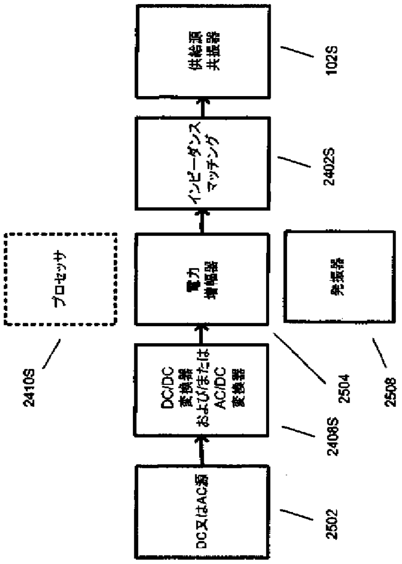


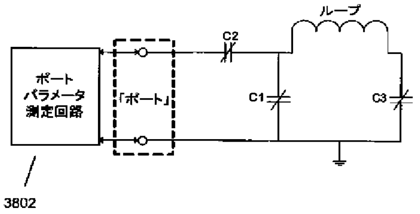
【図３９】



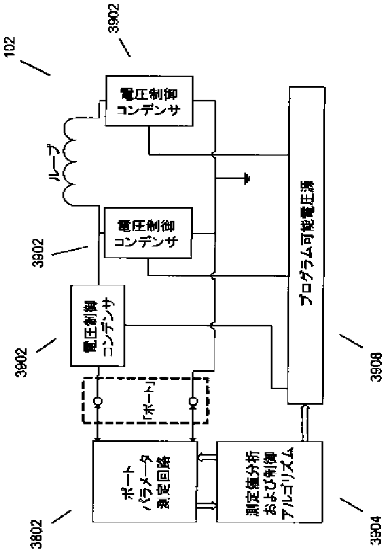
【図４０】



【図４１】



【図４２】



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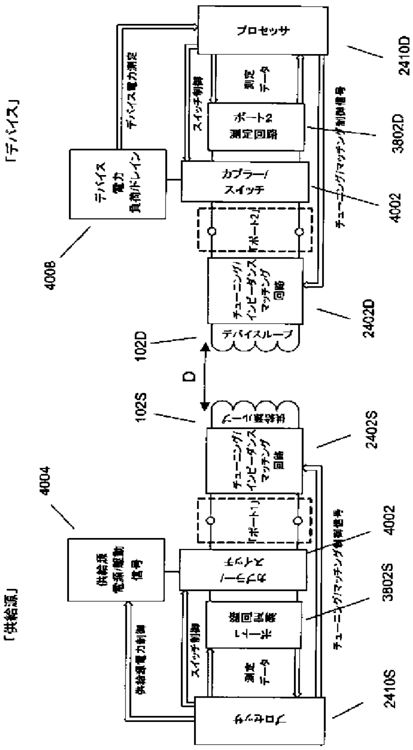
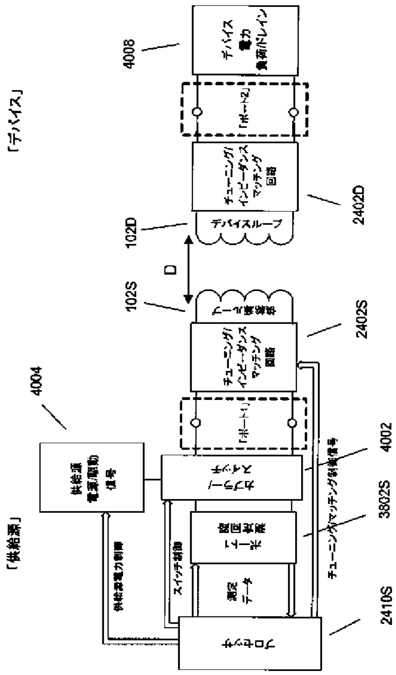


【図４４】



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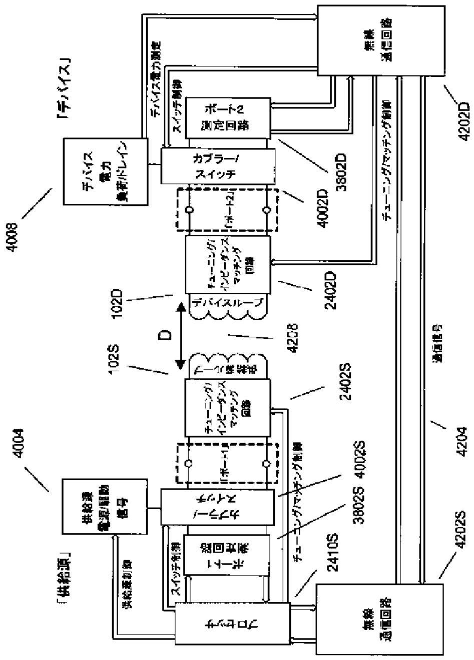

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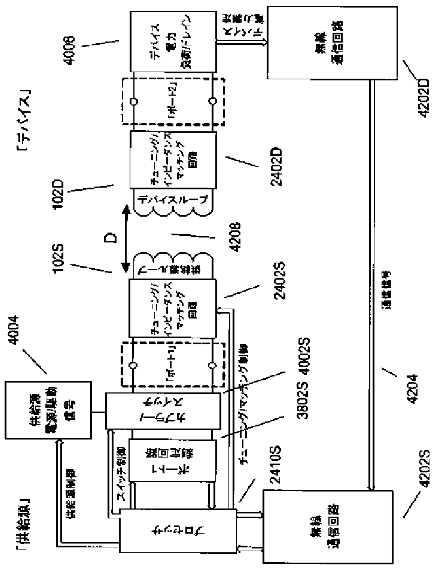

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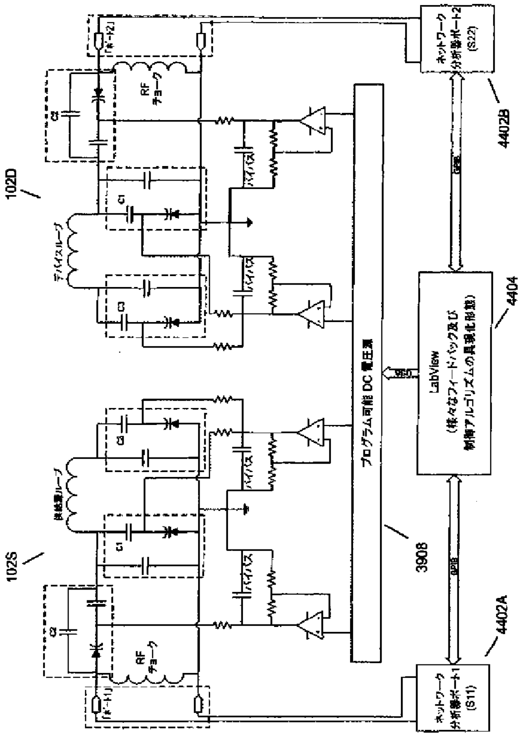

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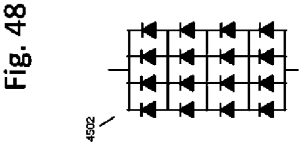

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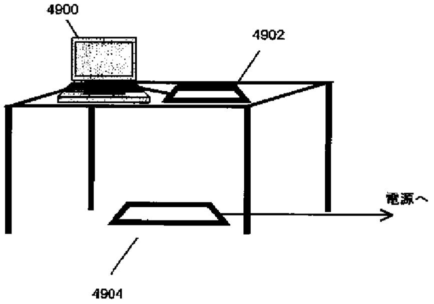

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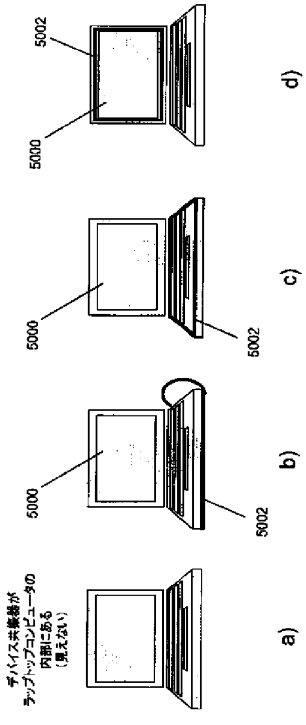
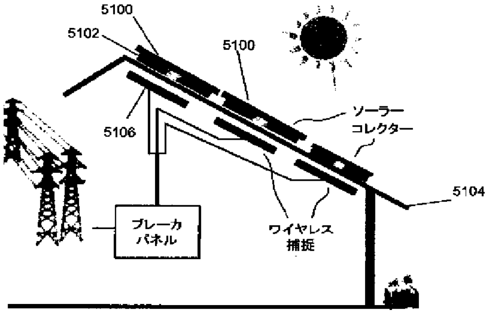
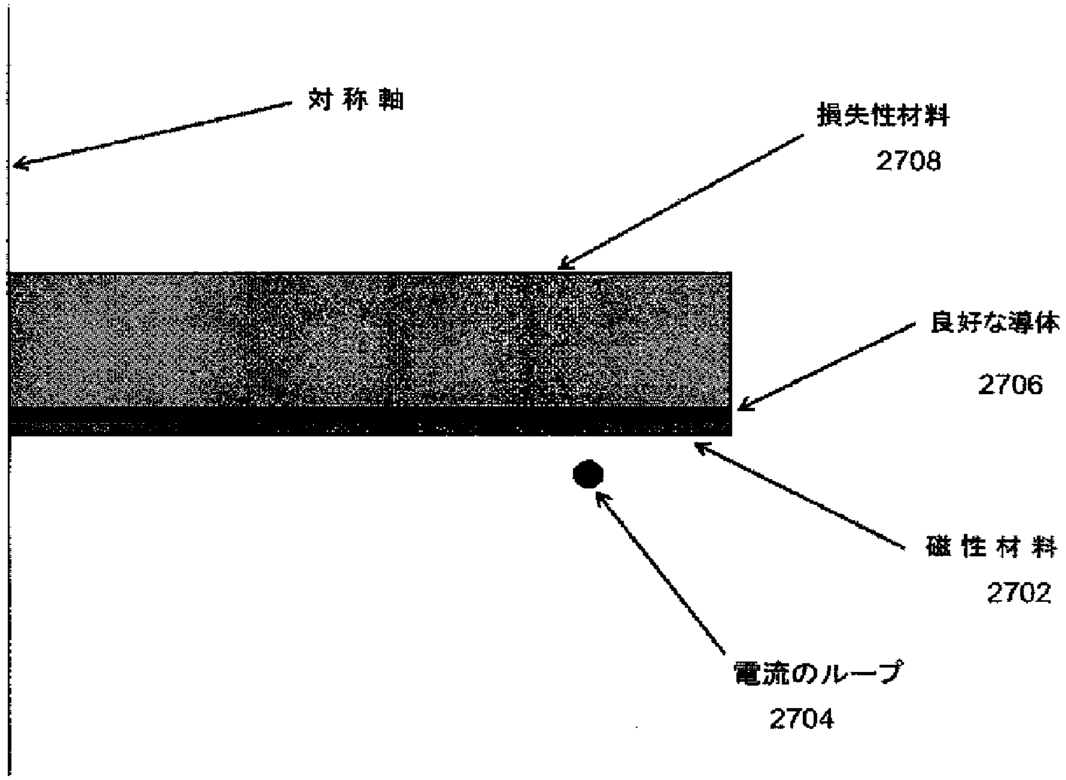


【図５１】



【図２７】



【手続補正書】
【提出日】平成23年5月31日(2011.5.31)
【手続補正１】
【補正対象書類名】特許請求の範囲
【補正対象項目名】全文
【補正方法】変更
【補正の内容】
【特許請求の範囲】
【請求項１】

無線電力伝送システムであって、

電力発生装置に結合された、少なくとも１つの供給源平面磁気共振器を有する供給源ユニットであって、前記少なくとも１つの供給源平面磁気共振器は、前記供給源平面磁気共振器の双極子モーメントが、前記供給源平面磁気共振器の平面に実質的に配向されるように構成されている、供給源ユニットと、

少なくとも１つのデバイス平面磁気共振器を有する少なくとも１つのデバイスユニットであって、前記少なくとも１つのデバイス平面磁気共振器は、前記デバイス平面磁気共振器の双極子モーメントが、前記デバイス平面磁気共振器の平面に実質的に配向されるように構成されている、少なくとも１つのデバイスユニットと、

前記供給源ユニットの周りの活性領域であって、前記デバイスユニットが前記少なくとも１つの供給源平面磁気共振器により生成された交番磁界の前記活性領域に配置された場合に、電流が前記デバイスユニットの前記少なくとも１つのデバイス平面磁気共振器に生じる、前記供給源ユニットの周りの活性領域とを含み、

前記電力伝送システムの前記活性領域が、前記供給源平面磁気共振器の周辺により包囲

された面積の少なくとも２倍である、無線電力伝送システム。

【請求項２】

前記活性領域は、前記供給源ユニットと前記デバイスユニットとの間の電力伝送効率が１０％を超える領域である、請求項１に記載のシステム。

【請求項３】

前記活性領域は、前記供給源ユニットと前記デバイスユニットとの間の電力伝送効率が５０％を超える領域である、請求項１に記載のシステム。

【請求項４】

前記活性領域が、前記供給源平面磁気共振器の周辺により包囲された面積の少なくとも５倍である、請求項１に記載のシステム。

【請求項５】

前記システムの少なくとも１つの平面磁気共振器が、磁性材料のコアに巻き付けられた少なくとも１つの導体からなる、請求項１に記載のシステム。

【請求項６】

少なくとも１つの調整可能な電気部品回路網を更に含み、前記電気部品回路網が前記少なくとも１つの導体に結合される、請求項５に記載のシステム。

【請求項７】

前記少なくとも１つの電気部品回路網が、少なくとも１つのコンデンサを含む、請求項６に記載のシステム。

【請求項８】

前記少なくとも１つの電気部品回路網が、少なくとも１つのインダクタを含む、請求項６に記載のシステム。

【請求項９】

前記少なくとも１つの電気部品回路網が、少なくとも１つの調整可能な構成要素を含む、請求項６に記載のシステム。

【請求項１０】

前記電気部品回路網が、直接的な物理的接続を用いて、少なくとも１つの導体に接続される、請求項６に記載のシステム。

【請求項１１】

前記導体が磁性材料のコアに巻き付けられて、一部が同軸でないループを形成する、請求項５に記載のシステム。

【請求項１２】

少なくとも１つの平面磁気共振器が、Ｑ＞１００のＱファクタを有する、請求項５に記載のシステム。

【請求項１３】

前記コアの最も小さい寸法が、最も大きい寸法の最大でも３０％である、請求項５に記載のシステム。

【請求項１４】

前記導体が、プリント導体トレースからなる、請求項５に記載のシステム。

【請求項１５】

少なくとも１つの供給源平面磁気共振器が、磁性材料のコアの直交する軸に巻き付けられた２つの導体からなる、請求項１に記載のシステム。

【請求項１６】

前記供給源ユニットが電子デバイスと一体化されている、請求項５に記載のシステム。

【請求項１７】

前記供給源共振器と前記デバイス共振器との間の結合を改善するように構成された中継器共振器を更に含む、請求項１に記載のシステム。

【請求項１８】

少なくとも１つの共振器が、前記共振器のパラメータに対する損失性物体の影響を低減するように配置された金属シールドを更に含む、請求項５に記載のシステム。

【請求項１９】
無線電力伝送の方法であって、
電力発生装置に結合された、少なくとも１つの供給源平面磁気共振器を有する供給源ユニットを設けるステップであって、前記少なくとも１つの供給源平面磁気共振器は、前記供給源平面磁気共振器の双極子モーメントが、前記供給源平面磁気共振器の平面に実質的に配向されるように構成されている、供給源ユニットを設けるステップと、
少なくとも１つのデバイス平面磁気共振器を有する少なくとも１つのデバイスユニットを設けるステップであって、前記少なくとも１つのデバイス平面磁気共振器は、前記デバイス平面磁気共振器の双極子モーメントが、前記デバイス平面磁気共振器の平面に実質的に配向されるように構成されている、少なくとも１つのデバイスユニットを設けるステップと、
前記供給源ユニットの周りに交番電磁界の活性領域を生成するために、前記電力発生装置を介して前記少なくとも１つの供給源平面磁気共振器に電力を供給するステップと、
前記供給源から有用な電力を受け取るために、前記供給源ユニットの周りの前記活性領域に前記少なくとも１つのデバイスユニットを配置するステップとを含み、
前記活性領域が、前記供給源平面磁気共振器の周辺により包囲された面積の少なくとも２倍である、方法。
【請求項２０】
前記活性領域は、前記供給源ユニットと前記デバイスユニットとの間の電力伝送効率が１％を超える領域である、請求項１９に記載の方法。
【請求項２１】
前記方法の少なくとも１つの平面磁気共振器が、磁性材料のコアに巻き付けられた少なくとも１つの導体からなる、請求項１９に記載の方法。
【請求項２２】
前記少なくとも１つの平面磁気共振器が、１００より大きいＱファクタを有する、請求項１９に記載の方法。
【請求項２３】
無線電力伝送システムであって、
電力発生装置に結合された、少なくとも１つの供給源平面磁気共振器を有する供給源ユニットであって、前記少なくとも１つの供給源平面磁気共振器は、前記供給源平面磁気共振器の双極子モーメントが、前記供給源平面磁気共振器の平面に実質的に配向されるように構成されている、供給源ユニットと、
少なくとも１つのデバイス平面磁気共振器を有する少なくとも１つのデバイスユニットであって、前記少なくとも１つのデバイス平面磁気共振器は、前記デバイス平面磁気共振器の双極子モーメントが、前記デバイス平面磁気共振器の平面に実質的に配向されるように構成されている、少なくとも１つのデバイスユニットとを含み、
前記供給源共振器および前記デバイス共振器が実質的に平行な方向で前記共振器の双極子モーメントを向けるように配置され、前記供給源共振器および前記デバイス共振器が実質的に異なる平面上にある、無線電力伝送システム。
【請求項２４】
前記システムの少なくとも１つの平面磁気共振器が、磁性材料のコアに巻き付けられた少なくとも１つの導体からなる、請求項２３に記載のシステム。
【請求項２５】
前記少なくとも１つの平面磁気共振器が、１００より大きいＱファクタを有する、請求項２３に記載のシステム。
【請求項２６】
前記双極子モーメントが、有用なエネルギー伝送を達成するために位置合わせされている、請求項２３に記載のシステム。
【請求項２７】
前記双極子モーメントの少なくとも１つの方向が、前記供給源ユニットの共振器と前記

デバイスユニットの共振器との間の結合を最大化するように変更され得る、請求項２３に記載のシステム。

【請求項２８】

無線電力伝送装置であって、

第１の平面磁気共振器であって、その共振器の周りに活性領域を有し、前記共振器は、前記第１の平面磁気共振器の双極子モーメントが、前記第１の平面磁気共振器の平面に実質的に配向されるように構成されている、第１の平面磁気共振器を含み、

前記第１の平面磁気共振器は、第２の平面磁気共振器構造体が前記第１の平面磁気共振器の前記活性領域の内部に配置された場合に、前記第２の平面磁気共振器構造体とエネルギー伝送するように構成されており、

前記第１の平面磁気共振器の前記活性領域が、前記第１の平面磁気共振器の周辺により包囲された面積の少なくとも２倍である、無線電力伝送装置。

【請求項２９】

前記活性領域は、電力伝送効率が１％を超える領域である、請求項２８に記載の装置。

【請求項３０】

前記活性領域は、電力伝送効率が１０％を超える領域である、請求項２８に記載の装置。

【請求項３１】

前記活性領域が、前記第１の平面磁気共振器の周辺により包囲された面積の少なくとも５倍である、請求項２９に記載の装置。

【請求項３２】

前記第１の平面磁気共振器が、磁性材料のコアに巻き付けられた少なくとも１つの導体からなる、請求項２９に記載の装置。

【請求項３３】

無線電力伝送の供給源であって、

供給源ユニットを含み、

前記供給源ユニットがそのユニットの周りに活性領域を有し、前記供給源ユニットが、電力発生装置に結合された少なくとも１つの供給源平面磁気共振器を含み、前記少なくとも１つの供給源平面磁気共振器は、前記供給源平面磁気共振器の双極子モーメントが、前記供給源平面磁気共振器の平面に実質的に配向されるように構成されており、

前記供給源ユニットが、少なくとも１つのデバイス平面磁気共振器を有する少なくとも１つのデバイスユニットとエネルギー伝送するように適合されており、前記少なくとも１つのデバイス平面磁気共振器は、前記デバイス平面磁気共振器の双極子モーメントが、前記デバイス平面磁気共振器の平面に実質的に配向されるように構成されており、

前記供給源ユニットの前記活性領域が、前記供給源ユニットの前記供給源平面磁気共振器の周辺により包囲された面積の少なくとも２倍である、無線電力伝送の供給源。

【請求項３４】

前記活性領域は、電力伝送効率が１％を超える領域である、請求項３３に記載の供給源。

【請求項３５】

前記活性領域は、電力伝送効率が１０％を超える領域である、請求項３３に記載の供給源。

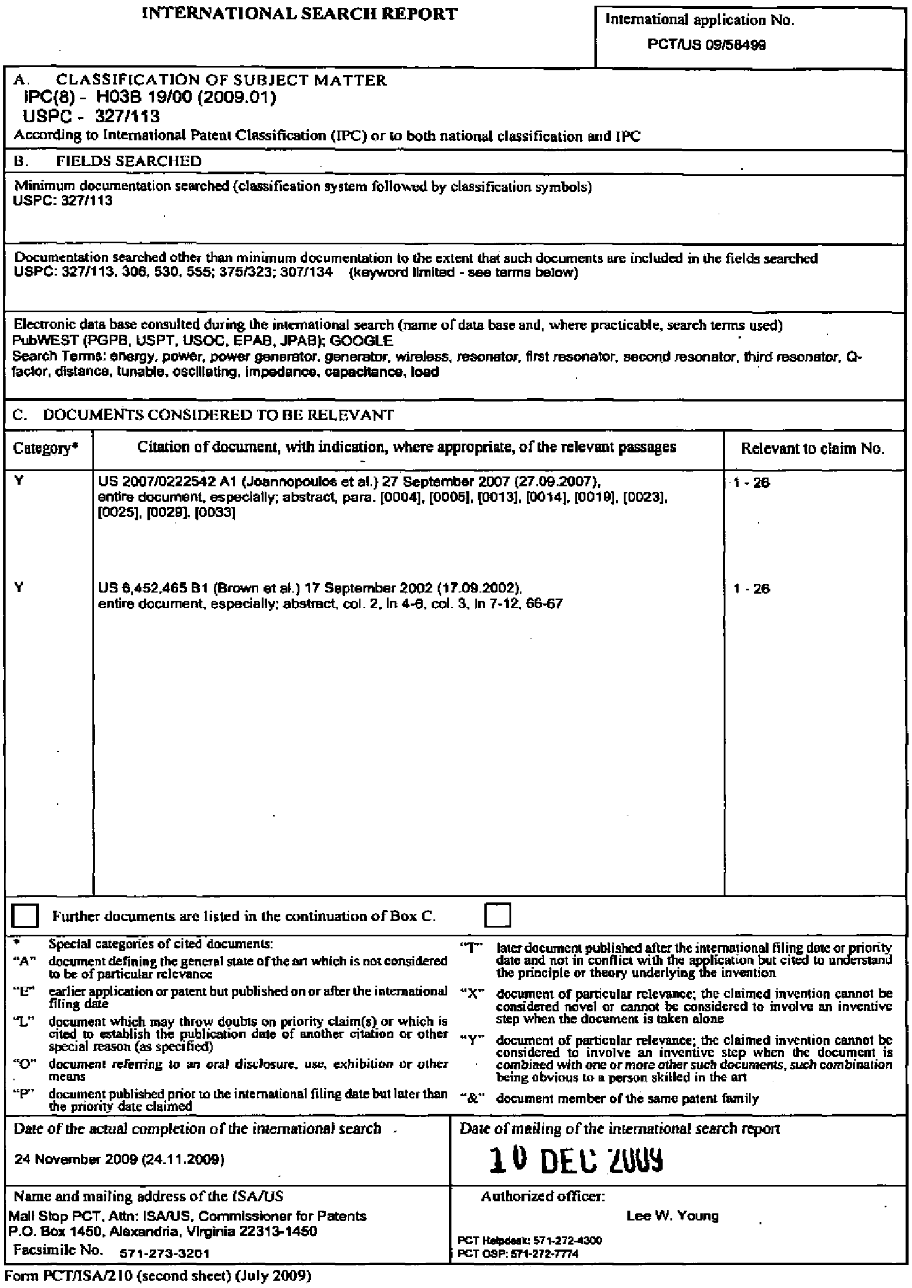
【請求項３６】

前記活性領域が、前記供給源平面磁気共振器の周辺により包囲された面積の少なくとも５倍である、請求項３３に記載の供給源。

【請求項３７】

前記供給源平面磁気共振器が、磁性材料のコアに巻き付けられた少なくとも１つの導体からなる、請求項３３に記載の供給源。

【国際調査報告】



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/58499

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H03B 19/00 (2009.01)
USPC - 327/113
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
USPC: 327/113

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 327/113, 306, 530, 555; 375/323; 307/134 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, USOC, EPAB, JPAB); GOOGLE
Search Terms: energy, power, power generator, generator, wireless, resonator, first resonator, second resonator, third resonator, Q-factor, distance, tunable, oscillating, impedance, capacitance, load

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0222542 A1 (Joannopoulos et al.) 27 September 2007 (27.09.2007), entire document, especially; abstract, para. [0004], [0005], [0013], [0014], [0019], [0023], [0025], [0029], [0033]	1 - 26
Y	US 6,452,465 B1 (Brown et al.) 17 September 2002 (17.09.2002), entire document, especially; abstract, col. 2, ln 4-8, col. 3, ln 7-12, 66-67	1 - 26

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 24 November 2009 (24.11.2009)	Date of mailing of the international search report 10 DEC 2009
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

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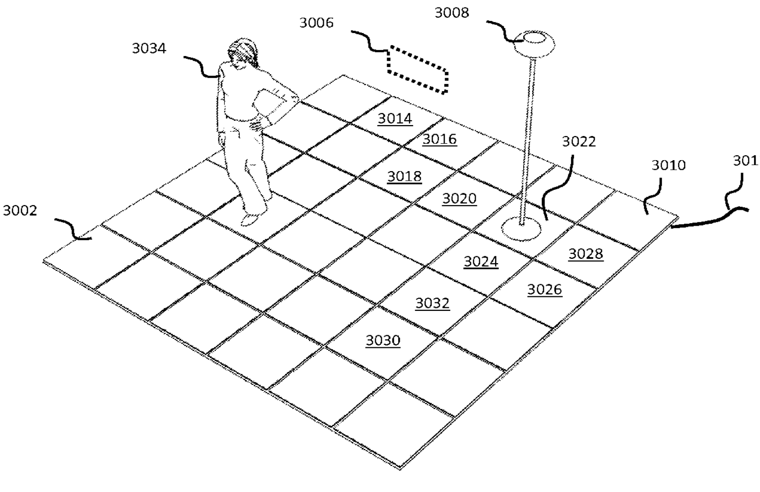
[Continued on next page]

(54) **Title**: WIRELESS ENERGY DISTRIBUTION SYSTEM

Fig. 30



(57) **Abstract**: Described herein are systems for wireless energy transfer distribution over a defined area. Energy may be distributed over the area via a plurality of repeater, source, and device resonators. The resonators within the area may be tunable and the distribution of energy or magnetic fields within the area may be configured depending on device position and power needs.

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WIRELESS ENERGY DISTRIBUTION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to the following U.S. Patent Applications, each of which is hereby incorporated by reference in its entirety; U.S. Provisional Appl. No. 61/382,806 filed September 14, 2010; U.S. 13/222,915 filed August 31, 2011; U.S. 13/154,131 filed June 6, 2011; U.S. 13/090,369 filed April 20, 2011; U.S. Patent Appl. No. 13/021,965 filed February 7, 2011; U.S. Patent Appl. No. 12/986,018 filed January 6, 2011;

[0002] The following U.S. Patent Applications are also incorporated by reference in its entirety; U.S. Patent Appl. No. 12/789,611 filed May 28, 2010; U.S. Patent Appl. No. 12/770,137 filed April 29, 2010; U.S. Provisional Application No. 61/173,747 filed April 29, 2009; U.S. Appl. No. 12/767,633 filed April 26, 2010; U.S. Provisional Application No. 61/172,633 filed April 24, 2009; U.S. Appl. No. 12/759,047 filed April 13, 2010; U.S. Appl. No. 12/757,716 filed April 9, 2010; U.S. Appl. No. 12/749,571 filed March 30, 2010; U.S. Appl. No. 12/639,489 filed December 16, 2009; U.S. Appl. No. 12/647,705 filed December 28, 2009, and U.S. App. No. 12/567,716 filed September 25, 2009. U.S. App. No. 61/100,721 filed September 27,2008; U.S. App. No. 61/108,743 filed October 27, 2008; U.S. App. No. 61/147,386 filed January 26, 2009; U.S. App. No. 61/152,086 filed February 12, 2009; U.S. App. No. 61/178,508 filed May 15, 2009; U.S. App. No. 61/182,768 filed June 1, 2009; U.S. App. No. 61/121,159 filed December 9, 2008; U.S. App. No. 61/142,977 filed January 7, 2009; U.S. App. No. 61/142,885 filed January 6, 2009; U.S. App. No. 61/142,796 filed January 6, 2009; U.S. App. No. 61/142,889 filed January 6, 2009; U.S. App. No. 61/142,880 filed January 6, 2009; U.S. App. No. 61/142,818 filed January 6, 2009; U.S. App. No. 61/142,887 filed January 6, 2009; U.S. App. No. 61/156,764 filed March 2, 2009; U.S. App. No. 61/143,058 filed January 7, 2009; U.S. App. No. 61/163,695 filed March 26, 2009; U.S. App. No. 61/172,633 filed April 24, 2009; U.S. App. No. 61/169,240 filed April 14, 2009, U.S. App. No. 61/173,747 filed April 29, 2009; U.S. Appl. No.12/721,118 filed March 10, 2010; U.S. Appl. No. 12/705,582 filed February 13, 2010; and U.S. Provisional Application No. 61/152,390 filed February 13, 2009.

BACKGROUND

[0003] Field:

[0004] This disclosure relates to wireless energy transfer, methods, systems and apparati to accomplish such transfer, and applications.

[0005] Description of the Related Art:

[0006] Energy distribution over an area to moving devices or devices that may be often repositioned is unpractical with wired connections. Moving and changing devices create the possibility of wire tangles, tripping hazards, and the like. Wireless energy transfer over a larger area may be difficult when the area or region in which devices may be present may be large compared to the size of the device. Large mismatches in a source and device wireless energy capture modules may pose challenges in delivering enough energy to the devices at a high enough efficiency to make the implementations practical or may be difficult to deploy.

[0007] Therefore a need exists for methods and designs for energy distribution that is wire free but easy to deploy and configurable while may deliver sufficient power to be practical to power many household and industrial devices.

SUMMARY

[0008] Resonators and resonator assemblies may be positioned to distribute wireless energy over a larger area. The wireless energy transfer resonators and components that may be used have been described in, for example, in commonly owned U.S. Patent Application No. 12/789,611 published on September 23, 2010 as U.S. Pat. Pub. No. 2010/0237709 and entitled "RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER," and U.S. Patent Application No. 12/722,050 published on July 22, 2010 as U.S. Pat. Pub. No. 2010/0181843 and entitled "WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION" the contents of which are incorporated in their entirety as if fully set forth herein.

[0009] In one aspect of the invention repeater resonators are positioned around one or more source resonators in a defined area. The one or more source may be coupled to an energy source and generate an oscillating magnetic field which may be transferred to the repeater resonators around the sources, and the repeater resonators may transfer the field to other repeaters around them thereby extending the energy over the defined area. In embodiments energy may be extended over an area of 10 cm^2 or 2 m^2 or more.

[0010] In the distribution system with multiple sources the frequency and phase of the sources may be synchronized.

[0011] In another aspect of the invention the distribution system may use tunable repeaters that may have a tunable resonant frequency or other parameters. The parameters of the repeaters may dynamically or periodically adjusted to change the magnetic field distribution within the defined area. In embodiments the resonators and components of the system may have a communication capability to coordinate tuning and parameter adjustment of the resonators and components of the system to route or distribute the energy to specific areas of the defined area or route the energy along a specific route of resonators that may be calculated using network routing algorithms and other methods.

[0012] In another aspect the components of the system may be integrated into flooring material such as tiles and distributed in a room floor or a wall or ceiling.

[0013] In one more aspect multiple resonators and power and control circuitry may be incorporated onto one sheet and may be trimmed or cut to fit desired dimensions.

[0014] Unless otherwise indicated, this disclosure uses the terms wireless energy transfer, wireless power transfer, wireless power transmission, and the like, interchangeably. Those skilled in the art will understand that a variety of system architectures may be supported by the wide range of wireless system designs and functionalities described in this application.

[0015] This disclosure references certain individual circuit components and elements such as capacitors, inductors, resistors, diodes, transformers, switches and the like; combinations of these elements as networks, topologies, circuits, and the like; and objects that have inherent characteristics such as "self-resonant" objects with capacitance or inductance distributed (or partially distributed, as opposed to solely lumped) throughout the entire object. It would be understood by one of ordinary skill in the art that adjusting and controlling variable components within a circuit or network may adjust the performance of that circuit or network and that those adjustments may be described generally as tuning, adjusting, matching, correcting, and the like. Other methods to tune or adjust the operating point of the wireless power transfer system may be used alone, or in addition to adjusting tunable components such as inductors and capacitors, or banks of inductors and capacitors. Those skilled in the art will recognize that a particular topology discussed in this disclosure can be implemented in a variety of other ways.

[0016] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of conflict with publications, patent applications, patents, and other references mentioned or incorporated herein by reference, the present specification, including definitions, will control.

[0017] Any of the features described above may be used, alone or in combination, without departing from the scope of this disclosure. Other features, objects, and advantages of the systems and methods disclosed herein will be apparent from the following detailed description and figures.

BRIEF DESCRIPTION OF FIGURES

[0018] Fig.1 is a system block diagram of wireless energy transfer configurations.

[0019] Figs. 2A-2E are exemplary structures and schematics of simple resonator structures.

[0020] Fig. 3 is a block diagram of a wireless source with a single-ended amplifier.

[0021] Fig. 4 is a block diagram of a wireless source with a differential amplifier.

[0022] Figs. 5A and 5B are block diagrams of sensing circuits.

[0023] Figs. 6A, 6B, and 6C are block diagrams of a wireless source.

[0024] Fig. 7 is a plot showing the effects of a duty cycle on the parameters of an amplifier.

[0025] Fig. 8 is a simplified circuit diagram of a wireless power source with a switching amplifier.

[0026] Fig. 9 shows plots of the effects of changes of parameters of a wireless power source.

[0027] Fig. 10 shows plots of the effects of changes of parameters of a wireless power source.

[0028] Figs. 11A, 11B, and 11C are plots showing the effects of changes of parameters of a wireless power source.

[0029] Fig. 12 shows plots of the effects of changes of parameters of a wireless power source.

[0030] Fig. 13 is a simplified circuit diagram of a wireless energy transfer system comprising a wireless power source with a switching amplifier and a wireless power device.

[0031] Fig. 14 shows plots of the effects of changes of parameters of a wireless power source.

[0032] Fig. 15 is a diagram of a resonator showing possible nonuniform magnetic field distributions due to irregular spacing between tiles of magnetic material.

[0033] Fig. 16 is a resonator with an arrangement of tiles in a block of magnetic material that may reduce hotspots in the magnetic material block.

[0034] Fig. 17A is a resonator with a block of magnetic material comprising smaller individual tiles and 17B and 17C is the resonator with additional strips of thermally conductive material used for thermal management.

[0035] Fig. 18 is block diagram of a wireless energy transfer system with in-band and out-of-band communication channels.

[0036] Fig. 19A and Fig. 19B are steps that may be used to verify the energy transfer channel using an out-of-band communication channel.

[0037] Fig. 20 is an isometric view of a conductor wire comprising multiple conductor shells.

[0038] Fig. 21 is an isometric view of a conductor wire comprising multiple conductor shells.

[0039] Fig 22 is a plot showing the current distributions for a solid conductor wire.

[0040] Fig 23 is a plot showing the current distributions for a conductor wire comprising 25 conductor shells.

[0041] Fig 24 is a plot showing the current distributions for a conductor wire comprising 25 conductor shells.

[0042] Fig 25 is plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1mm to the AC resistance of a solid conductor of the same diameter.

[0043] Fig 26 is plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1mm to the DC resistance of the same conductor (21.6 $\text{m}\Omega/\text{m}$).

[0044] Fig 27 is plot showing the ratio of the resistance of an optimized conducting-shell structure with overall diameter 1mm to the resistance with the same number of elements, but with shells of (optimized) uniform thickness around a copper core.

[0045] Fig. 28A and Fig. 28B are diagrams of embodiments of a wireless power enabled floor tile.

[0046] Fig. 29 is a block diagram of an embodiment of a wireless power enabled floor tile.

[0047] Fig. 30 is diagram of a wireless power enables floor system.

[0048] Fig. 31 is diagram of a cuttable sheet of resonators.

DETAILED DESCRIPTION

[0049] As described above, this disclosure relates to wireless energy transfer using coupled electromagnetic resonators. However, such energy transfer is not restricted to electromagnetic resonators, and the wireless energy transfer systems described herein are more general and may be implemented using a wide variety of resonators and resonant objects.

[0050] As those skilled in the art will recognize, important considerations for resonator-based power transfer include resonator efficiency and resonator coupling. Extensive discussion of such issues, e.g., coupled mode theory (CMT), coupling coefficients and factors, quality factors (also referred to as Q-factors), and impedance matching is provided, for example, in U.S. patent application 12/789,611 published on September 23, 2010 as US 20100237709 and entitled “RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER,” and U.S. patent application 12/722,050 published on July 22, 2010 as US 20100181843 and entitled “WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION” and incorporated herein by reference in its entirety as if fully set forth herein.

[0051] A **resonator** may be defined as a resonant structure that can store energy in at least two different forms, and where the stored energy oscillates between the two forms. The resonant structure will have a specific oscillation mode with a resonant (modal) frequency, f, and a resonant (modal) field. The angular resonant frequency, ω, may be defined as $\omega = 2\pi f$, the resonant period, T, may be defined as $T = 1/f = 2\pi/\omega$, and the resonant wavelength, λ, may be defined as $\lambda = c/f$, where c is the speed of the associated field waves (light, for electromagnetic resonators). In the absence of loss mechanisms, coupling mechanisms or external energy supplying or draining mechanisms, the total amount of energy stored by the resonator, W, would stay fixed, but the form of the energy would oscillate between the two forms supported by the resonator, wherein one form would be maximum when the other is minimum and vice versa.

[0052] For example, a resonator may be constructed such that the two forms of stored energy are magnetic energy and electric energy. Further, the resonator may be constructed such that the electric energy stored by the electric field is primarily confined within the structure while the magnetic energy stored by the magnetic field is primarily in the region surrounding the resonator. In other words, the total electric and magnetic energies would be equal, but their localization would be different. Using such structures, energy exchange between at least two structures may be mediated by the resonant magnetic near-field of the at least two resonators. These types of resonators may be referred to as **magnetic resonators**.

[0053] An important parameter of resonators used in wireless power transmission systems is the **Quality Factor,** or Q**-factor**, or Q, of the resonator, which characterizes the energy decay and is inversely proportional to energy losses of the resonator. It may be defined as $Q = \omega * W/P$, where P is the time-averaged power lost at steady state. That is, a resonator with a high-Q has relatively low intrinsic losses and can store energy for a relatively long time. Since the resonator loses energy at its intrinsic decay rate, 2Γ, its Q, also referred to as its intrinsic Q, is given by $Q = \omega/2\Gamma$. The quality factor also represents the number of oscillation periods, T, it takes for the energy in the resonator to decay by a factor of $e^{-2\pi}$. Note that the quality factor or intrinsic quality factor or Q of the resonator is that due only to intrinsic loss mechanisms. The Q of a resonator connected to, or coupled to a power generator, g, or load, l, may be called the "**loaded quality factor**" or the "loaded Q". The Q of a resonator in the presence of an extraneous object that is not intended to be part of the energy transfer system may be called the "**perturbed quality factor**" or the "perturbed Q".

[0054] Resonators, coupled through any portion of their near-fields may interact and exchange energy. The efficiency of this energy transfer can be significantly enhanced if the resonators operate at substantially the same resonant frequency. By way of example, but not limitation, imagine a source resonator with Q_s and a device resonator with Q_d. High-Q wireless energy transfer systems may utilize resonators that are high-Q. The Q of each resonator may be high. The geometric mean of the resonator Q's, $\sqrt{Q_s Q_d}$ may also or instead be high.

[0055] The **coupling factor**, k, is a number between $0 \leq |k| \leq 1$, and it may be independent (or nearly independent) of the resonant frequencies of the source and device resonators , when those are placed at sub-wavelength distances. Rather the coupling factor k may be determined mostly by the relative geometry and the distance between the source and device resonators where the physical decay-law of the field mediating their coupling is taken into account. The coupling coefficient used in CMT, $\kappa = k\sqrt{\omega_s \omega_d}/2$, may be a strong function of the resonant frequencies, as well as other properties of the resonator structures. In applications for wireless energy transfer utilizing the near-fields of the resonators, it is desirable to have the size of the resonator be much smaller than the resonant wavelength, so that power lost by radiation is reduced. In some embodiments, high-Q resonators are sub-wavelength structures. In some electromagnetic embodiments, high-Q resonator structures are designed to have resonant frequencies higher than 100 kHz. In other embodiments, the resonant frequencies may be less than 1 GHz.

[0056] In exemplary embodiments, the power radiated into the far-field by these sub wavelength resonators may be further reduced by lowering the resonant frequency of the resonators and the operating frequency of the system. In other embodiments, the far field radiation may be reduced by arranging for the far fields of two or more resonators to interfere destructively in the far field.

[0057] In a wireless energy transfer system a resonator may be used as a wireless energy source, a wireless energy capture device, a repeater or a combination thereof. In embodiments a resonator may alternate between transferring energy, receiving energy or relaying energy. In a wireless energy transfer system one or more magnetic resonators may be coupled to an energy source and be energized to produce an oscillating magnetic near-field. Other resonators that are within the oscillating magnetic near-fields may capture these fields and convert the energy into electrical energy that may be used to power or charge a load thereby enabling wireless transfer of useful energy.

[0058] The so-called “useful” energy in a useful energy exchange is the energy or power that must be delivered to a device in order to power or charge it at an acceptable rate. The transfer efficiency that corresponds to a useful energy exchange may be system or application-dependent. For example, high power vehicle charging applications that transfer kilowatts of power may need to be at least 80% efficient in order to supply useful amounts of power resulting in a useful energy exchange sufficient to recharge a vehicle battery without significantly heating up various components of the transfer system. In some consumer electronics applications, a useful energy exchange may include any energy transfer efficiencies greater than 10%, or any other amount acceptable to keep rechargeable batteries “topped off” and running for long periods of time. In implanted medical device applications, a useful energy exchange may be any exchange that does not harm the patient but that extends the life of a battery or wakes up a sensor or monitor or stimulator. In such applications, 100 mW of power or less may be useful. In distributed sensing applications, power transfer of microwatts may be useful, and transfer efficiencies may be well below 1%.

[0059] A useful energy exchange for wireless energy transfer in a powering or recharging application may be efficient, highly efficient, or efficient enough, as long as the wasted energy levels, heat dissipation, and associated field strengths are within tolerable limits and are balanced appropriately with related factors such as cost, weight, size, and the like.

[0060] The resonators may be referred to as source resonators, device resonators, first resonators, second resonators, repeater resonators, and the like. Implementations may include three (3) or more resonators. For example, a single source resonator may transfer energy to multiple device resonators or multiple devices. Energy may be transferred from a first device to a second, and then from the second device to the third, and so forth. Multiple sources may transfer energy to a single device or to multiple devices connected to a single device resonator or to multiple devices connected to multiple device resonators. Resonators may serve alternately or simultaneously as sources, devices, and/or they may be used to relay power from a source in one location to a device in another location. Intermediate electromagnetic resonators may be used to extend the distance range of wireless energy transfer systems and/or to generate areas of concentrated magnetic near-fields. Multiple resonators may be daisy-chained together, exchanging energy over extended distances and with a wide range of sources and devices. For example, a source resonator may transfer power to a device resonator via several repeater resonators. Energy from a source may be transferred to a first repeater resonator, the first repeater resonator may transfer the power to a second repeater resonator and the second to a third and so on until the final repeater resonator transfers its energy to a device resonator. In this respect the range or distance of wireless energy transfer may be extended and/or tailored by adding repeater resonators. High power levels may be split between multiple sources, transferred to multiple devices and recombined at a distant location.

[0061] The resonators may be designed using coupled mode theory models, circuit models, electromagnetic field models, and the like. The resonators may be designed to have tunable characteristic sizes. The resonators may be designed to handle different power levels. In exemplary embodiments, high power resonators may require larger conductors and higher current or voltage rated components than lower power resonators.

[0062] Fig. 1 shows a diagram of exemplary configurations and arrangements of a wireless energy transfer system. A wireless energy transfer system may include at least one source resonator (R1)**104** (optionally R6, **112**) coupled to an energy source **102** and optionally a sensor and control unit **108**. The energy source may be a source of any type of energy capable of being converted into electrical energy that may be used to drive the source resonator **104**. The energy source may be a battery, a solar panel, the electrical mains, a wind or water turbine, an electromagnetic resonator, a generator, and the like. The electrical energy used to drive the magnetic resonator is converted into oscillating magnetic fields by the resonator. The oscillating magnetic fields may be captured by other resonators which may be device resonators (R2) **106,** (R3) **116** that are optionally coupled to an energy drain **110**. The oscillating fields may be optionally coupled to repeater resonators (R4, R5) that are configured to extend or tailor the wireless energy transfer region. Device resonators may capture the magnetic fields in the vicinity of source resonator(s), repeater resonators and other device resonators and convert them into electrical energy that may be used by an energy drain. The energy drain **110** may be an electrical, electronic, mechanical or chemical device and the like configured to receive electrical energy. Repeater resonators may capture magnetic fields in the vicinity of source, device and repeater resonator(s) and may pass the energy on to other resonators.

[0063] A wireless energy transfer system may comprise a single source resonator **104** coupled to an energy source **102** and a single device resonator **106** coupled to an energy drain **110.** In embodiments a wireless energy transfer system may comprise multiple source resonators coupled to one or more energy sources and may comprise multiple device resonators coupled to one or more energy drains.

[0064] In embodiments the energy may be transferred directly between a source resonator **104** and a device resonator **106.** In other embodiments the energy may be transferred from one or more source resonators **104, 112** to one or more device resonators **106, 116** via any number of intermediate resonators which may be device resonators, source resonators, repeater resonators, and the like. Energy may be transferred via a network or arrangement of resonators **114** that may include subnetworks **118, 120** arranged in any combination of topologies such as token ring, mesh, ad hoc, and the like.

[0065] In embodiments the wireless energy transfer system may comprise a centralized sensing and control system **108**. In embodiments parameters of the resonators, energy sources, energy drains, network topologies, operating parameters, etc. may be monitored and adjusted from a control processor to meet specific operating parameters of the system. A central control processor may adjust parameters of individual components of the system to optimize global energy transfer efficiency, to optimize the amount of power transferred, and the like. Other embodiments may be designed to have a substantially distributed sensing and control system. Sensing and control may be incorporated into each resonator or group of resonators, energy sources, energy drains, and the like and may be configured to adjust the parameters of the individual components in the group to maximize or minimize the power delivered, to maximize energy transfer efficiency in that group and the like.

[0066] In embodiments, components of the wireless energy transfer system may have wireless or wired data communication links to other components such as devices, sources, repeaters, power sources, resonators, and the like and may transmit or receive data that can be used to enable the distributed or centralized sensing and control. A wireless communication channel may be separate from the wireless energy transfer channel, or it may be the same. In one embodiment the resonators used for power exchange may also be used to exchange information.

In some cases, information may be exchanged by modulating a component in a source or device circuit and sensing that change with port parameter or other monitoring equipment. Resonators may signal each other by tuning, changing, varying, dithering, and the like, the resonator parameters such as the impedance of the resonators which may affect the reflected impedance of other resonators in the system. The systems and methods described herein may enable the simultaneous transmission of power and communication signals between resonators in wireless power transmission systems, or it may enable the transmission of power and communication signals during different time periods or at different frequencies using the same magnetic fields that are used during the wireless energy transfer. In other embodiments wireless communication may be enabled with a separate wireless communication channel such as WiFi, Bluetooth, Infrared, NFC, and the like.

[0067] In embodiments, a wireless energy transfer system may include multiple resonators and overall system performance may be improved by control of various elements in the system. For example, devices with lower power requirements may tune their resonant frequency away from the resonant frequency of a high-power source that supplies power to devices with higher power requirements. For another example, devices needing less power may adjust their rectifier circuits so that they draw less power from the source. In these ways, low and high power devices may safely operate or charge from a single high power source. In addition, multiple devices in a charging zone may find the power available to them regulated according to any of a variety of consumption control algorithms such as First-Come-First-Serve, Best Effort, Guaranteed Power, etc. The power consumption algorithms may be hierarchical in nature, giving priority to certain users or types of devices, or it may support any number of users by equally sharing the power that is available in the source. Power may be shared by any of the multiplexing techniques described in this disclosure.

[0068] In embodiments electromagnetic resonators may be realized or implemented using a combination of shapes, structures, and configurations. Electromagnetic resonators may include an inductive element, a distributed inductance, or a combination of inductances with a total inductance, L, and a capacitive element, a distributed capacitance, or a combination of capacitances, with a total capacitance, C. A minimal circuit model of an electromagnetic resonator comprising capacitance, inductance and resistance, is shown in Fig. 2F. The resonator may include an inductive element **238** and a capacitive element **240**. Provided with initial energy, such as electric field energy stored in the capacitor **240**, the system will oscillate as the capacitor discharges transferring energy into magnetic field energy stored in the inductor **238** which in turn transfers energy back into electric field energy stored in the capacitor **240**. Intrinsic losses in these electromagnetic resonators include losses due to resistance in the inductive and capacitive elements and to radiation losses, and are represented by the resistor, R, **242** in Fig. 2F.

[0069] Fig. 2A shows a simplified drawing of an exemplary magnetic resonator structure. The magnetic resonator may include a loop of conductor acting as an inductive element **202** and a capacitive element **204** at the ends of the conductor loop. The inductor **202** and capacitor **204** of an electromagnetic resonator may be bulk circuit elements, or the inductance and capacitance may be distributed and may result from the way the conductors are formed, shaped, or positioned, in the structure.

[0070] For example, the inductor **202** may be realized by shaping a conductor to enclose a surface area, as shown in Figs. 2A. This type of resonator may be referred to as a capacitively-loaded loop inductor. Note that we may use the terms "loop" or "coil" to indicate generally a conducting structure (wire, tube, strip, etc.), enclosing a surface of any shape and dimension, with any number of turns. In Fig. 2A, the enclosed surface area is circular, but the surface may be any of a wide variety of other shapes and sizes and may be designed to achieve certain system performance specifications. In embodiments the inductance may be realized using inductor elements, distributed inductance, networks, arrays, series and parallel combinations of inductors and inductances, and the like. The inductance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[0071] There are a variety of ways to realize the capacitance required to achieve the desired resonant frequency for a resonator structure. Capacitor plates **204** may be formed and utilized as shown in Fig. 2A, or the capacitance may be distributed and be realized between adjacent windings of a multi-loop conductor. The capacitance may be realized using capacitor elements, distributed capacitance, networks, arrays, series and parallel combinations of capacitances, and the like. The capacitance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[0072] The inductive elements used in magnetic resonators may contain more than one loop and may spiral inward or outward or up or down or in some combination of directions. In general, the magnetic resonators may have a variety of shapes, sizes and number of turns and they may be composed of a variety of conducing materials. The conductor **210**, for example, may be a wire, a Litz wire, a ribbon, a pipe, a trace formed from conducting ink, paint, gels, and the like or from single or multiple traces printed on a circuit board. An exemplary embodiment of a trace pattern on a substrate **208** forming inductive loops is depicted in Fig. 2B.

[0073] In embodiments the inductive elements may be formed using magnetic materials of any size, shape thickness, and the like, and of materials with a wide range of permeability and loss values. These magnetic materials may be solid blocks, they may enclose hollow volumes, they may be formed from many smaller pieces of magnetic material tiled and or stacked together, and they may be integrated with conducting sheets or enclosures made from highly conducting materials. Conductors may be wrapped around the magnetic materials to generate the magnetic field. These conductors may be wrapped around one or more than one axis of the structure. Multiple conductors may be wrapped around the magnetic materials and combined in parallel, or in series, or via a switch to form customized near-field patterns and/or to orient the dipole moment of the structure. Examples of resonators comprising magnetic material are depicted in Figures 2C, 2D, 2E. In Fig. 2D the resonator comprises loops of conductor **224** wrapped around a core of magnetic material **222** creating a structure that has a magnetic dipole moment **228** that is parallel to the axis of the loops of the conductor **224**. The resonator may comprise multiple loops of conductor **216, 212** wrapped in orthogonal directions around the magnetic material **214** forming a resonator with a magnetic dipole moment **218, 220** that may be oriented in more than one direction as depicted in Fig. 2C, depending on how the conductors are driven.

[0074] An electromagnetic resonator may have a characteristic, natural, or resonant frequency determined by its physical properties. This resonant frequency is the frequency at which the energy stored by the resonator oscillates between that stored by the electric field, W_E, ($W_E = q^2/2C$, where q is the charge on the capacitor, C) and that stored by the magnetic field, W_B, ($W_B = Li^2/2$, where i is the current through the inductor, L) of the resonator. The frequency at which this energy is exchanged may be called the characteristic frequency, the natural frequency, or the resonant frequency of the resonator, and is given by ω,

$$\omega = 2\pi f = \sqrt{\frac{1}{LC}}.$$

The resonant frequency of the resonator may be changed by tuning the inductance, L, and/or the capacitance, C, of the resonator. In one embodiment system parameters are dynamically adjustable or tunable to achieve as close as possible to optimal operating conditions. However, based on the discussion above, efficient enough energy exchange may be realized even if some system parameters are not variable or components are not capable of dynamic adjustment.

[0075] In embodiments a resonator may comprise an inductive element coupled to more than one capacitor arranged in a network of capacitors and circuit elements. In embodiments the coupled network of capacitors and circuit elements may be used to define more than one resonant frequency of the resonator. In embodiments a resonator may be resonant, or partially resonant, at more than one frequency.

[0076] In embodiments, a wireless power source may comprise of at least one resonator coil coupled to a power supply, which may be a switching amplifier, such as a class-D amplifier or a class-E amplifier or a combination thereof. In this case, the resonator coil is effectively a power load to the power supply. In embodiments, a wireless power device may comprise of at least one resonator coil coupled to a power load, which may be a switching rectifier, such as a class-D rectifier or a class-E rectifier or a combination thereof. In this case, the resonator coil is effectively a power supply for the power load, and the impedance of the load directly relates also to the work-drainage rate of the load from the resonator coil. The efficiency of power transmission between a power supply and a power load may be impacted by how closely matched the output impedance of the power source is to the input impedance of the load. Power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load is equal to the complex conjugate of the internal impedance of the power supply. Designing the power supply or power load impedance to obtain a maximum power transmission efficiency is often called "impedance matching", and may also referred to as optimizing the ratio of useful-to-lost powers in the system. Impedance matching may be performed by adding networks or sets of elements such as capacitors, inductors, transformers, switches, resistors, and the like, to form impedance matching networks between a power supply and a power load. In embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching. For varying loads, the impedance matching network may include variable components that are dynamically adjusted to ensure that the impedance at the power supply terminals looking towards the load and the characteristic impedance of the power supply remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios.

[0077] In embodiments, impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power supply or by tuning a physical component within the power supply, such as a capacitor. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power supply and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power supply may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like.

[0078] In some wireless energy transfer systems the parameters of the resonator such as the inductance may be affected by environmental conditions such as surrounding objects, temperature, orientation, number and position of other resonators and the like. Changes in operating parameters of the resonators may change certain system parameters, such as the efficiency of transferred power in the wireless energy transfer. For example, high-conductivity materials located near a resonator may shift the resonant frequency of a resonator and detune it from other resonant objects. In some embodiments, a resonator feedback mechanism is employed that corrects its frequency by changing a reactive element (e.g., an inductive element or capacitive element). In order to achieve acceptable matching conditions, at least some of the system parameters may need to be dynamically adjustable or tunable. All the system parameters may be dynamically adjustable or tunable to achieve approximately the optimal operating conditions. However, efficient enough energy exchange may be realized even if all or some system parameters are not variable. In some examples, at least some of the devices may not be dynamically adjusted. In some examples, at least some of the sources may not be dynamically adjusted. In some examples, at least some of the intermediate resonators may not be dynamically adjusted. In some examples, none of the system parameters may be dynamically adjusted.

[0079] In some embodiments changes in parameters of components may be mitigated by selecting components with characteristics that change in a complimentary or opposite way or direction when subjected to differences in operating environment or operating point. In embodiments, a system may be designed with components, such as capacitors, that have an opposite dependence or parameter fluctuation due to temperature, power levels, frequency, and the like. In some embodiments, the component values as a function of temperature may be stored in a look-up table in a system microcontroller and the reading from a temperature sensor may be used in the system control feedback loop to adjust other parameters to compensate for the temperature induced component value changes.

[0080] In some embodiments the changes in parameter values of components may be compensated with active tuning circuits comprising tunable components. Circuits that monitor the operating environment and operating point of components and system may be integrated in the design. The monitoring circuits may provide the signals necessary to actively compensate for changes in parameters of components. For example, a temperature reading may be used to calculate expected changes in, or to indicate previously measured values of , capacitance of the system allowing compensation by switching in other capacitors or tuning capacitors to maintain the desired capacitance over a range of temperatures. In embodiments, the RF amplifier switching waveforms may be adjusted to compensate for component value or load changes in the system. In some embodiments the changes in parameters of components may be compensated with active cooling, heating, active environment conditioning, and the like.

[0081] The parameter measurement circuitry may measure or monitor certain power, voltage, and current, signals in the system, and processors or control circuits may adjust certain settings or operating parameters based on those measurements. In addition the magnitude and phase of voltage and current signals, and the magnitude of the power signals, throughout the system may be accessed to measure or monitor the system performance. The measured signals referred to throughout this disclosure may be any combination of port parameter signals, as well as voltage signals, current signals, power signals, temperatures signals and the like. These parameters may be measured using analog or digital techniques, they may be sampled and processed, and they may be digitized or converted using a number of known analog and digital processing techniques. In embodiments, preset values of certain measured quantities are loaded in a system controller or memory location and used in various feedback and control loops. In embodiments, any combination of measured, monitored, and/or preset signals may be used in feedback circuits or systems to control the operation of the resonators and/or the system.

[0082] Adjustment algorithms may be used to adjust the frequency, Q, and/or impedance of the magnetic resonators. The algorithms may take as inputs reference signals related to the degree of deviation from a desired operating point for the system and may output correction or control signals related to that deviation that control variable or tunable elements of the system to bring the system back towards the desired operating point or points. The reference signals for the magnetic resonators may be acquired while the resonators are exchanging power in a wireless power transmission system, or they may be switched out of the circuit during system operation. Corrections to the system may be applied or performed continuously, periodically, upon a threshold crossing, digitally, using analog methods, and the like.

[0083] In embodiments, lossy extraneous materials and objects may introduce potential reductions in efficiencies by absorbing the magnetic and/or electric energy of the resonators of the wireless power transmission system. Those impacts may be mitigated in various embodiments by positioning resonators to minimize the effects of the lossy extraneous materials and objects and by placing structural field shaping elements (e.g., conductive structures, plates and sheets, magnetic material structures, plates and sheets, and combinations thereof) to minimize their effect.

[0084] One way to reduce the impact of lossy materials on a resonator is to use high-conductivity materials, magnetic materials, or combinations thereof to shape the resonator fields such that they avoid the lossy objects. In an exemplary embodiment, a layered structure of high-conductivity material and magnetic material may tailor, shape, direct, reorient, etc. the resonator's electromagnetic fields so that they avoid lossy objects in their vicinity by deflecting the fields. Fig. 2D shows a top view of a resonator with a sheet of conductor **226** below the magnetic material that may used to tailor the fields of the resonator so that they avoid lossy objects that may be below the sheet of conductor **226.** The layer or sheet of good **226** conductor may comprise any high conductivity materials such as copper, silver, aluminum, as may be most appropriate for a given application. In certain embodiments, the layer or sheet of good conductor is thicker than the skin depth of the conductor at the resonator operating frequency. The conductor sheet may be preferably larger than the size of the resonator, extending beyond the physical extent of the resonator.

[0085] In environments and systems where the amount of power being transmitted could present a safety hazard to a person or animal that may intrude into the active field volume, safety measures may be included in the system. In embodiments where power levels require particularized safety measures, the packaging, structure, materials, and the like of the resonators may be designed to provide a spacing or “keep away” zone from the conducting loops in the magnetic resonator. To provide further protection, high- Q resonators and power and control circuitry may be located in enclosures that confine high voltages or currents to within the enclosure, that protect the resonators and electrical components from weather, moisture, sand, dust, and other external elements, as well as from impacts, vibrations, scrapes, explosions, and other types of mechanical shock . Such enclosures call for attention to various factors such as thermal dissipation to maintain an acceptable operating temperature range for the electrical components and the resonator. In embodiments, enclosure may be constructed of non-lossy materials such as composites, plastics, wood, concrete, and the like and may be used to provide a minimum distance from lossy objects to the resonator components. A minimum separation distance from lossy objects or environments which may include metal objects, salt water, oil and the like, may improve the efficiency of wireless energy transfer. In embodiments, a “keep away” zone may be used to increase the perturbed Q of a resonator or system of resonators. In embodiments a minimum separation distance may provide for a more reliable or more constant operating parameters of the resonators.

[0086] In embodiments, resonators and their respective sensor and control circuitry may have various levels of integration with other electronic and control systems and subsystems. In some embodiments the power and control circuitry and the device resonators are completely separate modules or enclosures with minimal integration to existing systems, providing a power output and a control and diagnostics interface. In some embodiments a device is configured to house a resonator and circuit assembly in a cavity inside the enclosure, or integrated into the housing or enclosure of the device.

[0087] **Example Resonator Circuitry**

[0088] Figures 3 and 4 show high level block diagrams depicting power generation, monitoring, and control components for exemplary sources of a wireless energy transfer system. Fig. 3 is a block diagram of a source comprising a half-bridge switching power amplifier and some of the associated measurement, tuning, and control circuitry. Fig. 4 is a block diagram of a source comprising a full-bridge switching amplifier and some of the associated measurement, tuning, and control circuitry.

[0089] The half bridge system topology depicted in Fig. 3 may comprise a processing unit that executes a control algorithm **328.** The processing unit executing a control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The processing unit may be a single device or it may be a network of devices. The control algorithm may run on any portion of the processing unit. The algorithm may be customized for certain applications and may comprise a combination of analog and digital circuits and signals. The master algorithm may measure and adjust voltage signals and levels, current signals and levels, signal phases, digital count settings, and the like.

[0090] The system may comprise an optional source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312.** The optional source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes the master control algorithm, it may a part or a circuit within a microcontroller **302**, it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission.

[0091] The system may comprise a PWM generator **306** coupled to at least two transistor gate drivers **334** and may be controlled by the control algorithm. The two transistor gate drivers **334** may be coupled directly or via gate drive transformers to two power transistors **336** that drive the source resonator coil **344** through impedance matching network components **342.** The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a variable bus voltage, Vbus. The Vbus controller may be controlled by the control algorithm **328** and may be part of, or integrated into, a microcontroller **302** or other integrated circuits. The Vbus controller **326** may control the voltage output of an adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344.**

[0092] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318, 320** that may shape, modify, filter, process, buffer, and the like, signals prior to their input to processors and/or converters such as analog to digital converters (ADC) **314, 316**, for example. The processors and converters such as ADCs **314, 316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals, the control algorithm **328** may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **306,** the communication controller **332**, the Vbus control **326**, the source impedance matching controller **338**, the filter/buffering elements, **318, 320,** the converters, **314, 316,** the resonator coil **344,** and may be part of, or integrated into, a microcontroller **302** or a separate circuit. The impedance matching networks **342** and resonator coils **344** may include electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to adjust the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planer resonator comprising a magnetic material or any combination thereof.

[0093] The full bridge system topology depicted in Fig. 4 may comprise a processing unit that executes a master control algorithm **328.** The processing unit executing the control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The system may comprise a source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312.** The source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes that master control algorithm, it may a part or a circuit within a microcontroller **302,** it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission.

[0094] The system may comprise a PWM generator **410** with at least two outputs coupled to at least four transistor gate drivers **334** that may be controlled by signals generated in a master control algorithm. The four transistor gate drivers **334** may be coupled to four power transistors **336** directly or via gate drive transformers that may drive the source resonator coil **344** through impedance matching networks **342.** The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a Vbus controller **326** which may be controlled by a master control algorithm. The Vbus controller **326** may control the voltage output of the adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344.**

[0095] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318, 320** and differential/single ended conversion circuitry **402, 404** that may shape, modify, filter, process, buffer, and the like, signals prior to being input to processors and/or converters such as analog to digital converters (ADC) **314, 316.** The processors and/or converters such as ADC **314, 316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals**,** the master control algorithm may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **410,** the communication controller **332**, the Vbus controller **326,** the source impedance matching controller **338,** the filter/buffering elements, **318, 320,** differential/single ended conversion circuitry **402, 404**, the converters, **314, 316,** the resonator coil **344,** and may be part of or integrated into a microcontroller **302** or a separate circuit.

[0096] Impedance matching networks **342** and resonator coils **344** may comprise electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to enable tuning of the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planar resonator comprising a magnetic material or any combination thereof.

[0097] Impedance matching networks may comprise fixed value components such as capacitors, inductors, and networks of components as described herein. Parts of the impedance matching networks , A, B and C, may comprise inductors, capacitors, transformers, and series and parallel combinations of such components, as described herein. In some embodiments, parts of the impedance matching networks A, B, and C, may be empty (short-circuited). In some embodiments, part B comprises a series combination of an inductor and a capacitor, and part C is empty.

[0098] The full bridge topology may allow operation at higher output power levels using the same DC bus voltage as an equivalent half bridge amplifier. The half bridge exemplary topology of Fig. 3 may provide a single-ended drive signal, while the exemplary full bridge topology of Fig. 4 may provide a differential drive to the source resonator **308**. The impedance matching topologies and components and the resonator structure may be different for the two systems, as discussed herein.

[0099] The exemplary systems depicted in Figures 3 and 4 may further include fault detection circuitry **340** that may be used to trigger the shutdown of the microcontroller in the source amplifier or to change or interrupt the operation of the amplifier. This protection circuitry may comprise a high speed comparator or comparators to monitor the amplifier return current, the amplifier bus voltage (Vbus) from the DC supply **304**, the voltage across the source resonator **308** and/or the optional tuning board, or any other voltage or current signals that may cause damage to components in the system or may yield undesirable operating conditions. Preferred embodiments may depend on the potentially undesirable operating modes associated with different applications. In some embodiments, protection circuitry may not be implemented or circuits may not be populated. In some embodiments, system and component protection may be implemented as part of a master control algorithm and other system monitoring and control circuits. In embodiments, dedicated fault circuitry **340** may include an output (not shown) coupled to a master control algorithm **328** that may trigger a system shutdown, a reduction of the output power (e.g. reduction of Vbus), a change to the PWM generator, a change in the operating frequency, a change to a tuning element, or any other reasonable action that may be implemented by the control algorithm **328** to adjust the operating point mode, improve system performance, and/or provide protection.

[00100] As described herein, sources in wireless power transfer systems may use a measurement of the input impedance of the impedance matching network **342** driving source resonator coil **344** as an error or control signal for a system control loop that may be part of the master control algorithm. In exemplary embodiments, variations in any combination of three parameters may be used to tune the wireless power source to compensate for changes in environmental conditions, for changes in coupling, for changes in device power demand, for changes in module, circuit, component or subsystem performance, for an increase or decrease in the number or sources, devices, or repeaters in the system, for user initiated changes, and the like. In exemplary embodiments, changes to the amplifier duty cycle, to the component values of the variable electrical components such as variable capacitors and inductors, and to the DC bus voltage may be used to change the operating point or operating range of the wireless source and improve some system operating value. The specifics of the control algorithms employed for different applications may vary depending on the desired system performance and behavior.

[00101] Impedance measurement circuitry such as described herein, and shown in Figures 3 and 4, may be implemented using two-channel simultaneous sampling ADCs and these ADCs may be integrated into a microcontroller chip or may be part of a separate circuit. Simultaneously sampling of the voltage and current signals at the input to a source resonator's impedance matching network and/or the source resonator, may yield the phase and magnitude information of the current and voltage signals and may be processed using known signal processing techniques to yield complex impedance parameters. In some embodiments, monitoring only the voltage signals or only the current signals may be sufficient.

[00102] The impedance measurements described herein may use direct sampling methods which may be relatively simpler than some other known sampling methods. In embodiments, measured voltage and current signals may be conditioned, filtered and scaled by filtering/buffering circuitry before being input to ADCs. In embodiments, the filter/buffering circuitry may be adjustable to work at a variety of signal levels and frequencies, and circuit parameters such as filter shapes and widths may be adjusted manually, electronically, automatically, in response to a control signal, by the master control algorithm, and the like. Exemplary embodiments of filter/buffering circuits are shown in Figures 3, 4, and 5.

[00103] Fig. 5 shows more detailed views of exemplary circuit components that may be used in filter/buffering circuitry. In embodiments, and depending on the types of ADCs used in the system designs, single-ended amplifier topologies may reduce the complexity of the analog signal measurement paths used to characterize system, subsystem, module and/or component performance by eliminating the need for hardware to convert from differential to single-ended signal formats. In other implementations, differential signal formats may be preferable. The implementations shown in Fig. 5 are exemplary, and should not be construed to be the only possible way to implement the functionality described herein. Rather it should be understood that the analog signal path may employ components with different input requirements and hence may have different signal path architectures.

[00104] In both the single ended and differential amplifier topologies, the input current to the impedance matching networks **342** driving the resonator coils **344** may be obtained by measuring the voltage across a capacitor **324,** or via a current sensor of some type. For the exemplary single-ended amplifier topology in Fig. 3, the current may be sensed on the ground return path from the impedance matching network **342**. For the exemplary differential power amplifier depicted in Fig. 4, the input current to the impedance matching networks **342** driving the resonator coils **344** may be measured using a differential amplifier across the terminals of a capacitor **324** or via a current sensor of some type**.** In the differential topology of Fig. 4, the capacitor **324** may be duplicated at the negative output terminal of the source power amplifier.

[00105] In both topologies, after single ended signals representing the input voltage and current to the source resonator and impedance matching network are obtained, the signals may be filtered **502** to obtain the desired portions of the signal waveforms. In embodiments, the signals may be filtered to obtain the fundamental component of the signals. In embodiments, the type of filtering performed, such as low pass, bandpass, notch, and the like, as well as the filter topology used, such as elliptical, Chebyshev, Butterworth, and the like, may depend on the specific requirements of the system. In some embodiments, no filtering will be required.

[00106] The voltage and current signals may be amplified by an optional amplifier **504**. The gain of the optional amplifier **504** may be fixed or variable. The gain of the amplifier may be controlled manually, electronically, automatically, in response to a control signal, and the like. The gain of the amplifier may be adjusted in a feedback loop, in response to a control algorithm, by the master control algorithm, and the like. In embodiments, required performance specifications for the amplifier may depend on signal strength and desired measurement accuracy, and may be different for different application scenarios and control algorithms.

[00107] The measured analog signals may have a DC offset added to them, **506**, which may be required to bring the signals into the input voltage range of the ADC which for some systems may be 0 to 3.3V. In some systems this stage may not be required, depending on the specifications of the particular ADC used.

[00108] As described above, the efficiency of power transmission between a power generator and a power load may be impacted by how closely matched the output impedance of the generator is to the input impedance of the load. In an exemplary system as shown in Fig. 6A, power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load **604** is equal to the complex conjugate of the internal impedance of the power generator or the power amplifier **602**. Designing the generator or load impedance to obtain a high and/or maximum power transmission efficiency may be called "impedance matching". Impedance matching may be performed by inserting appropriate networks or sets of elements such as capacitors, resistors, inductors, transformers, switches and the like, to form an impedance matching network **606,** between a power generator **602** and a power load **604** as shown in Fig. 6B. In other embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching. As described above for varying loads, the impedance matching network **606** may include variable components that are dynamically adjusted to ensure that the impedance at the generator terminals looking towards the load and the characteristic impedance of the generator remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios. In embodiments, dynamic impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power generator or by tuning a physical component within the power generator, such as a capacitor, as depicted in Fig. 6C. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power generator **608** and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network **606**, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power generator may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like. The impedance matching methods, architectures, algorithms, protocols, circuits, measurements, controls, and the like, described below, may be useful in systems where power generators drive high-Q magnetic resonators and in high-Q wireless power transmission systems as described herein. In wireless power transfer systems a power generator may be a power amplifier driving a resonator, sometimes referred to as a source resonator, which may be a load to the power amplifier. In wireless power applications, it may be preferable to control the impedance matching between a power amplifier and a resonator load to control the efficiency of the power delivery from the power amplifier to the resonator. The impedance matching may be accomplished, or accomplished in part, by tuning or adjusting the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power amplifier that drives the resonator.

[00109] Efficiency of switching amplifiers

[00110] Switching amplifiers, such as class D, E, F amplifiers, and the like or any combinations thereof, deliver power to a load at a maximum efficiency when almost no power is dissipated on the switching elements of the amplifier. This operating condition may be accomplished by designing the system so that the switching operations which are most critical (namely those that are most likely to lead to switching losses) are done when either or both of the voltage across the switching element and the current through the switching element are **nearly** zero. These conditions may be referred to as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) conditions respectively. When an amplifier operates at ZVS and/or ZCS either the voltage across the switching element or the current through the switching element is zero and thus no power can be dissipated in the switch. Since a switching amplifier may convert DC (or very low frequency AC) power to AC power at a specific frequency or range of frequencies, a filter may be introduced before the load to prevent unwanted harmonics that may be generated by the switching process from reaching the load and being dissipated there. In embodiments, a switching amplifier may be designed to operate at maximum efficiency of power conversion, when connected to a resonant load, with a quality factor (say Q>5), and of a specific impedance $Z_o^* = R_o + jX_o$, which leads to simultaneous ZVS and ZCS. We define $Z_o = R_o - jX_o$ as the characteristic impedance of the amplifier, so that achieving maximum power transmission efficiency is equivalent to impedance matching the resonant load to the characteristic impedance of the amplifier.

[00111] In a switching amplifier, the switching frequency of the switching elements, f_{switch}, wherein $f_{switch} = \omega/2\pi$ and the duty cycle, dc, of the ON switch-state duration of the switching elements may be the same for all switching elements of the amplifier. In this specification, we will use the term “class D” to denote both class D and class DE amplifiers, that is, switching amplifiers with dc<=50%.

[00112] The value of the characteristic impedance of the amplifier may depend on the operating frequency, the amplifier topology, and the switching sequence of the switching elements. In some embodiments, the switching amplifier may be a half-bridge topology and, in some embodiments, a full-bridge topology. In some embodiments, the switching amplifier may be class D and, in some embodiments, class E. In any of the above embodiments, assuming the elements of the bridge are symmetric, the characteristic impedance of the switching amplifier has the form

$$R_o = F_R(dc)/\omega C_a \,,X_o = F_X(dc)/\omega C_a \,, \qquad (1)$$

where *dc* is the duty cycle of ON switch-state of the switching elements, the functions $F_R(dc)$ and $F_X(dc)$ are plotted in Fig. 7 (both for class D and E), ω is the frequency at which the switching elements are switched, and $C_a = n_a C_{switc}$ where C_{switc} is the capacitance across each switch, including both the transistor output capacitance and also possible external capacitors placed in parallel with the switch, while $n_a = 1$ for a full bridge and $n_a = 2$ for a half bridge. For class D, one can also write the analytical expressions

$$F_R(dc) = sin^2 u/\pi, \quad F_X(dc) = (u - sinu * cosu)/\pi \,, \qquad (2)$$

where $u = \pi(1 - 2 * dc)$, indicating that the characteristic impedance level of a class D amplifier decreases as the duty cycle, *dc*, increases towards 50%. For a class D amplifier operation with dc=50%, achieving ZVS and ZCS is possible only when the switching elements have practically no output capacitance ($C_a = 0$) and the load is exactly on resonance ($X_o = 0$), while R_o can be arbitrary.

[00113] Impedance Matching Networks

[00114] In applications, the driven load may have impedance that is very different from the characteristic impedance of the external driving circuit, to which it is connected. Furthermore, the driven load may not be a resonant network. An Impedance Matching Network (IMN) is a circuit network that may be connected before a load as in Fig. 6B, in order to regulate the impedance that is seen at the input of the network consisting of the IMN circuit and the load. An IMN circuit may typically achieve this regulation by creating a resonance close to the driving frequency. Since such an IMN circuit accomplishes all conditions needed to maximize the power transmission efficiency from the generator to the load (resonance and impedance matching – ZVS and ZCS for a switching amplifier), in embodiments, an IMN circuit may be used between the driving circuit and the load.

[00115] For an arrangement shown in Fig. 6B, let the input impedance of the network consisting of the Impedance Matching Network (IMN) circuit and the load (denoted together from now on as IMN+load) be $Z_l = R_l(\omega) + jX_l(\omega)$. The impedance matching conditions of this network to the external circuit with characteristic impedance $Z_o = R_o - jX_o$ are then $R_l(\omega) = R_o, X_l(\omega) = X_o$.

[00116] Methods for tunable Impedance Matching of a variable load

[00117] In embodiments where the load may be variable, impedance matching between the load and the external driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components in the IMN circuit that may be adjusted to match the varying load to the fixed characteristic impedance Z_o of the external circuit (Fig. 6B). To match both the real and imaginary parts of the impedance two tunable/variable elements in the IMN circuit may be needed.

[00118] In embodiments, the load may be inductive (such as a resonator coil) with impedance $R + j\omega L$, so the two tunable elements in the IMN circuit may be two tunable capacitance networks or one tunable capacitance network and one tunable inductance network or one tunable capacitance network and one tunable mutual inductance network.

[00119] In embodiments where the load may be variable, the impedance matching between the load and the driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components or parameters in the amplifier circuit that may be adjusted to match the characteristic impedance Z_o of the amplifier to the varying (due to load variations) input impedance of the network consisting of the IMN circuit and the load (IMN+load), where the IMN circuit may also be tunable (Fig. 6C). To match both the real and imaginary parts of the impedance, a total of two tunable/variable elements or parameters in the amplifier and the IMN circuit may be needed. The disclosed impedance matching method can reduce the required number of tunable/variable elements in the IMN circuit or even completely eliminate the requirement for tunable/variable elements in the IMN circuit. In some examples, one tunable element in the power amplifier and one tunable element in the IMN circuit may be used. In some examples, two tunable elements in the power amplifier and no tunable element in the IMN circuit may be used.

[00120] In embodiments, the tunable elements or parameters in the power amplifier may be the frequency, amplitude, phase, waveform, duty cycle and the like of the drive signals applied to transistors, switches, diodes and the like.

[00121] In embodiments, the power amplifier with tunable characteristic impedance may be a tunable switching amplifier of class D, E, F or any combinations thereof. Combining Equations (1) and (2), the impedance matching conditions for this network are

$$R_l(\omega) = F_R(dc)/\omega C_a\,,\, X_l(\omega) = F_X(dc)/\omega C_a \qquad (3).$$

[00122] In some examples of a tunable switching amplifier, one tunable element may be the capacitance C_a, which may be tuned by tuning the external capacitors placed in parallel with the switching elements.

[00123] In some examples of a tunable switching amplifier, one tunable element may be the duty cycle *dc* of the ON switch-state of the switching elements of the amplifier. Adjusting the duty cycle, *dc*, via Pulse Width Modulation (PWM) has been used in switching amplifiers to achieve output power control. In this specification, we disclose that PWM may also be used to achieve impedance matching, namely to satisfy Eqs.(3), and thus maximize the amplifier efficiency.

[00124] In some examples of a tunable switching amplifier one tunable element may be the switching frequency, which is also the driving frequency of the IMN+load network and may be designed to be substantially close to the resonant frequency of the IMN+load network. Tuning the switching frequency may change the characteristic impedance of the amplifier and the impedance of the IMN+load network. The switching frequency of the amplifier may be tuned appropriately together with one more tunable parameters, so that Eqs.(3) are satisfied.

[00125] A benefit of tuning the duty cycle and/or the driving frequency of the amplifier for dynamic impedance matching is that these parameters can be tuned electronically, quickly, and over a broad range. In contrast, for example, a tunable capacitor that can sustain a large voltage and has a large enough tunable range and quality factor may be expensive, slow or unavailable for with the necessary component specifications

[00126] Examples of methods for tunable Impedance Matching of a variable load

[00127] A simplified circuit diagram showing the circuit level structure of a class D power amplifier **802**, impedance matching network **804** and an inductive load **806** is shown in Fig. 8. The diagram shows the basic components of the system with the switching amplifier **804**

comprising a power source **810,** switching elements **808**, and capacitors. The impedance matching network **804** comprising inductors and capacitors, and the load **806** modeled as an inductor and a resistor.

[00128] An exemplary embodiment of this inventive tuning scheme comprises a half-bridge class-D amplifier operating at switching frequency f and driving a low-loss inductive element $R + j\omega L$ via an IMN, as shown in Fig. 8.

[00129] In some embodiments L' may be tunable. L' may be tuned by a variable tapping point on the inductor or by connecting a tunable capacitor in series or in parallel to the inductor. In some embodiments C_a may be tunable. For the half bridge topology, C_a may be tuned by varying either one or both capacitors C_{switc} , as only the parallel sum of these capacitors matters for the amplifier operation. For the full bridge topology, C_a may be tuned by varying either one, two, three or all capacitors C_{switc} , as only their combination (series sum of the two parallel sums associated with the two halves of the bridge) matters for the amplifier operation.

[00130] In some embodiments of tunable impedance matching, two of the components of the IMN may be tunable. In some embodiments, L' and C_2 may be tuned. Then, Fig. 9 shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier, for $f = 250kHz$, $dc = 40\%$, $C_a = 640pF$ and $C_1 = 10nF$. Since the IMN always adjusts to the fixed characteristic impedance of the amplifier, the output power is always constant as the inductive element is varying.

[00131] In some embodiments of tunable impedance matching, elements in the switching amplifier may also be tunable. In some embodiments the capacitance C_a along with the IMN capacitor C_2 may be tuned. Then, Fig. 10 shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $dc = 40\%$, $C_1 = 10nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 10 that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[00132] In some embodiments of tunable impedance matching, the duty cycle *dc* along with the IMN capacitor C_2 may be tuned. Then, Fig. 11 shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_a = 640pF$, $C_1 = 10nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 11 that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[00133] In some embodiments of tunable impedance matching, the capacitance C_a along with the IMN inductor L' may be tuned. Then, Fig. 11A shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $dc = 40\%$, $C_1 = 10nF$ and $C_2 = 7.5nF$. It can be inferred from Fig. 11A that the output power decreases as R increases.

[00134] In some embodiments of tunable impedance matching, the duty cycle *dc* along with the IMN inductor L' may be tuned. Then, Fig. 11B shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_a = 640pF$, $C_1 = 10nF$ and $C_2 = 7.5nF$ as functions of the varying R of the inductive element. It can be inferred from Fig. 11B that the output power decreases as R increases.

[00135] In some embodiments of tunable impedance matching, only elements in the switching amplifier may be tunable with no tunable elements in the IMN. In some embodiments the duty cycle *dc* along with the capacitance C_a may be tuned. Then, Fig. 11C, shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_1 = 10nF$, $C_2 = 7.5nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 11C that the output power is a non-monotonic function of R. These embodiments may be able to achieve dynamic impedance matching when variations in L (and thus the resonant frequency) are modest.

[00136] In some embodiments, dynamic impedance matching with fixed elements inside the IMN, also when L is varying greatly as explained earlier, may be achieved by varying the driving frequency of the external frequency f (e.g. the switching frequency of a switching amplifier) so that it follows the varying resonant frequency of the resonator. Using the switching frequency *f* and the switch duty cycle *dc* as the two variable parameters, full impedance matching can be achieved as R and L are varying without the need of any variable components. Then, Fig. 12 shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $C_a = 640pF$, $C_1 = 10nF$, $C_2 = 7.5nF$ and $L' = 637\mu H$. It can be inferred from Fig. 12 that the frequency f needs to be tuned mainly in response to variations in L, as explained earlier.

[00137] Tunable Impedance Matching for systems of wireless power transmission

[00138] In applications of wireless power transfer the low-loss inductive element may be the coil of a source resonator coupled to one or more device resonators or other resonators, such as repeater resonators, for example. The impedance of the inductive element $R + j\omega L$ may include the reflected impedances of the other resonators on the coil of the source resonator. Variations of R and L of the inductive element may occur due to external perturbations in the vicinity of the source resonator and/or the other resonators or thermal drift of components. Variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to relative motion of the devices and other resonators with respect to the source. The relative motion of these devices and other resonators with respect to the source, or relative motion or position of other sources, may lead to varying coupling (and thus varying reflected impedances) of the devices to the source. Furthermore, variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to changes within the other coupled resonators, such as changes in the power draw of their loads. All the methods and embodiments disclosed so far apply also to this case in order to achieve dynamic impedance matching of this inductive element to the external circuit driving it.

[00139] To demonstrate the presently disclosed dynamic impedance matching methods for a wireless power transmission system, consider a source resonator including a low-loss source coil, which is inductively coupled to the device coil of a device resonator driving a resistive load.

[00140] In some embodiments, dynamic impedance matching may be achieved at the source circuit. In some embodiments, dynamic impedance matching may also be achieved at the device circuit. When full impedance matching is obtained (both at the source and the device), the effective resistance of the source inductive element (namely the resistance of the source coil

R_s plus the reflected impedance from the device) is $R = R_s\sqrt{1+U_{sd}^2}$. (Similarly the effective resistance of the device inductive element is $R_d\sqrt{1+U_{sd}^2}$, where R_d is the resistance of the device coil.) Dynamic variation of the mutual inductance between the coils due to motion results in a dynamic variation of $U_{sd} = \omega M_{sd}/\sqrt{R_s R_d}$. Therefore, when both source and device are dynamically tuned, the variation of mutual inductance is seen from the source circuit side as a variation in the source inductive element resistance R. Note that in this type of variation, the resonant frequencies of the resonators may not change substantially, since L may not be changing. Therefore, all the methods and examples presented for dynamic impedance matching may be used for the source circuit of the wireless power transmission system.

[00141] Note that, since the resistance R represents both the source coil and the reflected impedances of the device coils to the source coil, in Figures 9-12, as R increases due to the increasing U, the associated wireless power transmission efficiency increases. In some embodiments, an approximately constant power may be required at the load driven by the device circuitry. To achieve a constant level of power transmitted to the device, the required output power of the source circuit may need to decrease as U increases. If dynamic impedance matching is achieved via tuning some of the amplifier parameters, the output power of the amplifier may vary accordingly. In some embodiments, the automatic variation of the output power is preferred to be monotonically decreasing with R, so that it matches the constant device power requirement. In embodiments where the output power level is accomplished by adjusting the DC driving voltage of the power generator, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R will imply that constant power can be kept at the power load in the device with only a moderate adjustment of the DC driving voltage. In embodiments, where the "knob" to adjust the output power level is the duty cycle *dc* or the phase of a switching amplifier or a component inside an Impedance Matching Network, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R will imply that constant power can be kept at the power load in the device with only a moderate adjustment of this power "knob".

[00142] In the examples of Figures 9-12, if $R_s = 0.19\Omega$, then the range $R = 0.2 - 2\Omega$ corresponds approximately to $U_{sd} = 0.3 - 10.5$. For these values, in Fig. 14, we show with dashed lines the output power (normalized to DC voltage squared) required to keep a constant power level at the load, when both source and device are dynamically impedance matched. The similar trend between the solid and dashed lines explains why a set of tunable parameters with such a variation of output power may be preferable.

[00143] In some embodiments, dynamic impedance matching may be achieved at the source circuit, but impedance matching may not be achieved or may only partially be achieved at the device circuit. As the mutual inductance between the source and device coils varies, the varying reflected impedance of the device to the source may result in a variation of both the effective resistance R and the effective inductance L of the source inductive element. The methods presented so far for dynamic impedance matching are applicable and can be used for the tunable source circuit of the wireless power transmission system.

[00144] As an example, consider the circuit of Fig. 14, where $f = 250kHz$, $C_a = 640pF$, $R_s = 0.19\Omega$, $L_s = 100\mu H$, $C_{1s} = 10nF$, $\omega L_s' = 1000\Omega$, $R_d = 0.3\Omega$, $L_d = 40\mu H$, $C_{1d} = 87.5nF$, $C_{2d} = 13nF$, $\omega L_d' = 400\Omega$ and $Z_l = 50\Omega$, where *s* and *d* denote the source and device resonators respectively and the system is matched at $U_{sd} = 3$. Tuning the duty cycle *dc* of the switching amplifier and the capacitor C_{2s} may be used to dynamically impedance match the source, as the non-tunable device is moving relatively to the source changing the mutual inductance M between the source and the device. In Fig. 14, we show the required values of the tunable parameters along with the output power per DC voltage of the amplifier. The dashed line again indicates the output power of the amplifier that would be needed so that the power at the load is a constant value.

[00145] In some embodiments, tuning the driving frequency f of the source driving circuit may still be used to achieve dynamic impedance matching at the source for a system of wireless power transmission between the source and one or more devices. As explained earlier, this method enables full dynamic impedance matching of the source, even when there are variations in the source inductance L_s and thus the source resonant frequency. For efficient power transmission from the source to the devices, the device resonant frequencies must be tuned to follow the variations of the matched driving and source-resonant frequencies. Tuning a device capacitance (for example, in the embodiment of Fig. 13 C_{1d} or C_{2d}) may be necessary, when there are variations in the resonant frequency of either the source or the device resonators. In fact, in a wireless power transfer system with multiple sources and devices, tuning the driving frequency alleviates the need to tune only one source-object resonant frequency, however, all the rest of the objects may need a mechanism (such as a tunable capacitance) to tune their resonant frequencies to match the driving frequency.

[00146] **Resonator Thermal Management**

[00147] In wireless energy transfer systems, some portion of the energy lost during the wireless transfer process is dissipated as heat. Energy may be dissipated in the resonator components themselves. For example, even high-Q conductors and components have some loss or resistance, and these conductors and components may heat up when electric currents and/or electromagnetic fields flow through them. Energy may be dissipated in materials and objects around a resonator. For example, eddy currents dissipated in imperfect conductors or dielectrics surrounding or near-by the resonator may heat up those objects. In addition to affecting the material properties of those objects, this heat may be transferred through conductive, radiative, or convective processes to the resonator components. Any of these heating effects may affect the resonator Q, impedance, frequency, etc., and therefore the performance of the wireless energy transfer system.

[00148] In a resonator comprising a block or core of magnetic material, heat may be generated in the magnetic material due to hysteresis losses and to resistive losses resulting from induced eddy currents. Both effects depend on the magnetic flux density in the material, and both can create significant amounts of heat, especially in regions where the flux density or eddy currents may be concentrated or localized. In addition to the flux density, the frequency of the oscillating magnetic field, the magnetic material composition and losses, and the ambient or operating temperature of the magnetic material may all impact how hysteresis and resistive losses heat the material.

[00149] In embodiments, the properties of the magnetic material such as the type of material, the dimensions of the block, and the like, and the magnetic field parameters may be chosen for specific operating power levels and environments to minimize heating of the magnetic material. In some embodiments, changes, cracks, or imperfections in a block of magnetic material may increase the losses and heating of the magnetic material in wireless power transmission applications.

[00150] For magnetic blocks with imperfections, or that are comprised of smaller size tiles or pieces of magnetic material arranged into a larger unit, the losses in the block may be uneven and may be concentrated in regions where there are inhomogeneities or relatively narrow gaps between adjacent tiles or pieces of magnetic material. For example, if an irregular gap exists in a magnetic block of material, then the effective reluctance of various magnetic flux paths through the material may be substantially irregular and the magnetic field may be more concentrated in portions of the block where the magnetic reluctance is lowest. In some cases, the effective reluctance may be lowest where the gap between tiles or pieces is narrowest or where the density of imperfections is lowest. Because the magnetic material guides the magnetic field, the magnetic flux density may not be substantially uniform across the block, but may be concentrated in regions offering relatively lower reluctance. Irregular concentrations of the magnetic field within a block of magnetic material may not be desirable because they may result in uneven losses and heat dissipation in the material.

[00151] For example, consider a magnetic resonator comprising a conductor **1506** wrapped around a block of magnetic material composed of two individual tiles **1502, 1504** of magnetic material joined such that they form a seam **1508** that is perpendicular to the axis of the conductor **1506** loops as depicted in Fig. 15. An irregular gap in the seam **1508** between the tiles of magnetic material **1502, 1504** may force the magnetic field **1512** (represented schematically by the dashed magnetic field lines) in the resonator to concentrate in a sub region **1510** of the cross section of the magnetic material. Since the magnetic field will follow the path of least reluctance, a path including an air gap between two pieces of magnetic material may create an effectively higher reluctance path than one that traverses the width of the magnetic material at a point where the pieces of magnetic materials touch or have a smaller air gap. The magnetic flux density may therefore preferentially flow through a relatively small cross area of the magnetic material resulting in a high concentration of magnetic flux in that small area **1510**.

[00152] In many magnetic materials of interest, more inhomogeneous flux density distributions lead to higher overall losses. Moreover, the more inhomogeneous flux distribution may result in material saturation and cause localized heating of the area in which the magnetic flux is concentrated. The localized heating may alter the properties of the magnetic material, in some cases exacerbating the losses. For example, in the relevant regimes of operation of some materials, hysteresis and resistive losses increase with temperature. If heating the material increases material losses, resulting in more heating, the temperature of the material may continue to increase and even runaway if no corrective action is taken. In some instances, the temperature may reach 100C or more and may degrade the properties of the magnetic material and the performance of wireless power transfer. In some instances, the magnetic materials may be damaged, or the surrounding electronic components, packaging and/or enclosures may be damaged by the excessive heat.

[00153] In embodiments, variations or irregularities between tiles or pieces of the block of magnetic material may be minimized by machining, polishing, grinding, and the like, the edges of the tiles or pieces to ensure a tight fit between tiles of magnetic materials providing a substantially more uniform reluctance through the whole cross section of the block of magnetic material. In embodiments, a block of magnetic material may require a means for providing a compression force between the tiles to ensure the tiles are pressed tight together without gaps. In embodiments, an adhesive may be used between the tiles to ensure they remain in tight contact.

[00154] In embodiments the irregular spacing of adjacent tiles of magnetic material may be reduced by adding a deliberate gap between adjacent tiles of magnetic material. In embodiments a deliberate gap may be used as a spacer to ensure even or regular separations between magnetic material tiles or pieces. Deliberate gaps of flexible materials may also reduce irregularities in the spacings due to tile movement or vibrations. In embodiments, the edges of adjacent tiles of magnetic material may be taped, dipped, coated, and the like with an electrical insulator, to prevent eddy currents from flowing through reduced cross-sectional areas of the block, thus lowering the eddy current losses in the material. In embodiments a separator may be integrated into the resonator packaging. The spacer may provide a spacing of 1mm or less.

[00155] In embodiments, the mechanical properties of the spacer between tiles may be chosen so as to improve the tolerance of the overall structure to mechanical effects such as changes in the dimensions and/or shape of the tiles due to intrinsic effects (e.g,, magnetostriction, thermal expansion, and the like) as well as external shocks and vibrations. For example, the spacer may have a desired amount of mechanical give to accommodate the expansion and/or contraction of individual tiles, and may help reduce the stress on the tiles when they are subjected to mechanical vibrations, thus helping to reduce the appearance of cracks and other defects in the magnetic material.

[00156] In embodiments, it may be preferable to arrange the individual tiles that comprise the block of magnetic material to minimize the number of seams or gaps between tiles that are perpendicular to the dipole moment of the resonator. In embodiments it may be preferable to arrange and orient the tiles of magnetic material to minimize the gaps between tiles that are perpendicular to the axis formed by the loops of a conductor comprising the resonator.

[00157] For example, consider the resonator structure depicted in Fig. 16. The resonator comprises a conductor **1604** wrapped around a block of magnetic material comprising six separate individual tiles **1602** arranged in a three by two array. The arrangement of tiles results in two tile seams **1606, 1608** when traversing the block of magnetic material in one direction, and only one tile seam **1610** when traversing the block of magnetic material in the orthogonal direction. In embodiments, it may be preferable to wrap the conductor wire **1604** around the block of magnetic material such that the dipole moment of the resonator is perpendicular to the fewest number of tile seams. The inventors have observed that there is relatively less heating induced around seams and gaps **1606, 1608** that are parallel to the dipole moment of the resonator. Seams and gaps that run perpendicular to the dipole moment of the resonator may also be referred to as critical seams or critical seam areas. It may still be desirable, however, to electrically insulate gaps that run parallel to the dipole moment of the resonator (such as **1606** and **1608**) so as to reduce eddy current losses. Uneven contact between tiles separated by such parallel gaps may cause eddy currents to flow through narrow contact points, leading to large losses at such points.

[00158] In embodiments, irregularities in spacing may be tolerated with adequate cooling of the critical seam areas to prevent the localized degradation of material properties when the magnetic material heats up. Maintaining the temperature of the magnetic material below a critical temperature may prevent a runaway effect caused by a sufficiently high temperature. With proper cooling of the critical seam area, the wireless energy transfer performance may be satisfactory despite the additional loss and heating effects due to irregular spacing, cracks, or gaps between tiles.

[00159] Effective heatsinking of the resonator structure to prevent excessive localized heating of the magnetic material poses several challenges. Metallic materials that are typically used for heatsinks and thermal conduction can interact with the magnetic fields used for wireless energy transfer by the resonators and affect the performance of the system. Their location, size, orientation, and use should be designed so as to not excessively lower the perturbed Q of the resonators in the presence of these heatsinking materials. In addition, owing to the relatively poor thermal conductivity of magnetic materials such as ferrites, a relatively large contact area between the heatsink and the magnetic material may be required to provide adequate cooling which may require placement of substantial amount of lossy materials close to the magnetic resonator.

[00160] In embodiments, adequate cooling of the resonator may be achieved with minimal effect on the wireless energy transfer performance with strategic placement of thermally conductive materials. In embodiments, strips of thermally conductive material may be placed in between loops of conductor wire and in thermal contact with the block of magnetic material.

[00161] One exemplary embodiment of a resonator with strips of thermally conductive material is depicted in Fig. 17. Fig. 17A shows the resonator structure without the conducting strips and with the block of magnetic material comprising smaller tiles of magnetic material forming gaps or seams. Strips of thermally conductive **1708** material may be placed in between the loops of the conductor **1702** and in thermal contact with the block of magnetic material **1704** as depicted in Figs. 17B and 17C. To minimize the effects of the strips on the parameters of the resonator, in some embodiments it may be preferable to arrange the strips parallel to the loops of conductor or perpendicular to the dipole moment of the resonator. The strips of conductor may be placed to cover as much or as many of the seams or gaps between the tiles as possible especially the seams between tiles that are perpendicular to the dipole moment of the resonator.

[00162] In embodiments the thermally conductive material may comprise copper, aluminum, brass, thermal epoxy, paste, pads, and the like, and may be any material that has a thermal conductivity that is at least that of the magnetic material in the resonator (~5W/(K-m) for some commercial ferrite materials). In embodiments where the thermally conductive material is also electrically conducting, the material may require a layer or coating of an electrical insulator to prevent shorting and direct electrical contact with the magnetic material or the loops of conductor of the resonator.

[00163] In embodiments the strips of thermally conductive material may be used to conduct heat from the resonator structure to a structure or medium that can safely dissipate the thermal energy. In embodiments the thermally conductive strips may be connected to a heat sink such as a large plate located above the strips of conductor that can dissipate the thermal energy using passive or forced convection, radiation, or conduction to the environment. In embodiments the system may include any number of active cooling systems that may be external or internal to the resonator structure that can dissipate the thermal energy from the thermally conducting strips and may include liquid cooling systems, forced air systems, and the like. For example, the thermally conducting strips may be hollow or comprise channels for coolant that may be pumped or forced through to cool the magnetic material. In embodiments, a field deflector made of a good electrical conductor (such as copper, silver, aluminum, and the like) may double as part of the heatsinking apparatus. The addition of thermally and electrically conducting strips to the space between the magnetic material and the field deflector may have a marginal effect on the perturbed *Q*, as the electromagnetic fields in that space are typically suppressed by the presence of the field deflector. Such conducting strips may be thermally connected to both the magnetic material and the field deflector to make the temperature distribution among different strips more homogeneous.

[00164] In embodiments the thermally conducting strips are spaced to allow at least one loop of conductor to wrap around the magnetic material. In embodiments the strips of thermally conductive material may be positioned only at the gaps or seams of the magnetic material. In other embodiments, the strips may be positioned to contact the magnetic material at substantially throughout its complete length. In other embodiments, the strips may be distributed to match the flux density within the magnetic material. Areas of the magnetic material which under normal operation of the resonator may have higher magnetic flux densities may have a higher density of contact with the thermally conductive strips. In embodiments depicted in Fig 17A) for example, the highest magnetic flux density in the magnetic material may be observed toward the center of the block of magnetic material and the lower density may be toward the ends of the block in the direction of the dipole moment of the resonator.

[00165] To show how the use of thermally conducting strips helps to reduce the overall temperature in the magnetic material as well as the temperature at potential hot spots, the inventors have performed a finite element simulation of a resonator structure similar to that depicted in Fig. 17C. The structure was simulated operating at a frequency of 235 kHz and comprising a block of EPCOS N95 magnetic material measuring 30 cm x 30 cm x 5 mm excited by 10 turns of litz wire (symmetrically placed at 25 mm, 40 mm, 55 mm, 90 mm and 105 mm from the plane of symmetry of the structure) carrying 40 A of peak current each, and thermally connected to a 50 cm x 50 cm x 4 mm field deflector by means of three 3 x ¾ x 1' hollow square tubes (1/8" wall thickness) of aluminum (alloy 6063) whose central axes are placed at -75mm, 0 mm, and +75 from the symmetry plane of the structure. The perturbed Q due to the field deflector and hollow tubes was found to be 1400 (compared to 1710 for the same structure without the hollow tubes). The power dissipated in the shield and tubes was calculated to be 35.6 W, while that dissipated in the magnetic material was 58.3 W. Assuming the structure is cooled by air convection and radiation and an ambient temperature of 24 °C, the maximum temperature in the structure was 85 °C (at points in the magnetic material approximately halfway between the hollow tubes) while the temperature in parts of the magnetic material in contact with the hollow tubes was approximately 68 °C. By comparison, the same resonator without the thermally conducting hollow tubes dissipated 62.0 W in the magnetic material for the same excitation current of 40 W peak and the maximum temperature in the magnetic material was found to be 111 °C.

[00166] The advantage of the conducting strips is more apparent still if we introduce a defect in a portion of the magnetic material that is in good thermal contact with the tubes. An air gap 10 cm long and 0.5 mm placed at the center of the magnetic material and oriented perpendicular to the dipole moment increases the power dissipated in the magnetic material to 69.9 W (the additional 11.6W relative to the previously discussed no-defect example being highly concentrated in the vicinity of the gap), but the conducting tube ensures that the maximum temperature in the magnetic material has only a relative modest increase of 11 °C to 96 °C. In contrast, the same defect without the conducting tubes leads to a maximum temperature of 161 °C near the defect. Cooling solutions other than convection and radiation, such as thermally connecting the conducting tubes body with large thermal mass or actively cooling them, may lead to even lower operational temperatures for this resonator at the same current level.

[00167] In embodiments thermally conductive strips of material may be positioned at areas that may have the highest probability of developing cracks that may cause irregular gaps in the magnetic material. Such areas may be areas of high stress or strain on the material, or areas with poor support or backing from the packaging of the resonator. Strategically positioned thermally conductive strips may ensure that as cracks or irregular gaps develop in the magnetic material, the temperature of the magnetic material will be maintained below its critical temperature. The critical temperature may be defined as the Curie temperature of the magnetic material, or any temperature at which the characteristics of the resonator have been degraded beyond the desired performance parameters.

[00168] In embodiments the heastsinking structure may provide mechanical support to the magnetic material. In embodiments the heatsinking structure may be designed to have a desired amount of mechanical give (e.g., by using epoxy, thermal pads, and the like having suitable mechanical properties to thermally connect different elements of the structure) so as to provide the resonator with a greater amount of tolerance to changes in the intrinsic dimensions of its elements (due to thermal expansion, magnetostriction, and the like) as well as external shocks and vibrations, and prevent the formation of cracks and other defects.

[00169] In embodiments where the resonator comprises orthogonal windings wrapped around the magnetic material, the strips of conducting material may be tailored to make thermal contact with the magnetic material within areas delimited by two orthogonal sets of adjacent loops. In embodiments a strip may contain appropriate indentations to fit around the conductor of at least one orthogonal winding while making thermal contact with the magnetic material at least one point. In embodiments the magnetic material may be in thermal contact with a number of thermally conducting blocks placed between adjacent loops. The thermally conducting blocks may be in turn thermally connected to one another by means of a good thermal conductor and/or heatsinked.

[00170] Throughout this description although the term thermally conductive strips of material was used as an exemplary specimen of a shape of a material it should be understood by those skilled in the art that any shapes and contours may be substituted without departing from the spirit of the inventions. Squared, ovals, strips, dots, elongated shapes, and the like would all be within the spirit of the present invention.

[00171] <u>Communication in a Wireless Energy Transfer System</u>

[00172] A wireless energy transfer system may require a verification step to ensure that energy is being transferred between designated resonators. For example, in wireless energy transfer systems, source resonators, device resonators, and repeater resonators, do not require physical contact with each other in order to exchange energy, and these resonators may be separated from each other by distances of centimeters or meters, depending on the size and number of resonators in the system. In some configurations, multiple resonators may be in a position to generate or receive power, but only two or some of those resonators are designated resonators.

[00173] Communication of information between resonators in a wireless energy transfer system may be utilized to designate resonators. Communication of information between resonators may be implemented using in-band or out-of-band communications or communications channels. If at least some part of a magnetic resonator used to exchange power is also used to exchange information, and the carrier frequency of the information exchange is close to the resonant frequency used in the power exchange, we refer to that communication as in-band. Any other type of communication between magnetic resonators is referred to as out-of-band. An out-of-band communication channel may use an antenna and a signaling protocol that is separated from the energy transfer resonator and magnetic fields. An out-of-band communication channel may use or be based on Bluetooth, WiFi, Zigbee, NFC technology and the like.

[00174] Communication between resonators may be used to coordinate the wireless energy transfer or to adjust the parameters of a wireless energy transfer system, to identify and authenticate available power sources and devices, to optimize efficiency, power delivery, and the like, to track and bill energy preferences, usage, and the like, and to monitor system performance, battery condition, vehicle health, extraneous objects, also referred to as foreign objects, and the like. Methods for designating and verifying resonators for energy transfer may be different when in-band and out-of-band communication channels are used because the distance over which communication signals may be exchanged using out-of-band techniques may greatly exceed the distance over which the power signals may be exchanged. Also, the bandwidth of out-of-band communication signals may be larger than in-band communication signals. This difference in communication range and capability may affect the coordination of the wireless energy transfer system. For example, the number of resonators that may be addressed using out-of-band communication may be very large and communicating resonators may be farther apart than the distance over which they may efficiently exchange energy.

[00175] In some embodiments all of the signaling and communication may be performed using an in-band communication channel and the signals may be modulated on the fields used for energy transfer. In other embodiments, in-band communication may use substantially the same frequency spectrum as is used for energy transfer, but communication may occur while useful amounts of energy are not being transmitted. Using only the in-band communication channel may be preferable if separate or multiple verification steps are problematic, because the range of the communication may be limited to the same range as the power exchange or because the information arrives as a modulation on the power signal itself. In some embodiments however, a separate out-of-band communication channel may be more desirable. For example, an out-of-band communication channel may be less expensive to implement and may support higher data rates. An out-of-band communication channel may support longer distance communication, allowing resonator discovery and power system mapping. An out-of-band communication channel may operate regardless of whether or not power transfer is taking place and may occur without disruption of the power transfer.

[00176] An exemplary embodiment of a wireless energy system is shown in Fig. 18. This exemplary embodiment comprises two device resonators **1802, 1816** each with an out-of-band communication module **1804, 1818** respectively and two source resonators **1806, 1810** each with their own out-of-band communication modules **1808, 1812** respectively. The system may use the out-of-band communication channel to adjust and coordinate the energy transfer. The communication channel may be used to discover or find resonators in the proximity, to initiate power transfer, and to communicate adjustment of operating parameters such as power output, impedance, frequency, and the like of the individual resonators.

[00177] In some situations a device resonator may incorrectly communicate with one source but receive energy from another source resonator. For example, imagine that device **1802** sends an out-of-band communication signal requesting power from a source. Source **1810** may respond and begin to supply power to device **1802**. Imagine that device **1816** also sends an out-of-band communication signal requesting power from a source and that source **1806** responds and begins to supply power to device **1816**. Because of the proximity of device **1802** to source **1806**, it is possible that device **1802** receives some or most of its power from source **1806**. If the power level received by device **1802** becomes too high, device **1802** may send an out-of-band communication signal to source **1810** to reduce the power it is transmitting to device **1802**. However, device **1802** may still be receiving too much power, because it is receiving power from source **1806** but is not communicating control signals to that source **1806**.

[00178] Therefore, the separation of the energy transfer channel and the communication channel may create performance, control, safety, security, reliability, and the like issues in wireless energy transfer systems. In embodiments, it may be necessary for resonators in a wireless energy transfer system to identify/designate and verify any and all resonators with which it is exchanging power. As those skilled in the art will recognize, the example shown in Fig. 18 is just one example and there exist many configurations and arrangements of wireless power transmission systems that may benefit from explicit or implicit energy transfer verification steps.

[00179] In embodiments, the potential performance, control, safety, security, reliability and the like, issues may be avoided by providing at least one verification step that insures that the energy transfer channel and the communication channel used by a pair of resonators are associated with the same pair of resonators.

[00180] In embodiments the verification step may comprise some additional information exchange or signaling through the wireless energy transfer channel. A verification step comprising communication or information exchange using the energy transfer channel, or fields of the energy transfer channel may be used to verify that the out-of-band communication channel is exchanging information between the same two resonators that are or will be exchanging energy.

[00181] In embodiments with an out-of-band communication channel the verification step may be implicit or explicit. In some embodiments verification may be implicit. In embodiments an energy transfer channel may be implicitly verified by monitoring and comparing the behavior of the energy transfer channel to expected behavior or parameters in response to the out-of-band information exchange. For example, after establishing out-of-band communications, a device may request that a wireless source increase the amount of power it is transmitting. At the same time, parameters of the wireless energy transfer channel and resonators may be monitored. An observed increase of delivered power at the device may be used to infer that the out-of-band communication channel and the energy transfer channel are correctly linked to the designated resonators.

[00182] In embodiments an implicit verification step may involve monitoring any number of the parameters of the wireless energy transfer or parameters of the resonators and components used in the wireless energy transfer. In embodiments the currents, voltages, impedances, frequency, efficiency, temperatures, of the resonators and their drive circuits and the like may be monitored and compared to expected values, trends, changes and the like as a result of an out-of-band communication exchange.

[00183] In embodiments a resonator may store tables of measured parameters and expected values, trends, and/or changes to these parameters as a consequence of a communication exchange. A resonator may store a history of communications and observed parameter changes that may be used to verify the energy transfer channel. In some cases a single unexpected parameter change due to a communication exchange may be not be conclusive enough to determine the out-of-band channel is incorrectly paired. In some embodiments the history of parameter changes may be scanned or monitored over several or many communication exchanges to perform verification.

[00184] An example algorithm showing the series of steps which may be used to implicitly verify an energy transfer channel in a wireless energy transfer system using out-of-band communication is shown in Fig. 19A. In the first step **1902** an out-of-band communication channel between a source and a device is established. In the next step **1904** the source and device may exchange information regarding adjusting the parameters of the wireless energy transfer or parameters of the components used for wireless energy transfer. The information exchange on the out-of-band communication channel may be a normal exchange used in normal operation of the system to control and adjust the energy transfer. In some systems the out-of-band communication channel may be encrypted preventing eavesdropping, impersonation, and the like. In the next step **1906** the source and the device or just a source or just a device may monitor and keep track of any changes to the parameters of the wireless energy transfer or any changes in parameters in the components used in the energy transfer. The tracked changes may be compared against expected changes to the parameters as a consequence of any out-of-band communication exchanges. Validation may be considered failed when one or many observed changes in parameters do not correspond to expected changes in parameters.

[00185] In some embodiments of wireless energy transfer systems verification may be explicit. In embodiments a source or a device may alter, dither, modulate, and the like the parameters of the wireless energy transfer or the parameters of the resonators used in the wireless energy transfer to communicate or provide a verifiable signal to a source or device through the energy transfer channel. The explicit verification may involve changing, altering, modulating, and the like some parameters of the wireless energy transfer or the parameters of the resonators and components used in the energy transfer for the explicit purpose of verification and may not be associated with optimizing, tuning, or adjusting the energy transfer.

[00186] The changing, altering, modulating, and the like some parameters of the wireless energy transfer or the parameters of the resonators and components used in the energy transfer for the purpose of signaling or communicating with another wireless energy resonator or component may also be referred to as in-band communication. In embodiments, the in-band communication channel may be implemented as part of the wireless energy transfer resonators and components. Information may be transmitted from one resonator to another by changing the parameters of the resonators. Parameters such as inductance, impedance, resistance, and the like may be dithered or changed by one resonator. These changes may affect the impedance, resistance, or inductance of other resonators around the signaling resonator. The changes may manifest themselves as corresponding dithers of voltage, current, and the like on the resonators which may be detected and decoded into messages. In embodiments, in-band communication may comprise altering, changing, modulating, and the like the power level, amplitude, phase, orientation, frequency, and the like of the magnetic fields used for energy transfer.

[00187] In one embodiment the explicit in-band verification may be performed after an out-of-band communication channel has been established. Using the out-of-band communication channel a source and a device may exchange information as to the power transfer capabilities and in-band signaling capabilities. Wireless energy transfer between a source and a device may then be initiated. The source or device may request or challenge the other source or device to signal using the in-band communication channel to verify the connection between the out-of-band and communication channel and the energy transfer channel. The channel is verified when the agreed signaling established in the out-of-band communication channel is observed at the in-band communication channel.

[00188] In embodiments verification may be performed only during specific or pre-determined times of an energy exchange protocol such as during energy transfer startup. In other embodiments explicit verification steps may be performed periodically during the normal operation of the wireless energy transfer system. The verification steps may be triggered when the efficiency or characteristics of the wireless power transfer change which may signal that the physical orientations have changed. In embodiments the communication controller may maintain a history of the energy transfer characteristics and initiate a verification of the transfer that includes signaling using the resonators when a change in the characteristics is observed. A change in the energy transfer characteristics may be observed as a change in the efficiency of the energy transfer, the impedance, voltage, current, and the like of the resonators, or components of the resonators and power and control circuitry.

[00189] Those skilled in the art will appreciate a signaling and communication channel capable of transmitting messages may be secured with any number of encryption, authentication, and security algorithms. In embodiments the out-of-band communication may be encrypted and the secured communication channel may be used to transmit random sequences for verification using the in-band channel. In embodiments the in-band communication channel may be encrypted, randomized, or secured by any known security and cryptography protocols and algorithms. The security and cryptography algorithms may be used to authenticate and verify compatibility between resonators and may use a public key infrastructure (PKI) and secondary communication channels for authorization and authentication.

[00190] In embodiments of energy transfer systems between a source and a device a device may verify the energy transfer channel to ensure it is receiving energy from the desired or assumed source. A source may verify the energy transfer channel to ensure energy is being transferred to the desired or assumed source. In some embodiments the verification may be bidirectional and a source and device may both verify their energy transfer channels in one step or protocol operation. In embodiments, there may be more than two resonators and there may be repeater resonators. In embodiments of multiple resonators, communication and control may be centralized in one or a few resonators or communication and control may be distributed across many, most, or all the resonators in a network. In embodiments, communication and/or control may be effected by one or more semiconductor chips or microcontrollers that are coupled to other wireless energy transfer components.

[00191] An example algorithm showing the series of steps which may be used to explicitly verify an energy transfer channel in a wireless energy transfer system using out-of-band communication is shown in Fig. 19B. In the first step **1908** an out-of-band communication channel between a source and a device is established. In the next step **1910** the source and device may coordinate or agree on a signaling protocol, method, scheme, and the like that may be transmitted through the wireless energy transfer channel. To prevent eavesdropping and provide security the out-of-band communication channel may be encrypted and the source and device may follow any number of known cryptographic authentication protocols. In a system enabled with cryptographic protocols the verification code may comprise a challenge-response type exchange which may provide an additional level of security and authentication capability. A device, for example, may challenge the source to encrypt a random verification code which it sends to the source via the out-of-band communication channel using a shared secret encryption key or a private key. The verification code transmitted in the out-of-band communication channel may then be signaled **1912** through the in-band communication channel. In the case where the source and device are enabled with cryptographic protocols the verification code signaled in the in-band communication channel may be encrypted or modified by the sender with a reversible cryptographic function allowing the receiver to further authenticate the sender and verify that the in-band communication channels are linked with the same source or device associated with the out-of-band communication channel.

[00192] In situations when the verification fails a wireless energy transfer system may try to repeat the validation procedure. In some embodiments the system may try to re-validate the wireless energy transfer channel by exchanging another verification sequence for resignaling using the in-band communication channel. In some embodiments the system may change or alter the sequence or type of information that is used to verify the in-band communication channel after attempts to verify the in-band communication channel have failed. The system may change the type of signaling, protocol, length, complexity and the like of the in-band communication verification code.

[00193] In some embodiments, upon failure of verification of the in-band communication channel and hence the energy transfer channel, the system may adjust the power level, the strength of modulation, frequency of modulation and the like of the signaling method in the in-band communication channel. For example, upon failure of verification of a source by a device, the system may attempt to perform the verification at a higher energy transfer level. The system may increase the power output of the source generating stronger magnetic fields. In another example, upon failure of verification of a source by a device, the source that communicated the verification code to the device by changing the impedance of its source resonator may increase or even double the amount of change in the impedance of the source resonator for the signaling.

[00194] In embodiments, upon failure of verification of the energy transfer channel, the system may try to probe, find, or discover other possible sources or devices using the out-of-band communication channel. In embodiments the out-of-band communication channel may be used to find other possible candidates for wireless energy transfer. In some embodiments the system may change or adjust the output power or the range of the out-of-band communication channel to help minimize false pairings.

[00195] The out-of-band communication channel may be power modulated to have several modes, long range mode to detect sources and a short range or low power mode to ensure the communication is with another device or source that is within a specified distance. In embodiments the out-of-band communication channel may be matched to the range of the wireless channel for each application. After failure of verification of the energy transfer channel the output power of the out-of-band communication channel may be slowly increased to find other possible sources or devices for wireless energy transfer. As discussed above, an out-of-band communication channel may exhibit interferences and obstructions that may be different from the interferences and obstructions of the energy transfer channel and sources and devices that may require higher power levels for out-of-band communication may be in close enough proximity to allow wireless energy transfer.

[00196] In some embodiments the out-of-band communication channel may be directed, arranged, focused, and the like, using shielding or positioning to be only effective in a confined area (i.e., under a vehicle), to insure it is only capable of establishing communication with another source or device that is in close enough proximity, position, and orientation for energy transfer.

[00197] In embodiments the system may use one or more supplemental sources of information to establish an out-of-band communication channel or to verify an in-band energy transfer channel. For example, during initial establishment of an out-of-band communication channel the locations of the sources or devices may be compared to known or mapped locations or a database of locations of wireless sources or devices to determine the most probable pair for successful energy transfer. Out-of-band communication channel discovery may be supplemented with GPS data from one or more GPS receivers, data from positioning sensors, inertial guidance systems and the like.

[00198] It is to be understood that although example embodiments with verification were described in systems consisting of a source and device verification may be performed in systems with any number of sources, devices, or repeaters. A single source may provide verification to multiple devices. In some embodiments multiple sources may provide power to one or more devices concurrently each may be varied. In embodiments verification may be performed with a repeater. In some embodiments verification may be performed through a repeater. A device receiving power from a source via a repeater resonator may verify the source of power from the repeater. A device receiving power from a source via a repeater resonator may verify the source of energy through the repeater, i.e., the in-band communication may pass through the repeater to the source for verification. It should be clear to those skilled in the art that all of these and other configurations are within the scope of the invention.

[00199] **Low Resistance Electrical Conductors**

[00200] As described above, resonator structures used for wireless energy transfer may include conducting wires that conduct high frequency oscillating currents. In some structures the effective resistance of the conductors may affect the quality factor of the resonator structure and a conductor with a lower loss or lower resistance may be preferable. The inventors have discovered new structures for reducing the effective resistance of conducting wires at high frequencies compared to solid wire conductors or even Litz wire conductors of the same equivalent wire gauge (diameter).

[00201] In embodiments, structures comprising concentric cylindrical conducting shells can be designed that have much lower electrical resistance for frequencies in the MHz range than similarly sized solid wire conductors or commercially available Litz wires. At such frequencies, wire resistances are dominated by skin-depth effects (also referred to as proximity effects), which prevent electrical current from being uniformly distributed over the wire cross-section. At lower frequencies, skin-depth effects may be mitigated by breaking the wire into a braid of many thin insulated wire strands (e.g. Litz wire), where the diameter of the insulated strands are related to the conductor skin depth at the operating frequency of interest. In the MHz frequency range, the skin depth for typical conductors such as copper are on the order of $10\,\mu\mathrm{m}$, making traditional Litz wire implementations impractical.

[00202] The inventors have discovered that breaking the wire into multiple properly designed concentric insulated conducting shells can mitigate the skin depth effects for frequencies above 1 MHz. In embodiments, wires comprising fewer than 10 coaxial shells can lower AC resistance by more than a factor of 3 compared to solid wire. In embodiments, wires or conductors comprising thin concentric shells can be fabricated by a variety of processes such as electroplating, electrodeposition, vapor deposition, sputtering, and processes that have previously been applied to the fabrication of optical fibers.

[00203] In embodiments, conducting structures comprising nested cylindrical conductors may be analyzed using the quasistatic Maxwell equations. Of particular importance in the design of these conducting structures is taking account of the proximity losses induced by each conducting shell in the others via the magnetic fields. Modeling tools may be used to optimize the number of conducting shells, the size and shape of the conducting shells, the type and thickness of insulating materials for a given conductor diameter, operating frequency and environment, cost, and the like.

[00204] One embodiment of the new conductor structure comprises a number, N, of concentric conducting shells. Such a structure can be designed to have much lower AC resistance at frequencies in the 10 MHz range than similar gauge solid or stranded wires or commercially available Litz wires.

[00205] An embodiment of a wire or conductor comprising conducting shells may comprise at least two concentric conducting shells separated by an electrical insulator. An exemplary embodiment of an electrical conductor with four concentric shells is shown in Figure 20. Note that the conductor may have an unlimited length along the z axis. That is, the length along the z axis is the length of the wire or the conductor. Also, the wire or conductor may have any number of bends, curves, twists, and the like (not shown) as would other conductors of equivalent gauge or thickness. Also note that in embodiments where the cross-section of the shell is annular or substantially annular, the shell will consequently be cylindrical or substantially cylindrical. There is no limitation to the shape of the cross sections and thus the shape of the resulting three-dimensional structure. For example, the cross-sectional shape may be rectangular in embodiments.

[00206] An embodiment shown in Figure 20 comprises four concentric shells **2008, 2006, 2004, 2002** of an electrical conductor that extend through the complete length of the conducting wire along the z axis. The conductor shells may be referred to by their location with respect to the center or innermost conductor shell. For convention, the innermost shell may be referred to as the first shell, and each successive shell as the second shell, third shell, etc. The successive shells may also referred to as nested concentric shells. For example, in the embodiment shown in Fig. 20 conductor shell **2002** may be referred to as the first shell or the innermost shell and the conductor **2004** as the second shell, conductor **2006** as the third shell, and conductor **2008** as the fourth shell or the outermost shell. Each shell, except the innermost and the outermost shell, is in direct proximity to two neighboring shells, an inner neighbor and an outer neighbor shell. The innermost shell only has an outer neighbor, and the outermost shell only has an inner neighbor. For example, the third conductor **2006** has two shell neighbors, the inner neighbor being the second shell **2004** and the outer neighbor being the fourth shell **2008.** In embodiments, the inner shell may be a solid core(in embodiments, cylindrical with an inner diameter zero). Alternatively, it may have a finite inner diameter and surround a core made of insulating material and the like.

[00207] In embodiments each successive shell covers its inner neighbor shell long the z axis of the conductor. Each shell wraps around its inner neighbor shell except the faces of each shell that are exposed at the ends of the conductor. For example, in the embodiment shown in Fig. 20, shell **2002** is wrapped around by its outer neighbor shell **2004** and shell **2004** is wrapped by **2006** and etc.

[00208] In embodiments each successive shell may comprise one or more strips of conductor shaped so as to conform to the cylindrical geometry of the structure. In embodiments the strips in each shell may be mutually insulated and periodically connected to strips in adjacent shells so that the input impedances of the shells and/or strips naturally enforce the current distribution that minimizes the resistance of the structure. In embodiments the strips in each shell may be wound at a particular pitch. The pitch in different shells may be varied so as to assist in the impedance matching of the entire structure.

[00209] Fig. 20 shows an end section of the conductor with the conducting layers staggered to provide a clear illustration of the layers. The staggering of layers in the drawing should not be considered as a preferred termination of the conductor. The conductor comprising multiple shells may be terminated with all shells ending in the same plane or at different staggered planes as depicted in Fig. 20.

[00210] In embodiments, the innermost conductor shell **2002** may be solid as shown in Fig. 20. In embodiments the innermost conductor shell may be hollow defining a hole or cavity along its length along the z axis of the conductor.

[00211] In embodiments neighboring shells may be separated from each other by layers of an electrical insulator such that neighboring layers are not in electrical contact with one another. The thickness and material of the insulating layer may depend on the voltages, currents, and relative voltage potential between each neighboring shell. In general the insulator should be selected such that its breakdown voltage exceeds the voltage potential between neighboring conducting shells. In embodiments the outside of the outermost shell **2010** may be covered by additional electrical insulators or protective casing for electrical safety, durability, water resistance, and the like. In embodiments different shells and insulator layers may have different thicknesses depending on the application, frequency, power levels and the like.

[00212] Another view of a cross section of an embodiment of the conductor comprising four shells is shown in Fig. 21. The figure shows a cross-section, normal to the z-axis, of the conductor comprising the conductor shells **2102, 2104, 2106, 2108**. Note that in this figure, and in Fig. 20, the insulating layers are not shown explicitly, but are understood to be located between the various shells. In embodiments, the thickness of the insulating layers may be extremely thin, especially in comparison to the thickness of the conducting shells.

[00213] The thickness, relative thickness, size, composition, shape, number, fraction of total current carried and the like, of concentric conducing shells may be selected or optimized for specific criteria such as the voltage and/or current levels carried by the wire, the operating frequency of the resonator, size, weight and flexibility requirements of the resonator, required Q-values, system efficiencies, costs and the like. The appropriate size, number, spacing, and the like of the conductors may be determined analytically, through simulation, by trial and error, and the like.

[00214] The benefits of the concentric shell design may be seen by comparing the current distributions in conductors of similar diameters but with different conductor arrangements. By way of example, calculations of the current distributions in two concentric shell conductor structures and one solid conductor are shown in Figs. 22-24. The figures show one quarter of the cross section of the conductor with the conductor being symmetric around x=0, y=0 coordinate. The figures show the current density at 10 MHz for a copper conductor with an outside diameter (OD) of 1 mm and carrying a peak current of 1A. Note that the darker shadings indicate higher current densities, as shown in the legend on the right hand side of the figure.

[00215] Fig. 22 shows the current distribution for a wire comprising a single, 1 mm diameter, solid core of copper. Note that the current is concentrated on the outer perimeter of the solid conductor, limiting the area over which the current is distributed, and yielding an effective resistance of 265.9 $\mathrm{m}\Omega/\mathrm{m}$. This behavior is indicative of the known proximity effect.

[00216] Fig. 23 shows the current distribution for an embodiment where the 1 mm diameter wire comprises 24 mutually insulated 5.19 µm concentric conductive shells, around a solid innermost copper shell, totaling 25 conductive shell elements. Note that the optimal current density (i.e., the current distribution among the shells that minimizes the AC resistance, which may be found for any given structure using mathematical techniques familiar to those skilled in the art) in this structure is more uniformly distributed, increasing the cross section over which the current flows, and reducing the effective resistance of the wire to 55.2 $\mathrm{m}\Omega/\mathrm{m}$. Note that this wire comprising concentric conducting shells has an AC resistance that is approximately five times lower than the similarly sized solid conducting wire.

[00217] Fig. 24 shows the current distribution for an embodiment where the 1 mm diameter wire comprises 25 conductive shells (including an innermost solid core) whose thicknesses are varied from shell to shell so as to minimize the overall resistance. Each shell is of a different thickness with thinner and thinner shells towards the outside of the wire. In this embodiment, the thickness of the shells ranged from 16.3 µm to 3.6 µm (except for the solid innermost shell). The inset in Fig. 24 shows the radial locations of the interfaces between the shells. The effective resistance of the wire comprising the varying thickness shells as shown in Fig. 24 is 51.6 $\mathrm{m}\Omega/\mathrm{m}$. Note that the resistance of the conducting structures shown in Figs. 22-24 was calculated analytically using methods described in A. Kurs, M. Kesler, and S.G. Johnson, Optimized design of a low-resistance electrical conductor for the multimegahertz range, Appl. Phys. Lett. 98, 172504 (2011), as well as United States Provisional Application Serial No. 61/411,490, filed November 9, 2010 the contents of each which are incorporated herein by reference in their entirety as if fully set forth herein . For simplicity, the insulating gap between the shells was taken to be negligibly small for each structure.

[00218] Note that while the embodiments modeled in Figs. 23-24 comprised solid innermost conductor shells, most of the current flowing in that shell is confined to the outer layer of this innermost shell. In other embodiments, this solid innermost shell may be replaced by a hollow or insulator filled shell, a few skin-depths thick, without significantly increasing the AC resistance of the structure.

[00219] Figs. 25-27 show plots that compare the ratio of the lowest AC resistance (as a function of the number of shells, N, and the operating frequency, *f*) achievable for a 1 mm OD wire comprising concentric conducting shells and a 1 mm OD solid core wire, of the same conducting material.

[00220] Fig. 25 shows that an optimized cylindrical shell conductor can significantly outperform a solid conductor of the same OD. One can also see from Fig. 25 that much of the relative improvement of an optimized concentric shell conductor over a solid conductor occurs for structures with only a small number of elements or shells. For example, a wire comprising 10 concentric conducting shells has an AC resistance that is three times lower than a similarly sized solid wire over the entire 2-20 MHz range. Equivalently, since the resistance of a solid conductor in the regime $\kappa D \gg 1$ (κ being the inverse of the skin depth δ and D the diameter of the conductor) scales as $1/D$, the conductor comprising ten shells would have the same resistance per unit length as a solid conductor with a diameter that is 3.33 times greater (and roughly 10 times the cross area) than the wire comprising shells.

[00221] Increasing the number of shells to 20 and 30 further reduces the AC resistance to four times lower, and five times lower than the AC resistance for a similarly sized solid wire.

[00222] It should be noted that with the presented structures comprising multiple conductor shells it may be necessary to impedance match each shell to ensure an optimal current distribution. However due to the relatively small number of shell conductors for most applications (<40) a brute force approach of individually matching the impedance of each shell (e.g., with a lumped-element matching network) to achieve the optimal current distribution could be implemented (similar impedance matching considerations arise in multi-layer high- T_c superconducting power cables (see H. Noji, Supercond. Sci. Technol. 10, 552 (1997). and S. Mukoyama, K. Miyoshi, H. Tsubouti, T. Yoshida, M. Mimura, N. Uno, M. Ikeda, H. Ishii, S. Honjo, and Y. Iwata, IEEE Trans. Appl. Supercond. 9, 1269 (1999). the contents of which are incorporated in their entirety as if fully set forth herein), albeit at much lower frequencies).

[00223] In embodiments, concentric conducting shells of a wire may preferably be cylindrical or have circular cross-sections, however other shapes are contemplated and may provide for substantial improvement over solid conductors. Concentric conducting shells having an elliptical, rectangular, triangular, or other irregular shapes are within the scope of this invention. The practicality and usefulness of each cross-section shape may depend on the application, manufacturing costs, and the like.

[00224] In this section of the disclosure we may have referred to the structures comprising multiple shells of conductors as a wire. It is to be understood that the term wire should not be limited to mean any specific or final form factor of the structures. In embodiments the structures may comprise free standing conductors that may be used to replace traditional wires. In embodiments the structures comprising multiple shells may be fabricated or etched onto a multilayer printed circuit board or substrate. The structures may be etched, deposited on wafers, boards, and the like. In embodiments thin concentric shells can be fabricated by a variety of processes (such as electroplating, electro-deposition, vapor deposition, or processes utilized in optical fiber fabrication).

[00225] The conductor structures may be utilized in many resonator or coil structures used for wireless energy transfer. The multi-shell structures may be used as part of a resonator such as those shown in Fig. 2A-2E. The low loss conductors may be wrapped around a core of magnetic material to form low loss planar resonators. The low loss conductors may be etched or printed on a printed circuit board to form a printed coil and the like.

[00226] Wireless Energy Distribution System

[00227] Wireless energy may be distributed over an area using repeater resonators. In embodiments a whole area such as a floor, ceiling, wall, table top, surface, shelf, body, area, and the like may be wirelessly energized by positioning or tiling a series of repeater resonators and source resonators over the area. In some embodiments, a group of objects comprising resonators may share power amongst themselves, and power may be wireless transmitted to and/or through various objects in the group. In an exemplary embodiment, a number of vehicles may be parked in an area and only some of the vehicles may be positioned to receive wireless power directly from a source resonator. In such embodiments, certain vehicles may retransmit and/or repeat some of the wireless power to vehicles that are not parked in positions to receive wireless power directly from a source. In embodiments, power supplied by a vehicle charging source may use repeaters to transmit power into the vehicles to power devices such as cell phones, computers, displays, navigation devices, communication devices, and the like. In some embodiments, a vehicle parked over a wireless power source may vary the ratio of the amount of power it receives and the amount of power it retransmits or repeats to other nearby vehicles. In embodiments, wireless power may be transmitted from one source to device after device and so on, in a daisy chained fashion. In embodiments, certain devices may be able to self determine how much power that receive and how much they pass on. In embodiments, power distribution amongst various devices and/or repeaters may be controlled by a master node or a centralized controller.

[00228] Some repeater resonators may be positioned in proximity to one or more source resonators. The energy from the source may be transferred from the sources to the repeaters, and from those repeaters to other repeaters, and to other repeaters, and so on. Therefore energy may be wirelessly delivered to a relatively large area with the use of small sized sources being the only components that require physical or wired access to an external energy source.

[00229] In embodiments the energy distribution over an area using a plurality of repeater resonators and at least one source has many potential advantages including in ease of installation, configurability, control, efficiency, adaptability, cost, and the like. For example, using a plurality of repeater resonators allows easier installation since an area may be covered by the repeater resonators in small increments, without requiring connections or wiring between the repeaters or the source and repeaters. Likewise, a plurality of smaller repeater coils allows a greater flexibility of placement allowing the arrangement and coverage of an area with an irregular shape. Furthermore, the repeater resonators may be easily moved or repositioned to change the magnetic field distribution within an area. In some embodiments the repeaters and the sources may be tunable or adjustable allowing the repeater resonators to be tuned or detuned from the source resonators and allowing a dynamic reconfiguration of energy transfer or magnetic field distribution within the area covered by the repeaters without physically moving components of the system.

[00230] For example, in one embodiment, repeater resonators and wireless energy sources may be incorporated or integrated into flooring. In embodiments, resonator may be integrated into flooring or flooring products such as carpet tiles to provide wireless power to an area, room, specific location, multiple locations and the like. Repeater resonators, source resonators, or device resonators may be integrated into the flooring and distribute wireless power from one or more sources to one more devices on the floor via a series of repeater resonators that transfer the energy from the source over an area of the floor.

[00231] It is to be understood that the techniques, system design, and methods may be applied to many flooring types, shapes, and materials including carpet, ceramic tiles, wood boards, wood panels and the like. For each type of material those skilled in the art will recognize that different techniques may be used to integrate or attach the resonators to the flooring material. For example, for carpet tiles the resonators may be sown in or glued on the underside while for ceramic tiles integration of tiles may require a slurry type material, epoxy, plaster, and the like. In some embodiments the resonators may not be integrated into the flooring material but placed under the flooring or on the flooring. The resonators may, for example, come prepackaged in padding material that is placed under the flooring. In some embodiments a series or an array or pattern of resonators, which may include source, device, and repeater resonators, may be integrated in to a large piece of material or flooring which may be cut or trimmed to size. The larger material may be trimmed in between the individual resonators without disrupting or damaging the operation of the cut piece.

[00232] Returning now to the example of the wireless floor embodiment comprising individual carpet tiles, the individual flooring tiles may be wireless power enabled by integrating or inserting a magnetic resonator to the tile or under the tile. In embodiments resonator may comprise a loop or loops of a good conductor such as Litz wire and coupled to a capacitive element providing a specific resonant frequency which may be in the range of 10 KHz to 100MHz. In embodiments the resonator may be a high-Q resonator with a quality factor greater than 100. Those skilled in the art will appreciate that the various designs, shaped, and methods for resonators such as planar resonators, capacitively loaded loop resonators, printed conductor loops, and the like described herein may be integrated or combined within a flooring tile or other flooring material.

[00233] Example embodiments of a wireless power enabled floor tile are depicted in Fig. 28A and Fig. 28B. A floor tile **2802** may include loops of an electrical conductor **2804** that are wound within the perimeter of the tile. In embodiments the conductor **2804** of the resonator may be coupled to additional electric or electronic components **2806** such as capacitors, power and control circuitry, communication circuitry, and the like. In other embodiments the tile may include more than one resonator and more than one loop of conductors that may be arranged in an array or a deliberate pattern as described herein such as for example a series of multisized coils, a configurable size coil and the like.

[00234] In embodiments the coils and resonators integrated into the tiles may include magnetic material. Magnetic material may be used to construct planar resonator structures such those depicted in Fig. 2C or Fig. 2E. In embodiments the magnetic material may also be used for shielding of the coil of the resonator from lossy objects that may be under or around the flooring. In some embodiments the structures may further include a layer or sheet of a good electrical conductor under the magnetic material to increase the shielding capability of the magnetic material as described herein.

[00235] Tiles with a resonator may have various functionalities and capabilities depending on the control circuitry, communication circuitry, sensing circuitry, and the like that is coupled to the coil or resonator structure. In embodiments of a wireless power enabled flooring the system may include multiple types of wireless enabled tiles with different capabilities. One type of floor tile may comprise only a magnetic resonator and function as a fixed tuned repeater resonator that wirelessly transfers power from one resonator to another resonator without any direct or wired power source or wired power drain.

[00236] Another type of floor tile may comprise a resonator coupled to control electronics that may dynamically change or adjust the resonant frequency of the resonator by, for example, adjusting the capacitance, inductance, and the like of the resonator. The tile may further include an in-band or out-of-band communication capability such that it can exchange information with other communication enabled tiles. The tile may be then able to adjust its operating parameters such as resonant frequency in response to the received signals from the communication channel.

[00237] Another type of floor tile may comprise a resonator coupled to integrated sensors that may include temperature sensors, pressure sensors, inductive sensors, magnetic sensors, and the like. Some or all the power captured by the resonator may be used to wirelessly power the sensors and the resonator may function as a device or partially as a repeater.

[00238] Yet another type of wireless power enabled floor tile may comprise a resonator with power and control circuitry that may include an amplifier and a wired power connection for driving the resonator and function like a wireless power source. The features, functions, capabilities of each of the tiles may be chosen to satisfy specific design constraints and may feature any number of different combinations of resonators, power and control circuitry, amplifiers, sensors, communication capabilities and the like.

[00239] A block diagram of the components comprising a resonator tile are shown in Fig. 29. In a tile, a resonator **2902** may be optionally coupled to power and control circuitry **2906** to receive power and power devices or optional sensors **2904**. Additional optional communication circuitry **2908** may be connected to the power and control circuitry and control the parameters of the resonator based on received signals.

[00240] Tiles and resonators with different features and capabilities may be used to construct a wireless energy transfer systems with various features and capabilities. One embodiment of a system may include sources and only fixed tuned repeater resonator tiles. Another system may comprise a mixture of fixed and tunable resonator tiles with communication capability. To illustrate some of the differences in system capabilities that may be achieved with different types of floor tiles we will describe example embodiments of a wireless floor system.

[00241] The first example embodiment of the wireless floor system may include a source and only fixed tuned repeater resonator tiles. In this first embodiment a plurality of fixed tuned resonator tiles may be arranged on a floor to transfer power from a source to an area or location over or next to the tiles and deliver wireless power to devices that may be placed on top of the tiles, below the tiles, or next to the tiles. The repeater resonators may be fixed tuned to a fixed frequency that may be close to the frequency of the source. An arrangement of the first example embodiment is shown in Fig. 30. The tiles **3002** are arranged in an array with at least one source resonator that may be integrated into a tile **3010** or attached to a wall **3006** and wired **3012** to a power source. Some repeater tiles may be positioned next to the source resonator and arranged to transfer the power from the source to a desired location via one or more additional repeater resonators.

[00242] Energy may be transferred to other tiles and resonators that are further away from the source resonators using tiles with repeater resonators which may be used to deliver power to devices, integrated or connected to its own device resonator and device power and control electronics that are placed on top or near the tiles. For example, power from the source resonator **3006** may be transferred wirelessly from the source **3006** to an interior area or interior tile **3022** via multiple repeater resonators **3014, 3016, 3018, 3020** that are between the interior tile **3022** and the source **3006.** The interior tile **3022** may than transfer the power to a device such as a resonator built into the base of a lamp **3008.** Tiles with repeater resonators may be positioned to extend the wireless energy transfer to a whole area of the floor allowing a device on top of the floor to be freely moved within the area. For example additional repeater resonator tiles **3024, 3026, 3028** may be positioned around the lamp **3008** to create a defined area of power (tiles **3014, 3016, 3018, 3020, 3022, 3024, 3026, 3028**) over which the lamp may be placed to receive energy from the source via the repeater tiles. The defined area over which power is distributed may be changed by adding more repeater tiles in proximity to at least one other repeater or source tile. The tiles may be movable and configurable by the user to change the power distribution as needed or as the room configuration changes. Except a few tiles with source resonators which may need wired source or energy, each tile may be completely wireless and may be configured or moved by the user or consumer to adjust the wireless power flooring system.

[00243] A second embodiment of the wireless floor system may include a source and one or more tunable repeater resonator tiles. In embodiments the resonators in each or some of the tiles may include control circuitry allowing dynamic or periodic adjustment of the operating parameters of the resonator. In embodiments the control circuitry may change the resonant frequency of the resonator by adjusting a variable capacitor or a changing a bank of capacitors.

[00244] To obtain maximum efficiency of power transfer or to obtain a specific distribution of power transfer in the system of multiple wireless power enabled tiles it may be necessary to adjust the operating point of each resonator and each resonator may be tuned to a different operating point. For example, in some situations or applications the required power distribution in an array of tiles may be required to be non-uniform, with higher power required on one end of the array and lower power on the opposite end of the array. Such a distribution may be obtained, for example, by slightly detuning the frequency of the resonators from the resonant frequency of the system to distribute the wireless energy where it is needed.

[00245] For example, consider the array of tiles depicted in Fig.30 comprising 36 tunable repeater resonator tiles with a single source resonator **3006.** If only one device that requires power is placed on the floor, such as the lamp **3008,** it may be inefficient to distribute the energy across every tile when the energy is needed in only one section of the floor tile array. In embodiments the tuning of individual tiles may be used to change the energy transfer distribution in the array. In the example of the single lamp device **3008**, the repeater tiles that are not in direct path from the source resonator **3006** to the tile closes to the device **3022** may be completely or partially detuned from the frequency of the source. Detuning of the unused repeaters reduces the interaction of the resonators with the oscillating magnetic fields changing the distribution of the magnetic fields in the floor area. With tunable repeater tiles, a second device may be placed within the array of tiles or the lamp device **3008** is moved from its current location **3022** to another tile, say **3030,** the magnetic field distribution in the area of the tiles may be changed by retuning tiles that are in the path from the source **3006** to the new location **3030.**

[00246] In embodiments, to help coordinate the distribution of power and tuning of the resonators the resonator may include a communication capability. Each resonator may be capable of wirelessly communicating with one or more of its neighboring tiles or any one of the tiles to establish an appropriate magnetic field distribution for a specific device arrangement.

[00247] In embodiments the tuning or adjustment of the operating point of the individual resonators to generate a desired magnetic field distribution over the area covered by the tiles may be performed in a centralized manner from one source or one "command tile". In such a configuration the central tile may gather the power requirements and the state of each resonator and each tile via wireless communication or in band communication of each tile and calculate the most appropriate operating point of each resonator for the desired power distribution or operating point of the system. The information may be communicated to each individual tile wirelessly by an additional wireless communication channel or by modulating the magnetic field used for power transfer. The power may be distributed or metered out using protocols similar to those used in communication systems. For example, there may be devices that get guaranteed power, while others get best effort power. Power may be distributed according to a greedy algorithm, or using a token system. Many protocols that have been adapted for sharing information network resources may be adapted for sharing wireless power resources.

[00248] In other embodiments the tuning or adjustment of the operating point of the individual resonators may be performed in a decentralized manner. Each tile may adjust the operating point of its resonator on its own based on the power requirements or state of the resonators of tiles in its near proximity.

[00249] In both centralized and decentralized arrangements any number of network based centralized and distributed routing protocols may be used. For example, each tile may be considered as a node in network and shortest path, quickest path, redundant path, and the like, algorithms may be used to determine the most appropriate tuning of resonators to achieve power delivery to one or more devices.

[00250] In embodiments various centralized and decentralized routing algorithms may be used to tune and detune resonators of a system to route power via repeater resonators around lossy objects. If an object comprising lossy material is placed on some of the tiles it may the tiles, it may unnecessarily draw power from the tiles or may disrupt energy transmission if the tiles are in the path between a source and the destination tile. In embodiments the repeater tiles may be selectively tuned to bypass lossy objects that may be on the tiles. Routing protocols may be used to tune the repeater resonators such that power is routed around lossy objects.

[00251] In embodiments the tiles may include sensors. The tiles may include sensors that may be power wirelessly from the magnetic energy captured by the resonator built into the tile to detect objects, energy capture devices, people **3034**, and the like on the tiles. The tiles may include capacitive, inductive, temperature, strain, weight sensors, and the like. The information from the sensors may be used to calculate or determine the best or satisfactory magnetic field distribution to deliver power to devices and maybe used to detune appropriate resonators. In embodiments the tiles may comprise sensors to detect metal objects. In embodiments the presence of a lossy object may be detected by monitoring the parameters of the resonator. Lossy objects may affect the parameters of the resonator such as resonant frequency, inductance, and the like and may be used to detect the metal object.

[00252] In embodiments the wireless powered flooring system may have more than one source and source resonators that are part of the tiles, that are located on the wall or in furniture that couple to the resonators in the flooring. In embodiments with multiple sources and source resonators the location of the sources may be used to adjust or change the power distribution within in the flooring. For example, one side of a room may have devices which require more power and may require more sources closer to the devices. In embodiments the power distribution in the floor comprising multiple tiles may be adjusted by adjusting the output power (the magnitude of the magnetic field) of each source, the phase of each source (the relative phase of the oscillating magnetic field) of each source, and the like.

[00253] In embodiments the resonator tiles may be configured to transfer energy from more than one source via the repeater resonators to a device. Resonators may be tuned or detuned to route the energy from more than one source resonator to more than one device or tile.

[00254] In embodiments with multiple sources it may be desirable to ensure that the different sources and maybe different amplifiers driving the different sources are synchronized in frequency and/or phase. Sources that are operating at slightly different frequencies and/or phase may generate magnetic fields with dynamically changing amplitudes and spatial distributions (due to beating effects between the oscillating sources). In embodiments, Multiple source resonators may be synchronized with a wired or wireless synchronization signal that may be generated by a source or external control unit. In some embodiments one source resonator may be designed as a master source resonator that dictates the frequency and phase to other resonators. A master resonator may operate at its nominal frequency while other source resonators detect the frequency and phase of the magnetic fields generated by the master source and synchronize their signals with that of the master.

[00255] In embodiments the wireless power from the floor tiles may be transferred to table surfaces, shelves, furniture and the like by integrating additional repeater resonators into the furniture and tables that may extend the range of the wireless energy transfer in the vertical direction from the floor. For example, in some embodiments of a wireless power enabled floor, the power delivered by the tiles may not be enough to directly charge a phone or an electronic device that may be placed on top of a table surface that may be two or three feet above the wireless power enabled tiles. The coupling between the small resonator of the electronic device on the surface of the table and the resonator of the tile may be improved by placing a large repeater resonator near the surface of the table such as on the underside of the table. The relatively large repeater resonator of the table may have good coupling with the resonator of the tiles and, due to close proximity, good coupling between the resonator of the electronic device on the surface of the table resulting in improved coupling and improved wireless power transfer between the resonator of the tile and the resonator of the device on the table.

[00256] As those skilled in the art will recognize the features and capabilities of the different embodiments described may be rearranged or combined into other configurations. A system may include any number of resonator types, source, devices, and may be deployed on floors, ceilings, walls, desks, and the like. The system described in terms of floor tiles may be deployed onto, for example, a wall and distribute wireless power on a wall or ceiling into which enabled devices may be attached or positioned to receive power and enable various applications and configurations. The system techniques may be applied to multiple resonators distributed across table tops, surfaces, shelves, bodies, vehicles, machines, clothing, furniture, and the like. Although the example embodiments described tiles or separate repeater resonators that may be arranged into different configurations based on the teachings of this disclosure it should be clear to those skilled in the art that multiple repeater or source resonator may not be attached or positioned on separate physical tiles or sheets. Multiple repeater resonators, sources, devices, and their associated power and control circuitry may be attached, printed, etched, to one tile, sheet, substrate, and the like. For example, as depicted in Fig. 31, an array of repeater resonators **3104** may be printed, attached, or embedded onto one single sheet **3102.** The single sheet **3102** may be deployed similarly as the tiles described above. The sheet of resonators may be placed near, on, or below a source resonator to distribute the wireless energy through the sheet or parts of the sheet. The sheet of resonators may be used as a configurable sized repeater resonator in that the sheet may be cut or trimmed between the different resonators such as for example along line **3106** shown in Fig. 31.

[00257] In embodiments a sheet of repeater resonators may be used in a desktop environment. Sheet of repeater resonators may be cut to size to fit the top of a desk or part of the desk, to fit inside drawers, and the like. A source resonator may be positioned next to or on top of the sheet of repeater resonators and devices such as computers, computer peripherals, portable electronics, phones, and the like may be charged or powered via the repeaters.

[00258] In embodiments resonators embedded in floor tiles or carpets can be used to capture energy for radiant floor heating. The resonators of each tile may be directly connected to a highly resistive heating element via unrectified AC, and with a local thermal sensor to maintain certain floor temperature. Each tile may be able to dissipate a few watts of power in the thermal element to heat a room or to maintain the tiles at a specific temperature.

[00259] While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law.

[00260] All documents referenced herein are hereby incorporated by reference in their entirety as if fully set forth herein.

CLAIMS

What is claimed is:

1. A system for wireless energy distribution over a defined area, the system comprising:

   a source resonator coupled to an energy source and generating an oscillating magnetic field with a frequency,

   at least one repeater resonator positioned in a defined area and in proximity to the source resonator, and having a resonant frequency; and

   at least two other repeater resonators with a resonant frequency positioned in the defined area and in proximity to at least one of the repeater resonators,

   wherein the repeater resonators provide an effective wireless energy transfer area at least one of within or equal to the defined area.

2. The system of claim 1, wherein the defined area covered is at least 2 square meters.

3. The system of claim 1, wherein the defined area covered is at least 10 square centimeters.

4. The system of claim 1 further comprising at least one additional source resonator that generates an oscillating magnetic field with the frequency, wherein the at least one additional source resonator is positioned in proximity to defined area.

5. The system of claim 4, wherein the frequency and relative phase of the oscillating fields generated by the sources of the system are synchronized.

6. The system of claim 4, wherein the relative phase of the oscillating fields generated by the different sources of the system is adjustable.

7. The system of claim 4, wherein at least one repeater resonator comprises a capacitively loaded conducting loop.

8. The system of claim 4, wherein at least one of the repeater resonators have an adjustable resonant frequency.

9. The system of claim 8, wherein the resonant frequency of the repeater resonators may be detuned from the frequency of the magnetic fields generated by the source resonators to change the distribution of the magnetic fields in the defined area.

10. The system of claim 9, wherein some repeaters are detuned to maximize the magnetic fields in a region of the defined area.

11. The system of claim 10, wherein the detuning of repeaters is performed according to a network routing algorithm.

12. The system of claim 10, further comprising a communication channel between the resonators of the system.

13. The system of claim 12, wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution.

14. The system of claim 1, wherein the repeater resonators have a quality factor $Q>100$.

15. The system of claim 10, wherein the repeater resonators further comprise pressure sensors and wherein the information from the pressure sensors is used to change the magnetic field distribution.

16. The system of claim 1, wherein the defined area is a floor

17. The system of claim 16, wherein the resonators are integrated into flooring material.

18. The system of claim 1, wherein the defined area is a wall.

19. The system of claim 1, wherein the defined area is a ceiling.

20. A wireless energy transfer flooring system comprising:

at least one source resonator coupled to an energy source and generating an oscillating magnetic field with a frequency, at least one repeater resonator positioned in a defined area and in proximity to the source resonator, and having a tunable resonant frequency; and

at least two other repeater resonators with a tunable resonant frequency positioned in the defined area and in proximity to at least one other of the repeater resonators,

wherein the resonant frequency of at least one of the repeater resonators is detuned from the frequency of the oscillating magnetic field of the at least one source to change the distribution of magnetic fields in the defined area.

21. The system of claim 20, further comprising a communication channel between the resonators of the system.

22. The system of claim 21, wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution.

23. The system of claim 20, wherein the resonators are integrated into flooring material.

24. A method of distributing wireless energy from at least one source resonator to a specific location within an area having tunable repeater resonators, the method comprising:

determining a closest repeater resonators to the specific location, and

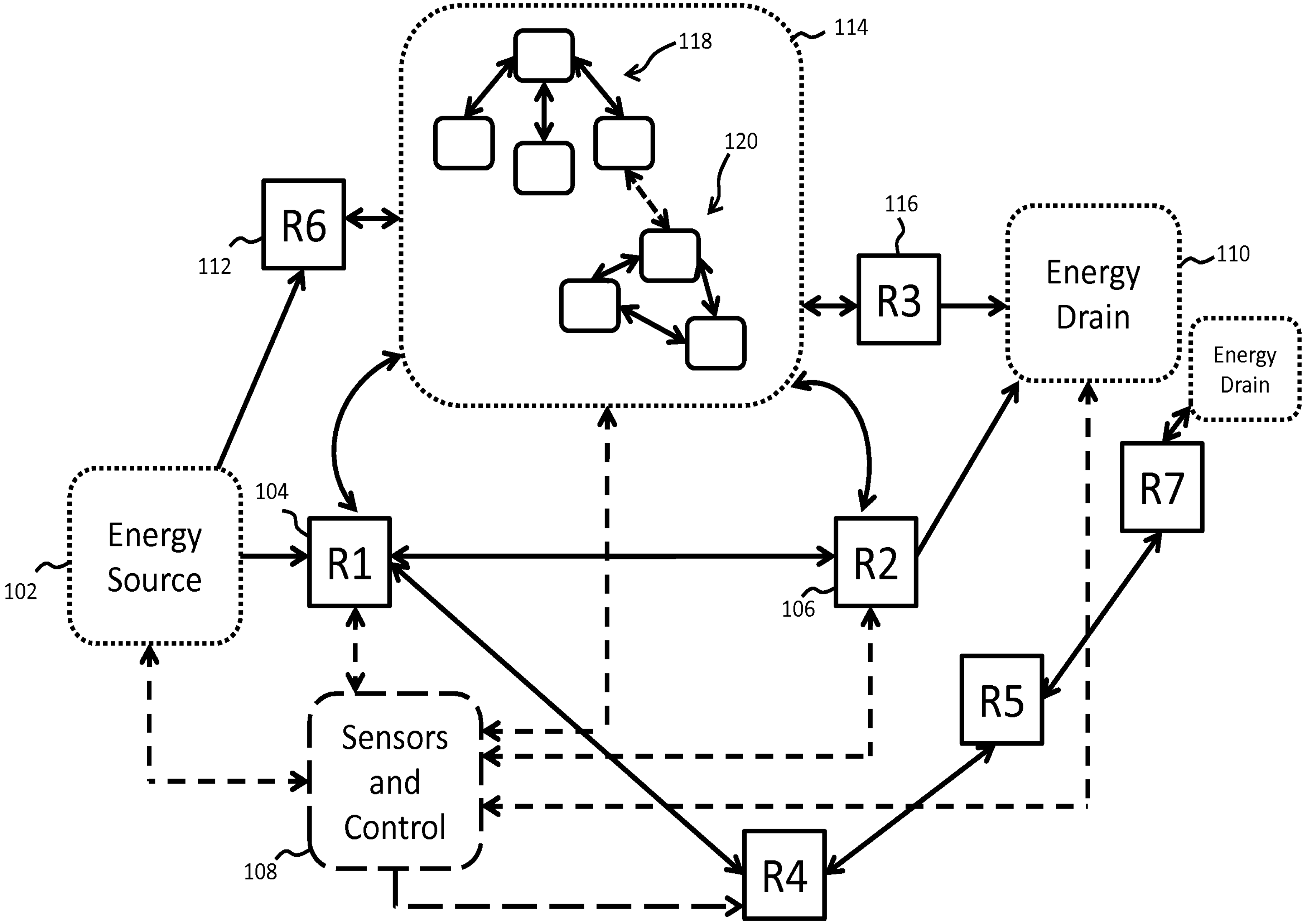
tuning the resonant frequency of the repeater resonators to provide for an energy transfer path from the source to the closest repeater resonators.

25. The method of claim 24, further comprising detuning resonators that are not in the energy transfer path.

26. The method of claim 24, wherein the energy transfer path is determined by a shortest path algorithm.

27. The method of claim 24, wherein the energy transfer path is determined by a central control.

Fig. 1


114
118
120
R6
112
116
R3
Energy
Drain
110
Energy
Drain
R7
104
Energy
Source
102
R1
R2
106
R5
Sensors
and
Control
108
R4

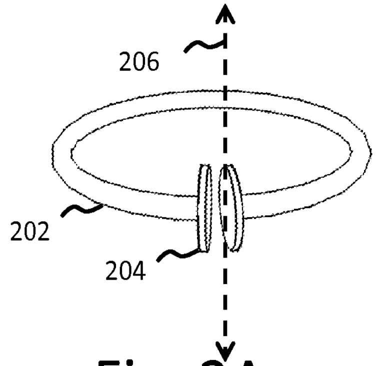


Fig. 2A

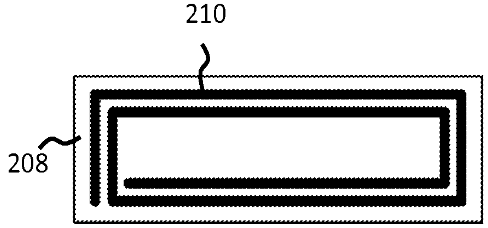


Fig. 2B

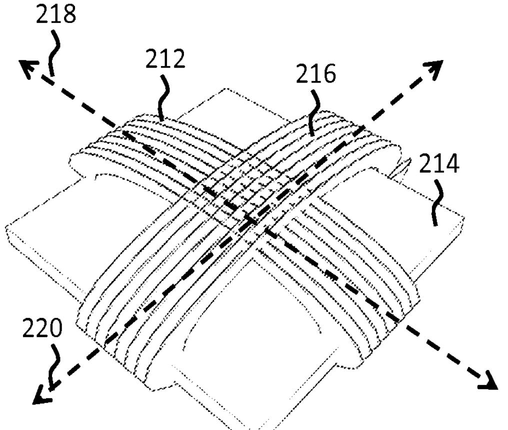


Fig. 2C

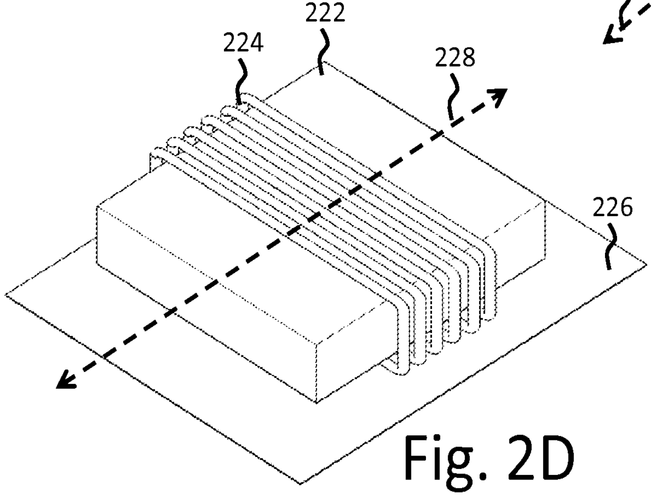


Fig. 2D

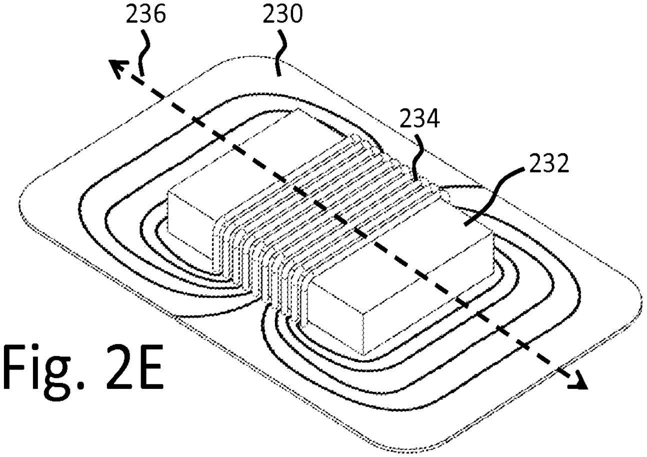


Fig. 2E

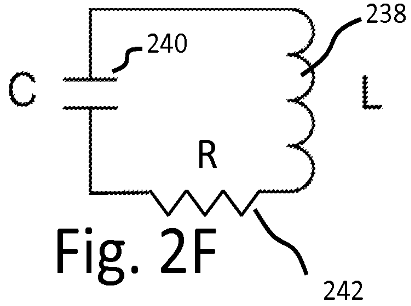


Fig. 2F

Fig. 3

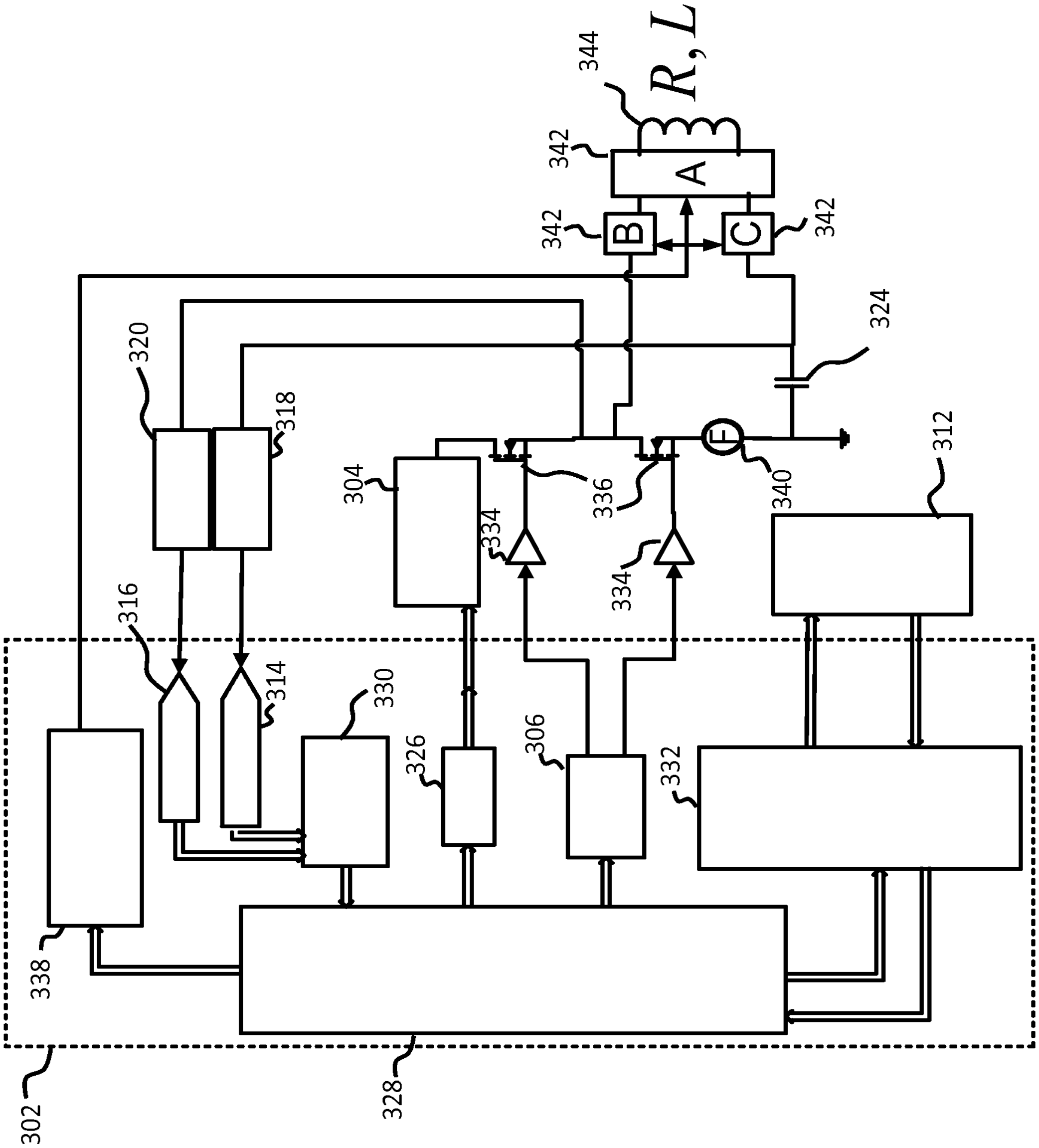
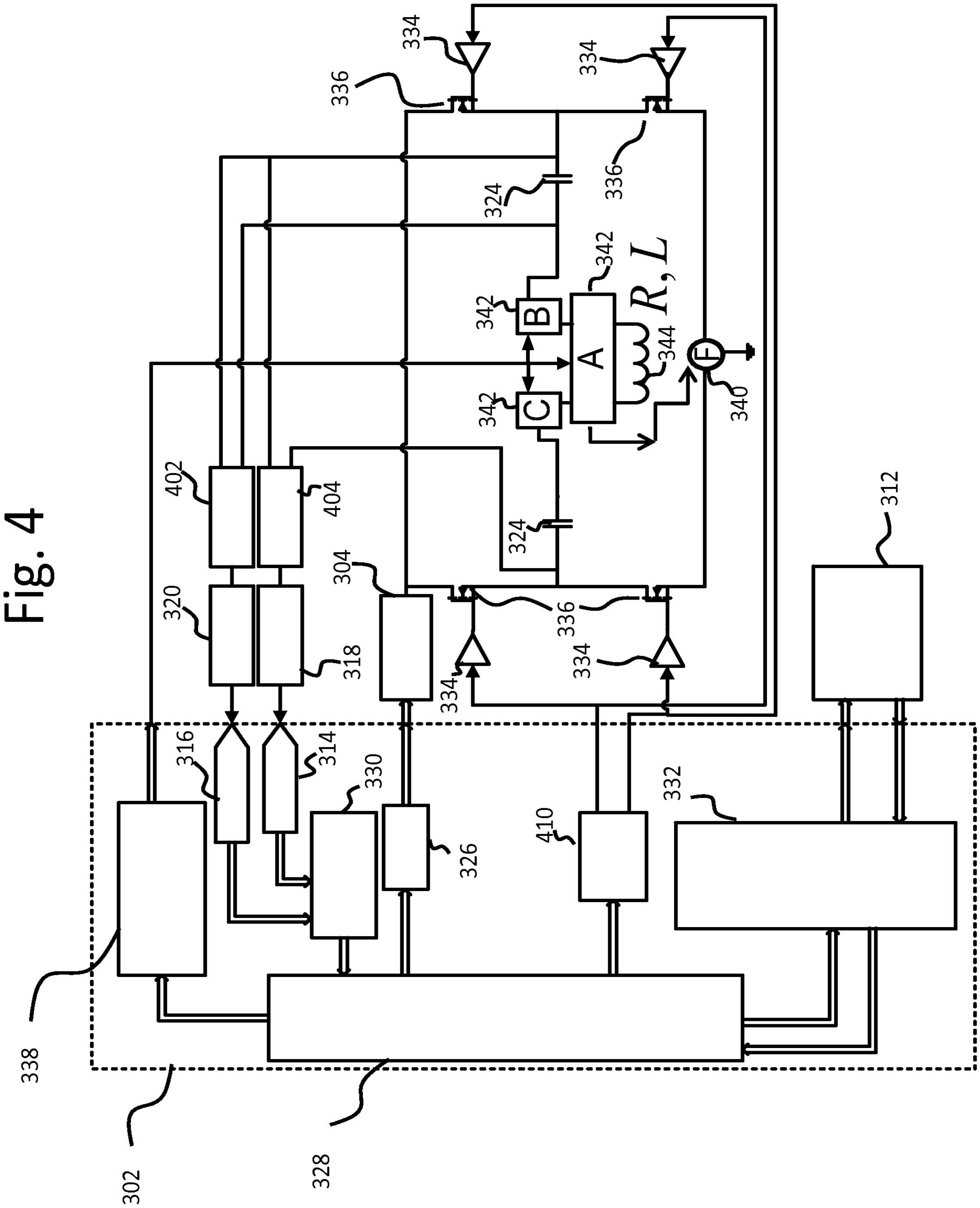

302
304
306
312
314
316
318
320
324
326
328
330
332
334
334
336
338
340
342
342
342
344
R, L
A
B
C
F

Fig. 4


334
336
334
336
324
342
R, L
342
B
A
344
C
342
340
F
402
404
324
312
320
304
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334
334
316
314
330
326
410
332
338
302
328

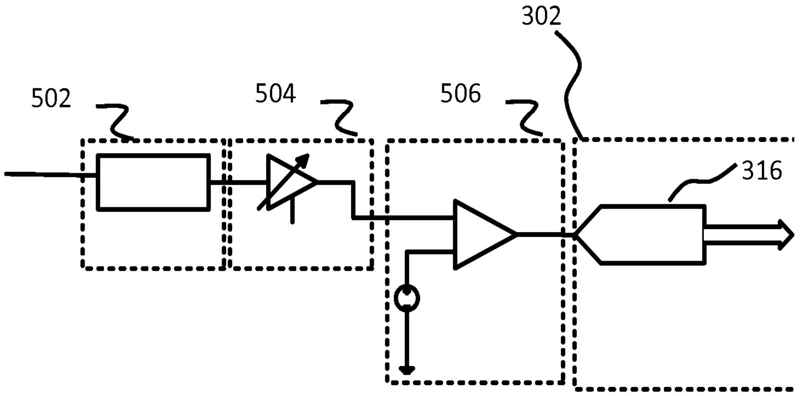


Fig. 5A

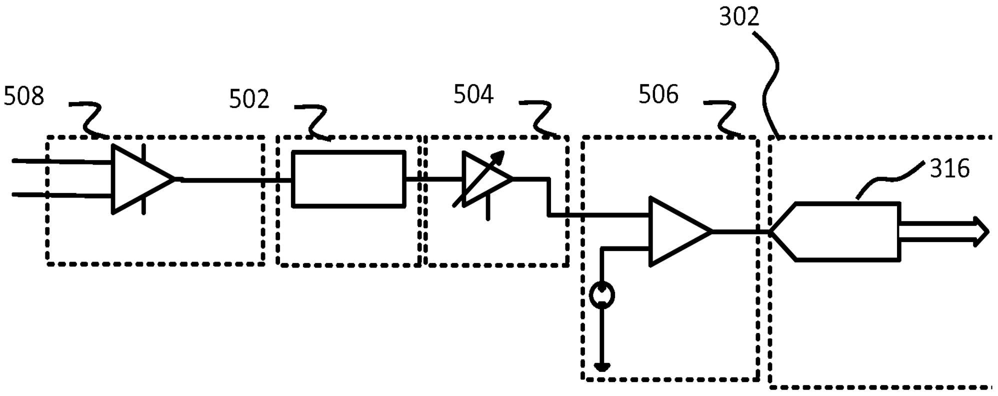


Fig. 5B

Fig. 6A

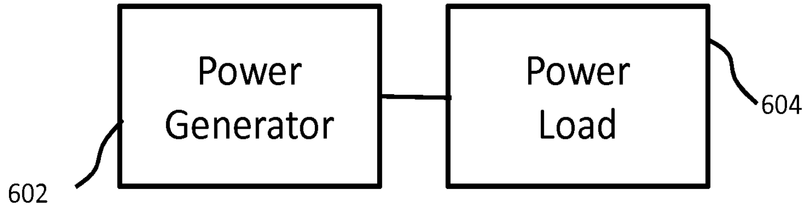


Fig. 6B

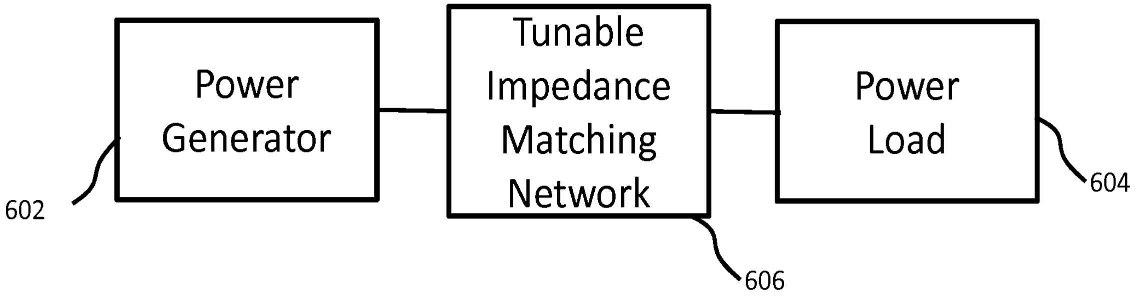


Fig. 6C

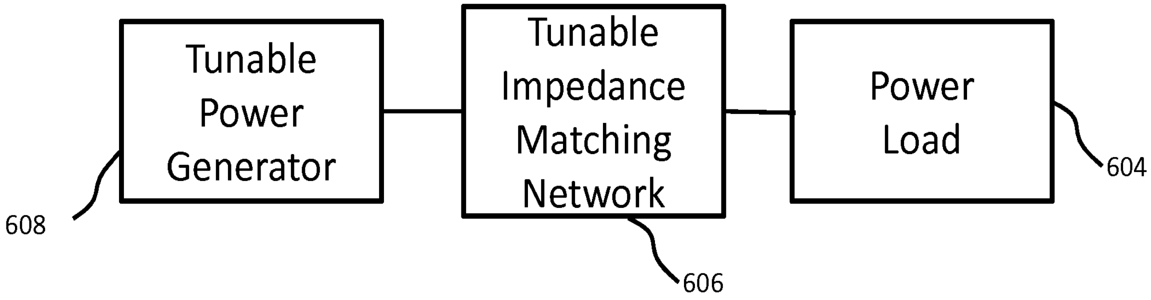


Fig. 7

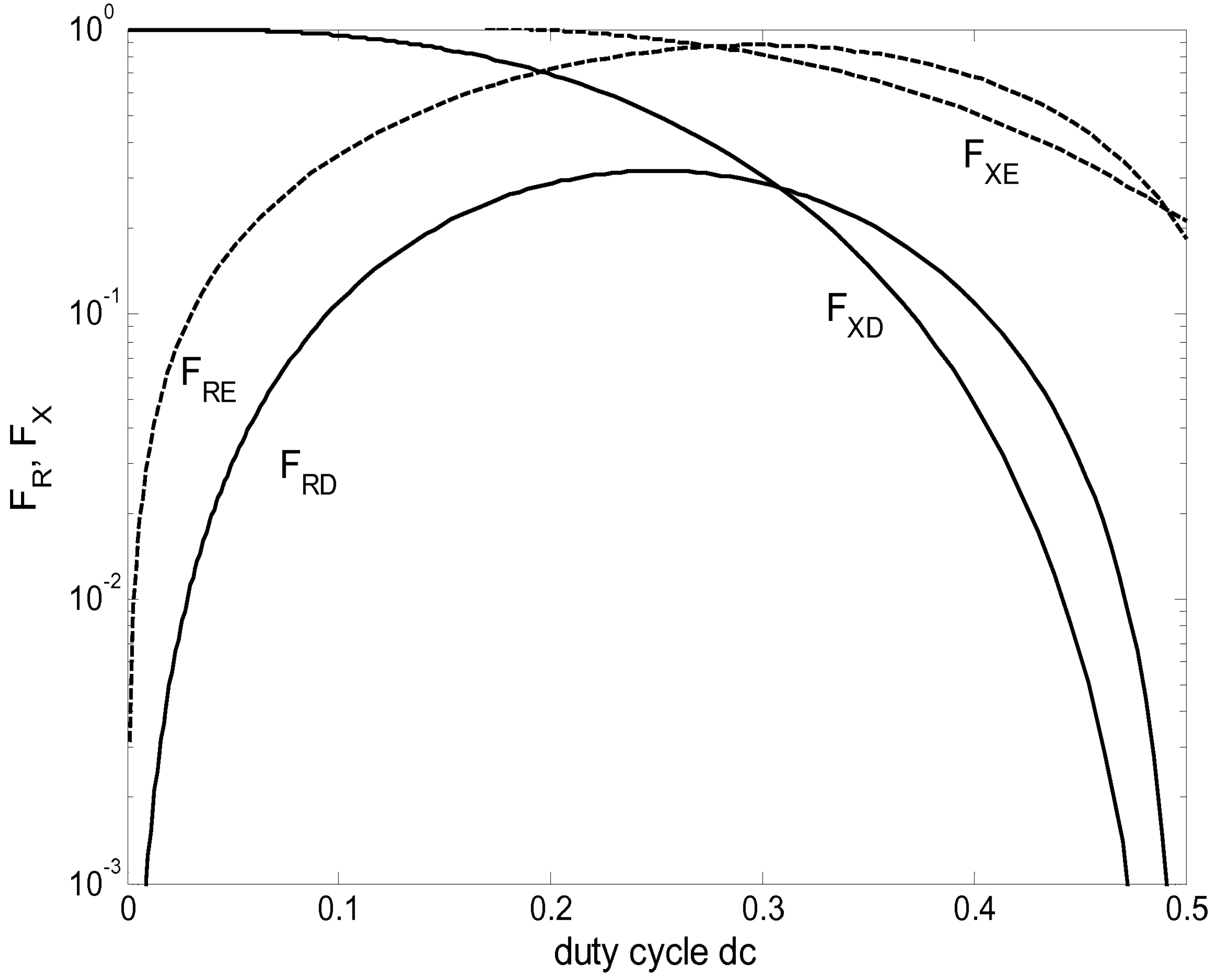

10^0
10^{-1}
10^{-2}
10^{-3}
F_R, F_X
0
0.1
0.2
0.3
0.4
0.5
duty cycle dc
F_{XE}
F_{XD}
F_{RE}
F_{RD}

Fig. 8

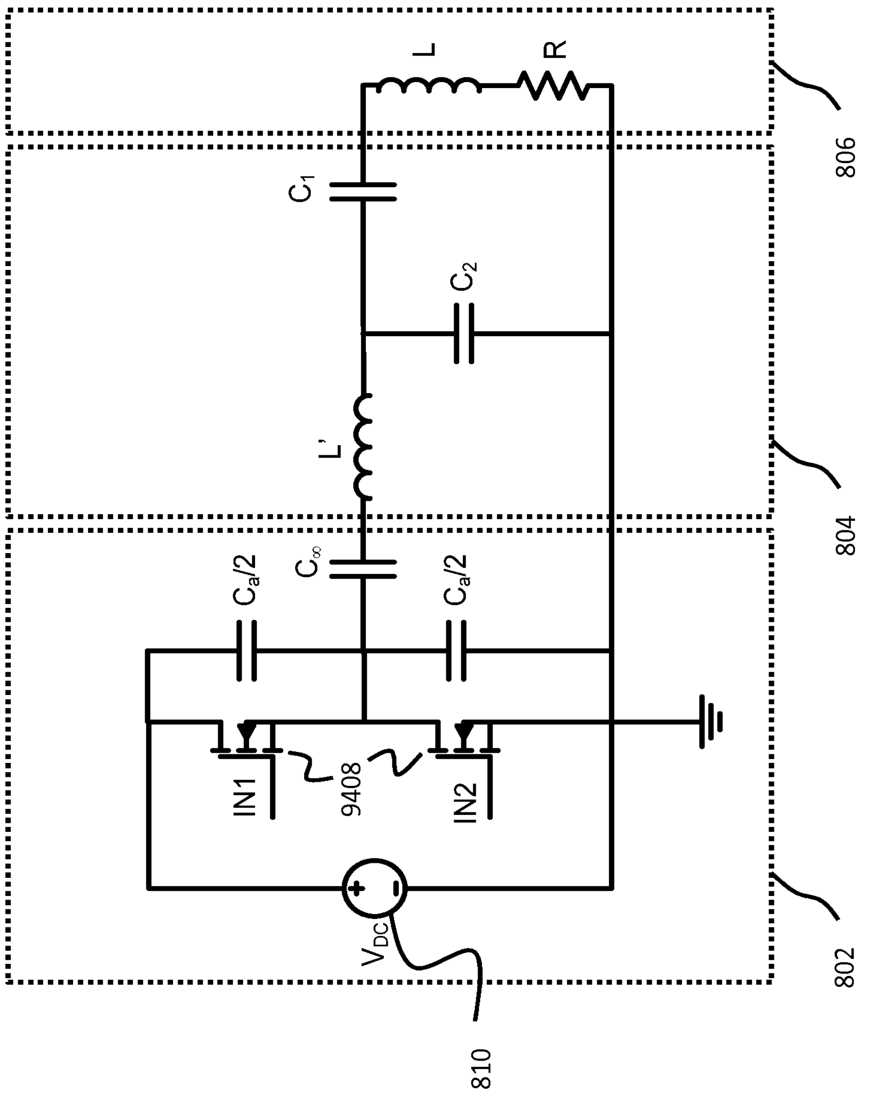
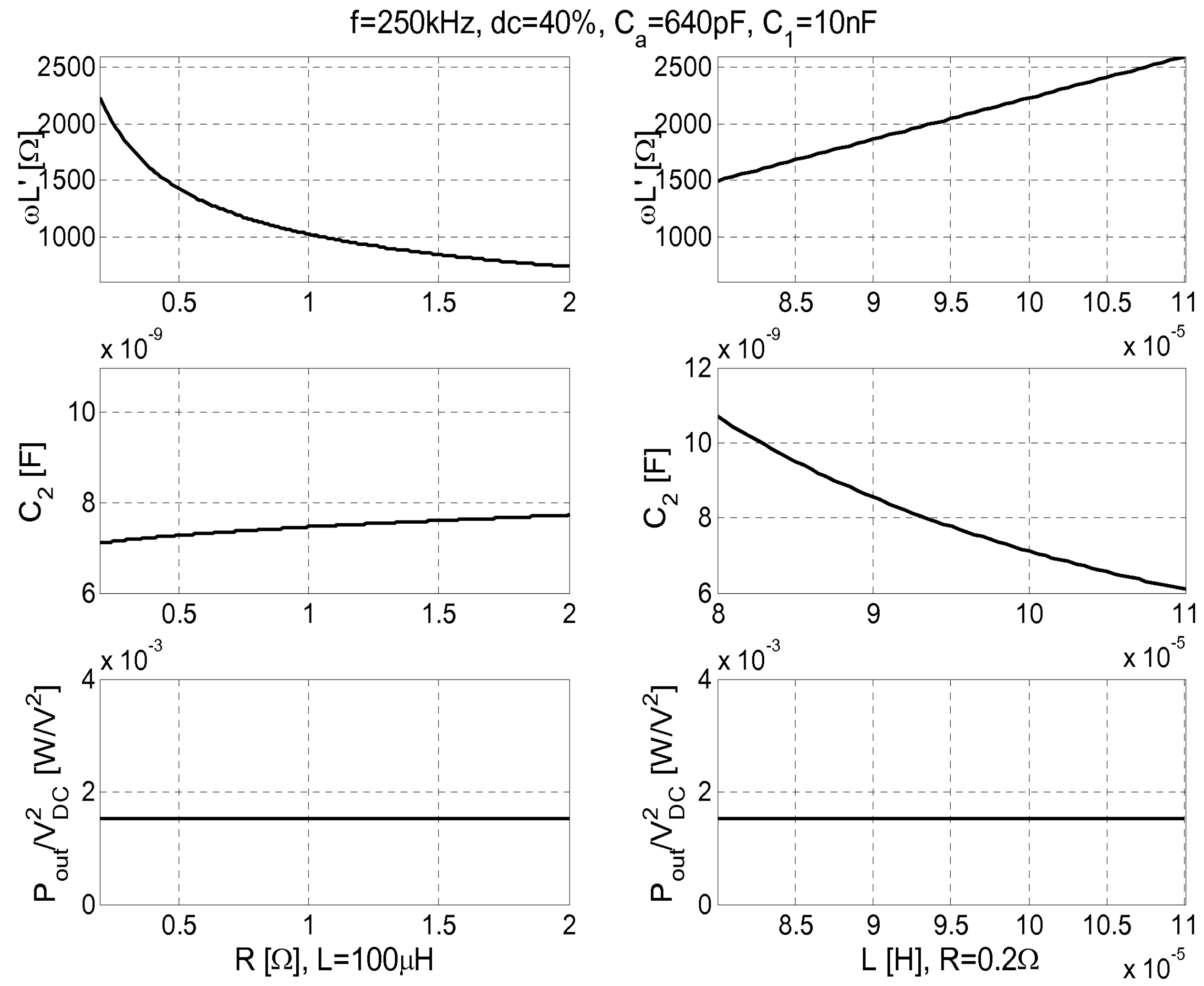


Fig. 9



f=250kHz, dc=40%, C_a=640pF, C_1=10nF

Fig. 10

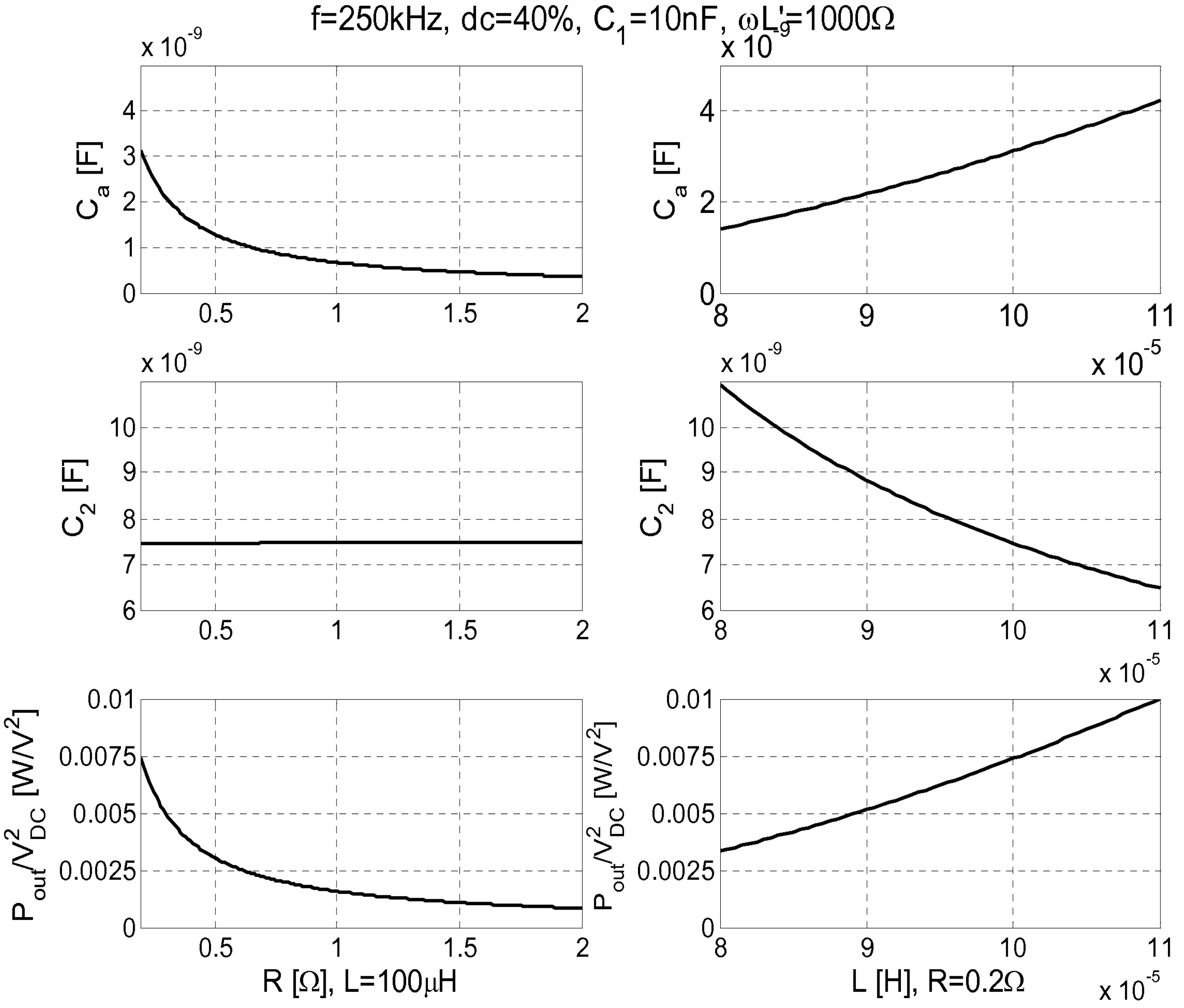

f=250kHz, dc=40%, C_1=10nF, ωL'$_g$=1000Ω
x 10^{-9}
C_a [F]
4
3
2
1
0
0.5
1
1.5
2
x 10^{-9}
C_a [F]
4
2
0
8
9
10
11
x 10^{-9}
C_2 [F]
10
9
8
7
6
0.5
1
1.5
2
x 10^{-9}
x 10^{-5}
C_2 [F]
10
9
8
7
6
8
9
10
11
x 10^{-5}
P_{out}/V^2_{DC} [W/V^2]
0.01
0.0075
0.005
0.0025
0
0.5
1
1.5
2
R [Ω], L=100μH
P_{out}/V^2_{DC} [W/V^2]
0.01
0.0075
0.005
0.0025
0
8
9
10
11
L [H], R=0.2Ω
x 10^{-5}

Fig. 11A

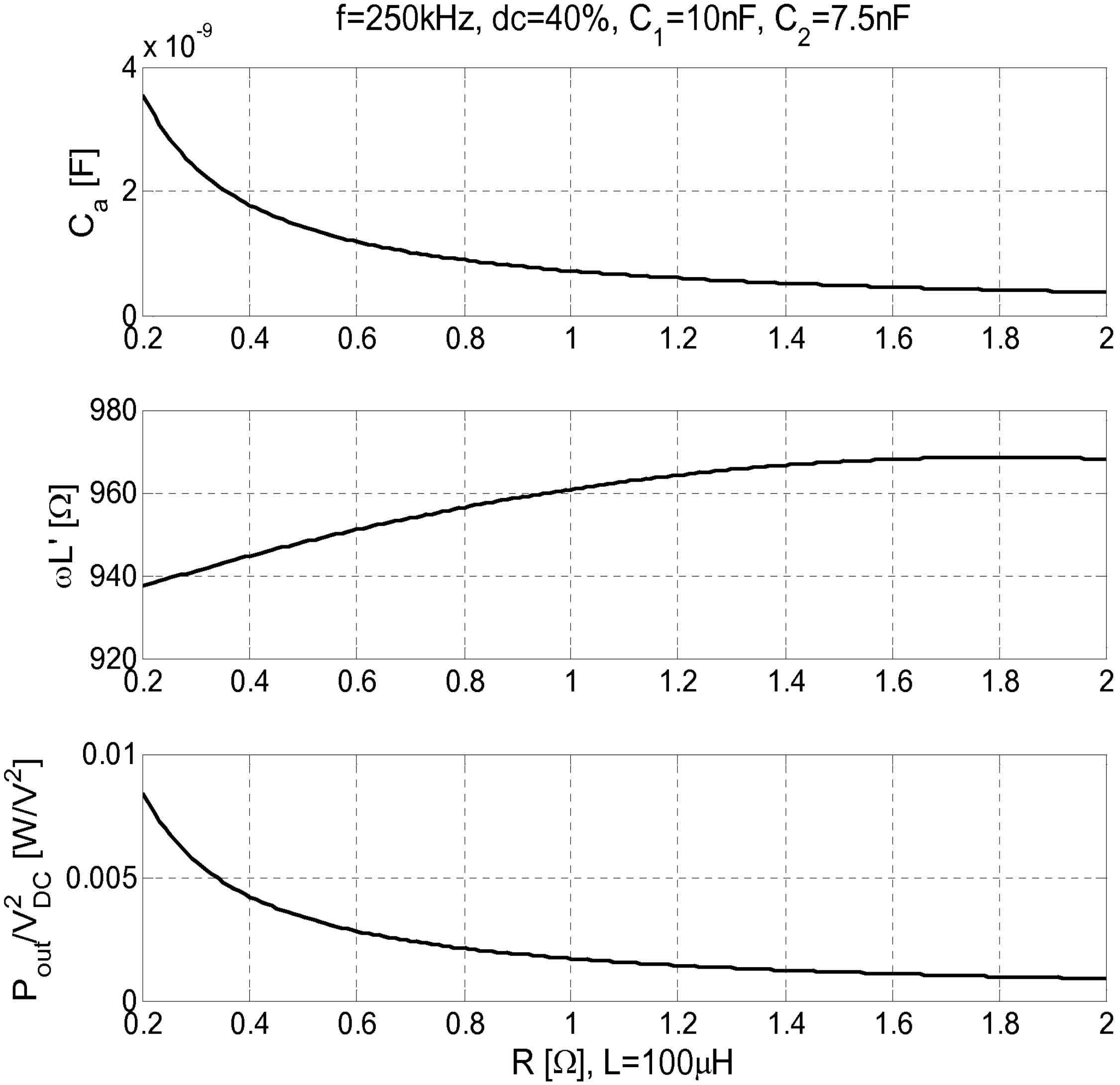

f=250kHz, dc=40%, C$_1$=10nF, C$_2$=7.5nF
x 10^{-9}
4
2
0
C$_a$ [F]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
980
960
940
920
ωL' [Ω]
0.01
0.005
0
P$_{out}$/V$^2_{DC}$ [W/V^2]
R [Ω], L=100μH

Fig. 11B

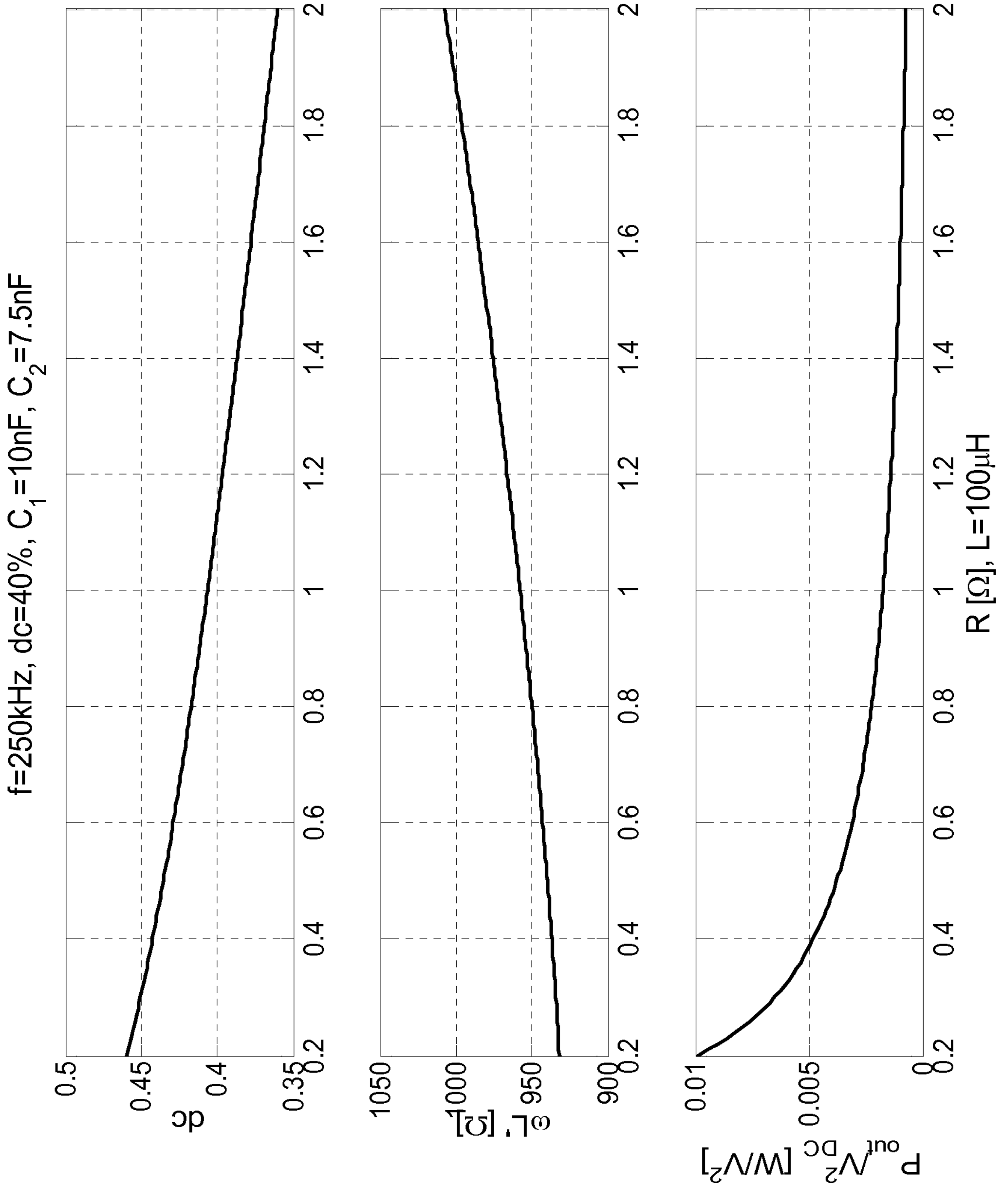

f=250kHz, dc=40%, C_1=10nF, C_2=7.5nF
dc
0.5
0.45
0.4
0.35
ωL' [Ω]
1050
1000
950
900
P_{out}/V^2_{DC} [W/V²]
0.01
0.005
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
R [Ω], L=100μH

Fig. 11C

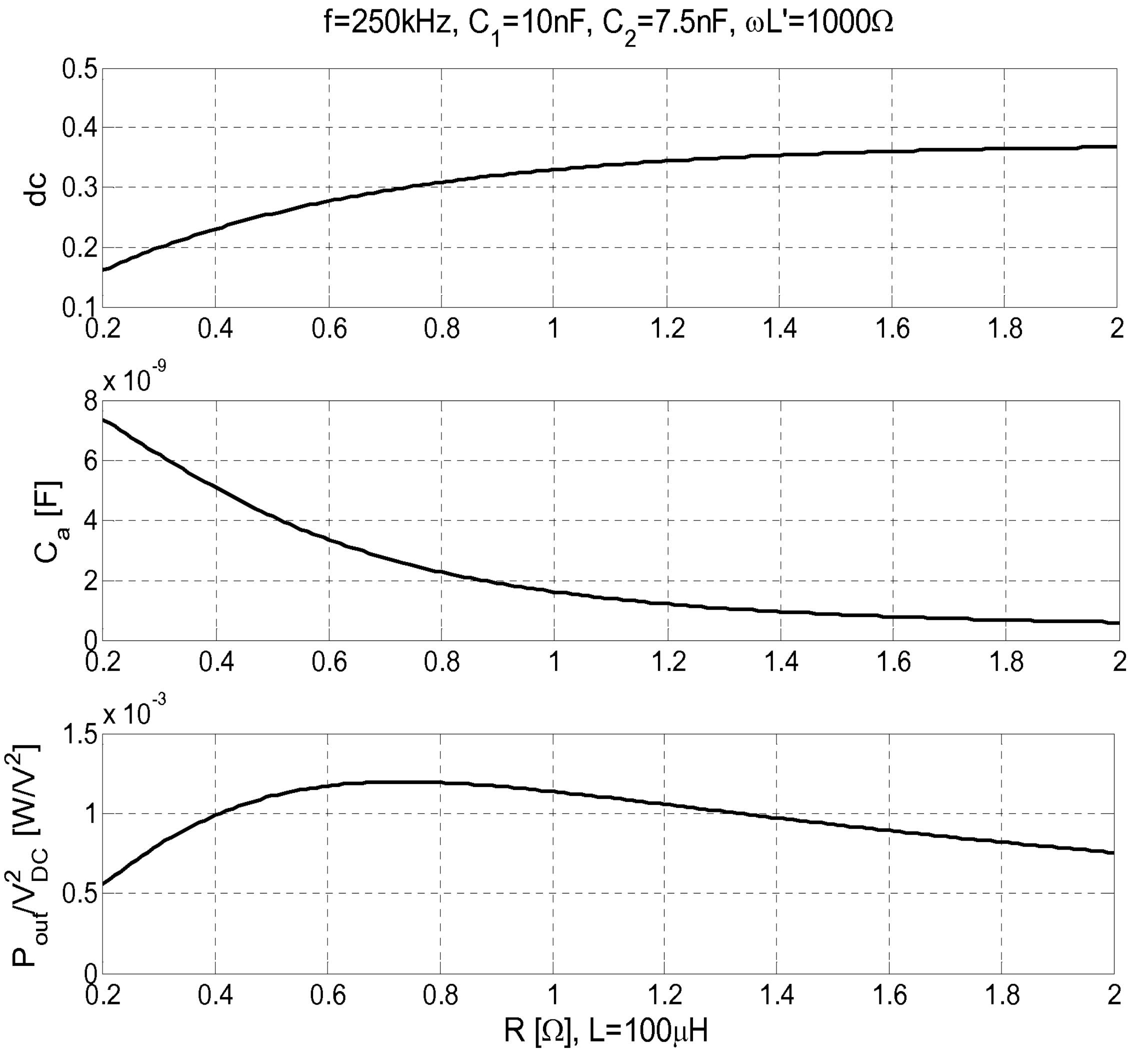

f=250kHz, C_1=10nF, C_2=7.5nF, ωL'=1000Ω
dc
0.5
0.4
0.3
0.2
0.1
C_a [F]
x 10^{-9}
8
6
4
2
0
P_{out}/V^2_{DC} [W/V^2]
x 10^{-3}
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
R [Ω], L=100μH

Fig. 12

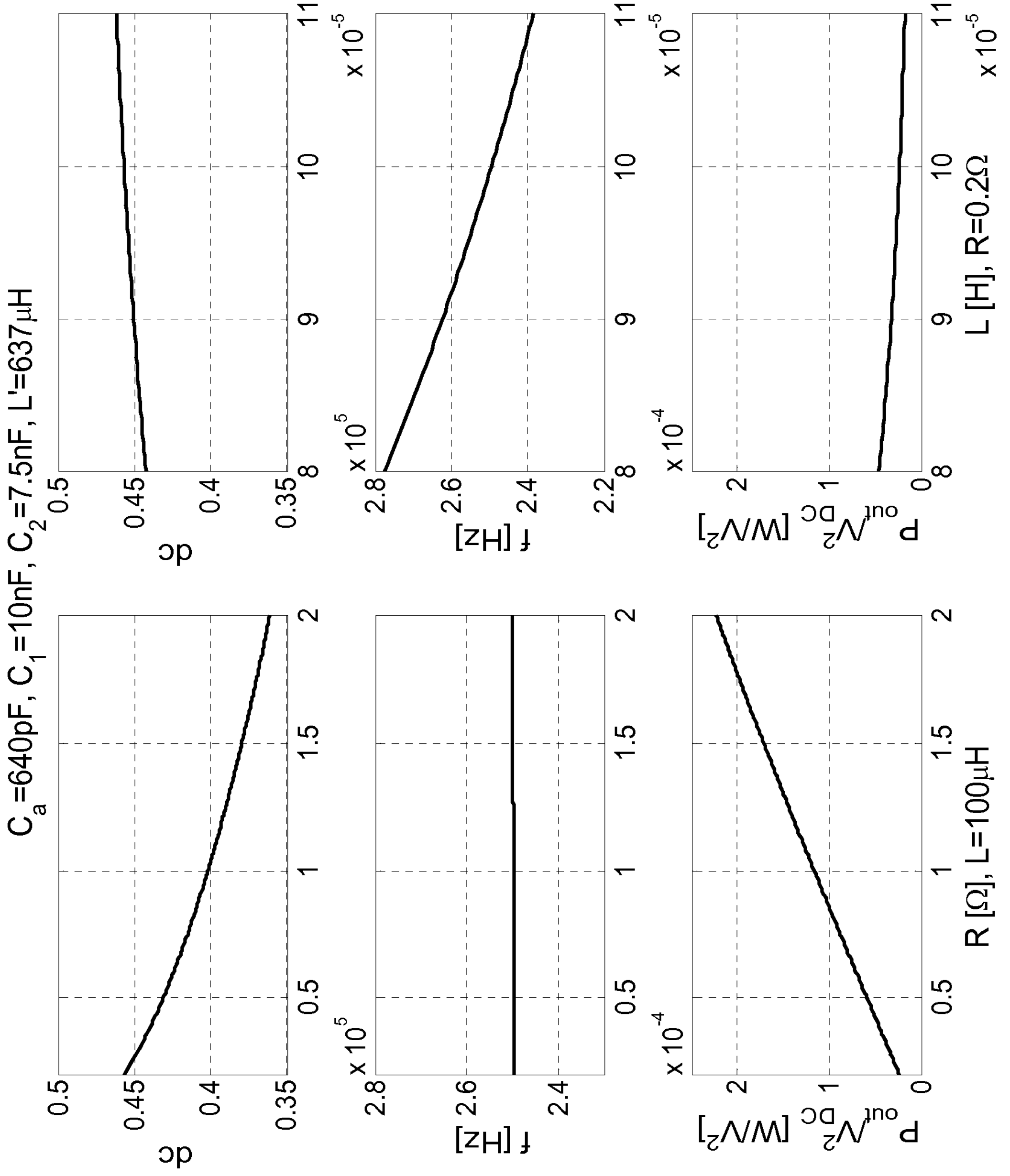

C_a=640pF, C_1=10nF, C_2=7.5nF, L'=637μH
dc
0.5
0.45
0.4
0.35
f [Hz]
2.8
2.6
2.4
2.2
x 10^5
P_out/V^2_DC [W/V^2]
2
1
0
x 10^-4
0.5
1
1.5
2
R [Ω], L=100μH
8
9
10
11
x 10^-5
L [H], R=0.2Ω

Fig. 13

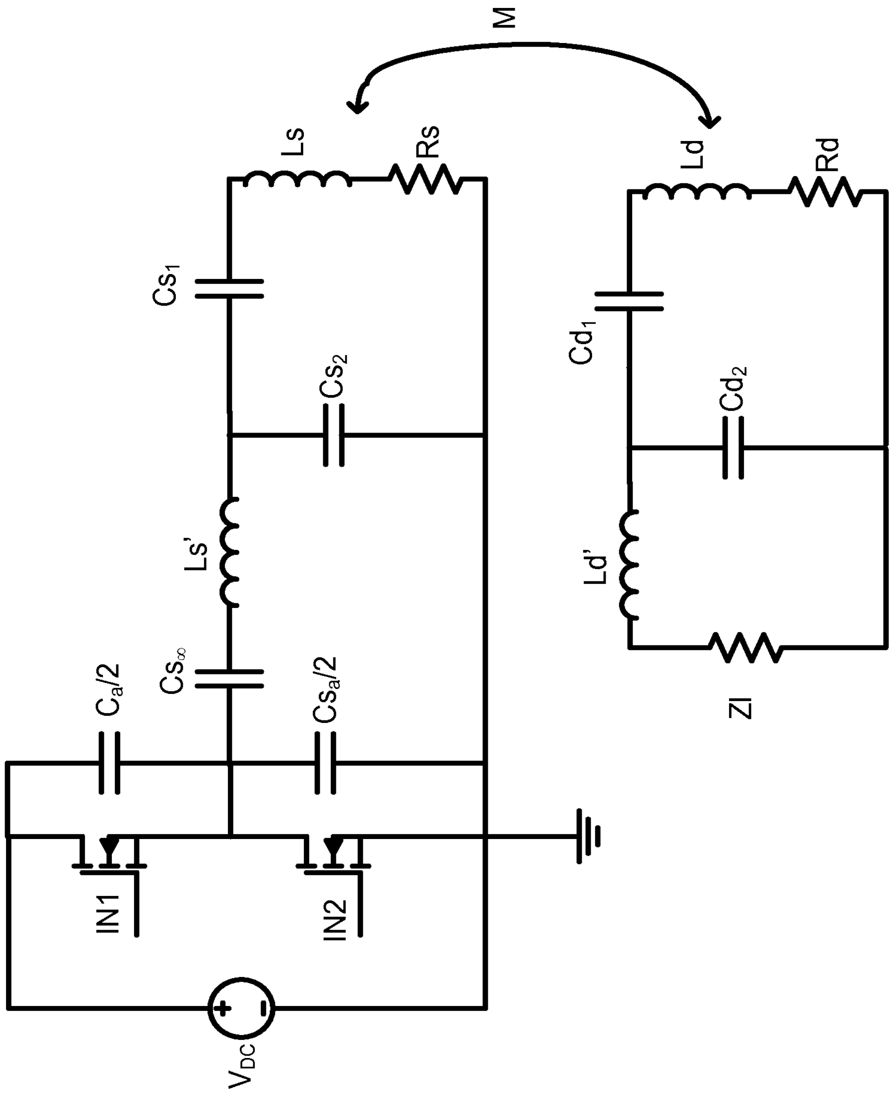


Fig. 14

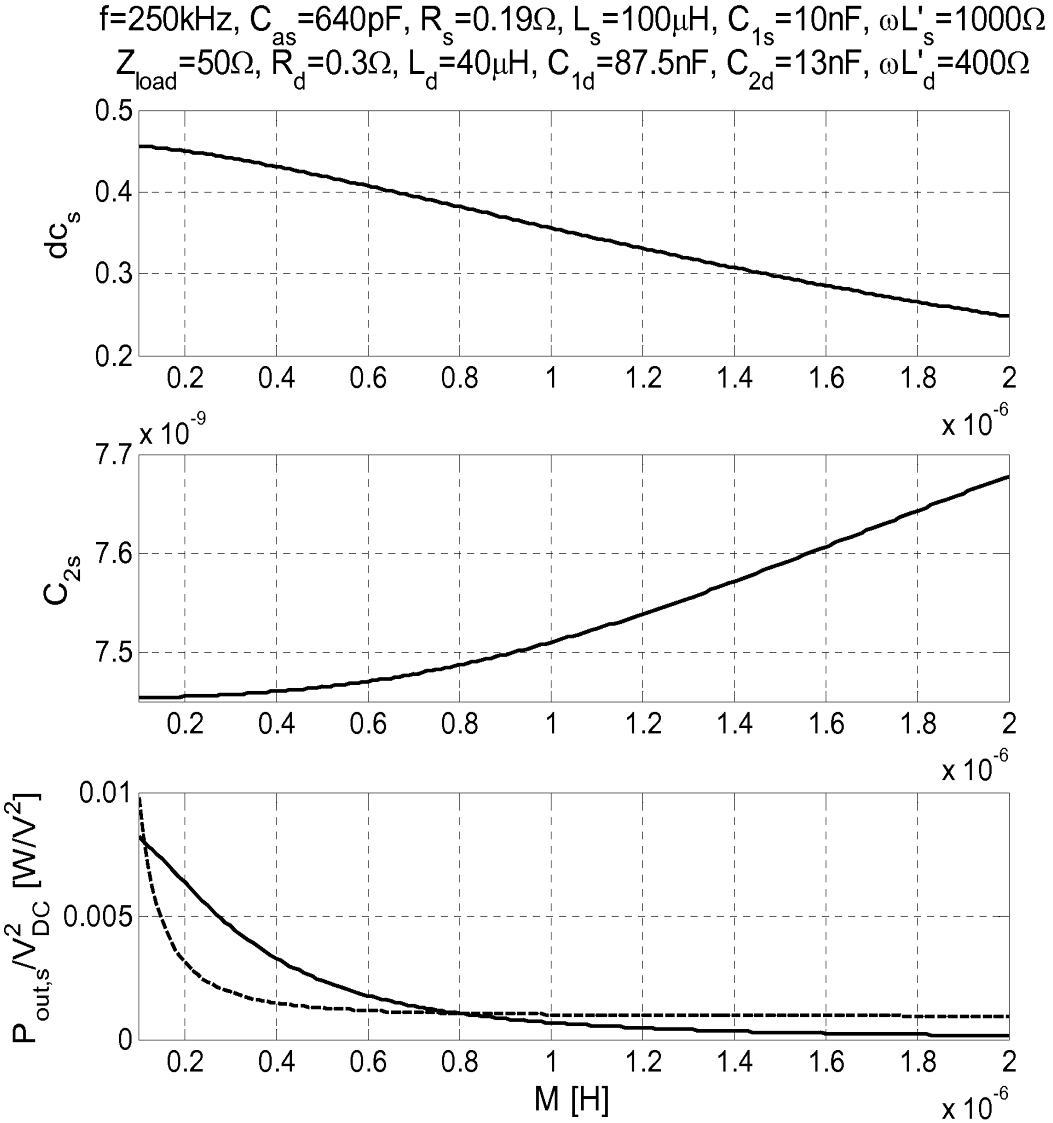

f=250kHz, C_{as}=640pF, R_s=0.19Ω, L_s=100μH, C_{1s}=10nF, ωL'$_s$=1000Ω
Z_{load}=50Ω, R_d=0.3Ω, L_d=40μH, C_{1d}=87.5nF, C_{2d}=13nF, ωL'$_d$=400Ω
dc_s
0.5
0.4
0.3
0.2
C_{2s}
x 10^{-9}
7.7
7.6
7.5
$P_{out,s}/V^2_{DC}$ [W/V^2]
0.01
0.005
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10^{-6}
M [H]

Fig. 15

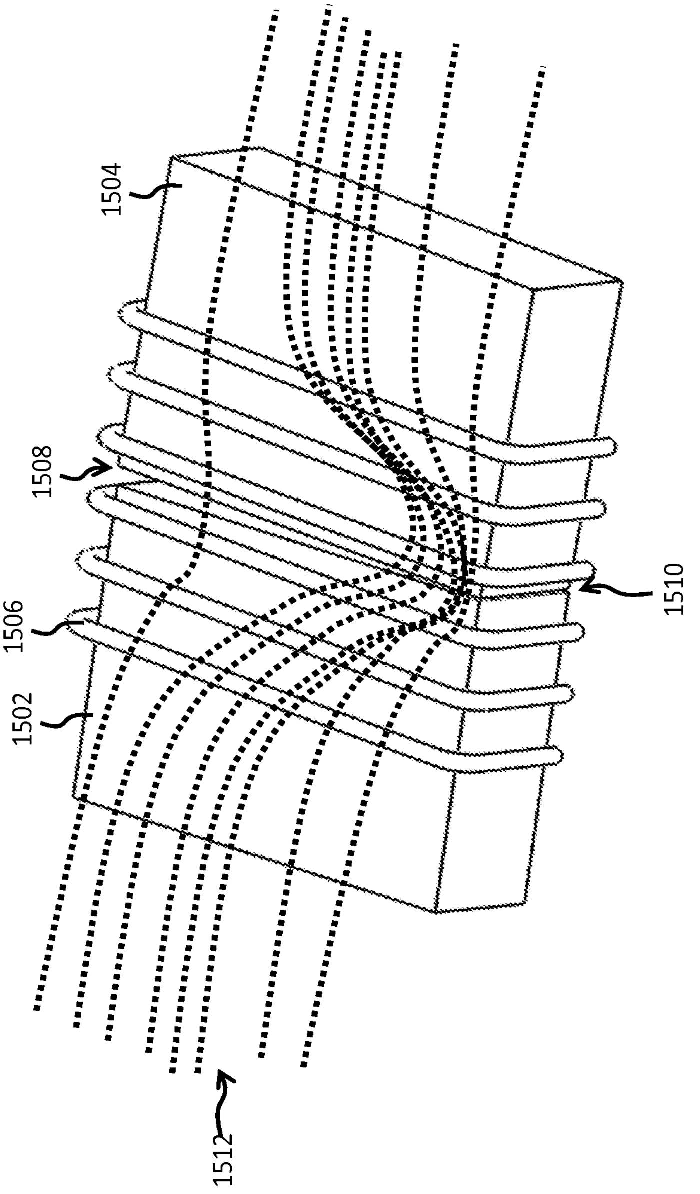
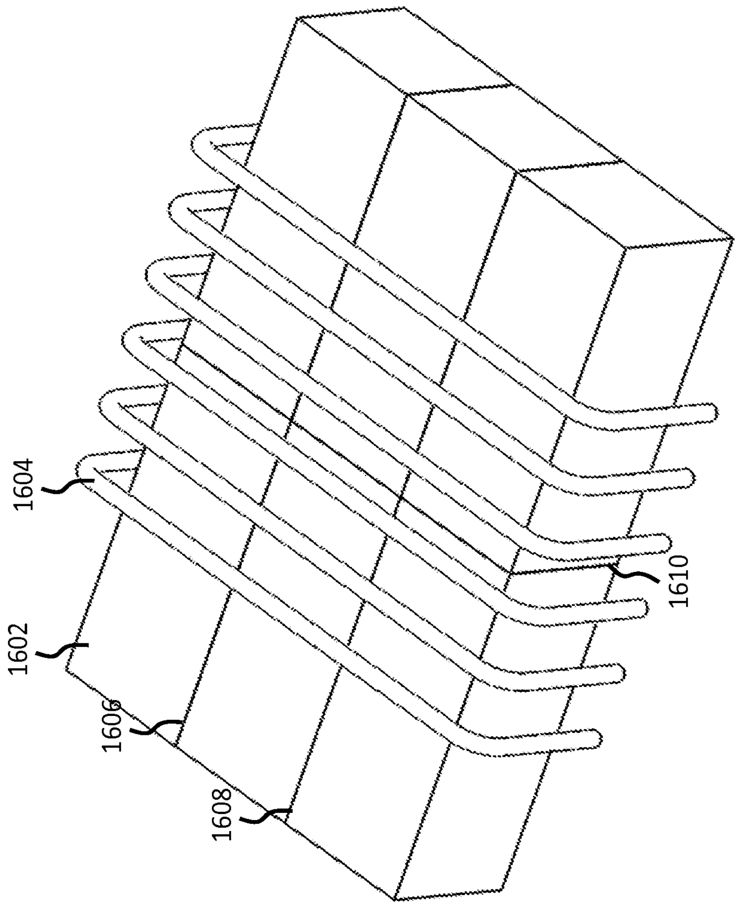


Fig. 16



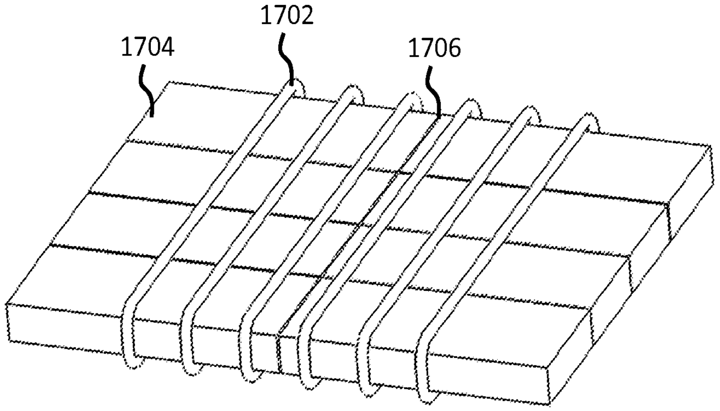


Fig. 17A

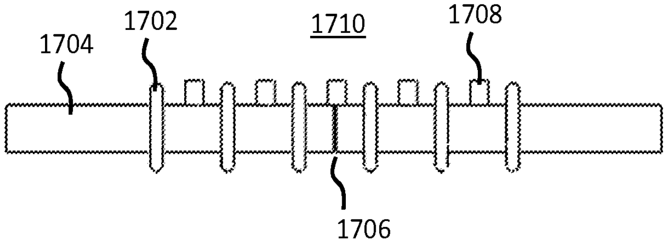


Fig. 17B

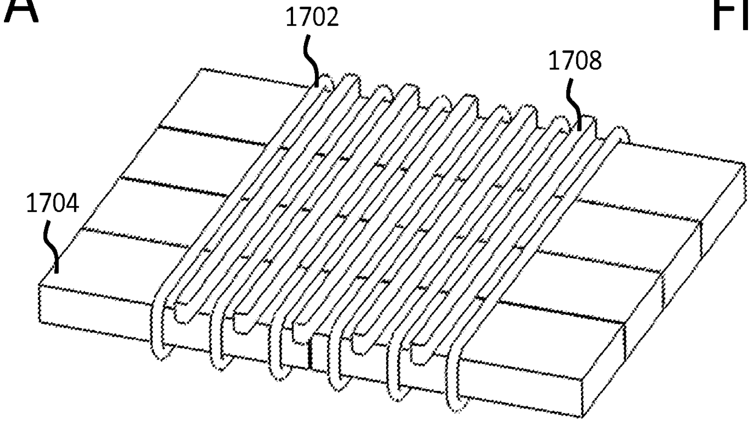


Fig. 17C

Fig. 18

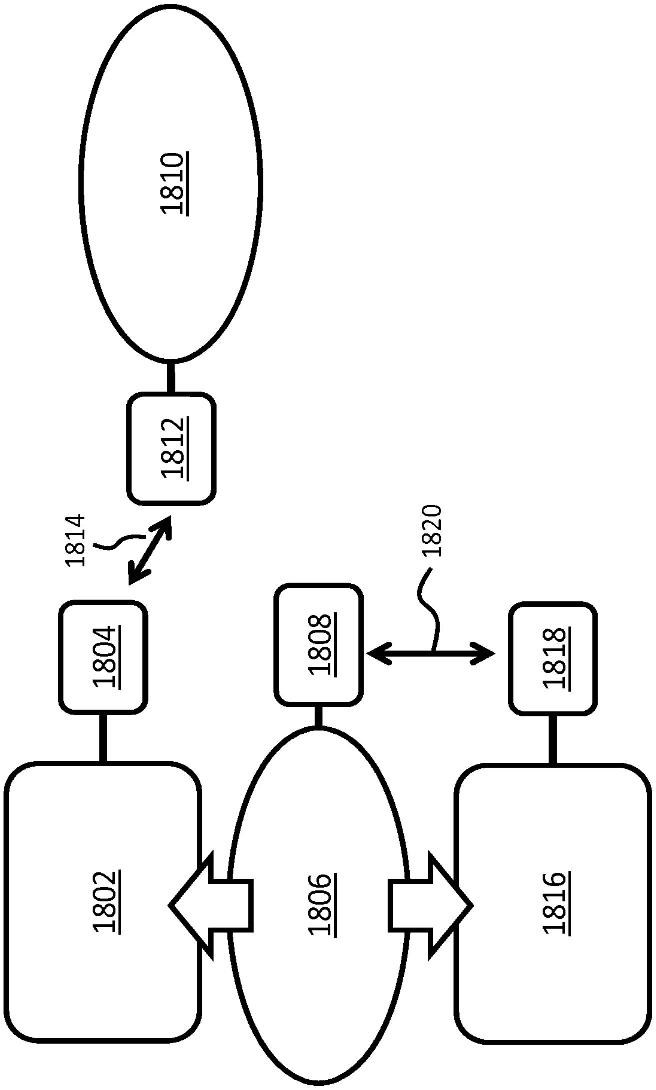


Fig. 19A

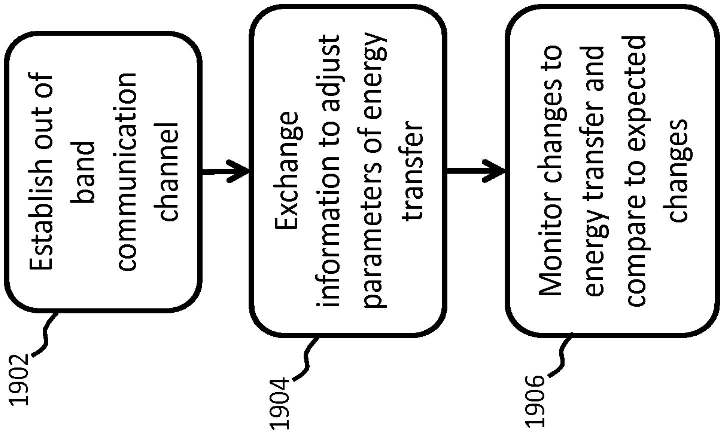


Fig. 19B

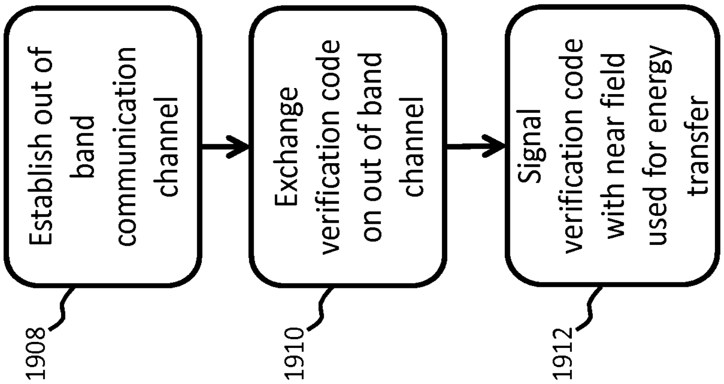


Fig. 20

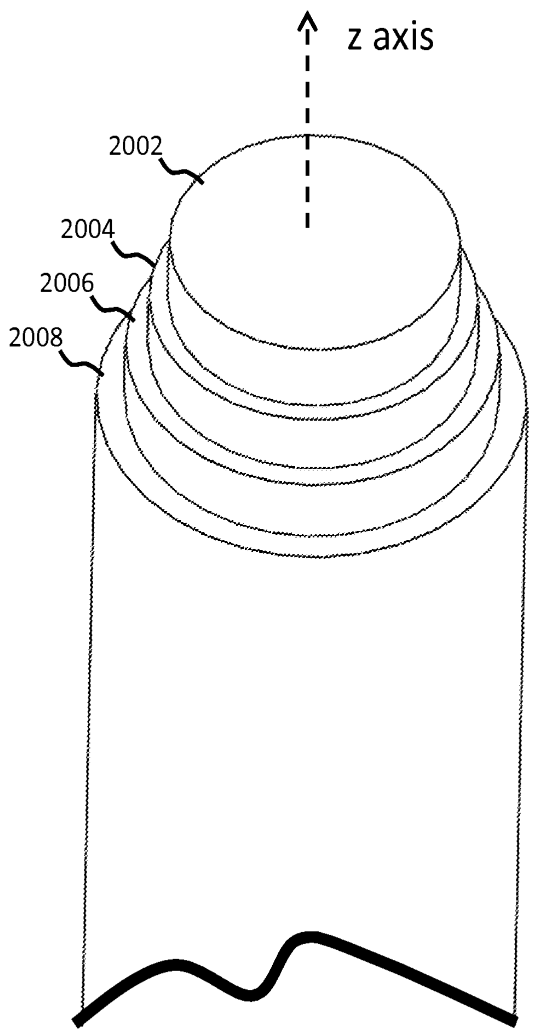


Fig. 21

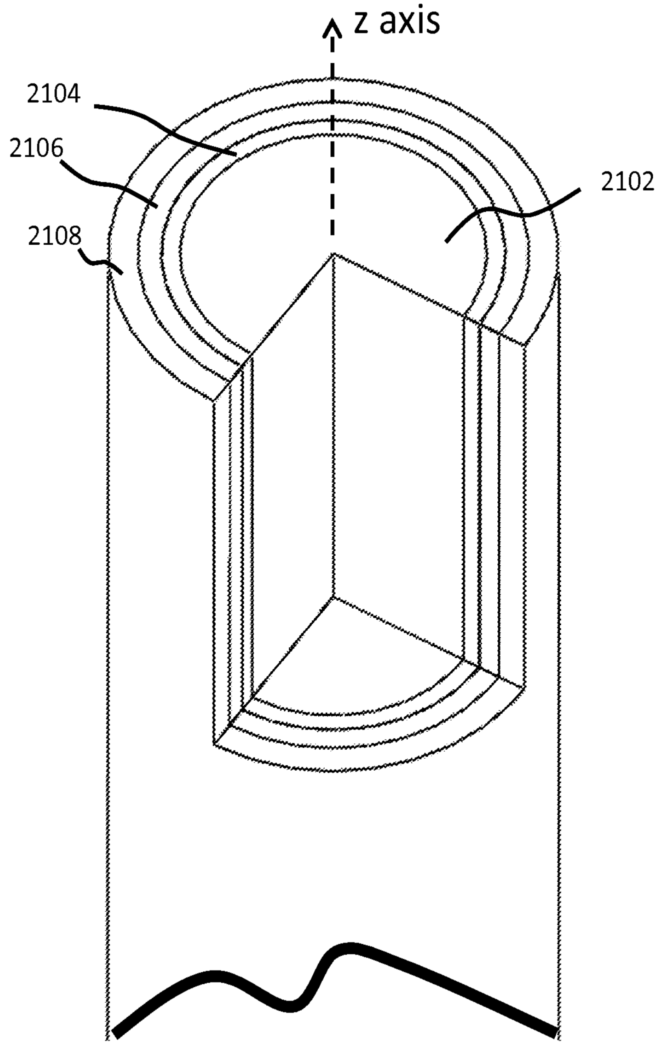


Fig. 22

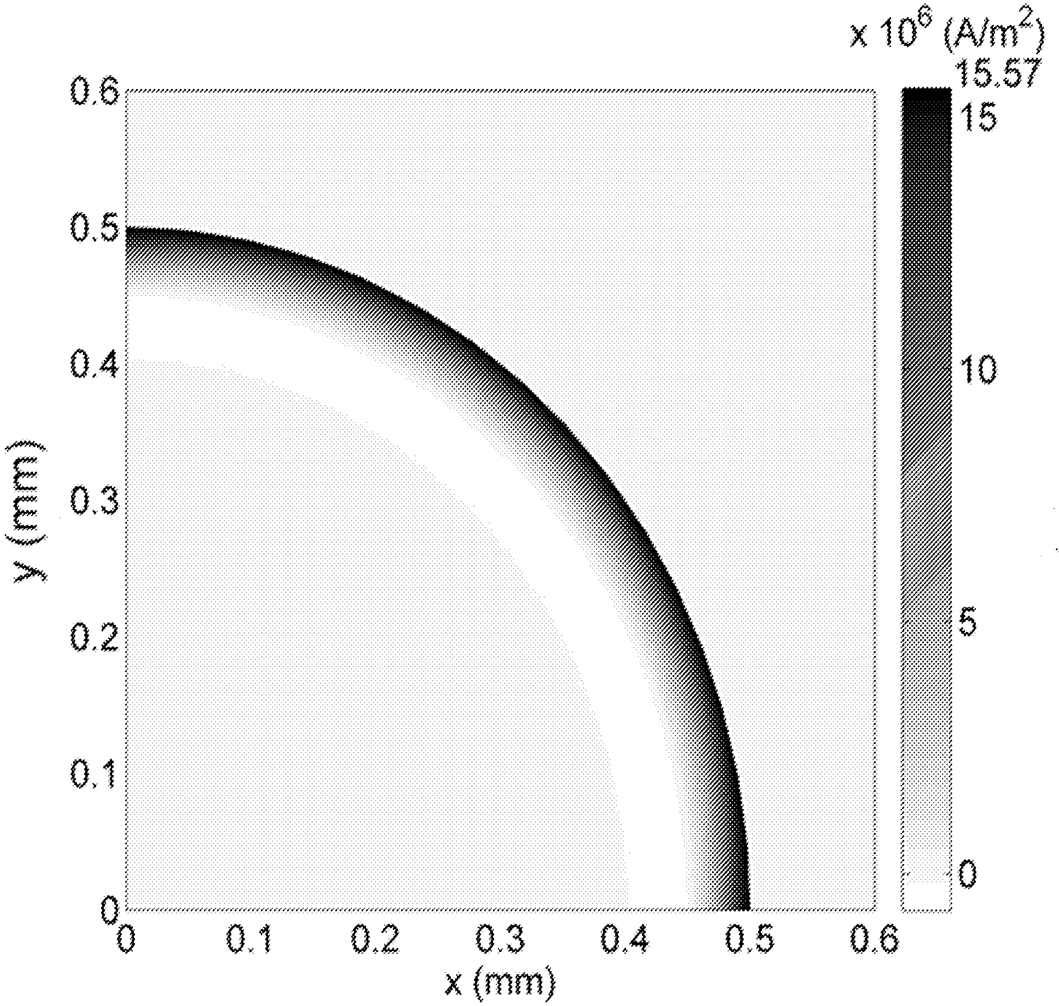


Fig. 23

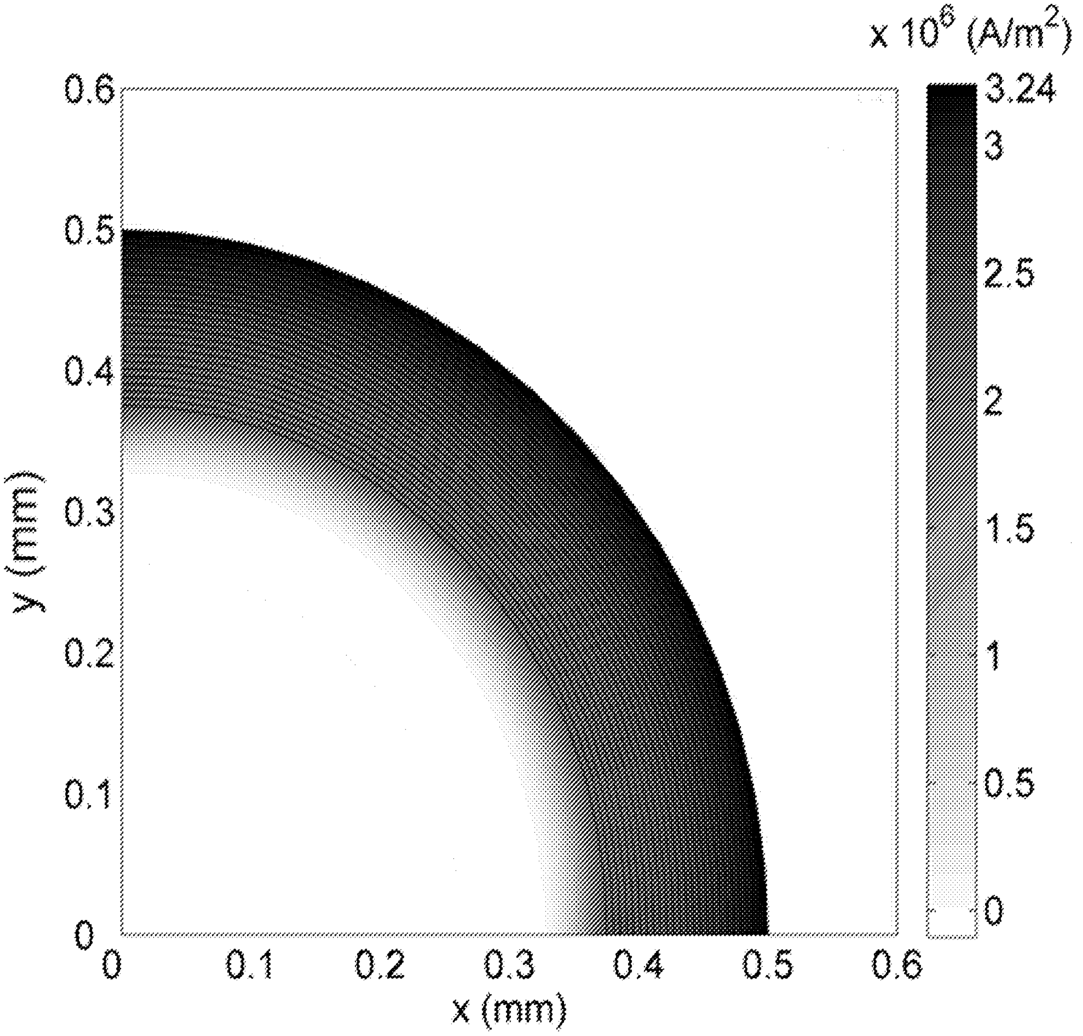

x 10^6 (A/m^2)
3.24
3
2.5
2
1.5
1
0.5
0
y (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
x (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6

Fig. 24

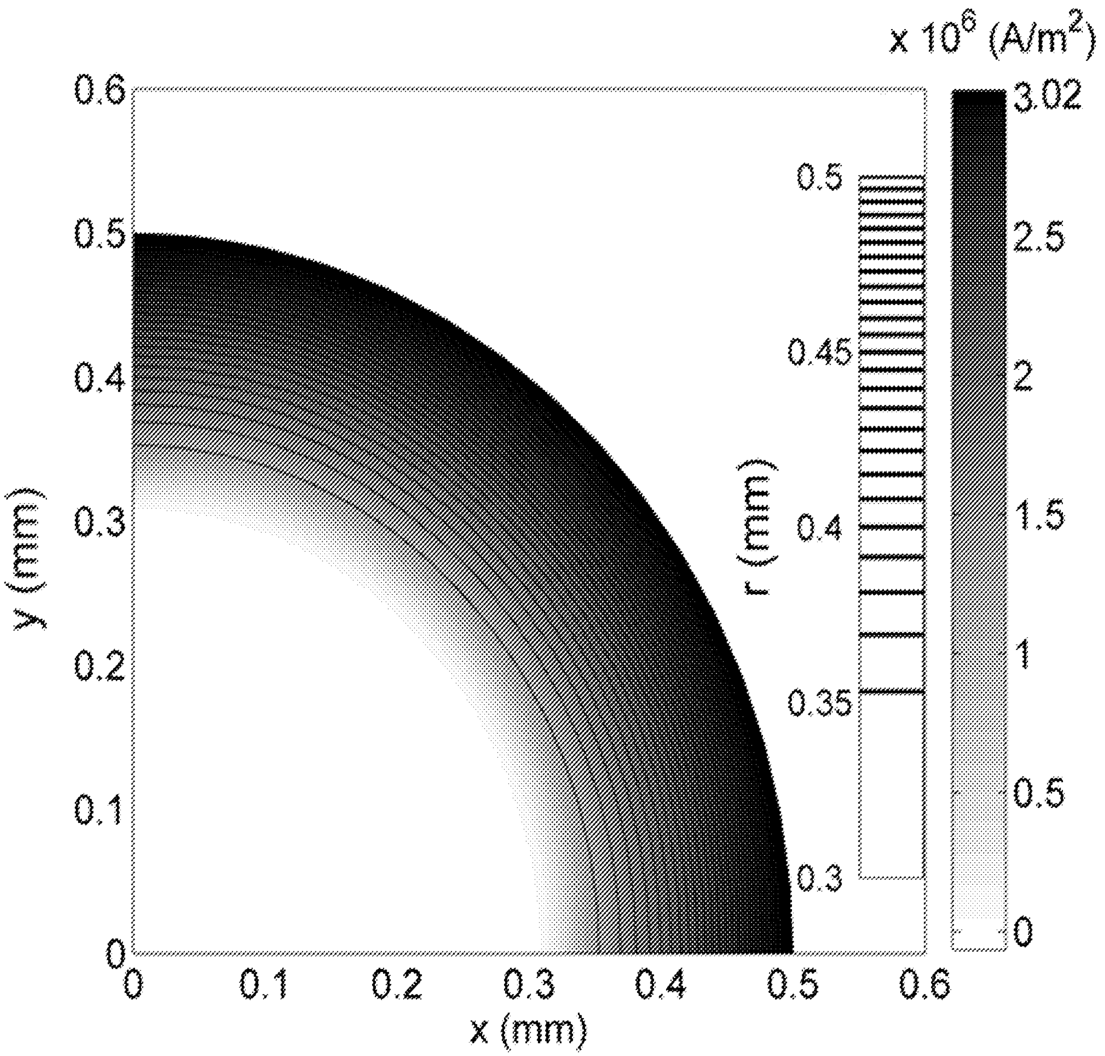

x 10^6 (A/m^2)
3.02
2.5
2
1.5
1
0.5
0
r (mm)
0.5
0.45
0.4
0.35
0.3
y (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
x (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6

Fig. 25

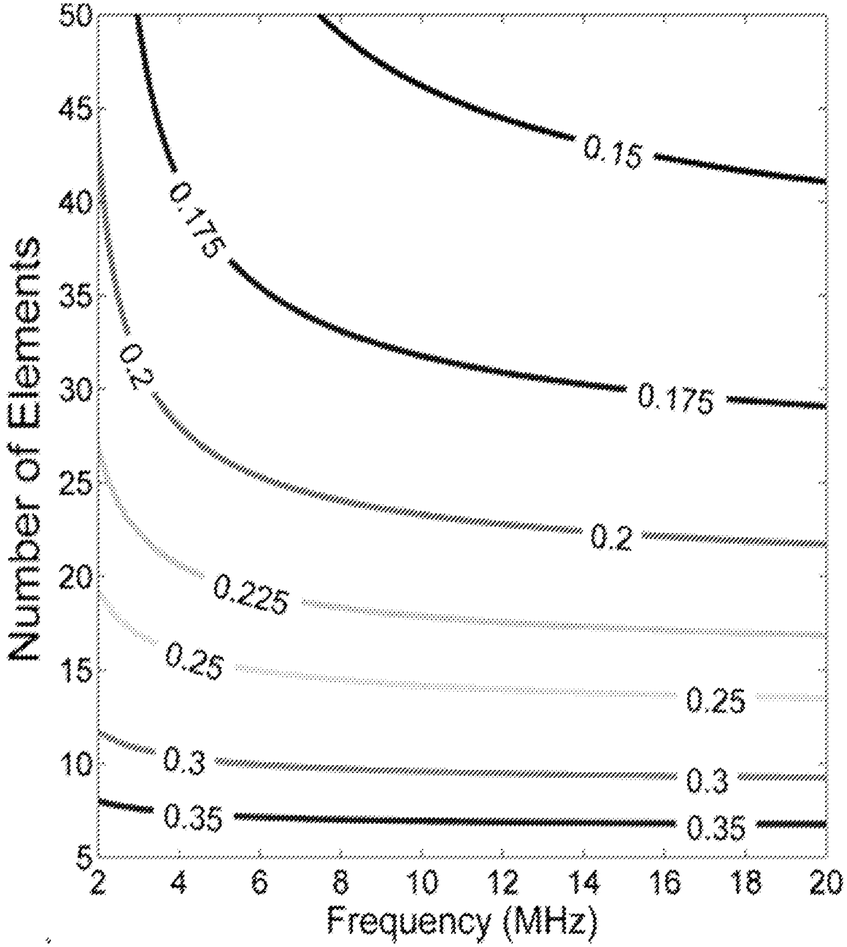
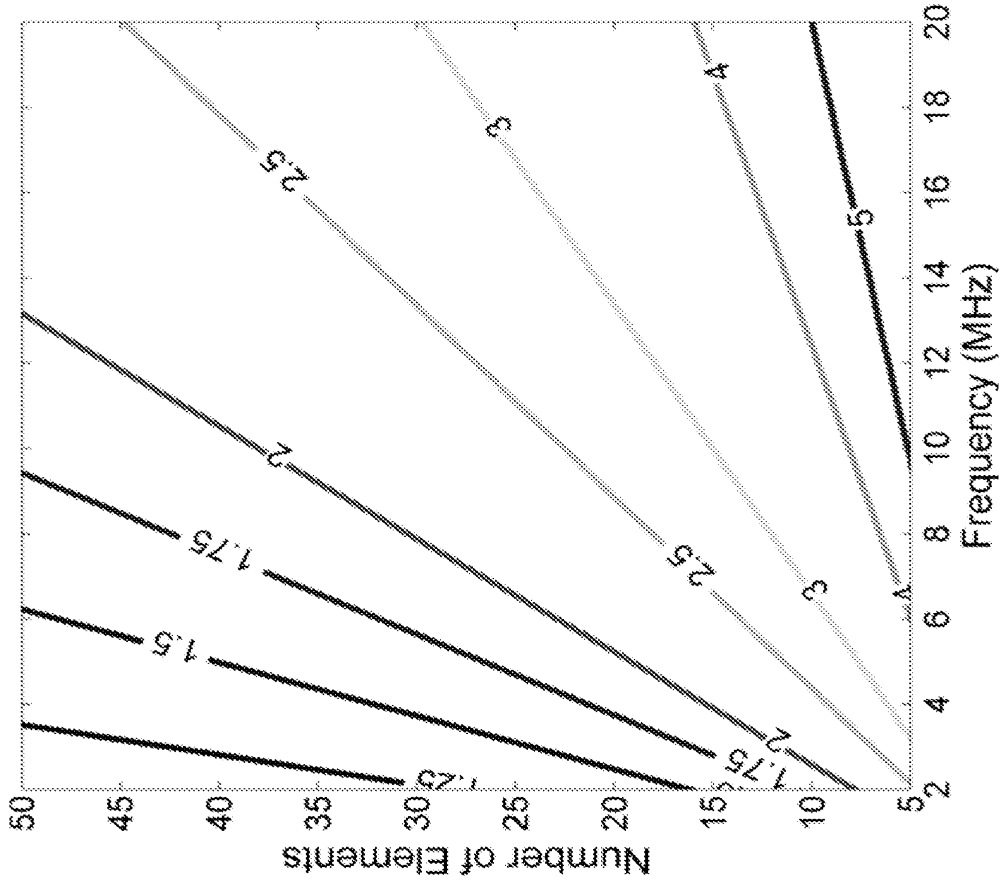

Number of Elements
50
45
40
35
30
25
20
15
10
5
2
4
6
8
10
12
14
16
18
20
Frequency (MHz)
0.15
0.175
0.175
0.2
0.2
0.225
0.25
0.25
0.3
0.3
0.35
0.35

Fig. 26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35
30
25
20
15
10
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Frequency (MHz)
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4
6
8
10
12
14
16
18
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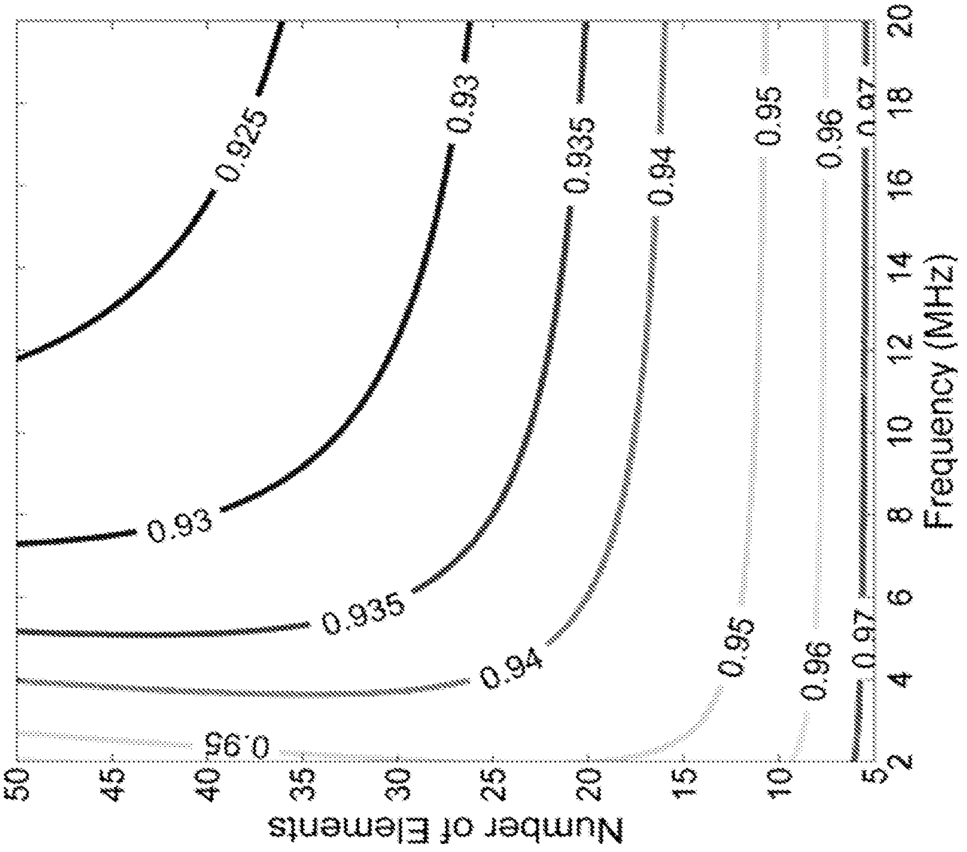
1.25
1.5
1.75
2
2.5
3
4
5

Fig. 27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Frequency (MHz)
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18
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0.93
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0.95
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0.95
0.96
0.96
0.97
0.97

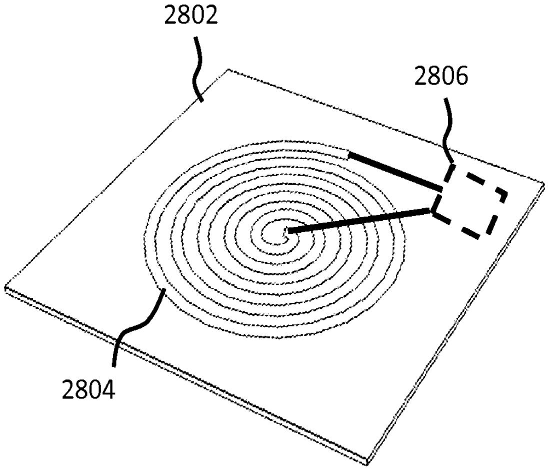


Fig. 28A

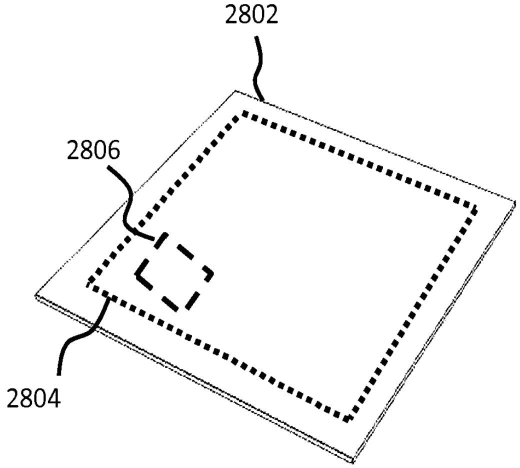


Fig. 28B

Fig. 29

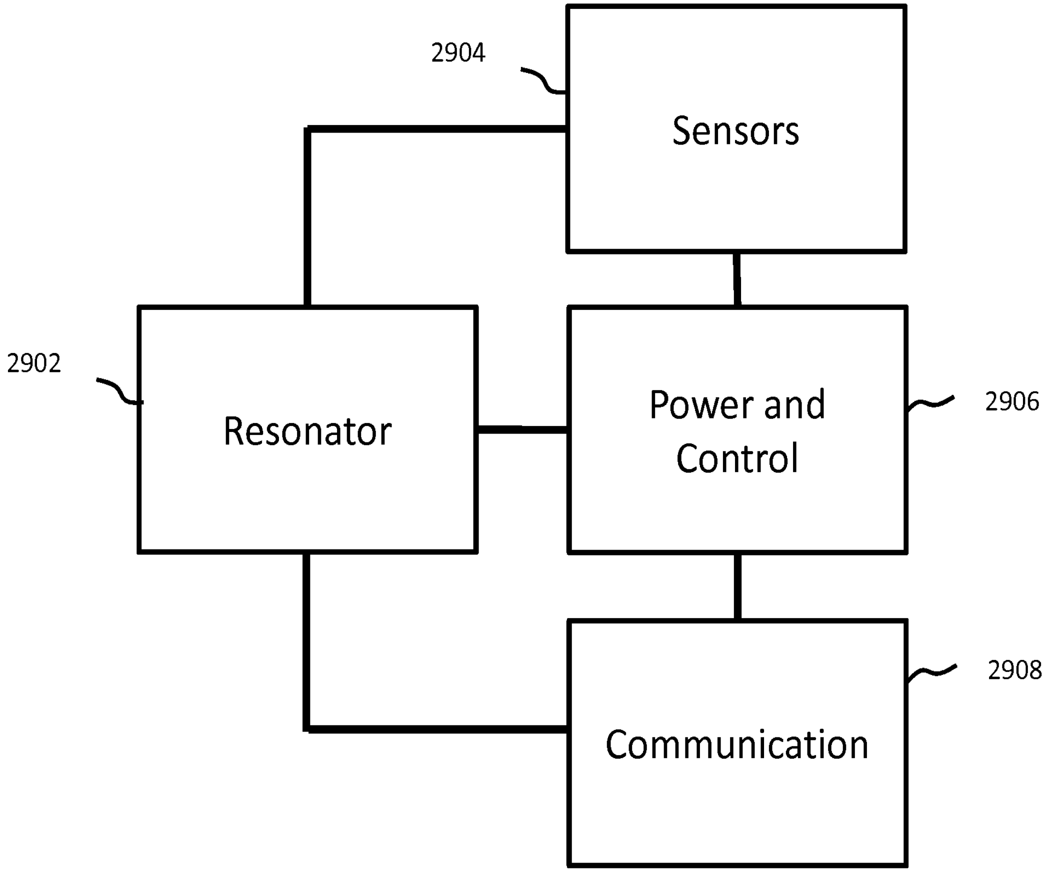
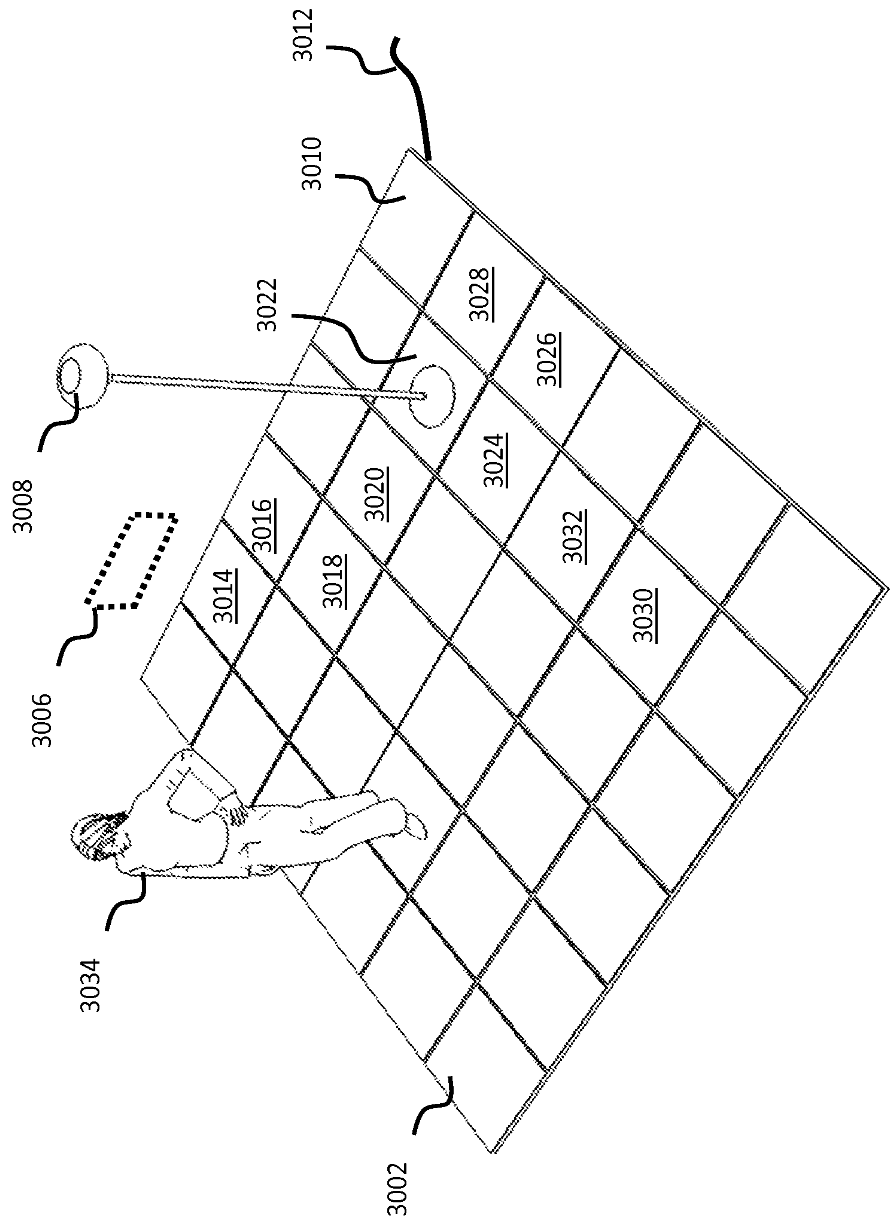

2904
Sensors
2902
Resonator
Power and
Control
2906
2908
Communication

Fig. 30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3010
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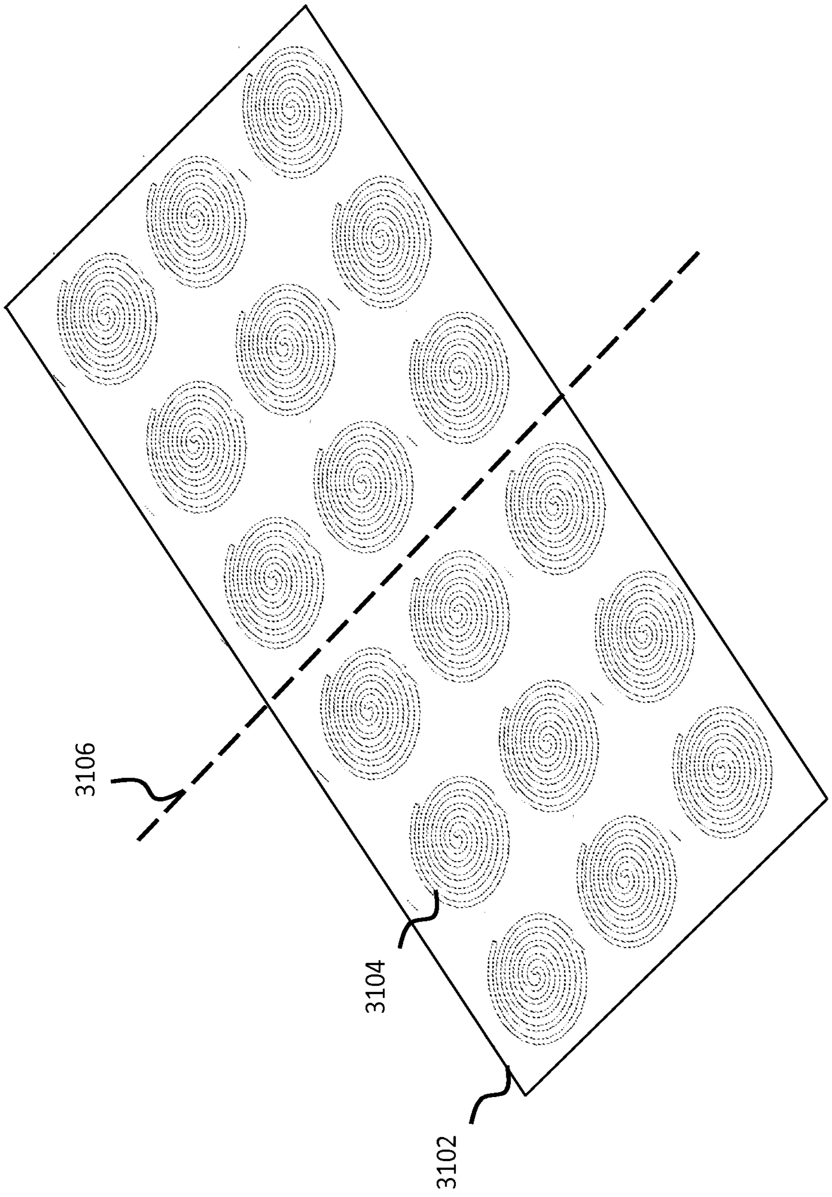
3008
3024
3020
3016
3014
3018
3032
3030
3006
3034
3002

Fig. 31



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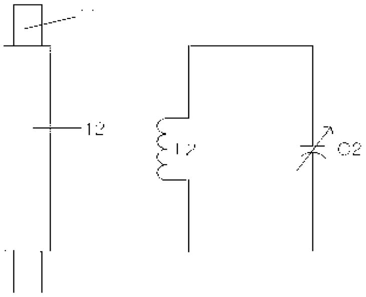
(54) Title: AN AMPLIFICATION RELAY DEVICE OF ELECTROMAGNETIC WAVE AND A RADIO ELECTRIC POWER CONVERSION APPARATUS USING THE ABOVE DEVICE



(57) Abstract: The present invention provides an amplifying repeater, which is constructed in such a manner that a ferrite core is inserted into a coil with a predetermined number of winds to increase an induced electromotive force caused by an increase in flux linkage using a time- varying magnetic field of electromagnetic waves at a position distant from various electromagnetic wave generating sources by a predetermined distance and the induction coil and a variable condenser for inducing resonance are connected to each other to increase current while reducing a resistant component existing in the induction coil to intensify and amplify the magnetic field of elec¬ tromagnetic waves. Furthermore, the present invention provides a wireless power conversion charging device using the magnetic field of electromagnetic waves, which is located between an electromagnetic wave generating source transmitter and a receiving coil or attached to the transmitter and receiving coil. The wireless power conversion charging device includes a rectifying diode for rectifying an electromotive force induced in a construction in which a resonance and impedance matching variable condenser is connected to a coil in series or in parallel in order to transmit maximum induced power to a charging battery that is a load using electromagnetic waves amplified by the amplifying repeater, and a smoothing condenser for smoothing the rectified voltage. Accordingly, charging power required for various small power electronic devices can be provided and power can be supplied to various loads.

WO 2006/011769 A1

Description

AN AMPLIFICATION RELAY DEVICE OF ELECTROMAGNETIC WAVE AND A RADIO ELECTRIC POWER CONVERSION APPARATUS USING THE ABOVE DEVICE

Technical Field

[1] The present invention relates to an amplifying repeater, which is constructed in such a manner that a ferrite core is inserted into a coil with a predetermined number of winds to increase an induced electromotive force caused by an increase in flux linkage using a time-varying magnetic field of electromagnetic waves at a position distant from an electromagnetic wave generating source by a predetermined distance, and that the coil and a variable condenser for inducing resonance are connected to each other to intensify and amplify the magnetic field of electromagnetic waves, and a wireless power converter using electromagnetic waves, which is located at a predetermined distance from the amplifying repeater, connects a resonance and impedance matching variable condenser to a coil to effectively transmit an induced power to a load, and rectifies and smoothes the induced power using a diode to supply the power to a charging battery or various loads.

Background Art

[2] The induced electromotive force obtained from a time variation of the magnetic field of electromagnetic waves using Faraday′s law is generated in proportion to the number of winds of an induction coil and a time variation of flux linkage. However, the intensity of the magnetic field is abruptly decreased in response to a distance from an electromagnetic wave generating source. Thus, the induced electromotive force is hardly induced to the induction coil at more than a predetermined distance so that energy according to wireless power conversion cannot be obtained. Furthermore, the induction coil must be disposed within a very short range from the electromagnetic wave generating source in a prior art so that its installation position is greatly restricted or it cannot be installed because of its bad appearance.

Disclosure of Invention

Technical Problem

[3] Accordingly, the present invention has been made in view of the above□mentioned problem, and it is an object of the present invention to provide an electromagnetic wave amplifying repeater, which is constructed in such a manner that a ferrite core is inserted into a coil with a predetermined number of winds to increase an induced electromotive force caused by an increase in flux linkage using a time-varying magnetic

field of electromagnetic waves at a position distant from an electromagnetic wave generating source by a predetermined distance, connect the induction coil to a variable condenser for inducing resonance to construct an amplifying repeater that maximizes a current while reducing a resistant component existing in the induction coil to intensify and amplify the magnetic field of electromagnetic waves, and to provide a wireless power converter using the amplifying repeater, which includes a rectifying diode for rectifying an electromotive force induced in a structure in which a resonance and impedance matching variable condenser is connected in parallel with a coil to effectively transmit an induced electromotive force using the electromagnetic waves amplified by the amplifying repeater, having a predetermined distance from the amplifying repeater, and a smoothing condenser for smoothing the rectified voltage.

[4] Another object of the present invention is to provide an amplifying repeater located at a very short distance from an electromagnetic wave generating source or attached to a wireless power converter to intensify and amplify the magnetic field of electromagnetic waves such that the amplifying repeater is installed unrestrictedly and an amplifying repeater and wireless power converter are applied in various ways according to wireless power conversion using the amplified electromagnetic waves.

Technical Solution

[5] To achieve the above objects, according to the present, there is provided an electromagnetic wave amplifying repeater capable of amplifying and repeating the magnetic field of electromagnetic waves generated artificially or generated from various electromagnetic wave generating sources, including: an induction coil formed by winding a coil with a predetermined thickness in a desired size and form by a predetermined number of winds; a magnetic substance having a predetermined size and form, the magnetic substance being combined with the induction coil to increase flux; and a variable condenser connected to the induction coil to construct a resonance circuit.

Brief Description of the Drawings

[6] Further objects and advantages of the invention can be more fully understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

[7] FIG. 1 illustrates the appearance and configuration of an amplifying repeater according to the present invention;

[8] FIG. 2 illustrates a wireless power converter having a charging function according to the present invention;

[9] FIG. 3 illustrates a construction for measuring a charging voltage, a charging current and a charging power using only a wireless power converter without using an

amplifying repeater;

[10] FIG. 4 illustrates a construction for measuring a charging voltage, a charging current and a charging power using a single magnetic field amplifying repeater and a wireless power converter;

[11] FIG. 5 illustrates a construction for measuring a charging voltage, a charging current and a charging power using two magnetic field amplifying repeaters and a wireless power converter (combined with one of the amplifying repeaters);

[12] FIG. 6 illustrates a construction for measuring a charging voltage, a charging current and a charging power using two magnetic field amplifying repeaters and a wireless power converter (independent);

[13] FIG. 7 illustrates a construction for measuring a charging voltage, a charging current and a charging power using magnetic field amplifying repeaters, a repeating amplifier and a wireless power converter, which are combined with each other;

[14] FIG. 8 illustrates a construction in which a transmission coil generates a magnetic field, and a voltage, current and power are measured using an amplifying repeater, a receiving coil and a wireless power converter;

[15] FIG. 9 illustrates a construction in which a transmission coil generates a magnetic field, and a voltage, current and power are measured at an output terminal using an amplifying repeater, a receiving coil wound on the upper part of a common core, and an amplifying repeater disposed at the lower part of the common core;

[16] FIG. 10 illustrates a transmitter and a receiver constructed in such a manner that an amplifying repeater and a transmission coil or a receiving coil are wound around a single core;

[17] FIG. 11 illustrates a construction in which an amplifying repeater composed of a spiral coil is attached onto a spiral coil, and a voltage, current and power are measured at an output terminal of a receiving coil;

[18] FIG. 12 illustrates a construction in which an amplifying repeater composed of a spiral coil is located between a transmission coil and a receiving coil, and a voltage, current and power are measured at an output terminal;

[19] FIG. 13 illustrates a construction in which an amplifying repeater is located outside a transmission coil, and a voltage, current and power are measured at an output terminal of a receiving coil; and

[20] FIG. 14 illustrates a construction in which an amplifying repeater is located outside each of a transmission coil and a receiving coil, and a voltage, current and power are measured at an output terminal of the receiving coil

[21] 11; Core, 12; Inducing Coil

[22] 20; AC Power Generator

[23] 21; Eectromagnetic Wave Generating Source

[24] 22; Receiver 23; Output Part
[25] 24; Ruler
[26] 25,26,27,28,30,32,34; Amplifying Repeater
[27] 29; Transmission Coil
[28] 31; Receiver1 , 33; Receiving Coil
[29] 51; Spiral Coil Type Receiving Coil
[30] 52; Spiral Coil Type Amplifying Repeater
[31] 53; Spiral Coil Type Transmission Coil
[32] L1: Receiving Coil,
[33] C1: Condenser for Impedance Matching,
[34] C2: Smoothing Condenser,
[35] 1.3V: Battery Voltage for Charging

Mode for the Invention

[36] The present invention will now be described in detail in connection with preferred embodiments with reference to the accompanying drawings. For reference, like reference characters designate corresponding parts throughout several views.

[37] The present invention provides an amplifying repeater, which is constructed in such a manner that a ferrite core is inserted into a coil with a predetermined number of winds to increase an induced electromotive force caused by an increase in flux linkage using a time-varying magnetic field of electromagnetic waves using Faraday′s law at a position distant from an electromagnetic wave generating source by a predetermined distance and the induction coil and a variable condenser for inducing resonance are connected to each other to maximize an induced current while reducing a resistant component existing in the induction coil to amplify the magnetic field of electromagnetic waves. Furthermore, the present invention provides a wireless power converter located at a predetermined distance from the amplifying repeater or attached to the amplifying repeater. The wireless power converter includes a rectifying diode for rectifying an electromotive force induced in a construction in which a magnetic core such as a ferrite core is inserted in an induction coil with a predetermined number of winds for transmitting maximum induced power to a charging battery that is a load using electromagnetic waves amplified by the amplifying repeater and the induction coil is connected to a variable condenser for controlling resonance and impedance matching, a smoothing condenser for smoothing the rectified voltage, and a receiving coil having a predetermined DC voltage and current.

[38] In receiving electromagnetic power using Faraday′s law, the present invention amplifies the magnetic field of time-varying electromagnetic waves generated in a television receiver or a monitor or electromagnetic waves artificially generated by

connecting a transmission coil to a load of an AC power generating circuit using an amplifying repeater to obtain an induced electromotive force using an induction coil at a position distant from an electromagnetic wave generating source by a predetermined distance and maximizes the obtained induced voltage and current, to thereby provide a magnetic field amplifying repeater for receiving electromagnetic power, which enables high efficiency electric energy conversion, and a high efficiency wireless power converter using the amplifying repeater.

[39] The construction of the amplifying repeater for amplifying an induced magnetic field of electromagnetic waves will now be described.

[40] The electromagnetic wave amplifying repeater according to the present invention obtains an induced electromotive force using electromagnetic waves generated from an electromagnetic wave generating source and emits the obtained induced power to the air. The present invention winds a coil round a bobbin having a predetermined diameter and size (having an internal diameter of 10mm and an external diameter of 15mm) by a predetermined number of times and a ferrite core is inserted in the bobbin to manufacture an induction coil. The diameter and the number of winds of the induction coil and the size of the ferrite core are designed such that the induced electromotive force is maximized. The induction coil can be constructed in parallel or in series in consideration of its resistance value. In the present invention, the diameter and length of the ferrite core are 9mm and 110mm, respectively, and two induction coils each have a diameter of 0.3mm and a number of winds of 160 are connected in parallel with each other. The induction coils are wound round the aforementioned bobbin, the ferrite core is inserted into the bobbin and a variable condenser is connected in parallel with the induction coils to construct a resonance circuit to maximize induced power and emit electromagnetic waves.

[41] The wireless power converter according to the present invention is located at a predetermined distance from the amplifying repeater or attached to the amplifying repeater and includes a ferrite core having a diameter of 9mm and a length of 110mm and two induction coils having a diameter of 0.3mm and a number of winds of 100, connected in parallel with each other. The induction coils are wound round a bobbin having a predetermined size (an internal diameter of 10mm and an external diameter of 15mm), the ferrite core is inserted into the bobbin and a variable condenser is connected in parallel with the induction coils to impedance-match with a resonance and load electronic circuit to maximize an induced electromotive force. The wireless power converter further includes a diode for rectifying the induced electromotive force and a smoothing condenser for smoothing the rectified voltage. The wireless power converter can be used as a power supply of a charging device because it generates a DC voltage having a specific current.

[42] FIG. 1 illustrates the electromagnetic field amplifying repeater manufactured according to the present invention on the left and a circuit constructing the amplifying repeater on the right. FIG. 2 is a circuit diagram of the wireless power converter constructed to obtain an electric energy using electromagnetic waves amplified by the amplifying repeater. In FIG. 2, L1 denotes a receiving coil, C1 represents a capacitor for impedance matching of resonance and maximum power transmission, C2 denotes a smoothing capacitor, and 1.3V represents a charging battery voltage. Table 1 represents a charging voltage, a charging current and a charging power obtained when the wireless power converter of FIG. 2 is located having a predetermined distance from an electromagnetic wave generating source 21, as shown in FIG. 3, without using the electromagnetic field amplifying repeater. From Table 1, it can be known that the charging current and charging power are hardly induced when the distance of a ruler 24 exceeds 4cm.

[43]

[44] Table 1 : A charging voltage, a charging current and a charging power Using the wireless power converter in Fig2.

[45]

Distance(cm)	ChargingVoltage(V)	Charging Current (mA)	ChargingPower(mW)
0	1.3	27	35.1
1	1.3	18.4	23.9
2	1.3	10.7	13.9
3	1.3	4	5.2
4	1.3	0	0

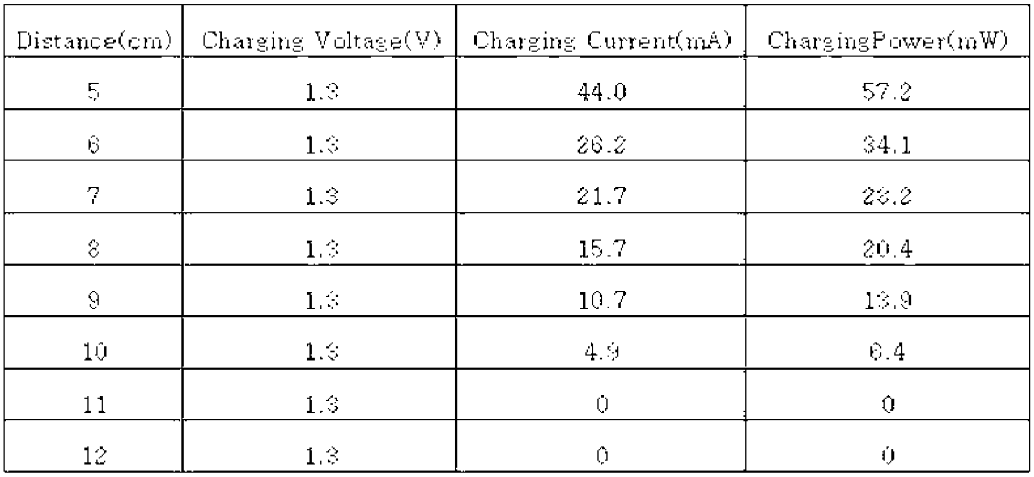
[46]

[47] FIG. 4 illustrates a construction in which a single electromagnetic field amplifying repeater 25 designed and manufactured according to the present invention is located in proximity to the electromagnetic wave generating source 21 and a charging voltage, a charging current and a charging power are measured using a receiver wireless power converter according to the present invention while varying the distance between the electromagnetic field amplifying repeater and the wireless power converter. The measurement result is represented in Table 2. Referring to Table 2, the charging current and charging power can be obtained even at a point at which the distance of the ruler is approximately 10cm.

[48]

[49] Table 2 : A charging voltage, a charging current and a charging power Using the wireless power converter in Fig4.

[50]



Distance(cm)	Charging Voltage(V)	Charging Current(mA)	ChargingPower(mW)
5	1.3	44.0	57.2
6	1.3	26.2	34.1
7	1.3	21.7	28.2
8	1.3	15.7	20.4
9	1.3	10.7	13.9
10	1.3	4.9	6.4
11	1.3	0	0
12	1.3	0	0

[51] FIG. 5 illustrates a construction using two electromagnetic field amplifying repeaters 25 and 26 according to the present invention. One of the amplifying repeaters is located having a predetermined distance from the electromagnetic wave generating source 21 and the other one is disposed in proximity of the receiver 22 and the wireless power converter. Here, the amplifying repeater 26 and the receiver 22 are combined with each other. Table 3 represents a charging voltage, a charging current and a charging power measured using this construction while varying the distance between the electromagnetic wave generating source and the amplifying repeater 26 and the receiver 22 attached to each other. Referring to Table 3, the charging current and charging power can be obtained even at a point distant from the electromagnetic wave generating source 21 by 12cm.

[52] Table 3 : A charging voltage, a charging current and a charging power Using the wireless power converter in Fig5.

[53]

Distance(cm)	Charging Voltage(V)	Charging Current(mA)	ChargingPower(mW)
5	1.3	51.2	66.5
6	1.3	36.8	47.8
7	1,3	29.2	37.9
8	1.3	21.4	27.8
9	1.3	16.6	21.5
10	1.3	12.7	16.5
11	1.3	4.7	6.1
12	1.3	1.2	1.6

[54] FIG. 6 illustrates a construction using two electromagnetic field amplifying repeaters 25 and 27 designed and manufactured according to the present invention. In this construction, one of the amplifying repeaters is located having a predetermined distance from the electromagnetic wave generating source 21, the other one is disposed having a distance of 5cm from the electromagnetic wave generating source 21, and a charging voltage, a charging current and a charging power are measured using the wireless power converter while varying the distance between the wireless power converter and the amplifying repeaters. Table 4 represents the measurement result. Referring to Table 4, a slightly increased charging power can be obtained and a specific charging current and charging power can be obtained even at a point distant from the electromagnetic wave generating source 21 by 13cm.

[55]

[56] Table 4 : A charging voltage, a charging current and a charging power Using the wireless power converter in Fig6.

[57]

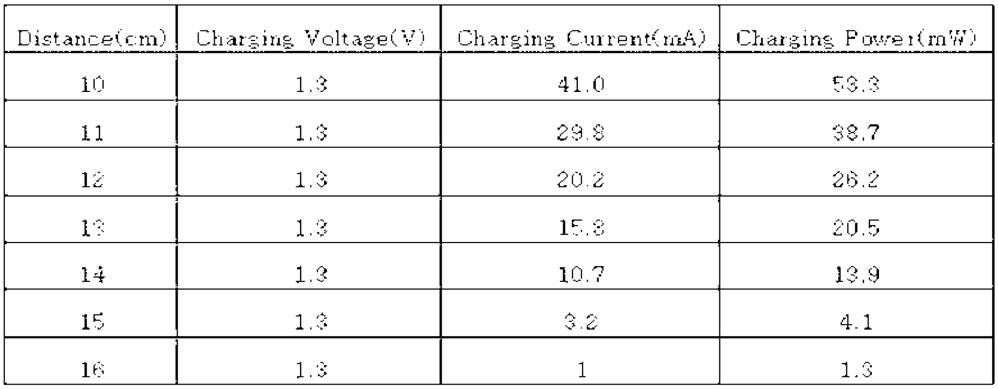
Distance(cm)	Charging Voltage(V)	Charging Current(mA)	Charging Power(mW)
10	1.3	34	44.2
11	1.3	22.3	29.0
12	1.3	6.3	8.2
13	1.3	1.7	2.2

[58] FIG. 7 illustrates a construction in which an electromagnetic field amplifying repeater 25 is manufactured in such a manner that a coil having the same diameter as the aforementioned coil is wound round a bobbin having the same size as the aforementioned bobbin by a number of winds of 200 to connect two induction coils in

parallel, a ferrite core is inserted into the induction coils and a variable condenser is connected in parallel with the induction coils to construct a resonance circuit, and the amplifying repeater 25 is located having a predetermined distance from the electromagnetic wave generating source 21. In addition, another amplifying repeater 27 identical to those used in FIGS. 3, 4, 5 and 6 is located at a point corresponding to 5cm of the ruler, and an amplifying repeater 28 and the wireless power converter are attached to each other to measure a charging voltage, a charging current and a charging power while varying the distance between the electromagnetic wave generating source and the wireless power converter. Table 5 represents the measured charging voltage, charging current and charging power. It can be known from Table 5 that a specific charging current and charging power can be obtained even at a point distant from the electromagnetic wave generating source 21 by 16cm.

[59] Table 5 : A charging voltage, a charging current and a charging power Using the wireless power converter in Fig7.

[60]



Distance(cm)	Charging Voltage(V)	Charging Current(mA)	Charging Power(mW)
10	1.3	41.0	53.3
11	1.3	29.8	38.7
12	1.3	20.2	26.2
13	1.3	15.8	20.5
14	1.3	10.7	13.9
15	1.3	3.2	4.1
16	1.3	1	1.3

[61] Various experiments were made using the electromagnetic field amplifying repeater designed and manufactured as above and the wireless power converter according to the present invention, as shown in FIGS. 3 through 7. In the case where only the wireless power converter is installed without having the amplifying repeater, as shown in FIG. 3, the induced electromotive force is hardly generated from the induction coil when the wireless power converter is located distant from the electromagnetic wave generating source by 4cm, as represented in Table 1. Thus, a charging current does not flow in a charging battery that is a load and charging battery power indicates zero. In the case where the amplifying repeater is added, as shown in FIG. 4, the maximum charging current of 44mA and charging power of 57.2mW are obtained when the wireless power converter is located distant from the electromagnetic wave generating source by 5cm and charging power of 6.4mW is obtained when the wireless power converter is

located distant from the electromagnetic wave generating source by 10cm, as represented in Table 2.

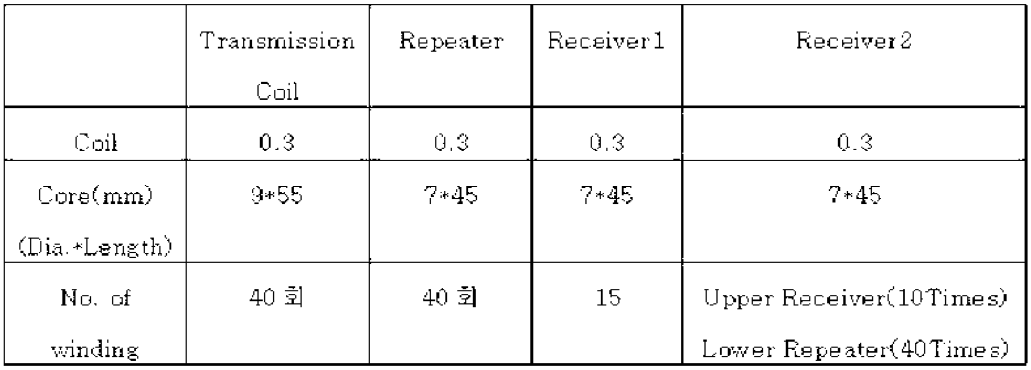
[62] When the wireless power converter is combined with the amplifying repeater, as shown in FIG. 5, the charging current and charging power are higher than those obtained from the construction of FIG. 4 at the same distance. When the two amplifying repeaters are used as shown in FIG. 6, the charging power at the point distant from the electromagnetic wave generating source by 10cm is 44.2mW as represented in Table 4, which is approximately seven times the charging power of 6.4mW obtained using only one amplifying repeater in FIG. 4. Furthermore, the charging current and charging power can be obtained even at a point distant from the electromagnetic wave generating source by a distance corresponding to 12cm of the ruler. Thus, it can be known that electromagnetic power is transmitted and induced-converted into an electrical energy to be transmitted to a load even at a distance four times the distance when the wireless power converter is used without using any amplifying repeater.

[63] In the construction in which two different amplifying repeaters 25 and 27 are in stalled and the amplifying repeater 28 is combined with a receiving coil and the wireless power converter, as shown in FIG. 7, increased charging current and charging power are measured at the same distance in the construction having no amplifying repeater of FIG. 6 and a distance capable of obtaining the charging current and charging power is increased to 16cm, as represented in Table 5.

[64] In another embodiment of the present invention, a transmission coil is connected to a load of an AC power generating circuit of a TV receiver, which is an artificial electromagnetic generating source, to construct a source of generating AC power waveform having a frequency of 130kHz, and the transmission coil, a repeater and coils used in first and second receivers are constructed, as shown in Table 6, to measure a receiving voltage, a receiving current and a receiving power in response to a ruler distance using the wireless power converter of FIG. 2.

[65] Table 6 : Coil Construction of Transmission coil, Repeater, Receiver1, Receiver2

[66]



	Transmission Coil	Repeater	Receiver1	Receiver2
Coil	0.3	0.3	0.3	0.3
Core(mm) (Dia.*Length)	9*55	7*45	7*45	7*45
No. of winding	40 회	40 회	15	Upper Receiver(10Times) Lower Repeater(40Times)

[67] In Table 6, the first receiver is constructed of a general solenoid coil constructed such that a coil is wound round a core and the second receiver includes a receiving coil wound round the upper part of a common core ten times and a repeater constructing a resonance circuit of a coil wound round the lower part of the common core forty times and a capacitor.

[68] FIG. 10 illustrates a transmitter and a receiver constructed by winding a transmission coil outputting power generated from the electromagnetic wave generating source or a receiving coil receiving electromagnetic waves round a common core provided with an electromagnetic wave amplifying repeater. This construction can obtain high wireless power conversion efficiency because it can maximize generation and reception of electromagnetic waves in the resonance circuit of the amplifying repeater.

[69] Table 7 represents the voltage, current and power measured at an output load terminal (tens of parallel LEDs) of a receiver 31 when a transmission coil 29, an amplifying repeater 30 and the receiver 31 manufactured as shown in Table 6 are installed as shown in FIG. 8. The amplifying repeater is located in proximity to an electromagnetic wave generating source. The voltage, current and power are measured while moving the receiver from the electromagnetic wave generating source to distances 5cm, 10cm and 15cm.

[70] Table 7 : A receiving voltage, current and power measured at an output load terminal of a receiver1.

[71]

Distance(cm)	Receiving voltage (V)	Receiving current (A)	Receiving power(W)
5	3.9	1.900	7.410
10	2.6	1.000	2.600
15	1.4	0.200	0.280

[72] Table 8 represents the voltage, current and power measured at an output load terminal of receivers 33 and 34 when the transmission coil 29, amplifying repeater 32 and receivers 33 and 34 manufactured as shown in Table 6 are installed as shown in FIG. 9. The amplifying repeater is located in proximity to an electromagnetic wave generating source. The voltage, current and power are measured while moving the receivers from the electromagnetic wave generating source to distances 5cm, 10cm, 15cm and 20cm.

[73] Table 8 : A receiving voltage, current and power measured at an output load terminal of a receiver2.

[74]

Distance(cm)	Receiving voltage(V)	Receiving current(A)	Receiving power (W)
5	4.6	3.500	16.100
10	4.4	3.500	15.400
15	2.7	1.700	4.590
20	2.0	0.700	1.400

[75] It can be known from Tables 7 and 8 that the receiving voltage, receiving current and receiving power in response to a distance are much larger when they are obtained using the receiver 31 manufactured by winding only an induction coil round a core than when they are obtained using the receivers 33 and 34 including an induction coil and a repeater constructed of a resonance circuit, which are attached to a single common core.

[76] Another embodiment of the present invention constructs induction coils by winding coils having various diameters round bobbins having various sizes by different numbers of winds in consideration of the size and scale of an electromagnetic wave generating source, connects the induction coils in series or in parallel, inserts ferrite cores having diameters and lengths fitted into the internal diameters of the bobbins, and connects the induction coils to a variable condenser to construct a resonance circuit. In this manner, an electromagnetic field amplifying repeater can be constructed

in various sizes and forms and an apparatus capable of obtaining charging voltage, charging current and charging power with various levels can be realized using the amplifying repeater and the wireless power converter.

[77] Another embodiment of the present invention constructs a transmission coil, a repeater and a receiver using the spiral structure disclosed in Korean Patent Application No. 10-2004-0000528 applied by the Applicant. In this case, an electromagnetic wave generating source that generates a voltage of AC 220V and 60Hz converted into an AC voltage waveform having a frequency of 120kHz through an AC-AC adapter is connected to the transmission coil in a spiral form, a receiving coil is connected to a charging circuit, and a received charging current and voltage are measured. The distance between the transmission coil and the receiving coil is 5cm. FIG. 11 shows a case where the amplifying repeater is located on the transmission coil in proximity to the transmission coil. Table 9 represents the internal diameters, external diameters, types and numbers of winds of the spiral transmission coil, repeater coil and receiving coil.

[78] Table 9 : Internal diameters, external diameters, types and numbers of winds of the spiral transmission coil, repeater coil and receiving coil.

[79]

	Internal diameters (mm)	External diameters (mm)	Coil spec.	Numbers of winds
Receiving coil	30	80	0.2*9	24
Repeater coil	30	80	0.2*9	24
Transmission coil	30	40	0.2*9	4

[80] In FIG. 11, transmission power output through the transmission coil of the electromagnetic wave generating source is 16W, charging voltage measured by the wireless power converter of FIG. 2 is 1.4V, charging current is 0.36A, and charging power is 0.50W. When the amplifying repeater is located between the transmission coil and the receiver, which are spiral coils having the dimension represented in Table 6, as shown in FIG. 12, charging voltage is 1.4V, charging current is 0.4A and charging power is 0.56W. In this case, current and power slightly higher than those obtained in the case of FIG. 11 can be obtained. For reference, when only the transmission coil 53

and receiving coil 51 are used without using the repeater and the distance between the transmission coil and the receiving coil is 5cm, charging voltage is 1.4V, charging current is 0.01A and charging power is 0.014W, which are very small.

[81] FIG. 13 shows a case where the amplifying repeater surrounds the transmission coil. Here, the repeater is not connected to the transmission coil through wire. Table 10 represents the internal diameters, external diameters, types and numbers of winds of the spiral transmission coil, repeater and receiver used in the construction shown in FIG. 13.

[82] In FIG. 13, transmission power output through the transmission coil of the electromagnetic wave generating source is 16W, charging voltage measured by the wireless power converter of FIG. 2 is 1.4V, charging current is 0.9A, and charging power is 1.26W. When the amplifying repeaters respectively surround the transmission and receiving coils, which are spiral coils having the dimension of Table 10, as shown in FIG. 14, charging voltage is 1.4V, charging current is 1.0A and charging power is 1.4W. That is, the highest current and power can be obtained in the experiments using the spiral coils. Here, the distance between the transmission coil and the receiving coil is 5cm.

[83] Table 10 : Internal diameters, external diameters, types and numbers of winds of the spiral transmission coil, repeater coil and receiving coil.

[84]

	Internal diameters (mm)	External diameters (mm)	Coil spec.	Numbers of winds
Receiving coil	30	80	0.2*9	24
Repeater coil	40	80	0.2*9	20
Transmission coil	30	40	0.2*9	4

[85] Furthermore, the present invention can construct a wireless charging device that generates an induced voltage and current with high efficiency and charges the induced voltage and current in a charger using a rectifying diode and a smoothing condenser by simultaneously winding two wires of the spiral coil disclosed in Korea Patent Application No. 10-2004-0000528 in the form of plate such that they are located in parallel vertically, placing a ferromagnetic substance in a doughnut shape on the coil in order to increase flux caused by flux linkage per hour and connecting a variable condenser to the coil in series or in parallel to construct a resonance circuit. Here, an

electromagnetic field amplifying repeater can be manufactured by constructing the resonance circuit using the spiral plate type coil, ferromagnetic substance in a doughnut shape and variable condenser. A method of manufacturing the electromagnetic field amplifying repeater is described in detail in Korea Patent Application No. 10-2004-0000528.

[86] The present invention constructs a magnetic field amplifying repeater for amplifying a magnetic field at a position having a predetermined distance from an electromagnetic wave generating source and locates an electromagnetic wave amplifying repeater and a wireless power conversion charging device converter at a position distant from the amplifying repeater by a predetermined distance. The wireless power conversion charging device include a rectifying diode that rectifies an electromotive force induced in a structure in which a resonance and impedance matching variable condenser and a coil are connected in parallel with each other to induce maximum power using electromagnetic waves amplified by the amplifying repeater to transmit the induced power to a load and a smoothing condenser smoothing the rectified voltage and a wireless power. Accordingly, the present invention can repeat power to a predetermined distance from the electromagnetic wave generating source and convert electromagnetic power to improve industrial applicability. For example, the present invention can be used to charge contactless wireless battery or transmit power in real time at a short distance in the air or an insulator of a small power electronic device.

[87] The present invention can locate the magnetic field amplifying repeater at a position having a predetermined distance from the electromagnetic wave generating source to install the wireless power converter using electromagnetic waves, and thus the wireless power converter can be freely located and applied in various ways.

[88] While the present invention has been described with reference to the particular illustrative embodiments, it is not to be restricted by the embodiments but only by the appended claims. It is to be appreciated that those skilled in the art can change or modify the embodiments without departing from the scope and spirit of the present invention.

Claims

[1] An electromagnetic wave amplifying repeater capable of amplifying and repeating the magnetic field of electromagnetic waves generated artificially or generated from various electromagnetic wave generating sources, comprising:
an induction coil formed by winding a coil with a predetermined thickness in a desired size and form by a predetermined number of winds;
a magnetic substance having a predetermined size and form, the magnetic substance being combined with the induction coil to increase flux; and
a variable condenser connected to the induction coil to construct a resonance circuit.

[2] The electromagnetic wave amplifying repeater as claimed in claim 1, wherein the induction coil wound by the predetermined number of winds is designed and manufactured in a solenoid or spiral form.

[3] The electromagnetic wave amplifying repeater as claimed in claim 1 or 2, wherein the magnetic substance combined with the induction coil to increase flux is a ferrite core or a substance having magnetism.

[4] The electromagnetic wave amplifying repeater as claimed in claim 3, wherein induction coils wound by a predetermined number of winds are connected in series or in parallel to control the resistance and inductance of the induction coils, to thereby effectively generate the magnetic field of electromagnetic waves.

[5] The electromagnetic wave amplifying repeater as claimed in claim 4, wherein the variable condenser constructing the resonance circuit is connected to the induction coil in series or in parallel to amplify the magnetic field of electromagnetic waves.

[6] A wireless power converter comprising:
an electromagnetic wave amplifying repeater including an induction coil formed by winding a coil with a predetermined diameter in a desired size and form by a predetermined number of winds, a magnetic substance, and a variable condenser, the electromagnetic wave amplifying repeater serving to amplify and repeat the magnetic field of electromagnetic waves generated artificially or generated from various electromagnetic wave generating sources;
an induction coil and a magnetic substance for generating an induced electromotive force using the magnetic field amplified by the amplifying repeater;
a variable condenser for performing resonance and impedance matching, the variable condenser being connected to the induction coil to improve power conversion efficiency;

a rectifying diode for rectifying a voltage induced by the induction coil and the variable condenser; and

a condenser for smoothing the voltage to form a voltage having a desired DC component.

[7] The wireless power converter as claimed in claim 6, wherein induction coils wound by a predetermined number of winds are connected in series or in parallel to control the resistance and inductance of the induction coils, to thereby improve power conversion efficiency.

[8] The wireless power converter as claimed in claim 6 or 7, wherein the amplifying repeater is attached to an electromagnetic wave generating source transmission coil and a receiving coil or to one of the electromagnetic wave generating source transmission coil and the receiving coil, and at least one amplifying repeater is installed between the electromagnetic wave generating source transmission coil and the receiving coil in consideration of the distance between the electromagnetic wave generating source and the receiving coil.

[9] The wireless power converter as claimed in claim 8, wherein the amplifying repeater and the receiving coil are designed and manufactured in a solenoid or spiral form.

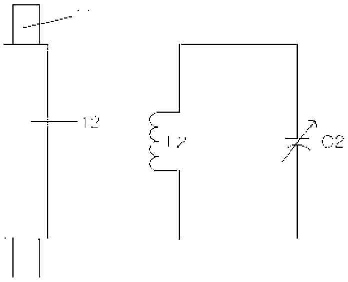
[10] The wireless power converter as claimed in claim 6, wherein the amplifying repeater and the wireless power converter including the amplifying repeater further comprise an electromagnetic wave generating source to which a spiral or solenoid transmission coil artificially generating electromagnetic waves is attached.

[11] The wireless power converter as claimed in claim 6, wherein the wireless power converter is constructed in such a manner that an induction coil is wound round one side of a core wound by a transmission coil of an artificial electromagnetic wave generating source and the induction coil is connected to a capacitor to construct an amplifying repeater, that an induction coil is wound round one side of a core wound by a receiving coil and the induction coil is connected to a capacitor to construct an amplifying repeater, or that amplifying repeaters are respectively set at both sides of the core of the transmission coil and receiving coil.

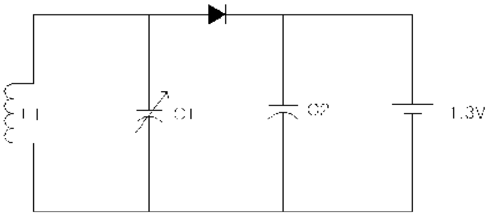
[12] The wireless power converter using an electromagnetic wave amplifying repeater as claimed in claim 6, wherein the wireless power converter is constructed in such a manner that a spiral coil is wound round the outside of a transmission spiral coil of an artificial electromagnetic wave generating source and connected to a capacitor to construct an amplifying repeater, that a spiral coil is wound round the outside a receiving spiral coil and connected to a capacitor to construct an amplifying repeater, and that spiral coils are respectively wound around the

outsides of transmission and receiving spiral coils and connected to a capacitor to construct an amplifying repeater.

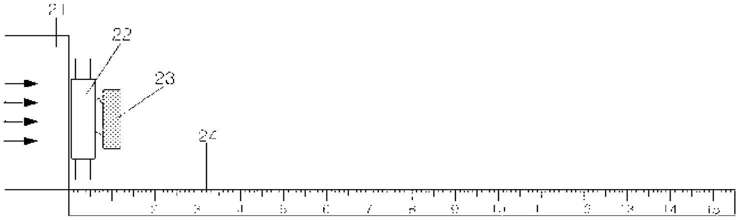
[Fig. 1]



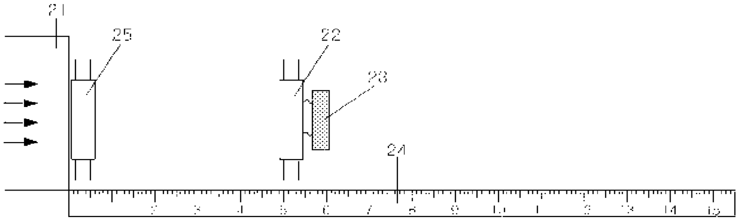
[Fig. 2]



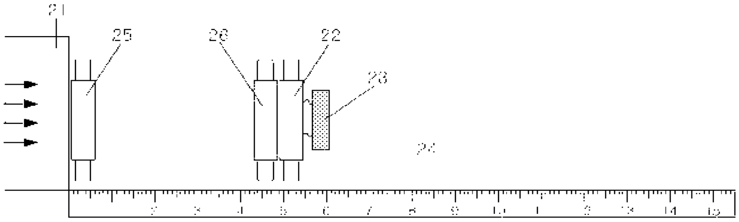
[Fig. 3]



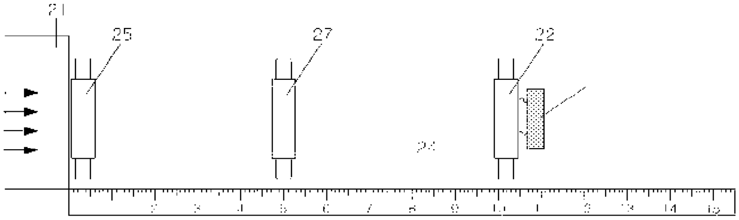
[Fig. 4]



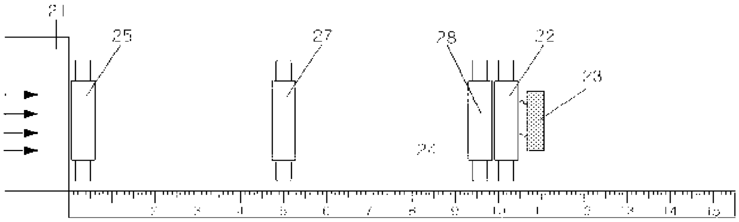
[Fig. 5]



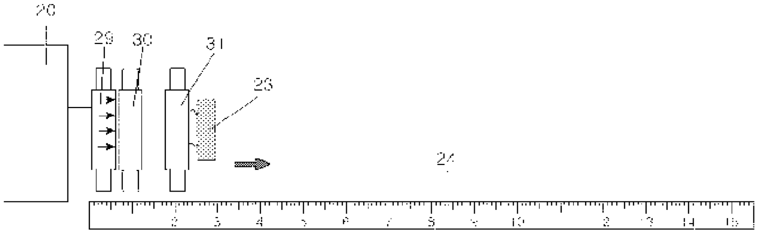
[Fig. 6]



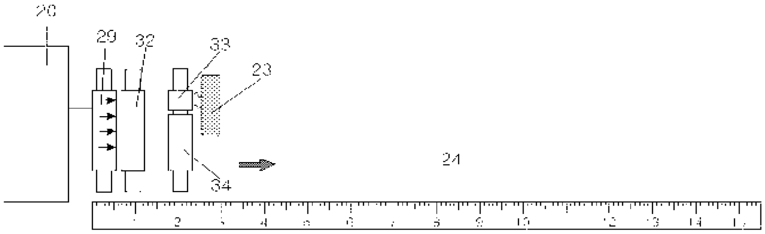
[Fig. 7]



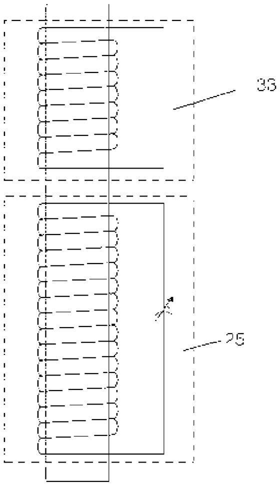
[Fig. 8]



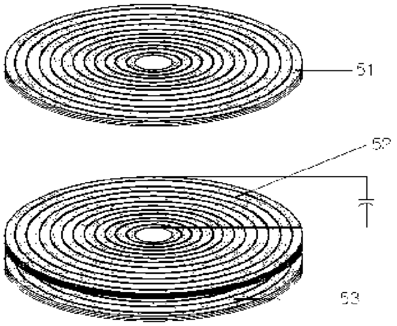
[Fig. 9]



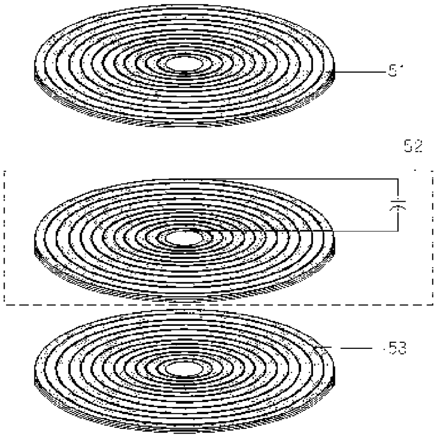
[Fig. 10]



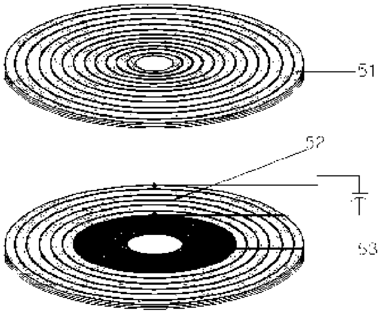
[Fig. 11]



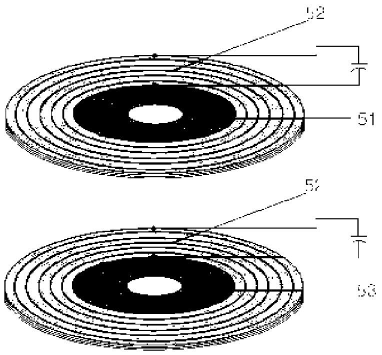
[Fig. 12]



[Fig. 13]



[Fig. 14]



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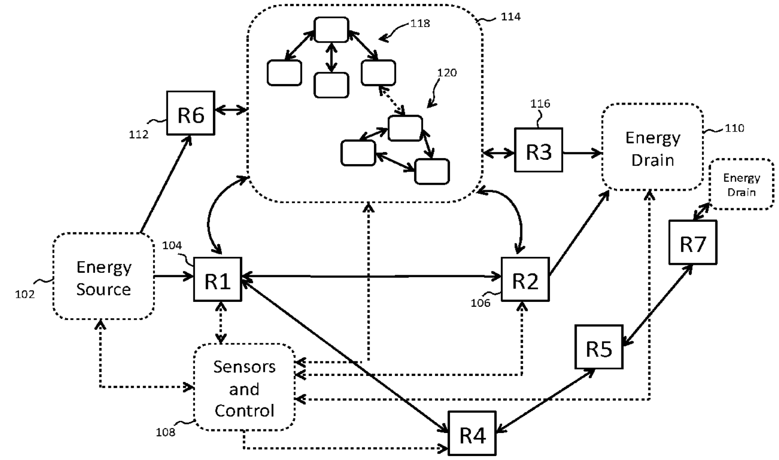
(54) Title: WIRELESS ENERGY TRANSFER CONVERTERS

Fig. 1



(57) Abstract: Described herein are improved configurations for a wireless power converter that includes at least one receiving magnetic resonator configured to capture electrical energy received wirelessly through a first oscillating magnetic field characterized by a first plurality of parameters, and at least one transferring magnetic resonator configured to generate a second oscillating magnetic field characterized by a second plurality of parameters different from the first plurality of parameters, wherein the electrical energy from the at least one receiving magnetic resonator is used to energize the at least one transferring magnetic resonator to generate the second oscillating magnetic field.

SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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WIRELESS ENERGY TRANSFER CONVERTERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to the following applications, each of which is incorporated herein by reference in its entirety: U.S. Patent Appl. No. 13/021,965 filed February, 7 2011; U.S. Patent Appl. No. 12/986,018 filed January 6, 2011; U.S. Patent Appl. No. 12/789,611 filed May 28, 2010; U.S. Patent Appl. No. 12/770,137 filed April 29, 2010; U.S. Appl. No. 12/767,633 filed April 26, 2010; U.S. Appl. No. 12/759,047 filed April 13, 2010; U.S. Appl. No. 12/757,716 filed April 9, 2010; U.S. Appl. No. 12/749,571 filed March 30, 2010; U.S. Appl. No.12/721,118 filed March 10, 2010; U.S. Patent Appl. No. 12/720,866 filed March 10, 2010, and U.S. Patent Appl. No. 61/326,051 filed April 20, 2010.

BACKGROUND

[0002] Field:

[0003] This disclosure relates to wireless energy transfer, methods, systems and apparati to accomplish such transfer, and applications.

[0004] Description of the Related Art:

[0005] Energy or power may be transferred wirelessly using a variety of techniques as detailed, for example, in commonly owned U.S. Patent Application No. 12/789,611 published on September 23, 2010 as U.S. Pat. Pub. No. 2010/0237709 and entitled "RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER," and U.S. Patent Application No. 12/722,050 published on July 22, 2010 as U.S. Pat. Pub. No. 2010/0181843 and entitled "WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION" the contents of which are incorporated in their entirety as if fully set forth herein. Prior art wireless energy transfer systems have been limited by a variety of factors including concerns over user safety, low energy transfer efficiencies and restrictive physical proximity/alignment tolerances for the energy supply and sink components.

SUMMARY

[0006] Unless otherwise indicated, this disclosure uses the terms wireless energy transfer, wireless power transfer, wireless power transmission, and the like, interchangeably. Those skilled in the art will understand that a variety of system architectures may be supported by the wide range of wireless system designs and functionalities described in this application.

[0007] In the wireless energy transfer systems described herein, power may be exchanged wirelessly between at least two resonators. Resonators may supply, receive, hold, transfer, and distribute energy. Sources of wireless power may be referred to as sources or supplies and receivers of wireless power may be referred to as devices, receivers and power loads. A resonator may be a source, a device, or both, simultaneously or may vary from one function to another in a controlled manner. Resonators configured to hold or distribute energy that do not have wired connections to a power supply or power drain may be called repeaters.

[0008] The resonators of the wireless energy transfer systems of this invention are able to transfer power over distances that are large compared to the size of the resonators themselves. That is, if the resonator size is characterized by the radius of the smallest sphere that could enclose the resonator structure, the wireless energy transfer system of this invention can transfer power over distances greater than the characteristic size of a resonator. The system is able to exchange energy between resonators where the resonators have different characteristic sizes and where the inductive elements of the resonators have different sizes, different shapes, are comprised of different materials, and the like.

[0009] The wireless energy transfer systems of this invention may be described as having a coupling region, an energized area or volume, all by way of describing that energy may be transferred between resonant objects that are separated from each other, they may have variable distance from each other, and that may be moving relative to each other. In some embodiments, the area or volume over which energy can be transferred is referred to as the active field area or volume. In addition, the wireless energy transfer system may comprise more than two resonators that may each be coupled to a power source, a power load, both, or neither.

[0010] Wirelessly supplied energy may be used to power electric or electronic equipment, recharge batteries or charge energy storage units. Multiple devices may be charged or powered simultaneously or power delivery to multiple devices may be serialized such that one or more devices receive power for a period of time after which power delivery may be switched to other devices. In various embodiments, multiple devices may share power from one or more sources with one or more other devices either simultaneously, or in a time multiplexed manner, or in a frequency multiplexed manner, or in a spatially multiplexed manner, or in an orientation multiplexed manner, or in any combination of time and frequency and spatial and orientation multiplexing. Multiple devices may share power with each other, with at least one device being reconfigured continuously, intermittently, periodically, occasionally, or temporarily, to operate as a wireless power source. Those of ordinary skill in the art will understand that there are a variety of ways to power and/or charge devices applicable to the technologies and applications described herein.

[0011] In embodiments a wireless power transfer system may have a wireless power converter that includes at least one receiving magnetic resonator configured to capture electrical energy received wirelessly through a first oscillating magnetic field characterized by a first plurality of parameters. The converter may also have at least one transferring magnetic resonator configured to generate a second oscillating magnetic field characterized by a second plurality of parameters different from the first plurality of parameters, wherein the electrical energy from the at least one receiving magnetic resonator is used to energize the at least one transferring magnetic resonator to generate the second oscillating magnetic field. In embodiments the first plurality of parameters may include a first frequency different from a second frequency of the second plurality of parameters and first frequency may be approximately an integer multiple of the second frequency. In other embodiments the first plurality of parameters may include a first magnitude different from a second magnitude of the second plurality of parameters. The first plurality of parameters may also include a first frequency hopping sequence different from a second frequency hopping sequence of the second plurality of parameters, likewise the first plurality of parameters may include a first on/off sequence different from a second on/off sequence of the second plurality of parameters.

[0012] In other embodiments a wireless power transfer system may include a source resonator configured to generate a first oscillating magnetic field characterized by a first plurality of parameters and a device resonator configured to capture electrical energy received wirelessly through a second oscillating magnetic field characterized by a second plurality of parameters different from the first plurality of parameters. In the system a wireless power converter that includes conversion circuitry may be configured and used to capture energy from the second oscillating magnetic field and to energize the source resonator to generate the first oscillating magnetic field. In embodiments the first plurality of parameters may include a first frequency different from a second frequency of the second plurality of parameters and first frequency may be approximately an integer multiple of the second frequency. In other embodiments the first plurality of parameters may include a first magnitude different from a second magnitude of the second plurality of parameters. The first plurality of parameters may also include a first frequency hopping sequence different from a second frequency hopping sequence of the second plurality of parameters, likewise the first plurality of parameters may include a first on/off sequence different from a second on/off sequence of the second plurality of parameters.

[0013] In other embodiments a wireless power coverter may be used for conversion by providing a configurable magnetic resonator, tuning the configurable magnetic resonator to capture a first oscillating magnetic field characterized by a first plurality of parameters, converting the oscillating magnetic field into electrical energy, storing the electrical energy as stored energy in an energy storage element, tuning the configurable magnetic resonator to generate a second oscillating magnetic field characterized by a second plurality of parameters, and energizing the configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field.

[0014] In other embodiments a resonator for wireless power transfer may include a conductor forming one or more loops and having an inductance L, a network of capacitors, having a capacitance, C, and a desired electrical parameter, coupled to the conductor, the network having at least one capacitor of a first type with a first temperature profile of the electrical parameter, and the network having at least one capacitor of a second type with a second temperature profile of the electrical parameter. The first temperature profile of the first type of capacitor may be complementary to the second temperature profile of the second type of capacitor such that there is less change in the electrical parameter of the network due to a temperature change than when only a one type of capacitor is used. In embodiments these parameters may be chosen such that there is substantially zero change in the electrical parameter due to a temperature change. In embodiments the electrical parameter may be capacitance, resistance, inductance, and the like.

[0015] In embodiments a resonator for wireless power transfer may include a conductor forming one or more loops, two or more types of electrical components having different temperature profiles for an electrical parameter, the electrical components forming a network connected to said conductor, wherein the electrical components are arranged such that the temperature profiles of the components are complementary and there is less change in the electrical parameter of the circuit due to a temperature change than when onlyone type of component is used. In embodiments there parameters may be chosen such that there is substantially zero change in the electrical parameter due to a temperature change. In embodiments the electrical parameter may be capacitance, resistance, inductance, and the like.

[0016] In embodiments wireless power transfer may include a source high-Q magnetic resonator coupled to a power source and generating an oscillating magnetic field, at least one device high-Q magnetic resonator configured to convert the oscillating magnetic field to electrical energy used to power a light coupled to the at least one device resonator, and at least one repeater resonator, larger than the device resonator. The repeater resonator may be positioned further from the source resonator than the device resonator to improve the power transfer efficiency between the source resonator and the device resonator. The system may be used to wirelessly power lights substantially below a cabinet from a source mounted on a wall with a repeater resonator positioned inside a cabinet above the device resonators. In embodiments the source resonator and the device resonators may be separated by 10 cm or more, or 20 cm or more, and the like. The source and device resonators may be tuned to substantially same resonant frequency.

[0017] In embodiments a device for wireless power transfer may include a conductor forming at least one loop of a high-Q resonator, a capacitive part electrically coupled to the conductor, and a power and control circuit electrically coupled to the conductor. The power and control circuit may provide two or more modes of operation and the power and control circuit selecting how the high-Q resonator receives and generates an oscillating magnetic field. The two or more modes of operation may include a repeater mode of operation wherein the high-Q resonator is used to wirelessly receive power from a source and wirelessly transmit power to a receiver. The two or more modes of operation may include a source mode of operation wherein the high-Q resonator is used to generate a magnetic field. The two or more modes of operation may include a device mode of operation wherein the high-Q resonator is used to convert an oscillating magnetic field into electrical energy.

[0018] In embodiments a resonator may be operated by providing a conductor forming at least one loop of a high-Q resonator, providing a capacitive part electrically coupled to the conductor, providing a power and control circuit electrically coupled to the conductor, measuring one or more operational parameters of one or more components of the high-Q resonator, and selecting one of a plurality of modes of operation of the power and control circuit based on the one or more operational parameters. The plurality of modes of operation may include a repeater mode of operation wherein the high-Q resonator is used to wirelessly receive power from a source and wirelessly transmit power to a receiver. The plurality of modes of operation may include a source mode of operation wherein the high-Q resonator is used to generate a magnetic field. The plurality of modes of operation may include a device mode of operation wherein the high-Q resonator is used to convert an oscillating magnetic field into electrical energy. The resonator may further include a battery that may be charged during the repeater or device modes of operation.

[0019] In another embodiment some resonators may have an enclosure that includes a support plate, a sheet of good conductor larger than the size of the resonator and positioned on one side of the support plate, a separator piece for maintaining a separation distance between the resonator and the sheet of good conductor, and a cover of a non-lossy material covering the resonator, the separator, the sheet of good conductor and attached to the support plate. The sheet of conductor may be copper, aluminum, and the like. The sheet of the good conductor may exceed the size of the resonator by at least 1cm, or at least 2 cm or more on all sides.

[0020] In yet another embodiment a resonator for wireless power transfer may include a magnetic material having a length along an axis, and a first conductor wrapped around the magnetic material to form a plurality of loops around the axis, the plurality of loops having a span over the magnetic material, wherein the length is a largest dimension of the magnetic material that is parallel to a dipole moment created by the plurality of loops, and the span of the plurality of loops is about one half of the length. The resonator may include one or more capacitors or inductors couple to the conductor. In some embodiments the the resonant frequency of the resonator may be tuned by these capacitors.

[0021] An embodiment of a system disclosed herein includes a source resonator including at least one high-Q magnetic resonator configured to generate an oscillating magnetic field, the source resonator located at a distance from a vehicle having a device resonator, and a positioning system that provides information on a relative alignment of the source resonator and the device resonator.

[0022] The positioning system may include a display adapted to display the information on the relative alignment to an operator of the vehicle. The positioning system may include a camera. The positioning system may employ machine vision.

[0023] The positioning system may measure a current in the source resonator. The positioning system may measure a phase of the current in the source resonator. The positioning system may measure a voltage in the source resonator. The positioning system may measure a phase of the voltage in the source resonator. The positioning system may include one or more sensors to detect a foreign object in a vicinity of the source resonator or the device resonator. The source resonator may reduce an output power when the foreign object is detected.

[0024] The positioning system may include one or more mechanical actuators configured to move the source resonator into a desired alignment with the device resonator. The positioning system may include one or more mechanical actuators configured to move the device resonator into a desired alignment with the source resonator.

[0025] The positioning system may be coupled to a control system of the vehicle and may be configured to provide a control signal to the control system for an automated positioning of the vehicle.

[0026] The source resonator and the device resonator each have a quality factor $Q>100$.

[0027] A system disclosed herein includes a source resonator including at least one source high-Q magnetic resonator configured to generate an oscillating magnetic field, the source resonator located at a distance from a vehicle, a device resonator attached to the vehicle, the device resonator including at least one device high-Q magnetic resonator configured to receive power through the oscillating magnetic field when the source resonator and the device resonator are in a desired alignment, wherein the source resonator and device resonator are sized and oriented to substantially maintain wireless power transfer efficiency within a range of misalignment from the desired alignment.

[0028] The source resonator may be larger than the device resonator. The source resonator may be 35% larger than the device resonator. The source resonator and the device resonator may each include a conductor wrapped around at least one axis of a magnetic material and wherein a dipole moment of each of the source resonator and the device resonator may be aligned with a longest dimension of the vehicle when the source resonator and the device resonator are in the desired alignment. The device resonator may be integrated into a recessed portion of the vehicle. The device resonator may include an active temperature control.

[0029] The active temperature control may be coupled to a cooling system of the vehicle to provide controllable cooling of the device resonator. The active temperature control may be coupled to a heating system of the vehicle to provide controllable heating of the device resonator.

[0030] The device resonator and the source resonator may each have a quality factor $Q>100$.

[0031] In another aspect, an embodiment of a system may include an apparatus comprising a plurality of resonators electrically interconnected and arranged in an array to form a composite resonator for wireless power transfer, each one of the plurality of resonators including a block of a magnetic material having a conductor wire wrapped around a cross section thereof to form at least one loop enclosing an area substantially equal to the cross section, wherein the plurality of resonators are oriented so that a dipole moment of each one of the plurality of resonators is aligned with a dipole moment of each other one of the plurality of resonators. The apparatus may further include a second plurality of resonators arranged in the array, the second plurality of resonators may each have a second dipole moment aligned with a second dipole moment of each other one of the second plurality of resonators. In another aspect the apparatus of may further include a second plurality of resonators arranged in the array, the second plurality of resonators electrically connected to one another in an electrical circuit separate from the first plurality of resonators. The apparatus may include at least one block of magnetic material without a wrapped conductor within the composite resonator. The separation between adjacent ones of the plurality of resonators in the array may be less than ten percent of the largest of the width, the height, and the length of the array.

[0032] In yet another aspect, an embodiment of a system may include an apparatus for wireless power transfer comprising a plurality of blocks of a magnetic material arranged in an array, and a plurality of conductor wires, each one of the plurality of conductor wires wrapped around at least one of the plurality of blocks to form a loop thereabout, thereby forming a plurality of resonators, wherein the plurality of resonators are electrically connected to one another and oriented with parallel dipole moments. The plurality of loops formed by the plurality of conductor wires may be substantially coaxial. The plurality of resonators may be spatially separated from one another by a plurality of gaps. The apparatus may include a plurality of power and control circuits, each one of the plurality of power and control circuits electrically connected to a different one of the plurality of resonators. Each resonator may further include at least two capacitors electrically connected to the array for setting a resonant frequency and an impedance of the apparatus.

[0033] In one more aspect of the invention an integrated magnetic resonator and shield structure is contemplated that may include a sheet of electrical conductor having a first side and a second side, a block of magnetic material covering an area of the first side of the sheet of conductor; and a plurality of conductor wire segments, each having a first end and a second end, wherein the ends of wire segments are routed over the block of magnetic material between points on the first side of the sheet of conductor. In some embodiments of the structure each conductor wire segment may not completely wrap around all sides of the block of magnetic material and the largest dimension of the sheet of conductor may be larger than the largest dimension of the block of magnetic material. The sheet of conductor may include a plurality of individual isolated conductor segments and in some embodiments the isolated conductor segments may be shaped to electrically connect different said conductor wire segments. In other embodiments the isolated conductor segments may be shaped to connect at least two of the conductor wire segments in series and the conductor segments may be shaped to form paths that surround the block of magnetic material and are substantially confined to the area of the sheet of conductor not overlapped by the block of magnetic material. The conductor segments may be sized , shaped, and interconnected so as to substantially equalize electrical current distribution in all of the conductor segments during the operation of the resonator. In addition, the sheet of conductor of the structure may include a cutout of a substantial part of the area overlapped by the block of magnetic material. The block of magnetic material of the structure may be shaped to have a recessed cavity accessible through said cutout in the sheet of conductor allowing placement of power and control circuitry in some embodiments. Furthermore, the conductor wire segments may be arranged to be substantially parallel to each other. In some embodiments some conductor wire segments may be arranged to be substantially non-parallel to generate a structure with more than one magnetic dipole moment. The conductor segments may be fabricated on a printed circuit board, the conductor wire segments may include Litz wire. The conductor wire segments and the conductor shield of the structure may be formed on a flex circuit and shaped to receive a block of magnetic material.

[0034] In still another aspect of the invention an integrated magnetic resonator and shield structure is contemplated that may include a sheet of electrical conductor, a block of magnetic material positioned on the first of the sheet of the conductor overlapping and covering an area of the sheet of conductor; and a plurality of conductor wire segments, wherein the ends of said wire segments are coupled at distinct points of the sheet of conductor and the said conductor wire segments are routed over the block of magnetic material and wherein the conductor shield is used as a current path for the conductor wire segments during operation of said resonator.

[0035] In an embodiment, tiles of magnetic material of a resonator may be arranged to minimize the number of tile seams or joints that are substantially perpendicular to the dipole moment of the resonator. In another aspect thermal conductors may be positioned in contact with the tiles of the magnetic material and oriented to be substantially perpendicular to the dipole moment of the resonator. The thermal conductors may be connected to an additional heatsink that through convection, conduction, or radiation, dissipates the heat transferred by the thermal conductors. For resonators comprising a block of magnetic material that is composed of smaller tiles of magnetic material, the thermal conductors are preferably located such that they cover seams between the tiles, especially the seams that are perpendicular to the dipole moment of the resonator.

[0036] In embodiments, in a system adapted for wireless power transfer, a tunable resonant amplifier circuit may be provided for driving an inductive load having a varying impedance, the circuit comprising: a switching amplifier with a variable duty cycle; an inductive load; a connection between the inductive load and the switching amplifier, the connection including at least one tunable component; and a feedback loop for adjusting the at least one tunable component and the duty cycle of the amplifier, wherein the feedback loop adjusts the duty cycle of the amplifier and the at least one tunable component to maintain substantially zero voltage switching and zero current switching at the output of the amplifier under different load conditions of the inductive load. The at least one tunable component may include a tunable capacitor. The tunable capacitor may be in series with the inductive load. The tunable capacitor may be in parallel with the inductive load. The connection between the inductive load and the switching amplifier may include more than one tunable component. The switching amplifier may use a variable switching frequency. A bus voltage of the switching amplifier may be variable and used to control an amount of power delivered to the inductive load. The feedback loop may include an impedance measuring facility. The feedback loop may include a processor, the processor configured to monitor an impedance at an output of the switching amplifier and to compute an adjustment to the variable duty cycle of the switching amplifier such that zero voltage switching is substantially maintained. The processor may be configured to compute a second adjustment to at least one tunable component such that zero current switching is substantially maintained. The inductive load may include a high-Q magnetic resonator. The circuit may be used as a source in a wireless power transmission system.

[0037] In embodiments, a method of tuning a resonant amplifier circuit in a wireless power transfer facility may be provided that includes a connection between a switching amplifier and an inductive load having a varying impedance, the method comprising the steps of: measuring a number of parameters at an output of the switching amplifier; adjusting a duty cycle of the switching amplifier; and adjusting at least one tunable component in the connection between the switching amplifier and the inductive load, wherein adjusting the duty cycle of the switching amplifier and adjusting at least one tunable component are controlled to maintain a substantially zero voltage switching and a substantially zero current switching at the output of the switching amplifier under different load conditions of the inductive load. The at least one tunable component may include a tunable capacitor. Measuring a number of parameters may include measuring an impedance at the output of the switching amplifier. Further, computing necessary adjustments to the duty cycle of the switching amplifier and adjustments to the at least one tunable component may be based on the impedance, to maintain substantially zero voltage and substantially zero current switching at the output of the switching amplifier. The inductive load and at least a part of the connection between the switching amplifier and the inductive load may form a high-Q magnetic resonator. The circuit may be used as a source in a wireless power transmission system.

[0038] This disclosure references certain individual circuit components and elements such as capacitors, inductors, resistors, diodes, transformers, switches and the like; combinations of these elements as networks, topologies, circuits, and the like; and objects that have inherent characteristics such as "self-resonant" objects with capacitance or inductance distributed (or partially distributed, as opposed to solely lumped) throughout the entire object. It would be understood by one of ordinary skill in the art that adjusting and controlling variable components within a circuit or network may adjust the performance of that circuit or network and that those adjustments may be described generally as tuning, adjusting, matching, correcting, and the like. Other methods to tune or adjust the operating point of the wireless power transfer system may be used alone, or in addition to adjusting tunable components such as inductors and capacitors, or banks of inductors and capacitors. Those skilled in the art will recognize that a particular topology discussed in this disclosure can be implemented in a variety of other ways.

[0039] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of conflict with publications, patent applications, patents, and other references mentioned or incorporated herein by reference, the present specification, including definitions, will control.

[0040] Any of the features described above may be used, alone or in combination, without departing from the scope of this disclosure. Other features, objects, and advantages of the systems and methods disclosed herein will be apparent from the following detailed description and figures.

BRIEF DESCRIPTION OF FIGURES

[0041] Fig.1 is a system block diagram of wireless energy transfer configurations.

[0042] Figs. 2A-2F are exemplary structures and schematics of simple resonator structures.

[0043] Fig. 3 is a block diagram of a wireless source with a single-ended amplifier.

[0044] Fig. 4 is a block diagram of a wireless source with a differential amplifier.

[0045] Figs. 5A and 5B are block diagrams of sensing circuits.

[0046] Figs. 6A, 6B, and 6C are block diagrams of a wireless source.

[0047] Fig. 7 is a plot showing the effects of a duty cycle on the parameters of an amplifier.

[0048] Fig. 8 is a simplified circuit diagram of a wireless power source with a switching amplifier.

[0049] Fig. 9 shows plots of the effects of changes of parameters of a wireless power source.

[0050] Fig. 10 shows plots of the effects of changes of parameters of a wireless power source.

[0051] Figs. 11A, 11B, and 11C are plots showing the effects of changes of parameters of a wireless power source.

[0052] Fig. 12 shows plots of the effects of changes of parameters of a wireless power source.

[0053] Fig. 13 is a simplified circuit diagram of a wireless energy transfer system comprising a wireless power source with a switching amplifier and a wireless power device.

[0054] Fig. 14 shows plots of the effects of changes of parameters of a wireless power source.

[0055] Fig. 15 is a diagram of a resonator showing possible nonuniform magnetic field distributions due to irregular spacing between tiles of magnetic material.

[0056] Fig. 16 is a resonator with an arrangement of tiles in a block of magnetic material that may reduce hotspots in the magnetic material block.

[0057] Fig. 17A is a resonator with a block of magnetic material comprising smaller individual tiles and 17B and 17C is the resonator with additional strips of thermally conductive material used for thermal management.

[0058] Fig. 18A and 18B are resonator configurations comprising repeater resonators.

[0059] Fig. 19A and 19B are resonator configurations comprising repeater resonators.

[0060] Fig. 20A is a configuration with two repeater resonators 20B is a resonator configuration with a device resonator acting as a repeater resonator.

[0061] Fig. 21 is an under the cabinet lighting application comprising repeater resonators.

[0062] Fig. 22 is a source resonator integrated into an electrical outlet cover.

[0063] Fig. 23 is an exploded view of a resonator enclosure.

[0064] Fig. 24A is a vehicle with device resonators mounded on the underside, 24B is a source resonator integrated into a mat, 24C is a vehicle with a device resonator and a source integrated with a mat, and 24D is a robot with a device resonator mounted to the underside.

[0065] Fig. 25 is a graph showing capacitance changes due to temperature of one ceramic capacitor.

[0066] Fig. 26A are example capacitance versus temperature profiles of two components which can be used for passive compensation 26B are example capacitance versus temperature profiles of three components which can be used for passive compensations.

[0067] Fig. 27A is diagram of a resonator showing the span of the conductor, 27B is a cross section of resonator that has a hollow compartment.

[0068] Fig. 28A is an isometric view of a resonator with a conductor shield comprising flaps, 28B is a side view of a resonator with a conductor shield comprising flaps.

[0069] Fig. 29 is a diagram of a system utilizing a repeater resonator with a desk environment.

[0070] Fig. 30 is a diagram of a system utilizing a resonator that may be operated in multiple modes.

[0071] Fig. 31 is a circuit block diagram of the power and control circuitry of a resonator configured to have multiple modes of operation.

[0072] Fig. 32A is a block diagram of a configuration of a system utilizing a wireless power converter, 32B is a block diagram of a configuration of a system utilizing a wireless power converter that may also function as a repeater.

[0073] Fig. 33 is a block diagram showing different configurations and uses of a wireless power converter.

[0074] Fig. 34A is a block diagram of a wireless power converter that uses two separate resonators and a AC to DC converter, 34B is a block diagram of a wireless power converter that uses two separate resonators and an AC to AC converter.

[0075] Fig. 35 is a circuit block diagram of a wireless power converter utilizing one resonator.

[0076] Fig. 36A,36B are circuit diagrams of system configurations utilizing a wireless power converter with differently sized resonators.

[0077] Fig. 37 is a diagram showing relative source and device resonator dimensions to allow lateral displacement or side to side positioning uncertainty of a vehicle.

[0078] Fig. 38A is a resonator comprising a single block of magnetic material, 38B, 38C, 38D are resonator comprising of multiple separate blocks of magnetic material.

[0079] Fig. 39A, 39B, 39C are isometric views of resonator configurations used for comparison of wirelss power transfer characteristics between resonators comprising one and more than one separate block of magnetic material.

[0080] Fig. 40 is an isometric view of a resonator comprising four separate blocks of magnetic material each wrapped with a conductor.

[0081] Fig. 41A is a top view of a resonator comprising two blocks of magnetic material with staggered conductor windings, 41B is a top view of a resonator comprising two block of magnetic material shaped to decrease the spacing between them.

[0082] Fig. 42A is an isometric view of a resonator with a conductor shield, 42B is an isometric view of an embodiment of a resonator with an integrated conductor shield, and 42C is an isometric view of a resonator with an integrated conductor shield with individual conductor segments.

[0083] Fig. 43A, 43B, 43C are the top, side, and front views of an embodiment of an integrated resonator-shield structure respectively.

[0084] Fig. 44 is an exploded view of an embodiment of an integrated resonator-shield structure.

[0085] Fig. 45A is the top view of an embodiment of an integrated resonator-shield structure with symmetric conductor segments on the conductor shield, 45B is an isometric view of another embodiment of an integrated resonator-shield structure.

[0086] Fig. 46A is an isometric view of an integrated resonator-shield structure with a cavity in the block of magnetic material, 46B is an isometric view of an embodiment of the conductor parts of the integrated resonator-shield structure.

[0087] Fig. 47 is an isometric view of an embodiment of an integrated resonator-shield structure with two dipole moments.

[0088] Fig 48 is a diagram showing application of wireless energy transfer to a surgical robot and a hospital bed.

[0089] Fig 49 is a diagram showing application of wireless energy transfer to a surgical robot and a hospital bed.

[0090] Fig. 50A is embodiment of a medical cart with wireless energy transfer, 50B is an embodiment of a computer cart with wireless energy transfer.

DETAILED DESCRIPTION

[0091] As described above, this disclosure relates to wireless energy transfer using coupled electromagnetic resonators. However, such energy transfer is not restricted to electromagnetic resonators, and the wireless energy transfer systems described herein are more general and may be implemented using a wide variety of resonators and resonant objects.

[0092] As those skilled in the art will recognize, important considerations for resonator-based power transfer include resonator efficiency and resonator coupling. Extensive discussion of such issues, e.g., coupled mode theory (CMT), coupling coefficients and factors, quality factors (also referred to as Q-factors), and impedance matching is provided, for example, in U.S. patent application 12/789,611 published on September 23, 2010 as US 20100237709 and entitled "RESONATOR ARRAYS FOR WIRELESS ENERGY TRANSFER," and U.S. patent application 12/722,050 published on July 22, 2010 as US 20100181843 and entitled "WIRELESS ENERGY TRANSFER FOR REFRIGERATOR APPLICATION" and incorporated herein by reference in its entirety as if fully set forth herein.

[0093] A **resonator** may be defined as a resonant structure that can store energy in at least two different forms, and where the stored energy oscillates between the two forms. The resonant structure will have a specific oscillation mode with a resonant (modal) frequency, f, and a resonant (modal) field. The angular resonant frequency, ω, may be defined as $\omega = 2\pi f$, the resonant period, T, may be defined as $T = 1/f = 2\pi/\omega$, and the resonant wavelength, λ, may be defined as $\lambda = c/f$, where c is the speed of the associated field waves (light, for electromagnetic resonators). In the absence of loss mechanisms, coupling mechanisms or external energy supplying or draining mechanisms, the total amount of energy stored by the resonator, W, would stay fixed, but the form of the energy would oscillate between the two forms supported by the resonator, wherein one form would be maximum when the other is minimum and vice versa.

[0094] For example, a resonator may be constructed such that the two forms of stored energy are magnetic energy and electric energy. Further, the resonator may be constructed such that the electric energy stored by the electric field is primarily confined within the structure while the magnetic energy stored by the magnetic field is primarily in the region surrounding the resonator. In other words, the total electric and magnetic energies would be equal, but their localization would be different. Using such structures, energy exchange between at least two structures may be mediated by the resonant magnetic near-field of the at least two resonators. These types of resonators may be referred to as **magnetic resonators**.

[0095] An important parameter of resonators used in wireless power transmission systems is the **Quality Factor,** or **Q-factor**, or Q, of the resonator, which characterizes the energy decay and is inversely proportional to energy losses of the resonator. It may be defined as $Q = \omega * W/P$, where P is the time-averaged power lost at steady state. That is, a resonator with a high-Q has relatively low intrinsic losses and can store energy for a relatively long time. Since the resonator loses energy at its intrinsic decay rate, 2Γ, its Q, also referred to as its intrinsic Q, is given by $Q = \omega/2\Gamma$. The quality factor also represents the number of oscillation periods, T, it takes for the energy in the resonator to decay by a factor of $e^{-2\pi}$. Note that the quality factor or intrinsic quality factor or Q of the resonator is that due only to intrinsic loss mechanisms. The Q of a resonator connected to, or coupled to a power generator, g, or load, l, may be called the "**loaded quality factor**" or the "loaded Q". The Q of a resonator in the presence of an extraneous object that is not intended to be part of the energy transfer system may be called the "**perturbed quality factor**" or the "perturbed Q".

[0096] Resonators, coupled through any portion of their near-fields may interact and exchange energy. The efficiency of this energy transfer can be significantly enhanced if the resonators operate at substantially the same resonant frequency. By way of example, but not limitation, imagine a source resonator with Q_s and a device resonator with Q_d. High-Q wireless energy transfer systems may utilize resonators that are high-Q. The Q of each resonator may be high. The geometric mean of the resonator Q's, $\sqrt{Q_s Q_d}$ may also or instead be high.

[0097] The **coupling factor**, k, is a number between $0 \leq |k| \leq 1$, and it may be independent (or nearly independent) of the resonant frequencies of the source and device resonators , when those are placed at sub-wavelength distances. Rather the coupling factor k may be determined mostly by the relative geometry and the distance between the source and device resonators where the physical decay-law of the field mediating their coupling is taken into account. The coupling coefficient used in CMT, $\kappa = k\sqrt{\omega_s \omega_d}/2$, may be a strong function of the resonant frequencies, as well as other properties of the resonator structures. In applications for wireless energy transfer utilizing the near-fields of the resonators, it is desirable to have the size of the resonator be much smaller than the resonant wavelength, so that power lost by radiation is reduced. In some embodiments, high-Q resonators are sub-wavelength structures. In some electromagnetic embodiments, high-Q resonator structures are designed to have resonant frequencies higher than 100 kHz. In other embodiments, the resonant frequencies may be less than 1 GHz.

[0098] In exemplary embodiments, the power radiated into the far-field by these sub wavelength resonators may be further reduced by lowering the resonant frequency of the resonators and the operating frequency of the system. In other embodiments, the far field radiation may be reduced by arranging for the far fields of two or more resonators to interfere destructively in the far field.

[0099] In a wireless energy transfer system a resonator may be used as a wireless energy source, a wireless energy capture device, a repeater or a combination thereof. In embodiments a resonator may alternate between transferring energy, receiving energy or relaying energy. In a wireless energy transfer system one or more magnetic resonators may be coupled to an energy source and be energized to produce an oscillating magnetic near-field. Other resonators that are within the oscillating magnetic near-fields may capture these fields and convert the energy into electrical energy that may be used to power or charge a load thereby enabling wireless transfer of useful energy.

[00100] The so-called "useful" energy in a useful energy exchange is the energy or power that must be delivered to a device in order to power or charge it at an acceptable rate. The transfer efficiency that corresponds to a useful energy exchange may be system or application-dependent. For example, high power vehicle charging applications that transfer kilowatts of power may need to be at least 80% efficient in order to supply useful amounts of power resulting in a useful energy exchange sufficient to recharge a vehicle battery without significantly heating up various components of the transfer system. In some consumer electronics applications, a useful energy exchange may include any energy transfer efficiencies greater than 10%, or any other amount acceptable to keep rechargeable batteries "topped off" and running for long periods of time. In implanted medical device applications, a useful energy exchange may be any exchange that does not harm the patient but that extends the life of a battery or wakes up a sensor or monitor or stimulator. In such applications, 100 mW of power or less may be useful. In distributed sensing applications, power transfer of microwatts may be useful, and transfer efficiencies may be well below 1%.

[00101] A useful energy exchange for wireless energy transfer in a powering or recharging application may be efficient, highly efficient, or efficient enough, as long as the wasted energy levels, heat dissipation, and associated field strengths are within tolerable limits and are balanced appropriately with related factors such as cost, weight, size, and the like.

[00102] The resonators may be referred to as source resonators, device resonators, first resonators, second resonators, repeater resonators, and the like. Implementations may include three (3) or more resonators. For example, a single source resonator may transfer energy to multiple device resonators or multiple devices. Energy may be transferred from a first device to a second, and then from the second device to the third, and so forth. Multiple sources may transfer energy to a single device or to multiple devices connected to a single device resonator or to multiple devices connected to multiple device resonators. Resonators may serve alternately or simultaneously as sources, devices, and/or they may be used to relay power from a source in one location to a device in another location. Intermediate electromagnetic resonators may be used to extend the distance range of wireless energy transfer systems and/or to generate areas of concentrated magnetic near-fields. Multiple resonators may be daisy-chained together, exchanging energy over extended distances and with a wide range of sources and devices. For example, a source resonator may transfer power to a device resonator via several repeater resonators. Energy from a source may be transferred to a first repeater resonator, the first repeater resonator may transfer the power to a second repeater resonator and the second to a third and so on until the final repeater resonator transfers its energy to a device resonator. In this respect the range or distance of wireless energy transfer may be extended and/or tailored by adding repeater resonators. High power levels may be split between multiple sources, transferred to multiple devices and recombined at a distant location.

[00103] The resonators may be designed using coupled mode theory models, circuit models, electromagnetic field models, and the like. The resonators may be designed to have tunable characteristic sizes. The resonators may be designed to handle different power levels. In exemplary embodiments, high power resonators may require larger conductors and higher current or voltage rated components than lower power resonators.

[00104] Fig. 1 shows a diagram of exemplary configurations and arrangements of a wireless energy transfer system. A wireless energy transfer system may include at least one source resonator (R1)**104** (optionally R6, **112**) coupled to an energy source **102** and optionally a sensor and control unit **108**. The energy source may be a source of any type of energy capable of being converted into electrical energy that may be used to drive the source resonator **104**. The energy source may be a battery, a solar panel, the electrical mains, a wind or water turbine, an electromagnetic resonator, a generator, and the like. The electrical energy used to drive the magnetic resonator is converted into oscillating magnetic fields by the resonator. The oscillating magnetic fields may be captured by other resonators which may be device resonators (R2) **106,** (R3) **116** that are optionally coupled to an energy drain **110**. The oscillating fields may be optionally coupled to repeater resonators (R4, R5) that are configured to extend or tailor the wireless energy transfer region. Device resonators may capture the magnetic fields in the vicinity of source resonator(s), repeater resonators and other device resonators and convert them into electrical energy that may be used by an energy drain. The energy drain **110** may be an electrical, electronic, mechanical or chemical device and the like configured to receive electrical energy. Repeater resonators may capture magnetic fields in the vicinity of source, device and repeater resonator(s) and may pass the energy on to other resonators.

[00105] A wireless energy transfer system may comprise a single source resonator **104** coupled to an energy source **102** and a single device resonator **106** coupled to an energy drain **110.** In embodiments a wireless energy transfer system may comprise multiple source resonators coupled to one or more energy sources and may comprise multiple device resonators coupled to one or more energy drains.

[00106] In embodiments the energy may be transferred directly between a source resonator **104** and a device resonator **106.** In other embodiments the energy may be transferred from one or more source resonators **104, 112** to one or more device resonators **106, 116** via any number of intermediate resonators which may be device resonators, source resonators, repeater resonators, and the like. Energy may be transferred via a network or arrangement of resonators **114** that may include subnetworks **118, 120** arranged in any combination of topologies such as token ring, mesh, ad hoc, and the like.

[00107] In embodiments the wireless energy transfer system may comprise a centralized sensing and control system **108**. In embodiments parameters of the resonators, energy sources, energy drains, network topologies, operating parameters, etc. may be monitored and adjusted from a control processor to meet specific operating parameters of the system. A central control processor may adjust parameters of individual components of the system to optimize global energy transfer efficiency, to optimize the amount of power transferred, and the like. Other embodiments may be designed to have a substantially distributed sensing and control system. Sensing and control may be incorporated into each resonator or group of resonators, energy sources, energy drains, and the like and may be configured to adjust the parameters of the individual components in the group to maximize the power delivered, to maximize energy transfer efficiency in that group and the like.

[00108] In embodiments, components of the wireless energy transfer system may have wireless or wired data communication links to other components such as devices, sources, repeaters, power sources, resonators, and the like and may transmit or receive data that can be used to enable the distributed or centralized sensing and control. A wireless communication channel may be separate from the wireless energy transfer channel, or it may be the same. In one embodiment the resonators used for power exchange may also be used to exchange information. In some cases, information may be exchanged by modulating a component in a source or device circuit and sensing that change with port parameter or other monitoring equipment. Resonators may signal each other by tuning, changing, varying, dithering, and the like, the resonator parameters such as the impedance of the resonators which may affect the reflected impedance of other resonators in the system. The systems and methods described herein may enable the simultaneous transmission of power and communication signals between resonators in wireless power transmission systems, or it may enable the transmission of power and communication signals during different time periods or at different frequencies using the same magnetic fields that are used during the wireless energy transfer. In other embodiments wireless communication may be enabled with a separate wireless communication channel such as WiFi, Bluetooth, Infrared, and the like.

[00109] In embodiments, a wireless energy transfer system may include multiple resonators and overall system performance may be improved by control of various elements in the system. For example, devices with lower power requirements may tune their resonant frequency away from the resonant frequency of a high-power source that supplies power to devices with higher power requirements. In this way, low and high power devices may safely operate or charge from a single high power source. In addition, multiple devices in a charging zone may find the power available to them regulated according to any of a variety of consumption control algorithms such as First-Come-First-Serve, Best Effort, Guaranteed Power, etc. The power consumption algorithms may be hierarchical in nature, giving priority to certain users or types of devices, or it may support any number of users by equally sharing the power that is available in the source. Power may be shared by any of the multiplexing techniques described in this disclosure.

[00110] In embodiments electromagnetic resonators may be realized or implemented using a combination of shapes, structures, and configurations. Electromagnetic resonators may include an inductive element, a distributed inductance, or a combination of inductances with a total inductance, L, and a capacitive element, a distributed capacitance, or a combination of capacitances, with a total capacitance, C. A minimal circuit model of an electromagnetic resonator comprising capacitance, inductance and resistance, is shown in Fig. 2F. The resonator may include an inductive element **238** and a capacitive element **240**. Provided with initial energy, such as electric field energy stored in the capacitor **240**, the system will oscillate as the capacitor discharges transferring energy into magnetic field energy stored in the inductor **238** which in turn transfers energy back into electric field energy stored in the capacitor **240**. Intrinsic losses in these electromagnetic resonators include losses due to resistance in the inductive and capacitive elements and to radiation losses, and are represented by the resistor, R, **242** in Fig. 2F.

[00111] Fig. 2A shows a simplified drawing of an exemplary magnetic resonator structure. The magnetic resonator may include a loop of conductor acting as an inductive element **202** and a capacitive element **204** at the ends of the conductor loop. The inductor **202** and capacitor **204** of an electromagnetic resonator may be bulk circuit elements, or the inductance and capacitance may be distributed and may result from the way the conductors are formed, shaped, or positioned, in the structure.

[00112] For example, the inductor **202** may be realized by shaping a conductor to enclose a surface area, as shown in Figs. 2A. This type of resonator may be referred to as a capacitively-loaded loop inductor or a capacitively-loaded conducting loop. Note that we may use the terms “loop” or “coil” to indicate generally a conducting structure (wire, tube, strip, etc.), enclosing a surface of any shape and dimension, with any number of turns. In Fig. 2A, the enclosed surface area is circular, but the surface may be any of a wide variety of other shapes and sizes and may be designed to achieve certain system performance specifications and/or to fit within certain volumes or spaces. In embodiments the inductance may be realized using inductor elements, distributed inductance, networks, arrays, series and parallel combinations of inductors and inductances, and the like. The inductance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[00113] There are a variety of ways to realize the capacitance required to achieve the desired resonant frequency for a resonator structure. Capacitor plates **204** may be formed and utilized as shown in Fig. 2A, or the capacitance may be distributed and be realized between adjacent windings of a multi-loop conductor. The capacitance may be realized using capacitor elements, distributed capacitance, networks, arrays, series and parallel combinations of capacitances, and the like. The capacitance may be fixed or variable and may be used to vary impedance matching as well as resonant frequency operating conditions.

[00114] The inductive elements used in magnetic resonators may contain more than one loop and may spiral inward or outward or up or down or in some combination of directions. In general, the magnetic resonators may have a variety of shapes, sizes and number of turns and they may be composed of a variety of conducing materials. The conductor **210**, for example, may be a wire, a Litz wire, a ribbon, a pipe, a trace formed from conducting ink, paint, gels, and the like or from single or multiple traces printed on a circuit board. An exemplary embodiment of a trace pattern on a substrate **208** forming inductive loops is depicted in Fig. 2B.

[00115] In embodiments the inductive elements may be formed using magnetic materials of any size, shape thickness, and the like, and of materials with a wide range of permeability and loss values. These magnetic materials may be solid blocks, they may enclose hollow volumes, they may be formed from many smaller pieces of magnetic material tiled and or stacked together, and they may be integrated with conducting sheets or enclosures made from highly conducting materials. Conductors may be wrapped around the magnetic materials to generate the magnetic field. These conductors may be wrapped around one or more than one axis of the structure. Multiple conductors may be wrapped around the magnetic materials and combined in parallel, or in series, or via a switch to form customized near-field patterns and/or to orient the dipole moment of the structure. Examples of resonators comprising magnetic material are depicted in Figs. 2C, 2D, 2E. In Fig. 2D the resonator comprises loops of conductor **224** wrapped around a core of magnetic material **222** creating a structure that has a magnetic dipole moment **228** that is parallel to the axis of the loops of the conductor **224**. The resonator may comprise multiple loops of conductor **216, 212** wrapped in orthogonal directions around the magnetic material **214** forming a resonator with a magnetic dipole moment **218, 220** that may be oriented in more than one direction as depicted in Fig. 2C, depending on how the conductors are driven.

[00116] An electromagnetic resonator may have a characteristic, natural, or resonant frequency determined by its physical properties. This resonant frequency is the frequency at which the energy stored by the resonator oscillates between that stored by the electric field, W_E,

($W_E = q^2/2C$, where q is the charge on the capacitor, C) and that stored by the magnetic field, W_B, ($W_B = Li^2/2$, where i is the current through the inductor, L) of the resonator. The frequency at which this energy is exchanged may be called the characteristic frequency, the natural frequency, or the resonant frequency of the resonator, and is given by ω,

$$\omega = 2\pi f = \sqrt{\frac{1}{LC}}.$$

The resonant frequency of the resonator may be changed by tuning the inductance, L, and/or the capacitance, C, of the resonator. In one embodiment system parameters are dynamically adjustable or tunable to achieve as close as possible to optimal operating conditions. However, based on the discussion above, efficient enough energy exchange may be realized even if some system parameters are not variable or components are not capable of dynamic adjustment.

[00117] In embodiments a resonator may comprise an inductive element coupled to more than one capacitor arranged in a network of capacitors and circuit elements. In embodiments the coupled network of capacitors and circuit elements may be used to define more than one resonant frequency of the resonator. In embodiments a resonator may be resonant, or partially resonant, at more than one frequency.

[00118] In embodiments, a wireless power source may comprise of at least one resonator coil coupled to a power supply, which may be a switching amplifier, such as a class-D amplifier or a class-E amplifier or a combination thereof. In this case, the resonator coil is effectively a power load to the power supply. In embodiments, a wireless power device may comprise of at least one resonator coil coupled to a power load, which may be a switching rectifier, such as a class-D rectifier or a class-E rectifier or a combination thereof. In this case, the resonator coil is effectively a power supply for the power load, and the impedance of the load directly relates also to the work-drainage rate of the load from the resonator coil. The efficiency of power transmission between a power supply and a power load may be impacted by how closely matched the output impedance of the power source is to the input impedance of the load. Power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load is equal to the complex conjugate of the internal impedance of the power supply. Designing the power supply or power load impedance to obtain a maximum power transmission efficiency is often called "impedance matching", and may also referred to as optimizing the ratio of useful-to-lost powers in the system. Impedance matching may be performed by adding networks or sets of elements such as capacitors, inductors, transformers, switches, resistors, and the like, to form impedance matching networks between a power supply and a power load. In embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching.For varying loads, the impedance matching network may include variable components that are dynamically adjusted to ensure that the impedance at the power supply terminals looking towards the load and the characteristic impedance of the power supply remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios.

[00119] In embodiments, impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or thefrequency of the driving signal of the power supply or by tuning a physical component within the power supply, such as a capacitor. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power supply and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power supply may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like.

[00120] In some wireless energy transfer systems the parameters of the resonator such as the inductance may be affected by environmental conditions such as surrounding objects, temperature, orientation, number and position of other resonators and the like. Changes in operating parameters of the resonators may change certain system parameters, such as the efficiency of transferred power in the wireless energy transfer. For example, high-conductivity materials located near a resonator may shift the resonant frequency of a resonator and detune it from other resonant objects. In some embodiments, a resonator feedback mechanism is employed that corrects its frequency by changing a reactive element (e.g., an inductive element or capacitive element). In order to achieve acceptable matching conditions, at least some of the system parameters may need to be dynamically adjustable or tunable. All the system parameters may be dynamically adjustable or tunable to achieve approximately the optimal operating conditions. However, efficient enough energy exchange may be realized even if all or some system parameters are not variable. In some examples, at least some of the devices may not be dynamically adjusted. In some examples, at least some of the sources may not be dynamically adjusted. In some examples, at least some of the intermediate resonators may not be dynamically adjusted. In some examples, none of the system parameters may be dynamically adjusted.

[00121] In some embodiments changes in parameters of components may be mitigated by selecting components with characteristics that change in a complimentary or opposite way or direction when subjected to differences in operating environment or operating point. In embodiments, a system may be designed with components, such as capacitors, that have an opposite dependence or parameter fluctuation due to temperature, power levels, frequency, and the like. In some embodiments, the component values as a function of temperature may be stored in a look-up table in a system microcontroller and the reading from a temperature sensor may be used in the system control feedback loop to adjust other parameters to compensate for the temperature induced component value changes.

[00122] In some embodiments the changes in parameter values of components may be compensated with active tuning circuits comprising tunable components. Circuits that monitor the operating environment and operating point of components and system may be integrated in the design. The monitoring circuits may provide the signals necessary to actively compensate for changes in parameters of components. For example, a temperature reading may be used to calculate expected changes in, or to indicate previously measured values of, capacitance of the system allowing compensation by switching in other capacitors or tuning capacitors to maintain the desired capacitance over a range of temperatures. In embodiments, the RF amplifier switching waveforms may be adjusted to compensate for component value or load changes in the system. In some embodiments the changes in parameters of components may be compensated with active cooling, heating, active environment conditioning, and the like.

[00123] The parameter measurement circuitry may measure or monitor certain power, voltage, and current, signals in the system, and processors or control circuits may adjust certain settings or operating parameters based on those measurements. In addition the magnitude and phase of voltage and current signals, and the magnitude of the power signals, throughout the system may be accessed to measure or monitor the system performance. The measured signals referred to throughout this disclosure may be any combination of port parameter signals, as well as voltage signals, current signals, power signals, temperatures signals and the like. These parameters may be measured using analog or digital techniques, they may be sampled and processed, and they may be digitized or converted using a number of known analog and digital processing techniques. In embodiments, preset values of certain measured quantities are loaded in a system controller or memory location and used in various feedback and control loops. In embodiments, any combination of measured, monitored, and/or preset signals may be used in feedback circuits or systems to control the operation of the resonators and/or the system.

[00124] Adjustment algorithms may be used to adjust the frequency, Q, and/or impedance of the magnetic resonators. The algorithms may take as inputs reference signals related to the degree of deviation from a desired operating point for the system and may output correction or control signals related to that deviation that control variable or tunable elements of the system to bring the system back towards the desired operating point or points. The reference signals for the magnetic resonators may be acquired while the resonators are exchanging power in a wireless power transmission system, or they may be switched out of the circuit during system operation. Corrections to the system may be applied or performed continuously, periodically, upon a threshold crossing, digitally, using analog methods, and the like.

[00125] In embodiments, lossy extraneous materials and objects may introduce potential reductions in efficiencies by absorbing the magnetic and/or electric energy of the resonators of the wireless power transmission system. Those impacts may be mitigated in various embodiments by positioning resonators to minimize the effects of the lossy extraneous materials and objects and by placing structural field shaping elements (e.g., conductive structures, plates and sheets, magnetic material structures, plates and sheets, and combinations thereof) to minimize their effect.

[00126] One way to reduce the impact of lossy materials on a resonator is to use high-conductivity materials, magnetic materials, or combinations thereof to shape the resonator fields such that they avoid the lossy objects. In an exemplary embodiment, a layered structure of high-conductivity material and magnetic material may tailor, shape, direct, reorient, etc. the resonator's electromagnetic fields so that they avoid lossy objects in their vicinity by deflecting the fields. Fig. 2D shows a top view of a resonator with a sheet of conductor **226** below the magnetic material that may be used to tailor the fields of the resonator so that they avoid lossy objects that may be below the sheet of conductor **226.** The layer or sheet of good **226** conductor may comprise any high conductivity materials such as copper, silver, aluminum, as may be most appropriate for a given application. In certain embodiments, the layer or sheet of good conductor is thicker than the skin depth of the conductor at the resonator operating frequency. The conductor sheet may be preferably larger than the size of the resonator, extending beyond the physical extent of the resonator.

[00127] In environments and systems where the amount of power being transmitted could present a safety hazard to a person or animal that may intrude into the active field volume, safety measures may be included in the system. In embodiments where power levels require particularized safety measures, the packaging, structure, materials, and the like of the resonators may be designed to provide a spacing or "keep away" zone from the conducting loops in the magnetic resonator. To provide further protection, high- Q resonators and power and control circuitry may be located in enclosures that confine high voltages or currents to within the enclosure, that protect the resonators and electrical components from weather, moisture, sand, dust, and other external elements, as well as from impacts, vibrations, scrapes, explosions, and other types of mechanical shock . Such enclosures call for attention to various factors such as thermal dissipation to maintain an acceptable operating temperature range for the electrical components and the resonator. In embodiments, enclosure may be constructed of non-lossy materials such as composites, plastics, wood, concrete, and the like and may be used to provide a minimum distance from lossy objects to the resonator components. A minimum separation distance from lossy objects or environments which may include metal objects, salt water, oil and the like, may improve the efficiency of wireless energy transfer. In embodiments, a "keep away" zone may be used to increase the perturbed Q of a resonator or system of resonators. In embodiments a minimum separation distance may provide for a more reliable or more constant operating parameters of the resonators.

[00128] In embodiments, resonators and their respective sensor and control circuitry may have various levels of integration with other electronic and control systems and subsystems. In some embodiments the power and control circuitry and the device resonators are completely separate modules or enclosures with minimal integration to existing systems, providing a power output and a control and diagnostics interface. In some embodiments a device is configured to house a resonator and circuit assembly in a cavity inside the enclosure, or integrated into the housing or enclosure of the device.

[00129] Example Resonator Circuitry

[00130] Figures 3 and 4 show high level block diagrams depicting power generation, monitoring, and control components for exemplary sources of a wireless energy transfer system. Fig. 3 is a block diagram of a source comprising a half-bridge switching power amplifier and some of the associated measurement, tuning, and control circuitry. Fig. 4 is a block diagram of a source comprising a full-bridge switching amplifier and some of the associated measurement, tuning, and control circuitry.

[00131] The half bridge system topology depicted in Fig. 3 may comprise a processing unit that executes a control algorithm **328.** The processing unit executing a control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The processing unit may be a single device or it may be a network of devices. The control algorithm may run on any portion of the processing unit. The algorithm may be customized for certain applications and may comprise a combination of analog and digital circuits and signals. The master algorithm may measure and adjust voltage signals and levels, current signals and levels, signal phases, digital count settings, and the like.

[00132] The system may comprise an optional source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312.** The optional source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes the master control algorithm, it may a part or a circuit within a microcontroller **302**, it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission**.**

[00133] The system may comprise a PWM generator **306** coupled to at least two transistor gate drivers **334** and may be controlled by the control algorithm. The two transistor gate drivers **334** may be coupled directly or via gate drive transformers to two power transistors

336 that drive the source resonator coil **344** through impedance matching network components **342.** The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a variable bus voltage, Vbus. The Vbus controller may be controlled by the control algorithm **328** and may be part of, or integrated into, a microcontroller **302** or other integrated circuits. The Vbus controller **326** may control the voltage output of an adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344.**

[00134] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318, 320** that may shape, modify, filter, process, buffer, and the like, signals prior to their input to processors and/or converters such as analog to digital converters (ADC) **314, 316**, for example. The processors and converters such as ADCs **314, 316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals, the control algorithm **328** may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **306,** the communication controller **332**, the Vbus control **326**, the source impedance matching controller **338**, the filter/buffering elements, **318, 320,** the converters, **314, 316,** the resonator coil **344,** and may be part of, or integrated into, a microcontroller **302** or a separate circuit. The impedance matching networks **342** and resonator coils **344** may include electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to adjust the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planar resonator comprising a magnetic material or any combination thereof.

[00135] The full bridge system topology depicted in Fig. 4 may comprise a processing unit that executes a master control algorithm **328.** The processing unit executing the control algorithm **328** may be a microcontroller, an application specific circuit, a field programmable gate array, a processor, a digital signal processor, and the like. The system may comprise a source/device and/or source/other resonator communication controller **332** coupled to wireless communication circuitry **312.** The source/device and/or source/other resonator communication controller **332** may be part of the same processing unit that executes that master control algorithm, it may a part or a circuit within a microcontroller **302,** it may be external to the wireless power transmission modules, it may be substantially similar to communication controllers used in wire powered or battery powered applications but adapted to include some new or different functionality to enhance or support wireless power transmission.

[00136] The system may comprise a PWM generator **410** with at least two outputs coupled to at least four transistor gate drivers **334** that may be controlled by signals generated in a master control algorithm. The four transistor gate drivers **334** may be coupled to four power transistors **336** directly or via gate drive transformers that may drive the source resonator coil **344** through impedance matching networks **342.** The power transistors **336** may be coupled and powered with an adjustable DC supply **304** and the adjustable DC supply **304** may be controlled by a Vbus controller **326** which may be controlled by a master control algorithm. The Vbus controller **326** may control the voltage output of the adjustable DC supply **304** which may be used to control power output of the amplifier and power delivered to the resonator coil **344.**

[00137] The system may comprise sensing and measurement circuitry including signal filtering and buffering circuits **318, 320** and differential/single ended conversion circuitry **402, 404** that may shape, modify, filter, process, buffer, and the like, signals prior to being input to processors and/or converters such as analog to digital converters (ADC) **314, 316.** The processors and/or converters such as ADC **314, 316** may be integrated into a microcontroller **302** or may be separate circuits that may be coupled to a processing core **330**. Based on measured signals, the master control algorithm may generate, limit, initiate, extinguish, control, adjust, or modify the operation of any of the PWM generator **410,** the communication controller **332**, the Vbus controller **326,** the source impedance matching controller **338,** the filter/buffering elements, **318, 320,** differential/single ended conversion circuitry **402, 404**, the converters, **314, 316,** the resonator coil **344,** and may be part of or integrated into a microcontroller **302** or a separate circuit.

[00138] Impedance matching networks **342** and resonator coils **344** may comprise electrically controllable, variable, or tunable components such as capacitors, switches, inductors, and the like, as described herein, and these components may have their component values or operating points adjusted according to signals received from the source impedance matching controller **338**. Components may be tuned to enable tuning of the operation and characteristics of the resonator including the power delivered to and by the resonator, the resonant frequency of the resonator, the impedance of the resonator, the Q of the resonator, and any other coupled systems, and the like. The resonator may be any type or structure resonator described herein including a capacitively loaded loop resonator, a planar resonator comprising a magnetic material or any combination thereof.

[00139] Impedance matching networks may comprise fixed value components such as capacitors, inductors, and networks of components as described herein. Parts of the impedance matching networks A, B and C, may comprise inductors, capacitors, transformers, and series and parallel combinations of such components, as described herein. In some embodiments, parts of the impedance matching networks A, B, and C, may be empty (short-circuited). In some embodiments, part B comprises a series combination of an inductor and a capacitor, and part C is empty.

[00140] The full bridge topology may allow operation at higher output power levels using the same DC bus voltage as an equivalent half bridge amplifier. The half bridge exemplary topology of Fig. 3 may provide a single-ended drive signal, while the exemplary full bridge topology of Fig. 4 may provide a differential drive to the source resonator **308**. The impedance matching topologies and components and the resonator structure may be different for the two systems, as discussed herein.

[00141] The exemplary systems depicted in Figs. 3 and 4 may further include fault detection circuitry **340** that may be used to trigger the shutdown of the microcontroller in the source amplifier or to change or interrupt the operation of the amplifier. This protection circuitry may comprise a high speed comparator or comparators to monitor the amplifier return current, the amplifier bus voltage (Vbus) from the DC supply **304**, the voltage across the source resonator **308** and/or the optional tuning board, or any other voltage or current signals that may cause damage to components in the system or may yield undesirable operating conditions. Preferred embodiments may depend on the potentially undesirable operating modes associated with different applications. In some embodiments, protection circuitry may not be implemented or circuits may not be populated. In some embodiments, system and component protection may be implemented as part of a master control algorithm and other system monitoring and control circuits. In embodiments, dedicated fault circuitry **340** may include an output (not shown) coupled to a master control algorithm **328** that may trigger a system shutdown, a reduction of the output power (e.g. reduction of Vbus), a change to the PWM generator, a change in the operating frequency, a change to a tuning element, or any other reasonable action that may be implemented by the control algorithm **328** to adjust the operating point mode, improve system performance, and/or provide protection.

[00142] As described herein, sources in wireless power transfer systems may use a measurement of the input impedance of the impedance matching network **342** driving source resonator coil **344** as an error or control signal for a system control loop that may be part of the master control algorithm. In exemplary embodiments, variations in any combination of three parameters may be used to tune the wireless power source to compensate for changes in environmental conditions, for changes in coupling, for changes in device power demand, for changes in module, circuit, component or subsystem performance, for an increase or decrease in the number or sources, devices, or repeaters in the system, for user initiated changes, and the like. In exemplary embodiments, changes to the amplifier duty cycle, to the component values of the variable electrical components such as variable capacitors and inductors, and to the DC bus voltage may be used to change the operating point or operating range of the wireless source and improve some system operating value. The specifics of the control algorithms employed for different applications may vary depending on the desired system performance and behavior.

[00143] Impedance measurement circuitry such as described herein, and shown in Figs. 3 and 4, may be implemented using two-channel simultaneous sampling ADCs and these ADCs may be integrated into a microcontroller chip or may be part of a separate circuit. Simultaneously sampling of the voltage and current signals at the input to a source resonator's impedance matching network and/or the source resonator, may yield the phase and magnitude information of the current and voltage signals and may be processed using known signal processing techniques to yield complex impedance parameters. In some embodiments, monitoring only the voltage signals or only the current signals may be sufficient.

[00144] The impedance measurements described herein may use direct sampling methods which may be relatively simpler than some other known sampling methods. In embodiments, measured voltage and current signals may be conditioned, filtered and scaled by filtering/buffering circuitry before being input to ADCs. In embodiments, the filter/buffering circuitry may be adjustable to work at a variety of signal levels and frequencies, and circuit parameters such as filter shapes and widths may be adjusted manually, electronically, automatically, in response to a control signal, by the master control algorithm, and the like. Exemplary embodiments of filter/buffering circuits are shown in Figs. 3, 4, and 5.

[00145] Fig. 5 shows more detailed views of exemplary circuit components that may be used in filter/buffering circuitry. In embodiments, and depending on the types of ADCs used in the system designs, single-ended amplifier topologies may reduce the complexity of the analog signal measurement paths used to characterize system, subsystem, module and/or component performance by eliminating the need for hardware to convert from differential to single-ended signal formats. In other implementations, differential signal formats may be preferable. The implementations shown in Fig. 5 are exemplary, and should not be construed to be the only possible way to implement the functionality described herein. Rather it should be understood that the analog signal path may employ components with different input requirements and hence may have different signal path architectures.

[00146] In both the single ended and differential amplifier topologies, the input current to the impedance matching networks **342** driving the resonator coils **344** may be obtained by measuring the voltage across a capacitor **324,** or via a current sensor of some type. For the exemplary single-ended amplifier topology in Fig. 3, the current may be sensed on the ground return path from the impedance matching network **342**. For the exemplary differential power amplifier depicted in Fig. 4, the input current to the impedance matching networks **342** driving the resonator coils **344** may be measured using a differential amplifier across the terminals of a capacitor **324** or via a current sensor of some type**.** In the differential topology of Fig. 4, the capacitor **324** may be duplicated at the negative output terminal of the source power amplifier.

[00147] In both topologies, after single ended signals representing the input voltage and current to the source resonator and impedance matching network are obtained, the signals may be filtered **502** to obtain the desired portions of the signal waveforms. In embodiments, the signals may be filtered to obtain the fundamental component of the signals. In embodiments, the type of filtering performed, such as low pass, bandpass, notch, and the like, as well as the filter topology used, such as elliptical, Chebyshev, Butterworth, and the like, may depend on the specific requirements of the system. In some embodiments, no filtering will be required.

[00148] The voltage and current signals may be amplified by an optional amplifier **504**. The gain of the optional amplifier **504** may be fixed or variable. The gain of the amplifier may be controlled manually, electronically, automatically, in response to a control signal, and the like. The gain of the amplifier may be adjusted in a feedback loop, in response to a control algorithm, by the master control algorithm, and the like. In embodiments, required performance specifications for the amplifier may depend on signal strength and desired measurement accuracy, and may be different for different application scenarios and control algorithms.

[00149] The measured analog signals may have a DC offset added to them, **506**, which may be required to bring the signals into the input voltage range of the ADC which for some systems may be 0 to 3.3V. In some systems this stage may not be required, depending on the specifications of the particular ADC used.

[00150] As described above, the efficiency of power transmission between a power generator and a power load may be impacted by how closely matched the output impedance of the generator is to the input impedance of the load. In an exemplary system as shown in Fig. 6A, power may be delivered to the load at a maximum possible efficiency, when the input impedance of the load **604** is equal to the complex conjugate of the internal impedance of the power generator or the power amplifier **602**. Designing the generator or load impedance to obtain a high and/or maximum power transmission efficiency may be called "impedance matching". Impedance matching may be performed by inserting appropriate networks or sets of elements such as capacitors, resistors, inductors, transformers, switches and the like, to form an impedance matching network **606,** between a power generator **602** and a power load **604** as shown in Fig. 6B. In other embodiments, mechanical adjustments and changes in element positioning may be used to achieve impedance matching. As described above for varying loads, the impedance matching network **606** may include variable components that are dynamically adjusted to ensure that the impedance at the generator terminals looking towards the load and the characteristic impedance of the generator remain substantially complex conjugates of each other, even in dynamic environments and operating scenarios. In embodiments, dynamic impedance matching may be accomplished by tuning the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power generator or by tuning a physical component within the power generator, such as a capacitor,as depicted in Fig. 6C. Such a tuning mechanism may be advantageous because it may allow impedance matching between a power generator **608** and a load without the use of a tunable impedance matching network, or with a simplified tunable impedance matching network **606**, such as one that has fewer tunable components for example. In embodiments, tuning the duty cycle, and/or frequency, and/or phase of the driving signal to a power generator may yield a dynamic impedance matching system with an extended tuning range or precision, with higher power, voltage and/or current capabilities, with faster electronic control, with fewer external components, and the like. The impedance matching methods, architectures, algorithms, protocols, circuits, measurements, controls, and the like, described below, may be useful in systems where power generators drive high-Q magnetic resonators and in high-Q wireless power transmission systems as described herein. In wireless power transfer systems a power generator may be a power amplifier driving a resonator, sometimes referred to as a source resonator, which may be a load to the power amplifier. In wireless power applications, it may be preferable to control the impedance matching between a power amplifier and a resonator load to control the efficiency of the power delivery from the power amplifier to the resonator. The impedance matching may be accomplished, or accomplished in part, by tuning or adjusting the duty cycle, and/or the phase, and/or the frequency of the driving signal of the power amplifier that drives the resonator.

[00151] **Efficiency of switching amplifiers**

[00152] Switching amplifiers, such as class D, E, F amplifiers, and the like or any combinations thereof, deliver power to a load at a maximum efficiency when no power is dissipated on the switching elements of the amplifier. This operating condition may be accomplished by designing the system so that the switching operations which are most critical (namely those that are most likely to lead to switching losses) are done when both the voltage across the switching element and the current through the switching element are zero. These conditions may be referred to as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) conditions respectively. When an amplifier operates at ZVS and ZCS either the voltage across the switching element or the current through the switching element is zero and thus no power can be dissipated in the switch. Since a switching amplifier may convert DC (or very low frequency AC) power to AC power at a specific frequency or range of frequencies, a filter may be introduced before the load to prevent unwanted harmonics that may be generated by the switching process from reaching the load and being dissipated there. In embodiments, a switching amplifier may be designed to operate at maximum efficiency of power conversion, when connected to a resonant load, with a nontrivial quality factor (say Q>5), and of a specific impedance $Z_o^* = R_o + jX_o$, which leads to simultaneous ZVS and ZCS. We define $Z_o = R_o - jX_o$ as the characteristic impedance of the amplifier, so that achieving maximum power transmission efficiency is equivalent to impedance matching the resonant load to the characteristic impedance of the amplifier.

[00153] In a switching amplifier, the switching frequency of the switching elements, f_{switch}, wherein $f_{switch} = \omega/2\pi$ and the duty cycle, dc, of the ON switch-state duration of the switching elements may be the same for all switching elements of the amplifier. In this specification, we will use the term “class D” to denote both class D and class DE amplifiers, that is, switching amplifiers with dc<=50%.

[00154] The value of the characteristic impedance of the amplifier may depend on the operating frequency, the amplifier topology, and the switching sequence of the switching elements. In some embodiments, the switching amplifier may be a half-bridge topology and, in some embodiments, a full-bridge topology. In some embodiments, the switching amplifier may be class D and, in some embodiments, class E. In any of the above embodiments, assuming the elements of the bridge are symmetric, the characteristic impedance of the switching amplifier has the form

$$R_o = F_R(dc)/\omega C_a \,, X_o = F_X(dc)/\omega C_a \,, \qquad (1)$$

where dc is the duty cycle of ON switch-state of the switching elements, the functions $F_R(dc)$ and $F_X(dc)$ are plotted in Fig. 7 (both for class D and E), ω is the frequency at which the switching elements are switched, and $C_a = n_a C_{switch}$ where C_{switch} is the capacitance across each switch, including both the transistor output capacitance and also possible external capacitors placed in parallel with the switch, while $n_a = 1$ for a full bridge and $n_a = 2$ for a half bridge. For class D, one can also write the analytical expressions

$$F_R(dc) = sin^2 u/\pi, \quad F_X(dc) = (u - sinu * cosu)/\pi \;, \qquad (2)$$

where $u = \pi(1 - 2 * dc)$, indicating that the characteristic impedance level of a class D amplifier decreases as the duty cycle, dc, increases towards 50%. For a class D amplifier operation with dc=50%, achieving ZVS and ZCS is possible only when the switching elements have practically no output capacitance ($C_a = 0$) and the load is exactly on resonance ($X_o = 0$), while R_o can be arbitrary.

[00155] **Impedance Matching Networks**

[00156] In applications, the driven load may have impedance that is very different from the characteristic impedance of the external driving circuit, to which it is connected. Furthermore, the driven load may not be a resonant network. An Impedance Matching Network (IMN) is a circuit network that may be connected before a load as in Fig. 6B, in order to regulate the impedance that is seen at the input of the network consisting of the IMN circuit and the load. An IMN circuit may typically achieve this regulation by creating a resonance close to the driving frequency. Since such an IMN circuit accomplishes all conditions needed to maximize the power transmission efficiency from the generator to the load (resonance and impedance matching – ZVS and ZCS for a switching amplifier), in embodiments, an IMN circuit may be used between the driving circuit and the load.

[00157] For an arrangement shown in Fig. 6B, let the input impedance of the network consisting of the Impedance Matching Network (IMN) circuit and the load (denoted together from now on as IMN+load) be $Z_l = R_l(\omega) + jX_l(\omega)$. The impedance matching conditions of this network to the external circuit with characteristic impedance $Z_o = R_o - jX_o$ are then $R_l(\omega) = R_o, X_l(\omega) = X_o$.

[00158] **Methods for tunable Impedance Matching of a variable load**

[00159] In embodiments where the load may be variable, impedance matching between the load and the external driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components in the IMN circuit that may be adjusted to match the varying load to the fixed characteristic impedance Z_o of the external circuit (Fig.

6B). To match both the real and imaginary parts of the impedance two tunable/variable elements in the IMN circuit may be needed.

[00160] In embodiments, the load may be inductive (such as a resonator coil) with impedance $R + j\omega L$, so the two tunable elements in the IMN circuit may be two tunable capacitance networks or one tunable capacitance network and one tunable inductance network or one tunable capacitance network and one tunable mutual inductance network.

[00161] In embodiments where the load may be variable, the impedance matching between the load and the driving circuit, such as a linear or switching power amplifier, may be achieved by using adjustable/tunable components or parameters in the amplifier circuit that may be adjusted to match the characteristic impedance Z_o of the amplifier to the varying (due to load variations) input impedance of the network consisting of the IMN circuit and the load (IMN+load), where the IMN circuit may also be tunable (Fig. 6C). To match both the real and imaginary parts of the impedance, a total of two tunable/variable elements or parameters in the amplifier and the IMN circuit may be needed. The disclosed impedance matching method can reduce the required number of tunable/variable elements in the IMN circuit or even completely eliminate the requirement for tunable/variable elements in the IMN circuit. In some examples, one tunable element in the power amplifier and one tunable element in the IMN circuit may be used. In some examples, two tunable elements in the power amplifier and no tunable element in the IMN circuit may be used.

[00162] In embodiments, the tunable elements or parameters in the power amplifier may be the frequency, amplitude, phase, waveform, duty cycle and the like of the drive signals applied to transistors, switches, diodes and the like.

[00163] In embodiments, the power amplifier with tunable characteristic impedance may be a tunable switching amplifier of class D, E, F or any combinations thereof. Combining Equations (1) and (2), the impedance matching conditions for this network are

$$R_l(\omega) = F_R(dc)/\omega C_a \, , X_l(\omega) = F_X(dc)/\omega C_a \qquad (3).$$

[00164] In some examples of a tunable switching amplifier, one tunable element may be the capacitance C_a, which may be tuned by tuning the external capacitors placed in parallel with the switching elements.

[00165] In some examples of a tunable switching amplifier, one tunable element may be the duty cycle *dc* of the ON switch-state of the switching elements of the amplifier. Adjusting the duty cycle, *dc*, via Pulse Width Modulation (PWM) has been used in switching amplifiers to achieve output power control. In this specification, we disclose that PWM may also be used to achieve impedance matching, namely to satisfy Eqs.(3), and thus maximize the amplifier efficiency.

[00166] In some examples of a tunable switching amplifier one tunable element may be the switching frequency, which is also the driving frequency of the IMN+load network and may be designed to be substantially close to the resonant frequency of the IMN+load network. Tuning the switching frequency may change the characteristic impedance of the amplifier and the impedance of the IMN+load network. The switching frequency of the amplifier may be tuned appropriately together with one more tunable parameters, so that Eqs.(3) are satisfied.

[00167] A benefit of tuning the duty cycle and/or the driving frequency of the amplifier for dynamic impedance matching is that these parameters can be tuned electronically, quickly, and over a broad range. In contrast, for example, a tunable capacitor that can sustain a large voltage and has a large enough tunable range and quality factor may be expensive, slow or unavailable for with the necessary component specifications

[00168] <u>Examples of methods for tunable Impedance Matching of a variable load</u>

[00169] A simplified circuit diagram showing the circuit level structure of a class D power amplifier **802**, impedance matching network **804** and an inductive load **806** is shown in Fig. 8. The diagram shows the basic components of the system with the switching amplifier **804** comprising a power source **810,** switching elements **808**, and capacitors. The impedance matching network **804** comprising inductors and capacitors, and the load **806** modeled as an inductor and a resistor.

[00170] An exemplary embodiment of this inventive tuning scheme comprises a half-bridge class-D amplifier operating at switching frequency f and driving a low-loss inductive element $R + j\omega L$ via an IMN, as shown in Fig. 8.

[00171] In some embodiments L' may be tunable. L' may be tuned by a variable tapping point on the inductor or by connecting a tunable capacitor in series or in parallel to the inductor. In some embodiments C_a may be tunable. For the half bridge topology, C_a may be tuned by varying either one or both capacitors C_{switch}, as only the parallel sum of these capacitors matters for the amplifier operation. For the full bridge topology, C_a may be tuned by varying either one, two, three or all capacitors C_{switch}, as only their combination (series sum of the two parallel sums associated with the two halves of the bridge) matters for the amplifier operation.

[00172] In some embodiments of tunable impedance matching, two of the components of the IMN may be tunable. In some embodiments, L' and C_2 may be tuned. Then, Fig. 9 shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier, for $f = 250kHz$, $dc = 40\%$, $C_a = 640pF$ and $C_1 = 10nF$. Since the IMN always adjusts to the fixed characteristic impedance of the amplifier, the output power is always constant as the inductive element is varying.

[00173] In some embodiments of tunable impedance matching, elements in the switching amplifier may also be tunable. In some embodiments the capacitance C_a along with the IMN capacitor C_2 may be tuned. Then, Fig. 10 shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $dc = 40\%$, $C_1 = 10nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 10 that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[00174] In some embodiments of tunable impedance matching, the duty cycle *dc* along with the IMN capacitor C_2 may be tuned. Then, Fig. 11 shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_a = 640pF$, $C_1 = 10nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 11 that C_2 needs to be tuned mainly in response to variations in L and that the output power decreases as R increases.

[00175] In some embodiments of tunable impedance matching, the capacitance C_a along with the IMN inductor L' may be tuned. Then, Fig. 11A shows the values of the two tunable components needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $dc = 40\%$, $C_1 = 10nF$ and $C_2 = 7.5nF$. It can be inferred from Fig. 11A that the output power decreases as R increases.

[00176] In some embodiments of tunable impedance matching, the duty cycle *dc* along with the IMN inductor L' may be tuned. Then, Fig. 11B shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_a = 640pF$, $C_1 = 10nF$ and $C_2 = 7.5nF$ as functions of the varying R of the inductive element. It can be inferred from Fig. 11B that the output power decreases as R increases.

[00177] In some embodiments of tunable impedance matching, only elements in the switching amplifier may be tunable with no tunable elements in the IMN. In some embodiments the duty cycle *dc* along with the capacitance C_a may be tuned. Then, Fig. 11C, shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $f = 250kHz$, $C_1 = 10nF$, $C_2 = 7.5nF$ and $\omega L' = 1000\Omega$. It can be inferred from Fig. 11C that the output power is a non-monotonic function of R. These embodiments may be able to achieve dynamic impedance matching when variations in L (and thus the resonant frequency) are modest.

[00178] In some embodiments, dynamic impedance matching with fixed elements inside the IMN, also when L is varying greatly as explained earlier, may be achieved by varying the driving frequency of the external frequency f (e.g. the switching frequency of a switching amplifier) so that it follows the varying resonant frequency of the resonator. Using the switching frequency f and the switch duty cycle *dc* as the two variable parameters, full impedance matching can be achieved as R and L are varying without the need of any variable components. Then, Fig. 12 shows the values of the two tunable parameters needed to achieve impedance matching as functions of the varying R and L of the inductive element, and the associated variation of the output power (at given DC bus voltage) of the amplifier for $C_a = 640pF$, $C_1 = 10nF$, $C_2 = 7.5nF$ and $L' = 637\mu H$. It can be inferred from Fig. 12 that the frequency f needs to be tuned mainly in response to variations in L, as explained earlier.

[00179] **Tunable Impedance Matching for systems of wireless power transmission**

[00180] In applications of wireless power transfer the low-loss inductive element may be the coil of a source resonator coupled to one or more device resonators or other resonators, such as repeater resonators, for example. The impedance of the inductive element $R + j\omega L$ may include the reflected impedances of the other resonators on the coil of the source resonator. Variations of R and L of the inductive element may occur due to external perturbations in the vicinity of the source resonator and/or the other resonators or thermal drift of components. Variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to relative motion of the devices and other resonators with respect to the source. The relative motion of these devices and other resonators with respect to the source, or relative motion or position of other sources, may lead to varying coupling (and thus varying reflected impedances) of the devices to the source. Furthermore, variations of R and L of the inductive element may also occur during normal use of the wireless power transmission system due to changes within the other coupled resonators, such as changes in the power draw of their loads. All the methods and embodiments disclosed so far apply also to this case in order to achieve dynamic impedance matching of this inductive element to the external circuit driving it.

[00181] To demonstrate the presently disclosed dynamic impedance matching methods for a wireless power transmission system, consider a source resonator including a low-loss source coil, which is inductively coupled to the device coil of a device resonator driving a resistive load.

[00182] In some embodiments, dynamic impedance matching may be achieved at the source circuit. In some embodiments, dynamic impedance matching may also be achieved at the device circuit. When full impedance matching is obtained (both at the source and the device), the effective resistance of the source inductive element (namely the resistance of the source coil R_s plus the reflected impedance from the device) is $R = R_s\sqrt{1 + U_{sd}^2}$. (Similarly the effective resistance of the device inductive element is $R_d\sqrt{1 + U_{sd}^2}$, where R_d is the resistance of the device coil.) Dynamic variation of the mutual inductance between the coils due to motion results in a dynamic variation of $U_{sd} = \omega M_{sd}/\sqrt{R_s R_d}$. Therefore, when both source and device are dynamically tuned, the variation of mutual inductance is seen from the source circuit side as a variation in the source inductive element resistance R. Note that in this type of variation, the

resonant frequencies of the resonators may not change substantially, since L may not be changing. Therefore, all the methods and examples presented for dynamic impedance matching may be used for the source circuit of the wireless power transmission system.

[00183] Note that, since the resistance R represents both the source coil and the reflected impedances of the device coils to the source coil, in Figs. 9-12, as R increases due to the increasing U, the associated wireless power transmission efficiency increases. In some embodiments, an approximately constant power may be required at the load driven by the device circuitry. To achieve a constant level of power transmitted to the device, the required output power of the source circuit may need to decrease as U increases. If dynamic impedance matching is achieved via tuning some of the amplifier parameters, the output power of the amplifier may vary accordingly. In some embodiments, the automatic variation of the output power is preferred to be monotonically decreasing with R, so that it matches the constant device power requirement. In embodiments where the output power level is set by adjusting the DC driving voltage of the power generator, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R may imply that constant power can be kept at the power load in the device with only a moderate adjustment of the DC driving voltage. In embodiments, where the "knob" to adjust the output power level is the duty cycle *dc* or the phase of a switching amplifier or a component inside an Impedance Matching Network, using an impedance matching set of tunable parameters which leads to monotonically decreasing output power vs. R may imply that constant power can be kept at the power load in the device with only a moderate adjustment of this power "knob".

[00184] In the examples of Figs. 9-12, if $R_s = 0.19\Omega$, then the range $R = 0.2 - 2\Omega$ corresponds approximately to $U_{sd} = 0.3 - 10.5$. For these values, in Fig. 14, we show with dashed lines the output power (normalized to DC voltage squared) required to keep a constant power level at the load, when both source and device are dynamically impedance matched. The similar trend between the solid and dashed lines explains why a set of tunable parameters with such a variation of output power may be preferable.

[00185] In some embodiments, dynamic impedance matching may be achieved at the source circuit, but impedance matching may not be achieved or may only partially be achieved at the device circuit. As the mutual inductance between the source and device coils varies, the varying reflected impedance of the device to the source may result in a variation of both the effective resistance R and the effective inductance L of the source inductive element. The methods presented so far for dynamic impedance matching are applicable and can be used for the tunable source circuit of the wireless power transmission system.

[00186] As an example, consider the circuit of Fig. 14, where $f = 250kHz$, $C_a = 640pF$, $R_s = 0.19\Omega$, $L_s = 100\mu H$, $C_{1s} = 10nF$, $\omega L_s^{'} = 1000\Omega$, $R_d = 0.3\Omega$, $L_d = 40\mu H$, $C_{1d} = 87.5nF$, $C_{2d} = 13nF$, $\omega L_d^{'} = 400\Omega$ and $Z_l = 50\Omega$, where *s* and *d* denote the source and device resonators respectively and the system is matched at $U_{sd} = 3$. Tuning the duty cycle *dc* of the switching amplifier and the capacitor C_{2s} may be used to dynamically impedance match the source, as the non-tunable device is moving relatively to the source changing the mutual inductance M between the source and the device. In Fig. 14, we show the required values of the tunable parameters along with the output power per DC voltage of the amplifier. The dashed line again indicates the output power of the amplifier that would be needed so that the power at the load is a constant value.

[00187] In some embodiments, tuning the driving frequency f of the source driving circuit may still be used to achieve dynamic impedance matching at the source for a system of wireless power transmission between the source and one or more devices. As explained earlier, this method enables full dynamic impedance matching of the source, even when there are variations in the source inductance L_s and thus the source resonant frequency. For efficient power transmission from the source to the devices, the device resonant frequencies must be tuned to follow the variations of the matched driving and source-resonant frequencies. Tuning a device capacitance (for example, in the embodiment of Fig. 13 C_{1d} or C_{2d}) may be necessary, when there are variations in the resonant frequency of either the source or the device resonators. In fact, in a wireless power transfer system with multiple sources and devices, tuning the driving frequency alleviates the need to tune only one source-object resonant frequency, however, all the rest of the objects may need a mechanism (such as a tunable capacitance) to tune their resonant frequencies to match the driving frequency.

[00188] **Resonator Thermal Management**

[00189] In wireless energy transfer systems, some portion of the energy lost during the wireless transfer process is dissipated as heat. Energy may be dissipated in the resonator components themselves. For example, even high-Q conductors and components have some loss or resistance, and these conductors and components may heat up when electric currents and/or electromagnetic fields flow through them. Energy may be dissipated in materials and objects around a resonator. For example, eddy currents dissipated in imperfect conductors or dielectrics surrounding or near-by the resonator may heat up those objects. In addition to affecting the material properties of those objects, this heat may be transferred through conductive, radiative, or convective processes to the resonator components. Any of these heating effects may affect the resonator Q, impedance, frequency, etc., and therefore the performance of the wireless energy transfer system.

[00190] In a resonator comprising a block or core of magnetic material, heat may be generated in the magnetic material due to hysteresis losses and to resistive losses resulting from induced eddy currents. Both effects depend on the magnetic flux density in the material, and both can create significant amounts of heat, especially in regions where the flux density or eddy currents may be concentrated or localized. In addition to the flux density, the frequency of the oscillating magnetic field, the magnetic material composition and losses, and the ambient or operating temperature of the magnetic material may all impact how hysteresis and resistive losses heat the material.

[00191] In embodiments, the properties of the magnetic material such as the type of material, the dimensions of the block, and the like, and the magnetic field parameters may be chosen for specific operating power levels and environments to minimize heating of the magnetic material. In some embodiments, changes, cracks, or imperfections in a block of magnetic material may increase the losses and heating of the magnetic material in wireless power transmission applications.

[00192] For magnetic blocks with imperfections, or that are comprised of smaller size tiles or pieces of magnetic material arranged into a larger unit, the losses in the block may be uneven and may be concentrated in regions where there are inhomogeneities or relatively narrow gaps between adjacent tiles or pieces of magnetic material. For example, if an irregular gap exists in a magnetic block of material, then the effective reluctance of various magnetic flux paths through the material may be substantially irregular and the magnetic field may be more concentrated in portions of the block where the magnetic reluctance is lowest. In some cases, the effective reluctance may be lowest where the gap between tiles or pieces is narrowest or where the density of imperfections is lowest. Because the magnetic material guides the magnetic field, the magnetic flux density may not be substantially uniform across the block, but may be concentrated in regions offering relatively lower reluctance. Irregular concentrations of the magnetic field within a block of magnetic material may not be desirable because they may result in uneven losses and heat dissipation in the material.

[00193] For example, consider a magnetic resonator comprising a conductor **1506** wrapped around a block of magnetic material composed of two individual tiles **1502, 1504** of magnetic material joined such that they form a seam **1508** that is perpendicular to the axis of the conductor **1506** loops as depicted in Fig. 15. An irregular gap in the seam **1508** between the tiles of magnetic material **1502, 1504** may force the magnetic field **1512** (represented schematically by the dashed magnetic field lines) in the resonator to concentrate in a sub region **1510** of the cross section of the magnetic material. Since the magnetic field will follow the path of least reluctance, a path including an air gap between two pieces of magnetic material may create an effectively higher reluctance path than one that traverses the width of the magnetic material at a point where the pieces of magnetic materials touch or have a smaller air gap. The magnetic flux density may therefore preferentially flow through a relatively small cross area of the magnetic material resulting in a high concentration of magnetic flux in that small area **1510**.

[00194] In many magnetic materials of interest, more inhomogeneous flux density distributions lead to higher overall losses. Moreover, the more inhomogeneous flux distribution may result in material saturation and cause localized heating of the area in which the magnetic flux is concentrated. The localized heating may alter the properties of the magnetic material, in some cases exacerbating the losses. For example, in the relevant regimes of operation of some materials, hysteresis and resistive losses increase with temperature. If heating the material increases material losses, resulting in more heating, the temperature of the material may continue to increase and even runaway if no corrective action is taken. In some instances, the temperature may reach 100 degrees C or more and may degrade the properties of the magnetic material and the performance of wireless power transfer. In some instances, the magnetic materials may be damaged, or the surrounding electronic components, packaging and/or enclosures may be damaged by the excessive heat.

[00195] In embodiments, variations or irregularities between tiles or pieces of the block of magnetic material may be minimized by machining, polishing, grinding, and the like, the edges of the tiles or pieces to ensure a tight fit between tiles of magnetic materials providing a substantially more uniform reluctance through the whole cross section of the block of magnetic material. In embodiments, a block of magnetic material may require a means for providing a compression force between the tiles to ensure the tiles are pressed tight together without gaps. In embodiments, an adhesive may be used between the tiles to ensure they remain in tight contact.

[00196] In embodiments the irregular spacing of adjacent tiles of magnetic material may be reduced by adding a deliberate gap between adjacent tiles of magnetic material. In embodiments a deliberate gap may be used as a spacer to ensure even or regular separations between magnetic material tiles or pieces. Deliberate gaps of flexible materials may also reduce irregularities in the spacings due to tile movement or vibrations. In embodiments, the edges of adjacent tiles of magnetic material may be taped, dipped, coated, and the like with an electrical insulator, to prevent eddy currents from flowing through reduced cross-sectional areas of the block, thus lowering the eddy current losses in the material. In embodiments a separator may be integrated into the resonator packaging. The spacer may provide a spacing of 1mm or less.

[00197] In embodiments, the mechanical properties of the spacer between tiles may be chosen so as to improve the tolerance of the overall structure to mechanical effects such as changes in the dimensions and/or shape of the tiles due to intrinsic effects (e.g,, magnetostriction, thermal expansion, and the like) as well as external shocks and vibrations. For example, the spacer may have a desired amount of mechanical give to accommodate the expansion and/or contraction of individual tiles, and may help reduce the stress on the tiles when they are subjected to mechanical vibrations, thus helping to reduce the appearance of cracks and other defects in the magnetic material.

[00198] In embodiments, it may be preferable to arrange the individual tiles that comprise the block of magnetic material to minimize the number of seams or gaps between tiles that are perpendicular to the dipole moment of the resonator. In embodiments it may be preferable to arrange and orient the tiles of magnetic material to minimize the gaps between tiles that are perpendicular to the axis formed by the loops of a conductor comprising the resonator.

[00199] For example, consider the resonator structure depicted in Fig. 16. The resonator comprises a conductor **1604** wrapped around a block of magnetic material comprising six separate individual tiles **1602** arranged in a three by two array. The arrangement of tiles results in two tile seams **1606, 1608** when traversing the block of magnetic material in one direction, and only one tile seam **1610** when traversing the block of magnetic material in the orthogonal direction. In embodiments, it may be preferable to wrap the conductor wire **1604** around the block of magnetic material such that the dipole moment of the resonator is perpendicular to the fewest number of tile seams. The inventors have observed that there is relatively less heating induced around seams and gaps **1606, 1608** that are parallel to the dipole moment of the resonator. Seams and gaps that run perpendicular to the dipole moment of the resonator may also be referred to as critical seams or critical seam areas. It may still be desirable, however, to electrically insulate gaps that run parallel to the dipole moment of the resonator (such as **1606** and **1608**) so as to reduce eddy current losses. Uneven contact between tiles separated by such parallel gaps may cause eddy currents to flow through narrow contact points, leading to large losses at such points.

[00200] In embodiments, irregularities in spacing may be tolerated with adequate cooling of the critical seam areas to prevent the localized degradation of material properties when the magnetic material heats up. Maintaining the temperature of the magnetic material below a critical temperature may prevent a runaway effect caused by a sufficiently high temperature. With proper cooling of the critical seam area, the wireless energy transfer performance may be satisfactory despite the additional loss and heating effects due to irregular spacing, cracks, or gaps between tiles.

[00201] Effective heatsinking of the resonator structure to prevent excessive localized heating of the magnetic material poses several challenges. Metallic materials that are typically used for heatsinks and thermal conduction can interact with the magnetic fields used for wireless energy transfer by the resonators and affect the performance of the system. Their location, size, orientation, and use should be designed so as to not excessively lower the perturbed Q of the resonators in the presence of these heatsinking materials. In addition, owing to the relatively poor thermal conductivity of magnetic materials such as ferrites, a relatively large contact area between the heatsink and the magnetic material may be required to provide adequate cooling which may require placement of substantial amount of lossy materials close to the magnetic resonator.

[00202] In embodiments, adequate cooling of the resonator may be achieved with minimal effect on the wireless energy transfer performance with strategic placement of thermally conductive materials. In embodiments, strips of thermally conductive material may be placed in between loops of conductor wire and in thermal contact with the block of magnetic material.

[00203] One exemplary embodiment of a resonator with strips of thermally conductive material is depicted in Fig. 17. Fig. 17A shows the resonator structure without the conducting strips and with the block of magnetic material comprising smaller tiles of magnetic material forming gaps or seams. Strips of thermally conductive **1708** material may be placed in between the loops of the conductor **1702** and in thermal contact with the block of magnetic material **1704** as depicted in Figs. 17B and 17C. To minimize the effects of the strips on the parameters of the resonator, in some embodiments it may be preferable to arrange the strips parallel to the loops of conductor or perpendicular to the dipole moment of the resonator. The strips of conductor may be placed to cover as much or as many of the seams or gaps between the tiles as possible especially the seams between tiles that are perpendicular to the dipole moment of the resonator.

[00204] In embodiments the thermally conductive material may comprise copper, aluminum, brass, thermal epoxy, paste, pads, and the like, and may be any material that has a thermal conductivity that is at least that of the magnetic material in the resonator (~5W/(K-m) for some commercial ferrite materials). In embodiments where the thermally conductive material is also electrically conducting, the material may require a layer or coating of an electrical insulator to prevent shorting and direct electrical contact with the magnetic material or the loops of conductor of the resonator.

[00205] In embodiments the strips of thermally conductive material may be used to conduct heat from the resonator structure to a structure or medium that can safely dissipate the thermal energy. In embodiments the thermally conductive strips may be connected to a heat sink such as a large plate located above the strips of conductor that can dissipate the thermal energy using passive or forced convection, radiation, or conduction to the environment. In embodiments the system may include any number of active cooling systems that may be external or internal to the resonator structure that can dissipate the thermal energy from the thermally conducting strips and may include liquid cooling systems, forced air systems, and the like. For example, the thermally conducting strips may be hollow or comprise channels for coolant that may be pumped or forced through to cool the magnetic material. In embodiments, a field deflector made of a good electrical conductor (such as copper, silver, aluminum, and the like) may double as part of the heatsinking apparatus. The addition of thermally and electrically conducting strips to the space between the magnetic material and the field deflector may have a marginal effect on the perturbed *Q*, as the the electromagnetic fields in that space are typically suppressed by the presence of the field deflector. Such conducting strips may be thermally connected to both the magnetic material and the field deflector to make the temperature distribution among different strips more homogeneous.

[00206] In embodiments the thermally conducting strips are spaced to allow at least one loop of conductor to wrap around the magnetic material. In embodiments the strips of thermally conductive material may be positioned only at some or all of the gaps or seams of the magnetic material. In other embodiments, the strips may be positioned to contact the magnetic material at substantially throughout its complete length. In other embodiments, the strips may be distributed to match the flux density within the magnetic material. Areas of the magnetic material which under normal operation of the resonator may have higher magnetic flux densities may have a higher density of contact with the thermally conductive strips. In embodiments, such as depicted in Fig 17A for example, the highest magnetic flux density in the magnetic material may be observed toward the center of the block of magnetic material and the lower density may be toward the ends of the block in the direction of the dipole moment of the resonator.

[00207] To show how the use of thermally conducting strips helps to reduce the overall temperature in the magnetic material as well as the temperature at potential hot spots, the inventors have performed a finite element simulation of a resonator structure similar to that depicted in Fig. 17C. The structure was simulated operating at a frequency of 235 kHz and comprising a block of EPCOS N95 magnetic material measuring 30 cm x 30 cm x 5 mm excited by 10 turns of litz wire (symmetrically placed at 25 mm, 40 mm, 55 mm, 90 mm and 105 mm from the plane of symmetry of the structure) carrying 40 A of peak current each, and thermally connected to a 50 cm x 50 cm x 4 mm field deflector by means of three 3 x ¾ x 1’ hollow square tubes (1/8” wall thickness) of aluminum (alloy 6063) whose central axes are placed at -

75mm, 0 mm, and +75 from the symmetry plane of the structure. The perturbed Q due to the field deflector and hollow tubes was found to be 1400 (compared to 1710 for the same structure without the hollow tubes). The power dissipated in the shield and tubes was calculated to be 35.6 W, while that dissipated in the magnetic material was 58.3 W. Assuming the structure is cooled by air convection and radiation and an ambient temperature of 24 ˚C, the maximum temperature in the structure was 85 ˚C (at points in the magnetic material approximately halfway between the the hollow tubes) while the temperature in parts of the magnetic material in contact with the hollow tubes was approximately 68 ˚C. By comparison, the same resonator without the thermally conducting hollow tubes dissipated 62.0 W in the magnetic material for the same excitation current of 40 W peak and the maximum temperature in the magnetic material was found to be 111 ˚C.

[00208] The advantage of the conducting strips is more apparent still if we introduce a defect in a portion of the magnetic material that is in good thermal contact with the tubes. An air gap 10 cm long and 0.5 mm placed at the center of the magnetic material and oriented perpendicular to the dipole moment increases the power dissipated in the magnetic material to 69.9 W (the additional 11.6W relative to the previously discussed no-defect example being highly concentrated in the vicinity of the gap), but the conducting tube ensures that the maximum temperature in the magnetic material has only a relative modest increase of 11 ˚C to 96 ˚C. In contrast, the same defect without the conducting tubes leads to a maximum temperature of 161 ˚C near the defect. Cooling solutions other than convection and radiation, such as thermally connecting the conducting tubes body with large thermal mass or actively cooling them, may lead to even lower operational temperatures for this resonator at the same current level.

[00209] In embodiments thermally conductive strips of material may be positioned at areas that may have the highest probability of developing cracks that may cause irregular gaps in the magnetic material. Such areas may be areas of high stress or strain on the material, or areas with poor support or backing from the packaging of the resonator. Strategically positioned thermally conductive strips may ensure that as cracks or irregular gaps develop in the magnetic material, the temperature of the magnetic material will be maintained below its critical temperature. The critical temperature may be defined as the Curie temperature of the magnetic material, or any temperature at which the characteristics of the resonator have been degraded beyond the desired performance parameters.

[00210] In embodiments the heastsinking structure may provide mechanical support to the magnetic material. In embodiments the heatsinking structure may be designed to have a desired amount of mechanical give (e.g., by using epoxy, thermal pads, and the like having suitable mechanical properties to thermally connect different elements of the structure) so as to provide the resonator with a greater amount of tolerance to changes in the intrinsic dimensions of its elements (due to thermal expansion, magnetostriction, and the like) as well as external shocks and vibrations, and prevent the formation of cracks and other defects.

[00211] In embodiments where the resonator comprises orthogonal windings wrapped around the magnetic material, the strips of conducting material may be tailored to make thermal contact with the magnetic material within areas delimited by two orthogonal sets of adjacent loops. In embodiments a strip may contain appropriate indentations to fit around the conductor of at least one orthogonal winding while making thermal contact with the magnetic material at at least one point. In embodiments the magnetic material may be in thermal contact with a number of thermally conducting blocks placed between adjacent loops. The thermally conducting blocks may be in turn thermally connected to one another by means of a good thermal conductor and/or heatsinked.

[00212] Throughout this description although the term thermally conductive strips of material was used as an exemplary specimen of a shape of a material it should be understood by those skilled in the art that any shapes and contours may be substituted without departing from the spirit of the inventions. Squared, ovals, strips, dots, elongated shapes, and the like would all be within the spirit of the present invention.

[00213] Wireless Power Repeater Resonators

[00214] A wireless power transfer system may incorporate a repeater resonator configured to exchange energy with one or more source resonators, device resonators, or additional repeater resonators. A repeater resonator may be used to extend the range of wireless power transfer. A repeater resonator may be used to change, distribute, concentrate, enhance, and the like, the magnetic field generated by a source. A repeater resonator may be used to guide magnetic fields of a source resonator around lossy and/or metallic objects that might otherwise block the magnetic field. A repeater resonator may be used to eliminate or reduce areas of low power transfer, or areas of low magnetic field around a source. A repeater resonator may be used to improve the coupling efficiency between a source and a target device resonator or resonators, and may be used to improve the coupling between resonators with different orientations, or whose dipole moments are not favorably aligned.

[00215] An oscillating magnetic field produced by a source magnetic resonator can cause electrical currents in the conductor part of the repeater resonator. These electrical currents may create their own magnetic field as they oscillate in the resonator thereby extending or changing the magnetic field area or the magnetic field distribution of the source.

[00216] In embodiments, a repeater resonator may operate as a source for one or more device resonators. In other embodiments, a device resonator may simultaneously receive a magnetic field and repeat a magnetic field. In still other embodiments, a resonator may alternate between operating as a source resonator, device resonator or repeater resonator. The alternation may be achieved through time multiplexing, frequency multiplexing, self-tuning, or through a centralized control algorithm. In embodiments, multiple repeater resonators may be positioned in an area and tuned in and out of resonance to achieve a spatially varying magnetic field. In embodiments, a local area of strong magnetic field may be created by an array of resonators, and the positioned of the strong field area may be moved around by changing electrical components or operating characteristics of the resonators in the array.

[00217] In embodiments a repeater resonator may be an air-core capacitively loaded loop magnetic resonator. In embodiments a repeater resonator may be a magnetic-material core capacitively loaded loop magnetic resonator. In embodiments the repeater resonator may be tuned to have a resonant frequency that is substantially equal to that of the frequency of a source or device or at least one other repeater resonator with which the repeater resonator is designed to interact or couple. In other embodiments the repeater resonator may be detuned to have a resonant frequency that is substantially greater than, or substantially less than the frequency of a source or device or at least one other repeater resonator with which the repeater resonator is designed to interact or couple. Preferably, the repeater resonator may be a high-Q magnetic resonator with an intrisic quality factor, Q_r, of 100 or more. In some embodiments the repeater resonator may have quality factor of less than 100. In some embodiments, $\sqrt{Q_s Q_r} > 100$. In other embodiments, $\sqrt{Q_d Q_r} > 100$. In still other embodiments, $\sqrt{Q_{r1} Q_{r2}} > 100$.

[00218] In embodiments, the repeater resonator may include only the inductive and capacitive components that comprise the resonator without any additional circuitry, for connecting to sources, loads, controllers, monitors, control circuitry and the like. In some embodiments the repeater resonator may include additional control circuitry, tuning circuitry, measurement circuitry, or monitoring circuitry. Additional circuitry may be used to monitor the voltages, currents, phase, inductance, capacitance, and the like of the repeater resonator. The measured parameters of the repeater resonator may be used to adjust or tune the repeater resonator. A controller or a microcontroller may be used by the repeater resonator to actively adjust the capacitance, resonant frequency, inductance, resistance, and the like of the repeater resonator. A tunable repeater resonator may be necessary to prevent the repeater resonator from exceeding its voltage, current, temperature, or power limits. A repeater resonator may for example detune its resonant frequency to reduce the amount of power transferred to the repeater resonator, or to modulate or control how much power is transferred to other devices or resonators that couple to the repeater resonator.

[00219] In some embodiments the power and control circuitry of the repeater resonators may be powered by the energy captured by the repeater resonator. The repeater resonator may include AC to DC, AC to AC, or DC to DC converters and regulators to provide power to the control or monitoring circuitry. In some embodiments the repeater resonator may include an additional energy storage component such as a battery or a super capacitor to supply power to the power and control circuitry during momentary or extended periods of wireless power transfer interruptions. The battery, super capacitor, or other power storage component may be periodically or continuously recharged during normal operation when the repeater resonator is within range of any wireless power source.

[00220] In some embodiments the repeater resonator may include communication or signaling capability such as WiFi, Bluetooth, near field, and the like that may be used to coordinate power transfer from a source or multiple sources to a specific location or device or to multiple locations or devices. Repeater resonators spread across a location may be signaled to selectively tune or detune from a specific resonant frequency to extend the magnetic field from a source to a specific location, area, or device. Multiple repeater resonators may be used to selectively tune, or detune, or relay power from a source to specific areas or devices.

[00221] The repeater resonators may include a device into which some, most, or all of the energy transferred or captured from the source to the repeater resonator may be available for use. The repeater resonator may provide power to one or more electric or electronic devices while relaying or extending the range of the source. In some embodiments low power consumption devices such as lights, LEDs, displays, sensors, and the like may be part of the repeater resonator.

[00222] Several possible usage configurations are shown in Figs. 18-20 showing example arrangements of a wireless power transfer system that includes a source **1804** resonator coupled to a power source **1800**, a device resonator **1808** coupled to a device **1802**, and a repeater resonator **1806**. In some embodiments, a repeater resonator may be used between the source and the device resonator to extend the range of the source. In some embodiments the repeater resonator may be positioned after, and further away from the source than the device resonator as shown in Fig. 18B. For the configuration shown in Fig. 18B more efficient power transfer between the source and the device may be possible compared to if no repeater resonator was used. In embodiments of the configuration shown in Fig. 18B it may be preferable for the repeater resonator to be larger than the device resonator.

[00223] In some embodiments a repeater resonator may be used to improve coupling between non-coaxial resonators or resonators whose dipole moments are not aligned for high coupling factors or energy transfer efficiencies. For example, a repeater resonator may be used to enhance coupling between a source and a device resonator that are not coaxially aligned by placing the repeater resonator between the source and device aligning it with the device resonator as shown in Fig. 19A or aligning with the source resonator as shown in Fig. 19B.

[00224] In some embodiments multiple repeater resonators may be used to extend the wireless power transfer into multiple directions or multiple repeater resonators, one after another, to extend the power transfer distance as shown in Fig. 20A. In some embodiments, a device resonator that is connected to a load or electronic device may operate simultaneously, or alternately as a repeater resonator for another device, repeater resonator, or device resonator as shown in Fig. 20B. Note that there is no theoretical limit to the number of resonators that may be used in a given system or operating scenario, but there may be practical issues that make a certain number of resonators a preferred embodiment. For example, system cost considerations may constrain the number of resonators that may be used in a certain application. System size or integration considerations may constrain the size of resonators used in certain applications.

[00225] In some embodiments the repeater resonator may have dimensions, size, or configuration that is the same as the source or device resonators. In some embodiments the repeater resonator may have dimensions, size, or configuration that is different than the source or device resonators. The repeater resonator may have a characteristic size that is larger than the device resonator or larger than the source resonator, or larger than both. A larger repeater resonator may improve the coupling between the source and the repeater resonator at a larger separation distance between the source and the device.

[00226] In some embodiments two or more repeater resonators may be used in a wireless power transfer system. In some embodiments two or more repeater resonators with two or more sources or devices may be used.

[00227] Under Cabinet Lighting with Repeater Resonators

[00228] A repeater resonator may be used to enhance power transfer in lighting applications. One example application of a wireless power transfer system using a repeater resonator is shown in Fig. 21 for a kitchen lighting configuration. Power transfer between a source resonator **2112, 2114** and a device resonator **2106** built into a light **2104** may be enhanced or improved, by an additional repeater resonator **2108** positioned above or next to the lights **2104** or the device resonators **2106**.

[00229] The addition of a larger repeater resonator next to the lights may increase the coupling and power transfer efficiency between the source and the lights and may allow the use of smaller, less obtrusive, and more efficient sources or source resonators, or smaller lights, or device resonators.

[00230] In embodiments, the repeater resonator may be a capacitively loaded loop wound in a planar, flat, rectangular coil sized to fit inside of a cabinet. The repeater resonator may be integrated into a rigid or flexible pad or housing allowing placement of regular cabinet contents on top of the resonator. The repeater resonator may be incorporated in materials typically used to line cabinets such as contact paper, mats, non-skid placemats, and the like. In embodiments the repeater resonator may be designed to attach to the bottom of the cabinet and may be integrated with an attachment mechanism or attachment points for lights. In some embodiments the lights may not require additional device resonators but may directly connect or may be integrated into the repeater resonator.

[00231] In embodiments a device resonator may be built into the light and designed to couple to the repeater resonator. Each light may be integrated with its own device resonator and power and control circuitry described herein. Each light my include appropriate AC to AC, AC to DC, or DC to DC converters and drivers to power and control the light emitting portion of the device. With a repeater resonator above the device resonators embedded in the lights, it may be possible to position the lights anywhere under the cabinet with freedom to point and move the light at specific areas or points under the cabinet. The lights with the integrated resonators and device power and control circuitry may be attached to the bottom of the cabinet using adhesives, or any number of known fasteners.

[00232] In embodiments the source resonator may be integrated in a source that is an electrical outlet cover or any type of wall plate. One example of a source for under cabinet lighting is depicted in Fig. 22. The source resonator **2204** may be integrated into a cover of an electrical outlet **2202** that may cover and fit around an existing outlet **2206**. The power and control circuitry **2208** of the source may be integrated into the cover. The cover may plug-in or connect to one of the outlets allowing the power and control circuitry to be powered directly from the outlet with 120 VAC or 230VAC, and the like, making the source self contained and not requiring any additional wiring, plugs, electrical outlets, junction boxes, and the like. The source may be retrofitted by end users by replacing the receptacle cover with the wireless source cover.

[00233] In embodiments the source resonator may be integrated in a source that plugs into an electrical located under the cabinet. The source may extend out or around the electrical outlet providing an extended volume or box into which the resonator and the power and control circuitry may be integrated.

[00234] In embodiments the source resonator may be designed to replace a complete outlet, where the outlet box or outlet junction box may be used for the power and control circuitry of the source. The cover replacing the outlet may have a similar shape or look as a functional outlet cover but may have a resonator integrated into the perimeter of the cover for transferring wireless power. In embodiments, the cover may be decorative to match the kitchen furnishings. In embodiments, the wireless power circuit may include fault interrupt circuits and other necessary safety, power saving, or regulatory circuits.

[00235] In embodiments the source may include manual or automatic switches or sensors for turning the source on or off and thereby allowing a central place for switching on or off the wirelessly powered lights. The source may be integrated with a timer or light sensor to automatically turn on or off when other lights in the area or turned on or off. For example, the wireless power transfer system may include motion sensors or timers to turn lights on and off according to the detected presence of someone in the room or a certain time of day.

[00236] In one example configuration, a 15 cm by 15 cm source resonator comprising 10 turns of Litz wire and having a quality factor Q greater than 100 is attached to a wall, 23 cm below a hanging cabinet. One round light with an integrated 7.5 cm diameter resonator comprising eight turns of Litz wire and having a quality factor greater than 100 is mounted 23 cm above the source resonator on the bottom of the cabinet. A rectangular repeater resonator, 29 cm by 86 cm, comprising 10 turns of Litz wire and having a quality factor greater than 100 is placed inside a cabinet 24 cm above the source. In this exemplary embodiment, the repeater resonator is used to enhance the efficiency of power transfer between the wall-mounted source and the under-cabinet-mounted lights. Without the repeater resonator, the efficiency of power transfer was less than 5%. With the repeater resonator positioned as described, the efficiency of power transfer was greater than 50%.

[00237] Note that while certain embodiments have been described in terms of one source resonator and one device resonator, systems using multiple sources and/or multiple devices are encompassed by this description. Note too that the resonators may be tuned to be either source resonators, device resonators, or repeater resonators, simultaneously or alternately.

[00238] High Power Resonator Enclosures

[00239] In embodiments, high-Q resonators and power and control circuitry may require special packaging or enclosures that confine high voltages or currents to within the enclosure, that protect the resonators and electrical components from weather, moisture, sand, dust, and other external elements, as well as from impacts, vibrations, scrapes, explosions, and other mechanical shocks. In embodiments, the packaging and enclosure may require special considerations for thermal dissipation to maintain an operating temperature range for the electrical components and the resonator in the enclosure. The packaging and enclosures may require special considerations to reduce losses or energy dissipation in materials or components of the enclosure or surroundings during wireless power transfer.

[00240] An exploded view of one embodiment of a resonator enclosure designed for vehicle charging applications is shown in Fig. 23. The enclosure includes a support plate **2306**, a layer or sheet of a good conductor **2304** a separator piece **2312**, and an enclosure cover **2302** that encloses the resonator **2310**, any or all of the power and control circuitry or electronic components **2308**, and any or all of the enclosure pieces. The support plate **2306** may be made from rigid materials that may support the structural integrity of the enclosure. For example, the support plate may be made from aluminum, steel, cast iron, brass, wood, plastic, any type of composite material, and the like, that provides sufficient rigidity for mounting the cover and sustaining the weight of the resonator which in some embodiments may be as much as 10 kilograms or as much as 20 kilograms. The support plate may comprise mounting holes for mounting the enclosure to a vehicle, in this exemplary embodiment.

[00241] A layer or sheet of good conductor **2304** may be included above the support plate **2306.** In some embodiments the layer or sheet of good conductor may be electrically and/or thermally isolated from the support plate. In other embodiments, it may be preferable to have the layer or sheet of good conductor in electrical and/or thermal contact with the support plate.

[00242] A separator piece **2312** may be located on top of the conductor sheet and may provide a certain separation distance between the layer or sheet of good conductor and the resonator **7910.** The preferable separation between the layer or sheet of good conductor and the resonator may depend on the operating frequency of the resonators, the dimensions of the resonators, the materials comprised by the resonators, the power level that will be transferred, the materials surrounding the resonators, and the like.

[00243] An enclosure cover **2302** may attach to the support plate in a manner that covers or encloses and protects the internal resonator and any internal components. For the enclosure design of Fig. 23, it may be preferable to use a planar resonator such as that depicted in Fig. 2D comprising a conductor wrapped around a rectangular form of magnetic material.

[00244] In embodiments, the layer or sheet of good conductor may comprise any high conductivity materials such as copper, silver, aluminum, and the like. In embodiments, the layer or sheet of good conductor may be thicker than the skin depth of the conductor at the resonator operating frequency. In embodiments, the layer or sheet of good conductor may be thicker than a few times the skin depth of the conductor at the resonator operating frequency. In embodiments, it may be beneficial for the conductor sheet to be larger than the size of the resonator, or to extend beyond the physical extent of the resonator, to shield the resonator from lossy and/or metallic materials that may be outside the enclosure and behind or beneath the support plate **2306**. In embodiments the conductor sheet may extend at least 1cm past the perimeter of the resonator. In other embodiments the conductor sheet may extend at least 2 cm past the perimeter of the resonator. In embodiments, the size of the conducting sheet may be chosen so that the perturbed Q of the mounted resonator is at least 2% of the perturbed Q of the resonator in the unmounted enclosure. In embodiments, the size of the conducting sheet may be chosen so that the perturbed Q of the mounted resonator is at least 10% of the perturbed Q of the resonator in the unmounted enclosure. In other embodiments, the size of the conducting sheet may be chosen so that the perturbed Q of the mounted resonator is at least 25% of the perturbed Q of the resonator in the unmounted enclosure. In embodiments, the size of the conducting sheet may be chosen so that the perturbed Q of the mounted resonator is at least 50% of the perturbed Q of the resonator in the unmounted enclosure. In other embodiments the conductor sheet may be as large as possible and still fitting into the enclosure.

[00245] In embodiments the separator piece, that provides spacing between the conductor sheet and the resonator may be an electrical insulator. In embodiments it may be advantageous for the separator piece to also be a good thermal conductor that may provide for heat dissipation from the resonator. In embodiments the separator piece may include provisions for active cooling comprising air or coolant circulation. The separator piece may be approximately the same size of the resonator of the enclosure or it may be smaller than the resonator. The size of the separator piece may depend on the rigidity of the resonator. In embodiments the separator piece may provide for at least of 0.5 cm of spacing between the resonator and the conductor sheet. In other embodiments the separator piece may provide for at least 1 cm of spacing between the resonator and the conductor sheet. In embodiments, the separator sheet may be shaped to provide more separation for certain portions of the resonator.

[00246] In embodiments, the thickness and material of the separator piece may be chosen so that the perturbed Q of the enclosed resonator is at least 2% of the unperturbed Q. In embodiments, the thickness and material of the separator piece may be chosen so that the perturbed Q of the enclosed resonator is at least 10% of the unperturbed Q. In embodiments, the thickness and material of the separator piece may be chosen so that the perturbed Q of the enclosed resonator is at least 25% of the unperturbed Q. In embodiments, the thickness and material of the separator piece may be chosen so that the perturbed Q of the enclosed resonator is at least 50% of the unperturbed Q.

[00247] In embodiments the enclosure cover may be made of a non-lossy material, preferably of a non-metallic material. In embodiments the enclosure cover may be made from plastic, nylon, Teflon, Rexolite, ABS (Acrylonitrile butadiene styrene), rubber, PVC (Polyvinyl chloride), acrylic, polystyrene, and the like. The material may be chosen to provide for sufficient structural strength to protect the resonator from impact, vibrations, and the sustained load on the cover. The material may be chosen to withstand the operating environment envisioned for the vehicle.

[00248] In embodiments, the enclosure may include additional layers to give added support, rigidity, ruggedness, tolerance, survivability, and the like. In embodiments, the enclosure may be mounted behind a Kevlar sheet or layer, or may be wrapped in Kevlar, in order to withstand bullets, grenades, improvised explosive devices (IEDs), and other weaponry. In environments, the enclosures may comprise special thermal materials, electrical materials, weatherproof materials, optical materials, and the like. In embodiments, the enclosures may include materials or parts to enable safety systems, control systems, monitoring systems, billing systems, and the like.

[00249] In some embodiments the enclosure and packaging may comprise electronic components and circuits. The electronic components may include capacitors, inductors, switches, and the like, of the resonator or capacitors, inductors, switches, and the like, used for impedance matching. In some embodiments the enclosure may enclose any and all parts of the power and control circuitry including amplifiers, rectifiers, controllers, voltage sensors, current sensors, temperature sensors, and the like. The power and control circuitry may require additional cooling or temperature regulation and may require an active cooling system or a connection to an external active cooling system that circulates air or coolant through the enclosure or parts of the enclosure. In embodiments it may be preferable to position or locate the electric or electronic components such that they are not in-line with the dipole moment of the resonator. In embodiments it may be preferable to position or locate the electric or electronic components such that they minimize the perturbed Q of the resonator. In embodiments it may be preferable to position or locate the electric or electronic components underneath the layer or sheet of good conductor in the enclosure, so that the components are shielded from the electromagnetic fields generated by the resonator, and so the resonator is shielded from the lossy portions of the electric and electronic enclosure.

[00250] The enclosures with device resonators may be sized and designed to mount under a car, robot, a cart, a scooter, a motorcycle, a bike, a motorized dolly or platform, a forklift, a piece of construction equipment, a truck, or any other vehicle. A few exemplary mounting and charging configurations are as shown in Fig. 24. The device and source resonators and enclosures may be sized and configured for the appropriate power levels for each application which may be more than 3 kW for a car charging system or may be 500 W for a robot charging system. The device resonator may be configured to receive energy from a source resonator and may be used to recharge batteries, power electronics or devices, and the like of the vehicle. One or more of the enclosures and device resonators **2404** may be mounted on the underside of a vehicle **2402**, in the front of the vehicle, towards the back of the vehicle, and the like as depicted in Fig. 24A. A vehicle may have one enclosure mounted on the underside or it may have multiple resonators with enclosures mounted on the underside.

[00251] In embodiments the resonator and the enclosure may be mounted inside the vehicle. In some vehicles the floor panels, the wheel wells, the spare tire well, or other parts of the car may be constructed of non-lossy or non non-metallic material, such as plastic, carbon fiber, composites, and the like, providing a window for the magnetic fields to pass through while the resonator is inside the car.

[00252] In embodiments, the device resonator may include connections to the vehicle for coolant to provide active cooling or heating to the electronics, components, and resonators inside the enclosure.

[00253] In embodiments the source resonator may be mounted in an enclosure **2408** and integrated into a rubber mat **2410**, or a platform as depicted in Fig. 24B. The rubber mat and enclosure may be placed on the floor of a garage or parking space and may connect to a power source allowing wireless power transfer to a vehicle when a vehicle drives over the pad and the source resonator aligning the device resonator with the source resonator as depicted in Fig. 24C.

[00254] An appropriately size enclosure and resonator **2412** may be designed to fit on the underside of a robot, a remotely controlled or an autonomous vehicle **2414.** The robot may be designed with a docking cage or charging area with a source resonator that may transfer electrical power to the robot.

[00255] **Passive Component Compensation**

[00256] Parameters of electrical components of a wireless power transfer system may be impacted by environmental conditions and/or operating parameters or characteristics of the system. The electrical values and performance of components may be impacted by the temperature, humidity, vibration, and the like of the environment and the wireless power transfer system modules. Changes in temperature for example, may change the capacitance of capacitors, the inductance of the conducting loop inductor, the loss of magnetic materials, and the like. High ambient temperatures may affect electrical components, changing their parameters, which may in turn impact the parameters of the wireless power transfer system. For example, a rise in ambient temperature may increase the capacitance of a capacitor which may shift or change the resonant frequency of a resonator in a wireless power transfer system which in turn may impact efficiency of the power transfer.

[00257] In some applications the changes of parameters due to the operating point or operation of the system may negatively impact wireless power transfer. For example, operating a wireless power transfer system at high power levels may require large electrical currents in components causing increased power dissipation and a temperature increase of the components.

The temperature increase may affect the capacitance, inductance, resistance, and the like of the components and can affect the efficiency, resonant frequency, and the like of the wireless power transfer system.

[00258] In some applications the changes of parameters due to the operating point may create a runaway effect that may negatively impact the performance of the wireless power transfer system. For example, power transfer and operation may heat components of the resonator, such as the capacitors, changing their effective capacitance. The change in capacitance may shift the resonant frequency of the resonator and may cause a drop in power transfer efficiency. The drop in power transfer efficiency may in turn lead to increased heating of components causing further change in capacitance, causing a larger shift in resonant frequency, and so on.

[00259] Fig. 25 shows a plot of the effect of temperature on the capacitance of one commercially available ceramic capacitor. Over the working temperature range of the capacitor, the capacitance value may change by 20%. For some technologies or types of capacitors the capacitance change over the working temperature range may be as much as 50% or 200% or more. The capacitance change as a function of temperature may be a monotonically increasing or decreasing function of temperature or it may be a complex function with one or more maxima and minima at one or more different temperatures. The shape and behavior of the capacitance curve as a function of temperature may be a design parameter for various capacitors technologies and the specific characteristics of a batch of components may be tailored during the design and manufacturing and of certain components. The design of temperature characteristics may be a tradeoff between other parameters such as breakdown voltage, total capacitance, temperature range, and the like and therefore for some applications the capacitance variations over its temperature range may not be completely customizable or optimizable.

[00260] In embodiments of a wireless power transfer system, components such as capacitors may be used in various parts of the system. Electrical components, such as capacitors, for example, may be used as part of the resonator and may set the resonant frequency of the resonator. Electrical components, such as capacitors, may be used in an impedance matching network and in other parts of the circuits as described herein. Changes in parameters of the components due to temperature may affect important characteristics of the wireless power transfer system such as the quality factor of the resonance, resonator frequency and impedance, system efficiency and power delivery and the like.

[00261] In some embodiments the changes in parameter values of components may be compensated with active tuning circuits comprising tunable components. Circuits which monitor the operating environment and operating point of components and system may be integrated in the design. The monitoring circuits may include tunable components that actively compensate for the changes in parameters. For example, a temperature reading may be used to calculate expected changes in capacitance of the system allowing compensation by switching in extra capacitors or tuning capacitors to maintain the desired capacitance.

[00262] In some embodiments the changes in parameters of components may be compensated with active cooling, heating, active environment conditioning, and the like.

[00263] In some embodiments changes in parameters of components may be mitigated by selecting components with characteristics that change in a complimentary or opposite way or direction when subjected to differences in operating environment or operating point. A system may be designed with components, such as capacitors, that have opposite dependence or parameter fluctuations due to temperature, power levels, frequency, and the like. For example, some capacitors or other components of the system may be selected or designed such that they have positive temperature coefficient over a specific temperature range, i.e. the capacitance of the component increases as the temperature increases as shown in Fig. 26A. Some capacitors or other components in the system may be selected or designed such that they have a negative temperature coefficient over a specific temperature range, i.e. the capacitance of the component decreases as the temperature decreases as shown in the second plot of Fig. 26A. By selecting the coefficients appropriately a parallel placement of the two capacitor components with the opposite temperature coefficients may cancel out capacitance variations due to a temperature change. That is, as the capacitance of one component rises due a rise in temperature, the capacitance of the other component will decreases thereby causing a net zero change in the overall capacitance.

[00264] The passive parameter variation compensation may be advantageous for many applications. A passive compensation method may be less expensive and simpler than an active tuning method since no active sensors and no control or controller may be needed. A passive compensation method may be advantageous for applications where traditional controllers and sensors may not function or may be difficult to deploy. High temperatures, high radiation environments may make digital or analog active monitoring and control circuitry impractical or impossible to deploy. A passive compensation method may have higher reliability, may be smaller and less expensive, because it requires fewer net components to achieve system performance stabilization.

[00265] In embodiments the passive compensation method may be combined with active tuning and control methods or systems. Passive compensation may reduce the range over which an active tuning and control method and system may need to operate or compensate. In some embodiments the compensation due to passive components may not be adequate. Variations in thermal coefficients or component values may result in imperfect passive compensation and require additional active tuning. An addition of passive compensation to active tuning method may reduce the required tuning range requirement for the active tuning method. The active tuning may only be required to compensate for small changes and imperfections due to incomplete or partial passive tuning compensation, which may be a small fraction of the total change in parameters that would have required compensation if passive compensation was not included in the system.

[00266] In some embodiments the passive compensation may be implemented over a complete temperature range or operation range of the system. In some embodiments passive compensation may be implemented over a partial temperature or operation range of the system and may require extra tuning from an active tuning system or method.

[00267] Passive compensation may be achieved by various arrangements of components with various thermal parameters using components placed in series, parallel, or in any combination thereof. Passive compensation may be achieved with at least two components having different parameter variations that result from the same environmental or component changes. In some embodiments it may be necessary to use three or more components placed in series, parallel, or any combination thereof to obtain the necessary compensation over a desired range. For example, three components with capacitance curves shown in Fig. 26B may be placed in parallel to achieve passive compensation due to capacitance variations over their complete temperature range. In some embodiments one component may be used to offset the variation of several components.

[00268] In some system embodiments, specific parts of a resonator or system may be exposed to larger parameter fluctuations than other parts. For example, some parts of the circuits may heat more than others, due to localized exposure to sun, a heat source, higher loss components, an enclosure or ventilation block, and the like. It some systems it may be advantageous to distribute the components throughout an enclosure, resonator, circuit, or design to prevent temperature differences of temperature gradients that may affect components in a non-symmetric way.

[00269] In some embodiments the variation of component parameters may be used as a safety mechanism or they may be used to adjust or enhance parameters of power transfer. Components may be chosen or designed to have a specific or predetermined parameter deviation. For example, components, such as capacitors, may be chosen to have a sharp increase or decrease in capacitance beyond, below, or in between a certain temperature value. Capacitors with capacitance curves that have a sharp increase after a specific temperature may used in a device or power capture resonator to automatically detune the device resonator when a threshold temperature is reached. Such a characteristic may be used as a passive safety feature since excessive heat may mean that a device is exceeding its power rating. With proper component selection, the components may detune a device resonator from the resonant frequency of the source reducing the power captured by the device resonator preventing overheating or exceeding power ratings of the devices.

[00270] It is to be understood that the methods and designs outlined in this section are applicable to many different types of electrical components and many types of parameter variations. Although the methods and designs were outlined primarily using capacitors, capacitance, and temperature as the cause of capacitance variations it should be clear to those skilled in the art that the methods and designs may be used in a variety of other components of a wireless power transfer system. Similar behavior may be exploited to compensate for changes of inductance of inductors, capacitance of capacitors, reluctance and loss of magnetic materials, and the like due to temperature variations, voltage levels, current levels, humidity, vibration, barometric pressure, magnetic field strength, electric field strength, exposure to the elements, and the like.

[00271] In some embodiments the variations of parameters of one type of component may be compensated with a variation of another type of component. For example, variations in inductance of the resonator coil may be compensated by temperature variations of other components such as capacitors.

[00272] Electrical elements with the passive compensation may be placed in series, or in parallel, or may be distributed across the inductors of a resonator, a wireless power source, or a wireless power device.

[00273] **Exemplary Resonator Optimizations**

[00274] Properties or performance of resonators and the parameters of wireless power transfer may be affected by changes in the structure, configuration, or operation of the resonators. Changes to the resonator configurations, structures, or operation may be used to optimize the quality factor of the resonator, change the distribution of magnetic fields, reduce losses, or reduce or change the interactions of the resonator with other objects.

[00275] In embodiments, the span of the conductor loops wrapped around magnetic material may affect the magnetic field distribution around the resonator. For a planar resonator structure, or a resonator comprising a conductor wrapped around magnetic material such as depicted in Fig. 27A, the distribution of the magnetic field around the structure may be altered or affected by the span of the conductor winding. A conductor **2704** wrapped around a core of magnetic material **2702** that comprises the resonator structure may be wrapped to have a specific span that covers the magnetic material (the span is depicted by the dimension B in Fig. 27A). This span or dimension may be chosen or modified, for example, by winding the conductor with larger or smaller spacing between individual conductor loops, by varying the number of loops of the conductor around the magnetic material, and the like. The span of the conductor loops, compared to the span or dimension of the magnetic material around which the conductor is wrapped (defined as dimension A in Fig. 27A), may affect the maximum magnetic fields generated or localized around the resonator. For example, when the span of the conductor (dimension B in Fig. 27A) is substantially equal to the length of the magnetic material around which the conductor is wrapped (dimension A in Fig. 27A), the magnetic fields generated or induced in the resonator may be guided and concentrated by the conductor loops to the ends of the magnetic material resulting in relatively high magnetic fields at the endpoints of the magnetic material of the resonator **2710**. If the span of the conductor is much smaller than the length of the magnetic material around which the conductor is wrapped, the magnetic fields generated by the resonator may be concentrated close to the conductor loops resulting in a high magnetic field at those locations. For some systems or applications, the maximum magnetic field strength around the resonator may be a critical parameter and it may be preferable ensure that the magnetic fields are, as much as possible, substantially evenly distributed around the resonator as to eliminate or reduce "magnetic field hot spots" or areas with a relatively high magnetic field compared to other areas around the resonator. For a more uniform field distribution it may be preferable to have the conductor loops span substantially 50% of the total length of the core material and be centered such that equal amounts of the magnetic material extend past the conductor loops in the direction of the dipole moment of the resonator. For systems or applications for which the maximum magnetic field strength around a resonator may be a critical parameter it may be preferable to have the span of the magnetic material to be substantially twice the span of the conductor wrapped around the magnetic material **2704.**

[00276] The differences in distribution of the magnetic fields were observed when finite element method simulations were performed comparing the maximum magnetic field strengths for three different spans of conductor winding on the same magnetic material structure. The simulations modeled wireless power transfer between resonators comprising a block of magnetic material 45 cm wide by 45 cm long by 1 cm thick. The maximum magnetic field strengths were calculated for a configuration transferring 3.3 kW of power at a 21 cm separation between the two resonators operating and resonant at 175 kHz. The fields were calculated for resonators with ten loops of conductor wrapped around the magnetic material with a span of 10 cm, 20 cm, and 30 cm. For the configuration having a conductor span that is roughly half the span of the magnetic material (20 cm)the maximum magnetic field at a distance of 3 cm from the device resonator was 0.75×10^{-3}T RMS. For the conductor spans of 10 cm and 30 cm the maximum magnetic field strengths were both 0.95×10^{-3}T RMS and concentrated at the conductor or at the ends of the magnetic material respectively.

[00277] In systems and applications for which the maximum magnetic field strength may be a critical parameter it may also be preferable to reduce sharp edges or corners of the magnetic material that is wrapped with the conductor loops. It may be preferable to chamfer or radius the corners of the magnetic material.

[00278] In embodiments, positioning power and control circuitry of a resonator in an enclosure comprising magnetic material may be used to optimize the perturbed quality factor of a resonator. External circuit boards or electronics which may be part of the power and control circuitry and are often required to be located near a resonator may affect the parameters of the resonator and the wireless power transfer system. A circuit board or electronic components may load the resonator, induce losses, and affect the capacitance, quality factor, inductance, and the like of the resonator. In embodiments the power and control circuitry, which may include amplifiers, power converters, microprocessors, switches, circuit boards, and other lossy objects may be completely or partially enclosed inside the magnetic material of a resonator which may eliminate or reduce the perturbing effects of the circuitry on the resonator parameters.

[00279] A drawing of one embodiment that uses the magnetic material of the resonator to house electronic components in shown in Fig. 27B. The figure shows the cross section of a magnetic resonator that comprises conductor loops **2704** wrapped around magnetic material **2702.** The magnetic material **2702** may be a hollow shell such that some or all of the power and control circuitry **2708** or other electrical or electronic circuitry and devices may be inside the magnetic material **2702.** Positioning and enclosing circuitry inside the magnetic material of the resonator may eliminate or substantially reduce the perturbing Q of the electronics on the resonator intrinsic Q and the resulting wireless power transfer efficiency compared to the circuitry being placed outside, or close to the resonator but not enclosed in the magnetic material. The magnetic material enclosure may guide the oscillating magnetic fields generated by the conductor of the resonator or by an external source around and away from the circuitry and objects inside the magnetic material thereby preventing the magnetic fields from interacting with the lossy electronic components and/or other objects.

[00280] An exemplary 11 cm x 5 cm x 20 cm magnetic resonator comprising a hollow box of magnetic material with a 0.5 cm wall thickness and twenty loops of Litz wire conductor wrapped around the middle of the magnetic material may be used to demonstrate the impact of lossy materials on the quality factor of a resonator, and the ability of a hollow shell of magnetic material to reduce the perturbing Q of these lossy materials. The intrinsic Q of the exemplary resonator described above had a quality factor, Q=360. A circuit board, which in some embodiments may be a circuit board containing power and control circuitry, placed directly on top of the resonator conductor on the outside of the magnetic material perturbed the resonator and reduced the perturbed quality factor of the structure to 130. However, placing the same circuit board inside the hollow box of magnetic material that comprised the resonator had no effect on the quality factor of the resonator, yielding a perturbed quality factor substantially equal to the intrinsic quality factor.

[00281] In embodiments the magnetic material of a resonator may include holes, notches, gaps, and the like that may be used for ventilation, communication, wiring, connections, mounting holes, cooling, and the like. When the power and control circuitry is configured to be mounted inside the magnetic material holes may be required for connection to the conductor or Litz wire on the outside of the resonator. In embodiments the magnetic material may have additional holes, gaps, spaces, voids, and the like on some or all faces or areas of the magnetic material that may have a minimal impact the quality factor of the resonator. For example, for the design depicted in Fig. 27B the walls of magnetic material **2712** on the opposite ends of the dipole moment of the resonator are less critical than the magnetic material on other sides and in some embodiments where minimizing the weight or cost of the resonator is a priority.

[00282] In embodiments the enclosure of magnetic material may comprise one or more sections, parts, tiles, blocks, or layers of similar or different magnetic materials. In some embodiments the magnetic material may require a substrate or supporting structure on to which the magnetic material is fastened, glued, or attached. In some embodiments, the surface of the magnetic material on the inside of the enclosure may be lined with one or more layers of a good electrical conductor, such as copper, silver, and the like. The inside of the magnetic material enclosure may further be lined with electrical insulator to prevent short circuits between the enclosure and any internal electrical components or devices. In some embodiments it may be preferable for the magnetic material enclosure to be designed from multiple parts such that it may be disassembled or assembled providing access to the internal electronics and components. In embodiments the magnetic material enclosure may be part of, or integrated into, device packaging surrounding the electronics of the device and the power and control circuitry of the resonator. The conductor loops of the resonator may wrap around the whole of the device and magnetic material enclosure. In embodiments, the magnetic material enclosure may be designed with a minimum number of critical seams and/or with cooling structures attached to reduce heating of the magnetic material as described above.

[00283] It should be clear to those skilled in the art that the shape of the magnetic material may include any number of extensions, protrusions, or various geometries while providing an enclosed structure in at least one part of the structure that can be used to completely or partially enclose objects such as circuit boards or electrical components. The designs and configurations may be further extended or modified to include features and designs described herein for resonators using magnetic materials or planar resonators such as using multiple conductors wrapped in orthogonal directions or combining the resonator with a capacitively loaded loop resonator without magnetic material.

[00284] In embodiments, shaping a conductor sheet used for shielding a resonator from loss inducing objects may increase the effective size of the conductor shield or increase the coupling of the resonator without increasing the physical dimensions of the shield. Shaping a conductor shield may also reduce losses or energy dissipation into external objects during wireless power transfer and may increase the quality factor of the resonator in the presence of perturbing objects. As described herein, a sheet of high conductivity material positioned between a high-Q resonator and its surrounding environment may reduce losses due to energy dissipation in objects in the surrounding environment but on the opposite side of the conductor sheet, as shown in Fig. 21. The dimensions of the conductor sheet may be reduced, or the effectiveness of the conductor shield may be improved by shaping the edges of the conductor sheet so they deflect magnetic fields away from objects around the sheet. Fig. 28A depicts a shaped conductor sheet **2802** above a resonator comprising a conductor **2704** wrapped around a block of magnetic material **2702**. In this configuration the conductor sheet **2802** shields any lossy objects above the sheet **2806** from the magnetic fields that may be induced or generated by the resonator below. In embodiments it may be preferable for the conductor sheet to have dimensions larger than the resonator or to extend past the resonator. In applications where the lossy objects are substantially larger than the resonator it may be beneficial to increase the dimensions or the size of the conductor sheet. However, in many applications the dimensions of the conductor sheet may be limited by practical considerations such as weight, available space, cost, and the like. The effectiveness or the effective size of the conductor sheet may be increased without increasing the physical area of the conductor sheet by shaping the edges of the conductor towards the resonator.

[00285] An exemplary embodiment of a conductor shield for the resonator comprising a conductor sheet with shaped edges is shown in Fig. 28A and Fig. 28B. In this exemplary embodiment, the ends the conductor shield **2802** are shaped or bent down, towards the resonator, producing two flaps **2804.** The shaped flaps **2804** of the conductor shield do not add to the overall length of the conductor shield (dimension C in Fig. 28B), but may improve the effective shielding of the conductor from lossy objects above **2806** the conductor shield. The conductor flaps may deflect and guide the magnetic field downwards reducing the field strength on the sides of the resonator and reducing the field interactions with lossy objects that may be above, or near the edge of the conductor shield. This configuration and shape of the conductor shield may increase the effectiveness of the conductor shield without increasing the length (dimension C in Fig. 28B).

[00286] In embodiments the shape, separation, and length of the conductor sheet flaps may be specifically configured for each application, environment, power level, positioning of other resonators, power transfer efficiency requirement, and the like. The length of the conductor shield flaps (dimension A in Fig. 28B) and the separation of the flaps from the resonator (dimension B in Fig. 28B) may be configured and changed to achieve desired power transfer parameters for each application

[00287] In an exemplary embodiment, the effectiveness of the conductor sheet shaping in resonator shielding applications may be demonstrated by finite element method simulations for exemplary shapes and sizes of conductor shield over a resonator comprising a 32 cm x 30 cm x 1 cm block of magnetic material wrapped with 10 loops of a conductor, spanning 20 cm of the magnetic material and wrapped such that the axis of the loops is parallel to the longest edge of the magnetic material. The resonator has a resonant frequency of 175 kHz and is positioned approximately 2 cm from an infinite sheet of steel, with the largest face of the magnetic material of the resonator parallel to the steel sheet. The perturbed quality factor of the resonator in the presence of the infinite sheet of steel may be calculated for various sizes and shapes of the conductor shield positioned between the resonator and the steel sheet. Without any shielding the perturbed quality factor of the resonator is calculated to be approximately 24. Placing a flat (unshaped) 42 cm by 47 cm copper shield between the resonator and the steel sheet improved the perturbed Q of the resonator to 227. Placing a flat (unshaped) 50 cm by 50 cm copper shield between the resonator and the steel sheet improved the perturbed Q of the resonator to 372. Shaping the conductor shields so that they had the same 42 cm by 47 cm, and 50 cm by 50 cm footprints, but now included 2.5 cm flaps on all edges improved the perturbed quality factors to 422 and 574 respectively. This exemplary embodiment shows just one way a conducting sheet may be shaped to improve the perturbed quality factor of a shielded resonator without increasing the footprint of the conductor shield.

[00288] It should be clear to those skilled in the art that the shape, size, and geometry of the conductor flaps may be varied and configured from the exemplary embodiments. In some embodiments the conductor shield may only be shaped on the edges that are perpendicular to the dipole moment of the resonator as depicted in Fig. 28. In some embodiments the conductor shield may be shaped on all sides. In some embodiments the length, size, thickness and the like of the flaps may not be uniform around the resonator. The size of the flap may be smaller for the side of the resonator with fewer loss inducing objects and larger on the side where there may be more loss inducing objects. In some embodiments the flaps may have one or more bends or curves. The flaps may be angled at 90 degrees or less with respect to the plane of the conductor.

[00289] **Repeater Resonator Modes of Operation**

[00290] A repeater resonator may be used to enhance or improve wireless power transfer from a source to one or more resonators built into electronics that may be powered or charged on top of, next to, or inside of tables, desks, shelves, cabinets, beds, television stands, and other furniture, structures, and/or containers. A repeater resonator may be used to generate an energized surface, volume, or area on or next to furniture, structures, and/or containers, without requiring any wired electrical connections to a power source. A repeater resonator may be used to improve the coupling and wireless power transfer between a source that may be outside of the furniture, structures, and/or containers, and one or more devices in the vicinity of the furniture, structures, and/or containers.

[00291] In one exemplary embodiment depicted in Fig. 29 a repeater resonator **2904** may be used with a table surface **2902** to energize the top of the table for powering or recharging of electronic devices **2910, 2916, 2914** that have integrated or attached device resonators **2912.** The repeater resonator **2904** may be used to improve the wireless power transfer from the source **2906** to the device resonators **2912**.

[00292] In some embodiments the power source and source resonator may be built into walls, floors, dividers, ceilings, partitions, wall coverings, floor coverings, and the like. A piece of furniture comprising a repeater resonator may be energized by positioning the furniture and the repeater resonator close to the wall, floor, ceiling, partition, wall covering, floor covering, and the like that includes the power source and source resonator. When close to the source resonator, and configured to have substantially the same resonant frequency as the source resonator, the repeater resonator may couple to the source resonator via oscillating magnetic fields generated by the source. The oscillating magnetic fields produce oscillating currents in the conductor loops of the repeater resonator generating an oscillating magnetic field, thereby extending, expanding, reorienting, concentrating, or changing the range or direction of the magnetic field generated by the power source and source resonator alone. The furniture including the repeater resonator may be effectively "plugged in" or energized and capable of providing wireless power to devices on top, below, or next to the furniture by placing the furniture next to the wall, floor, ceiling, etc. housing the power source and source resonator without requiring any physical wires or wired electrical connections between the furniture and the power source and source resonator. Wireless power from the repeater resonator may be supplied to device resonators and electronic devices in the vicinity of the repeater resonator. Power sources may include, but are not limited to, electrical outlets, the electric grid, generators, solar panels, fuel cells, wind turbines, batteries, super-capacitors and the like.

[00293] In embodiments, a repeater resonator may enhance the coupling and the efficiency of wireless power transfer to device resonators of small characteristic size, non-optimal orientation, and/or large separation from a source resonator. The efficiency of wireless power transfer may be inversely proportional to the separation distance between a source and device resonator, and may be described relative to the characteristic size of the smaller of the source or device resonators. For example, a device resonator designed to be integrated into a mobile device such as a smart phone **2912**, with a characteristic size of approximately 5cm, may be much smaller than a source resonator **2906**, designed to be mounted on a wall, with a characteristic size of 50 cm, and the separation between these two resonators may be 60 cm or more, or approximately twelve or more characteristic sizes of the device resonator, resulting in relatively low power transfer efficiency. However, if a 50 cm x 100 cm repeater resonator is integrated into a table, as shown in Fig. 29, the separation between the source and the repeater may be approximately one characteristic size of the source resonator, so that the efficiency of power transfer from the source to the repeater may be high. Likewise, the smart phone device resonator placed on top of the table or the repeater resonator, may have a separation distance of less than one characteristic size of the device resonator resulting in high efficiency of power transfer between the repeater resonator and the device resonator. While the total transfer efficiency between the source and device must take into account both of these coupling mechanisms, from the source to the repeater and from the repeater to the device, the use of a repeater resonator may provide for improved overall efficiency between the source and device resonators.

[00294] In embodiments, the repeater resonator may enhance the coupling and the efficiency of wireless power transfer between a source and a device if the dipole moments of the source and device resonators are not aligned or are positioned in non-favorable or non-optimal orientations. In the exemplary system configuration depicted in Fig. 29, a capacitively loaded loop source resonator integrated into the wall may have a dipole moment that is normal to the plane of the wall. Flat devices, such as mobile handsets, computers, and the like, that normally rest on a flat surface may comprise device resonators with dipole moments that are normal to the plane of the table, such as when the capacitively loaded loop resonators are integrated into one or more of the larger faces of the devices such as the back of a mobile handset or the bottom of a laptop. Such relative orientations may yield coupling and the power transfer efficiencies that are lower than if the dipole moments of the source and device resonators were in the same plane, for example. A repeater resonator that has its dipole moment aligned with that of the dipole moment of the device resonators, as shown in Fig. 29, may increase the overall efficiency of wireless power transfer between the source and device because the large size of the repeater resonator may provide for strong coupling between the source resonator even though the dipole moments of the two resonators are orthogonal, while the orientation of the repeater resonator is favorable for coupling to the device resonator.

[00295] In the exemplary embodiment shown in Fig. 29, the direct power transfer efficiency between a 50 cm x 50 cm source resonator **2906** mounted on the wall and a smart-phone sized device resonator **2912** lying on top of the table, and approximately 60 cm away from the center of the source resonator, with no repeater resonator present, was calculated to be approximately 19%. Adding a 50 cm x 100 cm repeater resonator as shown, and maintaining the relative position and orientation of the source and device resonators improved the coupling efficiency from the source resonator to the device resonator to approximately 60%. In this one example, the coupling efficiency from the source resonator to the repeater resonator was approximately 85% and the coupling efficiency from the repeater resonator to the device resonator was approximately 70%. Note that in this exemplary embodiment, the improvement is due both to the size and the orientation of the repeater resonator.

[00296] In embodiments of systems that use a repeater resonator such as the exemplary system depicted in Fig. 29, the repeater resonator may be integrated into the top surface of the table or furniture. In other embodiments the repeater resonator may be attached or configured to attach below the table surface. In other embodiments, the repeater resonator may be integrated in the table legs, panels, or structural supports. Repeater resonators may be integrated in table shelves, drawers, leaves, supports, and the like. In yet other embodiments the repeater resonator may be integrated into a mat, pad, cloth, potholder, and the like, that can be placed on top of a table surface. Repeater resonators may be integrated into items such as bowls, lamps, dishes, picture frames, books, tchotchkes, candle sticks, hot plates, flower arrangements, baskets, and the like.

[00297] In embodiments the repeater resonator may use a core of magnetic material or use a form of magnetic material and may use conducting surfaces to shape the field of the repeater resonator to improve coupling between the device and source resonators or to shield the repeater resonators from lossy objects that may be part of the furniture, structures, or containers.

[00298] In embodiments, in addition to the exemplary table described above, repeater resonators may be built into chairs, couches, bookshelves, carts, lamps, rugs, carpets, mats, throws, picture frames, desks, counters, closets, doors, windows, stands, islands, cabinets, hutches, fans, shades, shutters, curtains, footstools, and the like.

[00299] In embodiments, the repeater resonator may have power and control circuitry that may tune the resonator or may control and monitor any number of voltages, currents, phases, temperature, fields, and the like within the resonator and outside the resonator. The repeater resonator and the power and control circuitry may be configured to provide one or more modes of operation. The mode of operation of the repeater resonator may be configured to act only as repeater resonator. In other embodiments the mode of operation of the repeater resonator may be configured to act as a repeater resonator and/or as a source resonator. The repeater resonator may have an optional power cable or connector allowing connection to a power source such as an electrical outlet providing an energy source for the amplifiers of the power and control circuits for driving the repeater resonator turning it into a source if, for example, a source resonator is not functioning or is not in the vicinity of the furniture. In other embodiments the repeater resonator may have a third mode of operation in which it may also act as a device resonator providing a connection or a plug for connecting electrical or electronic devices to receive DC or AC power captured by the repeater resonator. In embodiments these modes be selected by the user or may be automatically selected by the power and control circuitry of the repeater resonator based on the availability of a source magnetic field, electrical power connection, or a device connection.

[00300] In embodiments the repeater resonator may be designed to operate with any number of source resonators that are integrated into walls, floors, other objects or structures. The repeater resonators may be configured to operate with sources that are retrofitted, hung, or suspended permanently or temporarily from walls, furniture, ceilings and the like.

[00301] Although the use of a repeater resonator with furniture has been described with the an exemplary embodiment depicting a table and table top devices it should be clear to those skilled in the art that the same configurations and designs may be used and deployed in a number of similar configurations, furniture articles, and devices. For example, a repeater resonator may be integrated into a television or a media stand or a cabinet such that when the cabinet or stand is placed close to a source the repeater resonator is able to transfer enough energy to power or recharge electronic devices on the stand or cabinet such as a television, movie players, remote controls, speakers, and the like.

[00302] In embodiments the repeater resonator may be integrated into a bucket or chest that can be used to store electronics, electronic toys, remote controls, game controllers, and the like. When the chest or bucket is positioned close to a source the repeater resonator may enhance power transfer from the source to the devices inside the chest or bucket with built in device resonators to allow recharging of the batteries.

[00303] Another exemplary embodiment showing the use of a repeater resonator is depicted in Fig. 30. In this embodiment the repeater resonator may be used in three different modes of operation depending on the usage and state of the power sources and consumers in the arrangement. The figure shows a handbag **3002** that is depicted as transparent to show internal components. In this exemplary embodiment, there may be a separate bag, satchel, pocket, or compartment **3006** inside the bag **3002** that may be used for storage or carrying of electronic devices **3010** such as cell-phones, MP3 players, cameras, computers, e-readers, iPads, netbooks, and the like. The compartment may be fitted with a resonator **3008** that may be operated in at least three modes of operation. In one mode, the resonator **3008** may be coupled to power and control circuitry that may include rechargeable or replaceable batteries or battery packs or other types of portable power supplies **3004** and may operate as a wireless power source for wirelessly recharging or powering the electronic devices located in the handbag **3002** or the handbag compartment **3006**. In this configuration and setting, the bag and the compartment may be used as a portable, wireless recharging or power station for electronics.

[00304] The resonator **3008** may also be used as a repeater resonator extending the wireless power transfer from an external source to improve coupling and wireless power transfer efficiency between the external source and source resonator (not shown) and the device resonators **3012** of the device **3010** inside the bag or the compartment**.** The repeater resonator may be larger than the device resonators inside the bag or the compartment and may have improved coupling to the source.

[00305] In another mode, the resonator may be used as a repeater resonator that both supplies power to electronic devices and to a portable power supply used in a wireless power source. When positioned close to an external source or source resonator the captured wireless energy may be used by a repeater resonator to charge the battery **3004** or to recharge the portable energy source of the compartment **3006** allowing its future use as a source resonator. The whole bag with the devices may be placed near a source resonator allowing both recharging of the compartment battery **3004** and the batteries of the devices **3010** inside the compartment **3006** or the bag **3002.**

[00306] In embodiments the compartment may be built into a bag or container or may be an additional or independent compartment that may be placed into any bag or storage enclosure such as a backpack, purse, shopping bag, luggage, device cases, and the like.

[00307] In embodiments, the resonator may comprise switches that couple the power and control circuitry into and out of the resonator circuit so that the resonator may be configured only as a source resonator, only as a repeater resonator, or simultaneously or intermittently as any combination of a source, device and repeater resonator. An exemplary block diagram of a circuit configuration capable of controlling and switching a resonator between the three modes of operation is shown in Fig. 31. In this configuration a capacitively loaded conducting loop **3008** is coupled to a tuning network **3128** to form a resonator. The tuning network **3128** may be used to set, configure, or modify the resonant frequency, impedance, resistance, and the like of the resonator. The resonator may be coupled to a switching element **3102,** comprising any number of solid state switches, relays, and the like, that may couple or connect the resonator to either one of at least two circuitry branches, a device circuit branch **3104** or a source circuit branch **3106,** or may be used to disconnect from any of the at least two circuit branches during an inactive state or for certain repeater modes of operation**.** A device circuit branch **3104** may be used when the resonator is operating in a repeater or device mode. A device circuit branch **3104** may convert electrical energy of the resonator to specific DC or AC voltages required by a device, load, battery, and the like and may comprise an impedance matching network **3108,** a rectifier **3110**, DC to DC or DC to AC converters **3110,** and any devices, loads, or batteries requiring power **3114.** A device circuit branch may be active during a device mode of operation and/or during a repeater mode of operation. During a repeater mode of operation, a device circuit branch may be configured to drain some power from the resonator to power or charge a load while the resonator is simultaneously repeating the oscillating magnetic fields from an external source to another resonator.

[00308] A source circuit branch **3106** may be used during repeater and/or source mode of operation of the resonator. A source circuit branch **3106** may provide oscillating electrical energy to drive the resonator to generate oscillating magnetic fields that may be used to wirelessly transfer power to other resonators. A source circuit branch may comprise a power source **3122,** which may be the same energy storage device such as a battery that is charged during a device mode operation of the resonator. A source circuit branch may comprise DC to AC or AC to AC converters **3120** to convert the voltages of a power source to produce oscillating voltages that may be used to drive the resonator through additional impedance matching components **3116**. A source circuit branch may be active during a source mode of operation and/or during a repeater mode of operation of the resonator allowing wireless power transfer from the power source **3122** to other resonators. During a repeater mode of operation, a source circuit branch may be used to amplify or supplement power to the resonator. During a repeater mode of operation, the external magnetic field may be too weak to allow the repeater resonator to transfer or repeat a strong enough field to power or charge a device. The power from the power source **3122** may be used to supplement the oscillating voltages induced in the resonator **3008** from the external magnetic field to generate a stronger oscillating magnetic field that may be sufficient to power or charge other devices.

[00309] In some instances, both the device and source circuit branches may be disconnected from the resonator. During a repeater mode of operation the resonator may be tuned to an appropriate fixed frequency and impedance and may operate in a passive manner. That is, in a manner where the component values in the capacitively loaded conducting loop and tuning network are not actively controlled. In some embodiments, a device circuit branch may require activation and connection during a repeater mode of operation to power control and measurement circuitry used to monitor, configure, and tune the resonator.

[00310] In embodiments, the power and control circuitry of a resonator enabled to operate in multiple modes may include a processor **3126** and measurement circuitry, such as analog to digital converters and the like, in any of the components or sub-blocks of the circuitry, to monitor the operating characteristics of the resonator and circuitry. The operating characteristics of the resonator may be interpreted and processed by the processor to tune or control parameters of the circuits or to switch between modes of operation. Voltage, current, and power sensors in the resonator, for example, may be used to determine if the resonator is within a range of an external magnetic field, or if a device is present, to determine which mode of operation and which circuit branch to activate.

[00311] It is to be understood that the exemplary embodiments described and shown having a repeater resonator were limited to a single repeater resonator in the discussions to simplify the descriptions. All the examples may be extended to having multiple devices or repeater resonators with different active modes of operation.

[00312] **Wireless Power Converter**

[00313] In some wireless energy transfer systems and configurations a wireless energy converter may be used to convert the parameters or configurations of wireless power transfer. In some embodiments a system may have one or more sources or one or more devices that are capable or configured to operate and transfer wireless energy with one or more different and possibly incompatible parameters. A wireless energy converter may be used to translate or convert the parameters or characteristics of wireless power transfer allowing energy transfer between sources and devices that may be configured to receive or capture wireless energy with incompatible or different parameters. Note that throughout this disclosure we may use the terms wireless power converter, wireless energy converter, wireless converter, and wireless power conversion, wireless energy conversion, and wireless conversion interchangeably.

[00314] In embodiments a wireless power converter may be used to convert the characteristics of wireless power transfer and allow power transfer between a source and a device that may be designed or configured for wireless energy transfer with different parameters or characteristics. For example, a source resonator may be configured or designed to operate at a specific resonant frequency and may transfer energy via oscillating magnetic fields at that frequency. A device resonator may be configured or designed to operate at a different resonant frequency and may be designed or configured to receive energy wirelessly only if the oscillating magnetic fields are at, or close to, the device resonant frequency. If the resonant frequencies of the source and device are substantially different, very little or no energy may be transferred. A wireless power converter may be used to convert the wireless energy transferred by the source to have characteristics or parameters such that the wireless energy may be utilized by the device. A wireless power converter may, for example, may receive energy via oscillating magnetic fields at one frequency and use the captured energy to generate oscillating magnetic fields at a different frequency that may be utilized and received by the device with a different resonant frequency than the source.

[00315] Fig. 32 shows exemplary functionality and uses of a wireless power converter. In wireless energy transfer systems one or more sources **3210** may generate oscillating magnetic fields **3214** at one or more frequencies. A wireless power converter **3208** may couple to the source **3210** and capture the energy from the oscillating magnetic field **3214** and transfer some or all of the captured energy by generating an oscillating magnetic field **3216** at one or more frequencies that may be different from the source resonator frequencies and that may be utilized by the device **3212**. It is important to note that the wireless power converter **3208** may not need to be located between the source **3210** and the device **3212**, but only in the general vicinity of both the source and device. Note that if a device is configured to operate or receive energy with different parameters or characteristics than what is generated by a source, the device may not receive significant amounts of power from the source, even if the source and device are close together. In embodiments, a wireless power converter may be used to adapt the parameters of the source to parameters that may be received by the device and may increase the efficiency of the wireless power transfer between what would be an incompatible source and device, in the absence of the converter. In some embodiments the wireless power converter may also serve as a repeater resonator and may extend, enhance, or modify the range of the wireless power transfer when it is placed between a source and a device or in the vicinity of the device.

[00316] A wireless power converter may be beneficial for many wireless power systems and applications. In some embodiments the wireless power converter may be used to convert the characteristics of wireless power transfer between normally incompatible resonators or wireless power transfer systems.

[00317] In some embodiments the wireless power converters may be utilized by the wireless power transfer system to manage, separate, or enhance the wireless power distribution between sources and devices of different power demands, power outputs, and the like. In embodiments, some wireless power transfer systems and configurations may employ devices with different power demands. Some devices in a system may have power demands for several hundred watts of power while other devices may require only a few watts of power or less. In systems without a wireless power converter, such differences in power demands and device power requirements may impose additional design constraints and limitations on the hardware and operation of the devices. For example, in a system where all devices are configured to operate at the same frequency, the devices with lower power demands of a few watts may need to be designed to withstand the voltages, currents, and magnetic field strengths equal to those of a device requiring several hundreds of watts of power. In embodiments, circuit components comprised by lower power device resonators may be required to dissipate large amounts of power as heat. One way to reduce the high voltage, current , power, and the like, requirements on lower power devices may be to detune the lower power device resonant frequency from the high power source resonant frequency, or to use frequency hopping or time multiplexing techniques to periodically, or at adjustable intervals, decouple the device from the source. These schemes may reduce the average power received by the device, and may expand the range of components that may be used in the device because components capable of withstanding high voltages, currents, powers, and the like, for short periods of time, may be smaller, less expensive, and more capable than components that must sustain such voltages, currents and powers, for extended periods of time, or for continuous operation.

[00318] In embodiments, such as when the resonant frequency of a device is not tunable, or when the resonant frequency can be tuned to an operating point that supports wireless power transmission between a high power source and a lower power device, a wireless power converter may be used to support wireless power transfer.

[00319] In an exemplary embodiment, a wireless power configuration may wirelessly transfer two hundred watts or more of power from a source in a wall to a television. In such an embodiment, it may be useful to also supply wireless power to television remote controllers, game controllers, additional displays, DVD players, music players, cable boxes, and the like, that may be placed in the vicinity of the television. Each of these devices may require different power levels and may require power levels much lower than is available from the source. In such an embodiment, it may not be possible to adjust the power available at the source without disrupting the operation of the television, for example. In addition, the television remote controllers, game controllers, additional displays, DVD players, music players, cable boxes, and the like, may also be able to receive power from other wireless power sources, such as a lower power energized surface source, situated on a shelf or a table, as shown in Fig. 15 for example.

Without a wireless power converter, it may be necessary to design the wireless power transfer hardware of the lower power devices to withstand the voltages, currents, and magnetic fields generated by a source capable of supplying hundreds of watts to a television, as well as to be efficient when the lower power devices receive power from a lower power energized surface source, for example. Circuits may be designed for the lower power devices that enable this type of operation, but in some embodiments, it may be preferable to optimize the lower power device circuits for operation with lower power sources, and to use a power converter to convert the high power levels available from a high power source to lower power levels, in some region of operation. A wireless power converter may capture some of the wireless energy generated by a high power source, may condition that power according to a variety of system requirements, and may resupply the conditioned power at different frequencies, power levels, magnetic field strengths, intervals, and the like, suitable for reception by the lower power devices referred to in this exemplary embodiment.

[00320] In some embodiments, for example, it may be preferable to operate high power devices requiring 50 watts of power or more at the lower frequencies such as in the range of 100 kHz to 500 kHz. Allowable magnetic field limits for safety considerations are relatively higher, and radiated power levels may be lower at lower operating frequencies. In some embodiments it may be preferable to operate smaller, lower power devices requiring 50 watts of power or less at higher frequencies of 500 kHz or more, to realize higher Q resonators and/or to utilize electric and electronic components such as capacitors, inductors, AC to DC converters, and the like, that may be smaller or more efficient allowing for smaller and/or tighter resonator and power and control circuitry integration.

[00321] In embodiments a wireless power converter may be used to convert wireless power transferred from multiple sources with different parameters to a single source and may be used to convert wireless power parameters to be compatible with more than one device. In embodiments a wireless power converter may be used to amplify a specific wireless power source by converting wireless power from other sources working with different parameters.

[00322] Exemplary embodiments of wireless power transfer system configurations employing wireless power converters are depicted in Fig. 33. As part of the configuration, a wireless power converter **3314** may capture energy from oscillating magnetic fields **3332, 3330**

from one or more sources **3322, 3324** that may be configured or designed to operate with different parameters. The wireless power converter **3314** may capture the energy and generate a magnetic field **3334, 3336, 3338** with one or more different parameters than the sources **3322**, **3324** from which the energy was received and transfer the energy to one or more devices **3316, 3318, 3320**. In another aspect of the configuration, a wireless power converter **3314** may be used to capture energy from one or more sources **3322, 3324** that may be designed to operate with different parameters and generate a magnetic field **3334** with parameters that match the field **3328** of another source **3326** providing "amplification" or a boost to a field from sources **3322, 3324** and fields **3330, 3332** with different parameters.

[00323] In embodiments a wireless power converter may comprise one or more magnetic resonators configured or configurable to capture wireless energy with one or more parameters and one or more resonators configured or configurable to transfer wireless energy with one or more parameters. For example, a wireless power converter designed to convert the frequency parameter of an oscillating magnetic field is depicted in Fig. 34A. The wireless power converter **3412** may have one or more magnetic resonators **3414, 3416** that are tuned or tunable to one or more frequencies. The oscillating voltages generated in the resonator **3414** by the oscillating magnetic fields **3402** may be rectified and used by a DC to AC converter **3408** to drive another resonator **3416** with oscillating currents generating an oscillating magnetic field **3404** with one or more different frequencies. In embodiments the DC to AC converter of the wireless power converter may be tuned or tunable using a controller **3410** to generate a range of frequencies and output power levels.

[00324] In embodiments the oscillating voltages of the receiving resonators **3414** may be converted to oscillating voltages at a different frequency using an AC to AC converter **3418** and used to energize a resonator **3416** of a wireless power converter without first converting the received voltages and currents to DC as depicted in Fig. 34B. In embodiments it may be preferable to configure and design a wireless power converter to convert the frequency of magnetic fields such that the captured and transferred magnetic fields are multiples of one another such that a diode, a nonlinear element, a frequency multiplier, a frequency divider, and the like, may be used to convert the frequency of the captured energy to a different frequency without first converting to a DC voltage.

[00325] In embodiments a wireless power converter may include one or more resonators that are time multiplexed between capturing energy at one frequency and transferring energy at a different frequency. The block diagram of time multiplexed power converter is depicted in Fig. 35. A time multiplexed wireless power converter **3502** may be tuned to capture oscillating magnetic fields **3504**, convert the generated AC energy to DC energy using an AC to DC converter **3514,** and charge an energy storage element **3508** such as a super capacitor, battery, and the like. After a period of time, the resonator **3516** may be tuned to a different frequency and the energy stored in the energy storage element **3508** may be used to power an amplifier or a DC to AC converter **3512** to drive the tuned resonator **3516** with an oscillating voltage at the new resonant frequency thereby generating an oscillating magnetic field. In embodiments the resonator **3516** may change from capturing to transferring power every few milliseconds, seconds, or minutes. The resonator may be configured to change from capturing to transferring of power as soon as energy in the storage element reaches a predetermined level and may switch back to capturing when the energy in the storage element drops below a predetermined level. In embodiments a wireless power converter that converts power from a high power source to a device with low power requirements may only need to capture power for a small fraction of the time multiplexed cycle and slowly transmit power at the required device power level for the remainder of the cycle.

[00326] In an embodiment system utilizing wireless power converters, an area, room, or region may be flooded or energized with low power magnetic fields by multiple sources that may be integrated into walls, ceilings, partitions and the like. Different wireless power converters may be distributed or strategically located at different locations to capture and convert the low power magnetic fields to different frequencies, parameters, and power levels to transfer power to different classes or types of devices within the area. In system embodiments utilizing wireless power converters, sources may be configured or extended to function and operate with a large number of various devices with specialized power demands or configurations without requiring changes or reconfiguration of the sources.

[00327] In embodiments a wireless power converter may not require any additional energy input and may simply convert the parameters and characteristics of wireless power transfer. In embodiments the wireless power converters may have additional energy inputs from batteries, solar panels, and the like that may be used to supplement the energy transferred.

[00328] In embodiments the wireless power converter may be tunable and configurable such that it may be tuned or configured to convert from any number of frequencies or power levels or energy multiplexing schemes to any number of frequencies or power levels or energy multiplexing schemes. It may be adjusted automatically by sensing power levels or frequencies of a source, or the source with the strongest or appropriate magnetic field, for example. The converter may include communication or signaling capability to allow configuration by a source or sources, device or devices, repeater or repeaters, master controller or controllers or other converters, as to parameters of the conversion that may be desired or required. The converter may communicate or signal to a source or sources to turn on or off, or to increase or decrease power levels, depending on the power requirements of the device or devices, repeater or repeaters, to which the converter is transferring energy or for which the converter is adapting, converting, or translating, the characteristics of the wireless power transfer.

[00329] Although many of the specific embodiments of a wireless power converter have been described in terms of a converter that changes the frequency of an oscillating magnetic field it is to be understood that frequency is an exemplary parameter and other parameters may be converted without departing from the spirit of the invention. In embodiments a power converter may change any number of parameters including phase, amplitude, and the like. In some embodiments a wireless power converter may change the sequence or timing of frequency hopping, or allow a single frequency source to power devices that employ or expect a constant or periodic frequency hopping mode of operation. In some embodiments, the converter may use time multiplexing techniques to adjust power levels, power distribution algorithms and sequences, and to implement preferential or hierarchical charging or powering services.

[00330] In embodiments a wireless power converter may convert the parameters of wireless power transfer and may also, or instead, change the distribution of the fields generated by a source field. A wireless power converter may include multi-sized or variable size resonators that may be configured to redistribute the magnetic field of a source to allow or enhance operation with a device of a different size or at different separations. In embodiments a small source resonator may not be the most efficient at transferring power to a large device resonator. Likewise, a large source resonator may not be the most efficient at transferring power to a small device resonator. A wireless power converter may include two or more differently sized resonators that capture and redistribute the magnetic field for improved efficiency of wireless power transfer to device resonators without requiring changes or reconfiguration of the source or device resonators.

[00331] For example, as depicted in Fig. 36A, a wireless power converter **3614** with a large capture resonator **3616** and a small transmitting resonator **3618** may be placed close to a small device resonator **3612** and may improve the wireless power transfer efficiency between a large distant source resonator **3608** and a small device resonator **3612**. Likewise, as depicted in Fig. 36B, a wireless power converter **3614** with a small capture resonator **3618** and a large transmitting resonator **3616** may placed close to a small source resonator **3608** and may improve the wireless power transfer efficiency between a large distant device resonator **3612** and the small source resonator **3608**. The converter resonator may include one or more capture resonators that are sized to maximize the efficiency of wireless power transfer from the source resonator to the converter resonator and one or more transfer resonators that are sized to maximize the efficiency of wireless power transfer from the converter resonator to the device resonator. In some embodiments energy captured by the capture resonator may be used to directly power the transmitting resonator. In embodiments the energy captured by the capture resonator may be converted, modified, metered or amplified before being used to energize the transmitter resonator. A wireless power converter with differently sized resonators may result in improved system efficiency.

[00332] **<u>Vehicle Charging Configurations</u>**

[00333] Wireless power transfer may be used for powering, charging, or delivering electrical energy to a vehicle. As described above, power may be delivered to a vehicle from one or more source resonators generating magnetic fields outside of a vehicle to one or more device resonators on, under, alongside, attached to, and the like, a vehicle, for charging a vehicle battery or for charging or powering electronic systems and devices in or on a vehicle.

[00334] In embodiments the source and device resonators of the vehicle charging system may require specific alignment or may have limits on operating parameters such as separation distance, lateral offset, axial misalignment, and the like. In embodiments the wireless power transfer system may include designs which ensure, enable, monitor, or facilitate that the distance, offset, alignment, and the like are within the specified operating parameters of the system. In embodiments the wireless power transfer system may include designs and systems which enable, monitor, or facilitate that the distance, offset, alignment, and the like are the best feasible or optimum operating characteristics with respect to safety, efficiency, magnitude of power transfer, and the like, for a specific configuration.

[00335] In car embodiments, for example, a device resonator mounted underneath the car may receive power from a source positioned under the car. A car may receive power, charge batteries, power peripherals, and the like from the energy captured by the device resonator by driving or parking over the source. Depending on the size, type, design, orientation, power levels, surroundings, and the like, the car source and the car may need to be positioned within a specific boundary or location with respect to the source. The wireless power transfer system may include features that enable, facilitate, guide, promote, or ensure proper orientation, position, or alignment of the source and device resonators or the vehicle.

[00336] In embodiments a digital camera coupled to a machine vision system may be used to aid or automate source and device resonator alignment. A video camera image of the source and device resonator may be displayed to the user in the vehicle providing guidance as to the location of the source. In some embodiments the camera and machine vision may be coupled with a processing unit and appropriate machine vision algorithms and preprocess alignment and positioning of the car to alert a user with positional information using auditory, vibrational, or visual indicators. The processing and alignment algorithms may include positioning and location information from other systems of the vehicle such that the positioning and location indicators take into account obstructions or position limitations of the car. For example, the processing and alignment algorithms may be coupled to infrared or acoustic sensors in the bumpers of the car to aid in the positioning within the confines of a parking space, garage, and the like.

[00337] In embodiments the camera system or machine vision system may be coupled with a processing unit and appropriate machine vision algorithms used to automate the process or parts of the process of resonator alignment. In some embodiments the source or device may be mounted on robotic, or automated tracks, arms, platforms that move into alignment using the camera for positioning and orientation information. In some embodiments the camera, machine vision algorithms, and processing unit may be coupled to a vehicle's sensors and controls allowing the car to position and park itself in proper alignment with the source.

[00338] In embodiments a camera system or machine vision system may detect, or help to detect obstructions and foreign objects and/or materials between the source and device resonators. In embodiments the camera and machine vision system may constantly monitor the gap and/or vicinity around the source and device for movement, extraneous objects, or any type of undefined or abnormal operating environments or configurations. The system may be designed to stop power or limit power transfer and may be designed to alert the driver, user, or operator when any undefined or abnormal operating environments or configurations are detected by the camera and/or algorithms. In embodiments the camera and machine vision system may be coupled or controlled with self learning or trainable algorithms that can be designed to function in or with a wide variety of environments, vehicles, sources, and systems and may learn or be trained to operate in many environments after periods of supervised operation.

[00339] In embodiments the camera may be mounted in or around the source and may transmit video or processed information wirelessly to electronics or users inside or outside the vehicle. In embodiments the camera may be mounted on the car and may be mounted under the car. In embodiments the camera may be fitted with an automated door or housing that opens only when the alignment procedure is initiated or when the device or source are in close proximity. The mechanical door or housing may open and close only as needed protecting the camera lens and electronics from road debris, water, dirt, and the like.

[00340] In embodiments, transmitted and/or reflected acoustic, microwave, RF, optical, and the like signals may be used to automatically, or with the help of a user, align source and device resonators to within a specified accuracy. The specified accuracy may be a user settable parameter or it may be a parameter that is set by a control system. The settable parameter may be adjusted depending on the time of day, the demand on the electric grid, the cost of electricity (quoted in kW hours for example), the availability of green energy and the like. The settable parameter may be controlled by a utility provider, by a local agency, by the car company, by a services company, by an individual user, and the like.

[00341] In embodiments various sensor systems may be used to aid or automate source and device resonator alignment. Acoustic, pressure, contact, inductive, capacitive, and the like sensors may be located in or around the vehicle to determine the vehicles position and guide the user of operator of the vehicle to establish the best alignment. Various bumpers, lasers, balls, whistles, scrapers, strings, bells, speakers, and the like may also be used as indicators to the users or operators for proper alignment positioning. In embodiments any number of parking guides, or parking assistant devices may be incorporated into the system to help guide or position the vehicle in proper or within the acceptable limits of the source.

[00342] In embodiments one or more pressure, temperature, capacitive, inductive, acoustic, infrared, ultraviolet, and the like sensors may be integrated into the source, device, source housing, vehicle, or surrounding area and may detect, or help to detect obstructions and foreign objects and/or materials between the source and device resonators. In embodiments the sensors and safety system may constantly monitor the gap and/or vicinity around the source and device for movement, extraneous objects, or any type of undefined or abnormal operating environments or configurations. In embodiments, for example, the housing covering the source resonator may include or may be mounted on top of a pressure sensor that monitors the weight or forces pushing on the enclosure of the source resonator. Extra pressure or additional detected weight, for example, may indicate a foreign or unwanted object that is left on top of the source indicating that it may be unsafe or undesirable to operate the wireless power transfer system. The output of the sensor may be coupled to the processing elements of the wireless power transfer system and may be used to stop or prevent wireless power transfer or prevent when the sensor is tripped or detects abnormalities. In embodiments the system and sensor may be coupled to auditory, visual, or vibrational indicator to alert the user or operator of the wireless power transfer interruption. In some embodiments multiple sensors, sensing multiple parameters may be used simultaneously to determine if an obstruction or a foreign object is present. In some embodiments the system may be configured such that at least two sensors must be tripped, such as a pressure and a temperature sensor, for example, to turn off or prevent the wireless power transfer.

[00343] In embodiments a theft deterrent or detection system may be incorporated into the source and device that utilizes the various sensors and cameras of the wireless power transmission system to detect unauthorized use of the vehicle.

[00344] In embodiments the source and device resonators may be of non-identical dimensions and geometries to reduce the dependence on alignment of the efficiency of power transfer between source and device coils. In some embodiments it may be beneficial to make the source resonator larger than the device resonator which may increase the positional tolerance for a desired energy transfer efficiency between the source and device resonators.

[00345] In embodiments various geometries of source and device resonators may be used to reduce the effects of source and device misalignments, such as those that may be associated with parking variations. Parking variations may include forward and back variations, side-to-side variations, angular offsets (when the vehicle is parked at an angle), and the like. For example, in some embodiments the source and device resonators may be prone to variations in alignment in the forward and backward direction of the vehicle. In such embodiments, the use of rectangular source inductive loop, oriented with the long axis of the inductive loop parallel to the direction of vehicle positional uncertainty—paired with a square device resonator having the same short axis length as the source resonator may yield a better average efficiency as a function of source-to-device resonator displacement than would be achieved by a square source resonator with the same dimensions as the device resonator. Note that the long axis of a rectangular source inductive loop may be aligned with the length of the vehicle, if the positional uncertainty is in that direction and may be aligned with the width of the vehicle if side-to-side positional uncertainty is expected. An exemplary embodiment, showing the relative geometries of a source and a device inductive loop for reducing lateral or side-to-side offset dependency on the vehicle is shown in Fig. 37. The figure shows exemplary relative geometries from the top perspective looking down at the car when the source resonator is located below the car and the device resonator is mounted to the underside of the car. To increase the side to side offset capability of the car **3702** the capacitively loaded loop resonators comprising the source and the device may be of different dimensions. The dimensions of the source **3704** may be larger in the in the side to side dimension or axis of the car than the dimensions of the device **3706.**

[00346] In embodiments the effects of misalignment between a source and a device may be mitigated or limited with resonator designs that do not require precise alignment. In embodiments the source and device resonator may include planar resonators or resonators comprising a conductor wrapped around a core of magnetic material. In embodiments the dipole moment of the planar resonators may be oriented perpendicular to the dimension of vehicle position uncertainty. The design of the resonators may allow misalignments perpendicular to the dipole moments of the resonators with minimal effects of power transfer efficiency.

[00347] In embodiments, device resonators and their respective power and control circuitry may have various levels of integration with other electronic and control systems and subsystems of a vehicle. In some embodiments the power and control circuitry and the device resonators may be completely separate modules or enclosures with minimal integration to existing systems of the vehicle, providing a power output and a control and diagnostics interface to the vehicle. In other embodiments the device resonator or parts of the resonator housing may be integrated into the body, structure, undercarriage, panels of the vehicle. In some embodiments the vehicle may be configured to house a resonator and circuit assembly in a recess area underneath the vehicle making the bottom face of the coil enclosure flush with the underbody. In some embodiments the recessed area may be further lined with a highly conductive material such as aluminum, copper, silver and the like which may electroplated, laminated, sprayed, applied, and the like to the recessed area.

[00348] In embodiments the device and source may include active cooling or heating. The device resonator and circuitry may be integrated into a vehicle's cooling system to prevent high temperatures in high power applications. In embodiments the device resonator and circuitry may include its own active cooling or heating system with radiators, fans, liquid coolant, and the like. In embodiments the resonators and power and control circuitry may include various shapes, profiles, protrusions, heat sinks, and the like to aid in temperature control.

[00349] In wireless power systems the vehicle power control system may include a power station reservation system that allows users to reserve charging stations for specific times of the day preventing others users from charging from the source. Central information may be used to let users choose specific power sources or sources which use more environmentally friendly sources of energy such as wind or solar power.

[00350] In embodiments the device resonator of a vehicle may also be used as a power source. In embodiments vehicle power may be used to power a building during a blackout or a cabin without power. In embodiments the vehicle may be used to transmit power to construction vehicles or tools at a job site.

[00351] **Resonator Arrays**

[00352] In embodiments two or more smaller resonators or two or more blocks of magnetic material wrapped with conductor may be arranged to form a larger resonator with an effective size that is larger than the physical size of the smaller resonators or larger than the size of the blocks of magnetic material. A resonator with a larger effective size may have improved coupling over a larger distance, may have a higher efficiency, improved invariance with respect to positional uncertainty, may be able to transfer higher power levels, and the like. An arrangement of smaller resonators or smaller blocks of magnetic material may offer advantages over a single large resonator with respect to manufacturability, cost, scalability, variability, and the like.

[00353] For example, in embodiments as shown in Fig. 38A a planar resonator comprising a conductor **3806** wrapped around a block of magnetic material **3804** may be implemented using one single resonator or one block of magnetic material. The resonator may comprise a substantially continuous block of magnetic material **3804** with a conductor **3806** wrapped around the complete width of the magnetic material forming loops with an enclosed area that are substantially equal to the cross section of the block of magnetic material. The resonator may have an effective size **3802** that is substantially equal to the physical dimensions of the resonator.

[00354] In other embodiments, a planar resonator may be implemented using an arrangement of two or more smaller resonators or blocks of magnetic material. These smaller resonators may comprise smaller blocks of magnetic material wrapped by conductors forming loops with enclosed areas that are substantially equal to the cross sectional area of the blocks of magnetic material. As depicted in an example embodiment in Fig. 38B, two smaller blocks of magnetic material **3808**, each wrapped with a conductor **3810** may be arranged side by side to create a resonator with an effective size **3802** that is substantially equal to the physical dimensions of the arrangement of the two blocks of magnetic material. In embodiments, more than two blocks of magnetic material, each comprising a conductor **3814** wrapped around the blocks **3812,** may be arranged in two or three dimensional arrays as depicted in Fig. 38C and Fig.

38D to create a larger effective resonator that has an effective size **3802** that is substantially equal to the physical dimensions of the arrangement of the blocks of magnetic material. The arrays of smaller resonators may be sized and arranged to create an array with the desired effective size and shape and the array may be used instead of a resonator comprising a single substantially continuous block of magnetic material.

[00355] In embodiments each block of magnetic material wrapped with a conductor may be treated as a separate resonator and may be coupled to additional electrical elements such as capacitors or inductors for parameter adjustment of each individual block. In other embodiments some or all of the conductors wrapped around the blocks of magnetic material may be connected together and coupled to additional electrical elements such as capacitors, inductors, and the like to make the complete arrangement of blocks of magnetic material and conductors a single resonator. In embodiments, the multiple smaller inductive or resonator structures may be connected in series, or in parallel, or in a network of serial and parallel connections.

[00356] In some embodiments, an arrangement of smaller resonators or arrangements of smaller blocks of magnetic material wrapped with a conductor may offer advantages over a single large resonator with respect to manufacturability, cost, scalability, variability, and the like. Magnetic materials are often brittle and a large continuous piece of magnetic material of the resonator, especially for a large resonator, may be susceptible to damage and cracking. Smaller arrays of resonators may be more resistant to vibrations and damage as it may be easier to isolate, reinforce, package, and the like the smaller separate blocks of magnetic material. Likewise, resonators comprising arrays of separate blocks of magnetic material wrapped with a conductor may be more scalable or expandable. A resonator array may be made larger or smaller by adding or removing individual resonator elements or adding or removing individual blocks of magnetic material from the array to increase or decrease the effective size of the resonator depending on the application or deployment configuration. Such arrangements may have advantages in that a large range of resonator effective sizes and shapes may be realized by assembling multiple smaller resonators. Then, a single or a few standard resonators may be stocked, tested, manufactured in volume, and the like, and used to support a wide variety of resonator sizes and shapes supplied for wireless power transfer systems.

[00357] In embodiments, resonators comprising arrangements of smaller resonators or arrangements of blocks of magnetic material may have substantially the same or similar system parameters and wireless power transfer characteristics as a resonator with a larger, substantially continuous piece of magnetic material and may be used to replace or substitute resonators with a larger, substantially continuous piece of magnetic material without a significant impact on the performance or characteristics of wireless power transfer. In one embodiment of a wireless power transfer configuration, the parameters of wireless power transfer between a source and a device were calculated and compared using finite element method models for arrangements for which the device resonator **3904** was implemented as a conductor wrapped around a single substantially continuous blocks of magnetic material (Fig. 39A), for which the device resonator **3904** was implemented as two conductors wrapped around two equally sized blocks of magnetic material (Fig. 39B), and for which the device resonator **3904** was implemented as four conductors wrapped around four equally sized blocks of magnetic material (Fig. 39C). In each configuration of the device, the effective size of the resonator was maintained at 30 cm by 32 cm and was aligned directly 20 cm above a 30 cm by 32 cm source resonator **3902** comprising a conductor wrapped around a substantially continuous block of magnetic material. In the configuration where the device resonator comprises a single block of magnetic material as shown by **3904** in Fig. 39A, the quality factor of the effective device resonator was calculated to be 450, and the coupling factor k between the source and the device was calculated to be 0.124, resulting in a predicted wireless power transfer efficiency of 96.4% between the source and the device. In the configuration where the device resonator comprises two smaller blocks of magnetic material wrapped with a conductor and separated by a 0.1 cm gap of air, as shown by **3904** in Fig. 39B, the quality factor of the effective device resonator was calculated to be 437, and the coupling factor k between the source and the device was calculated to be 0.115 resulting in a predicted wireless power transfer efficiency of 96.2% between the source and the device. In the configuration where the device resonator comprises four smaller blocks of magnetic material wrapped with conductors separated by a 0.2 cm air gap, as shown in Fig. 39C, the quality factor of the effective device resonator was calculated to be 437, the coupling factor k between the source and the device was calculated to be 0.109 resulting in a predicted wireless power transfer efficiency of 96% between the source and the device.

[00358] In embodiments, the parameters of the arrangement of resonators comprising smaller blocks of magnetic material may be affected by the orientation, positioning, arrangement, and configuration of the blocks of magnetic material, the conductor, and the like. One factor found to be of importance is the separation distance between the resonators and the smaller blocks of magnetic material that may comprise a resonator with a larger effective area. For example, consider a resonator with a large effective area comprising four separate smaller resonators with separate blocks of magnetic material is depicted in Fig. 40. The size of the separation distances, labeled as A and B in the Figure, may affect the parameters of the resonator and the efficiency of wireless power transfer. For example, for the configuration and orientation depicted in Fig. 39C and described above, changing both dimension A and dimension B from 0.2 cm to 2cm reduced the efficiency of wireless power transfer from the source to the device from 96% to 94.8%.

[00359] In embodiments it may be preferable to minimize the gaps between the blocks of magnetic material, and may be especially preferable for gaps that are not parallel to the axis of the dipole moments **4002** of the resonators. In embodiments the size of an acceptable or preferable air gap may be dependent on the overall or effective size of the larger resonator, the size of the individual small resonators, power levels, and the like. In embodiments it may be preferable to ensure that the gaps between the blocks of magnetic material be smaller than 10% of the largest dimension of the effective size of the resonator arrangement. In embodiments it may be preferable to ensure that the gaps between the blocks of magnetic material be smaller than 10% of the smallest dimension of the effective size of the resonator.

[00360] In embodiments, the individual smaller resonators or individual blocks of magnetic material wrapped with a conductor and comprising the effective larger resonator may include features, shapes, designs, notches, and the like to enable smaller separation gaps between the smaller blocks of magnetic material or the smaller resonators. In some embodiments, the gap **4106**, as shown in Fig. 41, between adjacent resonators may be reduced reduced by staggering the conductor windings **4104** of the adjacent resonators and allowing a conductor of a neighboring resonator to fit between adjacent windings of the conductor of an another resonator as shown in Fig. 41A**.** In some embodiments the blocks of magnetic material **4102** may be shaped and may have indentations, notches, holes, and the like **4108** to generate an indentation for the conductor **4104** allowing neighboring blocks of magnetic material to come close together and have a separation **4106** that may be smaller than the thickness of the conductor **4104** as shown in Fig. 41B.

[00361] In embodiments the gaps between the resonators may be filled completely or partially with magnetic material blocks, powder, epoxy, and the like. In some embodiments the magnetic material may be different from the blocks of magnetic material that comprise the smaller resonators. In some embodiments it may be preferable to use a flexible form of magnetic material which may prevent or reduce vibration or shock transfer between resonators.

[00362] In embodiments each of the smaller blocks of magnetic material comprising a larger effective resonator may be wrapped with separate pieces of conductors and coupled to separate tuning and matching networks. Each block of magnetic material with a wrapped conductor may be an individual resonator and may be tuned or adjusted independently from the other resonators. In embodiments each resonator or groups of resonators may be coupled to separate power and control circuitry which may be synchronized with an oscillator or clock to ensure all resonators and power and control circuitry are operating at the same frequency and phase or at predetermined frequencies and phase offsets. In embodiments a single power and control circuit may be used for all of the resonators and, in the case of a source, may drive all the resonators in parallel with an oscillating voltage, or in the case of a device, one power and control circuit may capture and convert the oscillating voltage on each resonator conductor.

[00363] In embodiments a single conductor may be used to sequentially wrap all or groups of blocks of magnetic material of the resonator. A conductor may be wrapped around one block of magnetic material and then wrapped around a second and so on providing a series connection between the conductors around multiple blocks of magnetic material. In such embodiments a single power and control circuit may be used to energize the conductor with oscillating current.

[00364] In embodiments the individual smaller resonators and blocks of magnetic material that comprise the resonator arrangement may all have substantially equal dimensions. In other embodiments the blocks of magnetic material may be non-uniform and may have varying thickness or irregular shapes.

[00365] In embodiments, the individual smaller resonators or individual blocks of magnetic material wrapped with a conductor comprising the effective larger resonator may all be wrapped such that all the loops formed by the conductor are coaxial or such that the axis of all the loops formed by the conductors are all parallel. In other embodiments, the conductors may be wrapped such that not all the axes of the loops formed by the conductors are parallel. Some blocks of magnetic material may be wrapped or arranged such the conductor forms loops with an axis that is perpendicular to other loops of other conductors and may be used to form a larger effective resonator that has, or has the capability of having a magnetic dipole moment in more than one direction.

[00366] In embodiments a resonator comprising an arrangement of smaller blocks of magnetic material may include blocks of magnetic material without a wrapped conductor.

[00367] In embodiments of a resonator comprising an arrangement of smaller blocks of magnetic material or smaller resonators the conductors may be selectively energized or activated depending on the power levels, distances, magnetic field limits, and the like during wireless power transfer. In embodiments, for example, a source resonator comprising an arrangement that includes multiple conductors may energize one or only a portion of the conductors when low levels of wireless power transfer are required and may energize most or all of the conductors when high levels of wireless power transfer are required.

[00368] In some embodiments different conductors or different numbers of conductors may be energized depending on the relative location of a source and a device including distance or lateral offset. For example, in embodiments for a vehicle charging application, where the source resonator may be of a larger dimension than the device resonator as shown in Fig. 37, the source resonator may comprise smaller blocks of magnetic material or smaller resonators for which only the blocks and conductors that are directly below the device resonator may be energized. In such an embodiment the source and device resonators may tolerate greater lateral offset while ensuring that the strongest magnetic fields are always confined to the area below the device resonator.

[00369] It is to be understood that any description of blocks of magnetic material, small or large, may refer to blocks that comprise a single monolithic block, tile, structure, crystal, sheet, square, shape, form, and the like, of magnetic material or may comprise any combination of separate smaller blocks, tiles, structures, crystals, sheets, squares, shapes, forms, and the like, of similar or different types of magnetic material that are attached, packed, assembled or secured together to form a substantially continuous form.

[00370] Integrated Resonator-Shield Structures

[00371] In some embodiments and applications of wireless power transfer it may be necessary or desirable to place the resonator structure in close proximity to another object such as electronic devices, circuit boards, metallic objects, lossy objects, and the like. In some embodiments close proximity to some types of objects, such as batteries, circuit boards, lossy objects, and/or metals, may adversely affect or perturb the performance of the power transfer system. Close proximity to some objects may reduce the quality factor of one or more of the resonators involved in the power transfer or may impact the coupling between two or more of the resonators. In some embodiments the electromagnetic fields generated by the resonators may also affect objects around the resonator by, for example, affecting the operation of electronic devices or circuits, or causing heating of the object.

[00372] In embodiments, the effects of the electromagnetic fields on objects as well as the effects of objects on the parameters of wireless power transfer or parameters of the resonators may be at least partially mitigated by introducing a shielding structure between the resonator and the object. In some embodiments, the shielding structure and the resonator may be integrated into one structure allowing the resonator structure to be placed or located near an object with minimal effects on quality factor Q of the resonator and likewise minimal effects on the external object. In some embodiments, an integrated resonator and shield structure may be smaller in at least one dimension, than a structure comprising a resonator and a shield assembled from each of its parts separately.

[00373] As described above, one method of shielding against perturbations from external objects for planar resonators, or resonators comprising a block of magnetic material, is to place a sheet of a good conductive material between the resonator and the object. For example, as shown in Fig. 42A for a planar resonator **4218** comprising a block of magnetic material **4214** and a conductor wire **4216** wrapped all the way around the block **4214**, a shield comprising a sheet of a good electrical conductor **4212** can be positioned next to the resonator **4218** at least partially shielding the resonator from the effects of objects located below **4220** the conductor shield **4212**, and likewise at least partially shielding the objects positioned below **4220** the shield from the effects of the electromagnetic fields that may be generated by the resonator. Note that while the figures may not show the resonator capacitors explicitly, it should be clear the magnetic resonators described here comprise inductive elements comprised of conductive wire loops, either in air or wrapped around a block of magnetic material and capacitive elements, as described above.

[00374] One physical effect of the addition of a conductive shield such as shown in Fig. 42A is the generation of an "image" resonator, on the other side of the conductive shield. One of ordinary skill in the art will recognize that the "image" described here is similar to the image charges and the method of images used to replicate electromagnetic boundary conditions along a perfect conductor. The "image" resonator will have "image" currents that mirror the electromagnetic currents in the resonator itself. In the limit where the size of the shield is infinitely larger than that of the resonator, the electromagnetic fields in the region of the actual resonator can be expressed as a superposition of the fields generated by the actual resonator and those generated by the image resonator. In some embodiments, an additional benefit of including a shield in the resonator structure is that the shield doubles the effective thickness of the magnetic material in the resonator structure.

[00375] In the limit where the shield is flat, large, close to the resonator, and highly conductive, the image currents and the actual currents flowing on the inner conductor segments (between the actual resonator and its image) of the real and image structures will be substantially equal and opposite and the electromagnetic fields they generate are substantially cancelled out . Therefore the wire segments that traverse the bottom of the magnetic material contribute very little to the overall field of the resonator. However, their resistive losses reduce the resonator Q and their thickness increases the overall thickness of the structure.

[00376] In some embodiments, a conductive shield may be placed in proximity to a planar resonator so that a thinner resonator may be used to achieve similar performance to one that is twice as thick. In other embodiments, the thin resonator may be made thinner by moving or removing the segments of the conducting wire that traverse the "bottom" of the magnetic material as shown in Fig. 42A. As described above, these wire segments contribute very little to the overall field, but their resistive losses reduce the resonator Q and their thickness increases the overall thickness of the structure. If these conducting wire segments are to be moved or removed from the resonator structure, an alternate electrical path for the current must be provided so that current can flow through the inductive element and around the magnetic material of the resonator.

[00377] One structure that removes the wire segments from below the block of magnetic material while preserving the shielding is shown in Fig. 42B. In embodiments, current may be returned to the remaining segments of the winding by connecting the remaining winding segments directly to the conductor shield. Such a resonator and shield combination may have a higher-Q than an equivalent resonator not electrically connected to a shield but using a continuous wire wrapping, provided that the current distribution in the newly integrated shield and remaining windings is substantially the same as in the configuration for which the conductor shield is separate. In some embodiments the same current distribution in the integrated resonator-shield structure may be achieved by driving or controlling the current in each conductor wire segment individually. In other embodiments the current distribution may be achieved by separating the shield into optimized individual conductor segments as will be shown below.

[00378] In embodiments it may be advantageous to explicitly incorporate the shield as part of the resonator, and use the conductor shield to carry currents that are directly connected to other parts of the resonator that do not have a shielding function. The integrated resonator-shield structure may eliminate the resistive losses of the image currents generated in the shield and may have an increased quality factor compared to a structure using a separate shield and resonator.

[00379] An example embodiment of the inductive portion of an integrated resonator-shield structure is shown in Fig. 42B and comprises a sheet of conductor **4222,** a block of magnetic material **4204**, and conductor wire segments **4210**. The block of magnetic material **4204** is positioned on top of the sheet of conductor **4222** and the core is partially wrapped by the conductor wire segments **4210.** The ends of the conductor wire segments **4210** are connected to opposite sides of the conductor shield not covered by the block of magnetic material. In other words, the conductor wire segments only partially wrap the block of magnetic material. That is, the conductor wire segments do not wrap completely around the core of magnetic material, but rather connect to the shield or segments of the shield to complete the electrical circuit. In Fig.

42B, the conductor wire segments wrap the top and both sides of the block of magnetic material. The conductor wire segments connect to the conductor shield which is used to complete the electrical connection between the two ends of the conductor wire segment. In embodiments, the conductor shield functions in part as the current path for the conductor wire segments.

[00380] In some embodiments, the overall current distribution in the winding segments and shield of an integrated resonator may differ substantially from that of the separate resonator and shield, even after accounting for the redundant currents. This difference may occur if, for example, the remaining segments of winding are simply electrically connected to the shield (e.g., by soldering), in which case the separate windings would all be connected in parallel with the shield and unless additional power control is added for each conductor wire segment the electrical current would flow preferentially in those portions of winding exhibiting the lowest impedance. Such a current distribution may not be suitable for all applications. For example, such a current distribution may not be the one that minimizes losses and/or optimizes performance.

[00381] One alternative embodiment of the integrated resonator-shield structure is to split the continuous conductor shield into distinct, electrically isolated conductor segments. In Fig. 42C the integrated resonator-shield structure comprises a conductor shield **4208** that is split or divided into distinct isolated conductor segments **4202, 4212,** etc that connect the ends of different conductor wire segments **4210, 4214** forming an electrical connection between the conductor wire segments and creating one continuous conducting path. The net result is a series connection of conductor wire segments alternated with electrically isolated segments of the conductor shield.

[00382] The top, side, front, and exploded views of one embodiment of the integrated resonator-shield structure are shown in Fig. 43A, 43B, 43C, and Fig. 44 respectively. The integrated resonator-shield structure has a conductor shield **4208** that is split into multiple isolated conductor segments or paths, **4202, 4212**, that are connected to the ends of the conductor wire segments **4210, 4214,** the conductor wire segments then partially wrap the block of magnetic material **4204,** or rather the conductor wire segments are routed so as to cover part of the magnetic material**.** As can be seen from the front view of the resonator in Fig. 43C, the conductor wire segment **4210** does not wrap completely around the core of magnetic material

4204, but only wraps partially with the ends of the conductor wire segment **4210** connected to different segments of the conductor shield **4208.**

[00383] In embodiments the conductor shield may be split into multiple segments and shaped such that the shield segments connect to the ends of the wire conductor segments in a manner that results in each or some of the wire conductors segments being connected in series. An exemplary conductor shield with segments shaped and configured to connect the conductor wire segments in series is shown in Fig. 43A. Each segment **4202, 4212** of the conductor shield **4208** is shaped to connect two ends of different conductor wire segments **4210.** In this configuration for example, the individual shield segments and the conductor wire segments are connected in series to produce one continuous conductor that partially wraps around the core of magnetic material **4204** top to bottom, and partially wraps around the block of magnetic material in the plane of the shield**.** For the embodiment shown in Fig. 43A for example, the effective conductor starts at the end of one conductor wire segment **4306** and alternates between the conductor wire segments above the block of magnetic material **4204** and the segments of the conductor shield **4208** that are routed around the block of magnetic material **4204.** The first conductor wire segment **4306** is routed over the block of magnetic material **4204** and connects to a conductor shield segment **4310** which in turn connects to another conductor wire segment **4312** that is routed over the magnetic material and connects to another conductor segment **4314** and the pattern of alternating conductor wire segments and conducting shield segments is repeated until the last conductor segment of the conductor shield **4308**. The combination of the segments on the conductor shield and the conductor wire segments above the core of magnetic material create an effective continuous conductor and thus a magnetic resonator with an integrated shield that may be used to transfer or capture wireless power via oscillating magnetic fields. In embodiments, the conductor wire segments may comprise any type of wire such as solid wire, Litz wire, stranded wire and the like. In other embodiments, the conductor wire segments may comprise PCB or flex circuit traces, conductor strapping, strips, tubing, tape, ink, gels, paint, and the like.

[00384] The structure shown in Fig. 43A, for example, may be used as a source magnetic resonator by coupling the two ends of the effective conductor **4306, 4308** to at least one capacitor and to an oscillating voltage power source. The oscillating currents in the effective conductor will generate oscillating magnetic fields that are substantially parallel to the conductor shield **4208** while providing shielding against lossy objects that may be positioned below **4304** the resonator-shield structure. In addition, the fields that are generated may appear as if they have been generated by a resonator with a block of magnetic material that is twice as thick as the actual dimension of the magnetic material block, *t,* under certain coupling scenarios.

[00385] In embodiments it may preferable to connect the conductor wire segments and the segments of the conductor shield such that when the effective conductor is energized by an external power source or by external oscillating magnetic field, the currents in the conductor wire segments flow substantially in the same direction. For example, for the embodiments shown in Fig. 43A, the conductor wire segments are connected such that when the effective conductor is energized through the conductor ends or leads **4308, 4306,** all the currents in all individual conductor wire segments **4210,**etc. flow in the same direction, wherein the direction depends on the polarity of the induced voltages on the effective conductor. Current flowing in the same direction in the conductor wire segments may generate the strongest magnetic field.

[00386] In embodiments it may be preferable to connect and arrange the segments of the conductor shield such that the currents in the shield segments flow in opposite directions for shield segments above or below the center line **4310** of the resonator. For example, for the embodiment shown in Fig. 43A, the conductor segments of the conductor shield are connected such that when the effective conductor is energized at the ends **4308, 4306**, the electric currents above the center line of the resonator **4310** flow in the opposite rotation than the currents below of the center line of the resonator **4310** in the conductor segments **4202, 4212** of the conductor shield **4208.** That is, if the currents in conductor segments above the center line flow in substantially a clockwise direction, the currents below the center line should flow substantially in the counterclockwise direction. The counter flowing current of the top and bottom portions of the segments of the conducting shield may direct the magnetic fields generated by the respective portions of the resonator to enhance one another or point toward the same direction strengthening the dipole moment of the resonator towards a plane parallel with the conductor shield.

[00387] In embodiments the splitting of the integrated shield that generates the conductor shield segments could be done self-consistently so that the resulting current distribution for the integrated structure would perform at least as well (as defined by the resulting quality factor, effectiveness in shielding, coupling to other resonators, and the like) as the original system comprising a separate resonator and shield.

[00388] In embodiments the shape and distribution of the segments on the conductor shield may be designed to equalize currents in each segment of the shield, in each conductor winding segment, or in sections of combined segments. It may be preferable to shape and divide the conductor shield and shape the shield segments such that each shield segment carries substantially equal electric current. Such a current distribution may reduce proximity losses for example. The shaping of the shield segments is often done so they are narrower or thinner when they are closest to the magnetic material and thicker or wider when they are farther away may be preferable in some embodiments because the distribution arising from driving all of the conductor segments in parallel with equal current best approximates the current distribution in a solid shield located close to a resonator in a non integrated resonator-shield structure.

[00389] The general characteristics of the pattern may be seen in the shield segment shapes in the embodiments shown in Fig. 43A for example. In the Figure, the conductor segments **4212, 4202** span or cover a larger area of the conductor shield **4208** the further the segments are from the block of magnetic material **4204.** In the non-integrated resonator-shield structure, the effective currents induced in the conductor shield increase in areas closer to the block of magnetic material **4204.** Shaping the shield segments as shown in Fig. 43A forces a substantially similar current distribution in the integrated structure with the segmented shield.

[00390] In embodiments, the conductor shield may not need to extend all the way below the block of magnetic material. In embodiments the area under the block of magnetic material may be substantially void of magnetic fields during operation of the resonator. In embodiments the conductor shield may have a hole or cut-out below the block of magnetic material (in the area where the block of magnetic material and the conductor shield would otherwise overlap). In embodiments, removing this shielding material may make the resonator structure lighter or less expensive to make. For example, Fig. 44 depicts an exploded view of an embodiment of a integrated resonator-shield structure which comprises a conductor shield **4208** with a cutout or hole **4402** in the area of the conductor shield which would otherwise overlap with the block of magnetic material **4204** in the assembled structure.

[00391] In embodiments, the effective size of the shield may be larger than the dimensions of the block of magnetic material or the inductive portion of the resonator. The exact dimension of the conductor shield may differ for different applications. For example, in resonators designed for small devices such as cell phones or other hand held electronics, it may be preferable to ensure that the conductor shield extends out at least 15-20% of the length of the block of magnetic material in each direction. This shield extension may provide additional shielding from lossy materials in the cell phones or other hand held electronics. The size of the shield with respect to the magnetic material may depend on the types and sizes of objects the shield is meant to be effective against. The size of the conductor shield may be reduced if, for example, objects or materials behind the shield are not very lossy. In embodiments where the resonator may placed on a plane of very lossy steel, however, it may be desirable to make the shield larger to minimize the losses in the steel and the shield may have dimensions larger than 30% larger or more than the dimensions of the block of magnetic material.

[00392] In embodiments the segmented shield may be manufactured by any number of fabrication techniques, including machining, electroplating, electro-deposition, etching, painting, patterning, and the like and by rigid and flexible printed, deposited, etched, and the like, circuit board techniques. The individual segments on the conductor shield may be formed by machining a single piece of conductor. In embodiments the separation between the shield segments may comprise an additional separation or insulation space, layer or material. Such additional separation may provide improved electrical isolation between the segments and may prevent electrical arcing between two adjacent conductor traces.

[00393] In embodiments, the conductor shield may be further divided into multiple layers of conductors separated by insulators. A layered shield may be used to increase the cross section of conductor over which electrical current flows beyond the limits set by the skin depth effect at the frequency of operation, as described in previous sections. In embodiments, a layered shield may reduce the AC resistance of the conductor segments and increase the quality factor of the structure. A layered shield may also be used to achieve an integrated resonator-shield structure having dipole moments with substantially mutually orthogonal orientations in a thin and compact structure. Such a structure might comprise conductor wire segments that are orthogonal to each other on top of the block of magnetic material. Each layer of shield segment may itself be further divided into narrower tracks of conductor that would provide additional control over the current density profile in the shield and may further increase the performance of the structure.

[00394] In embodiments the segments of the conductor shield may be shaped and arranged to provide a serial connection of the conductor wire segments that are partially wrapped around the block of magnetic material. For example, in the embodiment depicted in Fig. 43A, the shield segments **4212, 4202** are non symmetric with respect to the center line **4310** of the resonator. Each shield trace is shaped to connect the ends of two different conductor wire segments **4210** allowing the conductor wire segments to be arranged in a symmetric pattern with respect to the centerline **4310.** Such an arrangement may be advantageous for some configurations since it may allow simpler conductor wire design. The conductor wires that partially wrap around the block of magnetic material are all parallel and at right angles to the resonator structure. In other embodiments the shield segments may be completely or partially symmetric with respect to the center line of the conductor shield requiring the conductor wire segments that wrap partially above the magnetic core to be arranged such that they connect two ends of different shield segments. For example, in the embodiment depicted in Fig. 45A the shield segments **4506, 4510** of the conductor shield **4502** are symmetric with respect to the center line **4504** of the resonator. A serial connection of the conductor segments is provided by a non symmetric alignment, or diagonal alignment of the conductor wire segments **4508** that partially wrap the block of magnetic material **4204.** In some embodiments a combination of non-symmetrical or symmetric shield segments and non-symmetrical or symmetrical conductor wire segment routing may be used to connect some or all of the conductors in series or parallel depending on the desired properties of the resonator. For example, for some higher power configurations wherein large currents may be present in the resonator it may be advantageous to use an arrangement in which at least some of the conductor wire segments are connected in parallel to reduce losses in the conductors.

[00395] In embodiments the conductor wire segments that partially wrap the block of magnetic material may be comprised of individual wires or braided wires such as Litz wire. In embodiments the conductor wires may be comprised of flex circuits or traces or printed circuits or traces and may be shaped to fold over the block of magnetic material and may have appropriate contacts or attachments to make electrical connections with the conductor segments of the conductor shield. For example, Fig. 45B depicts an exemplary embodiment in which the conductor wire segment is integrated into a single piece **4514** that may be a printed circuit board, a flex circuit, and the like, and is formed to fold over the block of magnetic material **4204** and make appropriate electrical contacts with the conductor segments of the conductor shield **4502.**

[00396] In embodiments, the shield and conductor wire segments may be fabricated in the same process, potentially improving reproducibility and performance while reducing manufacturing costs. In embodiments, an integrated shield and conductor wire segments structure may be fabricated as a flexible PCB, and the resonator structure may be completed by simply inserting the block of magnetic material within the integrated shield and winding, and then connecting the resulting structure to the appropriate circuitry. In the exemplary embodiment depicted in Fig. 46B, the complete structure of the conductor shield **4614** with the conductor segments (not shown) and the conductor wire part **4612** comprising individual conductor segments (not shown) may be one printed circuit board wherein the conductor wire part **4612** is bent or shaped to facilitate or support the placement of a block of magnetic material.

[00397] In embodiments, some or all of the supporting circuitry of the resonator may be fabricated on the same printed circuit board as the conductor shield of the integrated resonator-shield structure. For example, one side of the printed circuit board may have the printed conductor traces of the conductor shield while the other side may have electronic components and printed traces and may be used to contain the power and control circuitry for the resonators.

[00398] In embodiments, the block of magnetic material may be hollow or may have a cavity on the side facing the conductor shield where the effective magnetic fields or the resonator are minimal. The cavity in the magnetic material may be used to house electric or electronic components such as amplifiers or rectifiers used to power and control the resonator. The electronic components may be located in the cavity without significantly affecting the properties and parameters of the resonators and likewise not being significantly affected by the magnetic fields of the resonator. For example, Fig. 46A depicts an exemplary integrated resonator-shield structure wherein the bottom side **4608**, or the side that faces the conductor shield **4502** of the magnetic material **4602** is shaped to have a cavity **4604** into which components or electronic devices may be located. Placing the components in the cavity **4604** may provide for an integrated resonator-shield structure with the power and control circuitry designed under the magnetic material and shield with minimal or no impact on the height or thickness of the resonator structure. In some embodiments, an antenna or the like may be placed in the cavity and may be operated at a frequency where the magnetic material is substantially transparent or at least not an effective shield. In such embodiments, the antenna may suffer little attenuation from the presence of the resonator.

[00399] In embodiments, the conductor shield of the integrated resonator-shield structure may have additional bends, curves, flaps, and the like to enhance, improve, or alter the magnetic fields generated or affecting the resonator. The conductor shield of the integrated resonator-shield structure may have any of the bends, curves, flaps and the like that were described herein for the designs comprising a separate resonator and conductor shield. For example, similarly to the conductor shield depicted in Fig. 28A in which the conductor shield **2802** is shaped to have flaps **2804**, the conductor shield of the integrated resonator-shield structure may be shaped to include flaps that extend towards the block of magnetic material which may increase the effective size of the integrated shield without requiring a larger size conductor shield.

[00400] In embodiments, the design of the integrated resonator-shield structure may be sized, modified, configured, and the like to operate at specific configurations, power levels, frequencies, orientations, environments, and the like which may be required for specific applications. The number of conductor wire segments, the number of separate conductor segments on the conductor shield, the wire gauge, the thickness of the conductor shield, the thickness of the magnetic material, the dimensions of the shield, and the like may all be modified and manipulated to meet specific design requirements.

[00401] In embodiments, the integrated resonator-shield structure may be modified and extended to structures that have more than one magnetic dipole moment. The block of magnetic material may be partially wrapped with conductor wire segments in orthogonal directions or in non-parallel directions with the segments of the conductor shield arranged to connect the conductor wire segments in a serial or parallel or switched configuration. For example, an exemplary embodiment of an integrated resonator-shield structure having two orthogonal dipole moments is shown in Fig. 47. In the embodiment a block of magnetic material **4704** with four protrusions **4708** is partially wrapped with conductor wire segments **4706** that extend around the block of magnetic material **4704** and connect to the conductor segments **4710** of the conductor shield **4702** of the structure. The shield segments **4710** may be shaped to connect the conductor wire segments **4706** in series, in parallel, or may comprise switches so that different dipole moments can be individually excited. The structure has conductor wire segments wrapping the block of magnetic material in orthogonal directions and is capable of producing two orthogonal magnetic dipole moments that are each parallel to the surface of the conductor shield. The segments of the conductor shield provide for a continuous current path while eliminating losses associated with non-integrated shields used to shield a resonator from perturbating objects that may be located below **4712** the structure.

[00402] **Medical and Surgical Applications**

[00403] Wireless power transfer may be used in hospital and operating room environments. A large number of electric and electronic equipment is used in hospitals and operating rooms to monitor patients, administer medications, perform medical procedures, maintain administrative and medical records, and the like. The electric and electronic equipment is often moved, repositioned, moved with a patient, or attached to a patient. The frequent movement may result in problems related to power delivery to the devices. Equipment and electronic devices that are often moved and repositioned may create a power cable hazards and management problem due to cables that become tangled, strained, unplugged, that become a tripping hazard, and the like. Devices with a battery backup that are capable of operating for a period of time without a direct electrical connection require frequent recharging or plugging and unplugging from electrical outlets every time a device is used or repositioned. Wireless power transfer may be used to eliminate the problems and hazards of traditional wired connection in hospital and operating room environments.

[00404] Wireless power transfer may be used to power surgical robots, equipment, sensors, and the like. Many medical procedures and surgical operations utilize robots or robotic equipment to perform or aid in medical procedures or operations. Wireless power transfer may be used to transfer power to the robotic equipment, to parts of the equipment, or to instruments or tools manipulated by the equipment which may reduce the potentially hazardous and troublesome wiring of the systems.

[00405] One example configuration of a surgical robot utilizing wireless power transfer is shown in Fig. 48. The figure depicts a surgical robot **4806** and an operating bed **4804**. In some embodiments the surgical robot may receive power wirelessly for operation or charging its battery or energy storage system. The received power may be distributed to systems or parts such as motors, controllers, and the like via conventional wired methods. The surgical robot may have a device resonator in its base **4816**, neck **4802**, main structure **4808**, and the like for capturing oscillating magnetic energy generated by a source. In some embodiments the robot may be wirelessly powered from a source **4814** that is integrated, attached, or next to the operating bed.

[00406] In some embodiments the source resonator or the device resonator may be mounted on an articulating arm, or a moving or configurable extension as depicted in Fig. 49. The arm or moving extension **4902** may be configured to respond to positional changes of the robot, power demands, or efficiency of the wireless power transfer to reposition the source or the device to ensure that adequate levels of power are delivered to the robot. In some embodiments the movable source or device may be moved manually by an operator or may be automatic or computerized and configured to align or to maintain a specific separation range or orientation between the source and the device.

[00407] In embodiments the movable arm or extension may be used in situations or configurations where there may be a positional offset, mismatch, later offset, or height offset between the source and the device. In embodiments the movable arm that houses or is used to position the source or device resonator may be computer controlled and may autonomously position itself to obtain the best power transfer efficiency. The arm, for example, may move in all directions scanning the most efficient configuration or position and may use learning or other algorithms to fine tune its position and alignment. In embodiments the controller may use any number of measurements from the sensor to try to align or seek the best or most efficient position including, but limited to, impedance, power, efficiency, voltage, current, quality factor, coupling rate, coupling coefficient measurements, and the like.

[00408] In other embodiments the surgical robot may use wireless power transfer to power motors, sensors, tools, circuits, devices, or systems of the robot, that are manipulated by the robot, or that are integrated into the robot. For example, many surgical robots may have complex appendages that have multiple degrees of freedom of movement. It may be difficult to provide power along or through the various joints or moving parts of the appendages due to bulkiness, inflexibility, or unreliability of wires.

[00409] Likewise, powering of the various tools or instruments necessary for a procedure may pose reliability and safety problems with power connections and connectors in the presence of body fluids. A surgical robot may utilize one or more source resonator **4802** and one or more device resonators **4810, 4812** located in the appendages or tools to power motors, electronics, or devices to allow movement of the appendages or powering of tools, cameras, and the like that the robot manipulates which may be inside, or outside of a patient. The power may be transferred wirelessly without any wires regardless of the articulation or rotation of the appendages and may increase the degrees or articulation capability of the appendages. In some embodiments the sources may be integrated into the robot and powered by the robot that may receive its own power wirelessly or from a wired connection. In some embodiments the source powering the appendages and the tools may be mounted on the operating bed, under the bed, or next to the patient.

[00410] As those skilled in the art will appreciate, the systems described and shown in the figures are specific exemplary embodiments and systems may utilize any one of many different robot devices of various shapes and capabilities, tools, and the like. Likewise the source may be mounted on any number of objects of various dimensions depending on the application and use of the robot. The source may be mounted on the operating room bed or pedestal as shown in the Fig. 48. In other embodiments a source may be mounted in the floor, walls, ceilings, other devices, and the like.

[00411] Wireless power transfer may be used to power or recharge movable equipment such as an IV or drug delivery racks or computer stands. Such stands or racks are often repositioned temporarily or moved from one location to another with a patient. The electronic devices attached to these racks often have battery backup allowing them to operate for a period of time without a direct electrical connection such that they can be moved or repositioned and maintain their functionality. However, every time a traditional rack is moved or repositioned it needs to be unplugged and plugged back into an outlet for recharging or powering and the cable must be wound or untangled from other cables.

[00412] The problems with traditional movable wired drug delivery, patient monitoring, or computer racks may be overcome by integrating a wireless power transfer system to the devices. For example, sample embodiments of a drug delivery rack and a computer rack are depicted in Fig. 50. Device resonators **5008, 5006** and power and control circuitry may be integrated or attached to the base or the body of the rack or the supporting structure allowing wireless power transfer from a source resonator mounted into the floor, wall, charging station, or other objects. To be charged or powered the rack **5002** or stand **5014** may be positioned in the proximity of the source, within a meter distance of the source, or within a foot separation of the source. The wireless power transfer enabled rack and the electrical equipment does not require plugging or unplugging or cable management. The wireless power transfer enabled rack or electrical equipment may be powered by positioning the rack or electrical equipment in a specific area of a room or in proximity to the source. In this configuration, for example, a device or rack that may is only used for short period of time to measure or diagnose a patient may be moved from the charging location and brought anywhere close to the patient to take a measurement and moved back into the charging location without requiring precise positioning or plugging or unplugging of the equipment.

[00413] While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law.

[00414] All documents referenced herein are hereby incorporated by reference in their entirety as if fully set forth herein.

CLAIMS

What is claimed is:

1. A wireless power converter comprising:

at least one receiving magnetic resonator configured to capture electrical energy received wirelessly through a first oscillating magnetic field characterized by a first plurality of parameters; and

at least one transferring magnetic resonator configured to generate a second oscillating magnetic field characterized by a second plurality of parameters different from the first plurality of parameters,

wherein the electrical energy from the at least one receiving magnetic resonator is used to energize the at least one transferring magnetic resonator to generate the second oscillating magnetic field.

2. The converter of claim 1, wherein the first plurality of parameters includes a first frequency different from a second frequency of the second plurality of parameters.

3. The converter of claim 2, wherein the first frequency is approximately an integer multiple of the second frequency.

4. The converter of claim 2, wherein the second frequency is approximately an integer multiple of the first frequency.

5. The converter of claim 1, wherein the first plurality of parameters includes a first magnitude different from a second magnitude of the second plurality of parameters.

6. The converter of claim 1, wherein the first plurality of parameters includes a first frequency hopping sequence different from a second frequency hopping sequence of the second plurality of parameters.

7. The converter of claim 1, wherein the first plurality of parameters includes a first on/off sequence different from a second on/off sequence of the second plurality of parameters.

8. The converter of claim 1, further comprising a first converter circuit configured to convert the electrical energy captured by the at least one receiving magnetic resonator into a irect current signal.

9. The converter of claim 8, further comprising a second converter circuit configured to convert the direct current signal from the first converter circuit into an alternating current signal, wherein the alternating current signal is used to energize the at least one transferring magnetic resonator.

10. The converter of claim 1, wherein at least one of the at least one receiving magnetic resonator and the at least one transferring magnetic resonator has a quality factor $Q>100$.

11. The converter of claim 1, wherein the at least one receiving magnetic resonator is configurable to capture energy from magnetic fields with different parameters.

12. The converter of claim 1, wherein the at least one transferring magnetic resonator is configurable to generate magnetic fields with different parameters.

13. The converter of claim 1, wherein the at least one receiving magnetic resonator and the at least one transferring resonator share a loop inductor.

14. A system comprising:

a source resonator configured to generate a first oscillating magnetic field characterized by a first plurality of parameters;

a device resonator configured to capture electrical energy received wirelessly through a second oscillating magnetic field characterized by a second plurality of parameters different from the first plurality of parameters; and

a wireless power converter including conversion circuitry configured to capture energy from the second oscillating magnetic field and to energize the source resonator to generate the first oscillating magnetic field.

15. The system of claim 14, wherein the first plurality of parameters and the second plurality of parameters are different in at least a frequency.

16. The system of claim 14, wherein the first plurality of parameters and the second plurality of parameters of the oscillating magnetic fields are different in at least a magnitude.

17. The system of claim 14, wherein the wireless power converter is powered by electrical energy captured by the device resonator.

18. The system of claim 14, wherein at least one of the source resonator and the device resonator has a quality factor $Q>100$.

19. The system of claim 14, wherein the source resonator and the device resonator include a shared loop inductor.

20. A method of wireless power conversion comprising:

providing a configurable magnetic resonator;

tuning the configurable magnetic resonator to capture a first oscillating magnetic field characterized by a first plurality of parameters;

converting the oscillating magnetic field into electrical energy;

storing the electrical energy as stored energy in an energy storage element;

tuning the configurable magnetic resonator to generate a second oscillating magnetic field characterized by a second plurality of parameters; and

energizing the configurable magnetic resonator using the stored energy to produce the second oscillating magnetic field.

21. The method of claim 20, wherein the first plurality of parameters include a first frequency different from a second frequency of the second plurality of parameters.

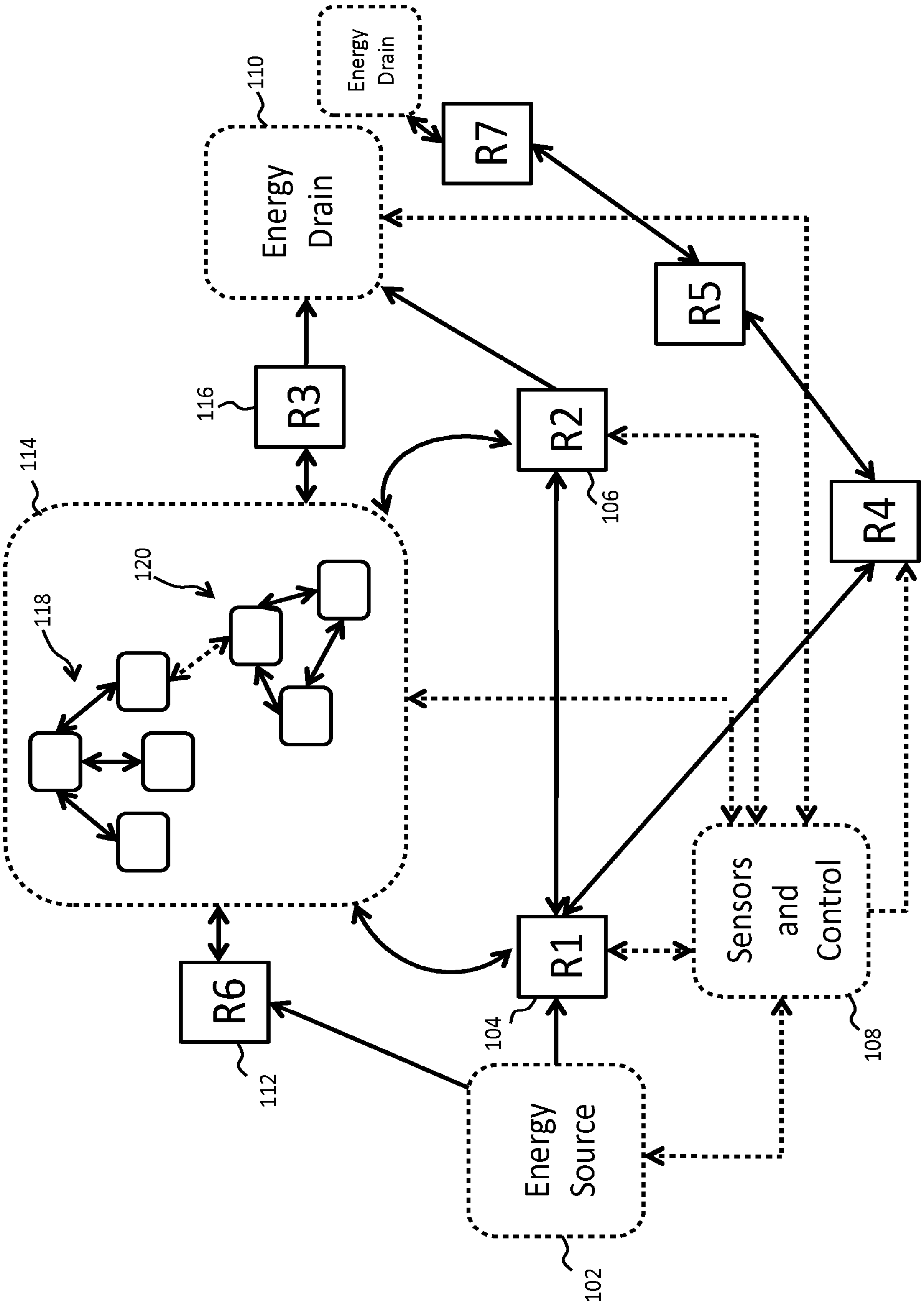
22. The method of claim 20, wherein the first plurality of parameters include a first magnitude different from a second magnitude of the second plurality of parameters.

23. The method of claim 20, wherein the configurable magnetic resonator has a quality factor $Q>100$.

24. The method of claim 20, further comprising converting the electrical energy into a direct current signal prior to storing the electrical energy in the energy storage element.

25. The method of claim 24, further comprising converting the stored energy into an alternating current signal prior to energizing the configurable magnetic resonator to produce the second oscillating magnetic field.

Fig. 1


Energy Drain
110
Energy Drain
R7
R5
R3
116
R2
106
R4
114
120
118
Sensors and Control
108
R1
104
R6
112
Energy Source
102

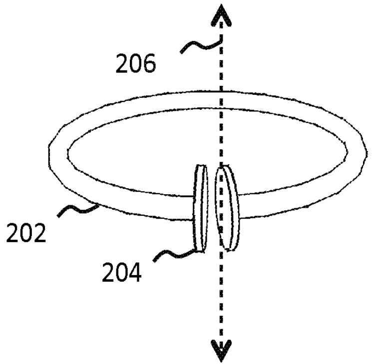


Fig. 2A

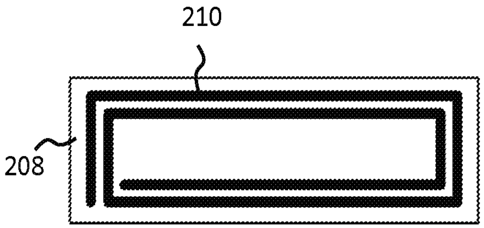


Fig. 2B

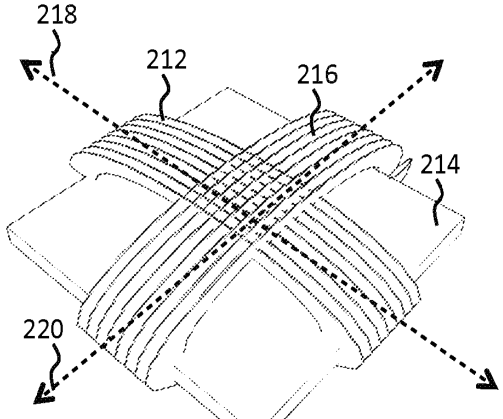


Fig. 2C

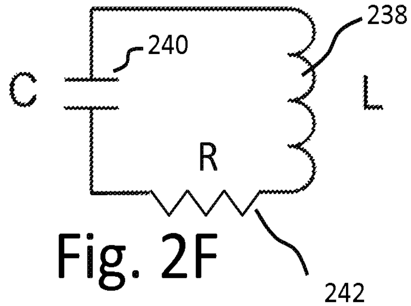


Fig. 2F

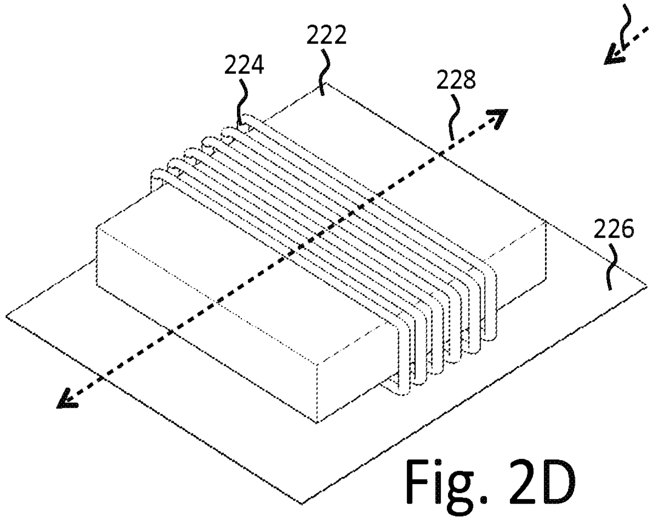


Fig. 2D

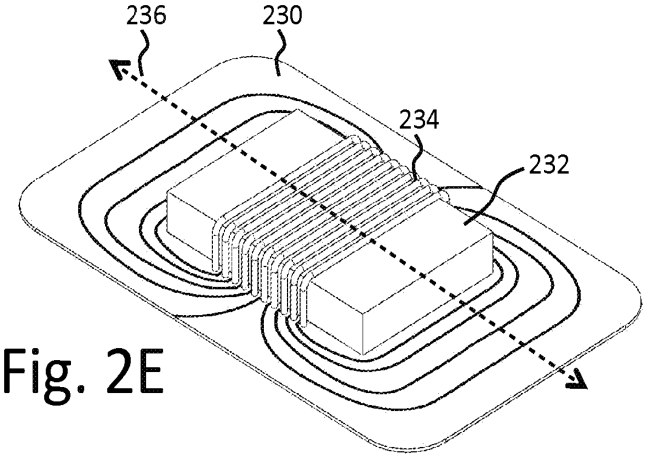
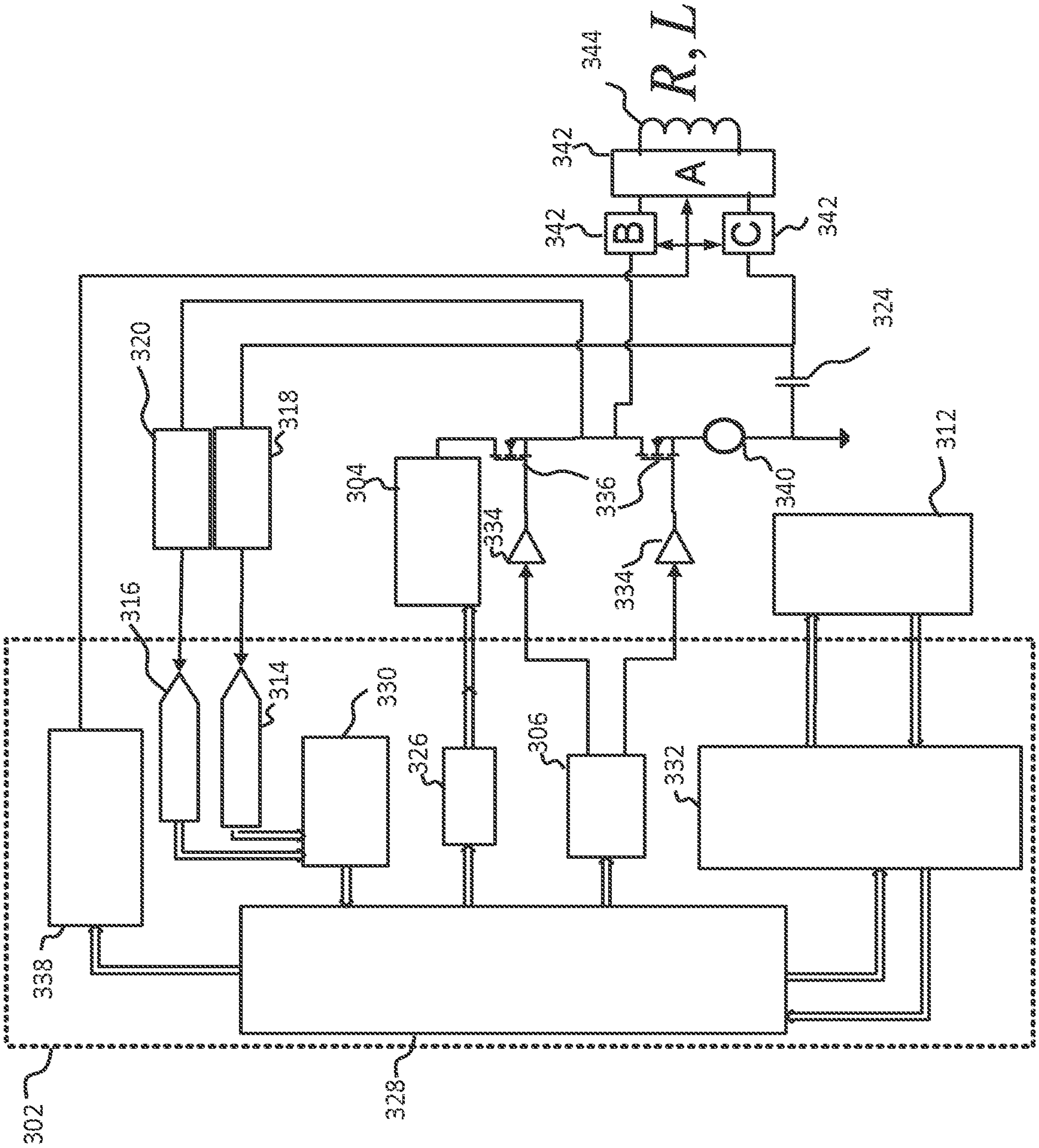


Fig. 2E

Fig. 3


344
R, L
342
A
342
B
C
342
324
320
318
304
336
336
340
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334
334
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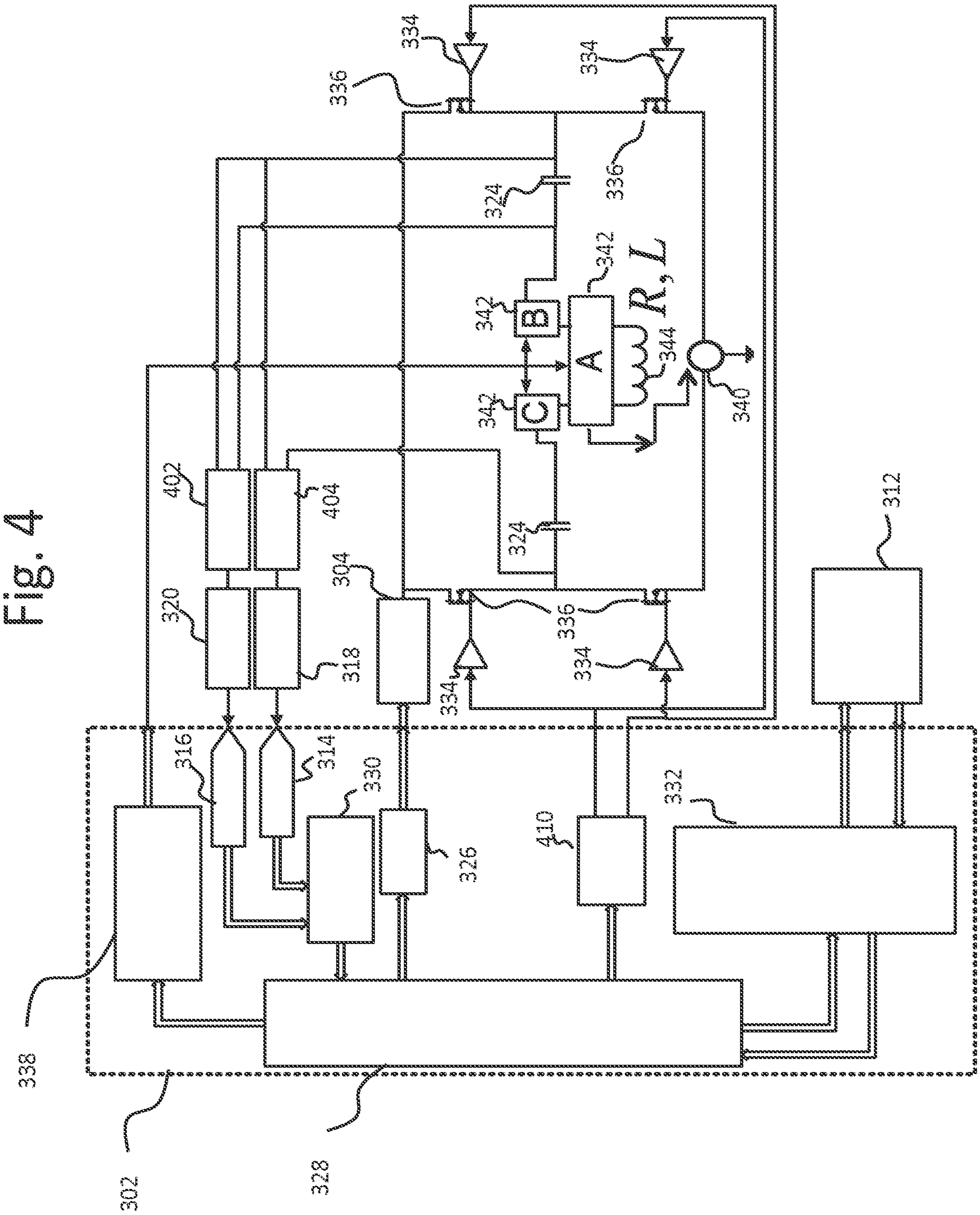
314
330
326
306
332
338
328
302

Fig. 4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R, L
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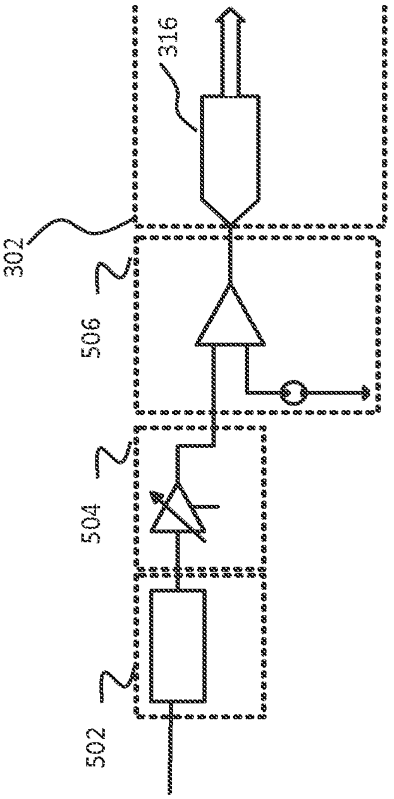


Fig. 5A

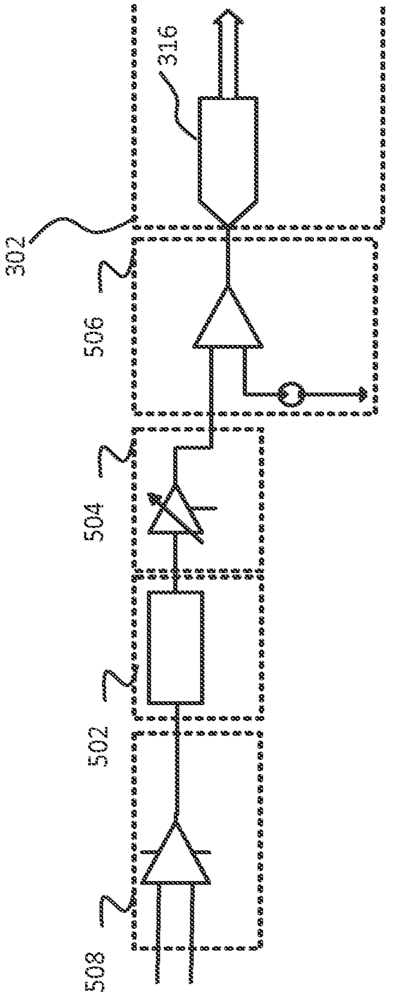


Fig. 5B

Fig. 6A

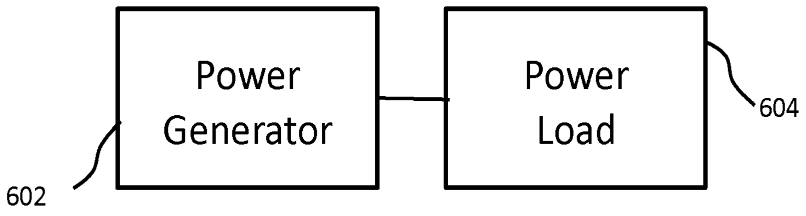


Fig. 6B

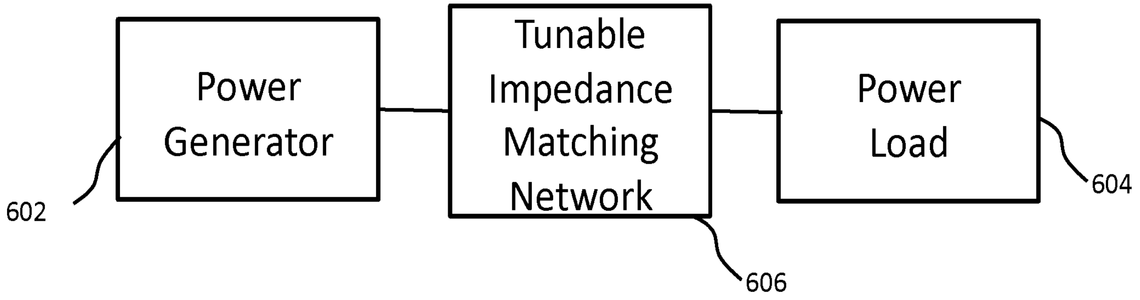


Fig. 6C

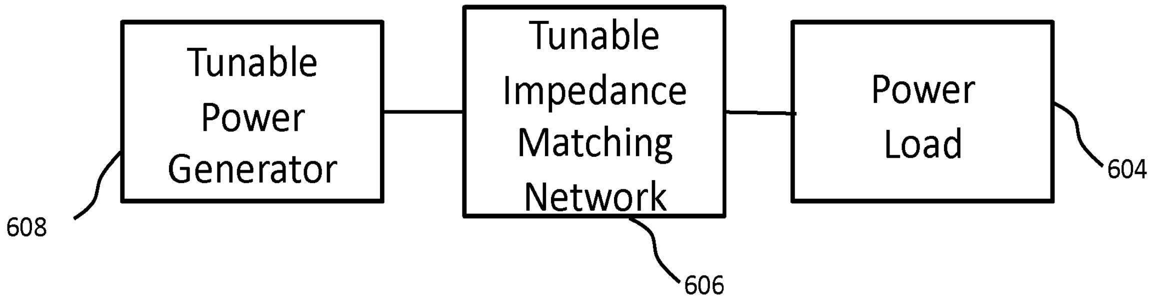


Fig. 7

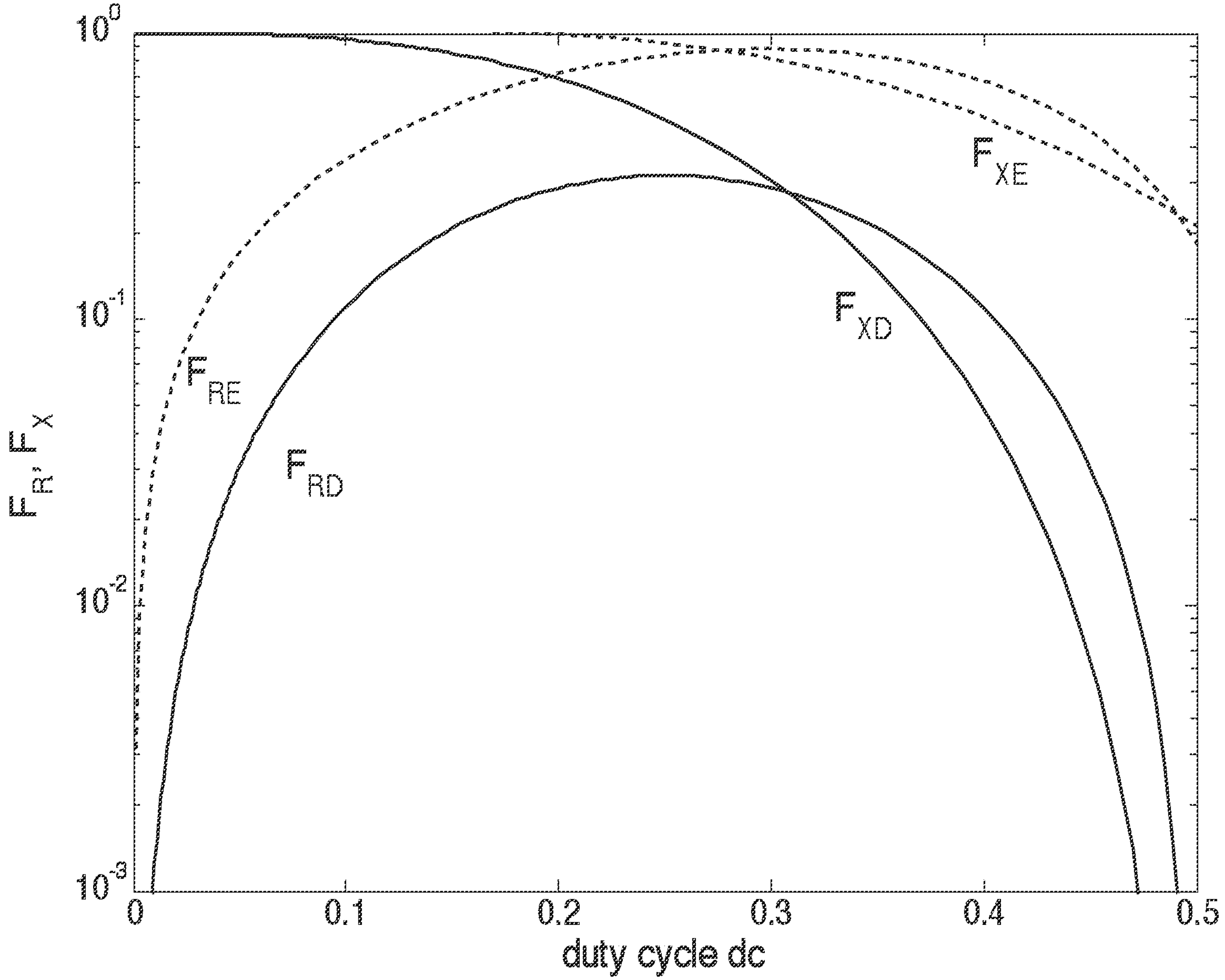

F_R, F_X
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.1
0.2
0.3
0.4
0.5
duty cycle dc
F_{XE}
F_{XD}
F_{RE}
F_{RD}

Fig. 8

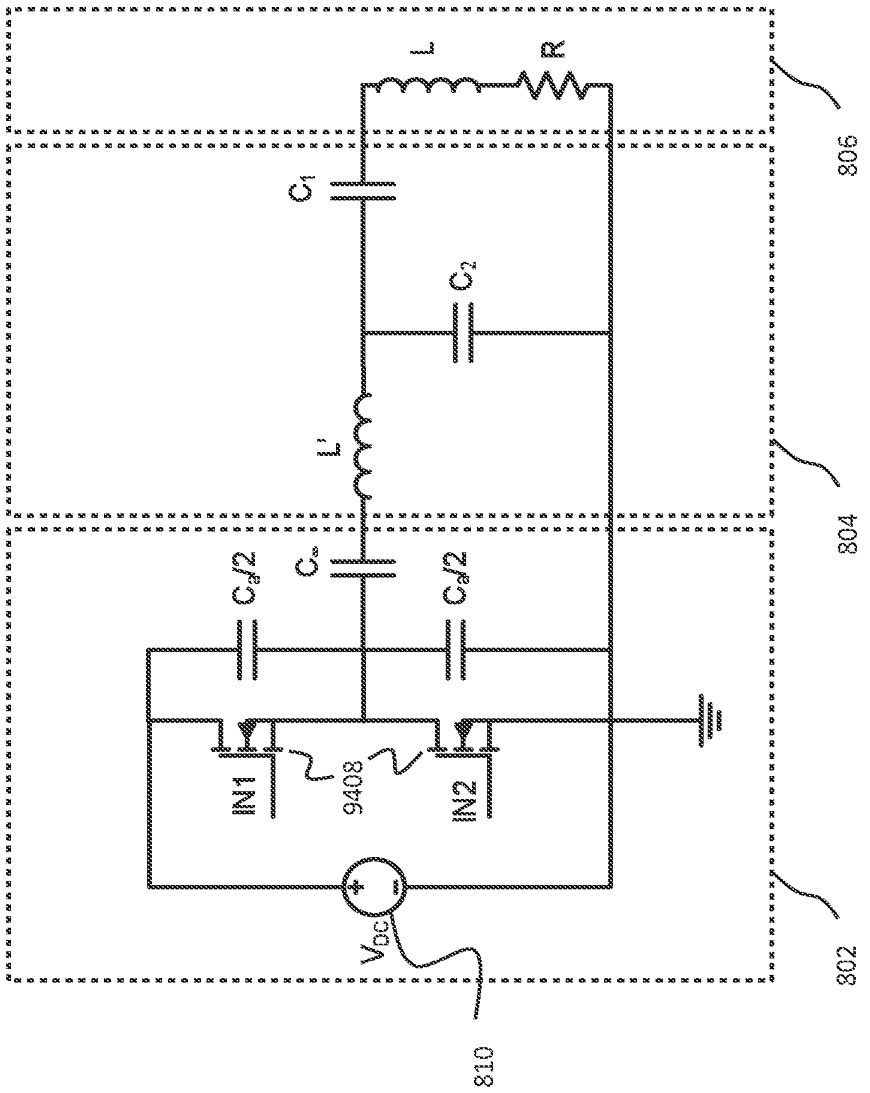
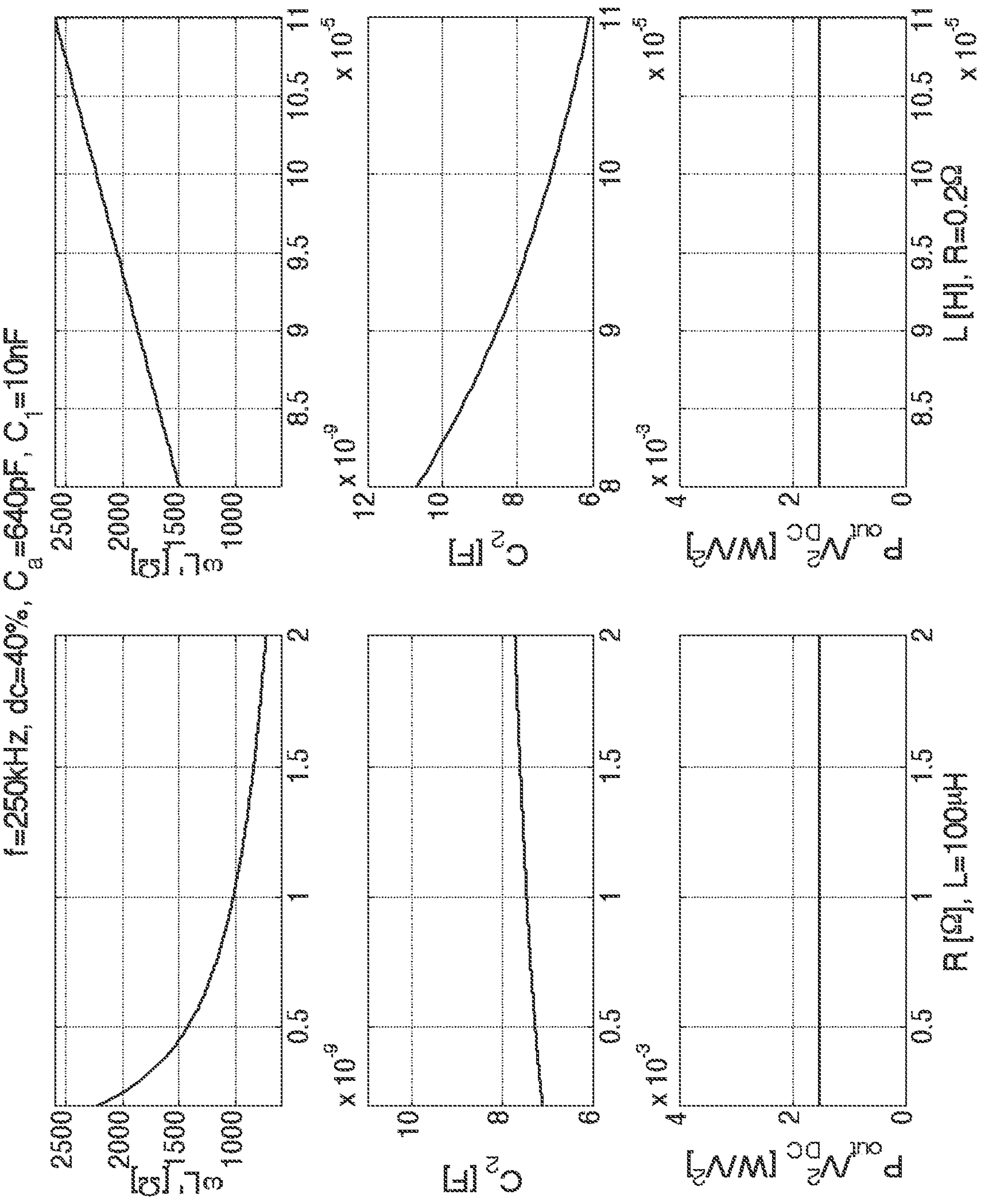


Fig. 9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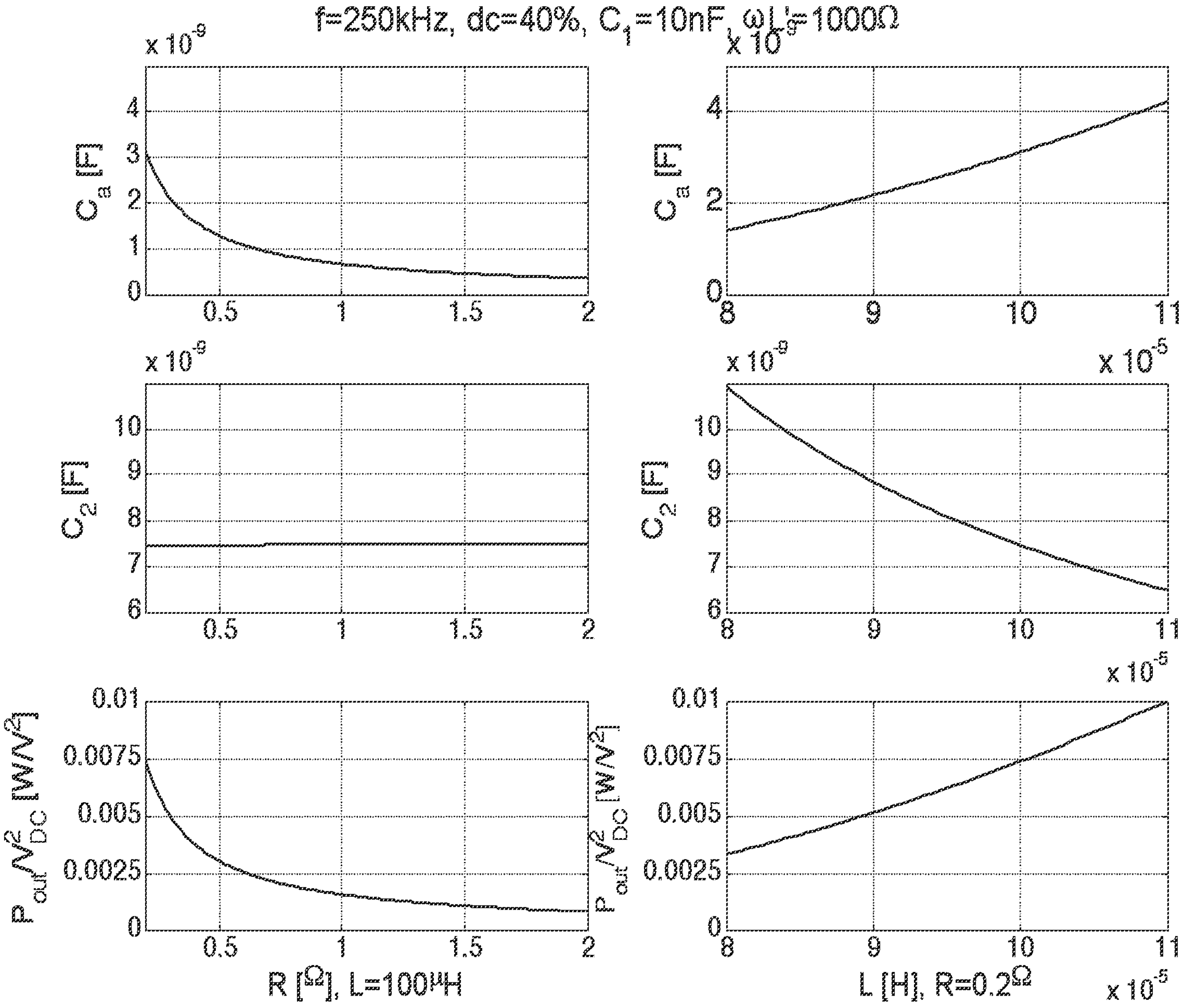
ω_L [Ω]
2500
2000
1500
1000
x 10^-9
0.5
1
1.5
2
C_2 [F]
10
8
6
P_{out}/V^2_{DC} [W/V²]
x 10^-3
4
2
0
R [Ω], L=100μH
12
x 10^-5
8.5
9
9.5
10
10.5
11
L [H], R=0.2Ω

Fig. 10


f=250kHz, dc=40%, C1=10nF, ωL'g=1000Ω
x 10-9
C_a [F]
4
3
2
1
0
0.5
1
1.5
2
x 10-9
C_2 [F]
10
9
8
7
6
0.5
1
1.5
2
P_out/V²_DC [W/V²]
0.01
0.0075
0.005
0.0025
0
0.5
1
1.5
2
R [Ω], L=100μH
x 10-9
C_a [F]
4
2
0
8
9
10
11
x 10-5
x 10-9
C_2 [F]
10
9
8
7
6
8
9
10
11
x 10-5
P_out/V²_DC [W/V²]
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0.0075
0.005
0.0025
0
8
9
10
11
L [H], R=0.2Ω
x 10-5

Fig. 11A

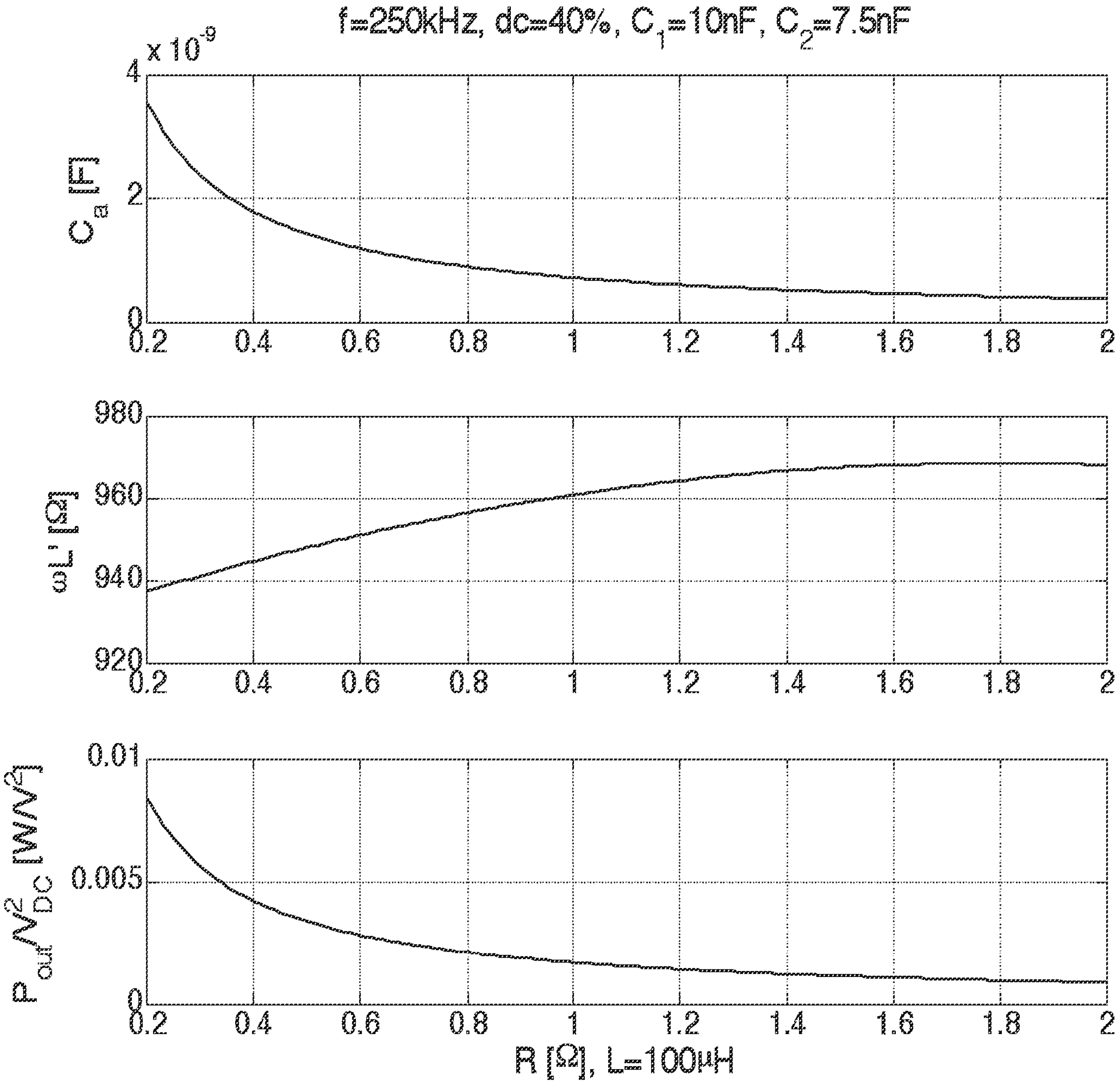

f=250kHz, dc=40%, C$_1$=10nF, C$_2$=7.5nF
x 10^{-9}
4
2
0
C$_a$ [F]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
980
960
940
920
ωL' [Ω]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.01
0.005
0
P$_{out}$/V$^2_{DC}$ [W/V^2]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
R [Ω], L=100μH

Fig. 11B

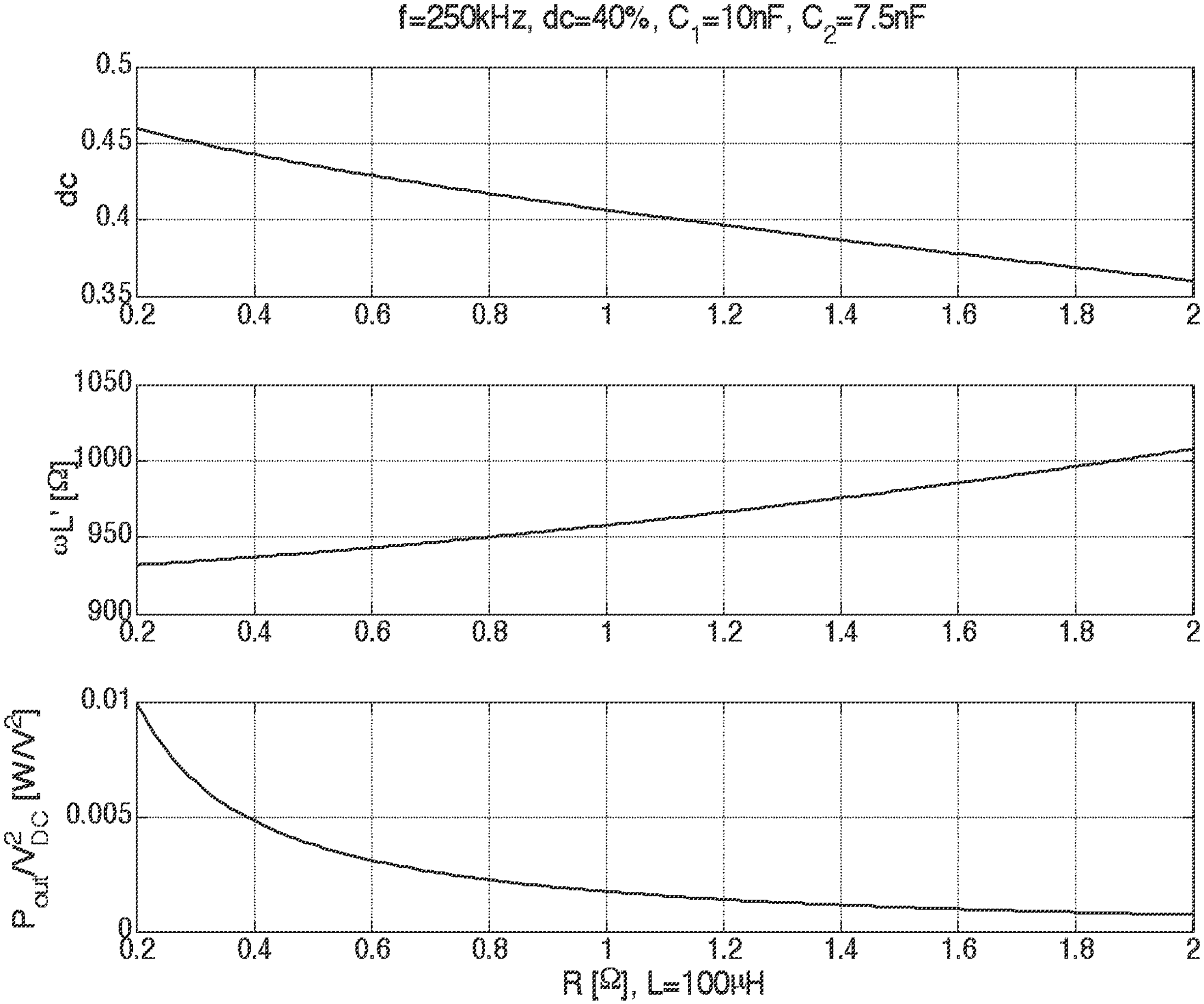

f=250kHz, dc=40%, C$_1$=10nF, C$_2$=7.5nF
dc
0.5
0.45
0.4
0.35
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
ωL' [Ω]
1050
1000
950
900
P$_{out}$/V$^2_{DC}$ [W/V^2]
0.01
0.005
0
R [Ω], L=100μH

Fig. 11C

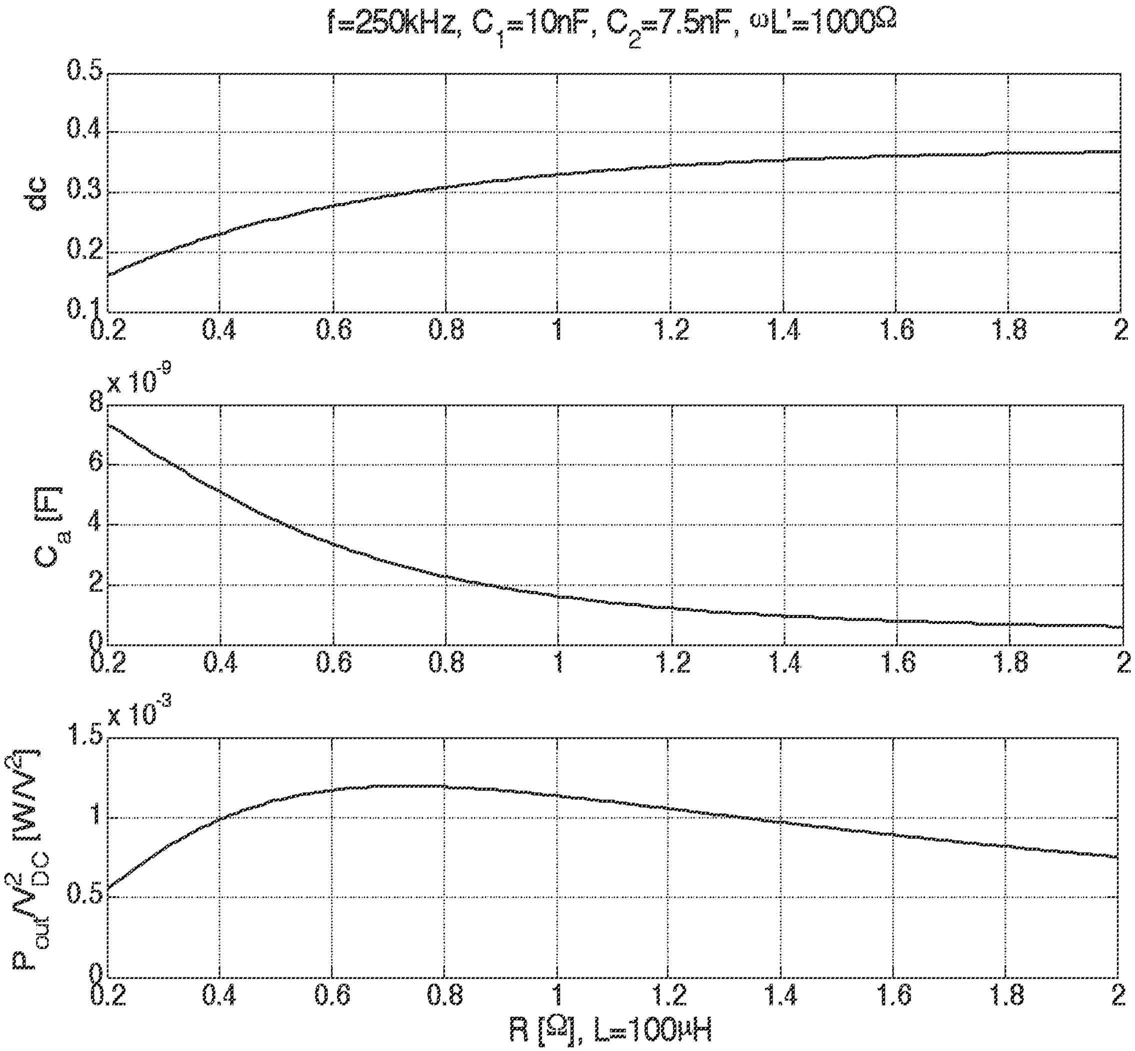

f=250kHz, C_1=10nF, C_2=7.5nF, ωL'=1000Ω
dc
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10^{-9}
C_a [F]
8
6
4
2
0
x 10^{-3}
P_{out}/V_{DC}^2 [W/V^2]
1.5
1
0.5
0
R [Ω], L=100μH

Fig. 12

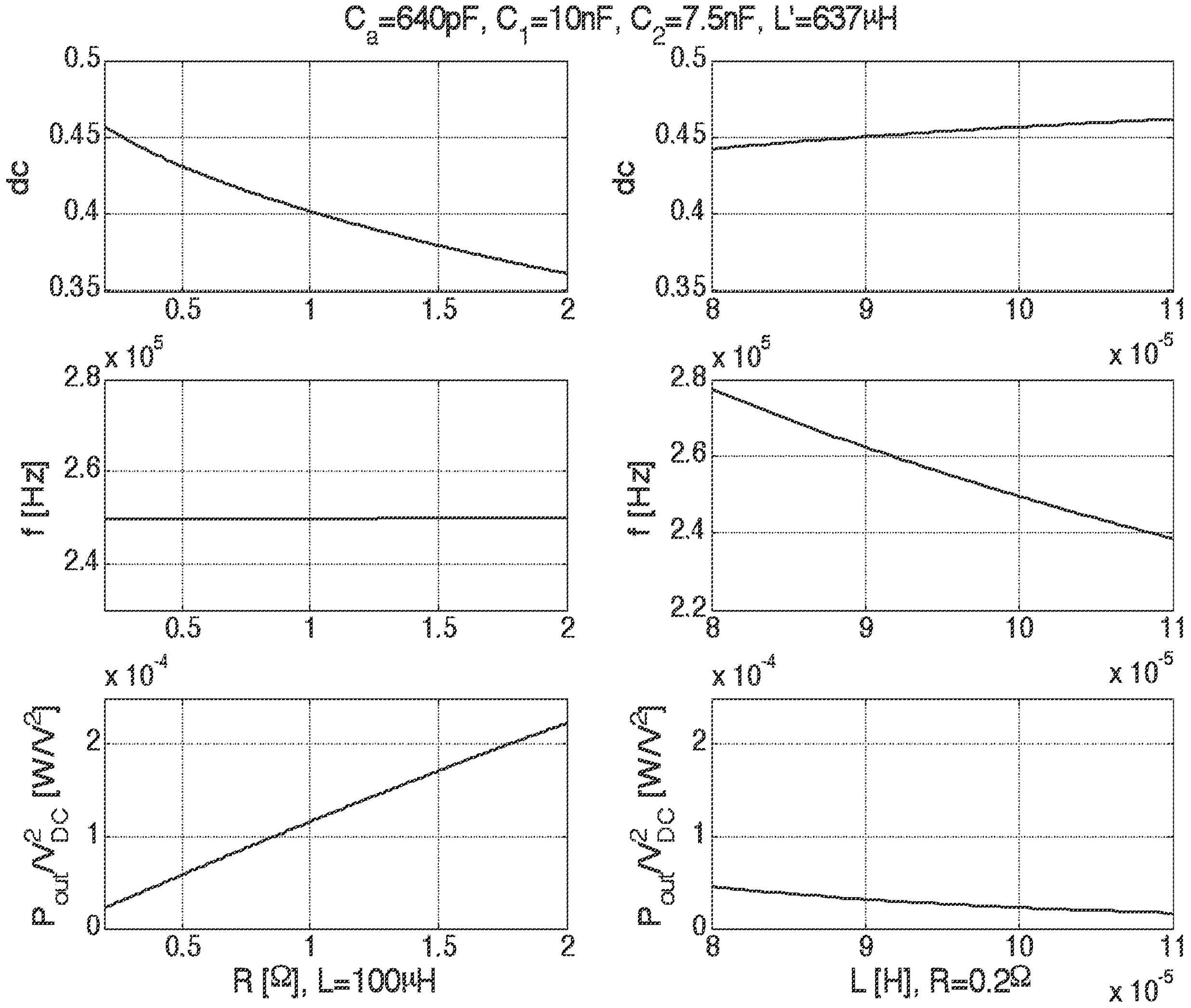

C_a=640pF, C_1=10nF, C_2=7.5nF, L'=637μH
dc
0.5
0.45
0.4
0.35
0.5
1
1.5
2
8
9
10
11
x 10^{-5}
f [Hz]
x 10^5
2.8
2.6
2.4
2.2
P_{out}/V_{DC}^2 [W/V²]
x 10^{-4}
2
1
0
R [Ω], L=100μH
L [H], R=0.2Ω

Fig. 13

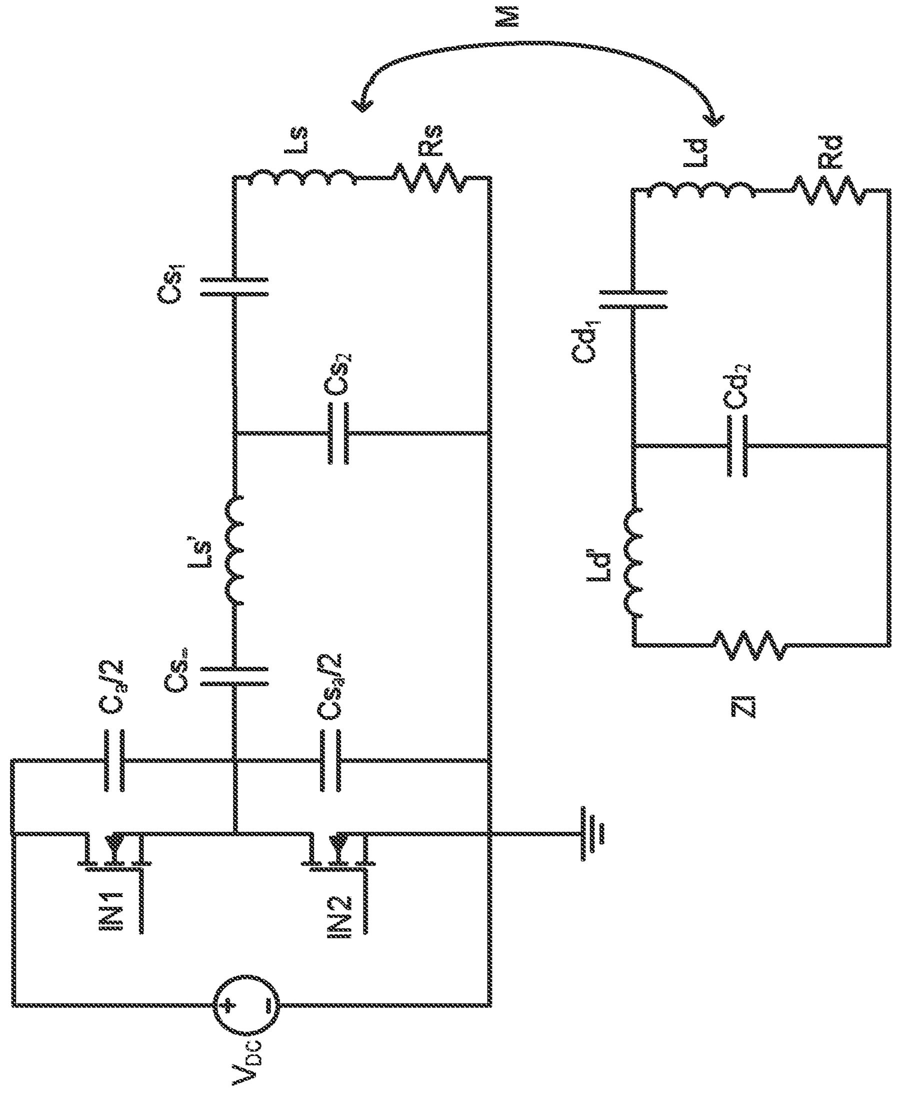


Fig. 14

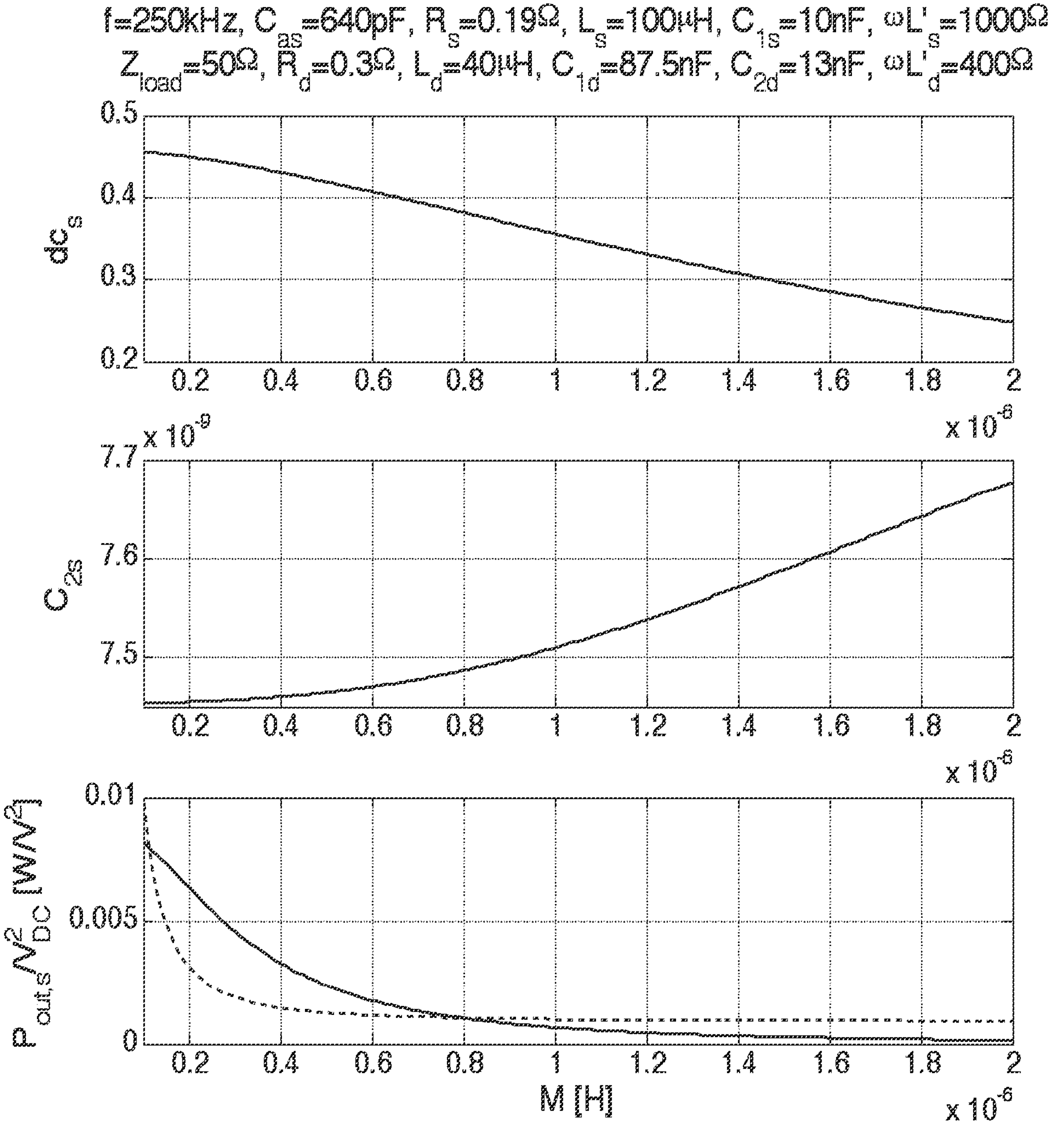

f=250kHz, C_as=640pF, R_s=0.19Ω, L_s=100μH, C_1s=10nF, ωL'_s=1000Ω
Z_load=50Ω, R_d=0.3Ω, L_d=40μH, C_1d=87.5nF, C_2d=13nF, ωL'_d=400Ω
dc_s
0.5
0.4
0.3
0.2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10^-6
C_2s
x 10^-9
7.7
7.6
7.5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10^-6
P_out,s/V^2_DC [W/V^2]
0.01
0.005
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
M [H]
x 10^-6

Fig. 15

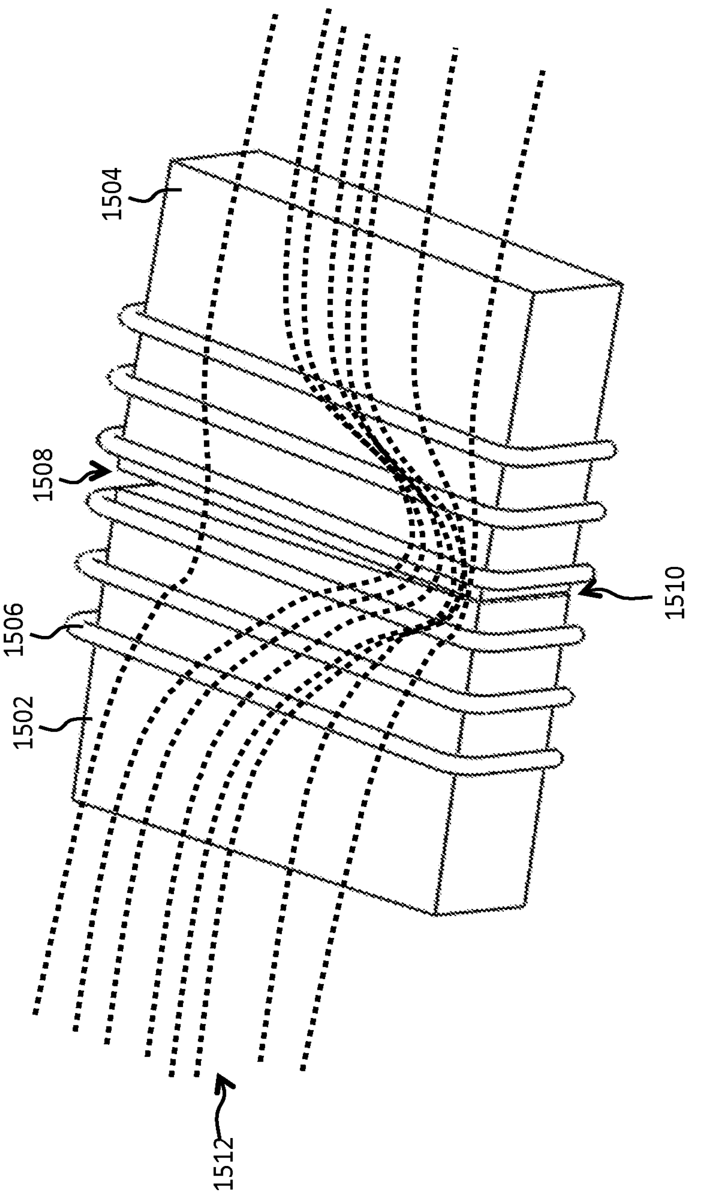
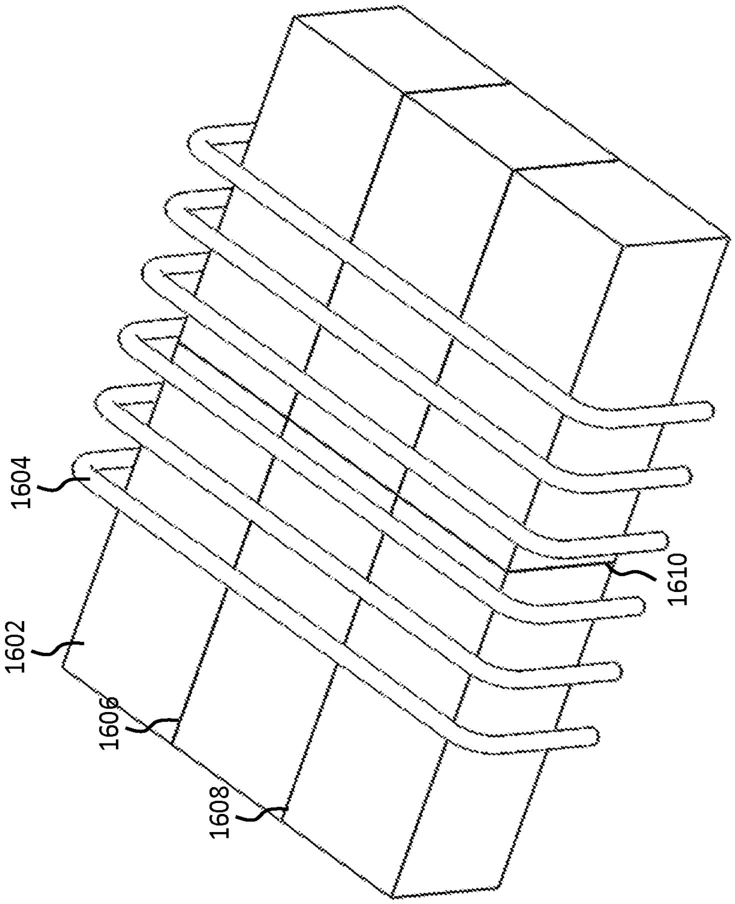


Fig. 16



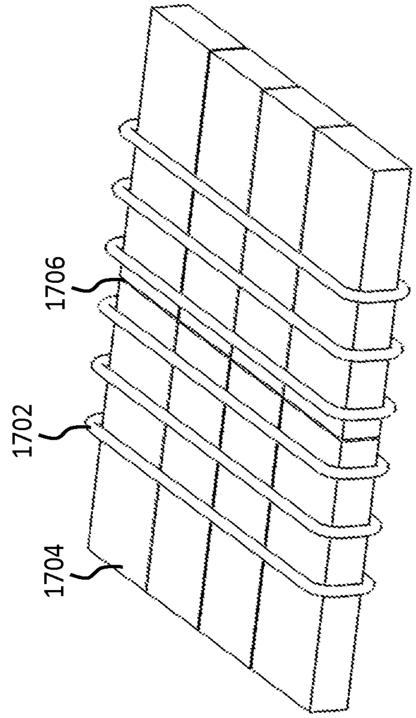


Fig. 17A

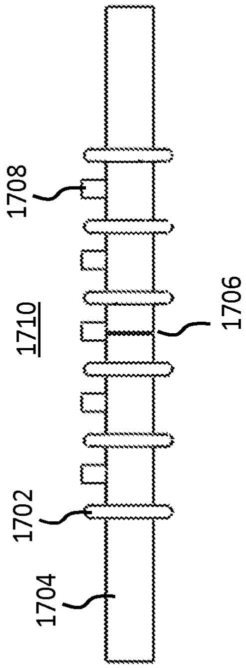


Fig. 17B

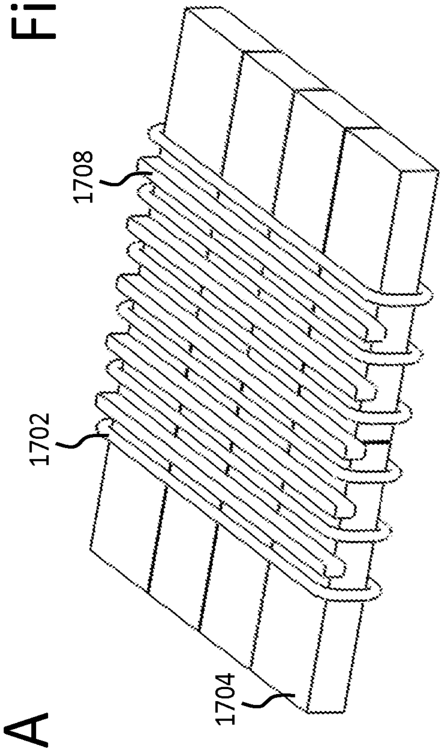


Fig. 17C

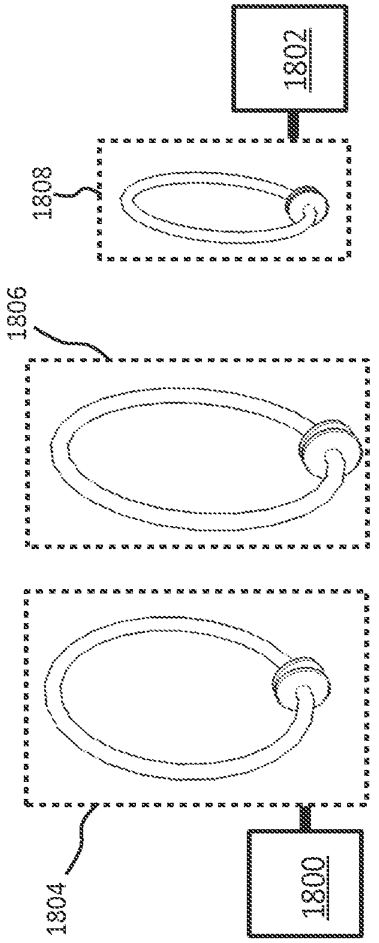


Fig. 18A

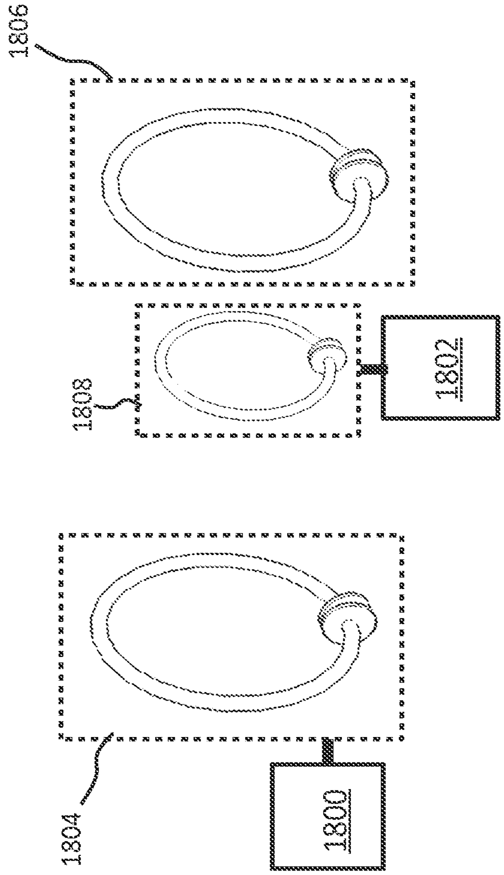


Fig. 18B

Fig. 19A

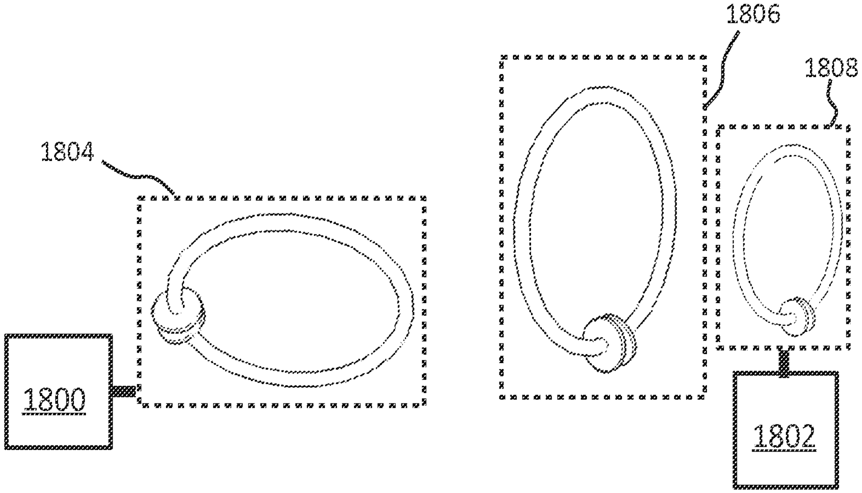
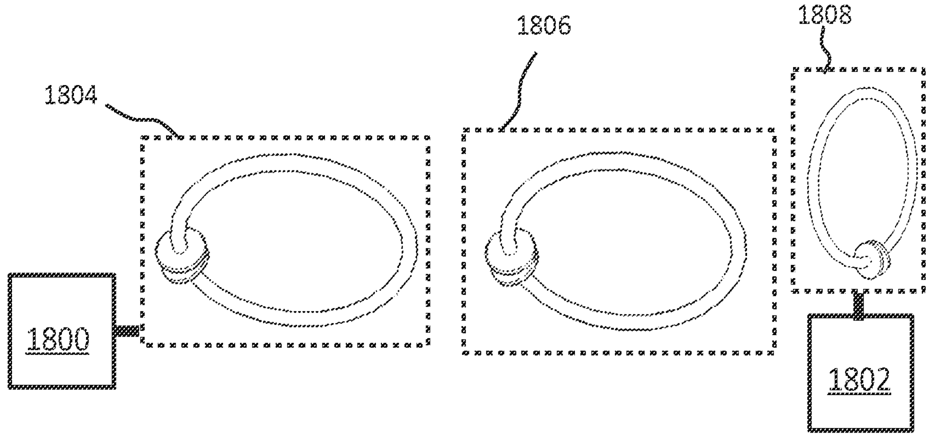


Fig. 19B



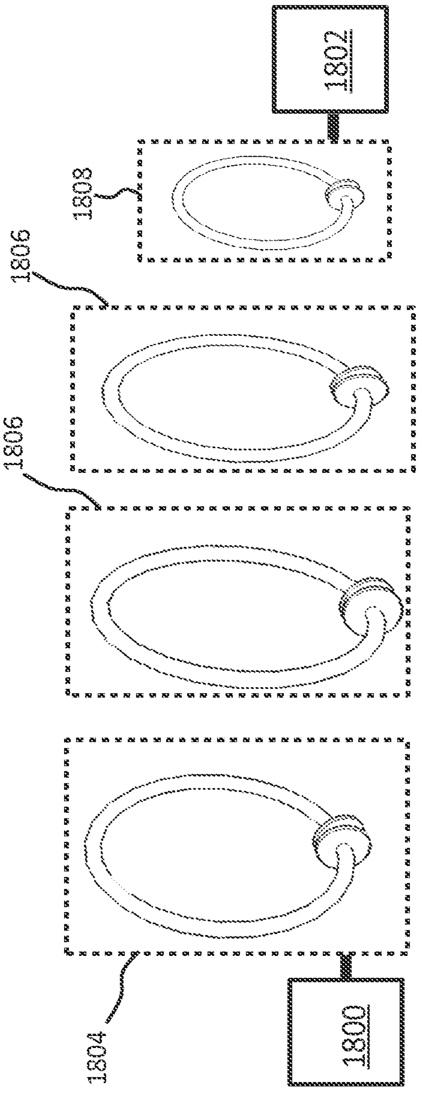


Fig. 20A

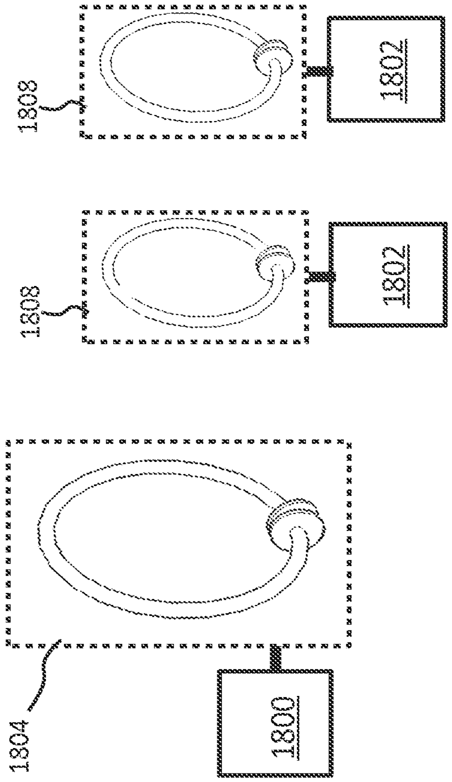


Fig. 20B

Fig. 21

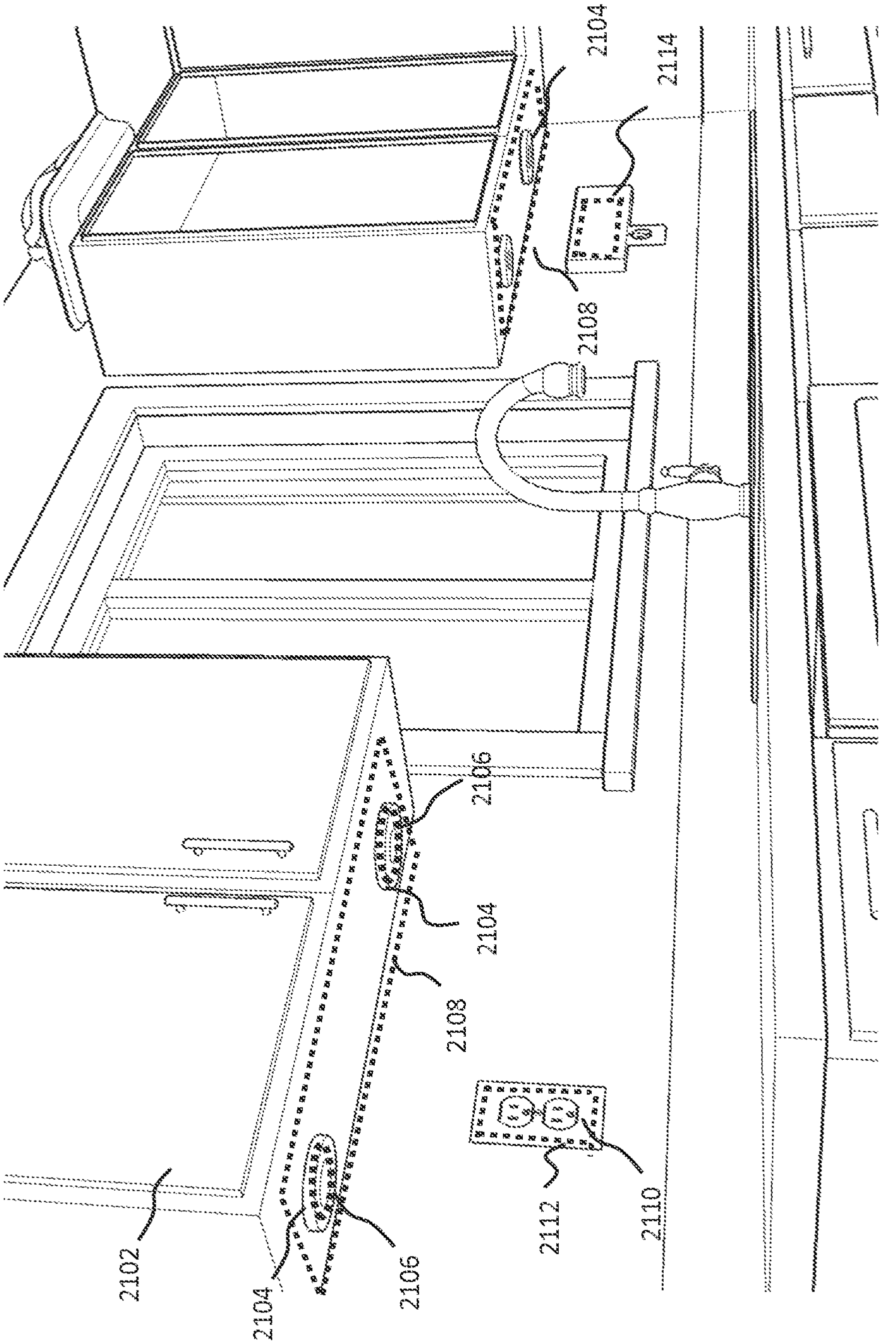


Fig. 22

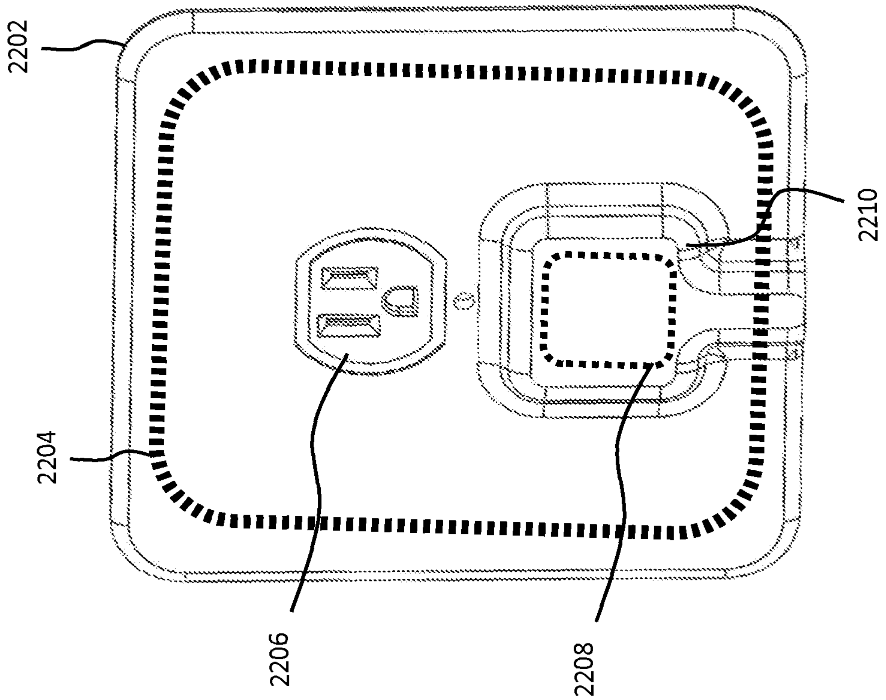
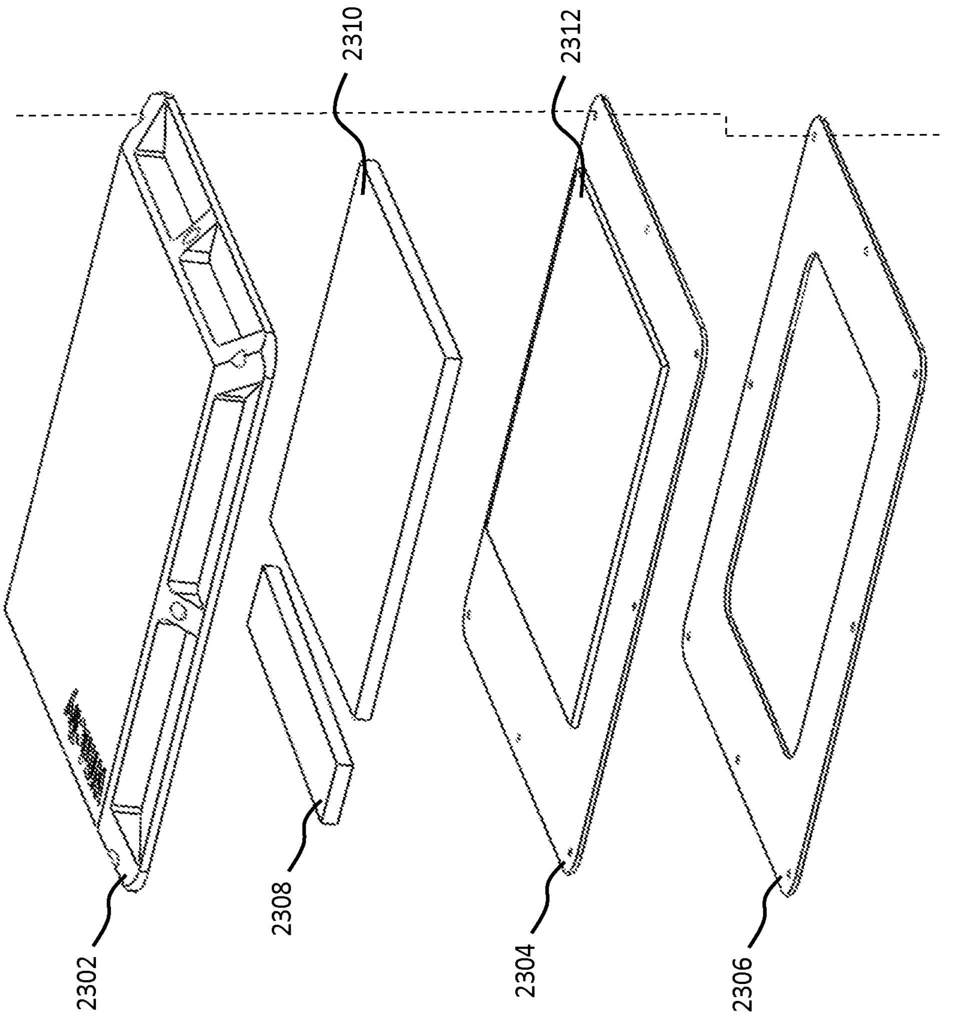


Fig. 23



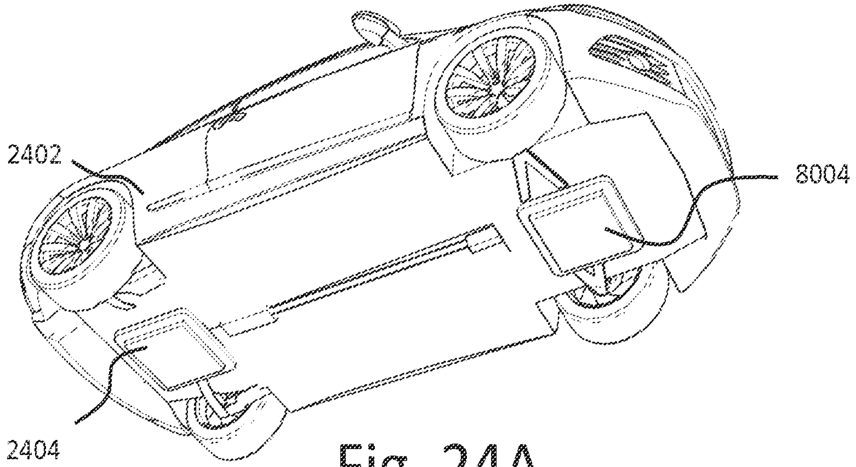


Fig. 24A

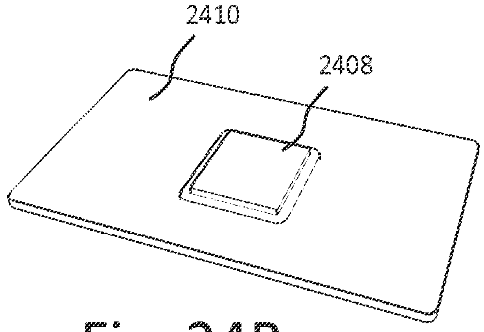


Fig. 24B

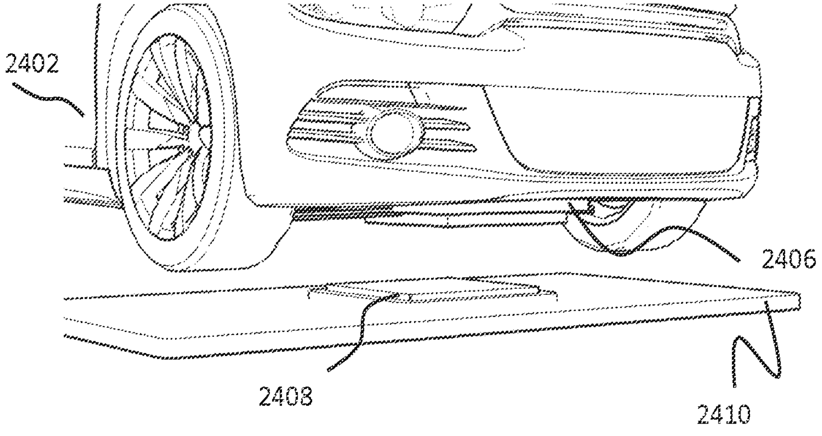


Fig. 24C

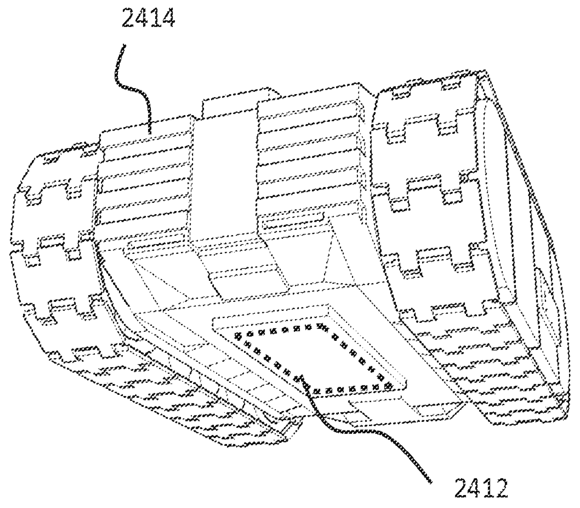
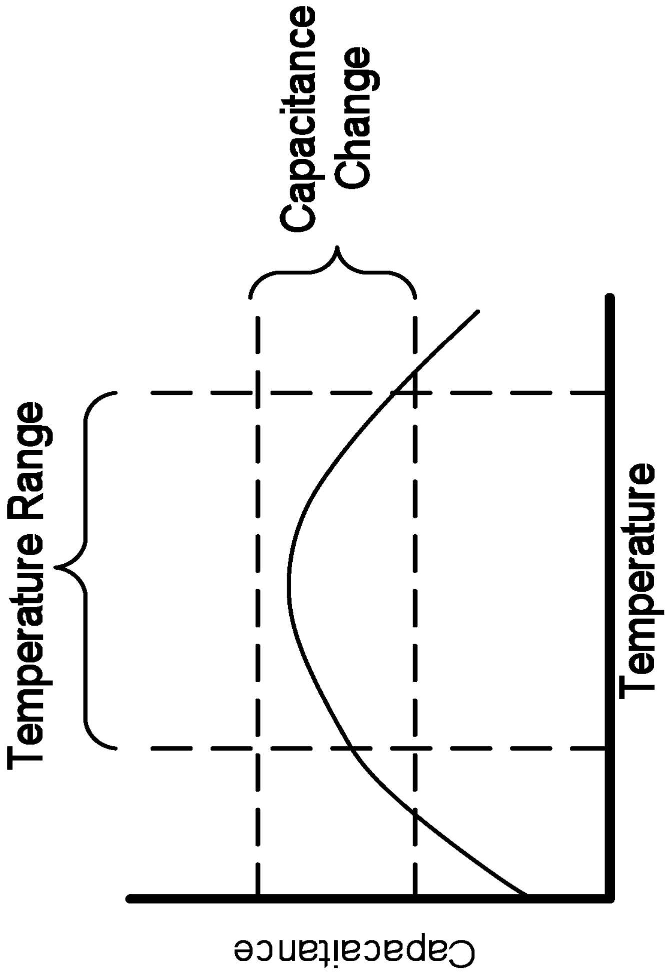


Fig. 24D

Fig. 25


Capacitance Change
Temperature Range
Temperature
Capacitance

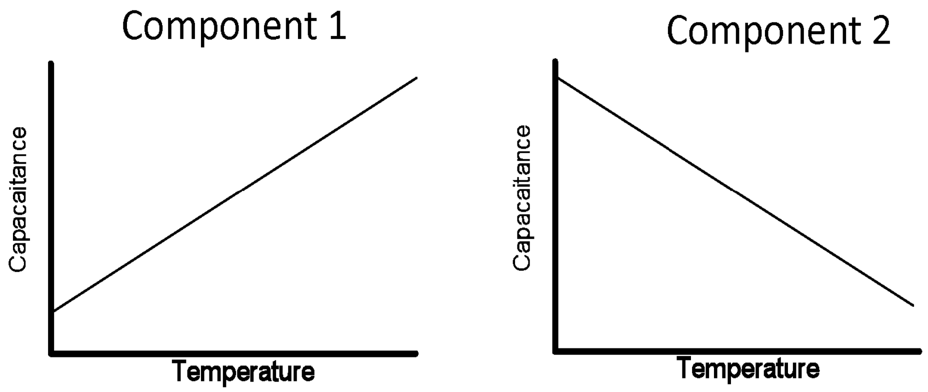


Fig. 26A

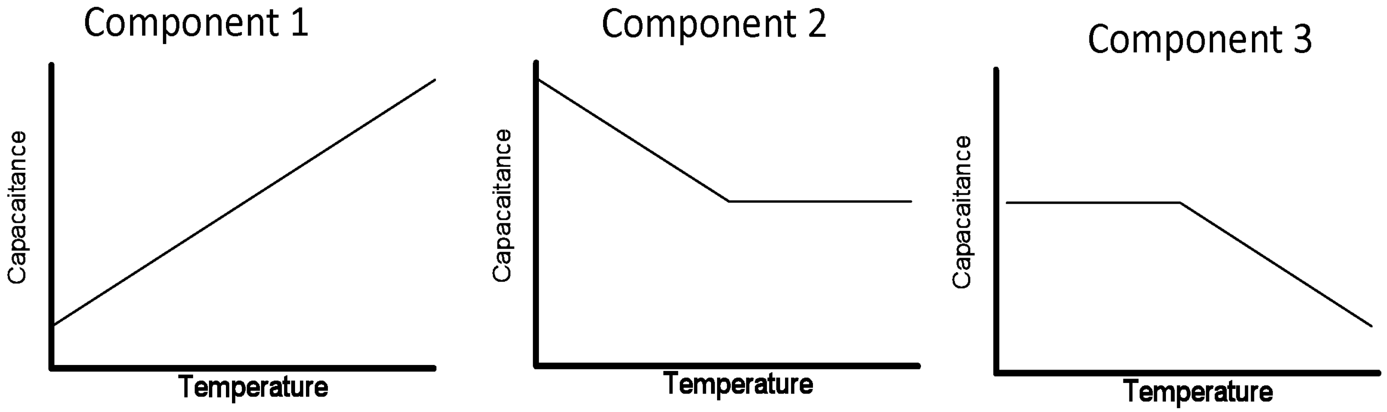


Fig. 26B

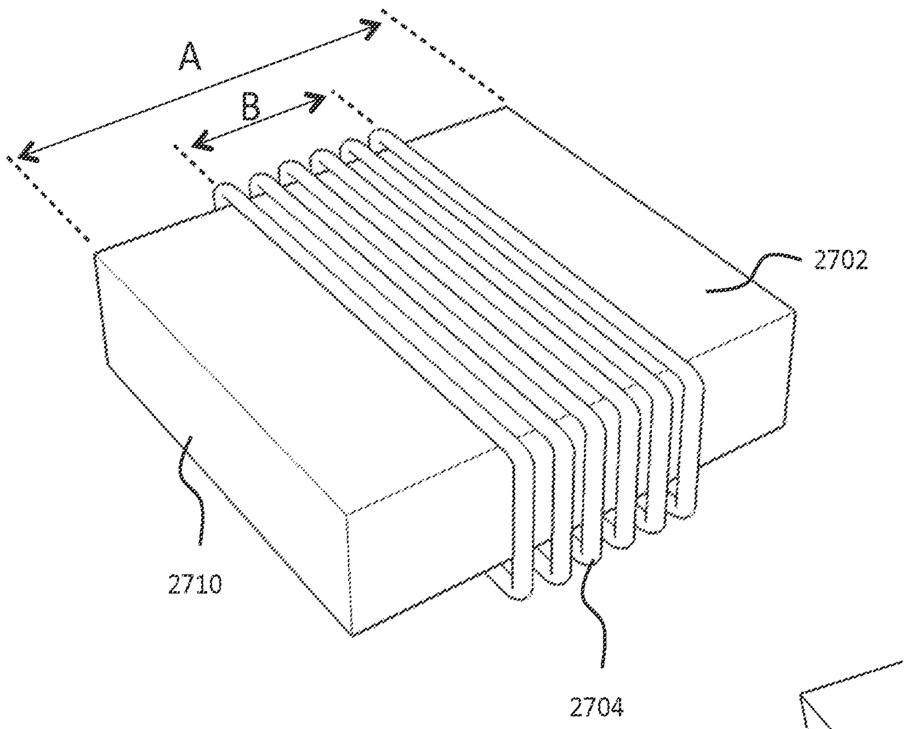


Fig. 27A

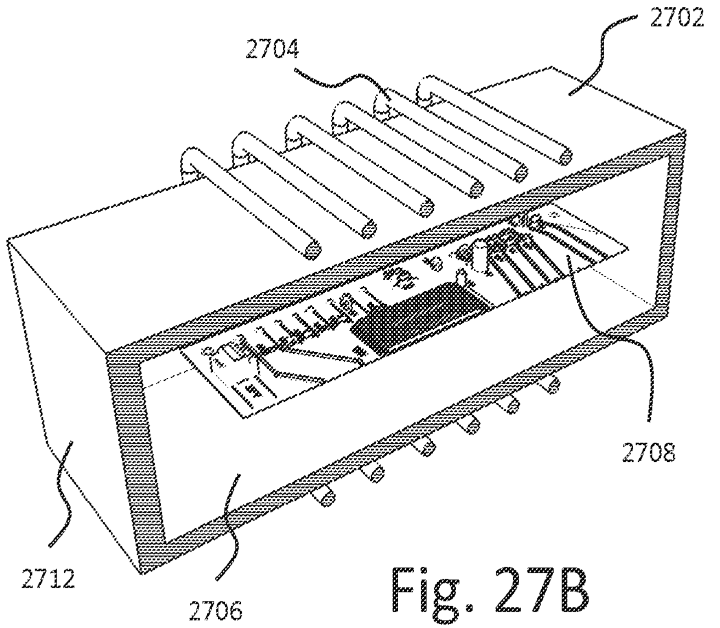


Fig. 27B

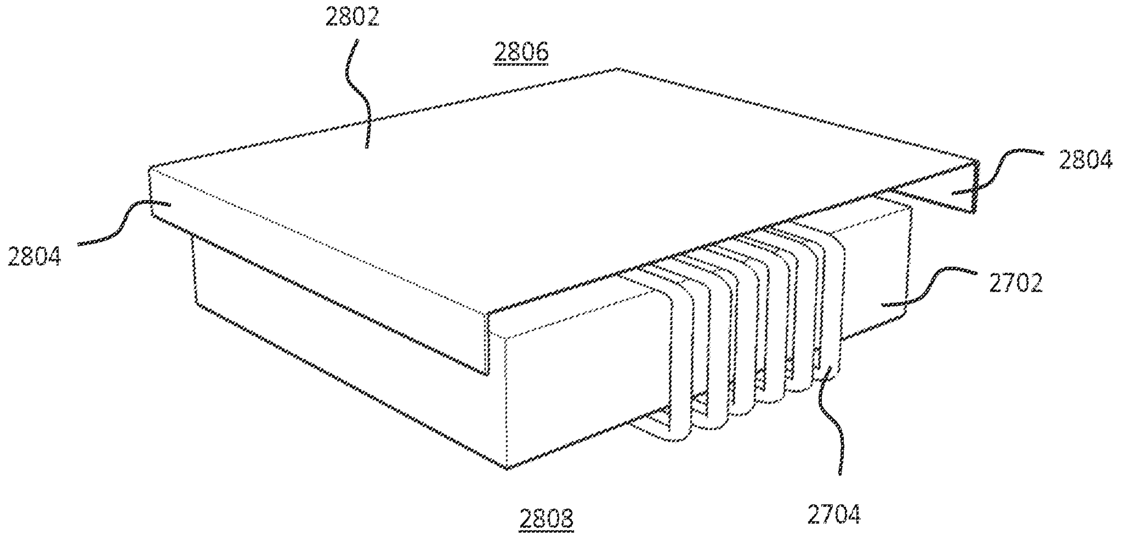


Fig. 28A

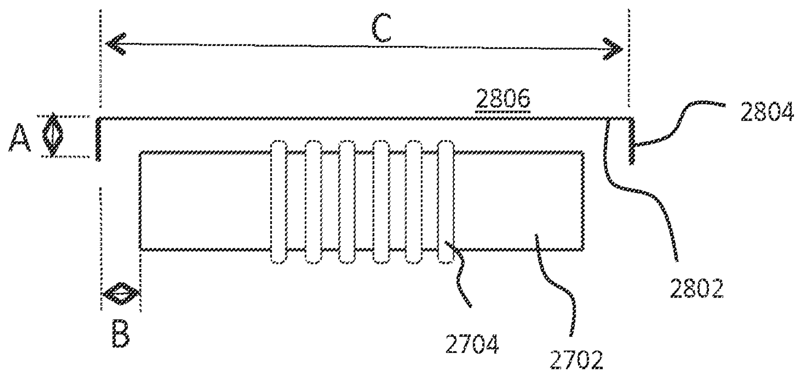


Fig. 28B

Fig. 29

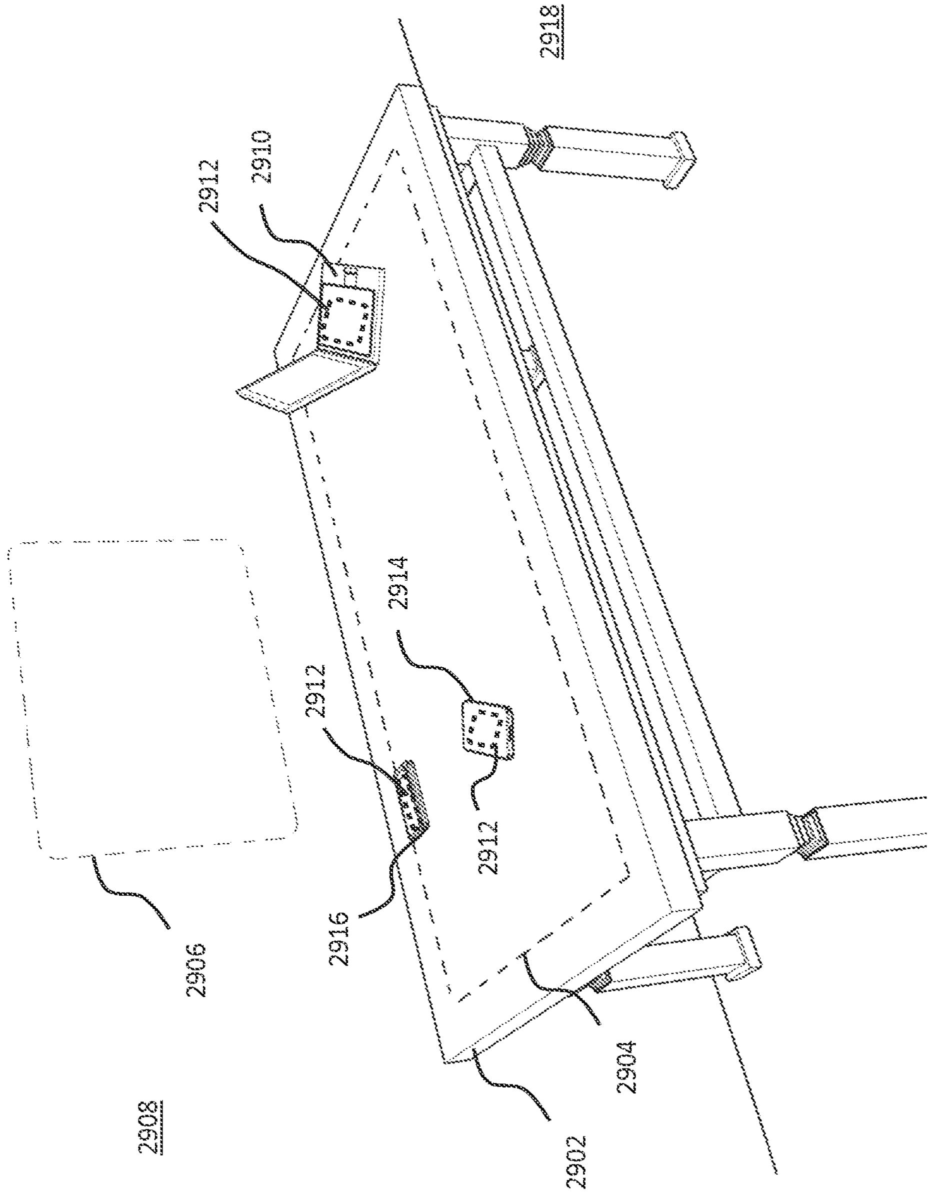


Fig. 30

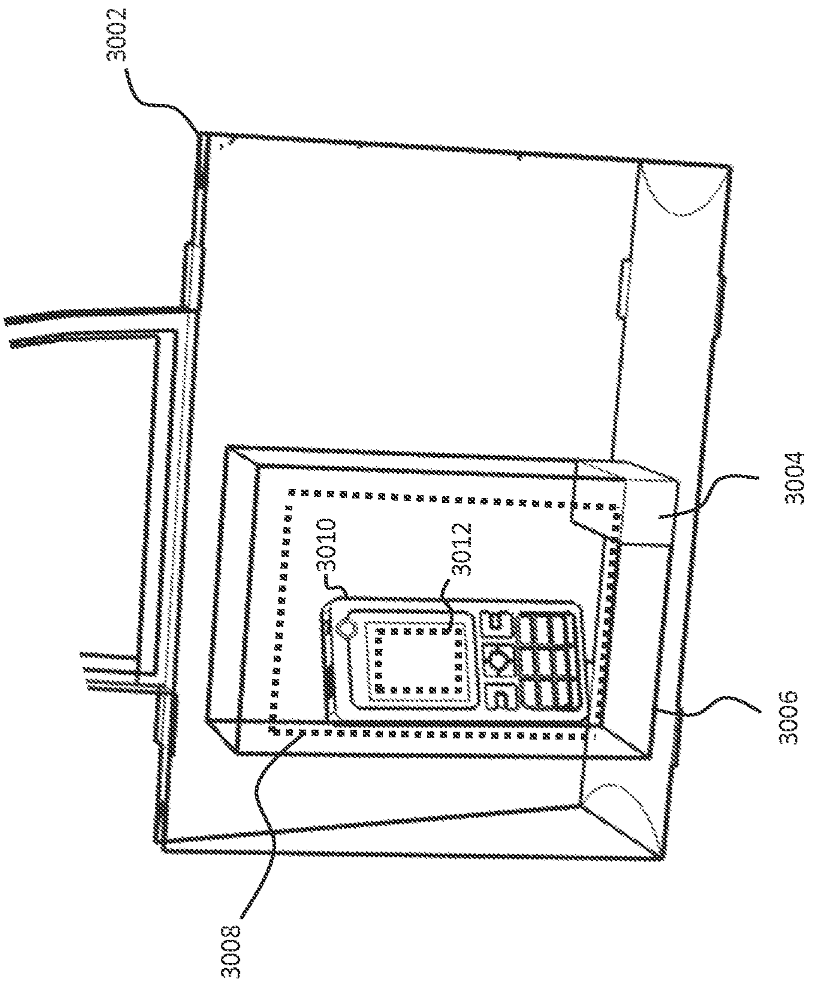
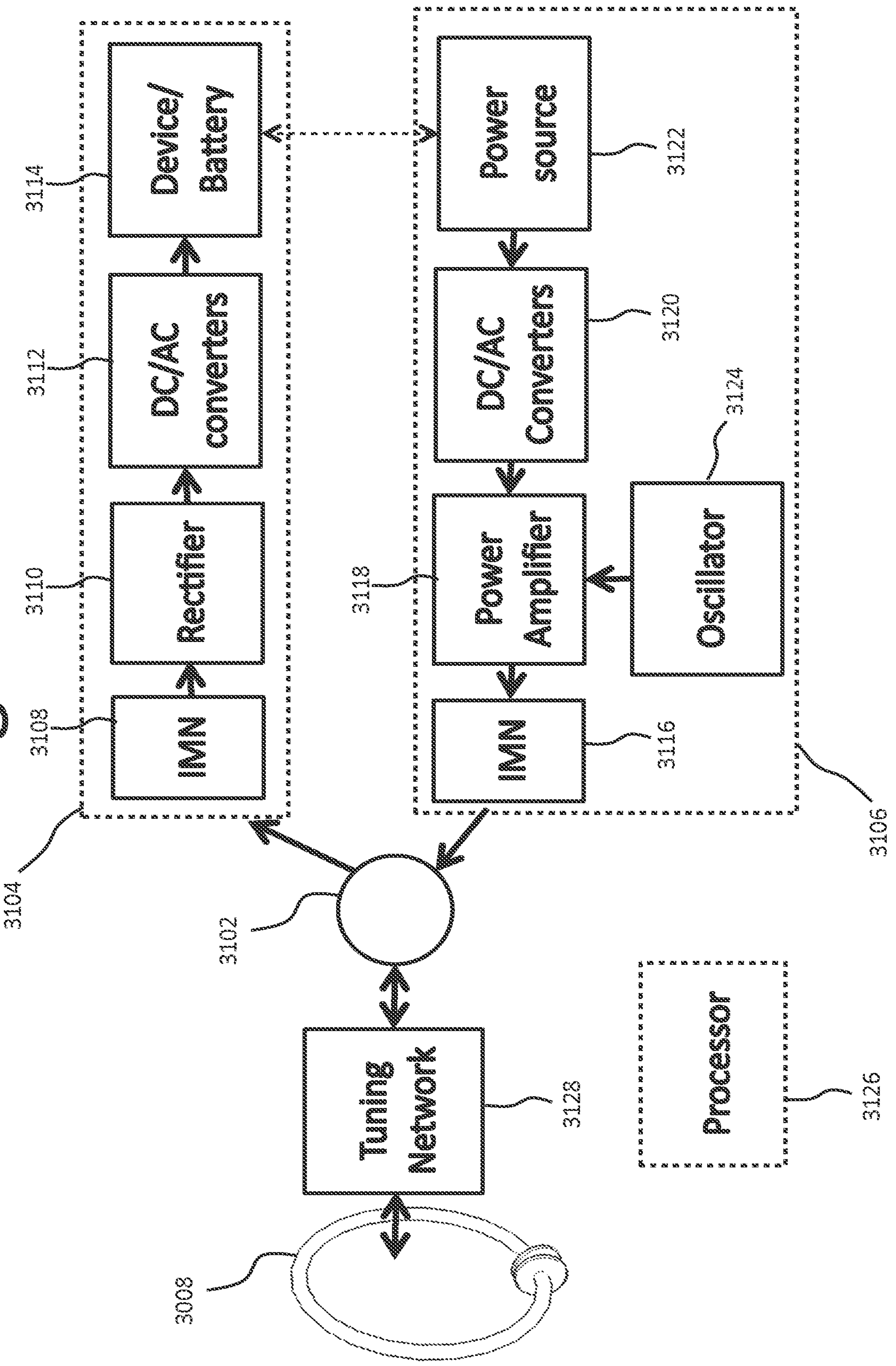


Fig. 31


Device/ Battery
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DC/AC converters
3112
Rectifier
3110
IMN
3108
3104
Power source
3122
DC/AC Converters
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Tuning Network
3128
Processor
3126
3008

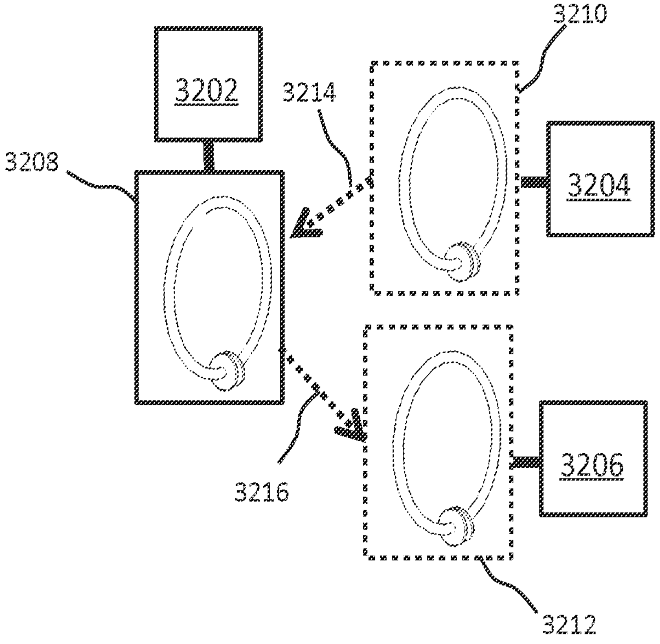


Fig. 32A

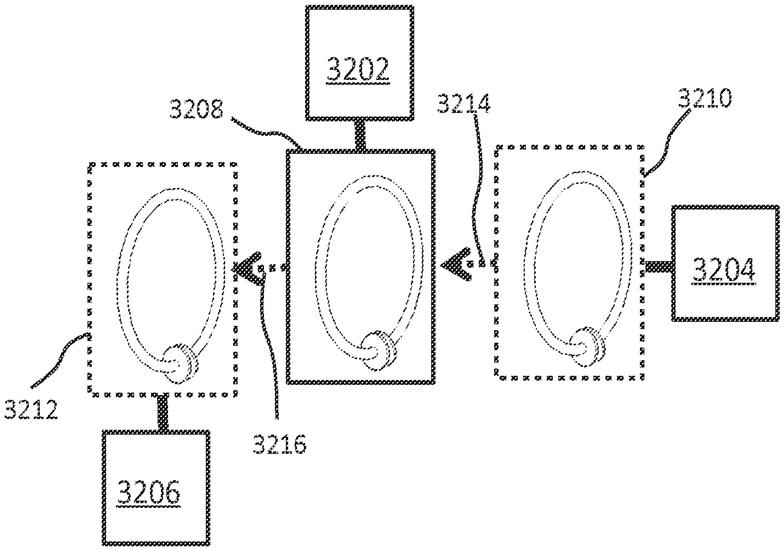
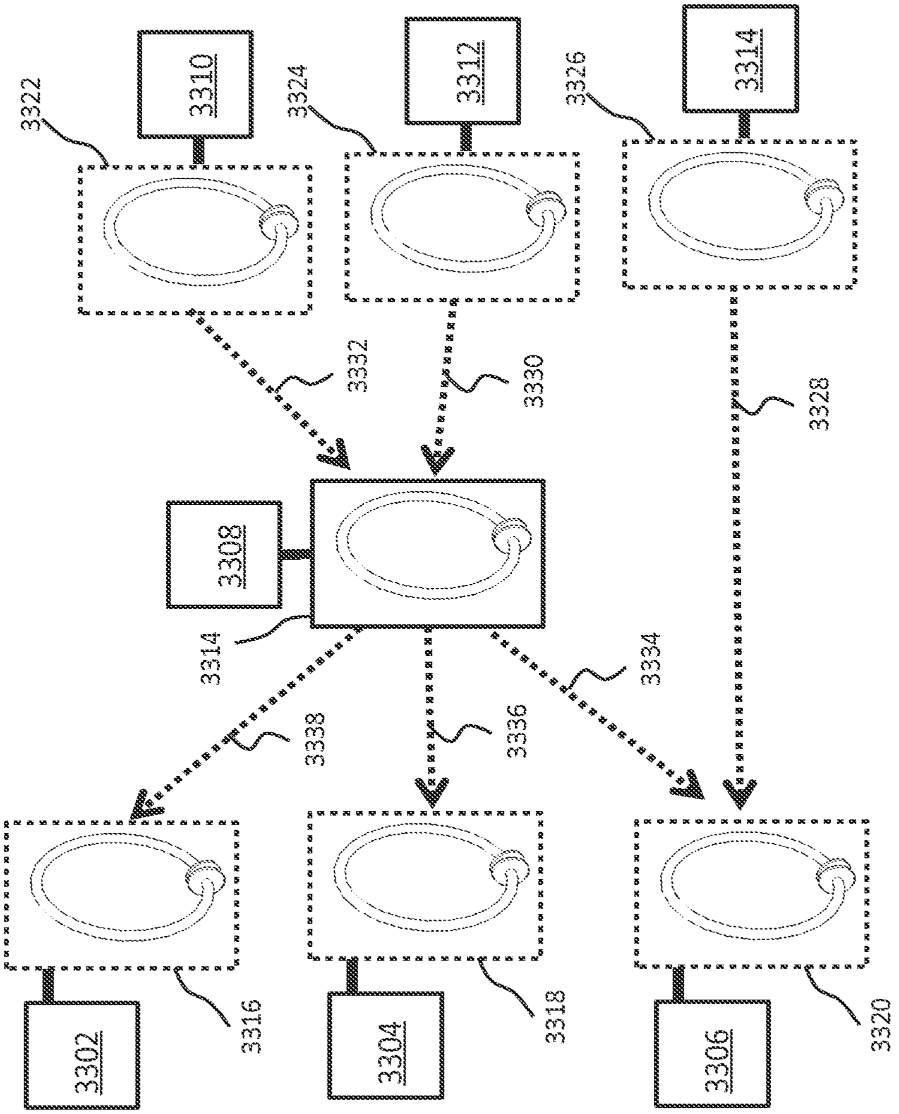


Fig. 32B

Fig. 33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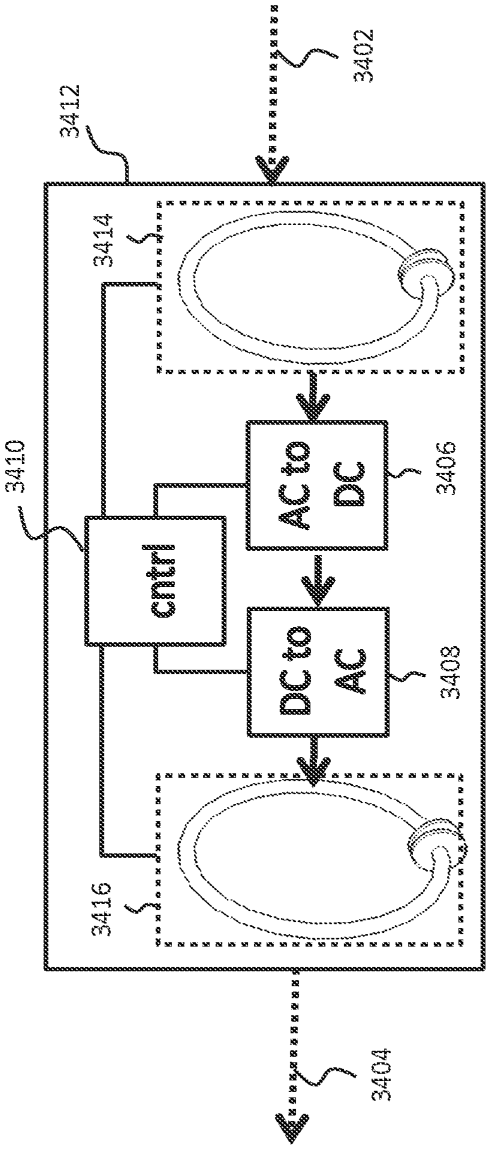


Fig. 34A

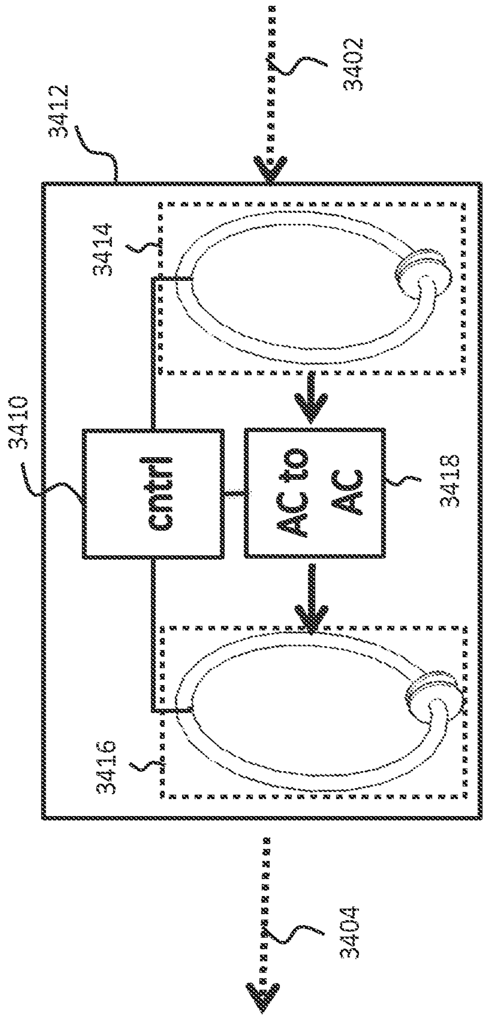


Fig. 34B

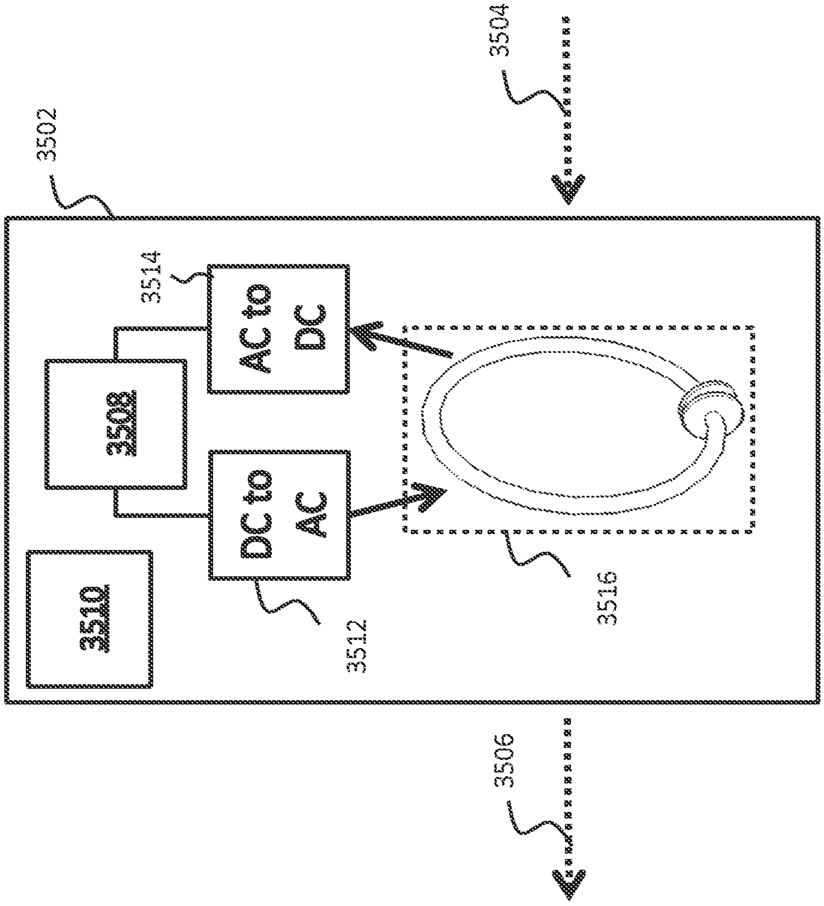


Fig. 35

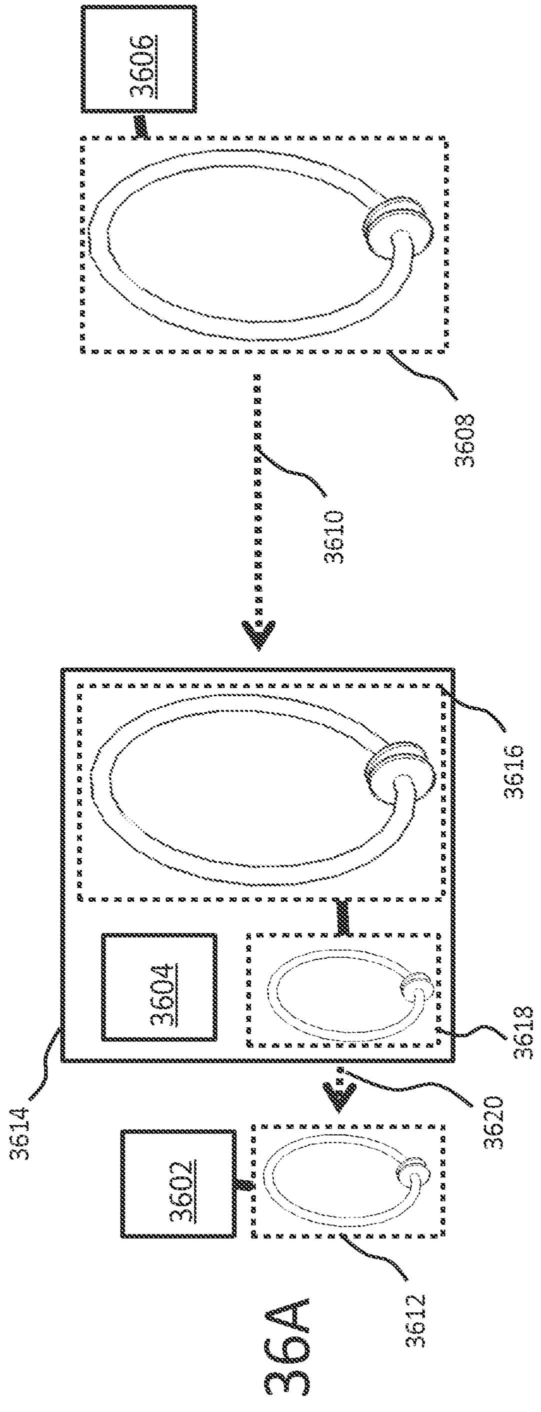


Fig. 36A

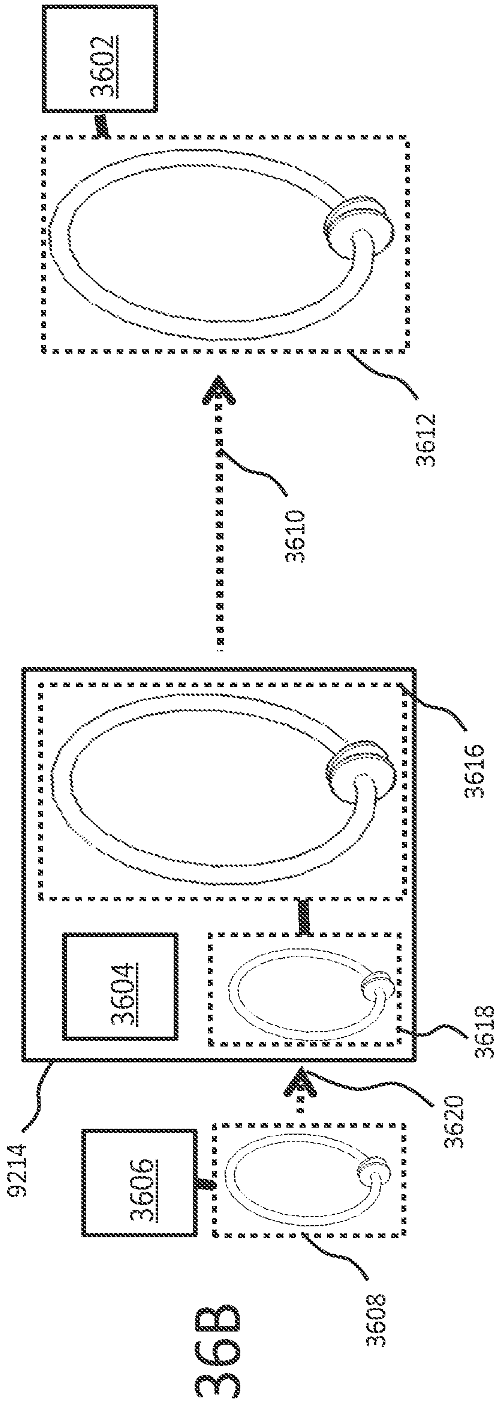
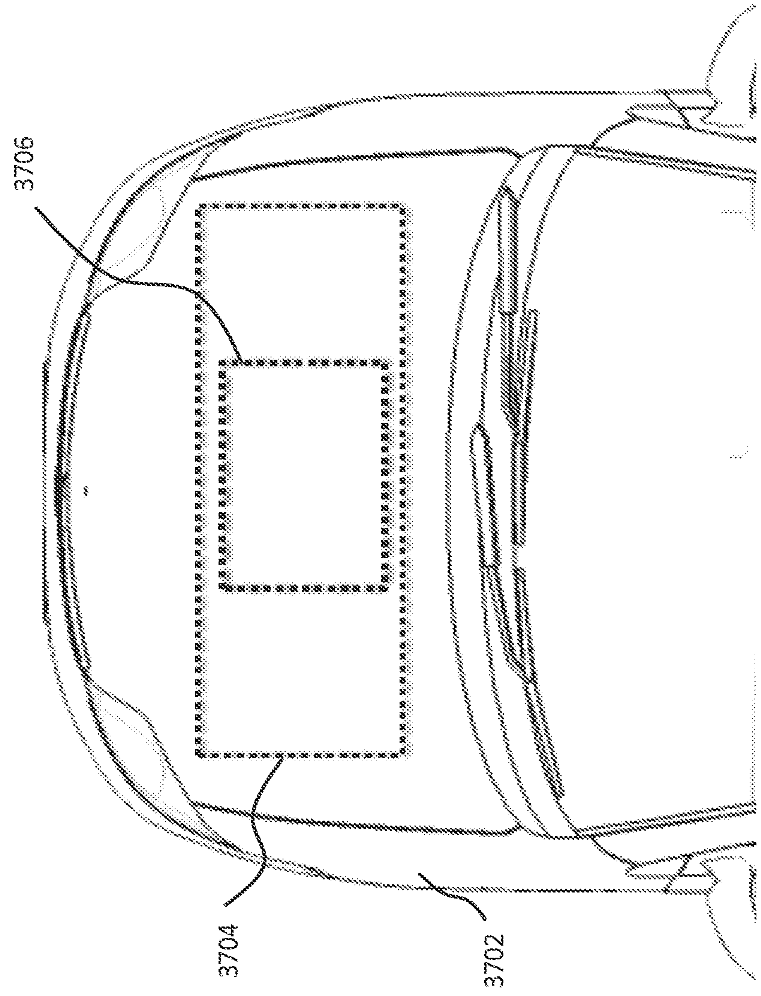


Fig. 36B

Fig. 37



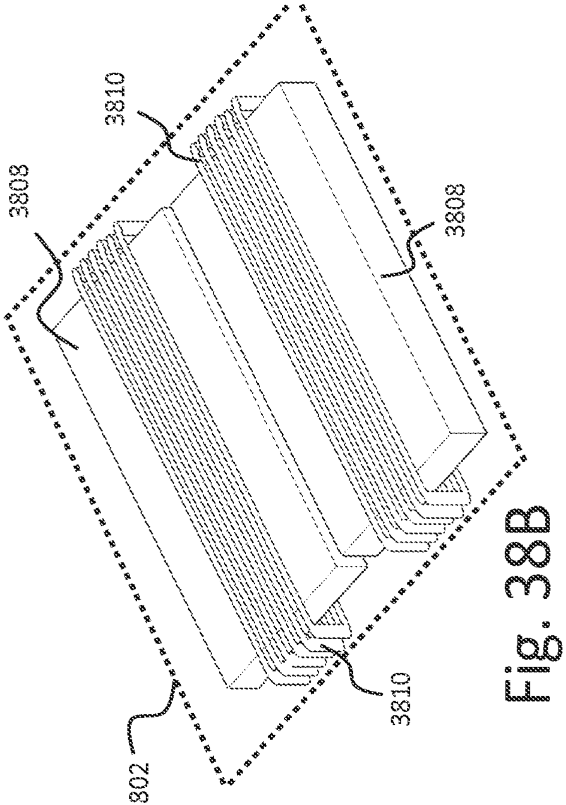


Fig. 38B

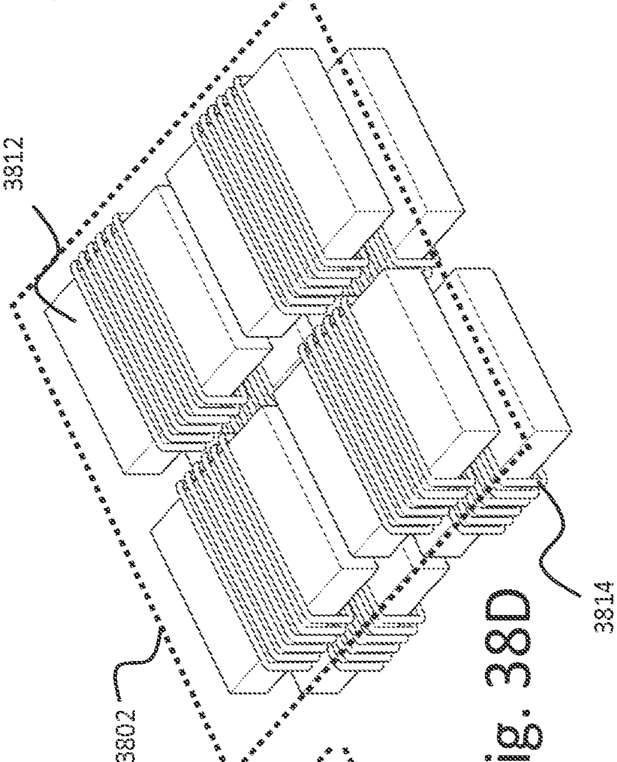


Fig. 38D

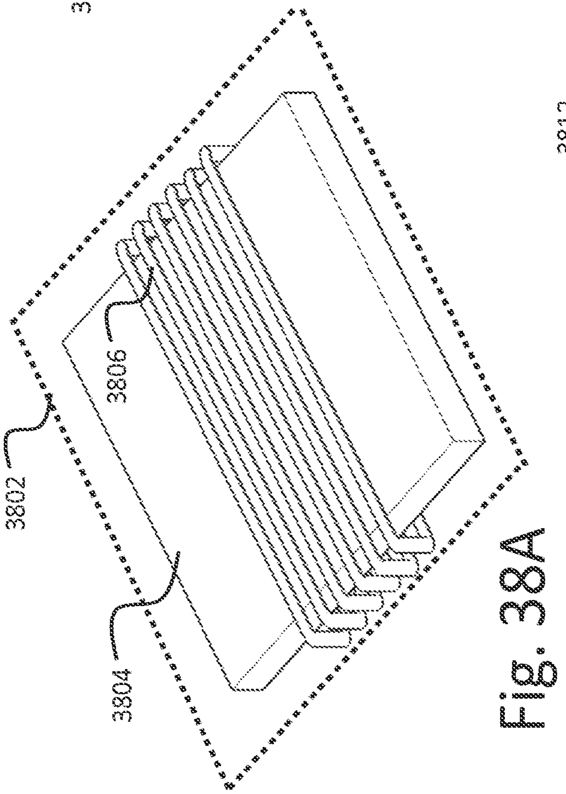


Fig. 38A

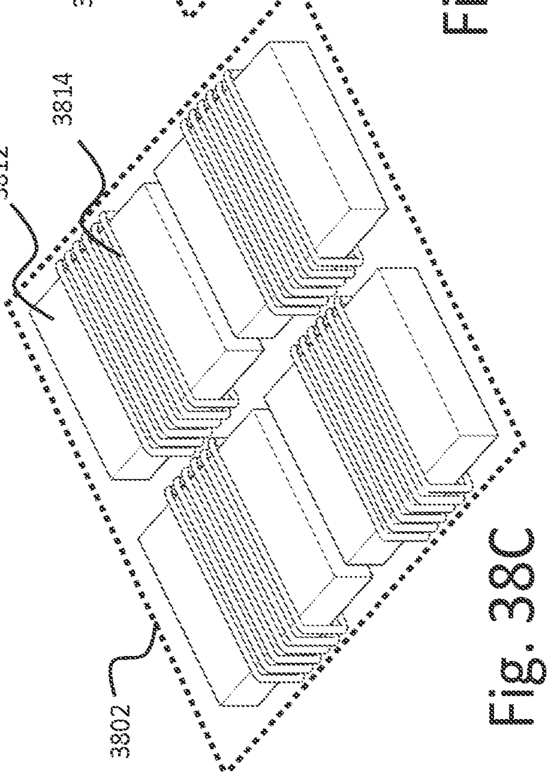


Fig. 38C

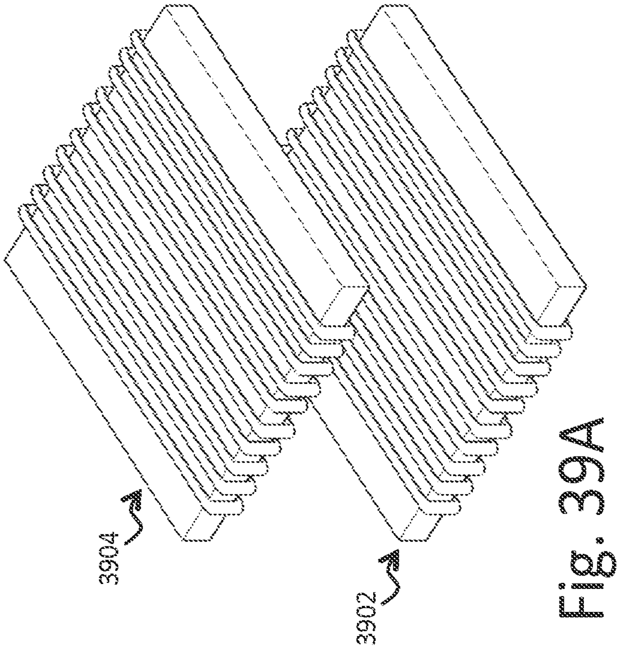


Fig. 39A

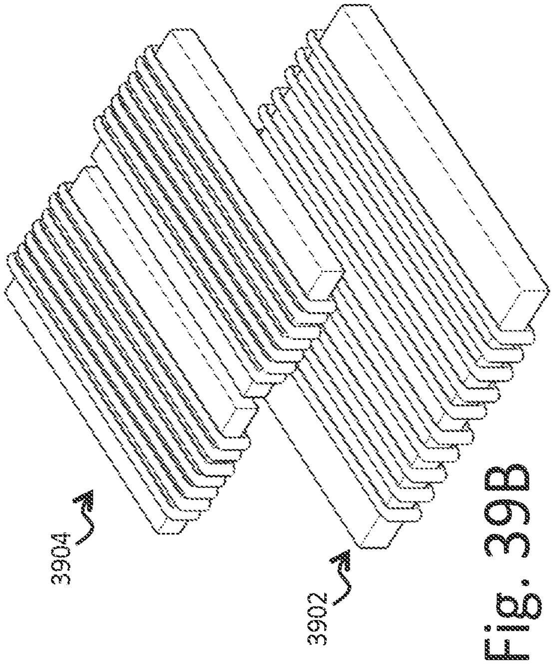


Fig. 39B

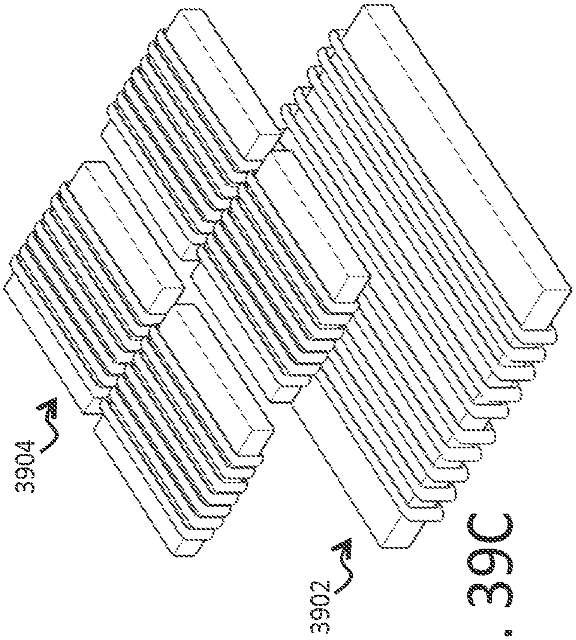
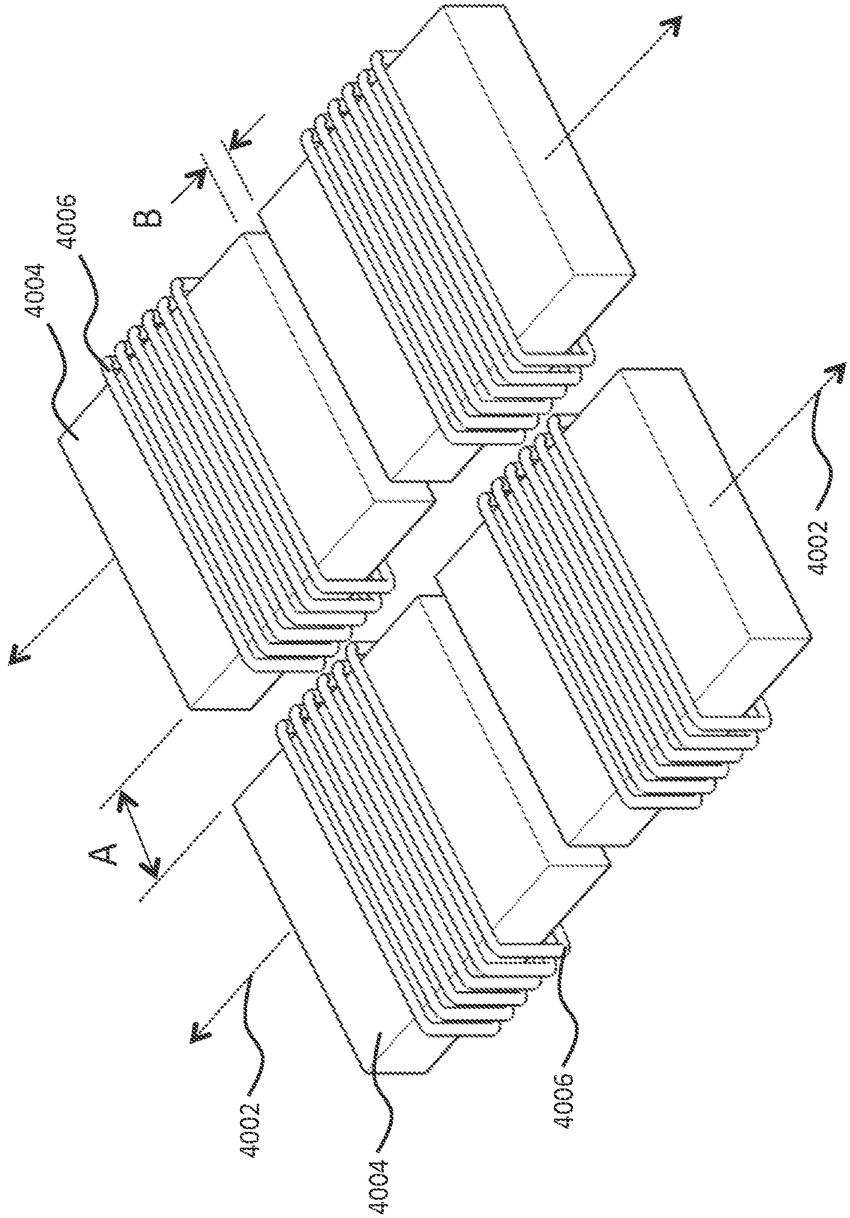


Fig. 39C

Fig. 40



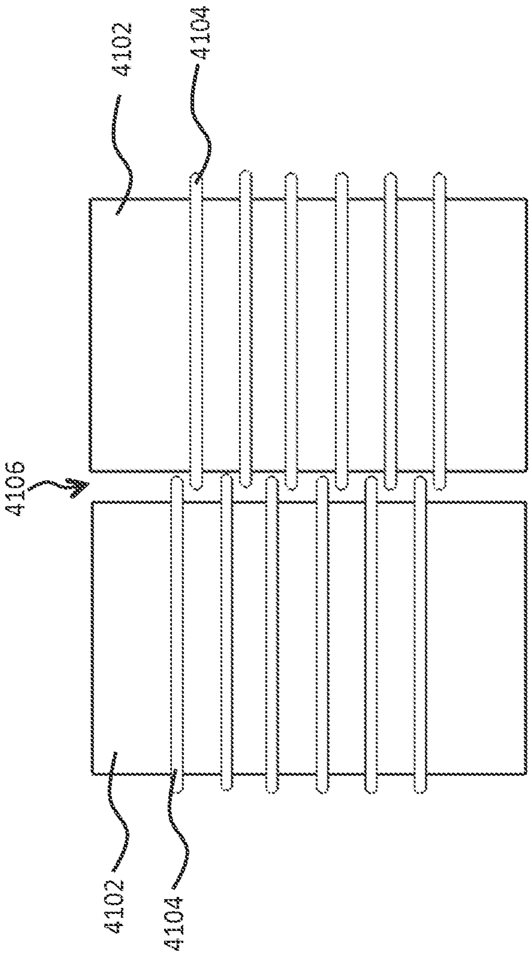


Fig. 41A

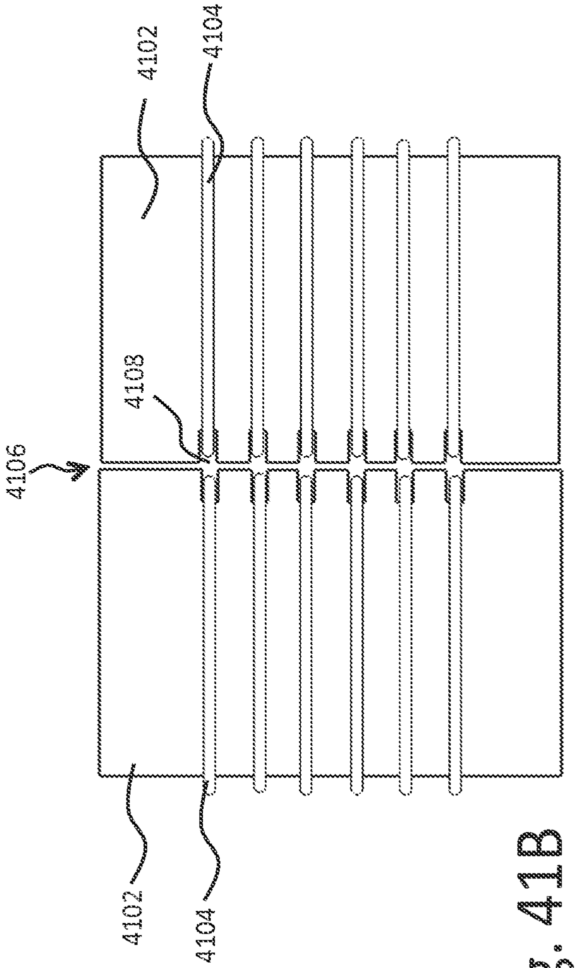


Fig. 41B

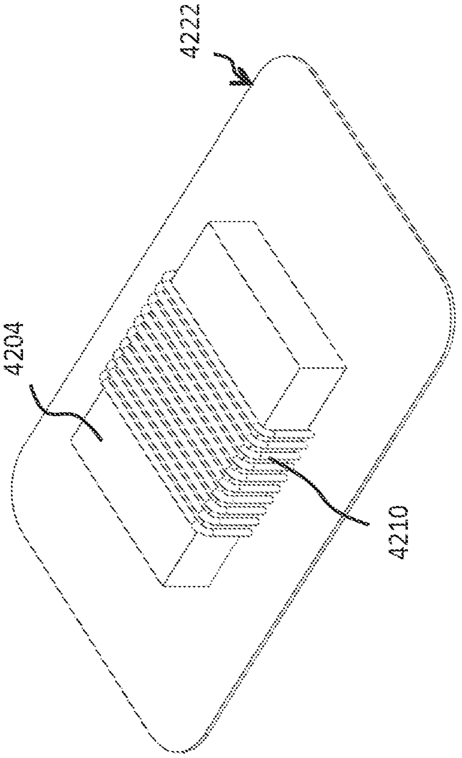


Fig. 42B

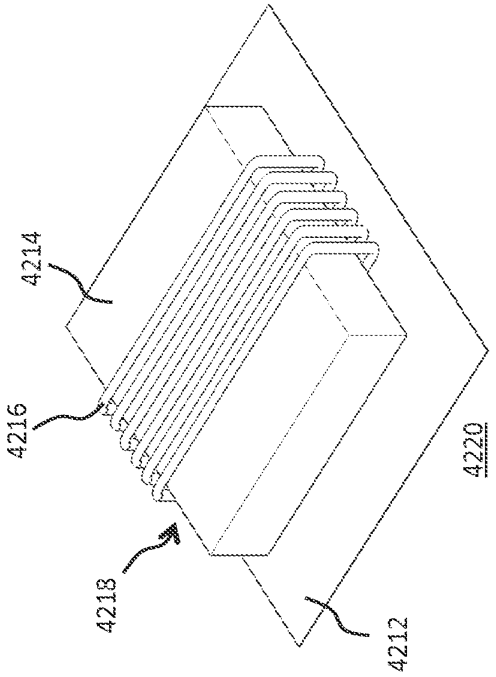


Fig. 42A

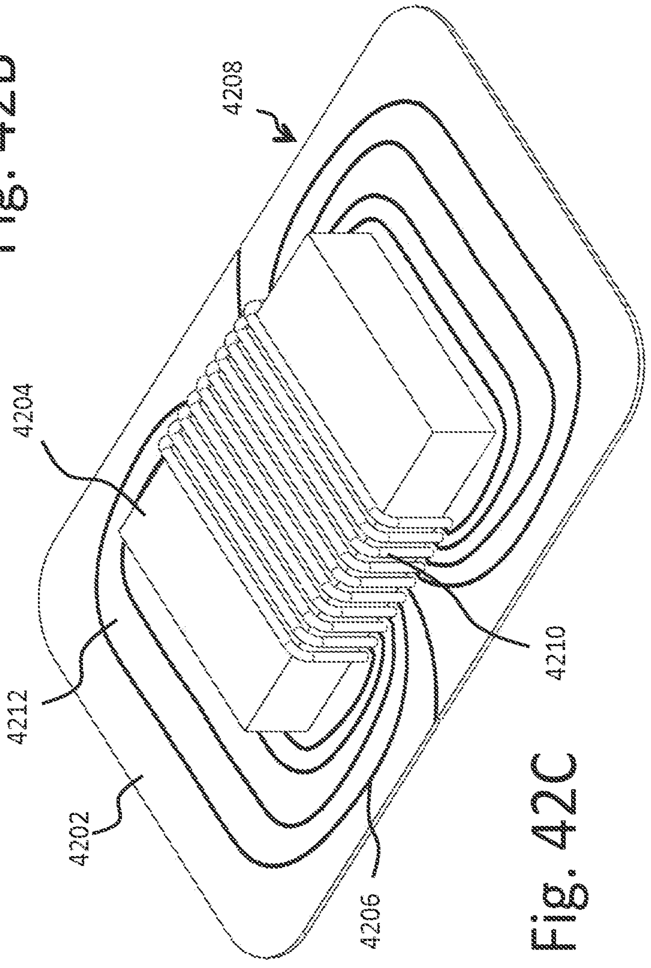


Fig. 42C

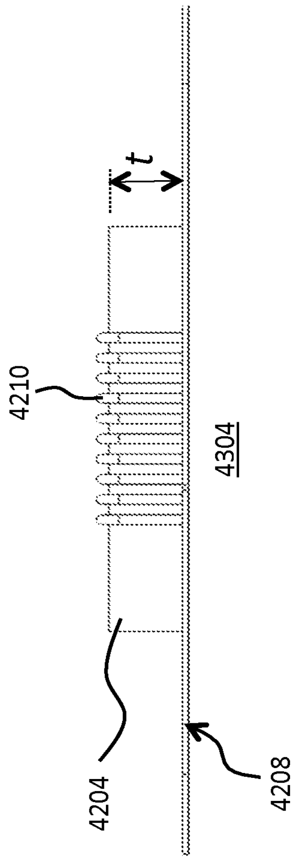


Fig. 43B

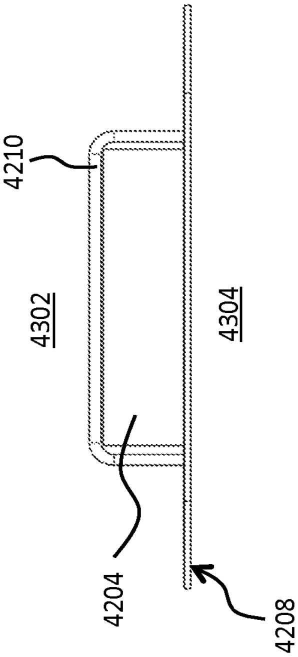


Fig. 43C

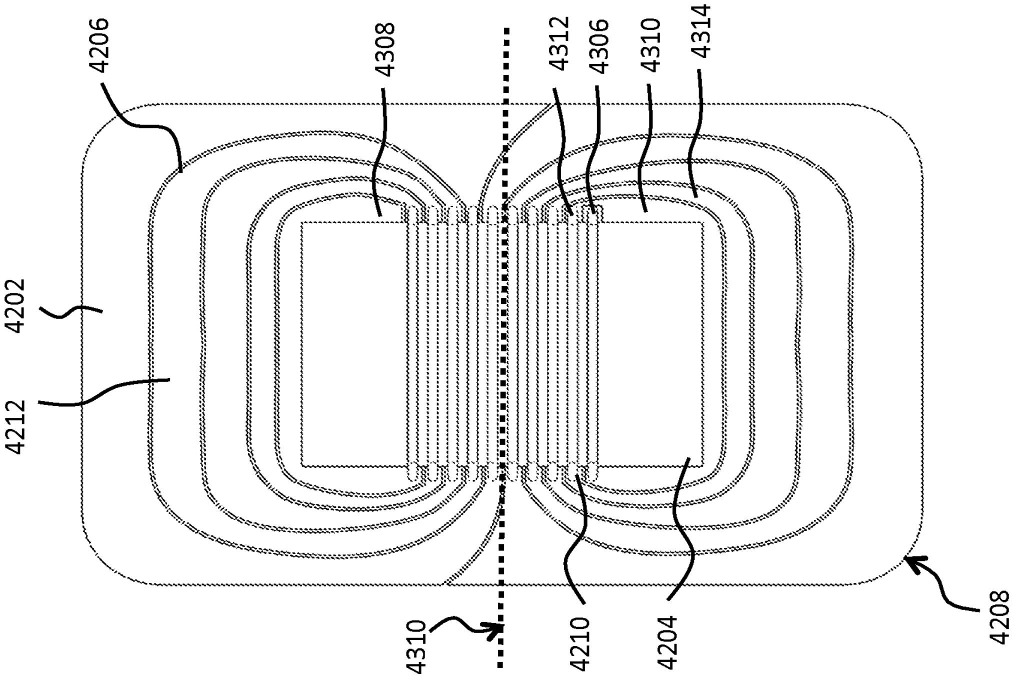
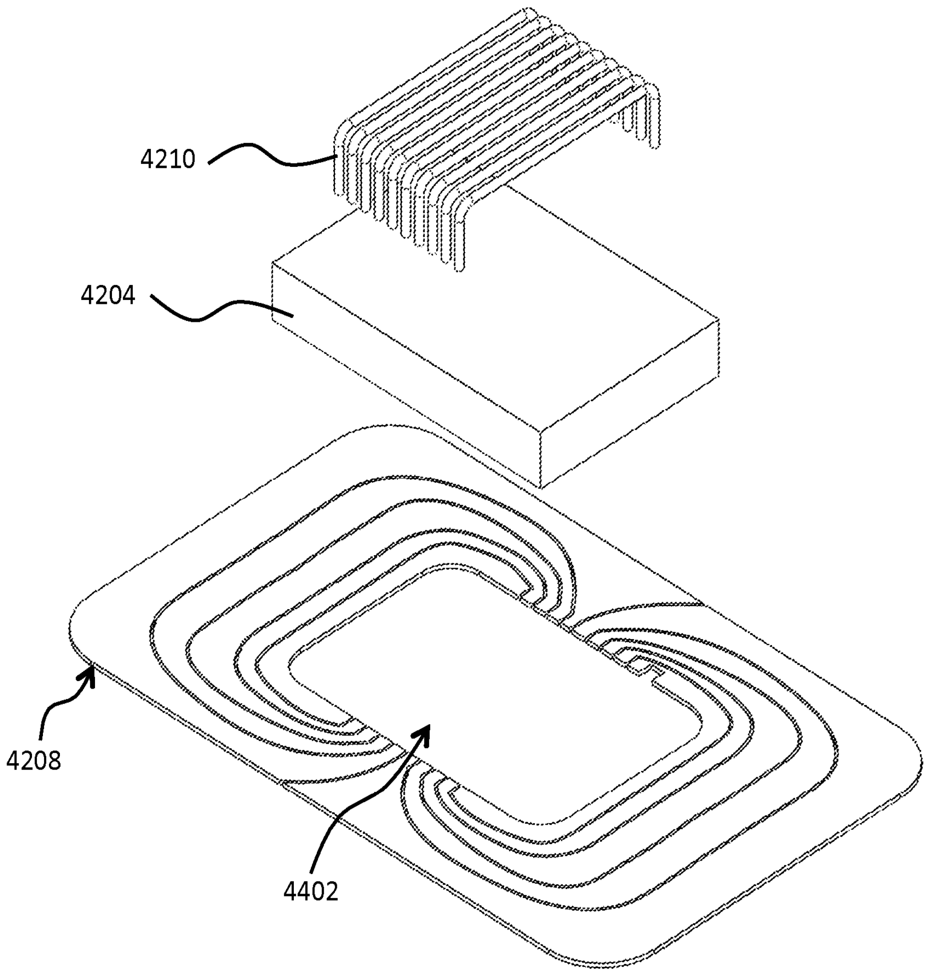


Fig. 43A

Fig. 44



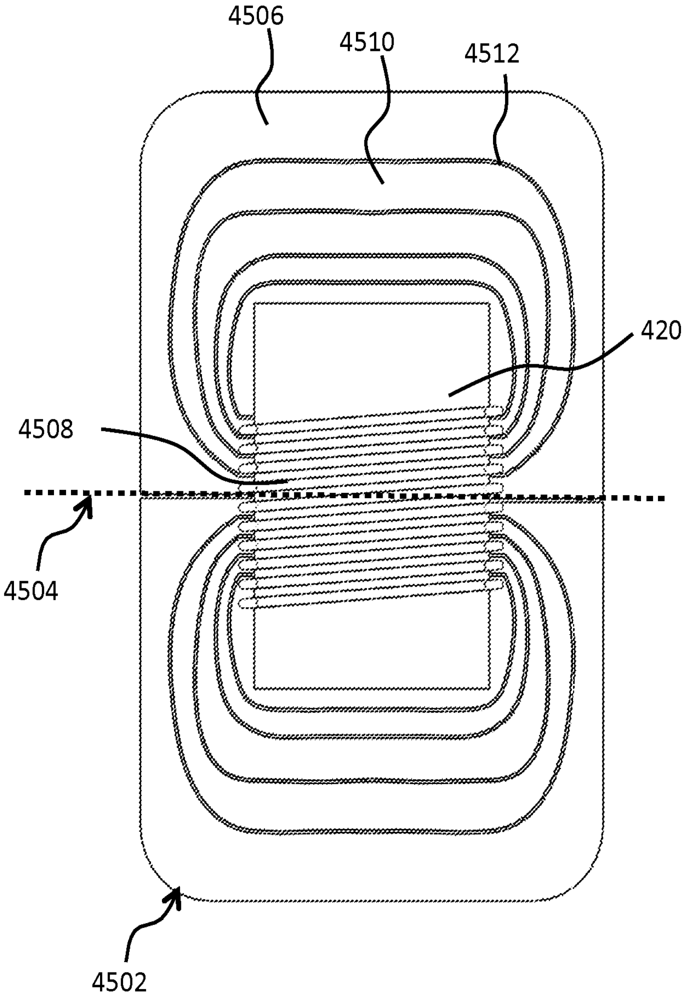


Fig. 45A

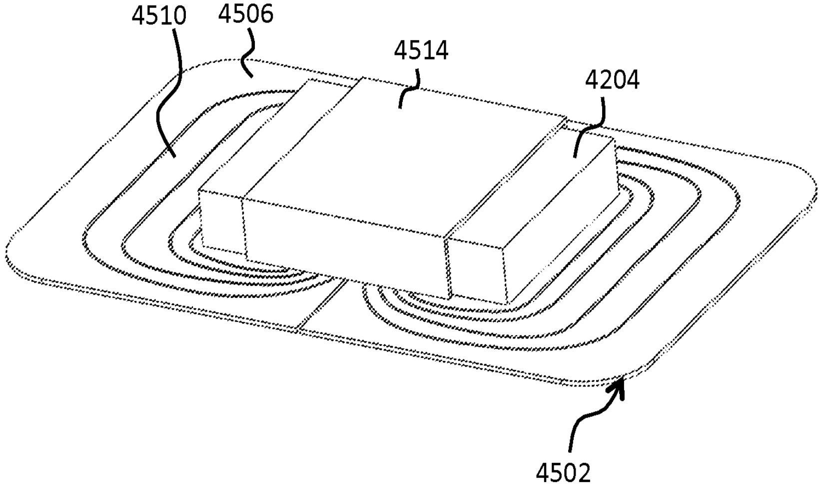


Fig. 45B

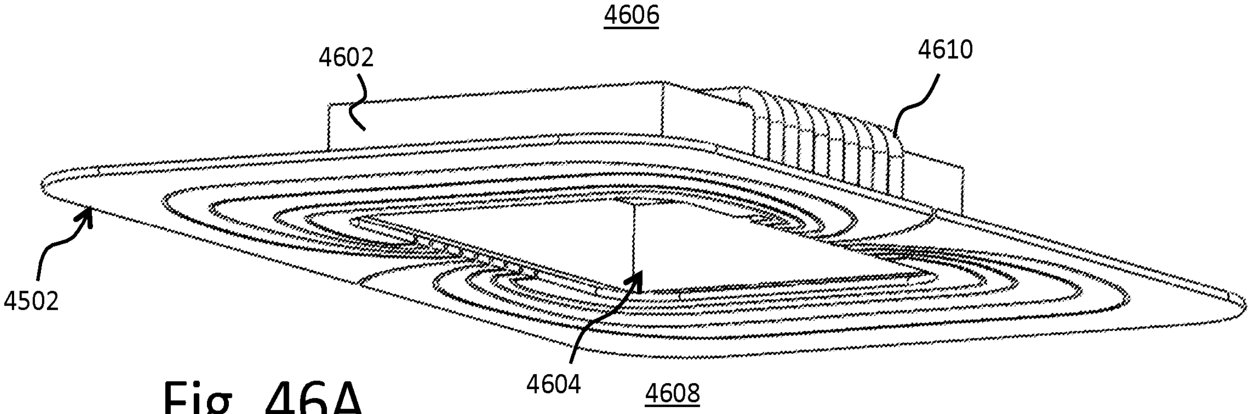


Fig. 46A

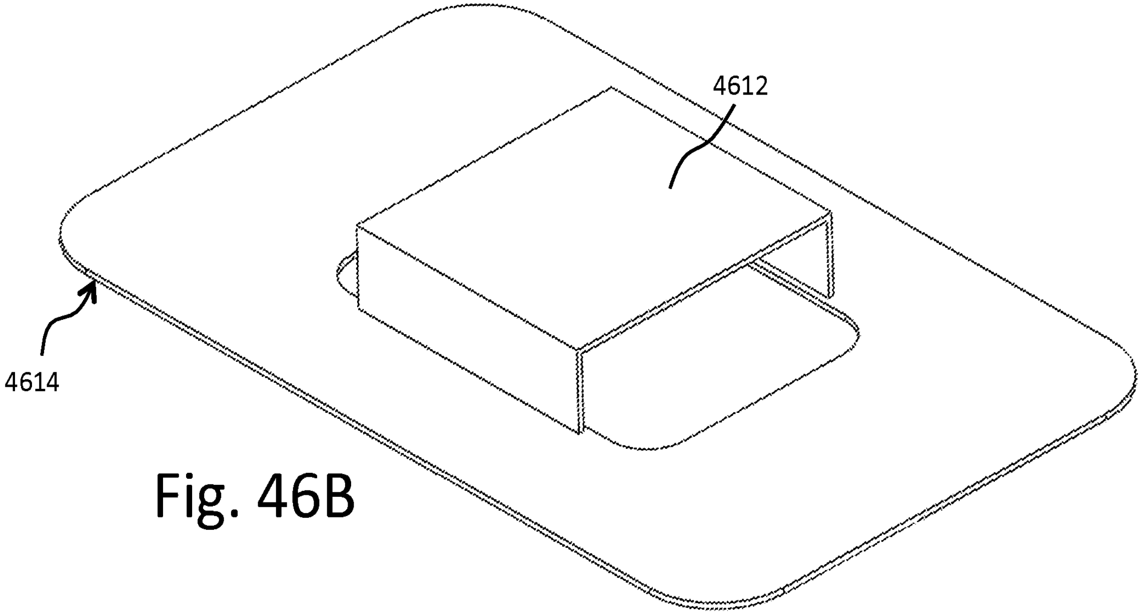


Fig. 46B

Fig. 47

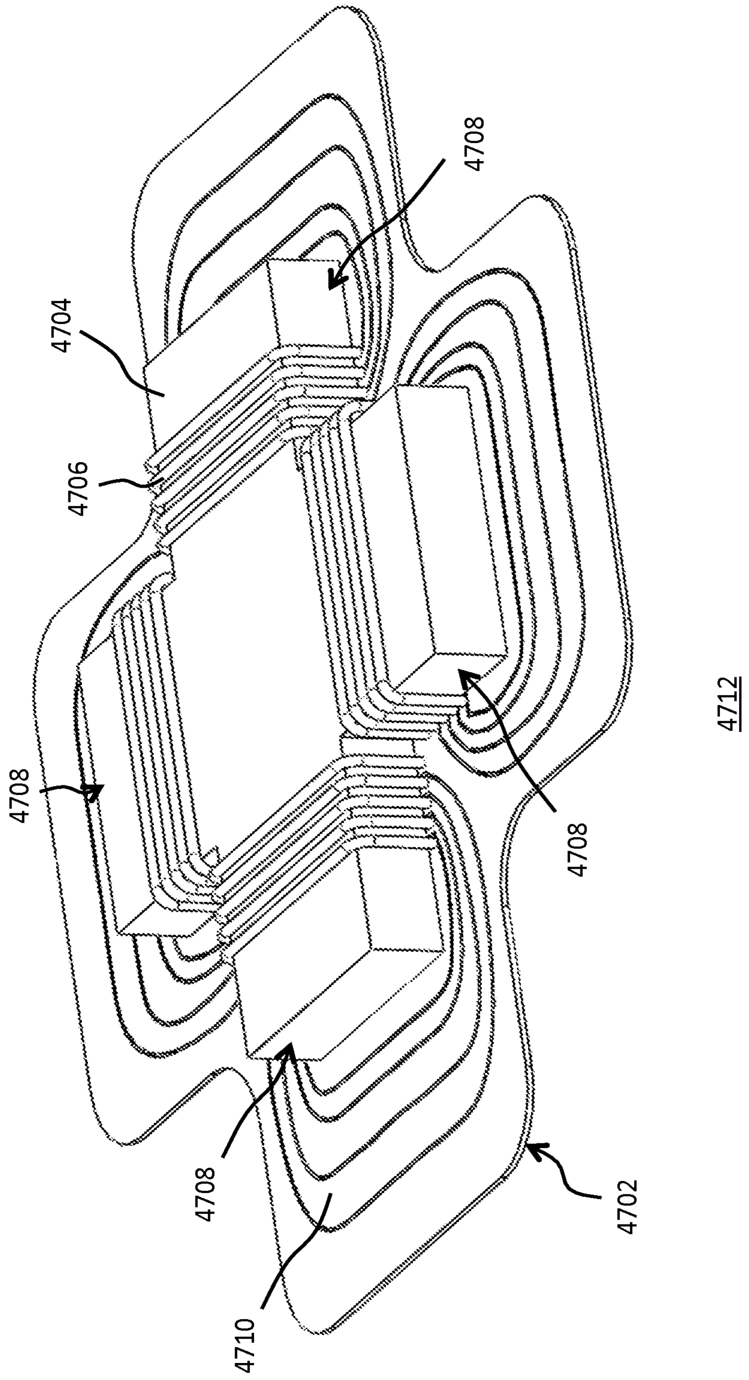
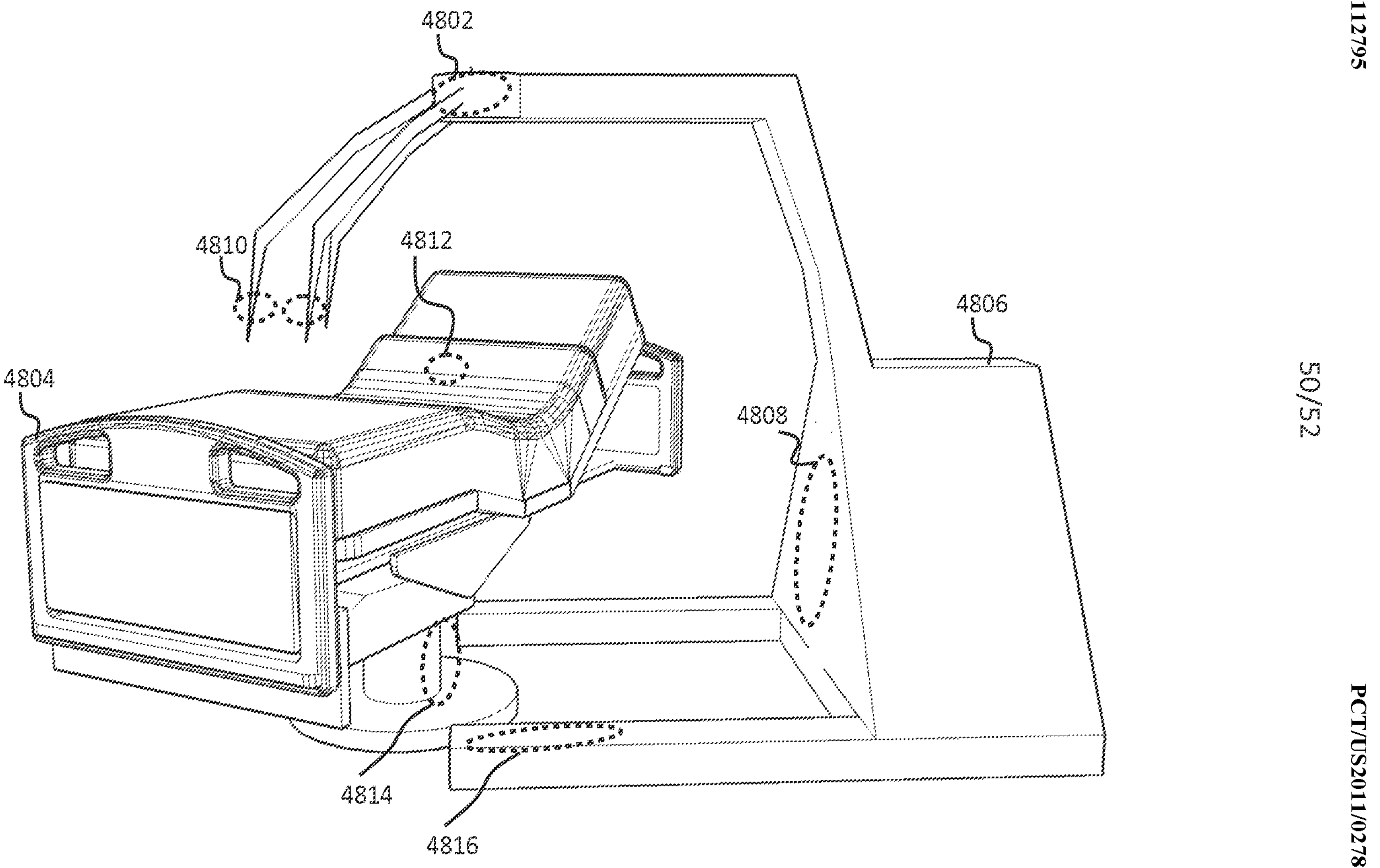


Fig. 48



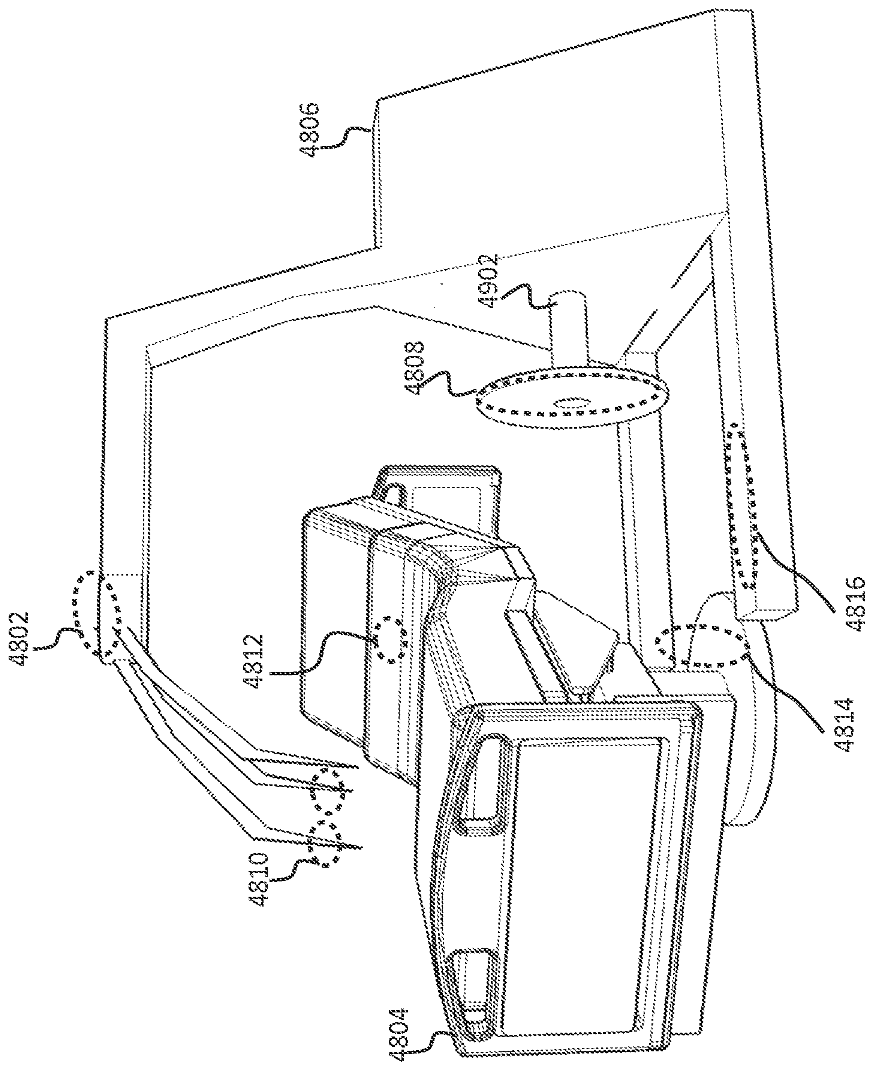


Fig. 49

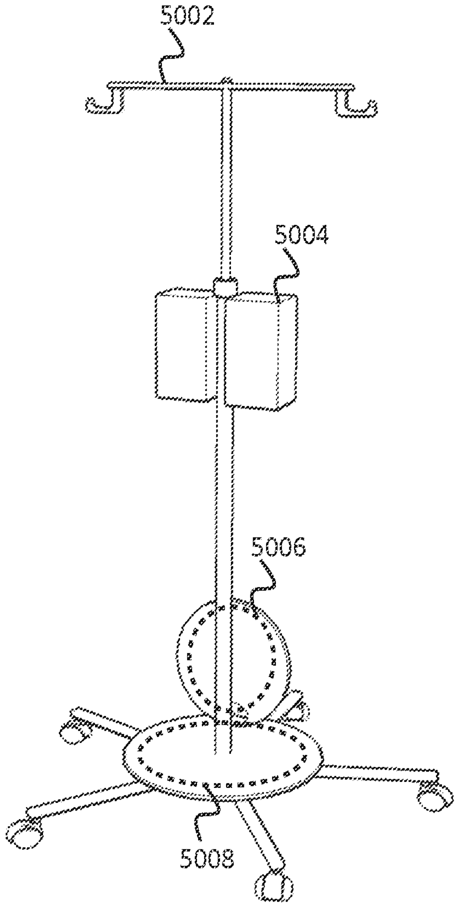


Fig. 50A

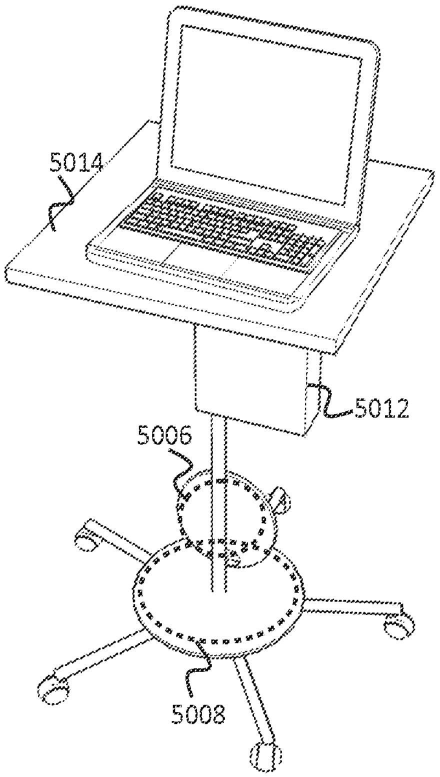


Fig. 50B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/027868

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H04B 5/00 (2011.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H04B 5/00; H01F 38/00; H02J 17/00; H01P 7/00, 7/06 (2011.01)
USPC - 307/104, 333/219, 230; 455/41.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent, Questel Orbit, USPTO EAST System (US-PGPUB; USPAT; USOCR; EPO; JPO; DERWENT), Google Patent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/0085408 A1 (BRUHN) 02 April 2009 (02.04.2009) entire document	1-4, 11-12, 14-15, 17
--		----
Y		5-10, 13, 16, 18-19
Y	US 2009/0243397 A1 (COOK et al) 01 October 2009 (01.10.2009) entire document	5, 8-10, 16, 18
Y	US 2007/0021140 A1 (KEYES, IV et al) 25 January 2007 (25.01.2007) entire document	6-7
Y	US 2008/0266748 A1 (LEE) 30 October 2008 (30.10.2008) entire document	13, 19
A	US 2008/0036588 A1 (IVERSON et al) 14 February 2008 (14.02.2008) entire document	20-25
A	US 6,664,770 B1 (BARTELS) 16 December 2003 (16.12.2003) entire document	1-25
A	US 2004/0000974 A1 (ODENAAL et al) 01 January 2004 (01.01.2004) entire document	1-25

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 27 June 2011	Date of mailing of the international search report 05 JUL 2011
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter I of the Patent Cooperation Treaty)

(PCT Rule 44*bis*)

Applicant's or agent's file reference WTCY0026PWO	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/US2009/058499	International filing date *(day/month/year)* 25 September 2009 (25.09.2009)	Priority date *(day/month/year)* 27 September 2008 (27.09.2008)
International Patent Classification (8th edition unless older edition indicated) See relevant information in Form PCT/ISA/237		
Applicant WITRICITY CORPORATION		

1. This international preliminary report on patentability (Chapter I) is issued by the International Bureau on behalf of the International Searching Authority under Rule 44 *bis*.1(a).

2. This REPORT consists of a total of 5 sheets, including this cover sheet.

   In the attached sheets, any reference to the written opinion of the International Searching Authority should be read as a reference to the international preliminary report on patentability (Chapter I) instead.

3. This report contains indications relating to the following items:

☒	Box No. I	Basis of the report
☐	Box No. II	Priority
☐	Box No. III	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
☐	Box No. IV	Lack of unity of invention
☒	Box No. V	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
☐	Box No. VI	Certain documents cited
☐	Box No. VII	Certain defects in the international application
☐	Box No. VIII	Certain observations on the international application

4. The International Bureau will communicate this report to designated Offices in accordance with Rules 44*bis*.3(c) and 93*bis*.1 but not, except where the applicant makes an express request under Article 23(2), before the expiration of 30 months from the priority date (Rule 44*bis* .2).

	Date of issuance of this report 29 March 2011 (29.03.2011)
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Dorothée Mülhausen e-mail: pt01.pct@wipo.int

Form PCT/IB/373 (January 2004)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: ROBERT A. MAZZARESE
STRATEGIC PATENTS, P.C.
C/O INTELLEVATE
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

	Date of mailing *(day/month/year)* 10 DEC 2009
Applicant's or agent's file reference WTCY0026PWO	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US 09/58499	25 September 2009 (25.09.2009)	27 September 2008 (27.09.2008)

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H03B 19/00 (2009.01)
USPC - 327/113

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:
   - ☒ Box No. I Basis of the opinion
   - ☐ Box No. II Priority
   - ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - ☐ Box No. IV Lack of unity of invention
   - ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - ☐ Box No. VI Certain documents cited
   - ☐ Box No. VII Certain defects in the international application
   - ☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

   If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

   If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

   For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US	Date of completion of this opinion	Authorized officer:
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	27 November 2009 (27.11.2009)	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 09/58499

Box No. I **Basis of this opinion**

1. With regard to the **language**, this opinion has been established on the basis of:

   ☒ the international application in the language in which it was filed.

   ☐ a translation of the international application into ______________________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

   a. (means)

   ☐ on paper

   ☐ in electronic form

   b. (time)

   ☐ in the international application as filed

   ☐ together with the international application in electronic form

   ☐ subsequently to this Authority for the purposes of search

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Form PCT/ISA/237 (Box No. I) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 09/58499

Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Claims	1 - 26	YES
	Claims	None.	NO
Inventive step (IS)	Claims	None.	YES
	Claims	1 - 26	NO
Industrial applicability (IA)	Claims	1 - 26	YES
	Claims	None.	NO

2. Citations and explanations:

Claims 1 - 26 lack an inventive step under PCT Article 33(3) as being obvious over US 2007/0222542 A1 to Joannopoulos et al. (hereinafter 'Joannopoulos'), in view of US 6,452,465 B1 to Brown et al. (hereinafter 'Brown').

Regarding claim 1, Joannopoulos teaches a system, comprising: a source resonator having a Q-factor Q1 and a characteristic size X1 (abstract, para. [0005]), coupled to a power generator (external power supply, para. [0005]), and a second resonator having a Q-factor Q2 and a characteristic size X2 (para. [0005]), coupled to a load located a distance D from the source resonator (distance between the two resonators can be larger than the characteristic size of each resonator, para. [0005]), wherein the source resonator and the second resonator are coupled to exchange energy wirelessly among the source resonator and the second resonator (abstract, para. [0004], [0013]). Joannopoulos does not teach that the square root of Q1Q2 > 100. However, Brown teaches multiple resonators that are tunable (abstract), and that filters may be fabricated with low quality factor resonators (col. 2, ln 4-6). It would have been obvious to one skilled in the art to combine the teachings of Joannopoulos with those of Brown in order to provide an inexpensive resonator structure. Neither Joannopoulos nor Brown specifically teach that the square root of Q1Q2 > 100. However, this configuration could have been determined via routine experimentation, and provided based on the specific application of the system.

Regarding claims 2 and 3, neither Joannopoulos nor Brown teaches that Q1 (or Q2 - claim 3) < 100. However, it was well known it the art at the time of the invention that resonator materials were available with low quality factors, e.g. Q1 (or Q2 - claim 3) < 100. It would have been obvious to one skilled in the art to provide Q1 (or Q2 - claim 3) < 100, in order to provide an inexpensive resonator structure.

Regarding claims 4 and 5, neither Joannopoulos nor Brown specifically teaches a third resonator having a Q-factor Q3 configured to transfer energy non-raditively with the source and second resonators, wherein the square root of Q1Q3 > 100 and the square root of Q2Q3 > 100, wherein Q3 < 100 (claim - 5). However, this configuration could have been determined via routine experimentation, and provided based on the specific application of the system.

Regarding claim 6, Joannopoulos teaches that the source resonator is coupled to the power generator with direct electrical connections (para. [0014]).

Regarding claim 7, Joannopoulos teaches that the source resonator is coupled and impedance matched to the power generator with direct electrical connections (para. [0014]).

Regarding claim 8, Brown teaches a tunable circuit wherein the source resonator is coupled to the power generator through the tunable circuit with direct electrical connections (abstract, col. 3, ln 7-12).

Regarding claim 9, Joannopoulos teaches that at least one of the direct electrical connections is configured to substantially preserve a resonant mode of the source resonator (resonant cavity, para. [0033]).

Regarding claim 10, neither Joannopoulos nor Brown specifically teaches that the source resonator has a first terminal, a second terminal, and a center terminal, and wherein an impedance between the first terminal and the center terminal and between the second terminal and the center terminal are substantially equal. However, this configuration could have been determined via routine experimentation and provided to maximize power transfer.

Regarding claim 11, Joannopoulos teaches that the source resonator includes a capacitive loaded loop having a first terminal, a second terminal, and a center terminal (para. [0019]), and wherein an impedance between the first terminal and the center terminal and between the second terminal and the center terminal are substantially equal (para. [0019]).

Regarding claim 12, neither Joannopoulos nor Brown specifically teaches that the source resonator is coupled to an impedance matching network and the impedance matching network further comprises a first terminal, a second terminal, and a center terminal, and wherein an impedance between the first terminal and the center terminal and between the second terminal and the center terminal are substantially equal. However, this configuration could have been determined via routine experimentation and provided to maximize power transfer.

---(continued in Supplemental Box)---

Form PCT/ISA/237 (Box No. V) (July 2009)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.

PCT/US 09/58499

Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of:

V.2 Citations and explanations:

Regarding claim 13, neither Joannopoulos nor Brown teaches that the first terminal and the second terminal are directly coupled to the power generator and driven with oscillating signals that are near 180 degrees out of phase. However, this configuration was well known in the art at the time of the invention, and could have been provided based on the specific application.

Regarding claim 14, Joannopoulos teaches that the source resonator has a resonant frequency WI and the first terminal and the second terminal are directly coupled to the power generator and driven with oscillating signals that are substantially equal to the resonant frequency omega sub 1 (para. [0023], [0025]).

Regarding claim 15, neither Joannopoulos nor Brown specifically that the center terminal is connected to an electrical ground. However, this configuration was well known in the art at the time of the invention, and could have been provided in order to provide a voltage reference point.

Regarding claim 16, neither Joannopoulos nor Brown teach that the source resonator has a resonant frequency omega sub 1 and the first terminal and the second terminal are directly coupled to the power generator and driven with a frequency substantially equal to the resonant frequency omega sub 1. However, this configuration could have been determined via routine experimentation and provided to maximize power transfer.

Regarding claim 17, Brown teaches a plurality of capacitors coupled to the power generator and the load (col., 3, ln 66-67).

Regarding claim 18, Joannopoulos that the source resonator and the second resonator are each enclosed in a low loss tangent material (para. [0023]).

Regarding claim 19, Joannopoulos teaches a power conversion circuit wherein the second resonator is coupled to the power conversion circuit to deliver DC power to the load (abstract).

Regarding claim 20, Joannopoulos teaches a power conversion circuit wherein the second resonator is coupled to the power conversion circuit to deliver AC power to the load (power, abstract, para. [0029]).

Regarding claim 21, Joannopoulos teaches a power conversion circuit, wherein the second resonator is coupled to the power conversion circuit to deliver both AC and DC power to the load (power, abstract, para. [0029]).

Regarding claim 22, Joannopoulos teaches a power conversion circuit and a plurality of loads, wherein the second resonator is coupled to the power conversion circuit (abstract), and the power conversion circuit is coupled to the plurality of loads (abstract).

Regarding claim 23, Brown teaches the system, wherein the impedance matching network comprises capacitors (col., 3, ln 66-67).

Regarding claim 24, Joannopoulos teaches that the impedance matching network comprises inductors (coils, para. [0025]).

Regarding claim 25, Brown teaches that the tunable circuit comprises variable capacitors (col., 3, ln 66-67).

Regarding claim 26, Joannopoulos teaches that the tunable circuit comprises variable inductors (para. [0025]).

Claims 1 - 26 have industrial applicability as defined by PCT Article 33(4) because the subject matter can be made or used in industry.

Form PCT/ISA/237 (Supplemental Box) (July 2009)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY0014PWO	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)	(Earliest) Priority Date *(day/month/year)* 13 February 2009 (13.02.2009)
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ____________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6*bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.
2. ☐ **Certain claims were found unsearchable** (see Box No. II).
3. ☐ **Unity of invention is lacking** (see Box No. III).
4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:
5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/24199

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01F 27/42 (2010.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): H01F 27/42 (2010.01)
USPC: 307/104

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): H01F 27/42 (2010.01) (text search)
USPC: 307/104; 340/855.8 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, EPAB, JPAB); Google Patent; Google Scholar: Search Terms: wireless power transmission coil magnetic field capacitive coupling dielectric ring electric conductive wire loop wireless resonant ferromagnetic medium contact-less power frequency amplitude

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2007/0222542 A1 (Joannopoulos) 27 September 2007 (27.09.2007), entire document, especially; para. [0001] through [0045], Fig. 1-6B	1-11, 16-26, 31 --- 12-15, 27-30
X --- Y	US 2008/0012569 A1 (Hall et al.) 17 January 2008 (17.01.2008), entire document, especially; para. [0034] through [0055], Fig. 1-14	32, 33 --- 14, 15, 29, 30
Y	US 2008/0030415 A1 (Homan et al.) 07 February 2008 (07.02.2008), para. [0005], [0042] through [0073], Fig. 9, 10	12, 13, 27, 28
A	US 2008/0278264 A1 (Karalis et al.) 13 November 2008 (13.11.2008), entire document	1 - 33
A	US 2009/0015075 A1 (Cook et al.) 15 January 2009 (15.01.2009), entire document	1 - 33

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 03 May 2010 (03.05.2010)	Date of mailing of the international search report 14 MAY 2010
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PCT/US2010/024199 14.05.2010

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN H. NORTRUP
STRATEGIC PATENTS, P.C.
C/O INTELLEVATE
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

		Date of mailing *(day/month/year)* **14 MAY 2010**
Applicant's or agent's file reference WTCY0014PWO		**FOR FURTHER ACTION** See paragraph 2 below
International application No. PCT/US 10/24199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)	Priority date *(day/month/year)* 13 February 2009 (13.02.2009)

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H01F 27/42 (2010.01)
USPC - 307/104

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:
   - ☒ Box No. I Basis of the opinion
   - ☐ Box No. II Priority
   - ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - ☐ Box No. IV Lack of unity of invention
   - ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - ☐ Box No. VI Certain documents cited
   - ☐ Box No. VII Certain defects in the international application
   - ☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

   If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

   If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

   For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Date of completion of this opinion 03 May 2010 (03.05.2010)	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2009)

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 10/24199

Box No. I **Basis of this opinion**

1. With regard to the **language**, this opinion has been established on the basis of:

☒ the international application in the language in which it was filed.

☐ a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

   a. (means)
      - ☐ on paper
      - ☐ in electronic form

   b. (time)
      - ☐ in the international application as filed
      - ☐ together with the international application in electronic form
      - ☐ subsequently to this Authority for the purposes of search

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 10/24199

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	12-15, 27-30	YES
	Claims	1-11, 16-26, 31-33	NO
Inventive step (IS)	Claims	None.	YES
	Claims	1 - 33	NO
Industrial applicability (IA)	Claims	1 - 33	YES
	Claims	None.	NO

2. Citations and explanations:

Claims 1-11, 16-26 and 31 lack novelty under PCT Article 33(2) as being anticipated by US 2007/0222542 A1 (Joannopoulos).

Regarding claim 1, Joannopoulos discloses a wireless power transfer system (source 1 and device 2; loop 10, loop 12, of N coils of radius r of conducting wire with circular cross-section, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising: at least one source magnetic resonator (source 1; loop 10, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) coupled to a power source (external power supply, para. [0005], [0006]) and configured to generate an oscillating magnetic field (long-lived oscillatory resonant electromagnetic modes, resonant frequency/Omega, para. [0002], [0013], [024], [0025], [0026], [0031]); and at least one device magnetic resonator (device 2; loop 12, para. [0015], [0024], [0025], [0028], Fig. 1, 3), distal from said source resonators (distances D, para. [0034], Fig. 1, 3), comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) configured to convert said oscillating magnetic fields into electrical energy (para. [0012], Fig. 6A, 6B); wherein at least one said resonator has a keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) around the resonator that surrounds the resonator with a layer of non-lossy material (air, para. [0017], [0018], [0020], [0024], [0025], [0032], [0037], Fig. 2A, 2B).

Regarding claim 2, Joannopoulos discloses the system of claim 1, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a symmetric distance around the resonator (air, supports high-Q whispering-gallery modes, para. [0008], [0017], [0018], [0020], Fig. 2A).

Regarding claim 3, Joannopoulos discloses the system of claim 1, wherein the keep-out zone (near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a asymmetric distance around the resonator (air, supports high-Q whispering-gallery modes, dielectric waveguides, can support guided modes, para. [0008], [0017], [0018], [0020], [0024], Fig. 2B).

Regarding claim 4, Joannopoulos discloses the system of claim 3, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is largest around regions of the resonator where the electric fields are the largest (proximal cavity 20, para. [0008], [0020], [0024], Fig. 2B)

Regarding claim 5, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 0.25 mm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 6, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 1 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 7, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 10 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 8, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 1.0 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

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Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
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V.2. Citations and explanations:

Regarding claim 9, Joannopoulos discloses the system of claim 1, wherein the smallest keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 0.1 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

Regarding claim 10, Joannopoulos discloses the system of claim 1, wherein the magnetic resonator further comprises a magnetic material (metallodielectric photonic crystals, para. [0022]).

Regarding claim 11, Joannopoulos discloses the system of claim 1, wherein at least one magnetic resonator has an intrinsic Q greater than 100 (Q.sub.rad = 1988, 1258, 702, 226; Q.sub.abs = 312530, 86980, 21864, 1662, para. [0034]).

Regarding claim 16, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is located inside a living creature (human, para. [0012], [0032], [0038] through [0041]).

Regarding claim 17, Joannopoulos discloses a method for wireless power transfer (source 1 and device 2; loop 10, loop 12, of N coils of radius r of conducting wire with circular cross-section, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising: energizing at least one source magnetic resonator (source 1; loop 10, para. [0015], [0024], [0025], [0028], Fig. 1, 3) comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) to generate an oscillating magnetic field (long-lived oscillatory resonant electromagnetic modes, resonant frequency/Omega, para. [0002], [0013], [024], [0025], [0026], [0031]); and providing at least one device magnetic resonator (device 2; loop 12, para. [0015], [0024], [0025], [0028], Fig. 1, 3), distal from said source resonators (distances D, para. [0034], Fig. 1, 3), comprising a capacitively-loaded conducting loop (capacitively-loaded conducting-wire loop, para. [0019], [0025], Fig. 3) configured to convert said oscillating magnetic fields into electrical energy (para. [0012], Fig. 6A, 6B); maintaining a keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) around at least one resonator to maintain a separation distance between the resonator and lossy material of the environment (background dielectric (free space/air, para. [0024], [0025]).

Regarding claim 18, Joannopoulos discloses the method of claim 17, wherein the keep-out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) extends at a symmetric distance around the resonator (air, supports high-Q whispering-gallery modes, para. [0008], [0017], [0018], [0020], Fig. 2A).

Regarding claim 19, Joannopoulos discloses the method of claim 17, wherein the keep-out zone (near field, para. [0014], [0018], [0021], [0026], [0027]) extends at an asymmetric distance around the resonator (air, supports high-Q whispering-gallery modes, dielectric waveguides, can support guided modes, para. [0008], [0017], [0018], [0020], [0024], Fig. 2B).

Regarding claim 20, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 0.25 mm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 21, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 1 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 22, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) exceeds 10 cm (microwave regime; appropriate for meter-range coupling applications; radial modal decay length, which determines the coupling strength, is on the order of the wavelength, para. [0008], [0021], [0022], [0023]).

Regarding claim 23, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 1.0 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

See Continuation sheet.

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V.2. Citations and explanations:

Regarding claim 24, Joannopoulos discloses the method of claim 17, wherein the smallest keep out zone (omnidirectional stationary (non-lossy) nature of the near field, para. [0014], [0018], [0021], [0026], [0027]) is approximately 0.1 per-cent of the characteristic size of the resonator (characteristic size L.sub.1, L.sub.2; distance between the two resonators can be larger than the characteristic size of each resonator; D/r; rough estimate in the microwave, one can use one coil (N=1) of copper wire and then for r=1 cm and .alpha.=1 mm, appropriate for example for a cell phone; r=30 cm for a laptop or a household robot; for r=1 m source loop on a room ceiling; r=30 cm and .alpha.=2 mm for a laptop or a household robot, para. [0005], [0016], [0027], [0028]).

Regarding claim 25, Joannopoulos discloses the method of claim 17, wherein the magnetic resonator further comprises a magnetic material (metallodielectric photonic crystals, para. [0022]).

Regarding claim 26, Joannopoulos discloses the method of claim 17, wherein at least one magnetic resonator has an intrinsic Q greater than 100 (Q.sub.rad = 1988, 1258, 702, 226; Q.sub.abs = 312530, 86980, 21864, 1662, para. [0034]).

Regarding claim 31, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is located inside a living creature (human, para. [0012], [0032], [0038] through [0041]).

Claims 32 and 33 lack novelty under PCT Article 33(2) as being anticipated by US 2008/0012569 A1 to Hall et al. (hereinafter 'Hall').

Regarding claim 32, Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a capacitively-loaded conducting loop (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) wrapped around a core of magnetic material (magnetic coupler 302 also comprises a coil 303 and an annular trough 404 made of magnetic material, para. [0042], [0043], [0045], Fig. 5, 6) and coupled to a power source (first coupler 304 may be optimized for the transfer of power; electronic device 210 is a power source 1301, para. [0041], [0049]) and configured to generate an oscillating magnetic field (magnetic coupler and the adjacent magnetic coupler may then be adapted to induce magnetic fields in each other when their coils are electrically energized; inductive couplers 302, 1102 may act as band pass filters due to their inherent inductance, capacitance and resistance such that a first frequency is allowed to pass at a first resonant frequency, and a second frequency is allowed to pass at a second resonant frequency, para. [0014], [0046], [0047]); wherein the conducting loops are oriented to be coaxial with length of the shaft (pin end 203 of downhole component 200, para. [0041], Fig.3).

Regarding claim 33, Hall discloses the source of claim 32, further comprising a plurality of capacitively-loaded conducting loops (magnetic coupler 302 comprises a coil 303 having a plurality of windings 601 of wire strands 602, para. [0043], Fig. 6) wrapped around cores of magnetic material (annular trough 404 made of magnetic material, para. [0042], [0043], [0045], Fig. 5, 6) arranged around the diameter of the shaft (pin end 203 of downhole component 200, para. [0041], Fig.3).

Claims 12, 13, 27 and 28 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos, in view of US 2008/0030415 A1 to Homan et al. (hereinafter 'Homan').

Regarding claim 12, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the magnetic resonator is immersed in water. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in water (water; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Regarding claim 13, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in oil. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in oil (oil; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Regarding claim 27, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the magnetic resonator is immersed in water. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in water (water; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

See Continuation sheet.

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 10/24199

Supplemental Box

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V.2. Citations and explanations:

Regarding claim 28, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in oil. Homan discloses a magnetic resonator (axial or tilted coil or antenna; toroidal strip 1200, para. [0042], [0043], [0073], Fig. 9, 10) immersed in oil (oil; electrical conductivity (or its inverse, resistivity) is an important property of subsurface formations in geological surveys and in prospecting for oil, gas, and water, para. [0005], [0073]). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the dielectric medium application of Homan, since such a combination would result in a down hole system with greater accuracy. (Homan: para. [0005]).

Claims 14, 15, 29 and 30 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos, in view of Hall.

Regarding claim 14, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in earthen materials. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in earthen materials (formation 18, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the earthen material application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 15, Joannopoulos discloses the system of claim 10, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is located in a well. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in well (formation 18 to form a borehole 20, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the well application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 29, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is immersed in earthen materials. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in earthen materials (formation 18, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the earthen material application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Regarding claim 30, Joannopoulos discloses the method of claim 26, wherein at least one magnetic resonator is immersed a dielectric medium (background dielectric; free space/air, para. [0024], [0025]), yet fails to disclose wherein the at least one magnetic resonator is located in a well. Hall discloses a source for wireless power transfer in a shaft (component 200, para. [0041], Fig. 3, 3A) comprising a magnetic resonator (coil 303, comprise between 5 and 40 wire strands 602 and between 1 and 15 coil turns para. [0041], [0042], [0043], Fig. 7, 8) immersed in well (formation 18 to form a borehole 20, para. [0043], Fig. 1). Since both references are directed toward wireless power transmission systems, it would have been obvious to one of skill in the art to combine the system of Joannopoulos within the well application of Hall, since such a combination would result in a down hole system with greater power efficiency. (Hall: para. [0048]).

Claims 1 - 33 have industrial applicability as defined by PCT Article 33(4) because the subject matter can be made or used in industry.

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN MONOCELLO III
GTC LAW GROUP LLP & AFFILIATES
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

	Date of mailing *(day/month/year)* 06 JAN 2012
Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011
Applicant WITRICITY CORPORATION	

LTC

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
   1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450	Authorized officer Blaine R. Copenheaver
Facsimile No. 571-273-3201	Telephone No. PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

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PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: JOHN MONOCELLO III
GTC LAW GROUP LLP & AFFILIATES
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

NOTIFICATION OF TRANSMITTAL OF THE INTERNATIONAL SEARCH REPORT AND THE WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY, OR THE DECLARATION

(PCT Rule 44.1)

Date of mailing *(day/month/year)*	0 6 JAN 2012
Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011
Applicant WITRICITY CORPORATION	

1. ☒ The applicant is hereby notified that the international search report and the written opinion of the International Searching Authority have been established and are transmitted herewith.

   Filing of amendments and statement under Article 19:
   The applicant is entitled, if he so wishes, to amend the claims of the international application (see Rule 46):

   When? The time limit for filing such amendments is normally two months from the date of transmittal of the international search report.

   Where? Directly to the International Bureau of WIPO, 34 chemin des Colombettes
   1211 Geneva 20, Switzerland, Facsimile No.: +41 22 338 82 70

   For more detailed instructions, see *PCT Applicant's Guide*, International Phase, paragraphs 9.004 – 9.011.

2. ☐ The applicant is hereby notified that no international search report will be established and that the declaration under Article 17(2)(a) to that effect and the written opinion of the International Searching Authority are transmitted herewith.

3. ☐ **With regard to any protest** against payment of (an) additional fee(s) under Rule 40.2, the applicant is notified that:

   ☐ the protest together with the decision thereon has been transmitted to the International Bureau together with any request to forward the texts of both the protest and the decision thereon to the designated Offices.

   ☐ no decision has been made yet on the protest; the applicant will be notified as soon as a decision is made.

4. **Reminders**

   The applicant may submit comments on an informal basis on the written opinion of the International Searching Authority to the International Bureau. The International Bureau will send a copy of such comments to all designated Offices unless an international preliminary examination report has been or is to be established. Following the expiration of 30 months from the priority date, these comments will also be made available to the public.

   Shortly after the expiration of **18 months** from the priority date, the international application will be published by the International Bureau. If the applicant wishes to avoid or postpone publication, a notice of withdrawal of the international application, or of the priority claim, must reach the International Bureau before the completion of the technical preparations for international publication (Rules 90*bis*.1 and 90*bis*.3).

   Within **19 months** from the priority date, but only in respect of some designated Offices, a demand for international preliminary examination must be filed if the applicant wishes to postpone the entry into the national phase **until 30 months** from the priority date (in some Offices even later); otherwise, the applicant must, **within 20 months** from the priority date, perform the prescribed acts for entry into the national phase before those designated Offices.

   In respect of other designated Offices, the time limit of **30 months** (or later) will apply even if no demand is filed within 19 months.

   For details about the applicable time limits, Office by Office, see www.wipo.int/pct/en/texts/time_limits.html and the *PCT Applicant's Guide*, National Chapters.

Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450	Authorized officer Blaine R. Copenheaver
Facsimile No. 571-273-3201	Telephone No. PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/220 (July 2010)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US2011/051634	International filing date *(day/month/year)* 14 September 2011	(Earliest) Priority Date *(day/month/year)* 14 September 2010
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into __________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.*6bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

2. ☐ **Certain claims were found unsearchable** (see Box No. II).

3. ☐ **Unity of invention is lacking** (see Box No. III).

4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 30
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/051634

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H02J 17/00 (2011.01)
USPC - 307/104
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H01F 27/42; H01F 38/00, 38/14; H01P 7/08; H02J 7/02; H02J 17/00 (2011.01)
USPC - 307/104; 320/108, 109; 333/219, 219.2; 336/92

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Scholar, Google Patents

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010/0181843 A1 (SCHATZ et al) 22 July 2010 (22.07.2010) entire document	1-27
Y	US 2009/0134712 A1 (COOK et al) 28 May 2009 (28.05.2009) entire document	1-27
A	US 2008/0211320 A1 (COOK et al) 04 September 2008 (04.09.2008) entire document	1-27
A	US 2010/0109445 A1 (KURS et al) 06 May 2010 (06.05.2010) entire document	1-27

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 22 December 2011	Date of mailing of the international search report 06 JAN 2012
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To: JOHN MONOCELLO III
GTC LAW GROUP LLP & AFFILIATES
C/O CPA GLOBAL
P.O. BOX 52050
MINNEAPOLIS, MN 55402

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing *(day/month/year)*	06 JAN 2012

Applicant's or agent's file reference WTCY-0048-PWO	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2011/051634	14 September 2011	14 September 2010

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H02J 17/00 (2011.01)
USPC - 307/104

Applicant WITRICITY CORPORATION

1. This opinion contains indications relating to the following items:
   - ☒ Box No. I Basis of the opinion
   - ☐ Box No. II Priority
   - ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - ☐ Box No. IV Lack of unity of invention
   - ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - ☐ Box No. VI Certain documents cited
   - ☐ Box No. VII Certain defects in the international application
   - ☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

   If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

   If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

   For further options, see Form PCT/ISA/220.

Name and mailing address of the ISA/US	Date of completion of this opinion	Authorized officer:
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	22 December 2011	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (July 2011)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/051634

Box No. I **Basis of this opinion**

1. With regard to the **language**, this opinion has been established on the basis of:

☒ the international application in the language in which it was filed.

☐ a translation of the international application into ____________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

2. ☐ This opinion has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43*bis*.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, this opinion has been established on the basis of a sequence listing filed or furnished:

a. (means)

☐ on paper

☐ in electronic form

b. (time)

☐ in the international application as filed

☐ together with the international application in electronic form

☐ subsequently to this Authority for the purposes of search

4. ☐ In addition, in the case that more than one version or copy of a sequence listing has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

5. Additional comments:

Form PCT/ISA/237 (Box No. I) (July 2011)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.

PCT/US2011/051634

Box No. V **Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	1-27	YES
	Claims	None	NO
Inventive step (IS)	Claims	None	YES
	Claims	1-27	NO
Industrial applicability (IA)	Claims	1-27	YES
	Claims	None	NO

2. Citations and explanations:

Claims 1-27 lack an inventive step under PCT Article 33(3) as being obvious over Schatz et al., hereinafter referred to as Schatz, in view of Cook et al., hereinafter referred to as Cook.

Regarding claim 1, Schatz disclose a system (par. 10, system) for wireless energy distribution over a defined area (par. 9, wireless energy transfer scheme the is capable of transmitting power over mid-range distance; abstract, wireless power transfer within refrigerator; par. 645-646, wireless power transfer system integrated in the refrigerator door), the system (par. 10, system) comprising: a source resonator (par. 10, source resonator) coupled to an energy source (par. 10, resonator connected to power source) and generating an oscillating magnetic field with a frequency (par. 23, generate an oscillating magnetic field; par. 29-30, generating magnetic field with resonant frequency), at least one repeater resonator (par. 14, designed as repeater resonators; par. 141, multiple resonators daisy chained together) in proximity to the source resonator (par. 141, resonators maybe positioned in daisy chain fashion for exchanging energy from source in particular area); and at least two other repeater resonators (par. 14, designed as repeater resonators, which plurality implies multiple or at least two; par. 396, multiple repeaters; par. 141, multiple resonators daisy chained together) in proximity to at least one of the repeater resonators (par. 141, multiple resonators are daisy chained together, which implies in proximity to one another), wherein the repeater resonators provide an effective wireless energy transfer area (par. 141-142, repeater resonators transfer energy over a distances; par. 646-647, additional resonators within the refrigerator provide for wireless energy transfer within the area), but is silent on the particulars of at least one repeater positioned in a defined area and in proximity to the source, and having a resonant frequency; and at least two other repeater with a resonant frequency positioned in the defined area and in proximity to at least one of the repeater resonators, wherein the repeater resonators provide an effective wireless energy transfer area at least one of within or equal to the defined area.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose at least one repeater (120, parasitic antenna; par. 28, parasitic antenna that re-radiates) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to a source (100, main antenna; fig. 1, depicts 120 in proximity to 100), and having a resonant frequency (par. 26, antenna 100 having a resonant frequency); and at least two repeaters (120, 130) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to at least one of a repeater resonators (fig. 1, depicts 120 and 130 within proximity of each other), wherein a repeater provides an effective wireless energy transfer area at least one of within or equal to the defined area (par. 29-32, parasitic antennas 120, 130 transmit within area). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook) .

Regarding claim 2, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area covered is at least 2 square meters (par. 483, the defined area could be a floor, which inherently is greater in size that 2 square meters).

Regarding claim 3, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area covered is at least 10 square centimeters (par. 646, the defined area is refrigerator, which inherently is greater in size than 10 centimeters).

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.

PCT/US2011/051634

Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of:

Regarding claim 4, modified Schatz disclose the system of claim 1, Schatz further disclose comprising at least one additional source resonator (par. 519, utilize source resonators; par. 600, source resonators; par. 646, another source resonator) that generates an oscillating magnetic field with the frequency (par. 23, generating an oscillating magnetic field; par. 113, inherently a resonator oscillates with a frequency), wherein the at least one additional source resonator is positioned in proximity to defined area (par. 646, additional source resonator can be integrated into the body of the refrigerator; par. 519, source resonators that are arranged in various configurations within an area).

Regarding claim 5, modified Schatz disclose the system of claim 4, Schatz further disclose wherein the frequency and relative phase of the oscillating fields generated by the sources of the system are synchronized (par. 594, oscillating magnetic fields of resonators are driven in-phase).

Regarding claim 6, modified Schatz disclose the system of claim 4, Schatz further disclose wherein the relative phase of the oscillating fields generated by the different sources of the system is adjustable (par. 594, oscillating field of multiple resonators can be adjusted either in-phase or out of phase).

Regarding claim 7, modified Schatz disclose the system of claim 4, Schatz further disclose wherein at least one repeater resonator, comprises a capacitively loaded conducting loop (par. 166, capacitively-loaded loop inductor; par. 179, capacitively-loaded conductive loops).

Regarding claim 8, modified Schatz disclose the system of claim 4, Schatz further disclose wherein at least one of the repeater resonators have an adjustable resonant frequency (par. 113, angular resonant frequency, varies based on resonant period; par. 173, resonant frequency of the resonator is tunable by changing the inductance or capacitor of the resonator).

Regarding claim 9, modified Schatz disclose the system of claim 8, Schatz further disclose wherein the resonant frequency of the repeater resonators may be detuned from the frequency of the magnetic fields generated by the source resonators to change the distribution of the magnetic fields in the defined area (par. 593, resonators may be detuned from other resonators).

Regarding claim 10, modified Schatz disclose the system of claim 9, Schatz further disclose wherein some repeaters are detuned to maximize the magnetic fields in a region of the defined area (par. 593-594, detuned resonators in order to create specific hotspot areas of concentrated magnetic energy).

Regarding claim 11, modified Schatz disclose the system of claim 10, Schatz further disclose wherein the detuning of repeaters is performed according to a network routing algorithm (par.593-597, detuning performed based on the drive signal to appropriately tune the resonator as it is activated in the bank, adjustments are also made based on a sharing algorithm; par. 387, power levels, frequencies and input impedances for resonators may be adjusted based on algorithm; par. 403, processor adjusts the resonator through algorithms).

Regarding claim 12, modified Schatz disclose the system of claim 10, Schatz further disclose comprising a communication channel (4204, wireless communication channel) between the resonators of the system (par. 431, wireless communication channel may allow resonators 102 to exchange information).

Regarding claim 13, modified Schatz disclose the system of claim 12, Schatz further disclose wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution (par. 431-433, communication channel communicates controls to the resonator, which could include detuning of the resonator to achieve specific distribution).

Regarding claim 14, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the repeater resonators have a quality factor Q>100 (par. 19, Q sub1 and sub2 are greater than 100; par. 26, resonator with quality factor Q greater than one hundred; par. 235, quality factor, Q, of 100 or higher and even Q of 1000 or higher; par. 239, quality factor, Q, of order of 1000 or higher).

Regarding claim 15, modified Schatz disclose the system of claim 10, modified Schatz further disclose wherein the repeater resonators further comprise pressure sensors (par. 533, pressure sensors) and wherein the information from the pressure sensors is used to change the magnetic field distribution (par. 533-534, information from sensors, such as pressure sensors, help to optimize magnetic field direction and resonator alignment).

Regarding claim 16, modified Schatz disclose the system of claim 1, wherein the defined area is a floor (par. 17, applications could include under the floor; par. 232-233, active area on the floor).

Regarding claim 17, modified Schatz disclose the system of claim 16, wherein the resonators are integrated into flooring material (par. 233, integrated into a floor).

Regarding claim 18, modified Schatz disclose the system of claim 1, modified Schatz further disclose wherein the defined area is a wall (par. 17, applications could include in the walls of a room; par. 232, walls).

Regarding claim 19, modified Schatz disclose the system of claim 1, Schatz further disclose wherein the defined area is a ceiling (par. 17, applications could include on the ceiling; par. 232, ceilings).

Form PCT/ISA/237 (Supplemental Box) (July 2011)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US2011/051634

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 20, Schatz disclose a wireless energy transfer flooring system (par. 483, wireless energy transfer may be integrated into the floor) comprising: at least one source resonator (par. 10, source resonator) coupled to an energy source (par. 10, resonator connected to power source) and generating an oscillating magnetic field with a frequency (par. 23, generate an oscillating magnetic field; par. 29-30, generating magnetic field with resonant frequency), at least one repeater resonator (par. 14, designed as repeater resonators; par. 141, multiple resonators daisy chained together) in proximity to the source resonator (par. 141, resonators maybe positioned in daisy chain fashion for exchanging energy from source in particular area); and at least two other repeater resonators (par. 14, designed as repeater resonators, which plurality implies multiple or at least two; par. 396, multiple repeaters; par. 141, multiple resonators daisy chained together) in proximity to at least one of the repeater resonators (par. 141, multiple resonators are daisy chained together, which implies in proximity to one another), wherein the resonant frequency of at least one of resonators is detuned from the frequency of the oscillating magnetic field of the at least one source to change the distribution of magnetic fields in the defined area (par. 589, in order to maximize distribution of magnetic fields around source operating parameters of resonators is adjusted, which implies detuned), but is silent on the particulars of at least one repeater positioned in a defined area and in proximity to the source, and having a resonant frequency; and at least two other repeater with a resonant frequency positioned in the defined area and in proximity to at least one of the repeater resonators, wherein the resonant frequency of at least one of the repeater resonators is detuned from the frequency of the oscillating magnetic field of the at least one source to change the distribution of magnetic fields in the defined area.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose at least one repeater (120, parasitic antenna; par. 28, parasitic antenna that re-radiates) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to a source (100, main antenna; fig. 1, depicts 120 in proximity to 100), and having a resonant frequency (par. 26, antenna 100 having a resonant frequency); and at least two repeaters (120, 130) positioned in a defined area (par. 23, antennas are positioned within a room) and in proximity to at least one of a repeater resonators (fig. 1, depicts 120 and 130 within proximity of each other), wherein the resonant frequency of at least one of the repeaters is detuned from a frequency of an oscillating magnetic field of a source (par. 68, detuning of resonant frequency of antennas, including parasitic antenna; par. 78, detuning of antenna to influence resonant frequency). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook).

Regarding claim 21, modified Schatz disclose the system of claim 20, Schatz further disclose comprising a communication channel (4204, wireless communication channel) between the resonators of the system (par. 431, wireless communication channel may allow resonators 102 to exchange information).

Regarding claim 22, modified Schatz disclose the system of claim 21, Schatz further disclose wherein the communication channel is used to coordinate detuning of the repeater resonators of the system to achieve a specific magnetic field distribution (par. 431-433, communication channel communicates controls to the resonator, which could include detuning of the resonator to achieve specific distribution).

Regarding claim 23, modified Schatz disclose the system of claim 20, Schatz further disclose wherein the resonators are integrated into flooring material (par. 233, resonators maybe integrated into a floor).

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Regarding claim 24, Schatz disclose a method of distributing wireless energy from at least one source resonator to a specific location within an area (abstract, source resonator distributing wireless energy to a refrigerator) having tunable repeater resonators (par. 20, resonators are tunable), the method comprising: determining a closest resonator to a specific location (par. 533, based on position and location information finding a nearby wireless power transmission source); tuning the resonant frequency of the repeater resonators to provide for an energy transfer path from the source (par. 538, the frequency is tuned to resonant frequency in order in order to transmit wireless power; par. 582-583, the source and device resonators are adjusted as move closer to each other), but is silent on determining a closest repeater resonators, and tuning the resonant frequency of the repeater resonators to provide for an energy transfer path to the closest repeater resonators.
However, Cook in discussing wireless power range increase using parasitic antennas (title) disclose determining a closest repeater (par. 28-30, parasitic antennas radiate within certain area based on location; fig. 1, depicts receivers 125-128 receiving power from there respective antennas), and tuning the resonant frequency of a repeater to provide for an energy transfer path to closest repeater (par. 26, parasitic, repeaters, are tuned to create areas of maximum power). Therefore, it would have been obvious to one of ordinary skill in the art at the time of the invention to incorporate the aforementioned improvements of Cook with the invention of Schatz for the purpose of providing a local areas where power is more efficiently received (abstract – Cook) .

Regarding claim 25, modified Schatz disclose the method of claim 24, Schatz further disclose comprising detuning resonators (par. 250, detuning resonators; par. 593, detune resonators) that are not in the energy transfer path (par. 593, detune non-active resonators, which implies those not in energy path).

Regarding claim 26, modified Schatz disclose the method of claim 24, Schatz further disclose wherein the energy transfer path is determined by a shortest path algorithm (par. 582, close to each other, power transfer efficiency; par. 596, devices are powered by resonators which are closer to them).

Regarding claim 27, modified Schatz disclose the method of claim 24, wherein the energy transfer path is determined by a central control (par. 533, central station or database is in communication with source, which guides the user to the source; par. 537, central authority authenticates sources and devices).

Claims 1-27 meet the criteria set out in PCT Article 33(4), and thus have industrial applicability because the subject matter claimed can be made or used in industry.

PCT Application No.: PCT-US2011-51634
Date of Search: 22 December 2011

Search History:

Limited Classification Search

The Patent Analyst performed a limited classification search within the following US, IPC, ECLA, or F-Term classification areas:

U.S. Class/Subclass(es): 307/104; 320/108, 109; 333/219, 219.2; 336/92

IPC (8) Class/Subclass(es): H01F 27/42; H01F 38/00, 38/14; H01P 7/08; H02J 7/02; H02J 17/00 (2011.01)

See Global Search Results.

Global Patent Literature Text Search

The Patent Analyst performed the following global text search, which was not limited by classification but may or may not have been limited by other criteria:

PATBASE

- 1) pn=(us20100181843 or us20100109445) (1)
- 2) (PA=(witricity corp)) (2)
- 3) (TAC=((wireless energy) or (wireless power))) (1512)
- 4) (TAC=((wireless energy) or (wireless power)) and defined w2 area) (3)
- 5) PN=(US2008278264 OR WO10093964) (2)
- 6) ctb 2 or ctf 2 (230)
- 7) pn=us2010/0259108 (1)
- 8) PA=(LOU_HERBERT_T OR LOU_HERBERT_TOBY OR FELDSTEIN_MICHAEL_A OR SCHATZ_DAVID_A OR GANEM_STEVEN_J OR GANEM_STEVEN_JOSEPH OR GILER_ERIC_R OR PERGAL_FRANK_J OR KURS_ANDRE_B OR CAMPANELLA_ANDREW_J OR EFE_VOLKAN OR SOLJACIC_MARIN OR FIORELLO_RON OR LI_QIANG OR HALL_KATHERINE_L OR KESLER_MORRIS_P OR KARALIS_ARISTEIDIS OR KULIKOWSKI_KONRAD OR KULIKOWSKI_KONRAD_J OR MACDONALD_MATTHEW_J) (472)
- 9) 8 and 3 (4)
- 10) (((wireless energy) or (wireless power))) and 8 (4)
- 11) 3 and (repeater w3 reson*) (10)
- 12) pd<20100914 (100000)
- 13) 11 and 12 (8)
- 14) 3 and 12 (966)
- 15) 14 and (resonator*) (60)
- 16) IC=("H01F27/42") (1671)
- 17) IC=("H01F38/00") (11012)
- 18) IC=("H01F38/14") (3896)
- 19) IC=("H01P7/08") (1831)
- 20) IC=("H02J17/00") (6354)
- 21) IC=("H02J7/02") (10622)
- 22) 16 or 17 or 18 or 19 or 20 or 21 (33311)
- 23) 22 and (repeat* w2 resonat*) (6)
- 24) 22 and (relay* w2 reson*) (11)
- 25) (repeat* w2 resona*) or (relay* w2 resona*) (767)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 17157 PCT	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US2011/054544	International filing date *(day/month/year)* 03 October 2011	(Earliest) Priority Date *(day/month/year)* 06 October 2010
Applicant WITRICITY CORPORATION		

This international search report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This international search report consists of a total of 2 sheets.

☐ It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of:
      ☒ the international application in the language in which it was filed.
      ☐ a translation of the international application into ______________ which is the language of a translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).
   b. ☐ This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.*6bis*(a)).
   c. ☐ With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.
2. ☐ **Certain claims were found unsearchable** (see Box No. II).
3. ☐ **Unity of invention is lacking** (see Box No. III).
4. With regard to the **title**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established by this Authority to read as follows:
5. With regard to the **abstract**,
   ☒ the text is approved as submitted by the applicant.
   ☐ the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.
6. With regard to the **drawings**,
   a. the figure of the **drawings** to be published with the abstract is Figure No. 1
      ☒ as suggested by the applicant.
      ☐ as selected by this Authority, because the applicant failed to suggest a figure.
      ☐ as selected by this Authority, because this figure better characterizes the invention.
   b. ☐ none of the figures is to be published with the abstract.

Form PCT/ISA/210 (first sheet) (July 2009)

PCT/US2011/054544 30.01.2012

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/054544

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H02J 7/02 (2011.01)
USPC - 320/109
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - B60L 11/18; B60Q 1/52; G01R 31/36; H02J 7/00, 7/02; H04B 5/00; H04M 10/44 (2012.01)
USPC - 180/65.29; 307/104; 320/108, 109, 149, 152

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Patents, Google Scholar

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2002/0167294 A1 (ODAOHHARA) 14 November 2002 (14.11.2002) entire document	1-56
Y	US 2010/0235006 A1 (BROWN) 16 September 2010 (16.09.2010) entire document	1-56
Y	US 2010/0156355 A1 (BAUERLE et al) 24 June 2010 (24.06.2010) entire document	3, 7, 26-30, 51, 54
Y	US 6,012,659 A (NAKAZAWA et al) 11 January 2000 (11.01.2000) entire document	5-6
Y	US 2010/0109445 A1 (KURS et al) 06 May 2010 (06.05.2010) entire document	10-12, 17, 28-30, 34, 39
Y	US 2007/0024246 A1 (FLAUGHER) 01 February 2007 (01.02.2007) entire document	18
Y	US 2006/0214626 A1 (NILSON et al) 28 September 2006 (28.09.2006) entire document	45

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 12 January 2012	Date of mailing of the international search report 30 JAN 2012
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

Electronic Patent Application Fee Transmittal

Application Number:	12647763
Filing Date:	28-Dec-2009
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Filer:	John A. Monocello/Jennifer Sammartin
Attorney Docket Number:	WTCY-0026-P07

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
Request for continued examination	1801	1	930	930
	Total in USD ($)			**930**

Electronic Acknowledgement Receipt

EFS ID:	13087210
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	22-JUN-2012
Filing Date:	28-DEC-2009
Time Stamp:	17:21:29
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$930
RAM confirmation Number	4625
Deposit Account	505087
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Request for Continued Examination (RCE)	WTCY-0026-P07_RCE.pdf	697865 5d769dd731f36e0e4c894934a70fa73b30aedf6a	no	3
Warnings:					
Information:					
2	Information Disclosure Statement (IDS) Form (SB08)	WTCY-0026-P07_IDS.pdf	616473 4a028de6f8f59f43e005a81a845d3c0fb020b7ba	no	14
Warnings:					
Information:					
3	Foreign Reference	CN102239633A.pdf	8206632 ba290ab0d0be67809345168fc8ba34b91f251a48	no	124
Warnings:					
Information:					
4	Foreign Reference	EP2340611A1.pdf	60916 7af03bf00445c431c31a41fd9c7294ee85e4ec91	no	2
Warnings:					
Information:					
5	Foreign Reference	EP2396796A1.pdf	60222 592d8f96ad03cc05b8b5fef0ba764e54901c9390	no	2
Warnings:					
Information:					
6	Foreign Reference	IN1734KOLNP2011.pdf	683843 fdf18080ee34b7936c74e7a508e07561edfbf373	no	54
Warnings:					
Information:					
7	Foreign Reference	JP2002097005A.pdf	779619 681716b0634b9675eb62cf66ea025d41a57f1179	no	9
Warnings:					
Information:					
8	Foreign Reference	JP2012504387A.pdf	6063888 654318d5fabf66d535e2e8a2df142fd7cebec2eb	no	128
Warnings:					
Information:					

9	Foreign Reference	WO2012037279A1.pdf	5076950 ae0fb64cba6c164524cd7d170a7edd28d402697b	no	105
Warnings:					
Information:					
10	Foreign Reference	WO2006011769A1.pdf	1005182 ac9a5fc52678190701c16247fa025b4163fe376c	no	22
Warnings:					
Information:					
11	Foreign Reference	WO2011112795.pdf	8840237 0e393fc591a5b69ecc584dec7183545e7d7b7638	no	176
Warnings:					
Information:					
12	Non Patent Literature	PCTUS2009058499_IPRP.pdf	253792 75a9a9e3fad0f3ec86b3f7ab4d34245d5da257cf	no	5
Warnings:					
Information:					
13	Non Patent Literature	PCTUS2010024199_ISR_WO.pdf	543907 25e977391bd4574331d7884584994599976e6c4d	no	8
Warnings:					
Information:					
14	Non Patent Literature	PCT2011051634ISRandWrittenOpinion.pdf	575826 06db1f82935bcc29a9fa9fbcbedfeb398a996ff5	no	11
Warnings:					
Information:					
15	Non Patent Literature	PCTUS2011054544_ISR.pdf	98465 e07c9f85854bb937cb36dedb033217a7d0a47314	no	2
Warnings:					
Information:					
16	Non Patent Literature	Jackson_ClassicalElectrodynamics.pdf	3591122 640e78f534cdb3eade80554a028fdbc9919fedb8	no	10
Warnings:					
Information:					
17	Non Patent Literature	Kurs_AppledPhysicsLetter98.pdf	757492 153c1b27729ca2f75ed293486a7675a4e01fc4f2	no	3
Warnings:					
Information:					

18	Non Patent Literature	60698442_APP_07-12-2005.pdf	885588 d2a66b16ecca7b7b309750452a9e97d5bd6256c3	no	14
Warnings:					
Information:					
19	Non Patent Literature	60908666_APP_03-28-2007.pdf	7318392 c28812389bd4dfef6d34413391163cab75f2714e	no	108
Warnings:					
Information:					
20	Fee Worksheet (SB06)	fee-info.pdf	30520 aa85e1522cf266fa0737ea9c4b57e1312b181053	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	46146931		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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Alexandria, Virginia 22313-1450
www.uspto.gov

NOTICE OF ALLOWANCE AND FEE(S) DUE

87084 7590 08/09/2012

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	
ART UNIT	PAPER NUMBER
2836	

DATE MAILED: 08/09/2012

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

TITLE OF INVENTION: WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS

APPLN. TYPE	SMALL ENTITY	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	$1740	$300	$0	$2040	11/09/2012

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED. THIS NOTICE OF ALLOWANCE IS NOT A GRANT OF PATENT RIGHTS. THIS APPLICATION IS SUBJECT TO WITHDRAWAL FROM ISSUE AT THE INITIATIVE OF THE OFFICE OR UPON PETITION BY THE APPLICANT. SEE 37 CFR 1.313 AND MPEP 1308.

THE ISSUE FEE AND PUBLICATION FEE (IF REQUIRED) MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED. SEE 35 U.S.C. 151. THE ISSUE FEE DUE INDICATED ABOVE DOES NOT REFLECT A CREDIT FOR ANY PREVIOUSLY PAID ISSUE FEE IN THIS APPLICATION. IF AN ISSUE FEE HAS PREVIOUSLY BEEN PAID IN THIS APPLICATION (AS SHOWN ABOVE), THE RETURN OF PART B OF THIS FORM WILL BE CONSIDERED A REQUEST TO REAPPLY THE PREVIOUSLY PAID ISSUE FEE TOWARD THE ISSUE FEE NOW DUE.

HOW TO REPLY TO THIS NOTICE:

I. Review the SMALL ENTITY status shown above.

If the SMALL ENTITY is shown as YES, verify your current SMALL ENTITY status:	If the SMALL ENTITY is shown as NO:
A. If the status is the same, pay the TOTAL FEE(S) DUE shown above.	A. Pay TOTAL FEE(S) DUE shown above, or
B. If the status above is to be removed, check box 5b on Part B - Fee(s) Transmittal and pay the PUBLICATION FEE (if required) and twice the amount of the ISSUE FEE shown above, or	B. If applicant claimed SMALL ENTITY status before, or is now claiming SMALL ENTITY status, check box 5a on Part B - Fee(s) Transmittal and pay the PUBLICATION FEE (if required) and 1/2 the ISSUE FEE shown above.

II. PART B - FEE(S) TRANSMITTAL, or its equivalent, must be completed and returned to the United States Patent and Trademark Office (USPTO) with your ISSUE FEE and PUBLICATION FEE (if required). If you are charging the fee(s) to your deposit account, section "4b" of Part B - Fee(s) Transmittal should be completed and an extra copy of the form should be submitted. If an equivalent of Part B is filed, a request to reapply a previously paid issue fee must be clearly made, and delays in processing may occur due to the difficulty in recognizing the paper as an equivalent of Part B.

III. All communications regarding this application must give the application number. Please direct all communications prior to issuance to Mail Stop ISSUE FEE unless advised to the contrary.

IMPORTANT REMINDER: Utility patents issuing on applications filed on or after Dec. 12, 1980 may require payment of maintenance fees. It is patentee's responsibility to ensure timely payment of maintenance fees when due.

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: Mail **Mail Stop ISSUE FEE**
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450
or Fax (571)-273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

87084 7590 08/09/2012

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

(Depositor's name)
(Signature)
(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

TITLE OF INVENTION: WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS

APPLN. TYPE	SMALL ENTITY	ISSUE FEE DUE	PUBLICATION FEE DUE	PREV. PAID ISSUE FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	$1740	$300	$0	$2040	11/09/2012

EXAMINER	ART UNIT	CLASS-SUBCLASS
DEBERADINIS, ROBERT L	2836	307-104000

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

(1) the names of up to 3 registered patent attorneys or agents OR, alternatively,

(2) the name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1____________________
2____________________
3____________________

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

PLEASE NOTE: Unless an assignee is identified below, no assignee data will appear on the patent. If an assignee is identified below, the document has been filed for recordation as set forth in 37 CFR 3.11. Completion of this form is NOT a substitute for filing an assignment.

(A) NAME OF ASSIGNEE

(B) RESIDENCE: (CITY and STATE OR COUNTRY)

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☐ Corporation or other private group entity ☐ Government

4a. The following fee(s) are submitted:

☐ Issue Fee
☐ Publication Fee (No small entity discount permitted)
☐ Advance Order - # of Copies ________________

4b. Payment of Fee(s): **(Please first reapply any previously paid issue fee shown above)**

☐ A check is enclosed.
☐ Payment by credit card. Form PTO-2038 is attached.
☐ The Director is hereby authorized to charge the required fee(s), any deficiency, or credit any overpayment, to Deposit Account Number __________ (enclose an extra copy of this form).

5. **Change in Entity Status** (from status indicated above)

☐ a. Applicant claims SMALL ENTITY status. See 37 CFR 1.27.
☐ b. Applicant is no longer claiming SMALL ENTITY status. See 37 CFR 1.27(g)(2).

NOTE: The Issue Fee and Publication Fee (if required) will not be accepted from anyone other than the applicant; a registered attorney or agent; or the assignee or other party in interest as shown by the records of the United States Patent and Trademark Office.

Authorized Signature ____________________ Date ____________________

Typed or printed name ____________________ Registration No. ____________________

This collection of information is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

PTOL-85 (Rev. 02/11) Approved for use through 08/31/2013. OMB 0651-0033 U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

UNITED STATES PATENT AND TRADEMARK OFFICE

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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

87084 7590 08/09/2012
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

EXAMINER	
DEBERADINIS, ROBERT L	
ART UNIT	PAPER NUMBER
2836	

DATE MAILED: 08/09/2012

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)

(application filed on or after May 29, 2000)

The Patent Term Adjustment to date is 265 day(s). If the issue fee is paid on the date that is three months after the mailing date of this notice and the patent issues on the Tuesday before the date that is 28 weeks (six and a half months) after the mailing date of this notice, the Patent Term Adjustment will be 265 day(s).

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Customer Service Center of the Office of Patent Publication at 1-(888)-786-0101 or (571)-272-4200.

PTOL-85 (Rev. 02/11)

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Notice of Allowability	**Application No.** 12/647,763	**Applicant(s)** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address--

All claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice of Allowance (PTOL-85) or other appropriate communication will be mailed in due course. **THIS NOTICE OF ALLOWABILITY IS NOT A GRANT OF PATENT RIGHTS.** This application is subject to withdrawal from issue at the initiative of the Office or upon petition by the applicant. See 37 CFR 1.313 and MPEP 1308.

1. ☒ This communication is responsive to *6/22/12*.
2. ☐ An election was made by the applicant in response to a restriction requirement set forth during the interview on _____; the restriction requirement and election have been incorporated into this action.
3. ☒ The allowed claim(s) is/are *1-23*.
4. ☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

   a) ☐ All b) ☐ Some* c) ☐ None of the:

   1. ☐ Certified copies of the priority documents have been received.
   2. ☐ Certified copies of the priority documents have been received in Application No. _____ .
   3. ☐ Copies of the certified copies of the priority documents have been received in this national stage application from the International Bureau (PCT Rule 17.2(a)).

   * Certified copies not received: _____.

Applicant has THREE MONTHS FROM THE "MAILING DATE" of this communication to file a reply complying with the requirements noted below. Failure to timely comply will result in ABANDONMENT of this application.
THIS THREE-MONTH PERIOD IS NOT EXTENDABLE.

5. ☐ A SUBSTITUTE OATH OR DECLARATION must be submitted. Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL PATENT APPLICATION (PTO-152) which gives reason(s) why the oath or declaration is deficient.
6. ☐ CORRECTED DRAWINGS (as "replacement sheets") must be submitted.

   (a) ☐ including changes required by the Notice of Draftsperson's Patent Drawing Review (PTO-948) attached

   1) ☐ hereto or 2) ☐ to Paper No./Mail Date _____.

   (b) ☐ including changes required by the attached Examiner's Amendment / Comment or in the Office action of Paper No./Mail Date _____.

   Identifying indicia such as the application number (see 37 CFR 1.84(c)) should be written on the drawings in the front (not the back) of each sheet. Replacement sheet(s) should be labeled as such in the header according to 37 CFR 1.121(d).

7. ☐ DEPOSIT OF and/or INFORMATION about the deposit of BIOLOGICAL MATERIAL must be submitted. Note the attached Examiner's comment regarding REQUIREMENT FOR THE DEPOSIT OF BIOLOGICAL MATERIAL.

Attachment(s)

1. ☐ Notice of References Cited (PTO-892)
2. ☐ Notice of Draftperson's Patent Drawing Review (PTO-948)
3. ☒ Information Disclosure Statements (PTO/SB/08), Paper No./Mail Date 6/22/12
4. ☐ Examiner's Comment Regarding Requirement for Deposit of Biological Material
5. ☐ Notice of Informal Patent Application
6. ☐ Interview Summary (PTO-413), Paper No./Mail Date _____ .
7. ☐ Examiner's Amendment/Comment
8. ☒ Examiner's Statement of Reasons for Allowance
9. ☐ Other _____.

DETAILED ACTION

Continued Examination Under 37 CFR 1.114

A request for continued examination under 37 CFR 1.114, including the fee set forth in 37 CFR 1.17(e), was filed in this application after allowance or after an Office action under *Ex Parte Quayle*, 25 USPQ 74, 453 O.G. 213 (Comm'r Pat. 1935). Since this application is eligible for continued examination under 37 CFR 1.114, and the fee set forth in 37 CFR 1.17(e) has been timely paid, prosecution in this application has been reopened pursuant to 37 CFR 1.114. Applicant's submission filed on 6/22/12 has been entered.

Allowable Subject Matter

Claims 1-23 allowed.

The following is an examiner's statement of reasons for allowance: the prior art of record does not disclose or suggest, inter alia, wherein the field of at least one of the source resonator and the second resonator is shaped using a conducting material and a magnetic material.

Any comments considered necessary by applicant must be submitted no later than the payment of the issue fee and, to avoid processing delays, should preferably accompany the issue fee. Such submissions should be clearly labeled "Comments on Statement of Reasons for Allowance."

Any inquiry concerning this communication should be directed to Robert L. DeBeradinis whose number is (571) 272-2049. The Examiner can normally be reached Monday-Friday from 8:30 am to 5:00 pm.

If attempts to reach the Examiner by telephone are unsuccessful, the Examiner's supervisor, Jared Fureman can be reached on (571) 272-2391. The Fax phone number for this Group is (571) 272-8300.

RLD

JULY 29, 2012

/Robert DeBeradinis/

Primary Examiner, Art Unit 2836

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UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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Alexandria, Virginia 22313-1450
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BIB DATA SHEET

CONFIRMATION NO. 2576

SERIAL NUMBER	FILING or 371(c) DATE	CLASS	GROUP ART UNIT	ATTORNEY DOCKET NO.
12/647,763	12/28/2009 RULE	307	2836	WTCY-0026-P07

APPLICANTS

Aristeidis Karalis, Boston, MA;
Andre B. Kurs, Chestnut Hill, MA;
Andrew J. Campanella, Waltham, MA;
Konrad J. Kulikowski, Somerville, MA;
Katherine L. Hall, Westford, MA;
Marin Soljacic, Belmont, MA;
Morris P. Kesler, Bedford, MA;

** **CONTINUING DATA** *************************

This application is a CIP of 12/567,716 09/25/2009
which claims benefit of 61/100,721 09/27/2008
and claims benefit of 61/108,743 10/27/2008
and claims benefit of 61/147,386 01/26/2009
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** **FOREIGN APPLICATIONS** *************************

** **IF REQUIRED, FOREIGN FILING LICENSE GRANTED** **

		STATE OR COUNTRY	SHEETS DRAWINGS	TOTAL CLAIMS	INDEPENDENT CLAIMS
Foreign Priority claimed ☐ Yes ☑ No 35 USC 119(a-d) conditions met ☐ Yes ☐ No Verified and Acknowledged /ROBERT L DEBERADINIS/ Examiner's Signature	☐ Met after Allowance Initials	MA	53	14	2

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Search Notes	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.	
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836	

SEARCHED

Class	Subclass	Date	Examiner
307	104	7/29/12	RLD

INTERFERENCE SEARCHED

Class	Subclass	Date	Examiner
INTERFERENCE		7/29/12	RLD

SEARCH NOTES (INCLUDING SEARCH STRATEGY)

	DATE	EXMR
TEXT	7/29/12	RLD

U.S. Patent and Trademark Office

Part of Paper No. 20120729

INFORMATION DISCLOSURE STATEMENT BY APPLICANT **(Not for submission under 37 CFR 1.99)**	Application Number	12647763
	Filing Date	2009-12-28
	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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Examiner Initial*	Cite No	Patent Number	Kind Code1	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
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Receipt date: 06/22/2012

12647763 - GAU: 2836

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	Attorney Docket Number	WTCY-0026-P07

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	Attorney Docket Number	WTCY-0026-P07	

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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U.S.PATENT APPLICATION PUBLICATIONS Remove

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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Examiner Name	Deberadinis, Robert L.
Attorney Docket Number	WTCY-0026-P07

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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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	First Named Inventor	Karalis, Aristeidis
	Art Unit	2836
	Examiner Name	Deberadinis, Robert L.
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	Examiner Name	Deberadinis, Robert L.
	Attorney Docket Number	WTCY-0026-P07

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Examiner Signature	/Robert Deberadinis/	Date Considered	07/29/2012

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

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	First Named Inventor	Karalis, Aristeidis	
	Art Unit	2836	
	Examiner Name	Deberadinis, Robert L.	
	Attorney Docket Number	WTCY-0026-P07	

CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☐ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/John A. Monocello, III/	Date (YYYY-MM-DD)	2012-06-22
Name/Print	John A. Monocello, III	Registration Number	51022

This collection of information is required by 37 CFR 1.97 and 1.98. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 1 hour to complete, including gathering, preparing and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

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6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

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Issue Classification	**Application/Control No.** 12/647,763	**Applicant(s)/Patent under Reexamination** KARALIS ET AL.
	Examiner ROBERT DEBERADINIS	**Art Unit** 2836

ISSUE CLASSIFICATION

ORIGINAL					CROSS REFERENCE(S)							
CLASS		SUBCLASS			CLASS	SUBCLASS (ONE SUBCLASS PER BLOCK)						
307		104										
INTERNATIONAL CLASSIFICATION												
H	0	1	F	27/42								
				/								
				/								
				/								
				/								

NONE (Assistant Examiner) (Date)	/ROBERT L. DEBERADINIS/ 7/29/12 (Primary Examiner) (Date)	**Total Claims Allowed: 23**
(Legal Instruments Examiner) (Date)		O.G. Print Claim(s): 1 O.G. Print Fig.: 1

☐ **Claims renumbered in the same order as presented by applicant** ☐ CPA ☐ T.D. ☐ R.1.47

Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original	Final	Original
1	1		31		61		91		121		151		181
2	2		32		62		92		122		152		182
3	3		33		63		93		123		153		183
4	4		34		64		94		124		154		184
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	30		60		90		120		150		180		210

EAST Search History

EAST Search History (Prior Art)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L3	145	RESONATOR SAME FIELD SAME SHAPED SAME CONDUCTING SAME MAGNETIC	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/07/29 11:21
L4	92	RESONATOR SAME FIELD SAME SHAPED SAME CONDUCTING SAME MAGNETIC SAME MATERIAL	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/07/29 11:21
L5	2	SECOND ADJ RESONATOR SAME FIELD SAME SHAPED SAME CONDUCTING SAME MAGNETIC SAME MATERIAL	US-PGPUB; USPAT; USOCR; FPRS; EPO; JPO; DERWENT; IBM_TDB	OR	ON	2012/07/29 11:22

7/29/2012 11:26:54 AM
C:\ Users\ rdeberadinis\ Documents\ EAST\ Workspaces\ 524.wsp

EAST Search History

EAST Search History (Interference)

Ref #	Hits	Search Query	DBs	Default Operator	Plurals	Time Stamp
L6	1	(RESONATOR SAME FIELD SAME SHAPED SAME CONDUCTING SAME MAGNETIC SAME MATERIAL).CLM.	US-PGPUB	OR	ON	2012/07/29 11:25

7/29/2012 11:27:08 AM
C:\ Users\ rdeberadinis\ Documents\ EAST\ Workspaces\ 524.wsp

PART B - FEE(S) TRANSMITTAL

Complete and send this form, together with applicable fee(s), to: Mail **Mail Stop ISSUE FEE**
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450
or Fax (571) 273-2885

INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE and PUBLICATION FEE (if required). Blocks 1 through 5 should be completed where appropriate. All further correspondence including the Patent, advance orders and notification of maintenance fees will be mailed to the current correspondence address as indicated unless corrected below or directed otherwise in Block 1, by (a) specifying a new correspondence address; and/or (b) indicating a separate "FEE ADDRESS" for maintenance fee notifications.

CURRENT CORRESPONDENCE ADDRESS (Note: Use Block 1 for any change of address)

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

Note: A certificate of mailing can only be used for domestic mailings of the Fee(s) Transmittal. This certificate cannot be used for any other accompanying papers. Each additional paper, such as an assignment or formal drawing, must have its own certificate of mailing or transmission.

Certificate of Mailing or Transmission

I hereby certify that this Fee(s) Transmittal is being deposited with the United States Postal Service with sufficient postage for first class mail in an envelope addressed to the Mail Stop ISSUE FEE address above, or being facsimile transmitted to the USPTO (571) 273-2885, on the date indicated below.

Jennifer Sammartin	(Depositor's name)
/Jennifer Sammartin/	(Signature)
October 5, 2012	(Date)

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07	2576

TITLE OF INVENTION:

APPLN. TYPE	SMALL ENTITY	ISSUE FEE	PUBLICATION FEE	TOTAL FEE(S) DUE	DATE DUE
nonprovisional	NO	$1770	$300	$2070	11/09/2012

EXAMINER	ART UNIT	CLASS-SUBCLASS

1. Change of correspondence address or indication of "Fee Address" (37 CFR 1.363).

☐ Change of correspondence address (or Change of Correspondence Address form PTO/SB/122) attached.

☐ "Fee Address" indication (or "Fee Address" Indication form PTO/SB/47; Rev 03-02 or more recent) attached. **Use of a Customer Number is required.**

2. For printing on the patent front page, list

(1) the names of up to 3 registered patent attorneys or agents OR, alternatively,

(2) the name of a single firm (having as a member a registered attorney or agent) and the names of up to 2 registered patent attorneys or agents. If no name is listed, no name will be printed.

1 GTC Law Group LLP & Affiliates
2 _
3 _

3. ASSIGNEE NAME AND RESIDENCE DATA TO BE PRINTED ON THE PATENT (print or type)

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(A) NAME OF ASSIGNEE	(B) RESIDENCE: (CITY and STATE OR COUNTRY)
WiTricity Corporation	Watertown, MA

Please check the appropriate assignee category or categories (will not be printed on the patent) : ☐ Individual ☑ Corporation or other private group entity ☐ Government

4a. The following fee(s) are enclosed:

☑ Issue Fee
☑ Publication Fee (No small entity discount permitted)
☐ Advance Order - # of Copies _

4b. Payment of Fee(s):

☐ A check in the amount of the fee(s) is enclosed.
☐ Payment by credit card. Form PTO-2038 is attached.
☑ The Director is hereby authorized by charge the required fee(s), or credit any overpayment, to Deposit Account Number 50-5087 .

5. **Change in Entity Status** (from status indicated above)

☐ a. Applicant claims SMALL ENTITY status. See 37 CFR 1.27. ☐ b. Applicant is no longer claiming SMALL ENTITY status. See 37 CFR 1.27(g)(2).

The Director of the USPTO is requested to apply the Issue Fee and Publication Fee (if any) or to re-apply any previously paid issue fee to the application identified above.
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Authorized Signature /John A. Monocello, III/ Date October 5, 2012

Typed or printed name John A. Monocello, III Registration No. 51,022

This collection of information is required by 37 CFR 1.311. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, Virginia 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, Virginia 22313-1450.

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PTOL-85 (Rev. 08-08) Approved for use through 08/31/2013. OMB 0651-0033 U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

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5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Electronic Patent Application Fee Transmittal

Application Number:	12647763
Filing Date:	28-Dec-2009
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Filer:	John A. Monocello/Jennifer Sammartin
Attorney Docket Number:	WTCY-0026-P07

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Pages:				
Claims:				
Miscellaneous-Filing:				
Publ. Fee- early, voluntary, or normal	1504	1	300	300
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Utility Appl issue fee	1501	1	1770	1770

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Extension-of-Time:				
Miscellaneous:				
		Total in USD ($)		**2070**

Electronic Acknowledgement Receipt

EFS ID:	13921968
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	05-OCT-2012
Filing Date:	28-DEC-2009
Time Stamp:	15:44:40
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$2070
RAM confirmation Number	2541
Deposit Account	505087
Authorized User	

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Charge any Additional Fees required under 37 C.F.R. Section 1.21 (Miscellaneous fees and charges)

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Issue Fee Payment (PTO-85B)	WTCY-0026-P07_Payment_of_Issue_Fee.pdf	221636 f5a0edd6bbe412a07bbed1506cd9e6a292828515	no	2
Warnings:					
Information:					
2	Fee Worksheet (SB06)	fee-info.pdf	32255 0e2e10df7c326d52867413a2cbc31cf697e4dca5	no	2
Warnings:					
Information:					
			Total Files Size (in bytes):	253891	

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Use as many sheets as necessary)

Complete if Known

Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet 5 of 13

Attorney Docket No: WTCY-0026-P07

Change(s) applied to document, /R.K.V./ 5/19/2012

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
		6831417	Dec 14, 2004	Baarman, David W.	
		6844702	Jan 18, 2005	Giannopoulos, Demetri et al.	
		6856291	Feb 15, 2005	Mickle, Marlin H., et al.	
		6906495	Jun 14, 2005	~~Cheng, Lily K., et al~~. Ka-Lai et al.	
		6917163	Jul 12, 2005	Baarman, David W.	
		6917431	Jul 12, 2005	Soljacic, Marin et al.	
		6937130	Aug 30, 2005	Scheible, Guntram	
		6960968	Nov 1, 2005	Odendaal, Willem G., et al.	
		6975198	Dec 13, 2005	Baarman, David W., et al.	
		7042196	May 9, 2006	Cheng, Lily K., et al.	
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		7116200	Oct 3, 2006	Baarman, David W., et al.	
		7118240	Oct 10, 2006	Baarman, David W., et al.	
		7126450	Oct 24, 2006	Baarman, David W., et al.	
		7132918	Nov 7, 2006	Baarman, David W., et al.	
		7180248	Feb 20, 2007	Kuennen, Roy W., et al.	
		7212414	May 1, 2007	Baarman, David W.	
		7239110	Jul 3, 2007	Cheng, Lily K., et al.	
		7248017	Jul 24, 2007	Cheng, Lily K., et al.	
		7375492	May 20, 2008	Calhoon, John C., et al.	
		7375493	May 20, 2008	Calhoon, John C., et al.	
		7378817	May 27, 2008	Calhoon, John C., et al.	
		7382636	Jun 3, 2008	Baarman, David W., et al.	
		7385357	Jun 10, 2008	Kuennen, Roy W., et al.	
		7462951	Dec 9, 2008	BAARMAN, David W.	
		7466213	Dec 16, 2008	Löbl, Hans-Peter et al.	
		7474058	Jan 6, 2009	Baarman, David W.	
		7518267	Apr 14, 2009	Baarman, David W.	
		7525283	Apr 28, 2009	Cheng, Lily K., et al.	
		7615936	Nov 10, 2009	Baarman, David W., et al.	
		7825543	Nov 2, 2010	Karalis, Aristeidis et al.	
		787412	Apr 18, 1905	Tesla, Nikola	

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Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet 4 of 13

Attorney Docket No: WTCY-0026-P07

Change(s) applied
to document
/R.K.V./
5/19/2012

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
		2010/0038970	Feb 18, 2010	Cook, Nigel P., et al.	
		20100109445A 1	May 6, 2010	Kurs, A. B., et al.	
		20100141042A1	Jun 10, 2010	Kesler, M. P., et al.	
		20100164297A1	Jul 1, 2010	Kurs, A B., et al.	
		20100164298A1	Jul 1, 2010	Karalis, A et al.	
		20100171368A1	Jul 8, 2010	~~David, A. et al.~~ Schatz et al.	
		2133494	Oct 18, 1938	WATERS, HARRY F.	
		3517350	Jun 23, 1970	BEAVER, WILLIAM D.	
		3535543	Oct 20, 1970	Dailey, Carroll C.	
		4088999	May 9, 1978	Fletcher, James C., et al.	
		5027709	Jul 2, 1991	Slagle, Glenn B.	
		5070293	Dec 3, 1991	Ishii, Naoki et al.	
		5216402	Jun 1, 1993	Carosa, Paul F.	
		5341083	Aug 23, 1994	Klontz, Keith W., et al.	
		5367242	Nov 22, 1994	Hulman, Fredericus W.	
		5437057	Jul 25, 1995	Richley, Edward A., et al.	
		5493691	Feb 20, 1996	Barrett, Terence W.	
		5528113	Jun 18, 1996	Boys, John T., et al.	
		5550452	Aug 27, 1996	Shirai, Ichiro et al.	
		5898579	Apr 27, 1999	Boys, John T., et al.	
		5999308	Dec 7, 1999	Nelson, Keith A., et al.	
		6184651	Feb 6, 2001	Fernandez, Jose M., et al.	
		6436299	Aug 20, 2002	Baarman, David W., et al.	
		6450946	Sep 17, 2002	Forsell, Peter	
		6452465	Sep 17, 2002	Brown, Andrew et al.	
		6515878	Feb 4, 2003	Meins, Jurgen G., et al.	
		6597076	Jul 22, 2003	Scheible, Guntram et al.	
		6673250	Jan 6, 2004	Kuennen, Roy W., et al.	
		6731071	May 4, 2004	Baarman, David W.	
		6749119	Jun 15, 2004	Scheible, Guntram et al.	
		6798716	Sep 28, 2004	Charych, Arthur	
		6806649	Oct 19, 2004	Mollema, Scott A., et al.	
		6812645	Nov 2, 2004	Baarman, David W.	
		6825620	Nov 30, 2004	Kuennen, Roy W., et al.	

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Substitute for form 1449A/PTO

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

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Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet	4	of	7	Attorney Docket No: WTCY-0026-P07

Change(s) applied to document, /R.K.V./ 5/19/2012

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
		2010/0213895	Aug 26, 2010	Keating, Virginia W., et al.	
		2010/0217553	Aug 26, 2010	Von Novak, William et al.	
		2010/0219695	Sep 2, 2010	Komiyama, Shinji et al.	
		2010/0219696	Sep 2, 2010	Kojima, Hideki	
		2010/0222010	Sep 2, 2010	Ozaki, Ernest T., et al.	
		2010/0225175	Sep 9, 2010	Karalis, Aristeidis et al.	
		2010/0225270	Sep 9, 2010	Jacobs, Paul E., et al.	
		2010/0225271	Sep 9, 2010	Oyobe, Hichirosai et al.	
		2010/0225272	~~Aug 12, 2010~~	Kirby, Miles A., et al. 9/2010	
		2010/0231053	Sep 16, 2010	Karalis, Aristeidis et al.	
		2010/0231163	Sep 16, 2010	Mashinsky, Alex	
		2010/0237706	Sep 23, 2010	Karalis, Aristeidis	
		2010/0237707	Sep 23, 2010	Karalis, Aristeidis	
		2010/0237708	Sep 23, 2010	Karalis, Aristeidis et al.	
		2010/0237709	Sep 23, 2010	Hall, Katherine L., et al.	
		2010/0244576	Sep 30, 2010	Hillan, John et al.	
		2010/0244577	Sep 30, 2010	Shimokawa, Satoshi	
		2010/0244578	Sep 30, 2010	Yoshikawa, Hiroyasu et al.	
		2010/0244579	Sep 30, 2010	Sogabe, Haruhiko et al.	
		2010/0244580	Sep 30, 2010	Uchida, Akiyoshi et al.	
		2010/0244581	Sep 30, 2010	Uchida, Akiyoshi	
		2010/0244582	Sep 30, 2010	Yoshikawa, Hiroyasu	
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		2010/0248622	Sep 30, 2010	Kirby, Miles A., et al.	
		2010/0253152	Oct 7, 2010	Karalis, Aristeidis	
		2010/0253281	Oct 7, 2010	Li, Peng	
		2010/0256831	Oct 7, 2010	Abramo, Keith et al.	
		2010/0259108	Oct 14, 2010	Giler, Eric R., et al.	
		2010/0259109	Oct 14, 2010	Sato, Kazushiro	
		2010/0264745	Oct 21, 2010	Karalis, Aristeidis et al.	
		2010/0264746	Oct 21, 2010	Kazama, Satoshi et al.	
		2010/0264747	Oct 21, 2010	Hall, Katherine L., et al.	
		2010/0276995	Nov 4, 2010	Marzetta, Thomas L., et al.	

EXAMINER /Robert Deberadinis/ **DATE CONSIDERED** 11/18/2011

Substitute Disclosure Statement Form (PTO-1449)

* EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.1 Applicant's unique citation designation number (optional) 2 Applicant is to place a check mark here if English language Translation is attached

ALL REFERENCES CONSIDERED EXCEPT WHERE LINED THROUGH. /RD/

PTO/SB/08a (01-08)
Approved for use through 07/31/2012. OMB 0651-0031
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Substitute for form 1449A/PTO

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

(Use as many sheets as necessary)

Complete if Known

Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet	3	of	7	Attorney Docket No: WTCY-0026-P07

Change(s) applied to document,
/R.K.V./
5/19/2012

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
		2010/0133918	Jun 3, 2010	Joannopoulos, John D.	
		2010/0133919	Jun 3, 2010	Joannopoulos, John D.	
		2010/0133920	Jun 3, 2010	Joannopoulos, John D.	
		2010/0148589	Jun 17, 2010	Hamam, Rafif E.	
		2010/0148723	Jun 17, 2010	Cook, Nigel P., et al.	
		2010/0151808	Jun 17, 2010	Toncich, Stanley S., et al.	
		2010/0156346	Jun 24, 2010	Takada, Kazuyoshi et al.	
		2010/0156570	Jun 24, 2010	Hong, Young-tack et al.	
		2010/0164295	Jul 1, 2010	Ichikawa, Katsuci et al.	
		2010/0171370	Jul 8, 2010	Karalis, Aristeidis et al.	
		2010/0181844	Jul 22, 2010	Karalis, Aristeidis et al.	
		2010/0181961	Jul 22, 2010	Von Novak, William et al.	
		2010/0184371	Jul 22, 2010	Cook, Nigel P., et al.	
		2010/0187911	Jul 29, 2010	Joannopoulos, John D.	
		2010/0187913	Jul 29, 2010	Smith, Joshua R., et al.	
		2010/0190435	Jul 29, 2010	Cook, Nigel P., et al.	
		2010/0190436	Jul 29, 2010	Cook, Nigel P., et al.	
		2010/0194206	Aug 5, 2010	Burdo, Rinat et al.	
		2010/0194207	Aug 5, 2010	Graham, David S.	
		2010/0194334	Aug 5, 2010	Kirby, Miles A., et al.	
		2010/0194335	Aug 5, 2010	Kirby, Miles A., et al.	
		2010/0201189	Aug 12, 2010	Kirby, Miles A., et al.	
		2010/0201201	Aug 12, 2010	Mobarhan, Ramin et al.	
		2010/0201202	Aug 12, 2010	Kirby, Miles A., et al.	
		2010/0201203	Aug 12, 2010	Schatz, David A., et al.	
		2010/0201204	~~Nov 12, 2010~~	Sakoda, Shimpel et al.	8/2010
		2010/0201205	Aug 12, 2010	Karalis, Aristeidis et al.	
		2010/0201310	Aug 12, 2010	Vorenkamp, Pieter et al.	
		2010/0201313	Aug 12, 2010	Vorenkamp, Pieter et al.	
		2010/0201316	Aug 12, 2010	Takada, Kazuyoshi et al.	
		2010/0201513	Aug 12, 2010	Vorenkamp, Pieter et al.	
		2010/0207458	Aug 19, 2010	Joannopoulos, John D.	
		2010/0210233	Aug 19, 2010	Cook, Nigel P., et al.	
		2010/0213770	Aug 26, 2010	Kikuchi, Hideo	

EXAMINER	/Robert Deberadinis/	**DATE CONSIDERED**	11/18/2011

Substitute Disclosure Statement Form (PTO-1449)
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Substitute for form 1449A/PTO

INFORMATION DISCLOSURE STATEMENT BY APPLICANT

Change(s) applied
to document,
/R.K.V./
5/21/2012

(Use as many sheets as necessary)

Complete if Known

Application Number	12/647,763
Filing Date	Dec 28, 2009
First Named Inventor	Aristeidis Karalis
Art Unit	2828
Examiner Name	Not Yet Known

Sheet	1	of	7

Attorney Docket No: WTCY-0026-P07

US PATENT DOCUMENTS

Examiner Initial *	Cite No	Document Number	Publication Date	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or RelevantFigures Appear
		2005/0288739	Dec 29, 2005	Hassler, Jr., William L., et al.	
		2005/0288740	Dec 29, 2005	Hassler, Jr., William L.	
		2007/0182367	Aug 9, 2007	Partovi, Afshin	
		2008/0067874	Mar 20, 2008	Tseng, Ryan	
		2008/0265684	Oct 30, 2008	Farkas, Laszlo	
		20080012569A1	Jan 17, 2008	Hall, D. R., et al.	
		20080030415A1	Feb 7, 2008	Homan, D. M., et al.	
		~~2009/0067198~~	May 6, 2010	Boys, John T., et al.	20100109604
		2009/0085408	Apr 2, 2009	Bruhn, Alfred et al.	
		2009/0096413	Apr 16, 2009	Partovi, Afshin et al.	
		2009/0108679	Apr 30, 2009	Porwal, Gunjan	
		2009/0108997	Apr 30, 2009	Petterson, Mike et al.	
		2009/0146892	Jun 11, 2009	Shimizu, Kanjiro et al.	
		2009/0160261	Jun 25, 2009	Elo, Harri H.	
		2009/0174263	Jul 9, 2009	Baarman, David W., et al.	
		2009/0189458	Jul 30, 2009	Kawasaki, Koji	
		2009/0237194	Sep 24, 2009	Waffenschmidt, Eberhard et al.	
		2009/0251008	Oct 8, 2009	Sugaya, Shigeru	
		2009/0267558	Oct 29, 2009	Jung, Chun-Kil	
		2009/0271047	Oct 29, 2009	Wakamatsu, Masataka	
		2009/0271048	Oct 29, 2009	Wakamatsu, Masataka	
		2009/0281678	Nov 12, 2009	Wakamatsu, Masataka	
		2009/0284082	Nov 19, 2009	Mohammadian, Alireza H.	
		2009/0284083	Nov 19, 2009	Karalis, Aristeidis	
		2009/0284218	Nov 19, 2009	Mohammadian, Alireza H., et al.	
		2009/0284220	Nov 19, 2009	Toncich, Stanley S., et al.	
		2009/0284227	Nov 19, 2009	Mohammadian, Alireza H., et al.	
		2009/0284245	Nov 19, 2009	Kirby, Miles A., et al.	
		2009/0284369	Nov 19, 2009	Toncich, Stanley S., et al.	
		2009/0286470	Nov 19, 2009	Mohammadian, Alireza H., et al.	
		2009/0286475	Nov 19, 2009	Toncich, Stanley S., et al.	

EXAMINER /Robert Deberadinis/ **DATE CONSIDERED** 11/18/2011

Substitute Disclosure Statement Form (PTO-1449)
* EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.1 Applicant's unique citation designation number (optional) 2 Applicant is to place a check mark here if English language Translation is attached

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UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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Alexandria, Virginia 22313-1450
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APPLICATION NO.	ISSUE DATE	PATENT NO.	ATTORNEY DOCKET NO.	CONFIRMATION NO.
12/647,763	11/06/2012	8304935	WTCY-0026-P07	2576

87084 7590 10/17/2012

GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

ISSUE NOTIFICATION

The projected patent number and issue date are specified above.

Determination of Patent Term Adjustment under 35 U.S.C. 154 (b)

(application filed on or after May 29, 2000)

The Patent Term Adjustment is 265 day(s). Any patent to issue from the above-identified application will include an indication of the adjustment on the front page.

If a Continued Prosecution Application (CPA) was filed in the above-identified application, the filing date that determines Patent Term Adjustment is the filing date of the most recent CPA.

Applicant will be able to obtain more detailed information by accessing the Patent Application Information Retrieval (PAIR) WEB site (http://pair.uspto.gov).

Any questions regarding the Patent Term Extension or Adjustment determination should be directed to the Office of Patent Legal Administration at (571)-272-7702. Questions relating to issue and publication fee payments should be directed to the Application Assistance Unit (AAU) of the Office of Data Management (ODM) at (571)-272-4200.

APPLICANT(s) (Please see PAIR WEB site http://pair.uspto.gov for additional applicants):

Aristeidis Karalis, Boston, MA;
Andre B. Kurs, Chestnut Hill, MA;
Andrew J. Campanella, Waltham, MA;
Konrad J. Kulikowski, Somerville, MA;
Katherine L. Hall, Westford, MA;
Marin Soljacic, Belmont, MA;
Morris P. Kesler, Bedford, MA;

IR103 (Rev. 10/09)

STATEMENT UNDER 37 CFR 3.73(b)

Applicant/Patent Owner: Kesler, et al.

Application No./Patent No.: 12/647,763 / 8,304,935 Filed/Issue Date: 12/28/2009 / 11/6/2012

Entitled: Wireless Energy Transfer Using Field Shaping To Reduce Loss

WiTricity Corporation
(Name of Assignee)

a corporation
(Type of Assignee, e.g., corporation, partnership, university, government agency, etc.)

states that it is:

1. ☒ the assignee of the entire right, title, and interest; or
2. ☐ an assignee of less than the entire right, title and interest.
   The extent (by, percentage) of its ownership interest is _______%
3. ☐ the assignee of an undivided interest in the entirety of (a complete assignment from one of the joint inventors was made)

in the patent application/patent identified above by virtue of either:

A. ☒ An assignment from the inventor(s) of the patent application/patent identified above. The assignment was recorded in the United States Patent and Trademark Office at Reel (023918), Frame (0491), or for which a copy thereof is attached.

OR

B. ☐ A chain of title from the inventor(s), of the patent application/patent identified above, to the current assignee as shown below:

1. From: ____________________ To ____________________
   The document was recorded in the United States Patent and Trademark Office at
   Reel __________, Frame __________________, or for which a copy thereof is attached.
2. From: ____________________ To ____________________
   The document was recorded in the United States Patent and Trademark Office at
   Reel _____________, Frame _______________, or for which a copy thereof is attached.
3. From: ____________________ To ____________________
   The document was recorded in the United States Patent and Trademark Office at
   Reel _______________, Frame _________________, or for which a copy thereof is attached.

☐ Additional documents in the chain of title are listed on a supplemental sheet.

☒ As required by 37 CFR 3.73(b)(1)(i), the documentary evidence of the chain of title from the original owner to the assignee was, or concurrently is being, submitted for recordation pursuant to 37 CFR 3.11.
[NOTE: A separate copy (*i.e.*, a true copy of the original assignment document(s)) must be submitted to Assignment Division in accordance with 37 CFR Part 3, if the assignment is to be recorded in the records of the USPTO. See MPEP 302.8]

The undersigned (whose title is supplied below) is authorized to act on behalf of the assignee.

/William E. Hunter, Reg. No. 47671/
Signature

October 23, 2014
Date

William E. Hunter , 47,671
Printed or Typed Name

(858) 678-5070
Telephone Number

Attorney for Assignee
Title

PTO/SB/80 (11-08)
Approved for use through 11/30/2011. OMB 0651-0035
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

POWER OF ATTORNEY TO PROSECUTE APPLICATIONS BEFORE THE USPTO

I hereby revoke all previous powers of attorney given in the application identified in the attached statement under 37 CFR 3.73(b).

I hereby appoint:

☒ Practitioners associated with the Customer Number: 26207

OR

☐ Practitioner(s) named below (if more than ten patent practitioners are to be named, then a customer number must be used):

Name	Registration Number	Name	Registration Number

as attorney(s) or agent(s) to represent the undersigned before the United States Patent and Trademark Office (USPTO) in connection with any and all patent applications assigned <u>only</u> to the undersigned according to the USPTO assignment records or assignment documents attached to this form in accordance with 37 CFR 3.73(b).

Please change the correspondence address for the application identified in the attached statement under 37 CFR 3.73(b) to:

☒ The address associated with Customer Number: 26207

OR

☐ Firm or Individual Name	Fish & Richardson P.C.		
Address	P.O. Box 1022		
City	Minneapolis	State MN	Zip 55440-1022
Country	United States		
Telephone		Email	

Assignee Name and Address:
WiTricity Corporation
149 Grove Street
Watertown, MA 02472

A copy of this form, together with a statement under 37 CFR 3.73(b) (Form PTO/SB/96 or equivalent) is required to be filed in each application in which this form is used. The statement under 37 CFR 3.73(b) may be completed by one of the practitioners appointed in this form if the appointed practitioner is authorized to act on behalf of the assignee, and must identify the application in which this Power of Attorney is to be filed.

SIGNATURE of Assignee of Record

The individual whose signature and title is supplied below is authorized to act on behalf of the assignee

Signature		Date	9/29/14
Name	ALEXANDER GRUZEN	Telephone	617.744.8109
Title	CEO		

This collection of information is required by 37 CFR 1.31, 1.32 and 1.33. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 3 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

Electronic Acknowledgement Receipt

EFS ID:	20499115
Application Number:	12647763
International Application Number:	
Confirmation Number:	2576
Title of Invention:	WIRELESS ENERGY TRANSFER USING FIELD SHAPING TO REDUCE LOSS
First Named Inventor/Applicant Name:	Aristeidis Karalis
Customer Number:	87084
Filer:	William E. Hunter/Cheryl Forrest
Filer Authorized By:	William E. Hunter
Attorney Docket Number:	WTCY-0026-P07
Receipt Date:	23-OCT-2014
Filing Date:	28-DEC-2009
Time Stamp:	14:59:11
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	0099001-POA.pdf	144274 6d6e160562b8b5f265901d8e843145f0cfa69efc	no	2

Warnings:

Information:

Total Files Size (in bytes):	144274

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

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United States Patent and Trademark Office
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APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/647,763	12/28/2009	Aristeidis Karalis	WTCY-0026-P07

CONFIRMATION NO. 2576

POWER OF ATTORNEY NOTICE

OC000000071628581

87084
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

Date Mailed: 11/03/2014

NOTICE REGARDING CHANGE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 10/23/2014.

- The Power of Attorney to you in this application has been revoked by the assignee who has intervened as provided by 37 CFR 3.71. Future correspondence will be mailed to the new address of record(37 CFR 1.33).

/sleutchit/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
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APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/647,763	12/28/2009	Aristeidis Karalis	25236-0099001

CONFIRMATION NO. 2576

POA ACCEPTANCE LETTER

26207
FISH & RICHARDSON P.C.
P.O. BOX 1022
MINNEAPOLIS, MN 55440-1022

OC000000071628611

Date Mailed: 11/03/2014

NOTICE OF ACCEPTANCE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 10/23/2014.

The Power of Attorney in this application is accepted. Correspondence in this application will be mailed to the above address as provided by 37 CFR 1.33.

/sleutchit/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	PATENT NUMBER	GROUP ART UNIT	REQUEST ID
12/647,763	8304935	2836	101023

PAIR Correspondence Address/Fee Address Change

The following fields have been changed to Customer Number 166872 on 12/03/2019 via Private PAIR in view of the certification copied below that authorized the change.

- Maintenance Fee Address

The address for Customer Number 166872 is:
166872
WiTricity Corporation
57 Water Street
Watertown, MA 02472

I certify, in accordance with 37 CFR 1.4(d)(4) that I am:

An attorney or Agent of Record registered to practice before the Patent and Trademark Office who has been given power of attorney in this application

Signature:	/Misha K. Hill/
Name:	Misha K. Hill
Registration Number:	59737

AO 120 (Rev. 08/10)

TO: **Mail Stop 8** **Director of the U.S. Patent and Trademark Office** **P.O. Box 1450** **Alexandria, VA 22313-1450**	**REPORT ON THE FILING OR DETERMINATION OF AN ACTION REGARDING A PATENT OR TRADEMARK**

In Compliance with 35 U.S.C. § 290 and/or 15 U.S.C. § 1116 you are hereby advised that a court action has been filed in the U.S. District Court for the District of Delaware on the following

☐ Trademarks or ☑ Patents. (☐ the patent action involves 35 U.S.C. § 292.):

DOCKET NO.	DATE FILED 12/9/2020	U.S. DISTRICT COURT for the District of Delaware
PLAINTIFF WiTricity Corporation, Massachusetts Institute of Technology and Auckland UniServices Limited		DEFENDANT Momentum Dynamics Corporation

PATENT OR TRADEMARK NO.	DATE OF PATENT OR TRADEMARK	HOLDER OF PATENT OR TRADEMARK
1 7,741,734 B2	6/22/2010	Massachusetts Institute of Technology
2 8,304,935 B2	11/6/2012	WiTricity Corporation
3 8,710,701 B2	4/29/2014	WiTricity Corporation
4 8,884,581 B2	11/11/2014	WiTricity Corporation
5 see additional patents		

In the above—entitled case, the following patent(s)/ trademark(s) have been included:

DATE INCLUDED	INCLUDED BY ☐ Amendment ☐ Answer ☐ Cross Bill ☐ Other Pleading

PATENT OR TRADEMARK NO.	DATE OF PATENT OR TRADEMARK	HOLDER OF PATENT OR TRADEMARK
1		
2		
3		
4		
5		

In the above—entitled case, the following decision has been rendered or judgement issued:

DECISION/JUDGEMENT

CLERK	(BY) DEPUTY CLERK	DATE

Copy 1—Upon initiation of action, mail this copy to Director Copy 3—Upon termination of action, mail this copy to Director
Copy 2—Upon filing document adding patent(s), mail this copy to Director Copy 4—Case file copy

Additional Patents

Patent or Trademark No.	Date of Patent or Trademark	Holder of Patent or Trademark
9,184,595 B2	11/10/2015	WiTricity Corporation
9,306,635 B2	4/5/2016	WiTricity Corporation
9,767,955 B2	9/19/2017	Auckland Uniservices Limited