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Application Number: 13752169 Document Date: 01/28/2013

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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
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Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	

Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS

City	State/Province	Country of Residence
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	

Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS

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Residence Information (Select One) ◉ US Residency ◯ Non US Residency ◯ Active US Military Service

City	Cambridge	**State/Province**	MA	**Country of Residence** i	US

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS	

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All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below. For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

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Application Information:

Title of the Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS		
Attorney Docket Number	WTCY-0075-P01	**Small Entity Status Claimed**	☐
Application Type	Nonprovisional		
Subject Matter	Utility		
Suggested Class (if any)		**Sub Class (if any)**	
Suggested Technology Center (if any)			
Total Number of Drawing Sheets (if any)	51	**Suggested Figure for Publication (if any)**	38

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS	

Please Select One:	(●) Customer Number	◯ US Patent Practitioner	◯ Limited Recognition (37 CFR 11.9)
Customer Number	87084		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	non provisional of	61/590856	2012-01-26

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

Foreign Priority Information:

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).

			Remove
Application Number	Country i	Filing Date (YYYY-MM-DD)	Priority Claimed
			◯ Yes ◯ No

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Authorization to Permit Access:

☒ Authorization to Permit Access to the Instant Application by the Participating Offices

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS	

If checked, the undersigned hereby grants the USPTO authority to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the World Intellectual Property Office (WIPO), and any other intellectual property offices in which a foreign application claiming priority to the instant patent application is filed access to the instant patent application. See 37 CFR 1.14(c) and (h). This box should not be checked if the applicant does not wish the EPO, JPO, KIPO, WIPO, or other intellectual property office in which a foreign application claiming priority to the instant patent application is filed to have access to the instant patent application.

In accordance with 37 CFR 1.14(h)(3), access will be provided to a copy of the instant patent application with respect to: 1) the instant patent application-as-filed; 2) any foreign application to which the instant patent application claims priority under 35 U.S.C. 119(a)-(d) if a copy of the foreign application that satisfies the certified copy requirement of 37 CFR 1.55 has been filed in the instant patent application; and 3) any U.S. application-as-filed from which benefit is sought in the instant patent application.

In accordance with 37 CFR 1.14(c), access may be provided to information concerning the date of filing this Authorization.

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section.

Remove

- (●) Assignee
- ( ) Legal Representative under 35 U.S.C. 117
- ( ) Person to whom the inventor is obligated to assign.
- ( ) Person who shows sufficient proprietary interest

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor :

If the Assignee is an Organization check here. [X]

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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	WTCY-0075-P01
	Application Number	

Title of Invention	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS

Email Address	

Additional Applicant Data may be generated within this form by selecting the Add button. Add

Signature:

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NOTE: This form must be signed in accordance with 37 CFR 1.33. See 37 CFR 1.4 for signature requirements and certifications

Signature	/Jeffrey Ambroziak/			Date (YYYY-MM-DD)	2013-01-28
First Name	Jeffrey	Last Name	Ambroziak	Registration Number	47387

Additional Signature may be generated within this form by selecting the Add button. Add

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The information provided by you in this form will be subject to the following routine uses:

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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.

Electronic Patent Application Fee Transmittal

Application Number:	
Filing Date:	
Title of Invention:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS
First Named Inventor/Applicant Name:	Andre B. Kurs
Filer:	Jeffrey R. Ambroziak/Jennifer Sammartin
Attorney Docket Number:	WTCY-0075-P01

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Utility application filing	1011	1	390	390
Utility Search Fee	1111	1	620	620
Utility Examination Fee	1311	1	250	250
Pages:				
Utility Appl Size fee per 50 sheets >100	1081	1	320	320
Claims:				
Miscellaneous-Filing:				
Late filing fee for oath or declaration	1051	1	130	130

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				
Miscellaneous:				
	Total in USD ($)			**1710**

Electronic Acknowledgement Receipt

EFS ID:	14812844
Application Number:	13752169
International Application Number:	
Confirmation Number:	6134
Title of Invention:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS
First Named Inventor/Applicant Name:	Andre B. Kurs
Customer Number:	87084
Filer:	Jeffrey R. Ambroziak/Jennifer Sammartin
Filer Authorized By:	Jeffrey R. Ambroziak
Attorney Docket Number:	WTCY-0075-P01
Receipt Date:	28-JAN-2013
Filing Date:	
Time Stamp:	19:05:06
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	Application Data Sheet	WTCY-0075-P01_ADS.pdf	1397122 8507d2151abea7d59abb433677256932c97b87a9	no	8

Warnings:

Information:

2		WTCY-0075-P01_Final_Jan_28.pdf	623190 37ded47befcdcb2db833ab75d6e0a12afed85b23	yes	84

Multipart Description/PDF files in .zip description

Document Description	Start	End
Specification	1	80
Claims	81	83
Abstract	84	84

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Information:

3	Drawings-only black and white line drawings	WTCY-0075-P01_Figures-final.pdf	7964180 7808b4492dd2e76e26c3a1ff3d78a480cd7a7116	no	51

Warnings:

Information:

4	Fee Worksheet (SB06)	fee-info.pdf	38282 e550e03c86be50c3a1eaa1dbd27848e5abbd6210	no	2

Warnings:

Information:

Total Files Size (in bytes):	10022774

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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.

CLAIMS

What is claimed is:

1. A magnetic resonator comprising:

    an inductor comprising a conductive first loop having a first dipole moment and a conductive second loop having a second dipole moment wherein a direction of the first dipole moment is substantially opposite to a direction of the second dipole moment; and

    at least one capacitor in series with at least one of the first loop and the second loop.

2. The magnetic resonator of claim 1 wherein a quality factor of the resonator is greater than 100.

3. The magnetic resonator of claim 1 wherein the first loop and second loop are substantially the same size and have the same number of turns.

4. The magnetic resonator of claim 1 wherein a magnitude of the first dipole moment and a magnitude of the second dipole moment are substantially equal.

5. The magnetic resonator of claim 1 wherein the resonator is one component of a wireless power source.

6. The magnetic resonator of claim 1 wherein the resonator is one component of a wireless power device.

7. The magnetic resonator of claim 1 wherein the resonator is one component of a wireless power repeater.

8. The magnetic resonator of claim 1 wherein the first loop and the second loop are substantially co-planar.

9. The magnetic resonator of claim 1 wherein the first loop and the second loop of the resonator are oriented such that an axis of the first loop is substantially parallel to an axis of the second loop.

10. The magnetic resonator of claim 1 wherein the capacitor is a variable capacitor.

11. The magnetic resonator of claim 1 further comprising a second capacitor in parallel with the inductor.

12. A magnetic resonator comprising:

a plurality of conductive loops each having a dipole moment comprising a magnitude and a direction; and

a control system for adjusting the dipole moment of at least one of the plurality of loops to produce a predetermined far field radiation level.

13. The magnetic resonator of claim 12 wherein a sum of the dipole moments of each of the plurality of conductive loops is approximately zero.

14. A method comprising:

providing a plurality of conductive loops each having a dipole moment comprising a magnitude and a direction; and

selectively altering at least one dipole moment of at least one of the plurality of loops to produce a predetermined far field radiation level.

15. The method of claim 14 wherein selectively altering at least one dipole moment comprises:

measuring an existing far field radiation level;

determining a difference between the existing far field radiation level and the predetermined far field radiation level; and

selectively altering at least one dipole moment of at least one of the plurality of loops to effectively counteract the difference.

16. The method of claim 14 wherein the predetermined far field radiation level is approximately zero.

17. A wireless power source comprising:

at least one high-Q magnetic resonator for generating an oscillating magnetic field, and

at least one conducting plate positioned substantially perpendicular to the dipole moment of the resonator.

18. The wireless power source of claim 17 wherein the conductor plate is positioned to reduce the dipole radiation of the resonator in the far field of the resonator.

19. A wireless power device comprising:

at least one high-Q magnetic resonator for generating a current in the presence of an oscillating magnetic field, and

at least one conducting plate positioned substantially perpendicular to the dipole moment of the resonator.

20. The wireless power device of claim 19 wherein the conductor plate is positioned to reduce the dipole radiation of the resonator in the far field of the resonator.

WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS

BACKGROUND

[0001] This application claims the benefit of U.S. provisional patent application Serial No. 61/590,856 filed January 26, 2012, which is hereby incorporated by reference in its entirety.

[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] 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, industrial devices, and commercial devices.

SUMMARY

[0006] Resonators and resonator assemblies may be positioned to distribute wireless energy over a larger area in packaging applications. 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.

[0007] 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.

[0008] 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.

[0009] In accordance with an exemplary and non-limiting embodiment, a magnetic resonator comprises an inductor comprising a conductive first loop having a first dipole moment and a conductive second loop having a second dipole moment wherein a direction of the first dipole moment is substantially opposite to a direction of the second dipole moment and at least one capacitor in series with at least one of the first loop and the second loop.

[0010] In accordance with another exemplary and non-limiting embodiment, a method comprises providing a plurality of conductive loops each having a dipole moment comprising a magnitude and a direction and selectively altering at least one dipole moment of at least one of the plurality of loops to produce a predetermined far field radiation level.

[0011] In accordance with another exemplary and non-limiting embodiment, a magnetic resonator comprises a plurality of conductive loops each having a dipole moment comprising a magnitude and a direction and a control system for adjusting the dipole moment of at least one of the plurality of loops to produce a predetermined far field radiation level.

[0012] In accordance with another exemplary and non-limiting embodiment, a wireless power source comprises at least one high-Q magnetic resonator for generating an oscillating magnetic field and at least one conducting plate positioned substantially perpendicular to the dipole moment of the resonator.

[0013] In accordance with another exemplary and non-limiting embodiment, a wireless power device comprises at least one high-Q magnetic resonator for generating a current in the presence of an oscillating magnetic field, and at least one conducting plate positioned substantially perpendicular to the dipole moment of the resonator.

[0014] 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.

[0015] 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

[0016] Fig.1 is a system block diagram of wireless energy transfer configurations.

[0017] Figs. 2A-2F are exemplary structures and schematics of simple resonator structures.

[0018] Fig. 3 is a block diagram of a wireless source with a single-ended amplifier.

[0019] Fig. 4 is a block diagram of a wireless source with a differential amplifier.

[0020] Figs. 5A and 5B are block diagrams of sensing circuits.

[0021] Figs. 6A, 6B, and 6C are block diagrams of a wireless source.

[0022] Fig. 7 is a plot showing the effects of a duty cycle on the parameters of an amplifier.

[0023] Fig. 8 is a simplified circuit diagram of a wireless power source with a switching amplifier.

[0024] Fig. 9 shows plots of the effects of changes of parameters of a wireless power source.

[0025] Fig. 10 shows plots of the effects of changes of parameters of a wireless power source.

[0026] Figs. 11A, 11B, and 11C are plots showing the effects of changes of parameters of a wireless power source.

[0027] Fig. 12 shows plots of the effects of changes of parameters of a wireless power source.

[0028] 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.

[0029] Fig. 14 shows plots of the effects of changes of parameters of a wireless power source.

[0030] Fig. 15(a) is a plot of wireless power transfer efficiency between a fixed size device resonator and different sized source resonators as a function of separation distance and (b) is a diagram of the resonator configuration used for generating the plot.

[0031] Fig. 16(a) is a plot of wireless power transfer efficiency between a fixed size device resonator and different sized source resonators as a function of lateral offset and (b) is a diagram of the resonator configuration used for generating the plot.

[0032] Fig. 17 is a diagram of a conductor arrangement of an exemplary system embodiment.

[0033] Fig. 18 is a diagram of another conductor arrangement of an exemplary system embodiment.

[0034] Fig. 19 is a diagram of an exemplary system embodiment of a source comprising an array of equally sized resonators.

[0035] Fig. 20 is a diagram of an exemplary system embodiment of a source comprising an array of multi-sized resonators.

[0036] Fig. 21 is a diagram of an exemplary embodiment of an adjustable size source comprising planar resonator structures.

[0037] Figs. 22(a)-(d) are diagrams showing usage scenarios for an adjustable source size.

[0038] Figs. 23(a-b) are diagram showing two resonator configurations with repeater resonators.

[0039] Figs. 24(a-b) are diagram showing two resonator configurations with repeater resonators.

[0040] Fig. 25(a) is a diagram showing a configuration with two repeater resonators (b) is a diagram showing a resonator configuration with a device resonator acting as a repeater resonator.

[0041] Fig. 26 is a diagram of a system utilizing a repeater resonator with a desk environment.

[0042] Fig. 27 is a diagram of a system utilizing a resonator that may be operated in multiple modes.

[0043] Fig. 28 is a circuit block diagram of the power and control circuitry of a resonator configured to have multiple modes of operation.

[0044] Fig. 29(a) is a block diagram of a configuration of a system utilizing a wireless power converter, (b) is a block diagram of a configuration of a system utilizing a wireless power converter that may also function as a repeater.

[0045] Fig. 30 is a block diagram showing different configurations and uses of a wireless power converter.

[0046] Fig. 31(a) is a block diagram of a wireless power converter that uses two separate resonators and a AC to DC converter, (b) is a block diagram of a wireless power converter that uses two separate resonators and an AC to AC converter.

[0047] Fig. 32 is a circuit block diagram of a wireless power converter utilizing one resonator.

[0048] Figs. 33(a-b) are circuit diagrams of system configurations utilizing a wireless power converter with differently sized resonators.

[0049] Fig. 34a and Fig. 34b are diagrams of embodiments of a wireless power enabled floor tile.

[0050] Fig. 35 is a block diagram of an embodiment of a wireless power enabled floor tile.

[0051] Fig. 36 is a diagram of a wireless power enables floor system.

[0052] Fig. 37 is a diagram of a cuttable sheet of resonators.

[0053] Fig. 38 is a diagram of a quadrupole resonator loop.

[0054] Fig. 39 is a diagram of a quadrupole resonator loop.

[0055] Fig. 40 is a diagram of a system with dipole cancellation using an additional source resonator.

[0056] Fig. 41 is a diagram of a system with dipole cancellation using an additional source and device resonator.

[0057] Fig. 42 is a diagram of a resonator with dipole cancellation using a conductor shield.

[0058] Fig. 43 is a diagram of a system with dipole cancellation using an a repeater resonator.

[0059] Fig. 44 is a diagram of a system with dipole cancellation using a conducting loop.

[0060] Fig. 45 is a diagram of a system with dipole cancellation using a conducting loop.

[0061] Fig. 46 is a diagram of a system with dipole cancellation.

[0062] Fig. 47 is a diagram of a system with dipole cancellation.

[0063] Fig. 48 is a diagram of a system with dipole cancellation.

[0064] Fig. 49 is a diagram of a system with dipole cancellation.

DETAILED DESCRIPTION

[0065] 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.

[0066] 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.

[0067] 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.

[0068] 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.

[0069] 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".

[0070] 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.

[0071] The coupling factor, k, is a number between $0 \le |k| \le 1$, 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.

[0072] 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.

[0073] 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.

[0074] 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%.

[0075] 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.

[0076] 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.

[0077] 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.

[0078] 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.

[0079] 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.

[0080] 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.

[0081] 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.

[0082] 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.

[0083] 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.

[0084] 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.

[0085] 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.

[0086] 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.

[0087] 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.

[0088] 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.

[0089] 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.

[0090] 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.

[0091] 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.

[0092] 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.

[0093] 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.

[0094] 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.

[0095] 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.

[0096] 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.

[0097] 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.

[0098] 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.

[0099] 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.

[00100] 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.

[00101] 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.

[00102] 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.

[00103] <u>Example Resonator Circuitry</u>

[00104] 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.

[00105] 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.

[00106] 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.

[00107] 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.

[00108] 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.

[00109] 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.

[00110] 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.

[00111] 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.

[00112] 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.

[00113] 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.

[00114] 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.

[00115] 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.

[00116] 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.

[00117] 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.

[00118] 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.

[00119] 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.

[00120] 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.

[00121] 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.

[00122] 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.

[00123] 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.

[00124] 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.

[00125] Efficiency of switching amplifiers

[00126] 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.

[00127] 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%.

[00128] 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.

[00129] Impedance Matching Networks

[00130] 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.

[00131] 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 $R_l(\omega) = R_o, X_l(\omega) = X_o$.

[00132] Methods for tunable Impedance Matching of a variable load

[00133] 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.

[00134] 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.

[00135] 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.

[00136] 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.

[00137] 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

$$R_l(\omega) = F_R(dc)/\omega C_a \, , X_l(\omega) = F_X(dc)/\omega C_a \qquad (3).$$

[00138] 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.

[00139] 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.

[00140] 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.

[00141] 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

[00142] <u>Examples of methods for tunable Impedance Matching of a variable load</u>

[00143] 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.

[00144] 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.

[00145] 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.

[00146] 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.

[00147] 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.

[00148] 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.

[00149] 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.

[00150] 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.

[00151] 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.

[00152] 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.

[00153] Tunable Impedance Matching for systems of wireless power transmission

[00154] 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.

[00155] 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.

[00156] 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.

[00157] 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".

[00158] 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.

[00159] 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.

[00160] 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.

[00161] 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.

[00162] Adjustable Source Size

[00163] 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.

[00164] 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.

[00165] 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.

[00166] 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.

[00167] The relationship between wireless power transfer efficiency and source-device resonator separation is shown in Figure 15(a). The plot in Figure 15(a) shows the wireless power transfer efficiency for the configuration shown in Figure 15(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 15(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.

[00168] 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.

[00169] 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.

[00170] 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.

[00171] 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 16(a) shows the wireless power transfer efficiency for the configuration shown in Figure 16(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 16(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.

[00172] 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 17 which depicts a bank of three differently sized resonators. In the example of Figure 17, 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 18, arranged in an array, and the like.

[00173] 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 18. 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.

[00174] 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.

[00175] 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 relative phase 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.

[00176] 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.

[00177] 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.

[00178] 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 19. 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 19, 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.

[00179] 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.

[00180] 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.

[00181] 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.

[00182] 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 20. 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 20, 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.

[00183] 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 21(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.

[00184] Another embodiment of an adjustable size source with a cored resonator is shown in Figure 21(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 21(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.

[00185] Another embodiment of an adjustable size source with a cored resonator is shown in Figure 21(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 21(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.

[00186] As those skilled in the art will appreciate, the methods and designs depicted in Figure 21 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.

[00187] 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.

[00188] 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.

[00189] 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.

[00190] 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.

[00191] Figure 22 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 22(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 22(b). When a device with a small resonator 6602 is misaligned, the source 6604 may energize the larger resonator 6602 as shown in Figure 22(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 22(d) to maximize the power transfer efficiency.

[00192] 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.

[00193] Wireless Power Repeater Resonators

[00194] 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.

[00195] 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.

[00196] 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.

[00197] In embodiments a repeater resonator may be a capacitively loaded loop magnetic resonator. In embodiments a repeater resonator may be a capacitively loaded loop magnetic resonator wrapper around magnetic material. 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, $\sqrt{Q_{r1} Q_{r2}} > 100$.

[00198] 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.

[00199] 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.

[00200] 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.

[00201] 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.

[00202] Several possible usage configurations are shown in Figures 23-25 showing example arrangements of a wireless power transfer system that includes a source 7404 resonator coupled to a power source 7400, a device resonator 7408 coupled to a device 7402, and a repeater resonator 7406. 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 Figure 23(b). For the configuration shown in Figure 23(b) 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 Figure 23(b) it may be preferable for the repeater resonator to be larger than the device resonator.

[00203] 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 Figure 24(a) or aligning with the source resonator as shown in Figure 24(b).

[00204] In some embodiments multiple repeater resonators may be used to extend the wireless power transfer into multiple directions or multiple repeater resonators may one after another to extend the power transfer distance as shown in Figure 25(a). In some embodiments, a device resonator that is connected to load or electronic device may operate simultaneously, or alternately as a repeater resonator for another device, repeater resonator, or device resonator as shown in Figure 25(b). 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.

[00205] 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.

[00206] 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.

[00207] Repeater Resonator Modes of Operation

[00208] 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.

[00209] In one exemplary embodiment depicted in Figure 26, a repeater resonator 8504 may be used with a table surface 8502 to energize the top of the table for powering or recharging of electronic devices 8510, 8516, 8514 that have integrated or attached device resonators 8512. The repeater resonator 8504 may be used to improve the wireless power transfer from the source 8506 to the device resonators 8512.

[00210] 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.

[00211] 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. As described above in this document, and as shown in Figures 15, 16 and 23, 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 8512, with a characteristic size of approximately 5cm, may be much smaller than a source resonator 8506, 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 low power transfer efficiency. However, if a 50 cm x 100 cm repeater resonator is integrated into a table, as shown in Figure 26, 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.

[00212] 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 Figure 26, 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 Figure 26, 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.

[00213] In the exemplary embodiment shown in Figure 26, the direct power transfer efficiency between a 50 cm x 50 cm source resonator 8506 mounted on the wall and a smart-phone sized device resonator 8512 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.

[00214] In embodiments of systems that use a repeater resonator such as the exemplary system depicted in Figure 26, 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.

[00215] 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.

[00216] 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.

[00217] 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.

[00218] 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.

[00219] 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.

[00220] 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.

[00221] Another exemplary embodiment showing the use of a repeater resonator is depicted in Figure 27. 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 8602 that is depicted as transparent to show internal components. In this exemplary embodiment, there may be a separate bag, satchel, pocket, or compartment 8606 inside the bag 8602 that may be used for storage or carrying of electronic devices 8610 such as cell-phones, MP3 players, cameras, computers, e-readers, iPads, netbooks, and the like. The compartment may be fitted with a resonator 8608 that may be operated in at

least three modes of operation. In one mode, the resonator 8608 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 8604 and may operate as a wireless power source for wirelessly recharging or powering the electronic devices located in the handbag 8602 or the handbag compartment 8606. In this configuration and setting, the bag and the compartment may be used as a portable, wireless recharging or power station for electronics.

[00222] The resonator 8608 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 8612 of the device 8610 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.

[00223] 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 8604 or to recharge the portable energy source of the compartment 8606 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 8604 and the batteries of the devices 8610 inside the compartment 8606 or the bag 8602.

[00224] 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.

[00225] 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 Figure 28. In this configuration a capacitively loaded conducting loop 8608 is coupled to a tuning network 8728 to form a resonator. The tuning network 8728 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 8702, 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 8704 or a source circuit branch 8706, 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 8704 may be used when the resonator is operating in a repeater or device mode. A device circuit branch 8704 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 8708, a rectifier 8710, DC to DC or DC to AC converters 8710, and any devices, loads, or batteries requiring power 8714. 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.

[00226] A source circuit branch 8706 may be used during repeater and/or source mode of operation of the resonator. A source circuit branch 8706 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 8722, 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 8720 to convert the voltages of a power source to produce oscillating voltages that may be used to drive the resonator through an impedance matching network 8716. 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 8722 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 8722 may be used to supplement the oscillating voltages induced in the resonator 8608 from the external magnetic field to generate a stronger oscillating magnetic field that may be sufficient to power or charge other devices.

[00227] 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.

[00228] In embodiments, the power and control circuitry of a resonator enabled to operate in multiple modes may include a processor 8726 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.

[00229] 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.

[00230] Wireless Power Converter

[00231] 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.

[00232] 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.

[00233] Figure 29 shows exemplary functionality and uses of a wireless power converter. In wireless energy transfer systems one or more sources 8810 may generate oscillating magnetic fields 8814 at one or more frequencies. A wireless power converter 8808 may couple to the source 8810 and capture the energy from the oscillating magnetic field 8814 and transfer some or all of the captured energy by generating an oscillating magnetic field 8816 at one or more frequencies that may be different from the source resonator frequencies and that may be utilized by the device 8812. It is important to note that the wireless power converter 8808 may not need to be located between the source 8810 and the device 8812, 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.

[00234] 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.

[00235] 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.

[00236] 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.

[00237] 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 Figure 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.

[00238] 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 500kHz. 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 500kHz 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.

[00239] 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.

[00240] Exemplary embodiments of wireless power transfer system configurations employing wireless power converters are depicted in Figure 30. As part of the configuration, a wireless power converter 8914 may capture energy from oscillating magnetic fields 8932, 8930 from one or more sources 8922, 8924 that may be configured or designed to operate with different parameters. The wireless power converter 8914 may capture the energy and generate a magnetic field 8934, 8936, 8938 with one or more different parameters than the sources 8922, 8924 from which the energy was received and transfer the energy to one or more devices 8916, 8918, 8920. In another aspect of the configuration, a wireless power converter 8914 may be used to capture energy from one or more sources 8922, 8924 that may be designed to operate with different parameters and generate a magnetic field 8934 with parameters that match the field 8928 of another source 8926 providing "amplification" or a boost to a field from sources 8922, 8924 and fields 8930, 8932 with different parameters.

[00241] 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 a oscillating magnetic field is depicted in Figure 31(a). The wireless power converter 9012 may have one or more magnetic resonators 9014, 9016 that are tuned or tunable to one or more frequencies. The oscillating voltages generated in the resonator 9014 by the oscillating magnetic fields 9002 may be rectified and used by a DC to AC converter 9008 to drive another resonator 9016 with oscillating currents generating an oscillating magnetic field 9004 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 9010 to generate a range of frequencies and output power levels.

[00242] In embodiments the oscillating voltages of the receiving resonators 9014 may be converted to oscillating voltages at a different frequency using an AC to AC converter 9018 and used to energize a resonator 9016 of a wireless power converter without first converting the received voltages and currents to DC as depicted in Figure 31(b). 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.

[00243] 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 Figure 32. A time multiplexed wireless power converter 9102 may be tuned to capture oscillating magnetic fields 9104, convert the generated AC energy to DC energy using an AC to DC converter 9114, and charge an energy storage element 9108 such as a super capacitor, battery, and the like. After a period of time, the resonator 9116 may be tuned to a different frequency and the energy stored in the energy storage element 9108 may be used to power an amplifier or an DC to AC converter 9112 to drive the tuned resonator 9116 with an oscillating voltage at the new resonant frequency thereby generating an oscillating magnetic field. In embodiments the resonator 9116 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.

[00244] 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.

[00245] 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.

[00246] 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.

[00247] 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.

[00248] 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.

[00249] For example, as depicted in Figure 33(a), a wireless power converter 9214 with a large capture resonator 9216 and a small transmitting resonator 9218 may be placed close to a small device resonator 9212 and may improve the wireless power transfer efficiency between a large distant source resonator 9208 and a small device resonator 9212. Likewise, as depicted in Figure 33(b), a wireless power converter 9214 with a small capture resonator 9218 and a large transmitting resonator 9216 may placed close to a small source resonator 9208 and may improve the wireless power transfer efficiency between a large distant device resonator 9212 and the small source resonator 9208. 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.

[00250] <u>Wireless Energy Distribution System</u>

[00251] 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.

[00252] 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.

[00253] 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.

[00254] 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.

[00255] 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.

[00256] 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.

[00257] Example embodiments of a wireless power enabled floor tile are depicted in Fig. 34(a) and Fig. 34(b). A floor tile 12902 may include loops of an electrical conductor 12904 that are wound within the perimeter of the tile. In embodiments the conductor 12904 of the resonator may be coupled to additional electric or electronic components 12906 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.

[00258] 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. 98(a) or 98(c). 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.

[00259] 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.

[00260] 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.

[00261] 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.

[00262] 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.

[00263] A block diagram of the components comprising a resonator tile are shown in Fig. 35. In a tile, a resonator 13002 may be optionally coupled to power and control circuitry 13006 to receive power and power devices or optional sensors 13004. Additional optional communication circuitry 13008 may be connected to the power and control circuitry and control the parameters of the resonator based on received signals.

[00264] 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.

[00265] 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. 36. The tiles 13102 are arranged in an array with at least one source resonator that may be integrated into a tile 13110 or attached to a wall 13106 and wired 13112 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.

[00266] 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 13106 may be transferred wirelessly from the source 13106 to an interior area or interior tile 13122 via multiple repeater resonators 13114, 13116, 13118, 13120 that are between the interior tile 13122 and the source 13106. The interior tile 13122 may than transfer the power to a device such as a resonator built into the base of a lamp 13108. 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 13124, 13126, 13128 may be positioned around the lamp 13108 to create a defined area of power (tiles 13114, 13116, 13118, 13120, 13122, 13124, 13126, 13128) 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.

[00267] 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.

[00268] 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.

[00269] For example, consider the array of tiles depicted in Fig. 36 comprising 36 tunable repeater resonator tiles with a single source resonator 13106. If only one device that requires power is placed on the floor, such as the lamp 13108, 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 13108, the repeater tiles that are not in direct path from the source resonator 13106 to the tile closes to the device 13122 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 13108 is moved from its current location 13122 to another tile, say 13130, the magnetic field distribution in the area of the tiles may be changed by retuning tiles that are in the path from the source 13106 to the new location 13130.

[00270] 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.

[00271] 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.

[00272] 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.

[00273] 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.

[00274] 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.

[00275] 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 13134, 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.

[00276] 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.

[00277] 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.

[00278] 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.

[00279] 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.

[00280] 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. 37, an array of repeater resonators 13204 may be printed, attached, or embedded onto one single sheet 13202. The single sheet 13202 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 13206 shown in Fig. 37.

[00281] 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.

[00282] 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.

[00283] Wireless Energy Transfer With Reduced Fields

[00284] In some wireless power transfer applications, it may be beneficial to minimize or reduce the electric and magnetic fields at a distance away from the system, at distances substantially larger than the system, and sometimes at a distance within several centimeters away from the system. The fields that need to be minimized or reduced can be either the far-field, or the near-field (if the wavelength is much larger than the distance between the wireless power transfer system to the point of interest). One would like to accomplish this without a substantial decrease of the performance of the system, and/or dramatic changes to the external geometry of the system. An opportunity for accomplishing this arises from the fact that the fields far from the system are substantially different than the fields close to the system (whose properties determine the performance of the power transfer system). Thereby, to a large extent, it may be possible to tune these two sets of fields fairly independently, ensuring that the fields far from the system are weak, or reduced, without drastically reducing the performance (efficiency, amount of power tranfered) of the power transfer. Far from the system, one can decompose the fields into a multipole expansion. In this disclosure, we show how one can design the systems so that the lowest (dipole) component of the expansion is zero or nearly zero. This way, the fields far from the system will be weak, because the higher order components decay substantially faster (as a function of distance) than the dipole component. In typical wireless power transfer systems, this can often lead to reduction of the relevant fields far from the system by orders of magnitude.

[00285] In one embodiment, both the device and the source can be designed to be quadrupole magnetic resonators. With the quadrupole design the field far from the system will identically have no dipole component. In embodiments a quadrupole magnetic resonator may comprise two or more loops of a conductor configured such that the current flows in opposite direction through each loop or series of loops. In embodiments the loops of the conductor may be

co-planar. In other embodiments the loops may be oriented such that the axis of the loops are all substantially parallel. One example of a quadrupole magnetic resonator is shown in Fig 38. In that figure, the conductor of the resonator is twisted to form two coplanar loops. When the conductor is energized with an electric current, the current will flow substantially in opposite directions in each of the loops, clockwise in one and counterclockwise in the other. Each of the two loops by itself has a magnetic dipole, but since their dipoles are identical, and the currents are circulating in them in the opposite directions, the dipole components far from the object cancel, and we are left with only a quadrupole field.

[00286] Another example of a resonator that has only a quadrupole moment is shown in Fig.39. In the figure, the conductor of the resonator is twisted to form two coplanar and coaxial loops. The arrows in each of the figures represent the direction of the flow of the current in the corresponding part of the resonator. Like in the example of Fig. 38, when the conductor is energized with an electric current, the current will flow substantially in opposite directions in each of the loops.

[00287] In embodiments each of the loops of the conductor shown in Figs. 38 and 134 may comprise of more than one loops of conductor. A single conductor may first shaped to form multiple loops or turns such that the current flows in the same direction in each of the loops or turns and then formed to make an additional set of loops or turns with the current flowing in the same direction in each of the second set of loops or turns but opposite direction with respect to the first set of loops or turns.

[00288] In the embodiment of Fig. 39 it should be noted that since the loops do not have identical sizes, one has to make sure that the inner loop has more turns of wire than the outer loop to compensate; roughly, the ratio of the areas of the loops should correspond to the inverse of the ratio of the number of turns of wire.

[00289] Another embodiment of cancelation of the dipole moment may be achieved with an additional source or active resonator as illustrated in Fig. 40. In the embodiment, in addition to a source resonator (source 1) and a device resonator (device 1), an additional resonator (source R) is used whose main purpose is to cancel the dipole moment far from the system. In embodiments the current of the additional resonator (source R) is adjusted to be exactly or substantially out of phase with the source resonator (source 1). In embodiments, to get the most cancellation it may be preferable to ensure source 1 and source R are of identical or

near identical sizes and have an equal number of wires, that the orientation of their dipoles are substantially the same, and that they circulate substantially the same amount of current.

[00290] Since the device shown in Fig. 40 is smaller, its contribution to the field is smaller and in some application may be neglected. Nevertheless, for some applications one can easily take the device's contribution into account. One adds the dipole moment of the device (as a complex vector) $\mathbf{p}_D$ to the dipole moment of the source 1 (as a complex vector) $\mathbf{p}_{S1}$: they are often $\pi/2$ out of phase with respect to each other. Sometimes these vectors are parallel to each other (if source 1 and device 1 are parallel), but sometimes they are not: that is why it is crucial to add them as vectors in this consideration. Next, one ensures that source R has the complex dipole moment $\mathbf{p}_{SR} = -(\mathbf{p}_{S1} + \mathbf{p}_D)$, which will ensure that the dipole field is canceled far from the entire system shown in Fig. 40. To ensure that this is the case, one will (most generally) have to tune the orientation of the source R (to make sure the vectors are parallel), the phase of the current (so it exactly cancels the other dipole), and the current going thru it (to make sure that the magnitude of the vectors are the same). Note that if the source R is substantially larger than the source 1 and/or the device 1, even a very weak current in the source R will be sufficient: the impact on the fields close to the system (and the total power in the source R) will be very small, yet the impact on the field far from the system can be large. This scheme works better if the centers of the wireless power system and the source R are not very far from each other. The source R can be positioned fairly arbitrarily: in fact it can even be surrounding the wireless power transfer system.

[00291] In yet another embodiment the dipole component may be cancelled if one can ensure to have two (independent) wireless power transfer systems, sufficiently close to each other, operating at the same time. If the dipole moment vectors of the two systems are the same in direction and in magnitude, and one ensures to operate the systems π out of phase, the dipole component will be canceled far from the systems. Note that the intrinsic details of the systems can be substantially different (different sizes, powers, etc.): only the dipole components of the fields have to be substantially similar. A possible configuration of the system is shown in Fig. 41. The figure shows two power transfer systems, one comprising source 1 and device 1 and the other source 2 and device 2. Source 1 transfers energy to device 1 and source 2 transfers energy to device 2. The two sources and devices can transfer power to the same object (e.g. both of

these systems can be installed on the same car, charging that particular single car), or they can be completely independent systems (i.e. charging two separate cars). For example, in a garage with 2N cars (where N is integer), one can ensure that the dipole components of all the cars cancel pair-wise far from the garage. In the case when there is an odd number of cars in the garage (e.g. 3 cars), one ensures that they are $2\pi/3$ out of phase with respect to each other, so when dipole moments of the 3 cars are added, they cancel together: $1+e^{-i2\pi/3}+e^{-i4\pi/3}=0$. If the dipole moment vectors of the systems are not the same, one has to make sure the sum of their complex vectors cancels far from the system, similarly as we discussed in the previous paragraph.

[00292] In embodiments of the system depicted in Fig. 41, each of the source coils may be driven and controlled by a separate amplifier operating out of phase of one another. In embodiments each of the device resonators may be connected to separate rectifier and control circuits. In other embodiments the two or more source coils may be driven by the same amplifier in series. Likewise, in some embodiments the two device resonators may be connected to the same rectifier and control circuitry.

[00293] In another embodiment a quadrupole magnetic resonator may be implemented with the use of a conducting plane positioned substantially perpendicular to the dipole moment of the resonator as depicted in Fig. 42. If one places a conducting plane below the dipole, there will be an image dipole generated below the plane. If the original dipole is perpendicular to the plane, the image dipole will be also perpendicular, but opposite. Hence, far from the object, the field will look like a quadrupole. In fact, since the Earth itself is partially conducting, it can often provide the same purpose as a conducting plane.

[00294] In another embodiment the dipole term far from the system may be reduced by adding one or more repeater resonators, as in Fig. 43. In some wireless power transfer system, a single repeater will be $\pi/2$ out of phase with respect to the source, and $-\pi/2$ out of phase with respect to the device. This means that the source and the device are π out of phase, and that their fields tend to cancel the dipole term far from the system. If the repeater's dipole moment is substantially smaller than the source, or the device, the dipole term far from the system will be small. In embodiments, two or more repeaters can be placed between the source and device. In embodiments, an even number of repeaters placed between the source and device can improve cancellation of the far-field radiation. By tuning the phases, and geometries of the system, one could potentially reduce the dipole term far from the system even further: the fact that the system

consists of 3 resonators (instead of the usual 2) provides further opportunities for dipole cancelation far from the system.

[00295] Another way to reduce the far-field dipole radiation involves configuring one or more conductors so that an electric current flows through them in a direction that creates a magnetic dipole moment that substantially opposes the magnetic dipole of the wireless energy transfer system. In embodiments, the conductors are distal from the near-field region of the wireless energy transfer system. This allows the conductors to attenuate the far-field radiation without substantially attenuating the near-field resonant energy transfer.

[00296] Fig. 44 depicts an embodiment where a conducting loop is configured so that the fringing magnetic fields from the resonators induce an oscillating current that flows through the loop. The induced current will produce a magnetic dipole M that opposes the magnetic dipole of the resonator system. The circle with a concentric dot represents magnetic field lines flowing out of the page while the circle with a cross represents magnetic field lines flowing into the page. The far-field dipole will therefore be attenuated by the partial cancellation of the resonator system's dipole by the induced dipole. Fig. 45 depicts an embodiment in which a current is directly excited in the conducting loop. The current in the loop can substantially cancel the far-field radiation from the dipole of the resonator system. The magnetic dipole magnitude is the product of three factors: the current, the number of turns in the loop, and the effective area of the loop. In embodiments, the effective area of the outer loop is substantially larger than the effective area of the of the resonator system. This allows use of an excitation current in the outer loop that is substantially less than the currents flowing in the resonator system.

[00297] Fig. 46 depicts an embodiment a two or more conductors are configured as short monopole antennas that are capacitively loaded at their tops. Each individual conductor is similar to a so-called top-hat antenna. With sufficient capacitive loading at the top, currents of opposite phase can be induced in the two conductors by the magnetic-dipole field of the resonator system. These induced currents create a dipole field that can partially cancel the far-field radiation from the dipole of the resonator system. Fig. 47 depicts an embodiment in which currents of opposite direction are directly excited in the two conductors. These opposing currents can create a dipole field that can substantially cancel the far-field radiation from the resonators.

[00298] In some embodiments, two or more resonators are exchanging wireless energy in a configuration where larger conducting objects are located above and below the resonators.

Two or more conductors can be placed outside of the resonators in a way that the conductors are electrically connected to one object and capacitively coupled to the second object as shown in Fig. 48. In embodiments, a stiff wire with a conducting plate on top would enhance the capacitive coupling to the second object. In embodiments, two or more top-hat antennas would couple capacitively to the second object. In embodiments, brushes or alignment aids or conducting posts could be configured to act as capacitively-coupled conductors. The currents induced in the outer conductors can partially cancel the far-field dipole radiation of the resonator system. Fig. 49 depicts an embodiment in which currents of opposite sign are excited in the two antennas. These opposing currents can create a dipole field that can substantially cancel the far-field radiation from the resonators.

[00299] In the embodiments discussed above, the goal is to eliminate or reduce the dipole contribution to the field far from a wireless power system. There exists a natural measure (figure of merit) to establish to what extent has the dipole term been successfully suppressed. A magnetic resonator has a characteristic area A. Typically, such a resonator will have magnetic dipole moment far from the resonator proportional to IA, where I is the current flowing in the resonator. If one measures the field far from the system and concludes that the field has magnetic dipole moment «IA, that means that the scheme we propose has been implemented successfully.

[00300] It is to be understood that the techniques and embodiments described may be used with any number of different resonator types and configurations. Although many figures and embodiment examples were described and shown with a cpacitively loaded loop resonator other resonator types may also be used in the embodiments. For example, planar resonators comprising a block of magnetic material such as shown in Fig. 2D or 2E may be used. The techniques may be used with resonator coil comprising solid conducting wire, Litz wire, or printed conductor traces that may be etched on a printed circuit board.

[00301] 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. For example, designs, methods, configurations of components, etc. related to transmitting wireless power have been described above along with various specific applications and examples thereof. Those skilled in the art will appreciate where the designs, components, configurations or components described herein can be used in combination, or

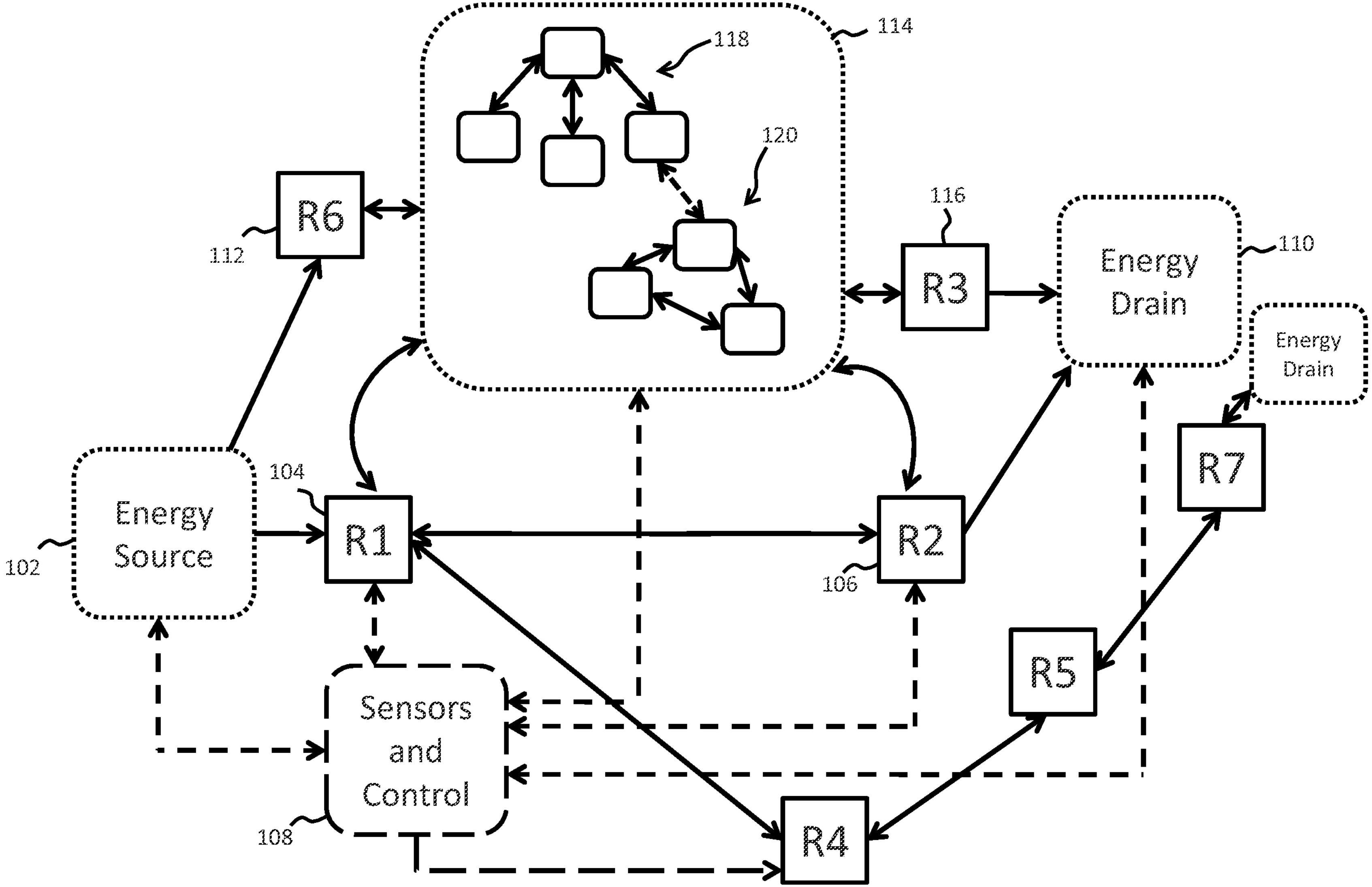
interchangeably, and that the above description does not limit such interchangeability or combination of components to only that which is described herein.

[00302] All documents referenced herein are hereby incorporated by reference.

ABSTRACT

[00303] A magnetic resonator includes an inductor comprising a conductive first loop having a first dipole moment and a conductive second loop having a second dipole moment wherein a direction of the first dipole moment is substantially opposite to a direction of the second dipole moment and at least one capacitor in series with at least one of the first loop and the second loop.

Fig. 1


114
118
120
R6
112
116
R3
Energy
Drain
110
Energy
Drain
104
Energy
Source
102
R1
R2
106
R7
R5
Sensors
and
Control
108
R4

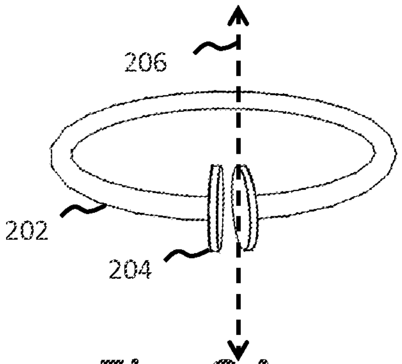


Fig. 2A

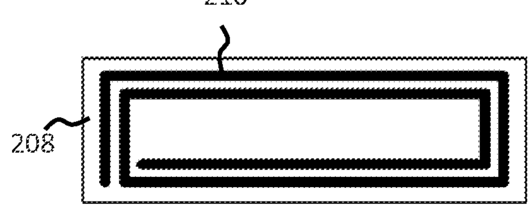


Fig. 2B

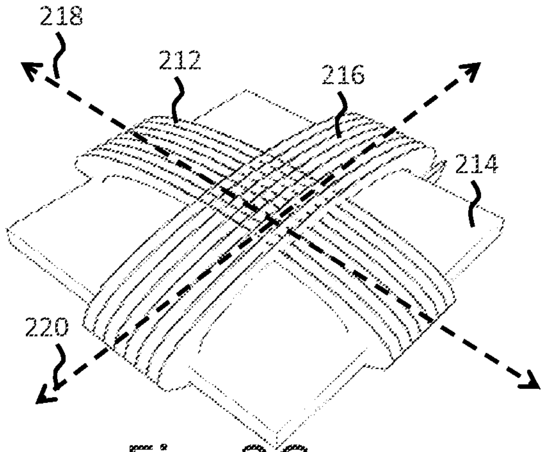


Fig. 2C

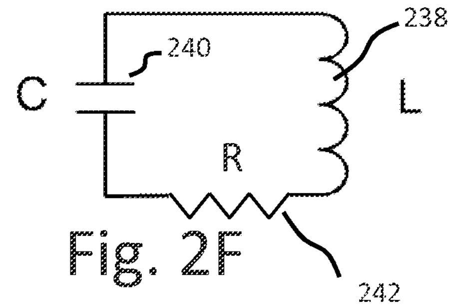


Fig. 2F

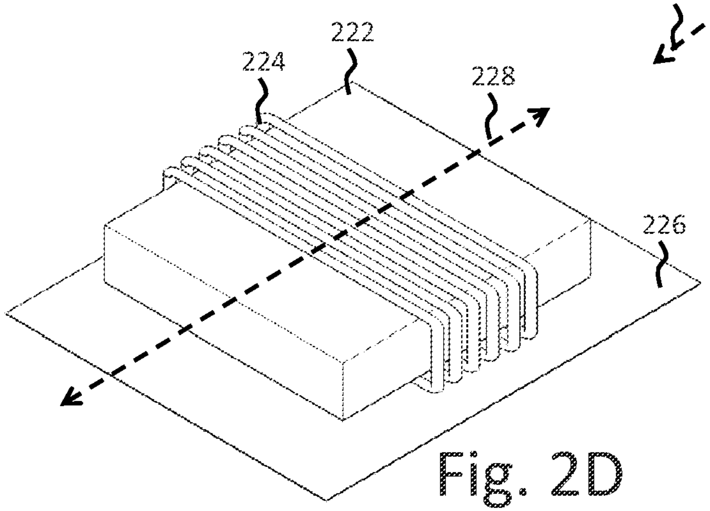


Fig. 2D

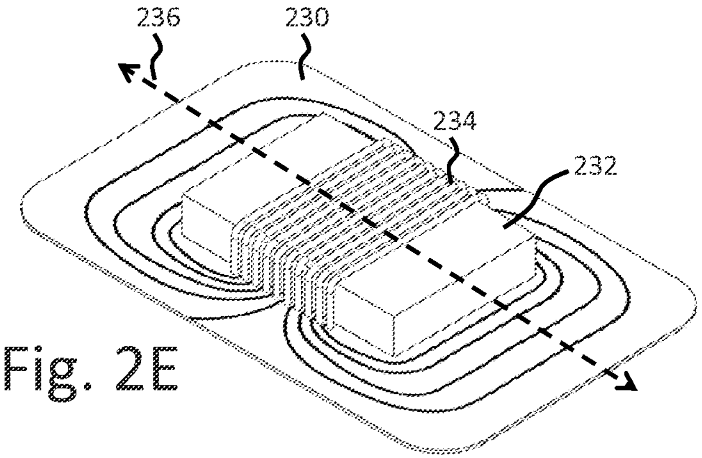


Fig. 2E

Fig. 3

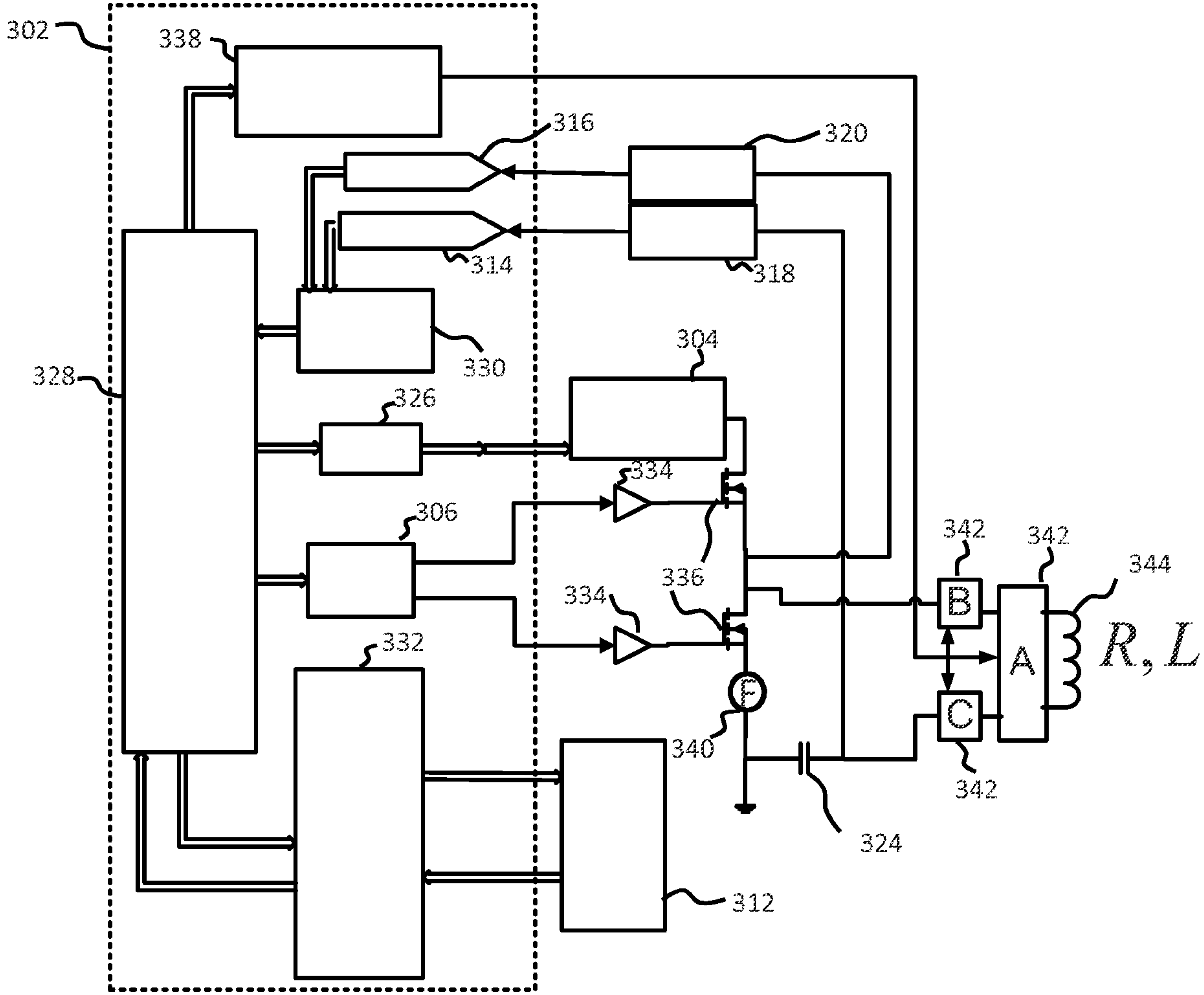
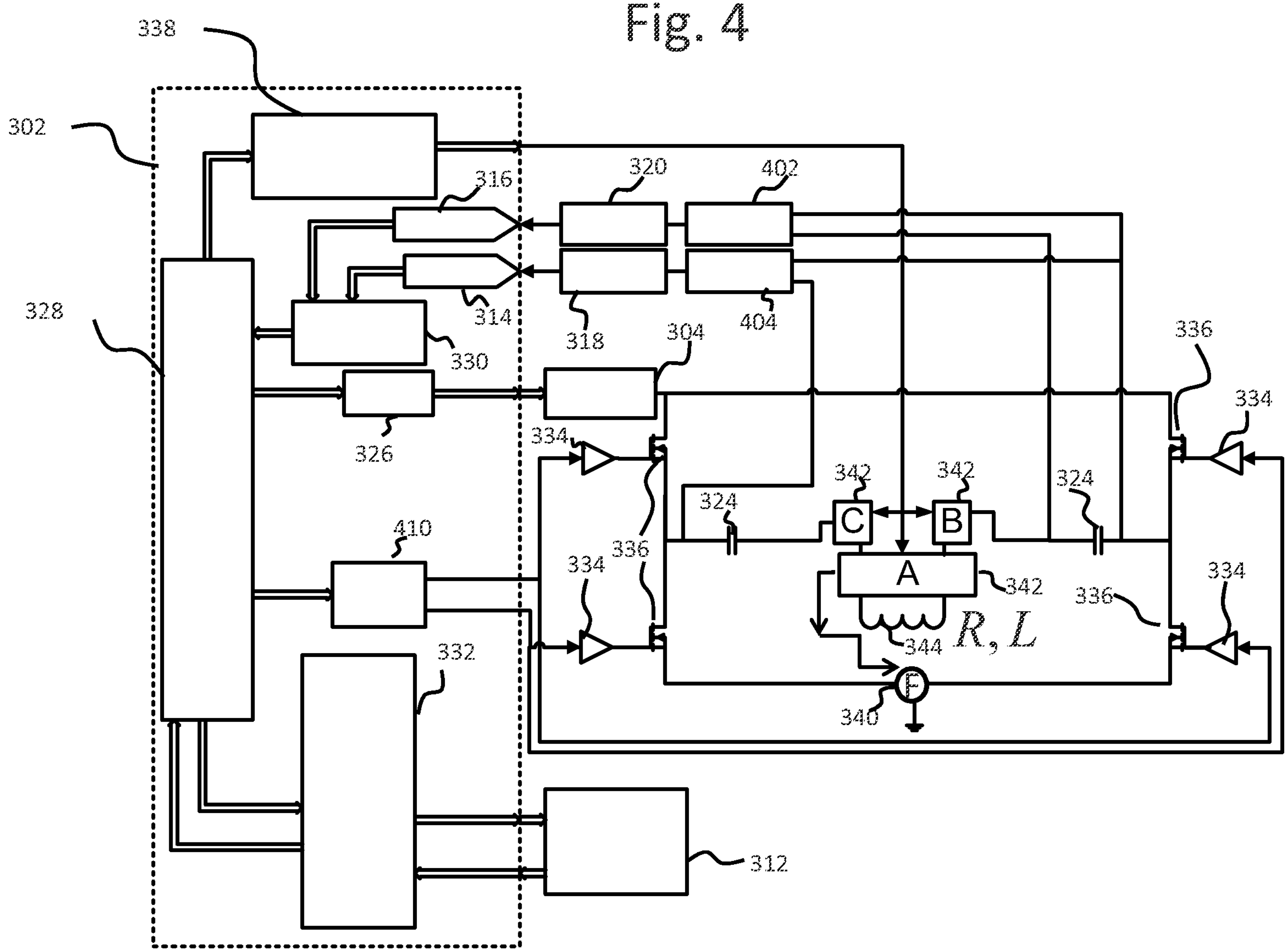

302
338
316
320
314
318
328
330
304
326
334
306
342
342
344
336
334
B
A
R, L
332
F
C
340
342
324
312

Fig. 4


338
302
316
320
402
328
314
318
404
304
330
336
334
326
334
342
342
324
324
410
C
B
A
336
334
334
336
342
R, L
344
332
340
312

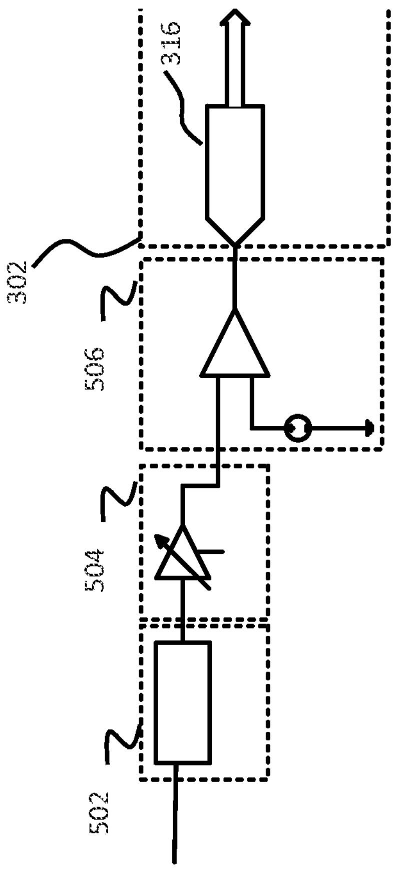


Fig. 5A

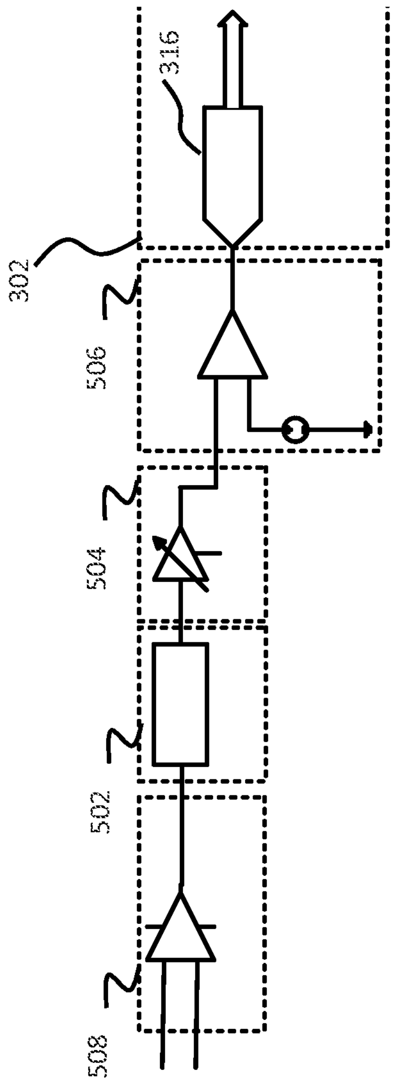


Fig. 5B

Fig. 6A

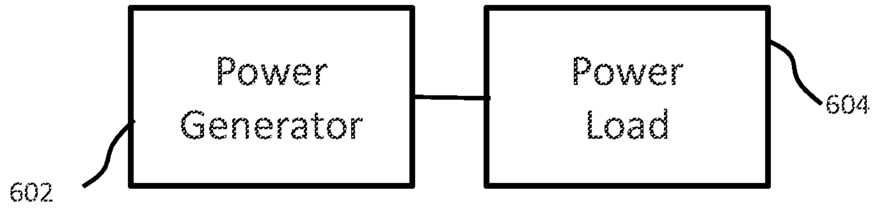


Fig. 6B

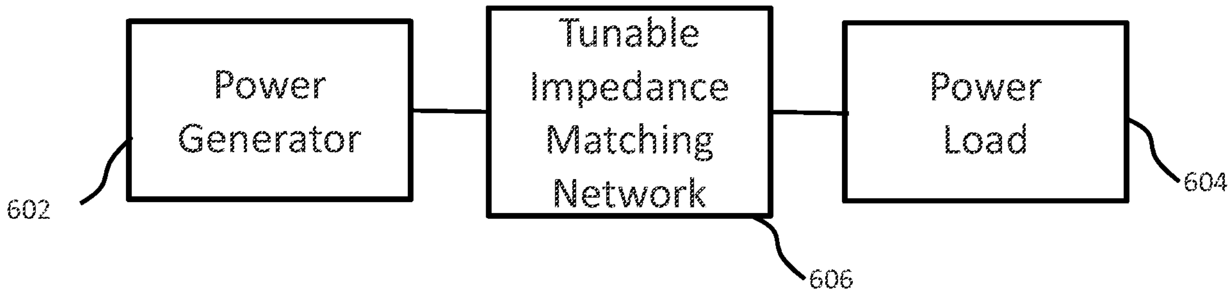


Fig. 6C

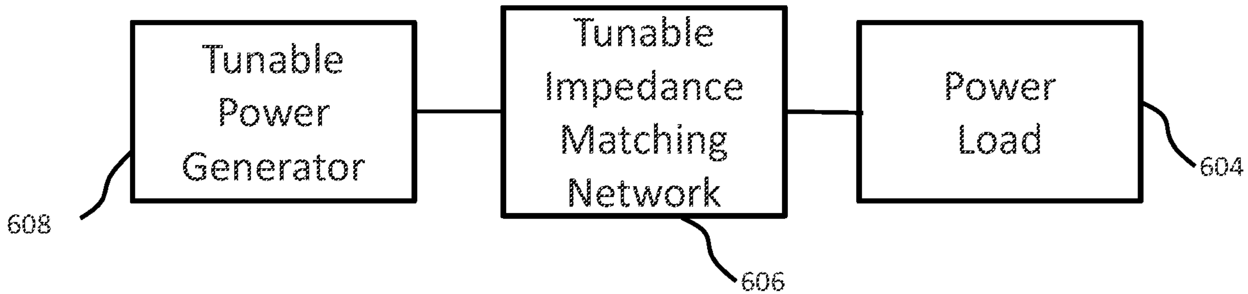


Fig. 7

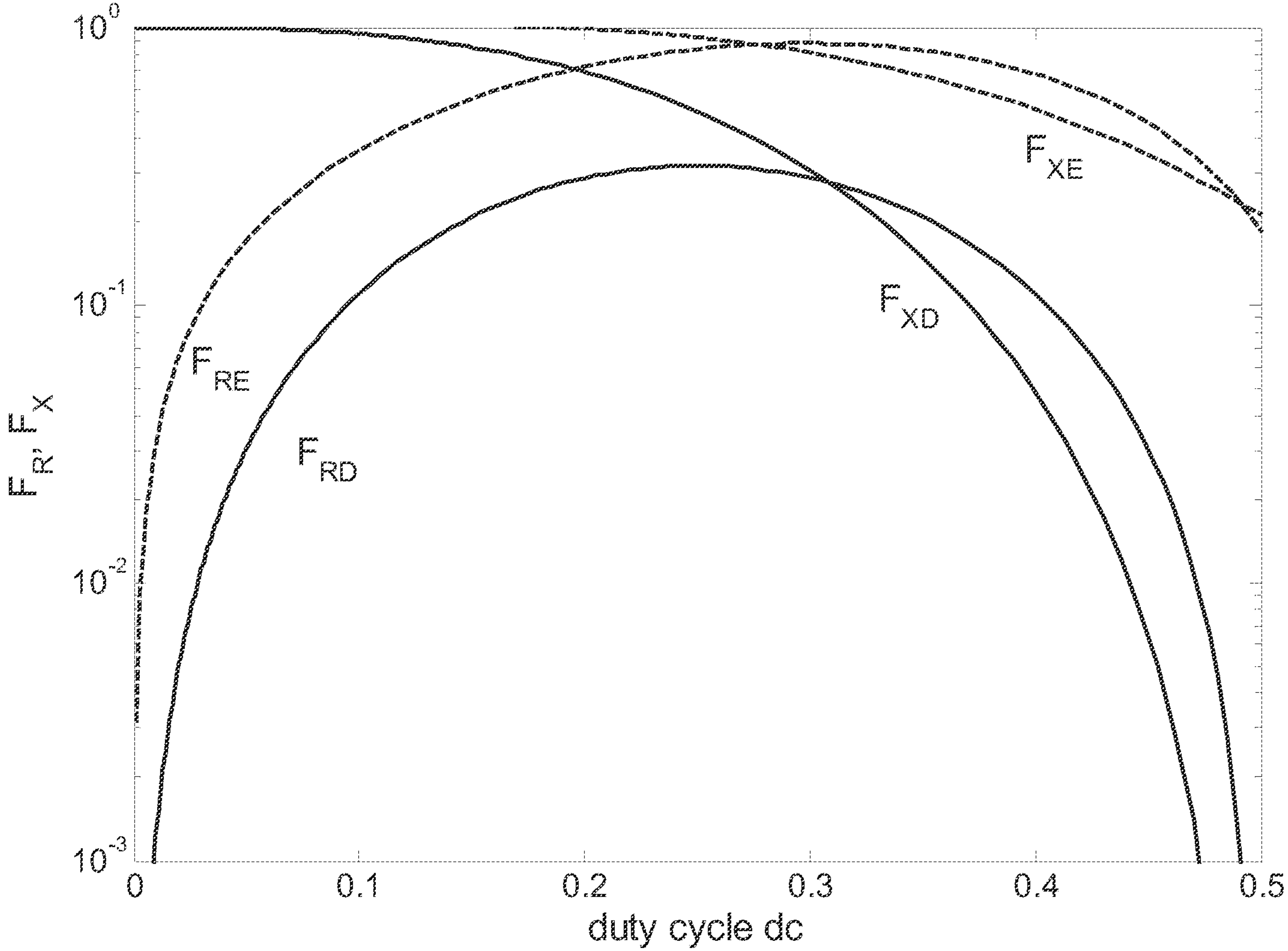

10^0
10^{-1}
10^{-2}
10^{-3}
F_R, F_X
0
0.1
0.2
0.3
0.4
0.5
duty cycle dc
F_{XE}
F_{XD}
F_{RE}
F_{RD}

Fig. 8

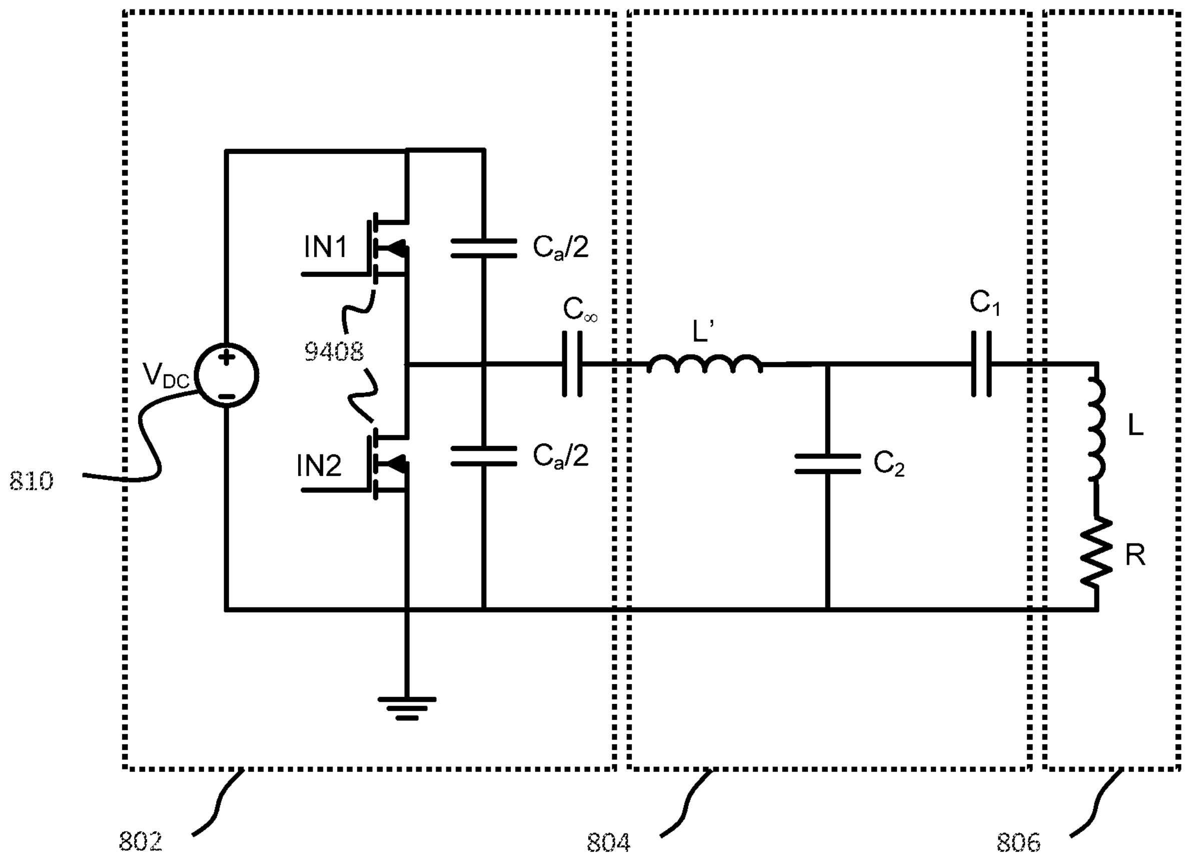


Fig. 9

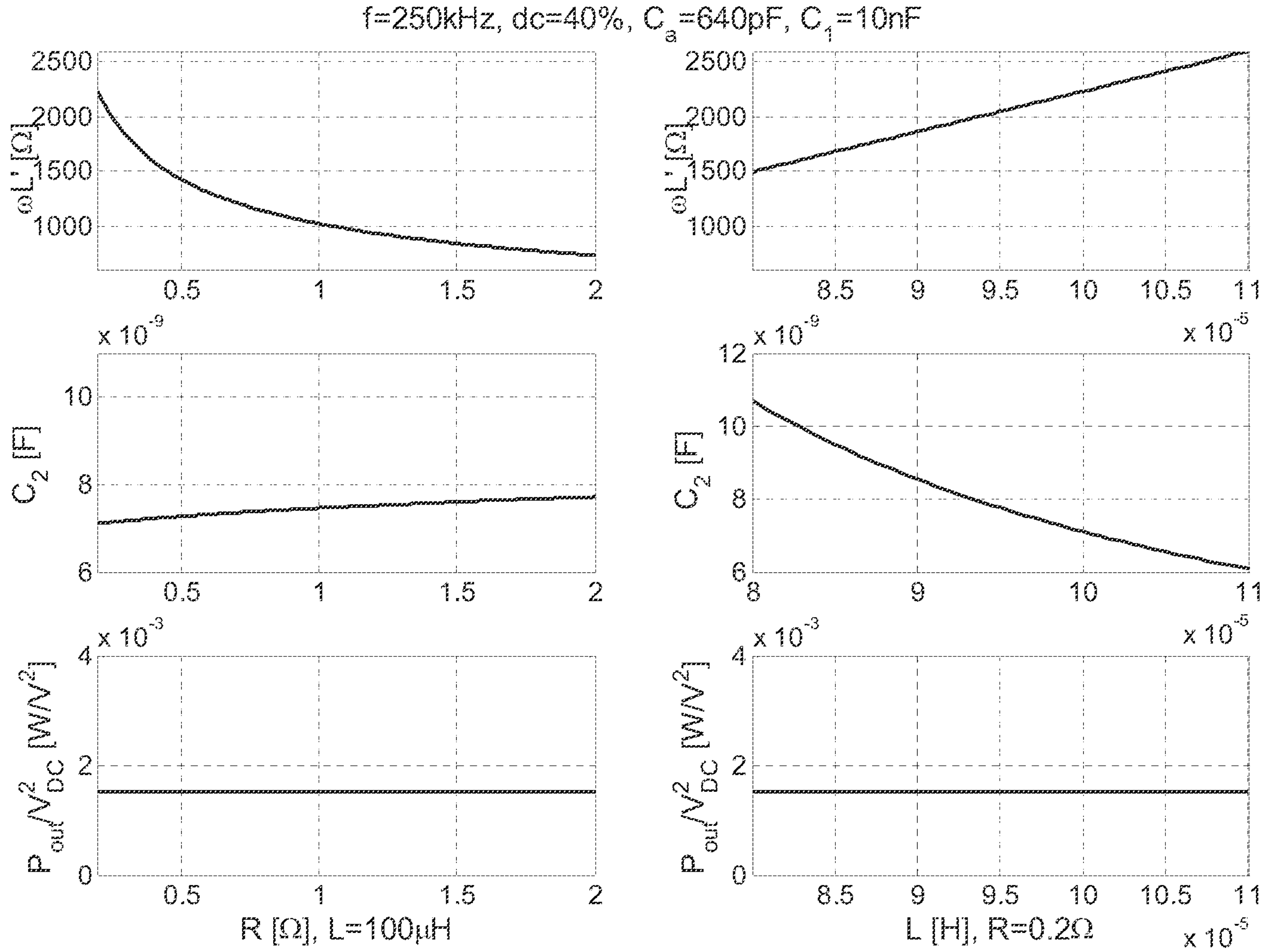

f=250kHz, dc=40%, Ca=640pF, C1=10nF
ωL' [Ω]
2500
2000
1500
1000
0.5
1
1.5
2
8.5
9
9.5
10
10.5
11
x 10^-9
x 10^-5
C2 [F]
12
10
8
6
Pout/V2DC [W/V2]
x 10^-3
4
2
0
R [Ω], L=100μH
L [H], R=0.2Ω

Fig. 10

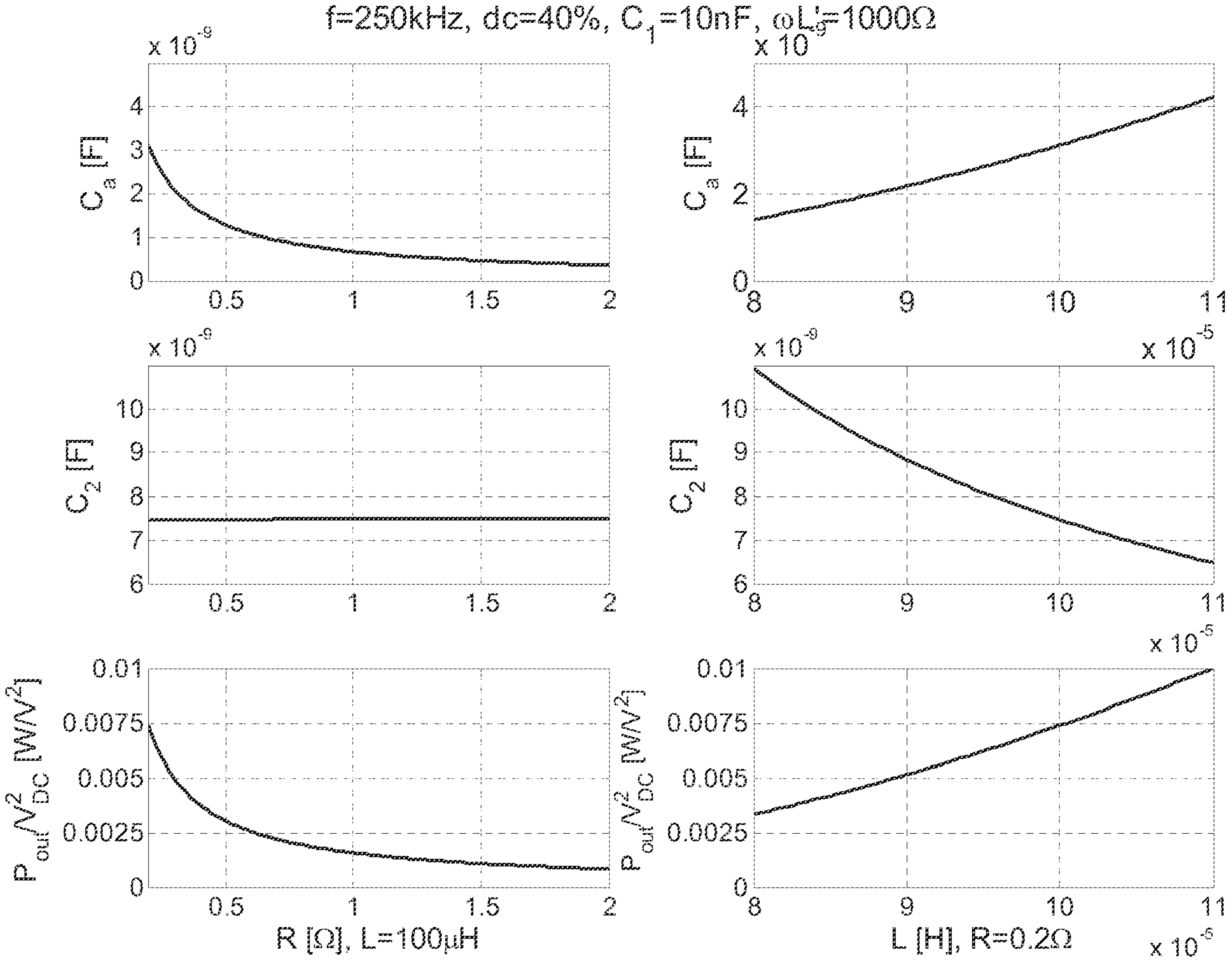
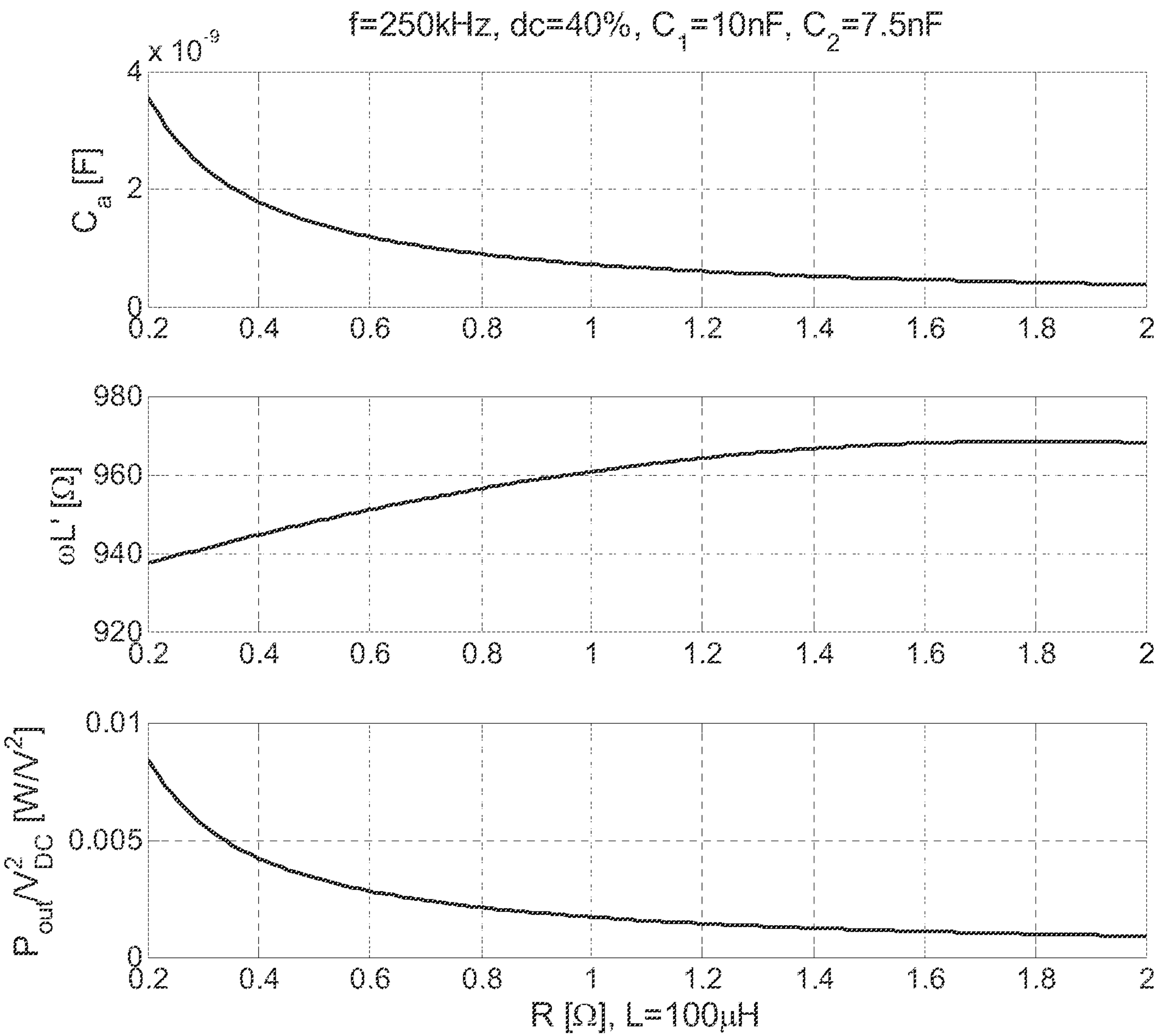

f=250kHz, dc=40%, C1=10nF, ωL'g=1000Ω
x 10-9
Ca [F]
C2 [F]
Pout/V2DC [W/V2]
R [Ω], L=100μH
L [H], R=0.2Ω
x 10-5

Fig. 11A



f=250kHz, dc=40%, C1=10nF, C2=7.5nF
x 10-9
4
2
0
Ca [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
Pout/V2DC [W/V2]
R [Ω], L=100μH

Fig. 11B

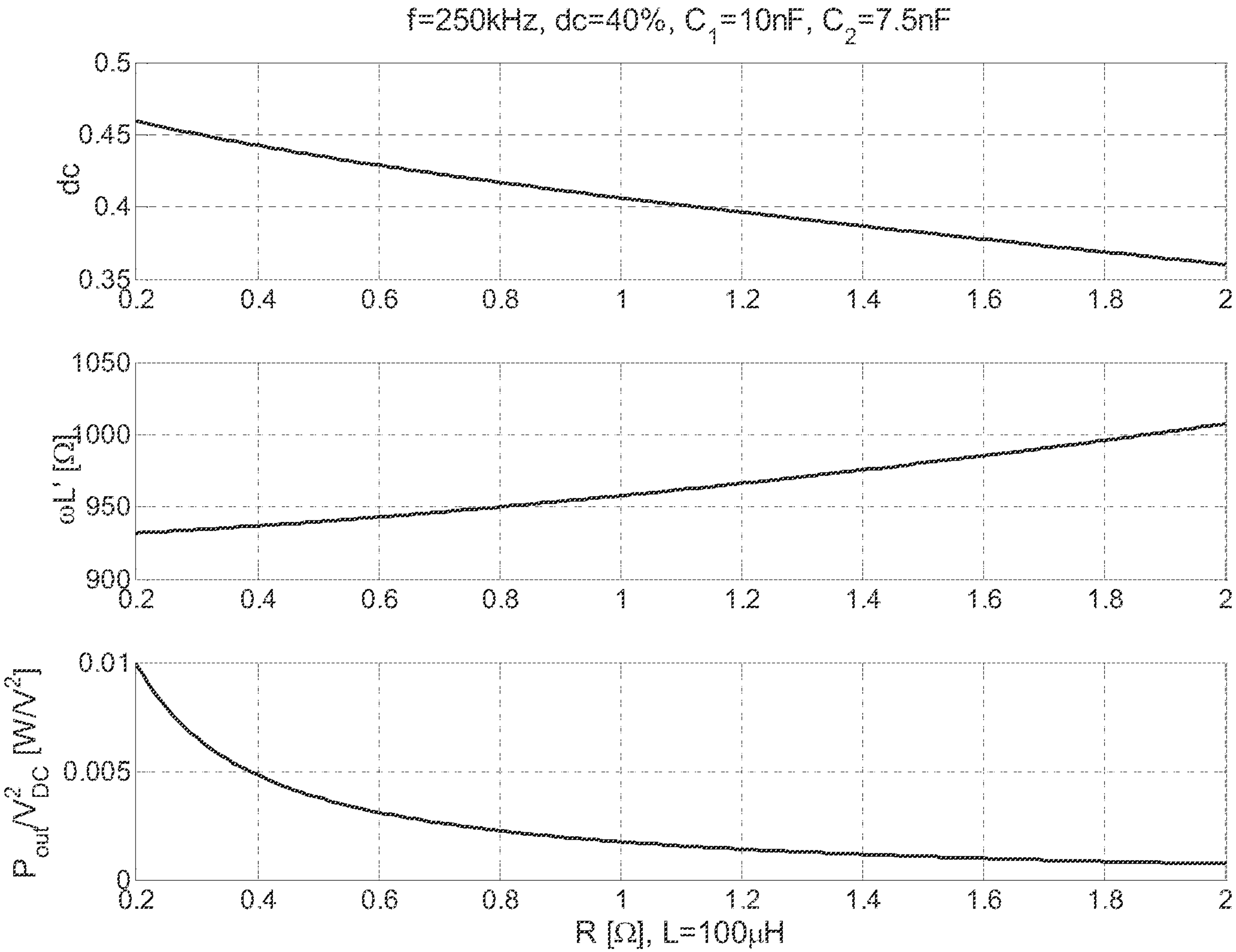

f=250kHz, dc=40%, C1=10nF, C2=7.5nF
0.5
0.45
0.4
0.35
dc
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
1050
1000
950
900
ωL' [Ω]
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0.01
0.005
0
Pout/V2DC [W/V2]
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
R [Ω], L=100μH

Fig. 11C

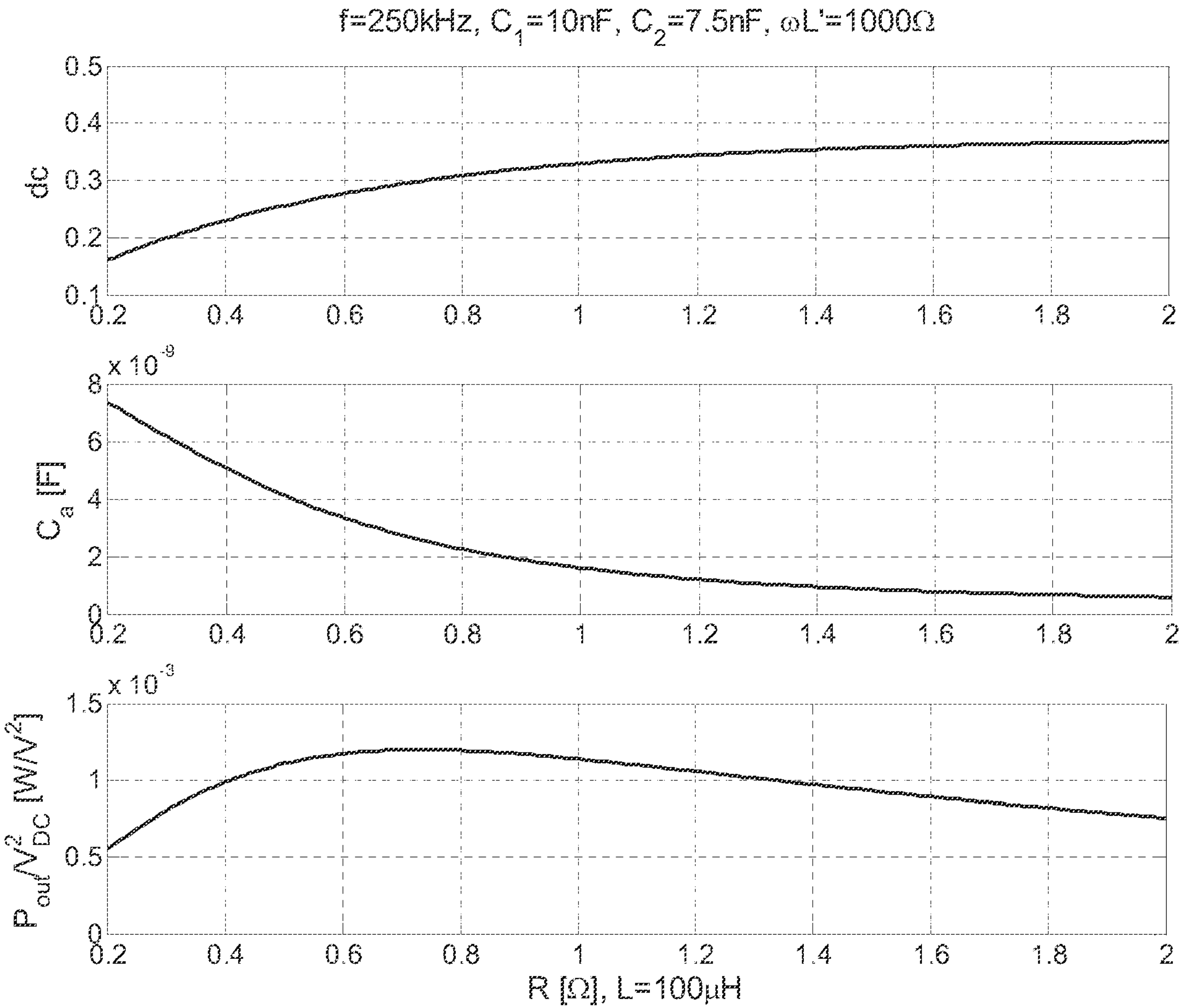

f=250kHz, C1=10nF, C2=7.5nF, ωL'=1000Ω
dc
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10-9
Ca [F]
8
6
4
2
0
x 10-3
Pout/V2DC [W/V2]
1.5
1
0.5
0
R [Ω], L=100μH

Fig. 12

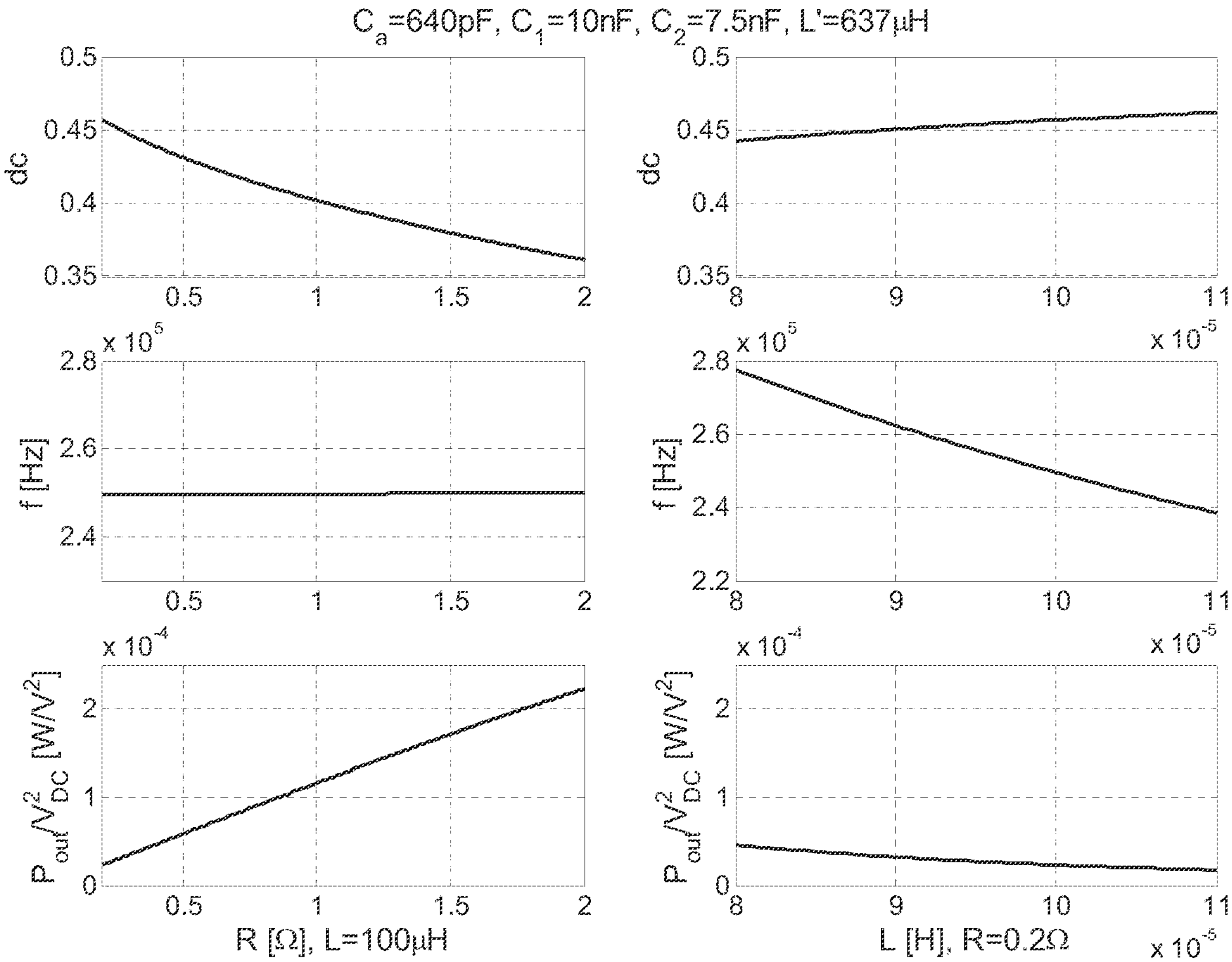

Ca=640pF, C1=10nF, C2=7.5nF, L'=637μH
dc
f [Hz]
x 10^5
x 10^-4
x 10^-5
Pout/V2DC [W/V2]
R [Ω], L=100μH
L [H], R=0.2Ω

Fig. 13

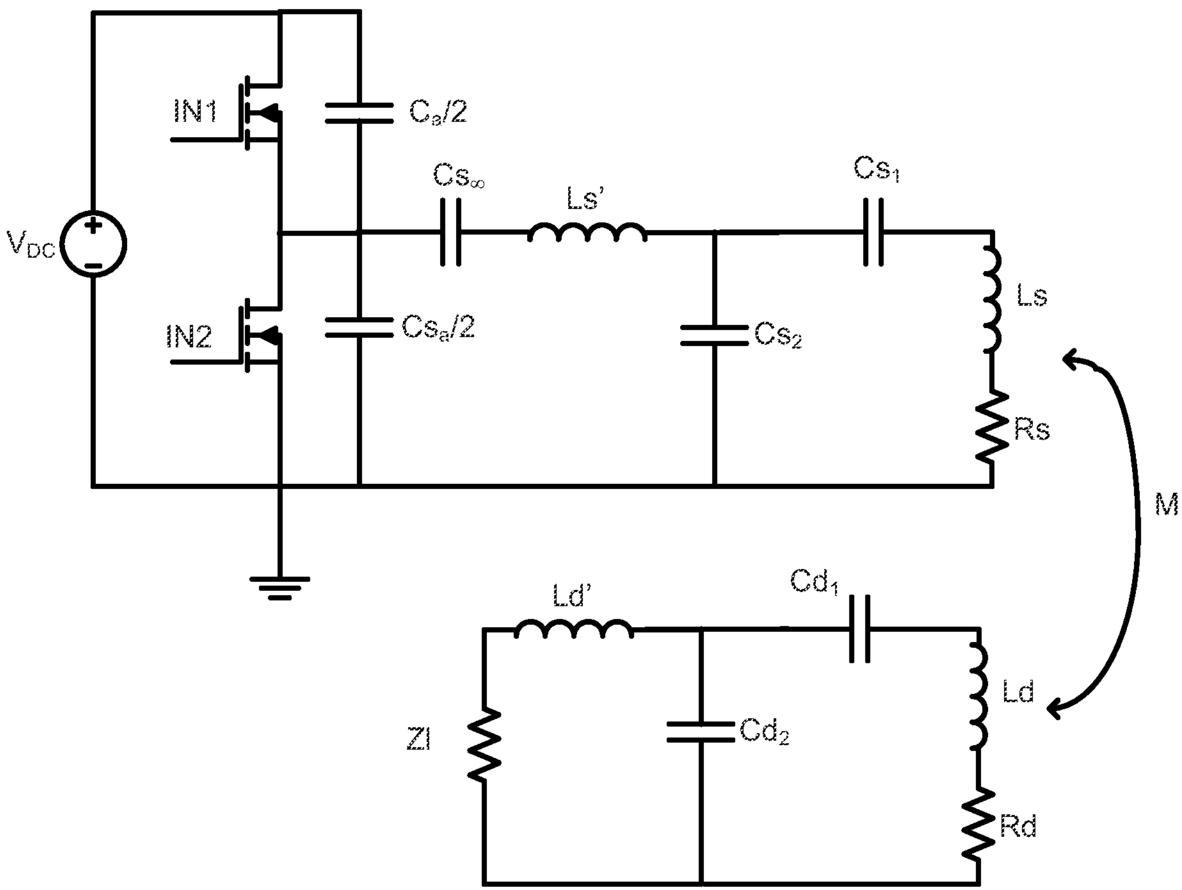
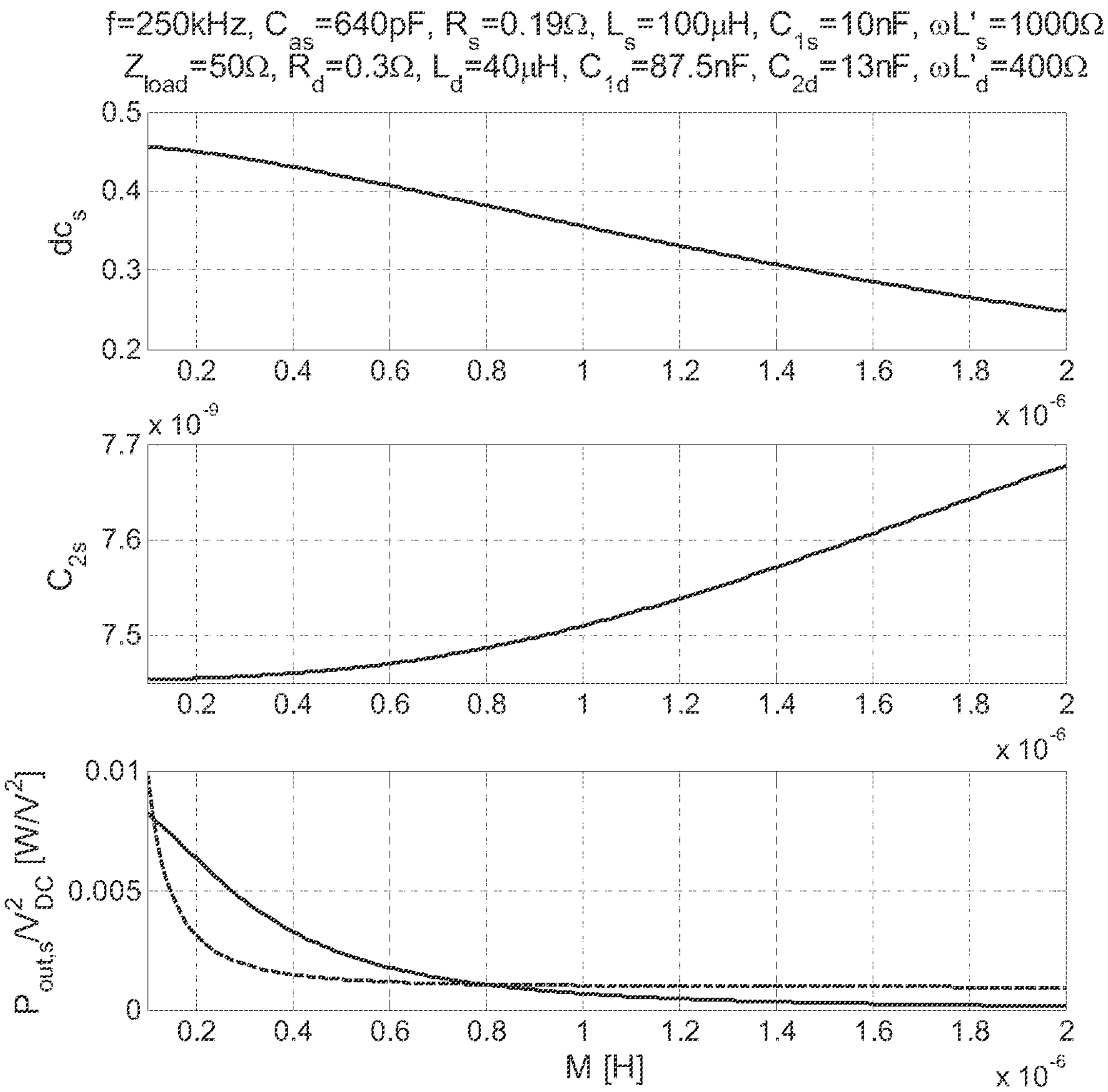
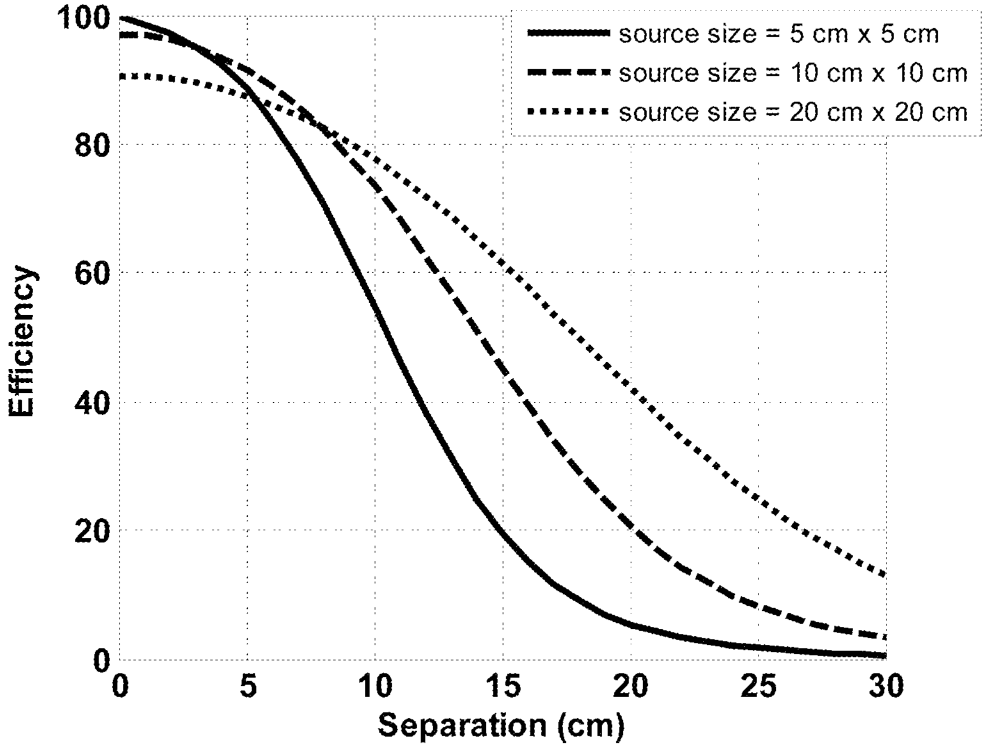


Fig. 14

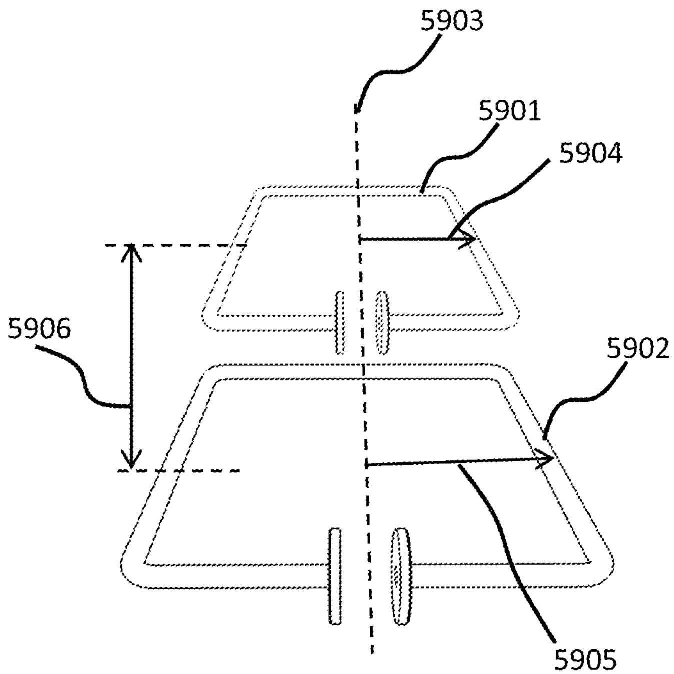


f=250kHz, C_as=640pF, R_s=0.19Ω, L_s=100µH, C_1s=10nF, ωL'_s=1000Ω
Z_load=50Ω, R_d=0.3Ω, L_d=40µH, C_1d=87.5nF, C_2d=13nF, ωL'_d=400Ω
dc_s
0.5
0.4
0.3
0.2
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
x 10^-6
C_2s
x 10^-9
7.7
7.6
7.5
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
x 10^-6
P_out,s/V²_DC [W/V²]
0.01
0.005
0
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
M [H]
x 10^-6

Fig. 15

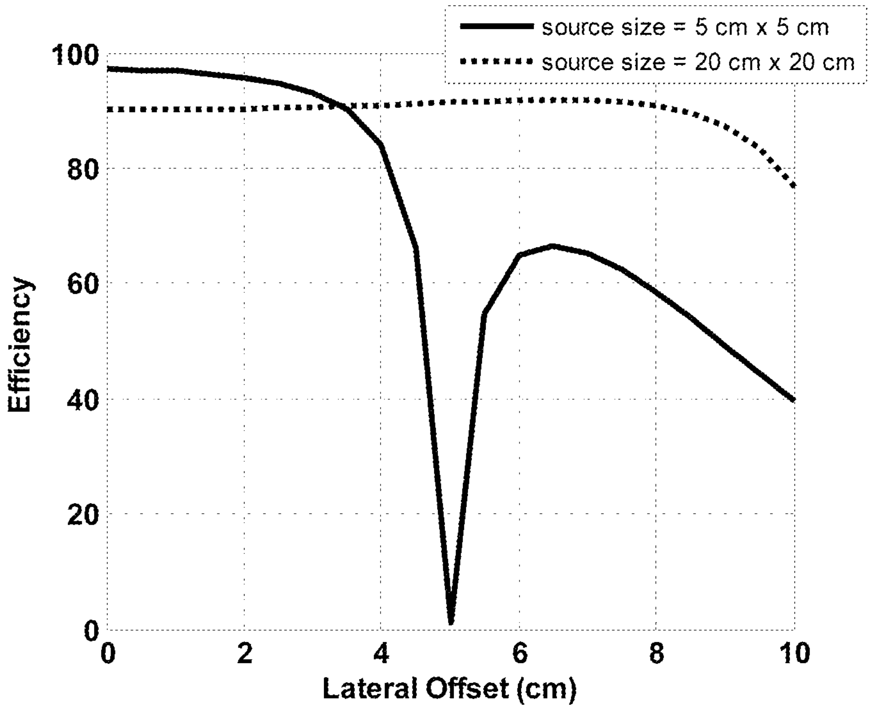

source size = 5 cm x 5 cm
source size = 10 cm x 10 cm
source size = 20 cm x 20 cm
Efficiency
100
80
60
40
20
0
0
5
10
15
20
25
30
Separation (cm)

(a)


5903
5901
5904
5906
5902
5905

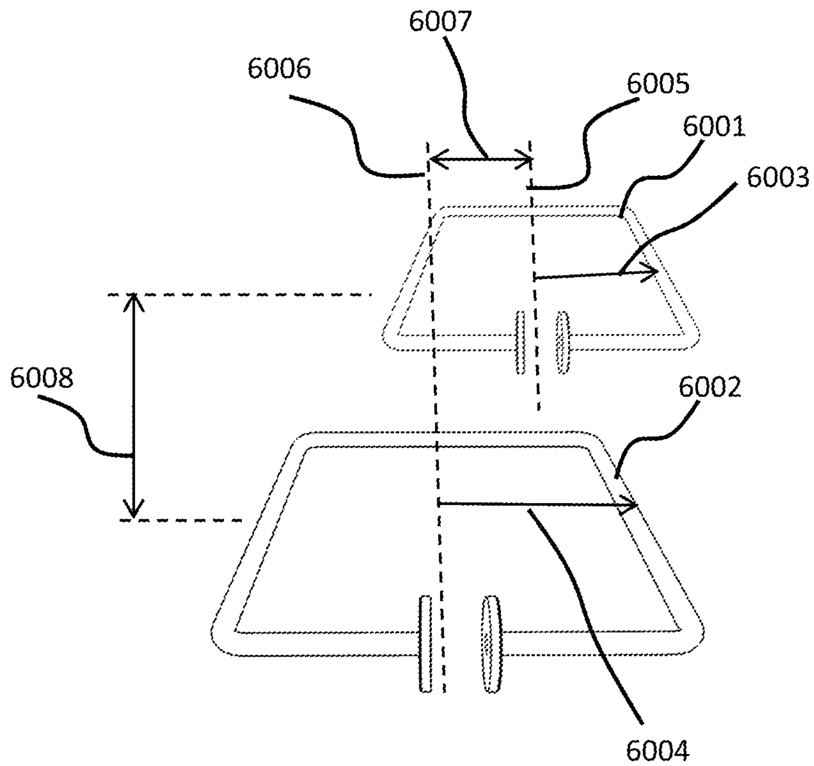
(b)

Fig. 16



source size = 5 cm x 5 cm
source size = 20 cm x 20 cm
100
80
60
40
20
0
Efficiency
0
2
4
6
8
10
Lateral Offset (cm)

(a)



6007
6006
6005
6001
6003
6008
6002
6004

(b)

Fig. 17

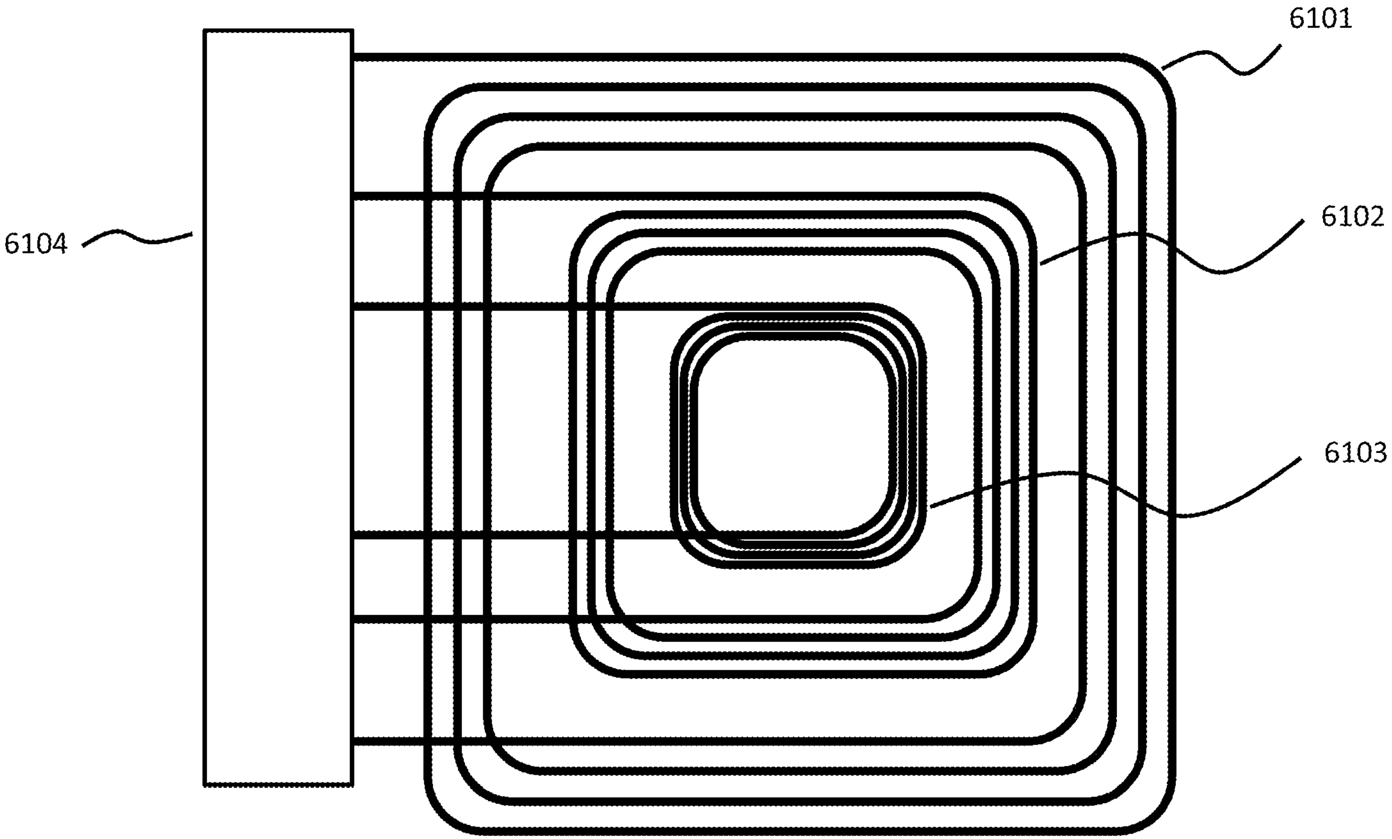


Fig. 18

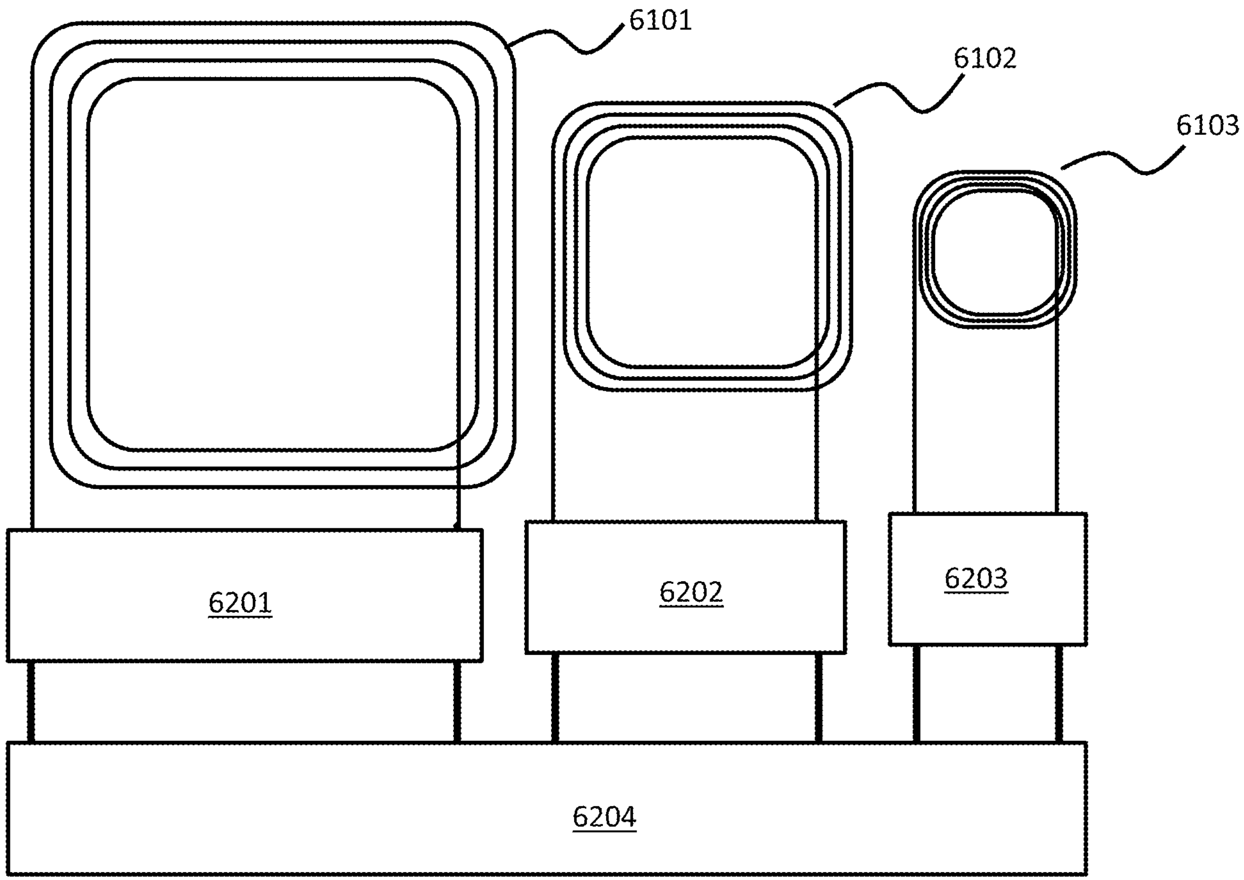


Fig.19

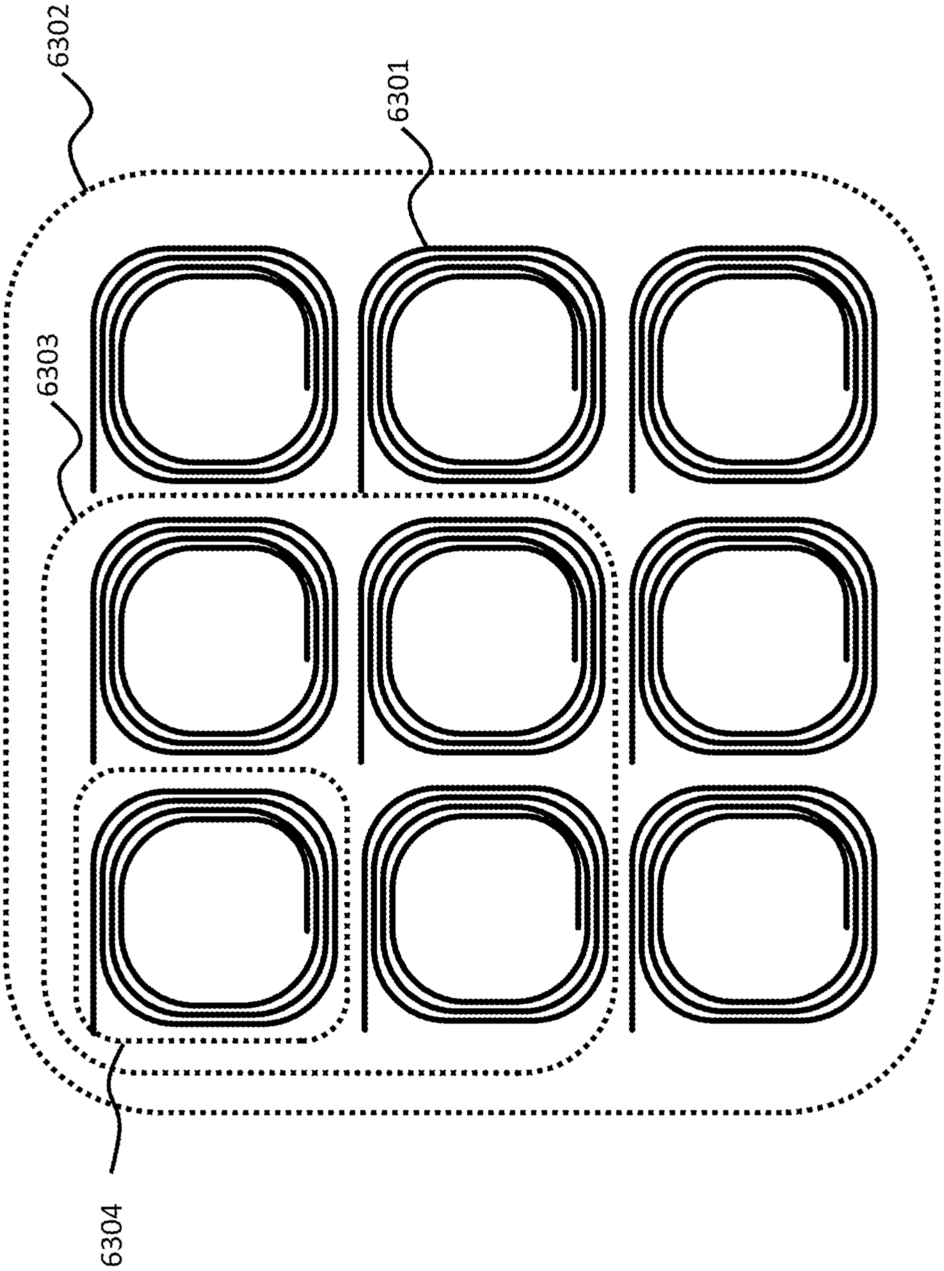


Fig.20

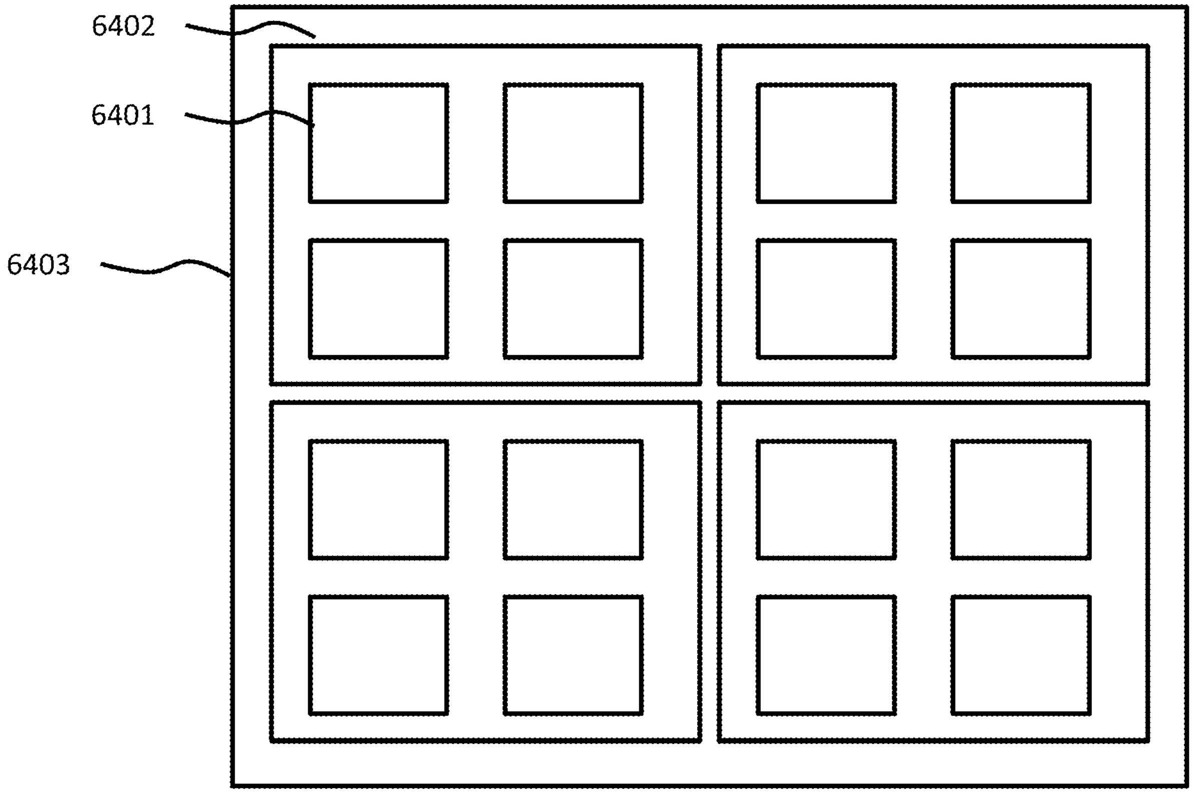


Fig. 21

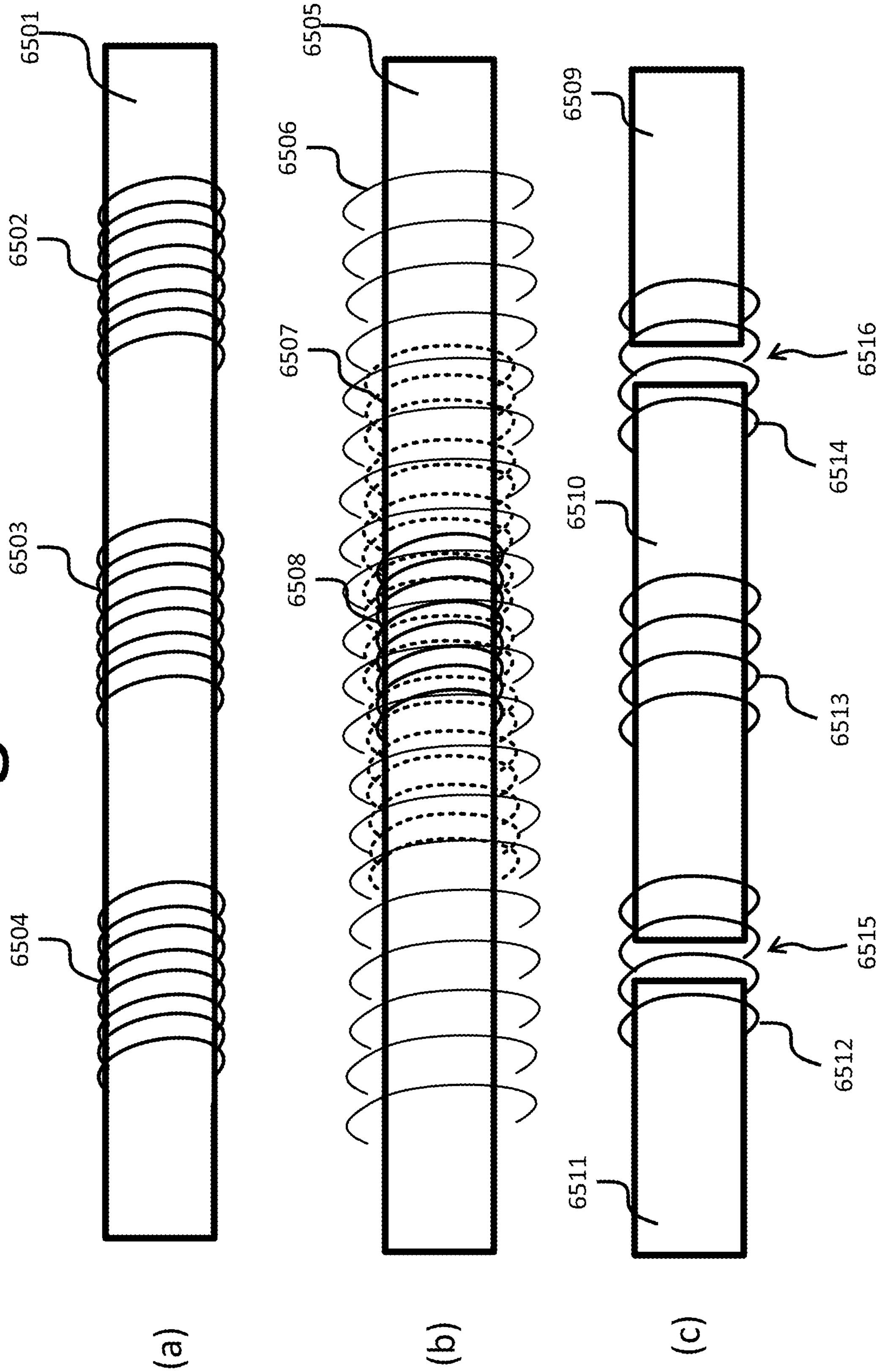

6501
6502
6503
6504
6505
6506
6507
6508
6509
6510
6511
6512
6513
6514
6515
6516
(a)
(b)
(c)

Fig. 22

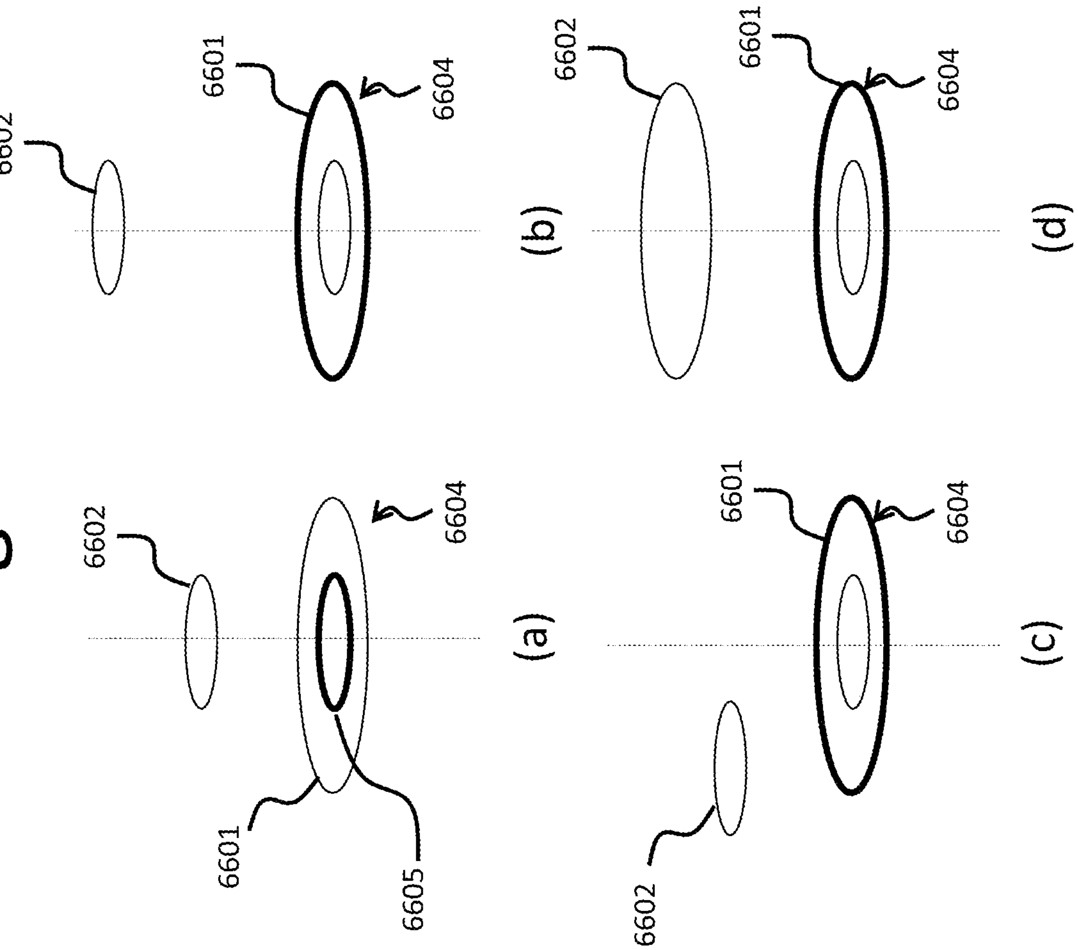

6602
6601
6605
6604
(a)
6602
6601
6604
(b)
6602
6601
6604
(c)
6602
6601
6604
(d)

Fig. 23

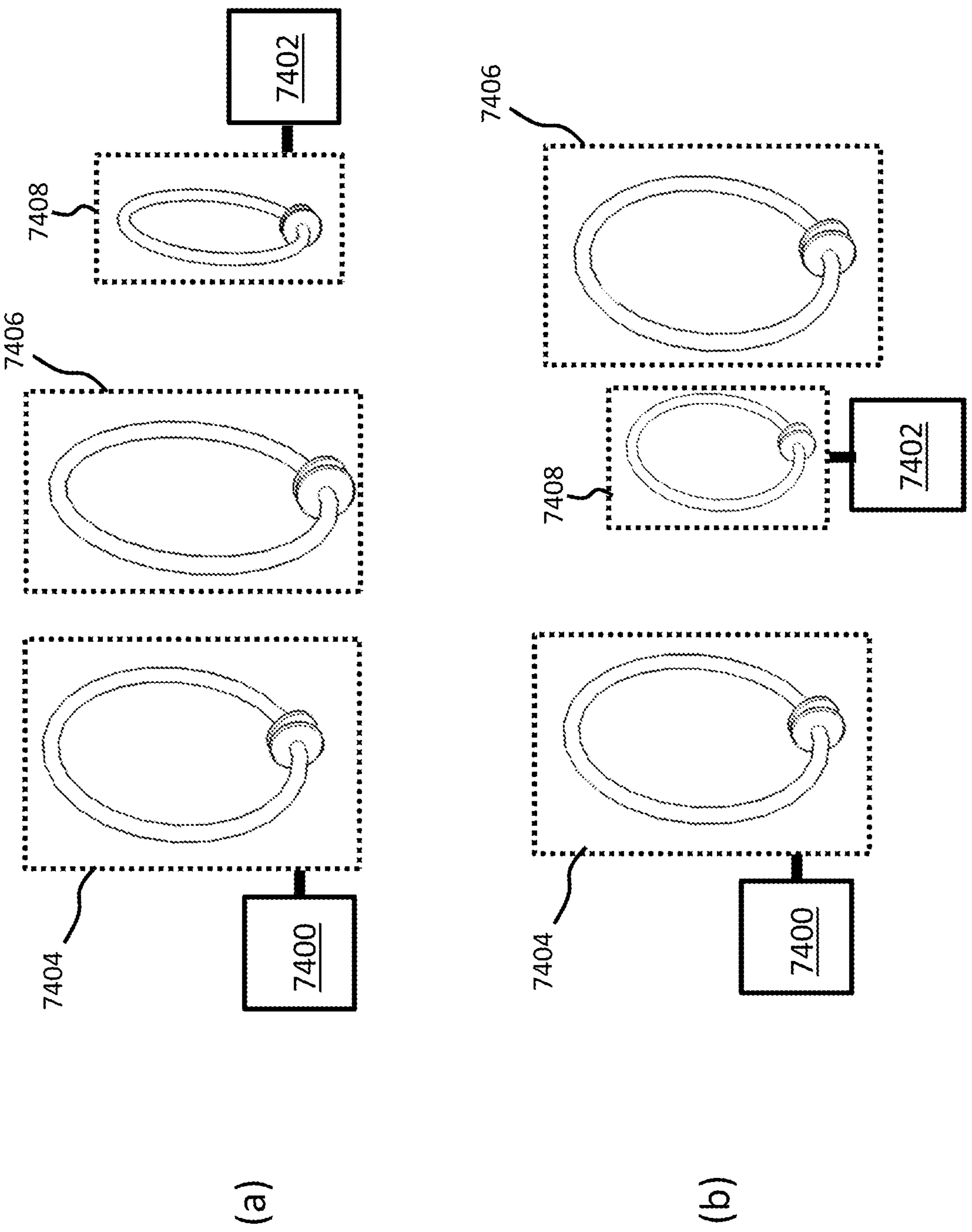


Fig. 24

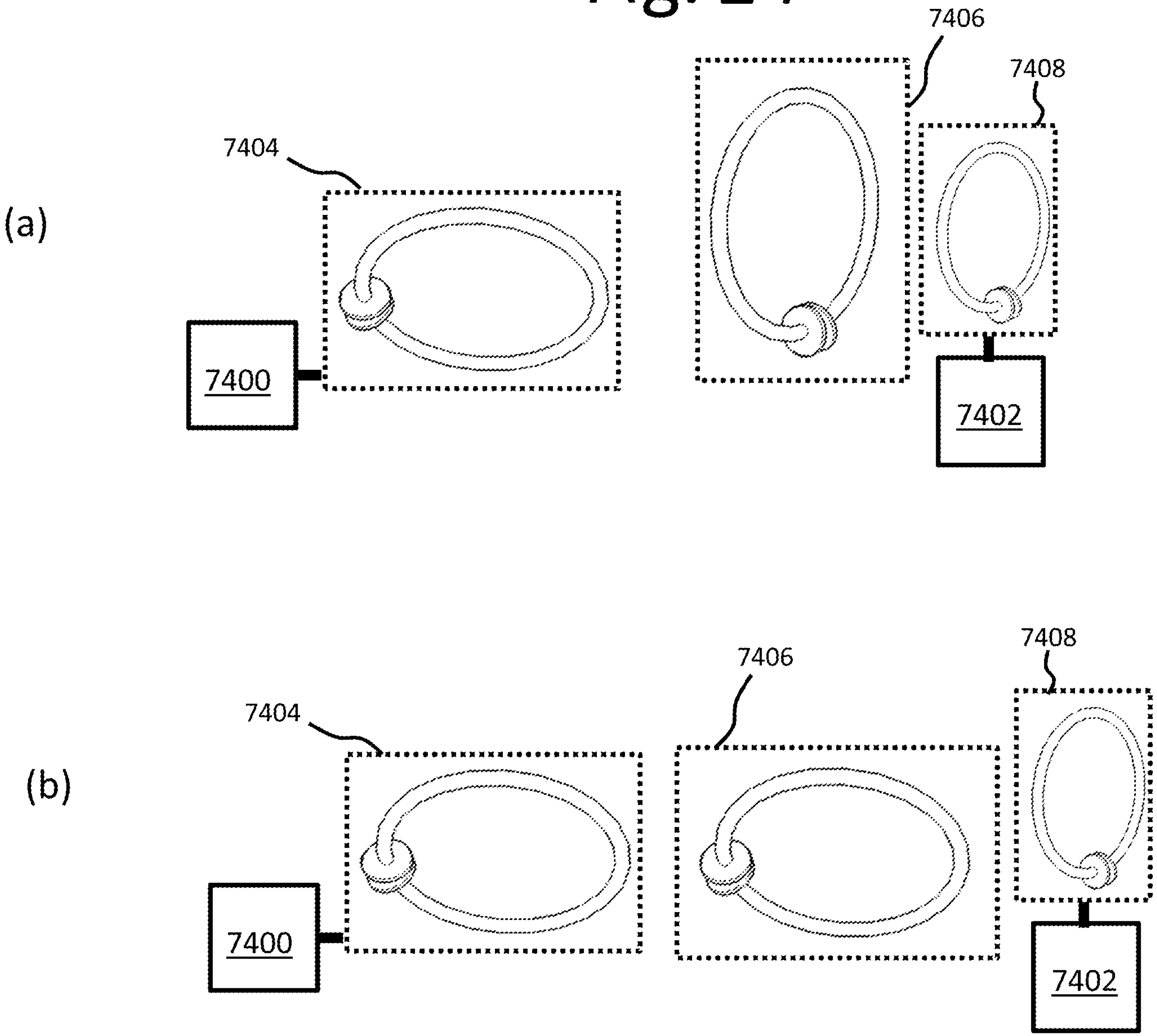
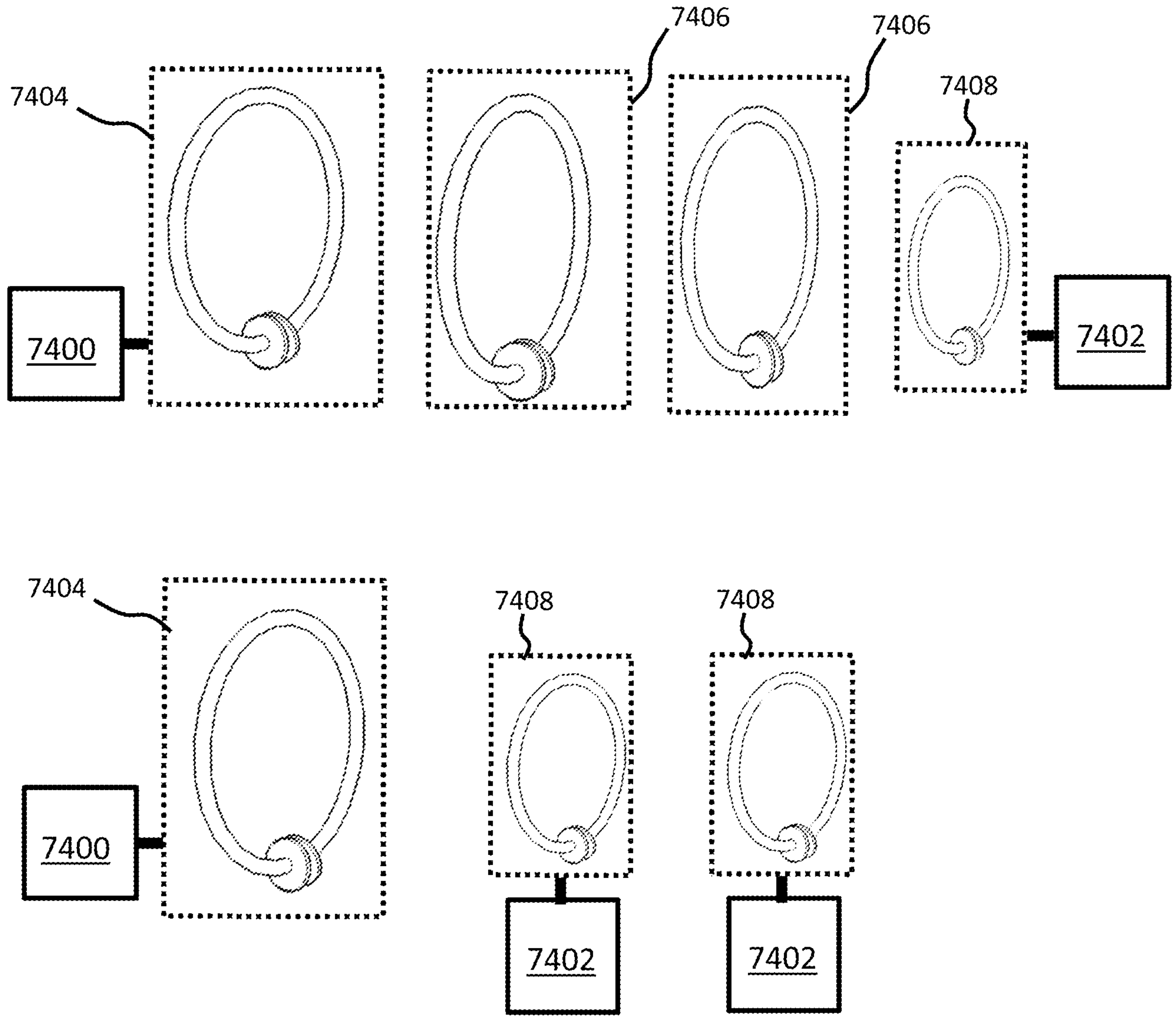


Fig. 25

(a)

(b)



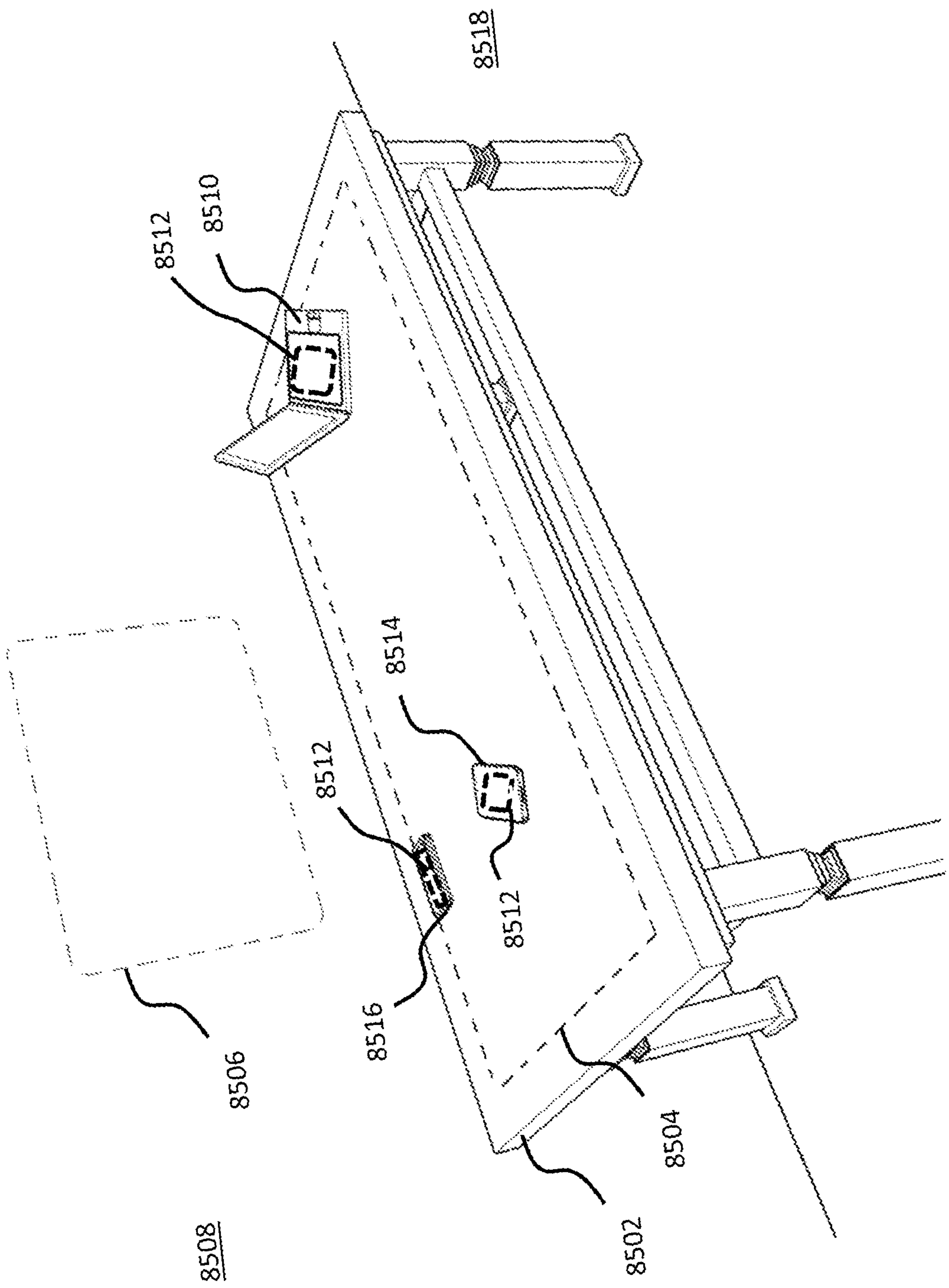


Fig. 26

Fig. 27

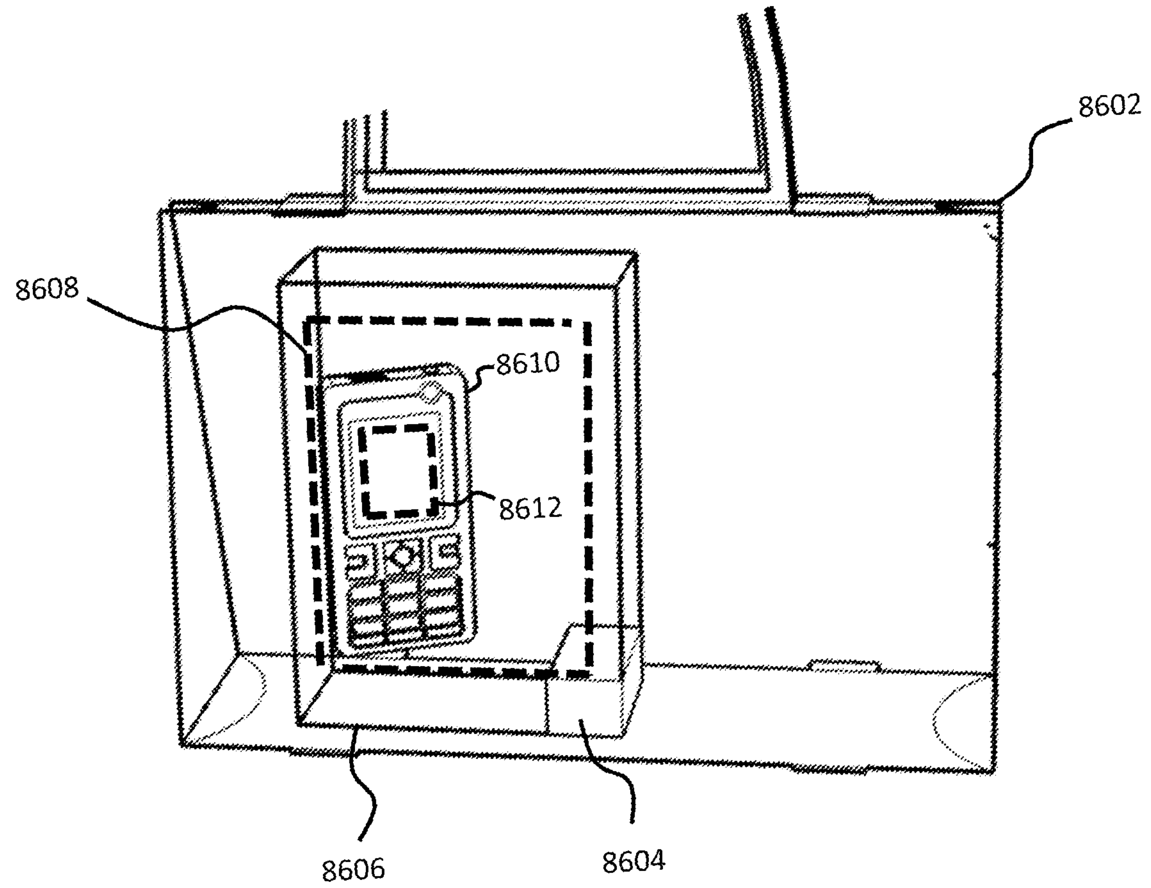


Fig. 28

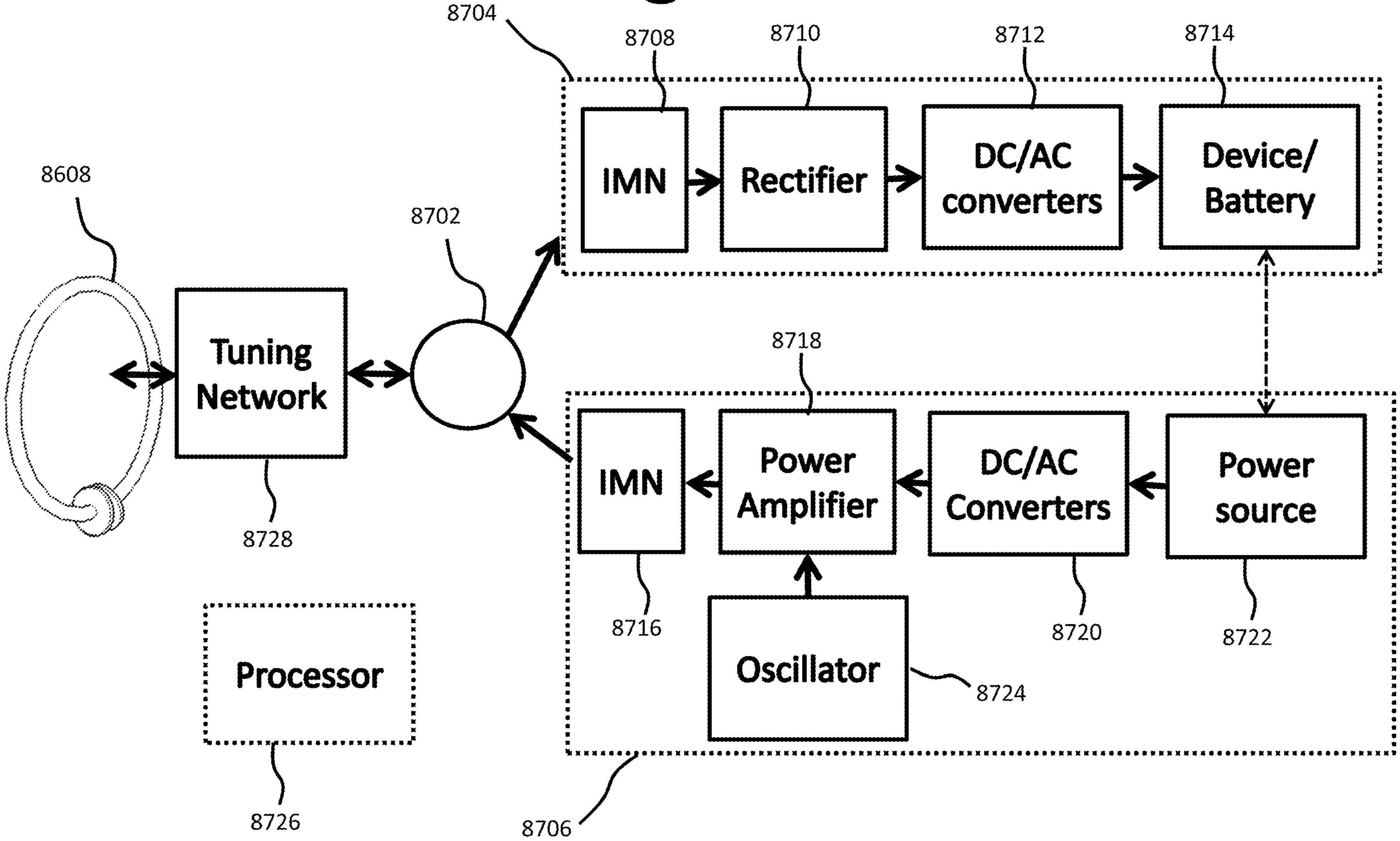

8704
8708
8710
8712
8714
IMN
Rectifier
DC/AC converters
Device/ Battery
8608
8702
Tuning Network
8718
IMN
Power Amplifier
DC/AC Converters
Power source
8728
8716
8720
8722
Oscillator
8724
Processor
8726
8706

Fig. 29

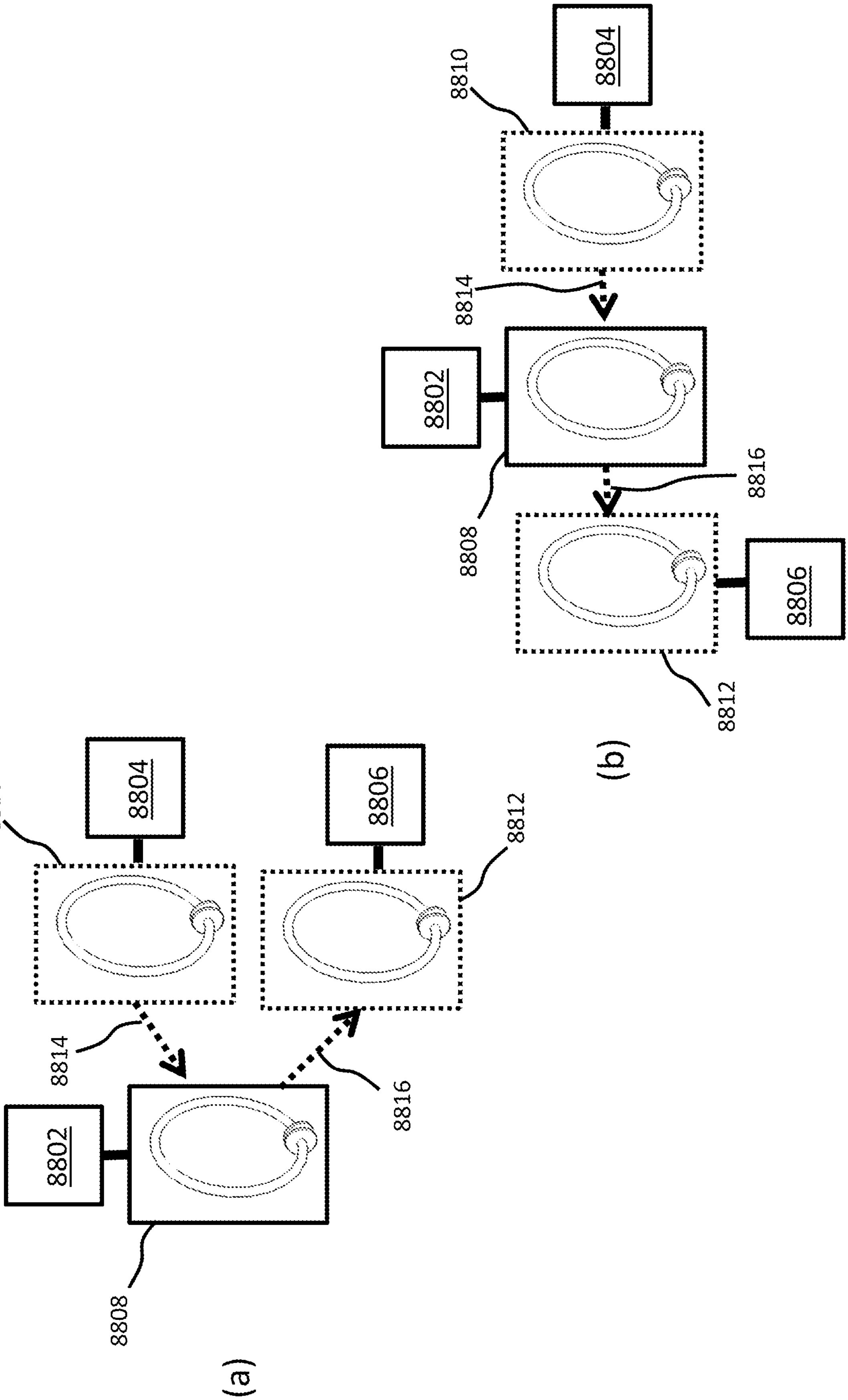


Fig. 30

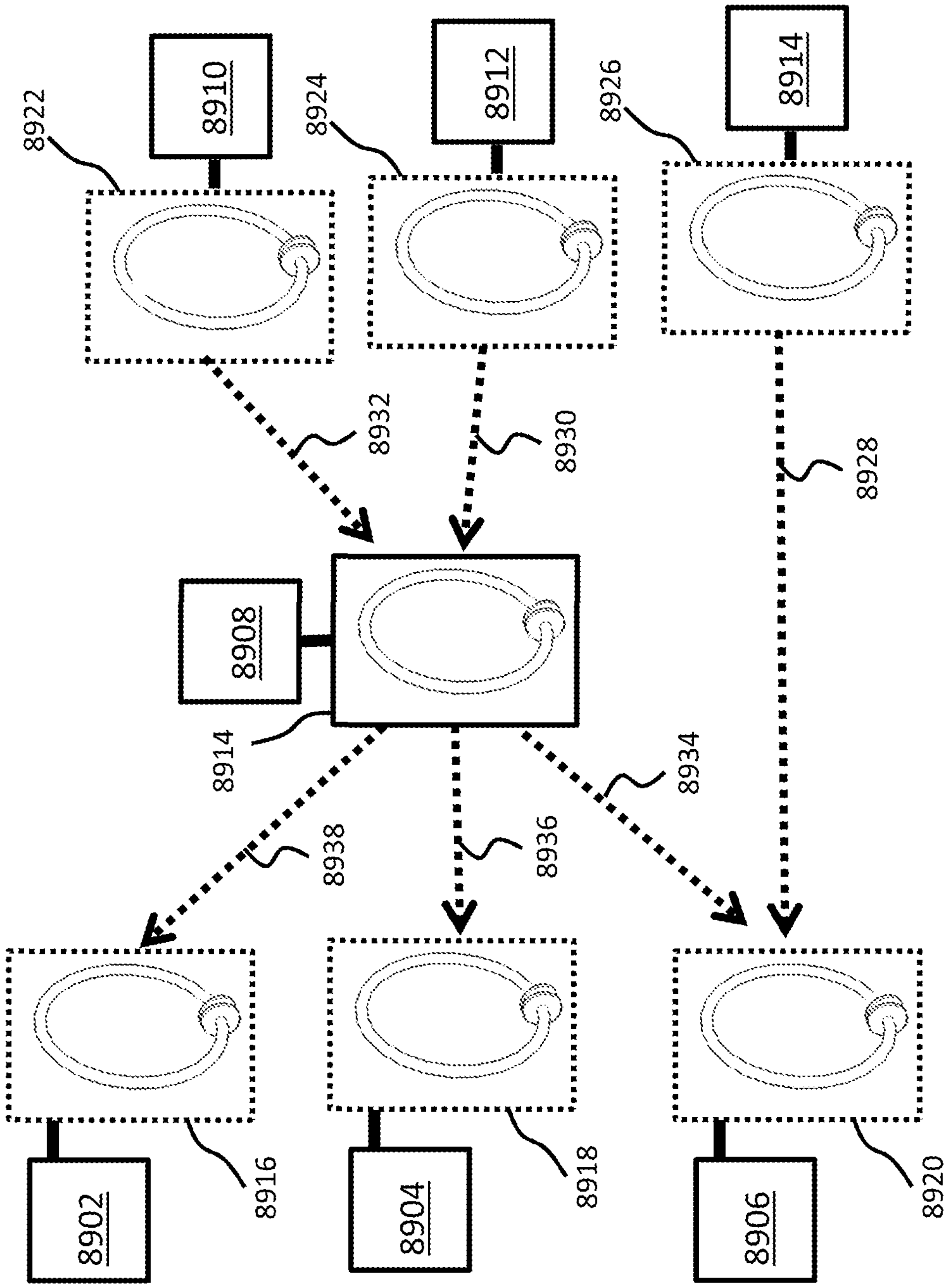

8910
8912
8914
8922
8924
8926
8932
8930
8928
8908
8914
8934
8936
8938
8902
8904
8906
8916
8918
8920

Fig. 31

(a)

(b)

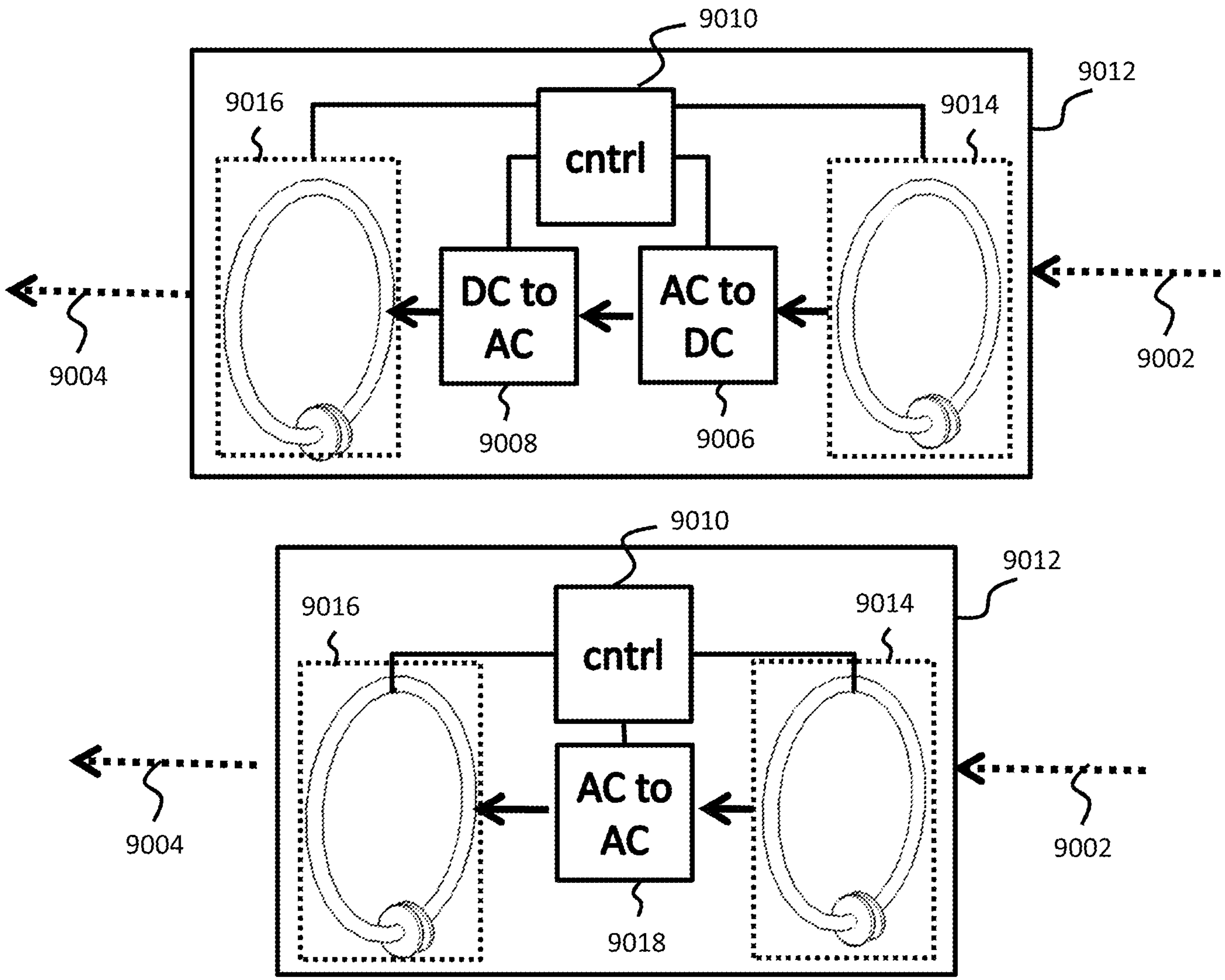

9010
9012
9016
9014
cntrl
DC to AC
AC to DC
9004
9002
9008
9006
9010
9012
9016
9014
cntrl
AC to AC
9004
9002
9018

Fig. 32

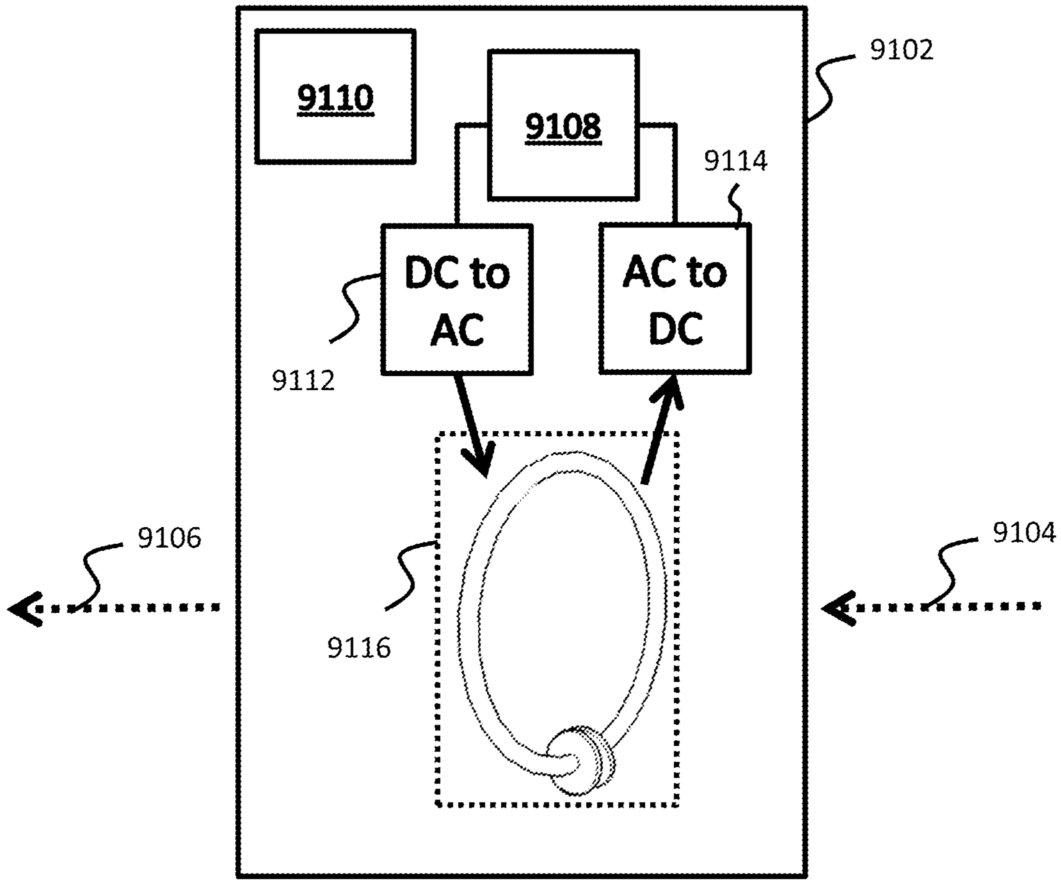
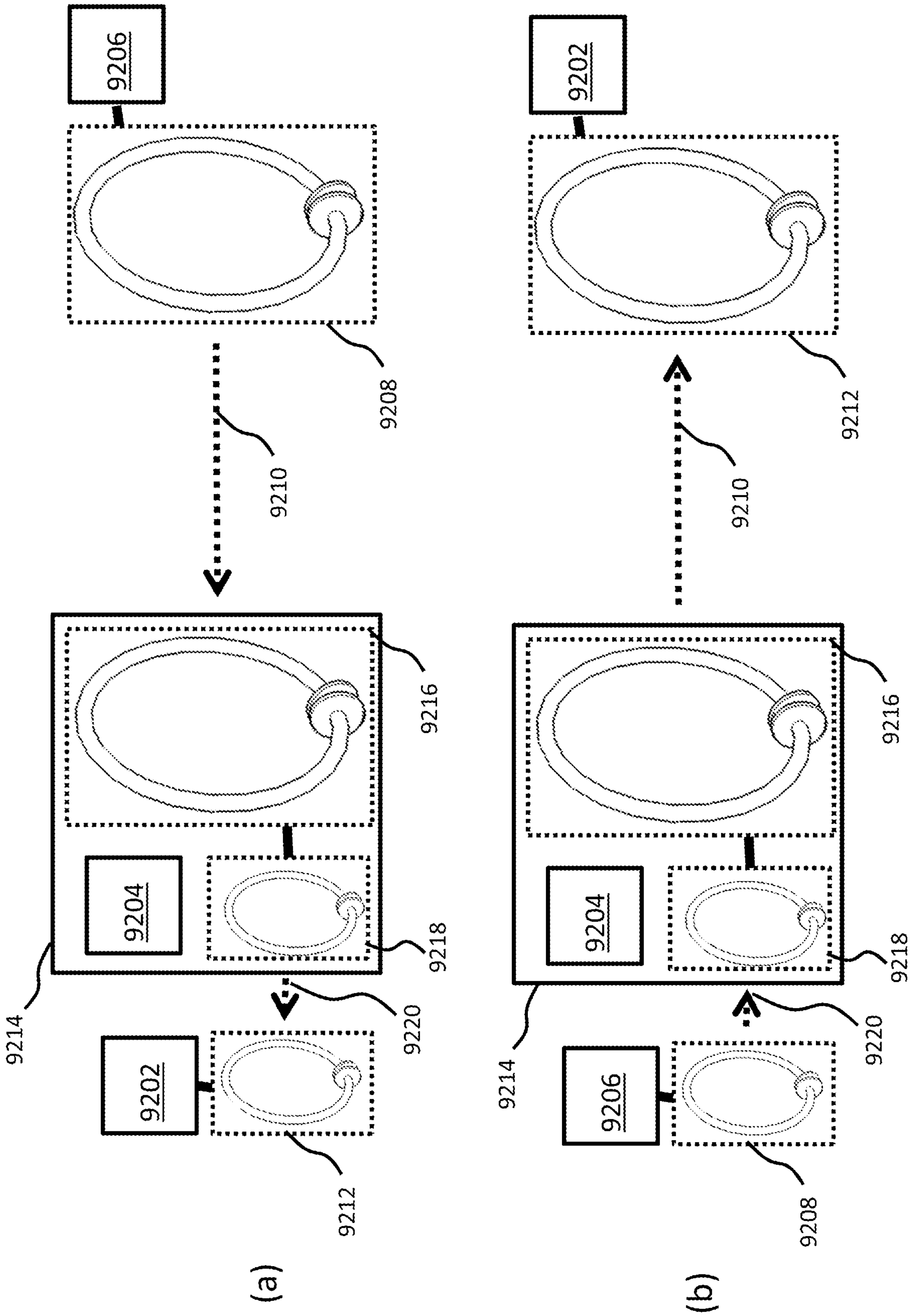


Fig. 33


(a)
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9216
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9218
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9212
(b)
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9206
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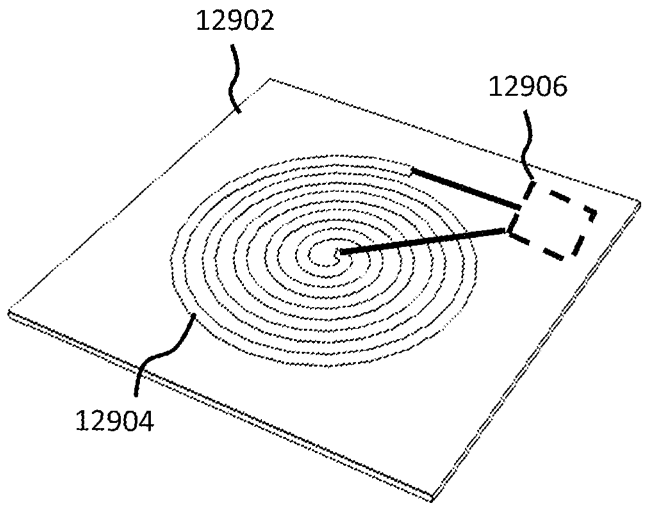


Fig. 34a

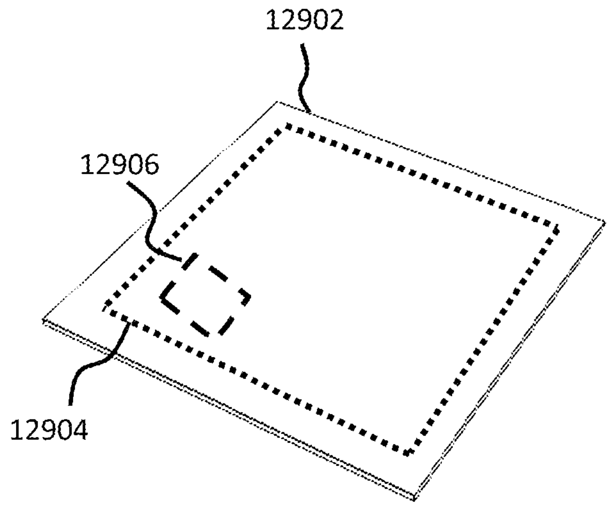


Fig. 34b

Fig. 35

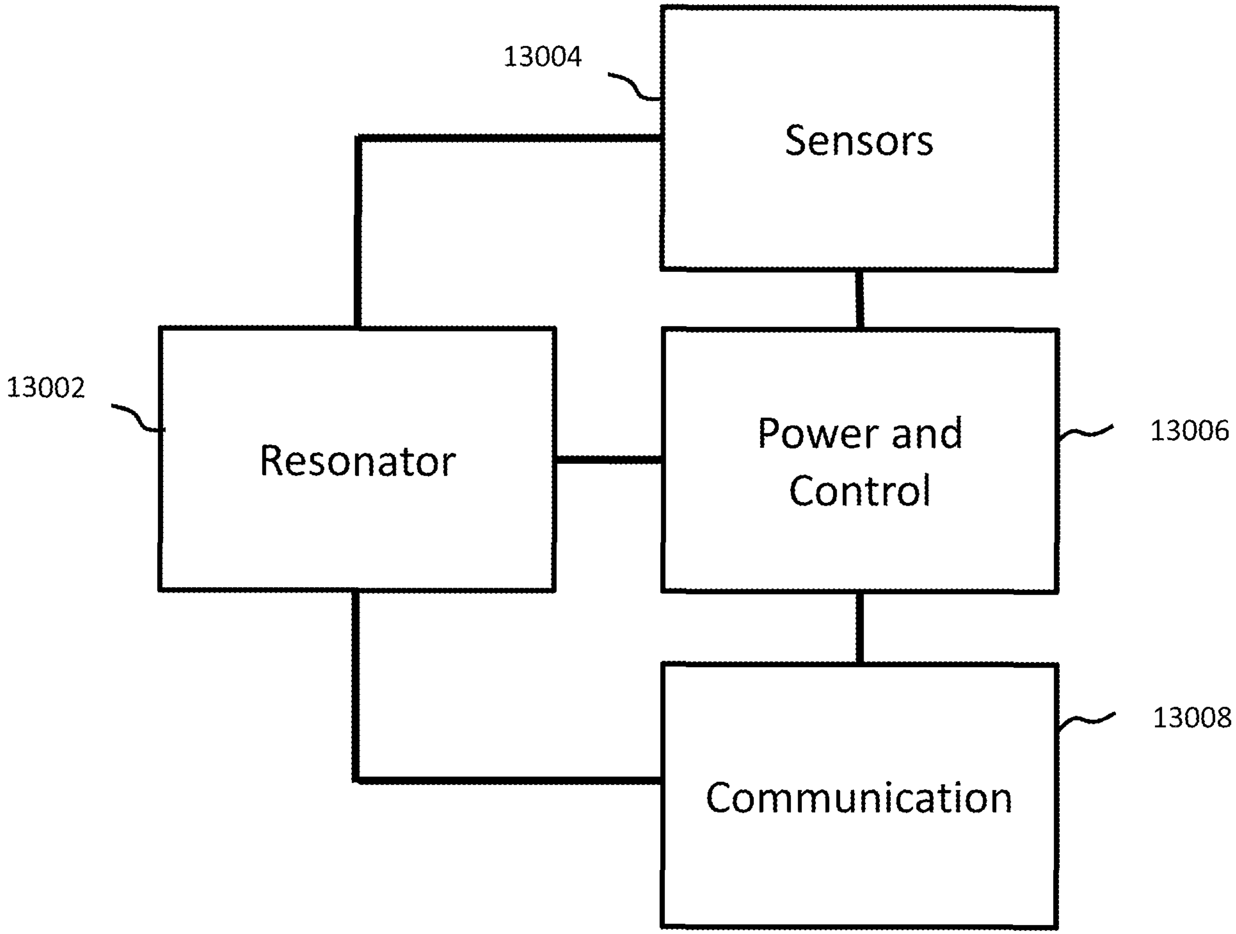
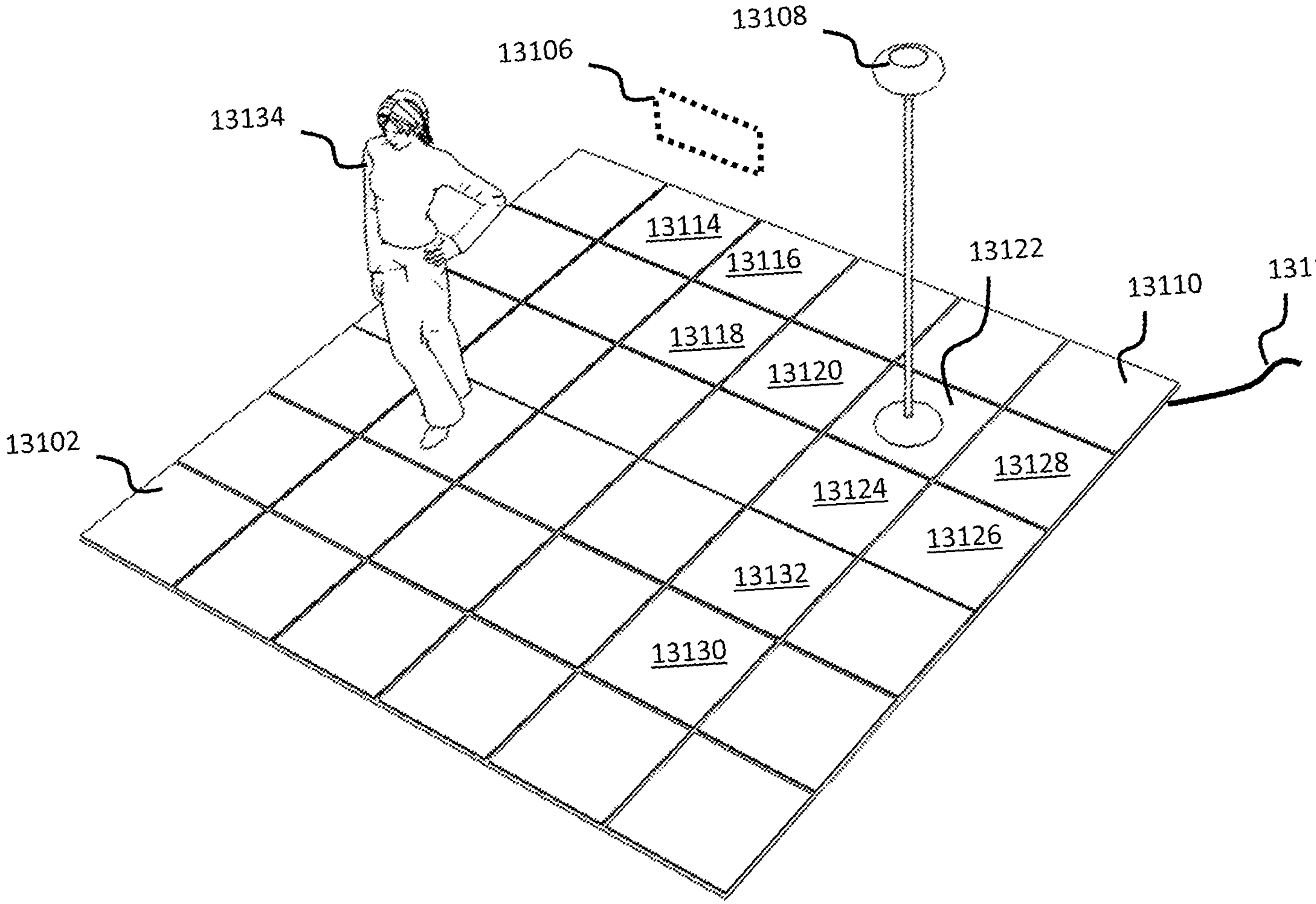

13004
Sensors
13002
Resonator
Power and Control
13006
13008
Communication

Fig. 36



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13106
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13114
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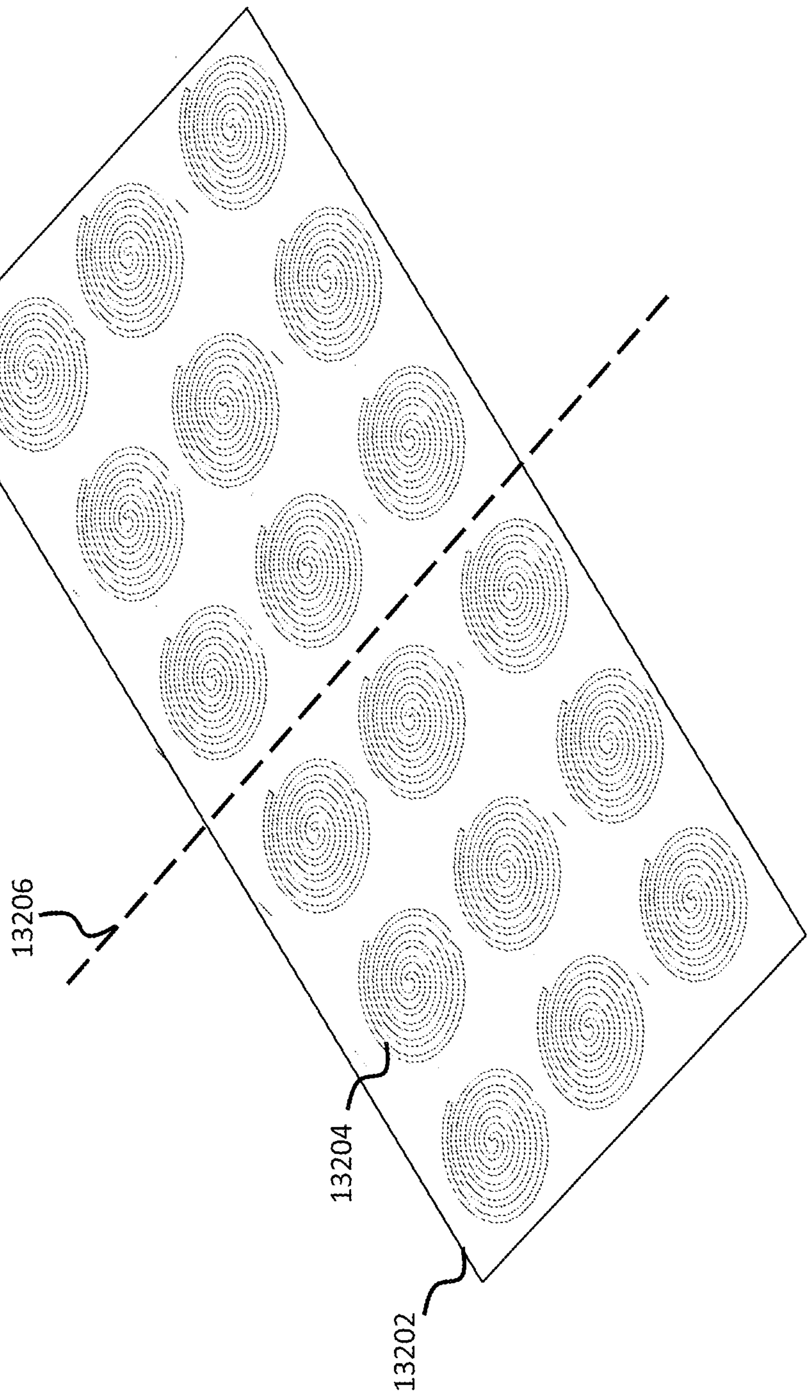
13130

Fig. 37



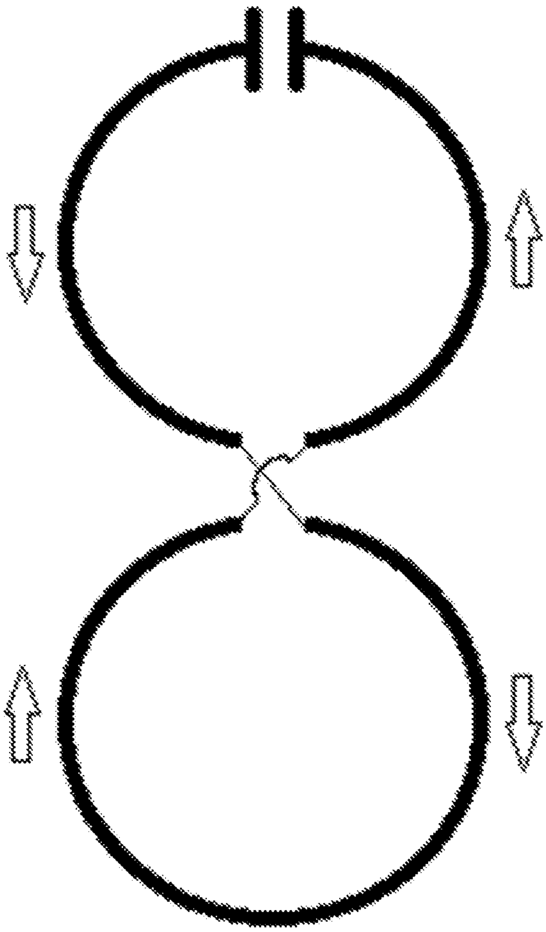


Fig. 38

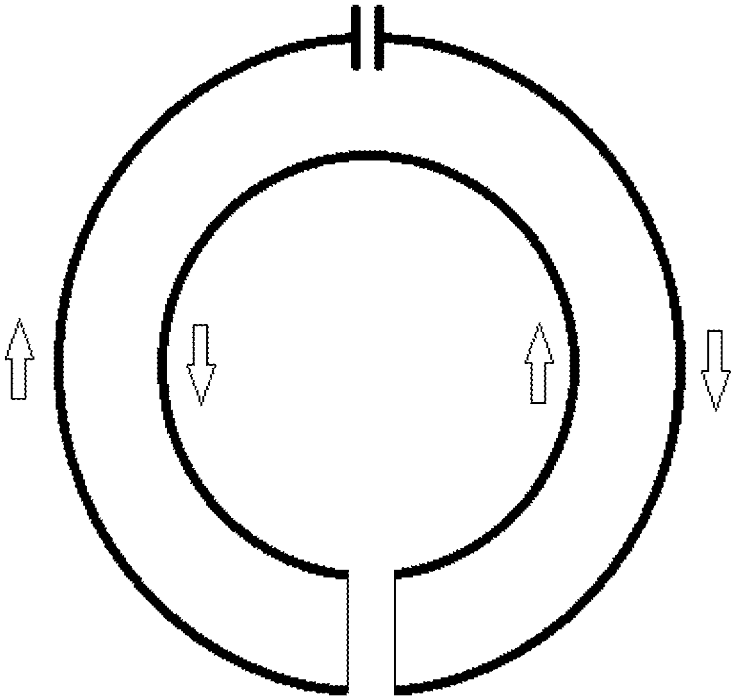


Fig. 39

Fig. 40

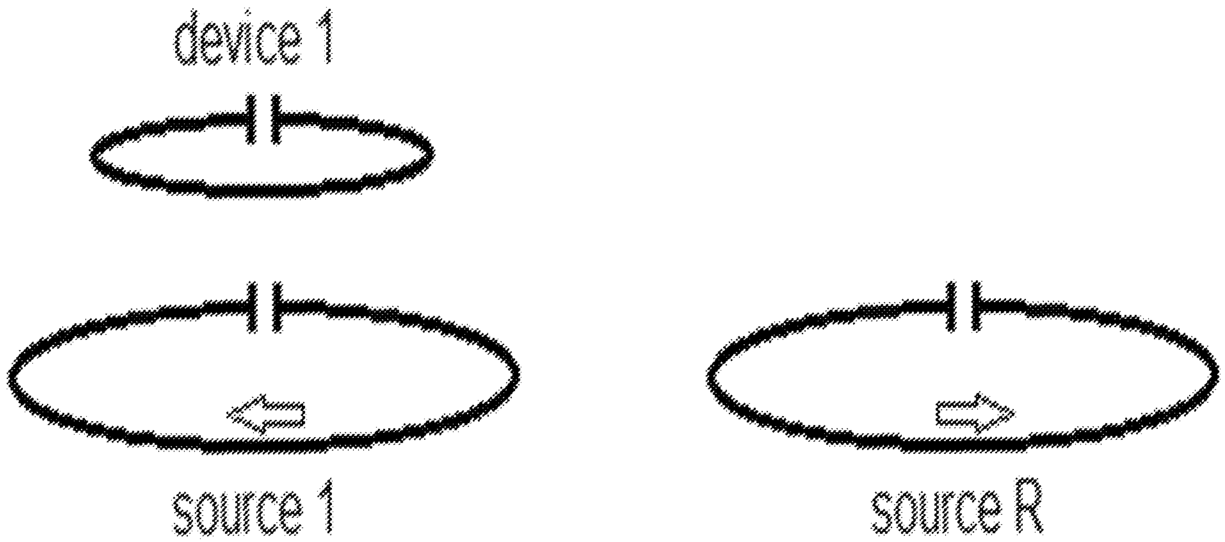


Fig. 41

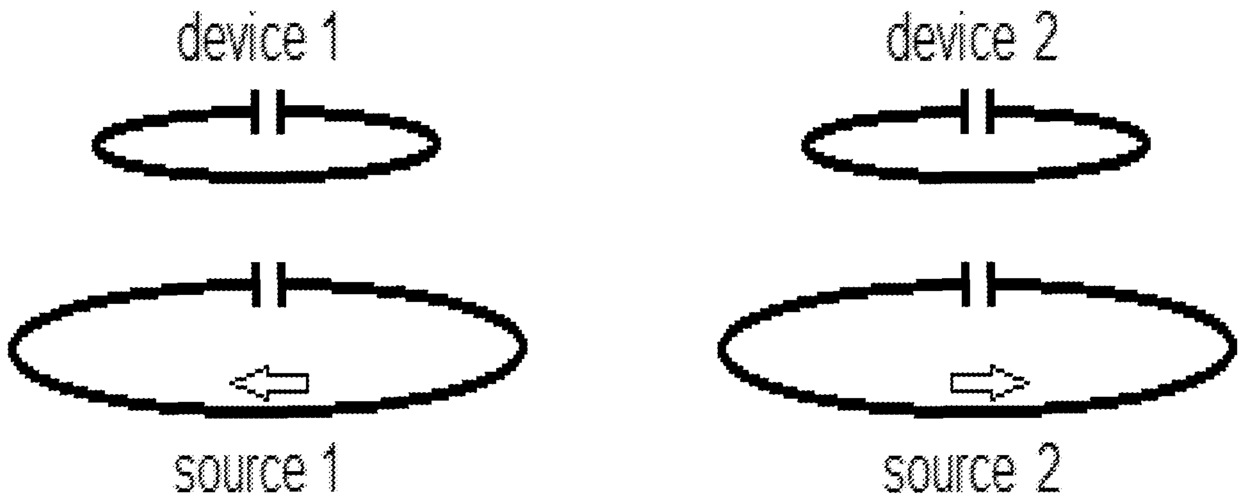


Fig. 42

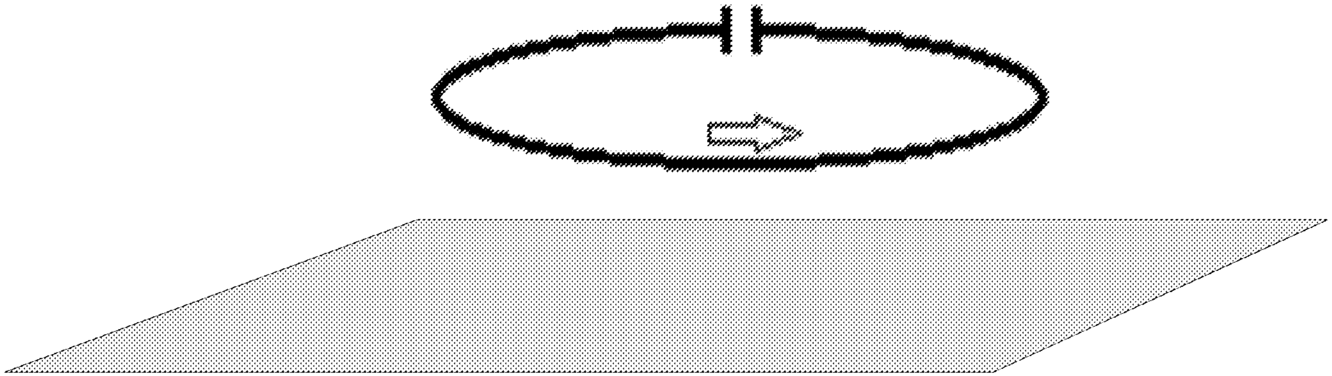


Fig. 43

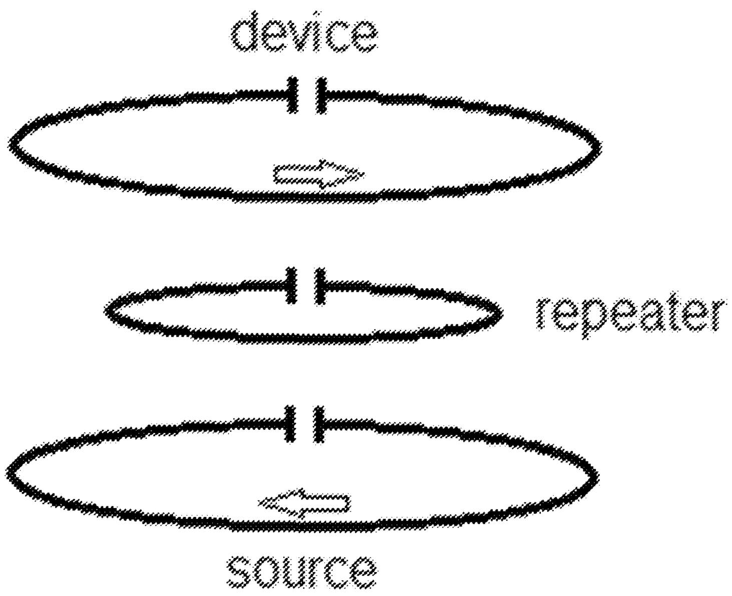
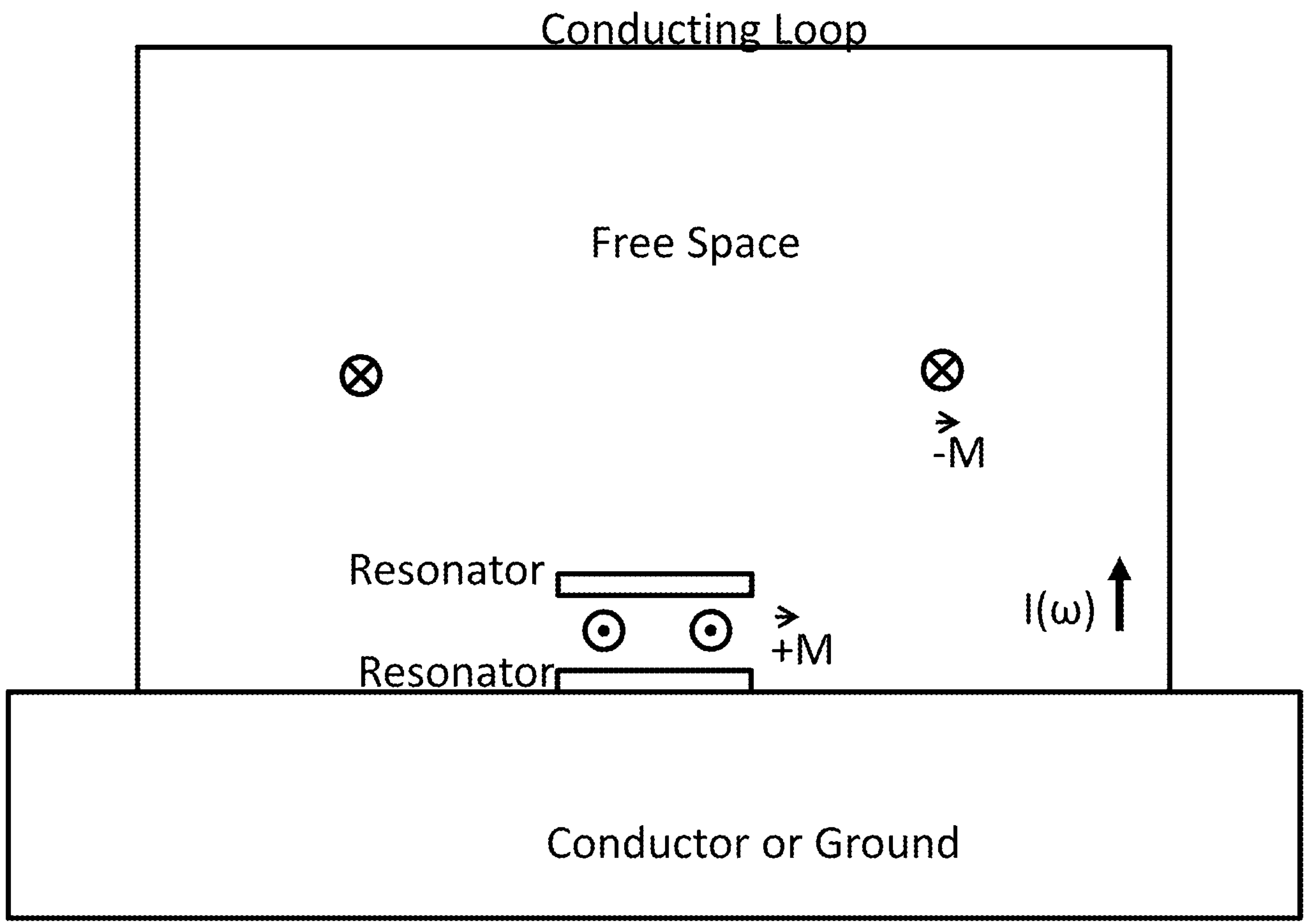
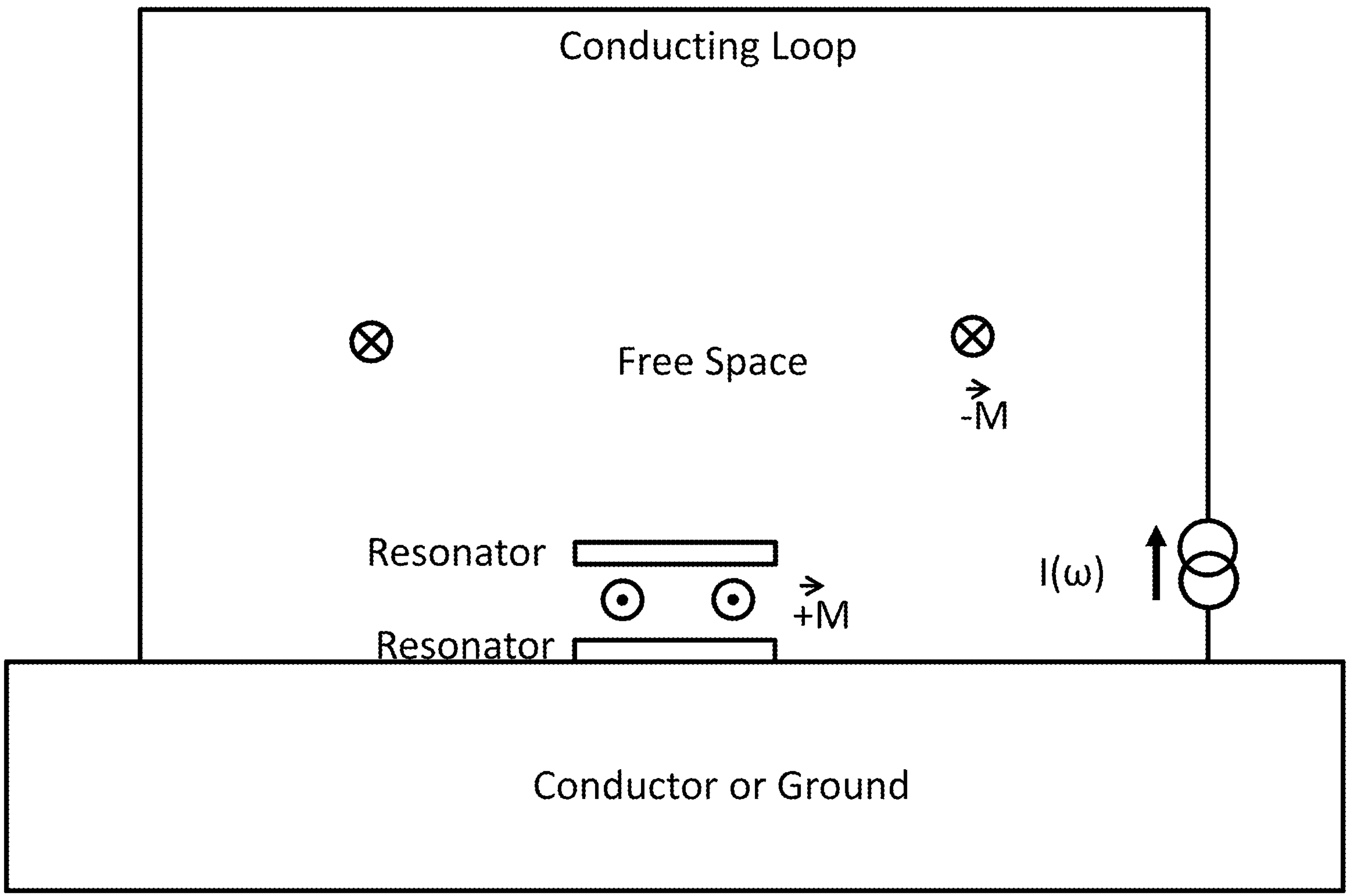


Fig. 44



Conducting Loop
Free Space
-M
Resonator
I(ω)
+M
Resonator
Conductor or Ground

Fig. 45



Conducting Loop
Free Space
-M
Resonator
Resonator
+M
I(ω)
Conductor or Ground

Fig. 46

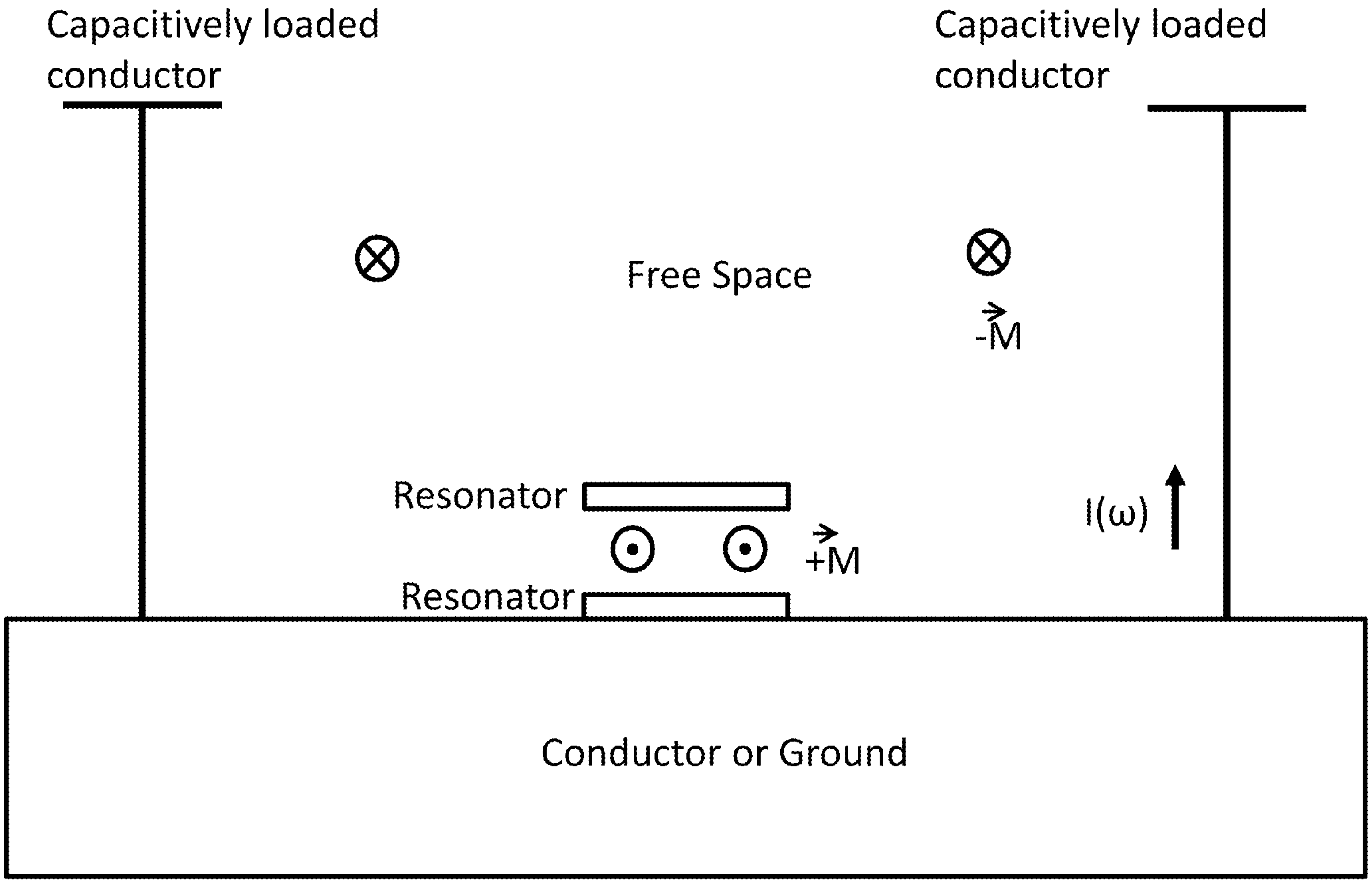

Capacitively loaded conductor
Capacitively loaded conductor
Free Space
-M
Resonator
Resonator
+M
I(ω)
Conductor or Ground

Fig. 47

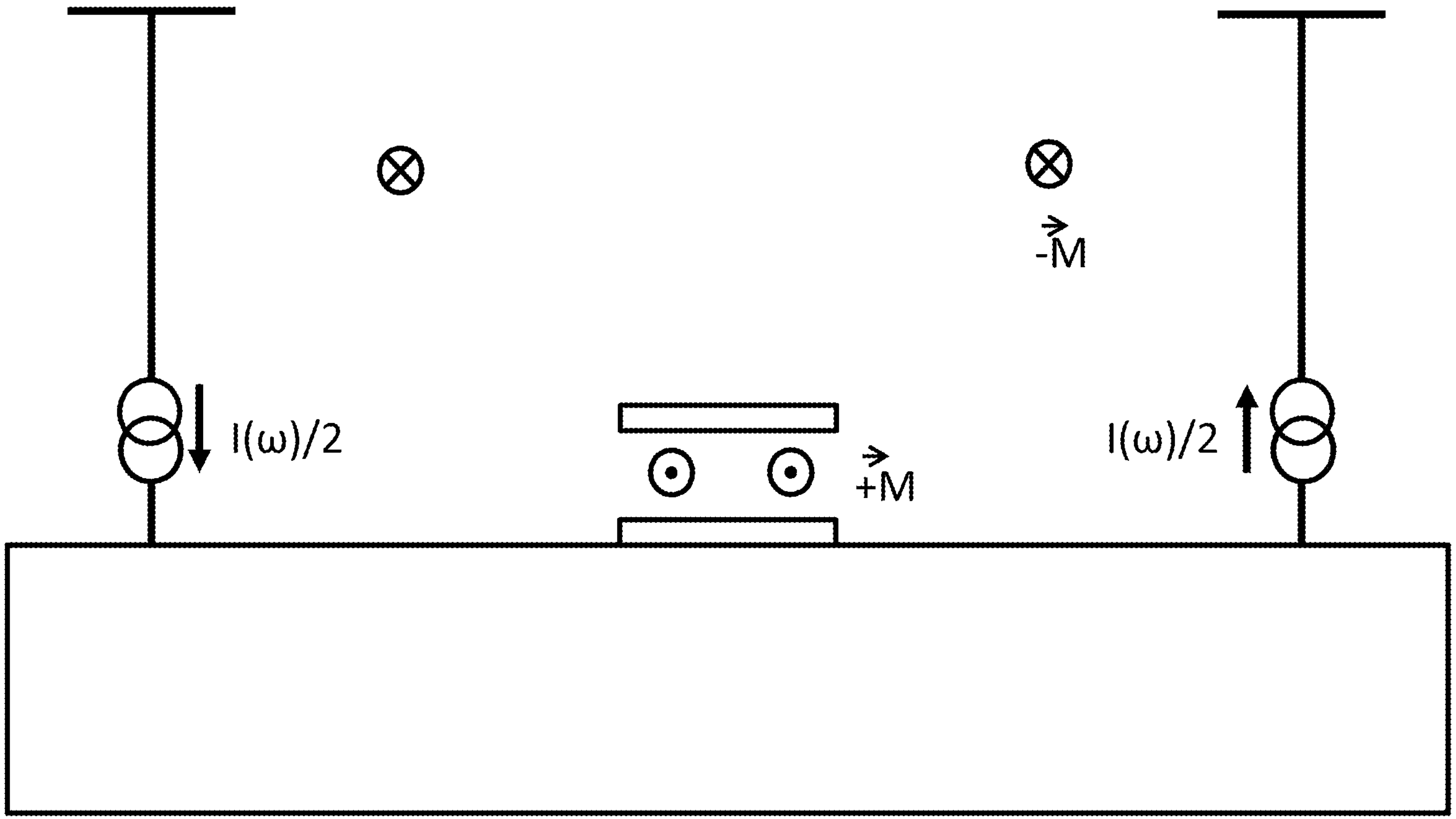


Fig. 48

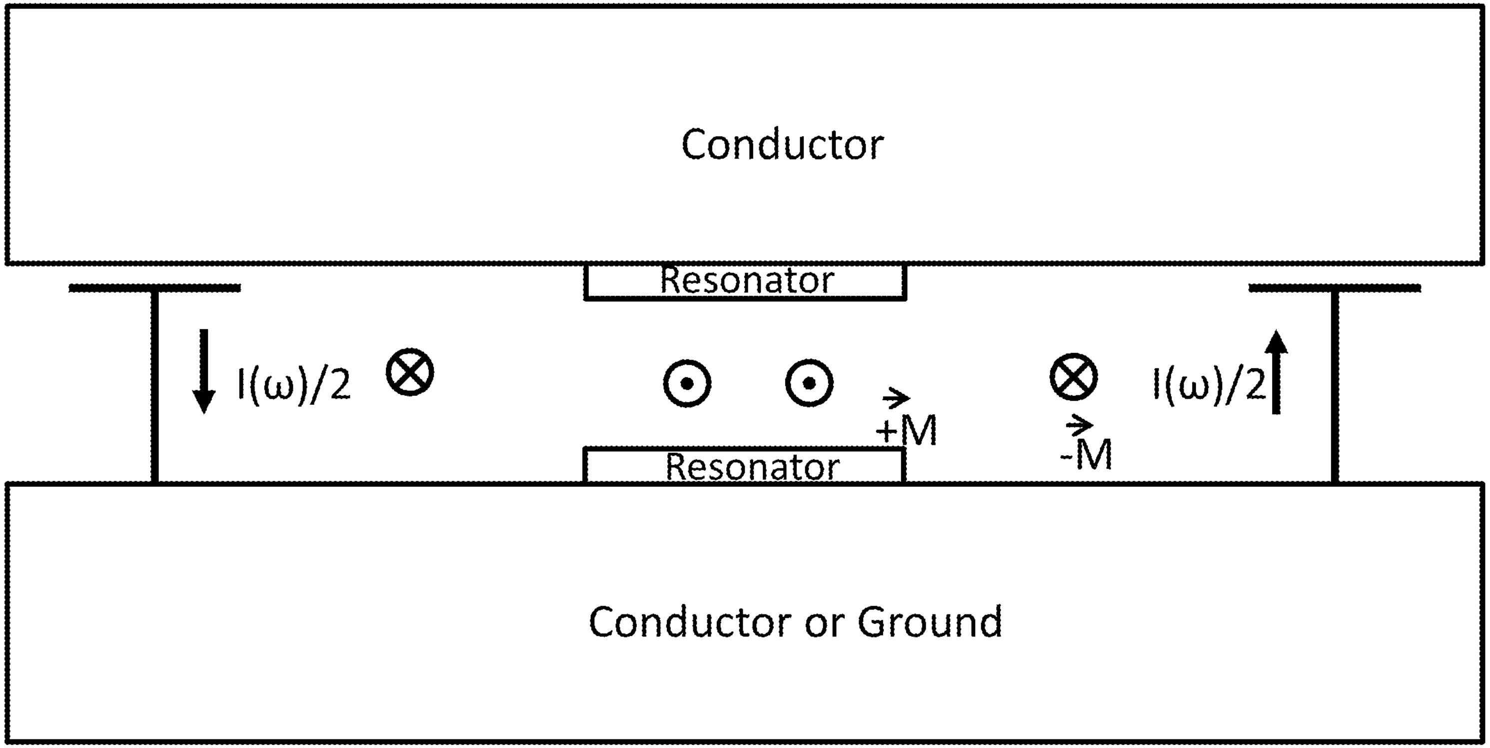
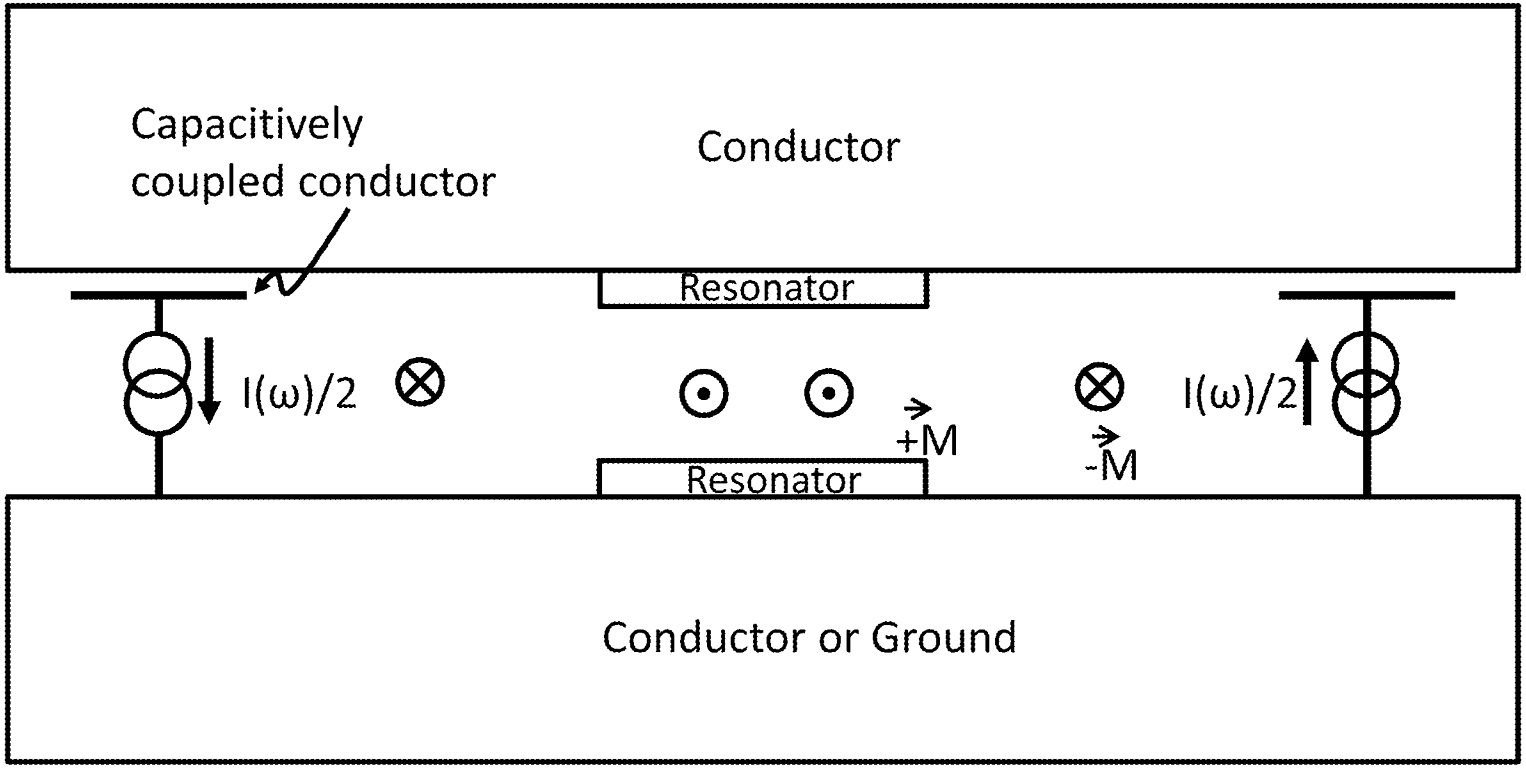

Conductor
Resonator
I(ω)/2
I(ω)/2
+M
-M
Resonator
Conductor or Ground

Fig. 49



Capacitively
coupled conductor
Conductor
Resonator
I(ω)/2
I(ω)/2
+M
-M
Resonator
Conductor or Ground

PATENT APPLICATION FEE DETERMINATION RECORD

Substitute for Form PTO-875

Application or Docket Number
13/752,169

APPLICATION AS FILED - PART I

FOR	NUMBER FILED (Column 1)	NUMBER EXTRA (Column 2)	SMALL ENTITY RATE($)	SMALL ENTITY FEE($)	OR	OTHER THAN SMALL ENTITY RATE($)	OTHER THAN SMALL ENTITY FEE($)
BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A	N/A			N/A	390
SEARCH FEE (37 CFR 1.16(k), (i), or (m))	N/A	N/A	N/A			N/A	620
EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A	N/A			N/A	250
TOTAL CLAIMS (37 CFR 1.16(i))	20 minus 20 =	*			OR	x 62 =	0.00
INDEPENDENT CLAIMS (37 CFR 1.16(h))	5 minus 3 =	* 2				x 250 =	500
APPLICATION SIZE FEE (37 CFR 1.16(s))	If the specification and drawings exceed 100 sheets of paper, the application size fee due is $310 ($155 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).						0.00
MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))							0.00
			TOTAL			TOTAL	1760

* If the difference in column 1 is less than zero, enter "0" in column 2.

APPLICATION AS AMENDED - PART II

AMENDMENT A

	CLAIMS REMAINING AFTER AMENDMENT (Column 1)		HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2)	PRESENT EXTRA (Column 3)	SMALL ENTITY RATE($)	SMALL ENTITY ADDITIONAL FEE($)	OR	OTHER THAN SMALL ENTITY RATE($)	OTHER THAN SMALL ENTITY ADDITIONAL FEE($)
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	

AMENDMENT B

	CLAIMS REMAINING AFTER AMENDMENT (Column 1)		HIGHEST NUMBER PREVIOUSLY PAID FOR (Column 2)	PRESENT EXTRA (Column 3)	RATE($)	ADDITIONAL FEE($)	OR	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 found in the appropriate box in column 1.

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United States Patent and Trademark Office
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Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
13/752,169	01/28/2013	Andre B. Kurs	WTCY-0075-P01

CONFIRMATION NO. 6134

87084
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

FORMALITIES LETTER

OC000000059387510

Date Mailed: 02/21/2013

NOTICE TO FILE MISSING PARTS OF NONPROVISIONAL APPLICATION

FILED UNDER 37 CFR 1.53(b)

Filing Date Granted

Items Required To Avoid Abandonment:

An application number and filing date have been accorded to this application. The item(s) indicated below, however, are missing. Applicant is given **TWO MONTHS** from the date of this Notice within which to file all required items below to avoid abandonment. Extensions of time may be obtained by filing a petition accompanied by the extension fee under the provisions of 37 CFR 1.136(a).

- The statutory basic filing fee is missing.
  Applicant must submit $390 to complete the basic filing fee for a non-small entity. If appropriate, applicant may make a written assertion of entitlement to small entity status and pay the small entity filing fee (37 CFR 1.27).

The applicant needs to satisfy supplemental fees problems indicated below.

The required item(s) identified below must be timely submitted to avoid abandonment:

- Additional claim fees of $ **500** as a non-small entity, including any required multiple dependent claim fee, are required. Applicant must submit the additional claim fees or cancel the additional claims for which fees are due.
- A surcharge (for late submission of the basic filing fee, search fee, examination fee or inventor's oath or declaration) as set forth in 37 CFR 1.16(f) of $ **130** for a non-small entity, must be submitted.

SUMMARY OF FEES DUE:

Total fee(s) required within **TWO MONTHS** from the date of this Notice is $ **1890** for a non-small entity
- $ **390** Statutory basic filing fee.
- $ **130** Surcharge.
- The application search fee has not been paid. Applicant must submit $ **620** to complete the search fee.
- The application examination fee has not been paid. Applicant must submit $ **250** to complete the examination fee for a non-small entity.
- Total additional claim fee(s) for this application is $ **500**
  - $ **500** for **2** independent claims over 3.

Items Required To Avoid Processing Delays:

Applicant is notified that the above-identified application contains the deficiencies noted below. No period for reply is set forth in this notice for correction of these deficiencies. However, if a deficiency relates to the inventor's oath or declaration, the applicant must file an oath or declaration in compliance with 37 CFR 1.63, or a substitute statement in compliance with 37 CFR 1.64, executed by or with respect to each actual inventor no later than the expiration of the time period set in the "Notice of Allowability" to avoid abandonment. See 37 CFR 1.53(f).

- A properly executed inventor's oath or declaration has not been received for the following inventor(s):
  All
  Applicant may submit the inventor's oath or declaration at any time before the Notice of Allowance and Fee(s) Due, PTOL-85, is mailed.

Replies must be received in the USPTO within the set time period or must include a proper Certificate of Mailing or Transmission under 37 CFR 1.8 with a mailing or transmission date within the set time period. For more information and a suggested format, see Form PTO/SB/92 and MPEP 512.

Replies should be mailed to:

Mail Stop Missing Parts
Commissioner for Patents
P.O. Box 1450
Alexandria VA 22313-1450

Registered users of EFS-Web may alternatively submit their reply to this notice via EFS-Web.
https://sportal.uspto.gov/authenticate/AuthenticateUserLocalEPF.html

For more information about EFS-Web please call the USPTO Electronic Business Center at **1-866-217-9197** or visit our website at http://www.uspto.gov/ebc.

If you are not using EFS-Web to submit your reply, you must include a copy of this notice.

/fhadera/

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

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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
13/752,169	01/28/2013	2821	0.00	WTCY-0075-P01	20	5

CONFIRMATION NO. 6134

87084
GTC Law Group LLP & Affiliates
c/o CPA Global
P.O. Box 52050
Minneapolis, MN 55402

FILING RECEIPT

OC000000059387509

Date Mailed: 02/21/2013

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Inventor(s)

Andre B. Kurs, Chestnut Hill, MA;
Morris P. Kesler, Bedford, MA;
Katherine L. Hall, Arlington, MA;
Aristeidis Karalis, Boston, MA;
Simon Verghese, Arlington, MA;
Volkan Efe, Watertown, MA;
Marin Soljacic, Belmont, MA;
Alexander P. McCauley, Cambridge, MA;
Maria Empar Rollano Hijarrubia, Cambridge, MA;

Applicant(s)

WiTricity Corporation, Watertown, MA

Assignment For Published Patent Application

WITRICITY CORPORATION, Watertown, MA

Power of Attorney: None

Domestic Priority data as claimed by applicant

This appln claims benefit of 61/590,856 01/26/2012

Foreign Applications for which priority is claimed (You may be eligible to benefit from the **Patent Prosecution Highway** program at the USPTO. Please see http://www.uspto.gov for more information.) - None.
Foreign application information must be provided in an Application Data Sheet in order to constitute a claim to foreign priority. See 37 CFR 1.55 and 1.76.

Permission to Access - A proper **Authorization to Permit Access to Application by Participating Offices** (PTO/SB/39 or its equivalent) has been received by the USPTO.

If Required, Foreign Filing License Granted: 02/16/2013

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 13/752,169**

Projected Publication Date: To Be Determined - pending completion of Missing Parts

Non-Publication Request: No

Early Publication Request: No

Title

WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS

Preliminary Class

343

PROTECTING YOUR INVENTION OUTSIDE THE UNITED STATES

Since the rights granted by a U.S. patent extend only throughout the territory of the United States and have no effect in a foreign country, an inventor who wishes patent protection in another country must apply for a patent in a specific country or in regional patent offices. Applicants may wish to consider the filing of an international application under the Patent Cooperation Treaty (PCT). An international (PCT) application generally has the same effect as a regular national patent application in each PCT-member country. The PCT process **simplifies** the filing of patent applications on the same invention in member countries, but **does not result** in a grant of "an international patent" and does not eliminate the need of applicants to file additional documents and fees in countries where patent protection is desired.

Almost every country has its own patent law, and a person desiring a patent in a particular country must make an application for patent in that country in accordance with its particular laws. Since the laws of many countries differ in various respects from the patent law of the United States, applicants are advised to seek guidance from specific foreign countries to ensure that patent rights are not lost prematurely.

Applicants also are advised that in the case of inventions made in the United States, the Director of the USPTO must issue a license before applicants can apply for a patent in a foreign country. The filing of a U.S. patent application serves as a request for a foreign filing license. The application's filing receipt contains further information and guidance as to the status of applicant's license for foreign filing.

Applicants may wish to consult the USPTO booklet, "General Information Concerning Patents" (specifically, the section entitled "Treaties and Foreign Patents") for more information on timeframes and deadlines for filing foreign patent applications. The guide is available either by contacting the USPTO Contact Center at 800-786-9199, or it can be viewed on the USPTO website at http://www.uspto.gov/web/offices/pac/doc/general/index.html.

For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, http://www.stopfakes.gov. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4158).

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Title 37, Code of Federal Regulations, 5.11 & 5.15

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INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	13/752,169
	Filing Date	Jan 28, 2013
	First Named Inventor	Morris P. Kesler
	Art Unit	Not Yet Assigned
	Examiner Name	Not Yet Assigned
	Attorney Docket Number	WTCY-0075-P01

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
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	2	649621		1900-05-15	Tesla, N.	
	3	787412		1905-04-18	Tesla, N.	
	4	1119732		1914-12-01	Tesla, N.	
	5	2133494		1938-10-18	Waters, H. F.	
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	7	3535543		1970-10-20	Dailey, C. C.	
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	9	3871176		1975-03-18	Schukei, Glen Elwin	
	10	4088999		1978-05-09	Fletcher, James C., et al.	
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INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	13/752,169
	Filing Date	Jan 28, 2013
	First Named Inventor	Morris P. Kesler
	Art Unit	Not Yet Assigned
	Examiner Name	Not Yet Assigned
	Attorney Docket Number	WTCY-0075-P01

	13	5027709	A	1991-07-02	Slagle, Glenn B.	
	14	5053774	A	1991-10-01	Schuermann et al.	
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	25	5522856	A	1996-06-04	Reineman, Henk	

Modified 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

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (Not for submission under 37 CFR 1.99)		
	Application Number	13/752,169
	Filing Date	Jan 28, 2013
	First Named Inventor	Morris P. Kesler
	Art Unit	Not Yet Assigned
	Examiner Name	Not Yet Assigned
	Attorney Docket Number	WTCY-0075-P01

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	First Named Inventor	Morris P. Kesler
	Art Unit	Not Yet Assigned
	Examiner Name	Not Yet Assigned
	Attorney Docket Number	WTCY-0075-P01

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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.

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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.

☒ 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/	Date (YYYY-MM-DD)	2013-02-28
Name/Print	John A. Monocello	Registration Number	51022

PATENT COOPERATION TREATY

ADVANCE E-MAIL

PCT

NOTIFICATION CONCERNING TRANSMITTAL OF COPY OF INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY (CHAPTER I OF THE PATENT COOPERATION TREATY)

(PCT Rule 44bis.1(c))

From the INTERNATIONAL BUREAU

To:

NORTRUP, John, H.
Strategic Patents, P.C.
Intellevate
P.O. Box 52050
Minneapolis, MN 55402
ETATS-UNIS D'AMERIQUE

Date of mailing *(day/month/year)* 25 August 2011 (25.08.2011)		
Applicant's or agent's file reference WTCY0014PWO	**IMPORTANT NOTICE**	
International application No. PCT/US2010/024199	International filing date *(day/month/year)* 13 February 2010 (13.02.2010)	Priority date *(day/month/year)* 13 February 2009 (13.02.2009)
Applicant WITRICITY CORPORATION et al		

The International Bureau transmits herewith a copy of the international preliminary report on patentability (Chapter I of the Patent Cooperation Treaty)

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/326 (January 2004)

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 WTCY0014PWO	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/US2010/024199	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 (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 7 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 16 August 2011 (16.08.2011)
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: 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	FOR FURTHER ACTION
WTCY0014PWO	See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US 10/24199	13 February 2010 (13.02.2010)	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:

- [x] 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
- [x] 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	03 May 2010 (03.05.2010)	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:
   - [X] 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

International application No.
PCT/US 10/24199

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

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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International application No.
PCT/US 10/24199

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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]).

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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.

Electronic Acknowledgement Receipt

EFS ID:	15084702
Application Number:	13752169
International Application Number:	
Confirmation Number:	6134
Title of Invention:	WIRELESS ENERGY TRANSFER WITH REDUCED FIELDS
First Named Inventor/Applicant Name:	Andre B. Kurs
Customer Number:	87084
Filer:	John A. Monocello/Keisha Forsman
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	WTCY-0075-P01
Receipt Date:	28-FEB-2013
Filing Date:	28-JAN-2013
Time Stamp:	17:26:52
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.)
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Warnings:

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(54) **Title:** WIRELESS POWER APPARATUS AND METHODS

(57) **Abstract:** Wireless energy transfer system. Antennas are maintained at resonance with High Q. Techniques of maintaining the high-Q resonance matching are disclosed.

WIRELESS POWER APPARATUS AND METHODS

[0001] Related Applications

[0002] This application is related to co-owned and co-pending U.S. patent application Serial No. 11/408,793 Filed April 21, 2006 and entitled "Method and System for Powering an Electronic Device Via a Wireless Link", and U.S. patent application Serial No. 111654,883 filed January 17, 2007 entitled "Method and Apparatus for Delivering Energy to an Electrical or Electronic Device Via a Wireless Link", each of the foregoing incorporated herein by reference in its entirety.

[0003] This application claims priority from provisional application number 60/904,628, filed March 2, 2007; the disclosure of which is herewith incorporated herein by reference.

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Background

[0006] Delivery of power to portable devices often uses wires of various types to carry out the power delivery. Devices such as cell phones, portable computers, or any other device that can operate from stored power such as a battery, all require and use such a source of power to operate the device and/or charge the battery.

Summary

[0007] Techniques of wireless power transfer are disclosed herein.

Detailed Description

[0008] Embodiments describe the use of wireless power transfer to a receiving source.

[0009] As used herein, the terms "wireless power" and "wireless energy" include without limitation any form of power or energy, including that associated with electric fields, magnetic fields, electromagnetic energy, or otherwise, that is transmitted between one point, area, location or device and another without having to use a wire line connection.

[0010] An embodiment discloses a wireless powering and charging system. An embodiment describes using a transmitter of a size allowing it to be embedded into another item, e.g., a desk or a shelf, or plugged into a wall, or embedded into another structure or surface such as a wall, floor, door, etc. A receiver is associated with a small mobile unit or client device carried by the user, or mounted on a portable device, vehicle, or with a stationary device such as a lamp, toaster, flat-screen TV on a wall, computer or computerized device, PDA, personal media device, etc. When the receiver is in range of the transmitter, power is delivered to the mobile unit.

[0011] In one embodiment, a wireless powering-charging system is disclosed, based on a transmitter that sends a substantially unmodulated signal or beacon (e.g., the carrier only). A receiver may be tuned to extract energy from the radiated field of the transmitter. The receiver powers an electronic device or charges a battery.

[0012] Other embodiments may use beacons that are slightly modulated.

[0013] Multiple receivers may be used. Multiple transmitters may be used to transmit to one or multiple receivers.

[0014] The antenna used by this system allows an efficient means of energy transmission and reception. The antenna is preferably of a small size to allow it to fit into a mobile, handheld device where the available space for the antenna may be limited. An embodiment describes a high efficiency antenna for the specific characteristics and environment for the power being transmitted and received.

[0015] Antenna theory suggests that a highly efficient but small antenna will typically have a narrow band of frequencies over which it will be efficient. Many of skill in the art have, therefore, avoided the use of these antennas, to enable more flexible transmit and/or receive characteristics. In an embodiment, an adaptive tuning circuit is used in certain configurations to allow tuning of an efficient yet narrowband antenna.

[0016] One embodiment describes an efficient power transfer between two antennas by storing energy in the near field of the transmitting antenna, rather than sending the energy into free space in the form of a travelling electromagnetic wave. This embodiment increases the quality factor (Q) of the antennas. This can reduce radiation resistance (R_r) and loss resistance (R_ℓ).

[0017] In one embodiment, two high-Q antennas are placed such that they react similarly to a loosely coupled transformer, with one antenna inducing power into the other. The antennas preferably have Qs that are greater than 1000.

[0018] Another embodiment describes maximum Permissible Exposure (MPE) where the maximum exposure limits are defined by European and US standards (as well as others). They are defined in terms of power density limits (W/m^2), magnetic field limits (A/m) and electric field limits (V/m). The limits are related through the impedance of free space, 377 W.

[0019] In the US, the applicable standard is FCC CFR Title 47: §2.1091 Radiofrequency radiation exposure evaluation: mobile devices. A mobile device is a transmitting device designed to be used in such a way that the separation distance of at least 20cm is normally maintained between the transmitter's radiating structure(s) and the body of the user or nearby persons. The limits to be used for evaluation are specified in §1.310 of Title 47. - §1.1310 Radiofrequency radiation exposure limits (see Table 1).

[0020] Table 1: FCC limits for radiation exposure Limits FOR MAXIMUM PERMISSIBLE EXPOSURE (MPE)

Table 1: FCC limits for radiation exposure

LIMITS FOR MAXIMUM PERMISSIBLE EXPOSURE (MPE)

Frequency range (MHz)	Electric field strength (V/m)	Magnetic field strength (A/m)	Power density (mW/cm²)	Averaging time (minutes)
(A) Limits for Occupational/Controlled Exposures				
0.3–3.0	614	1.63	*(100)	6
3.0–30	1842/f	4.89/f	*(900/f²)	6
30–300	61.4	0.163	1.0	6
300–1500			f/300	6
1500–100 000			5	6
(B) Limits for General Population/Uncontrolled Exposure				
0.3–1.34	614	1.63	*(100)	30
1.34–30	824/f	2.19/f	*(180/f²)	30
30–300	27.5	0.073	0.2	30
300–1500			f/1500	30
1500–100 000			1.0	30

f = frequency in MHz
* = Plane-wave equivalent power density

NOTE 1 TO TABLE 1: Occupational/controlled limits apply in situations in which persons are exposed as a consequence of their employment provided those persons are fully aware of the potential for exposure and can exercise control over their exposure. Limits for occupational/controlled exposure also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

NOTE 2 TO TABLE 1: General population/uncontrolled exposures apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or can not exercise control over their exposure.

[0021]

[0022] In Europe, the applicable standard is EN60215. This has been derived from the ICNIRP (International Commission on Non-

Ionizing Radiation Protection) guidelines [ICN], The limits are given in Table 2.

[0023] Table 2: European limits for radiation exposure

Table 2: European limits for radiation exposure

Table 2: European limits for radiation exposure

Frequency range (MHz)	*Electric field strength (V/m)*	*Magnetic field strength (A/m)*	*Power density (W/m^2)*	*Averaging time (min)*
0.15-1	87	0.73/f	-	6
1-10	$87/f^{1/2}$	0.73/f	-	6
10-400	28	0.073	2	6
400-2000	$1375\ f^{1/2}$	$0.0037\ f^{1/2}$	f/200	6
2000-300,000	61	0.16	10	6

[0024]

The power density limits and magnetic field limits are of particular interest in one embodiment. Using the data from Table 1 and Table 2, limit curves can be determined. Figure 1 shows a plot of power density with the FCC limit curve 100, and the EN curve 102. Figure 2 shows a plot of maximum H field, with the FCC curve 200, and the EN curve 202.

[0025] Figures 1 and 2 illustrate how the US limits are more generous at frequencies below 30MHz and could offset the effect of reduced antenna efficiency at low frequency. This study tests a range of frequencies to see which frequencies are the best for wireless power transfer.

[0026] This application also provides an exemplary theoretical analysis of various aspects of wireless energy and power transfer.

[0027] Embodiments disclosed herein describe antenna types.

[0028] A loop antenna is a "magnetic" antenna and may be less sensitive to changes in its surroundings than a dipole, which is an "electric" antenna. The loop antenna may have certain advantages when the device is exposed to changes in its surroundings, e.g., when placed on a table, held in the hand, or put in a pocket, based on stray capacitance, or other effects. In an embodiment, an air loop antenna is used. Another embodiment may use a loop antenna with a ferrite core, or others may be used.

[0029] In one embodiment, an air loop antenna may be preferred over a loop antenna with a ferrite core. The air loop antenna may be more resistant to detuning from permanent magnets or other magnetic influences in its vicinity. The air loop antenna will, in general, be more efficient than the ferrite loop antenna, since the ferrite core can cause losses. The ferrite antenna is often heavier, and cannot typically have components placed "inside" it. In contrast, other components can be placed inside the loop of an air loop antenna. The form-factor of the loop may be modified or otherwise adapted to fit within a form-factor of certain portable devices being charged.

[0030] The same type of antenna may be used for both transmitter and receiver. The transmit and receive antennas can be the same or different sizes.

[0031] An embodiment describes a tuning circuit that becomes part of the antenna circuit. A typical loop antenna is inherently inductive. A capacitive element may be used in the tuning circuit to induce resonance in the antenna. Even though a loop antenna is less sensitive to changes in its surroundings than a dipole antenna, it will still be detuned to some degree by changes in its surroundings. Therefore, it may be desireable in certain embodiments to adaptively tune either the transmitter antenna or the receiver antenna or both, to maintain the quality of the link therebetween.

[0032] Adaptive tuning is achieved in one embodiment by changing the value of a capacitive element used in series with the loop antenna to adjust the resonant frequency of the circuit. The adaptive tuning circuit at the transmitter and/or at the receiver. A goal is to choose tuning components with high quality factors (Q) to ensure that that the Q of the overall receiver circuit is degraded as little as possible. In an embodiment, high Q is used to maximize efficiency, even at the cost of narrow bandwidth.

[0033] Figure 3 illustrates an air loop antenna of an embodiment. The antenna may have maximum dimensions of 5 cm (i.e. a radius r of 2.5cm) and N turns of wire 300 of diameter $2b_{rx}$ =500 um is used for one embodiment. The antenna can, for example, be placed around the perimeter of a mobile device. The loop will be assumed circular, but can be of other shapes. A capacitor 302 is used with the loop inductive resonator to bring the loop antenna to resonance. The capacitor value may be defined as:

$$\omega^2 = \frac{1}{LC}$$

[0034]

[0035]

[0036] By calculating the inductance of the air loop antenna using the Equation and a wire diameter of 500 um, the required capacitance can be calculated for any of a number of frequencies.

[0037] In one embodiment, the capacitor 302 can be a high Q fixed chip capacitor in parallel with a high Q varactor diode operating as a voltage-tunable capacitor to bring the receiver air loop to resonance and to maintain tuning. Figure 4 shows a schematic of the series-resonant circuit formed with tuning circuit 400, that itself is formed of variable capacitance 402, in series with its equivalent series resistance 404. A fixed capacitor is shows as 406 in series with its ESR 408. The antenna overall ohmic resistance 410 is shown separated as radiation resistance 410 in series with overall antenna resistance 412. Load resistance 414 and inductance 416 are also shown.

[0038] In the circuit, the symbols have the following meanings:

V_0:	The induced voltage across the loop antenna
L_{rx}:	The inductance of the loop antenna
R_{L_rx}, R_{r_rx}, R_{a_rx}:	Receive-antenna loss (ohmic) resistance, radiation resistance and overall antenna resistance (the sum of the previous two)
C_{var}, R_{esr_var}:	The capacitance of the tuning varactor and its associated Equivalent Series Resistance (ESR)
C_{fix}, R_{esr_fix}:	The fixed capacitance and its associated ESR
R_{load_rx}:	The load resistance

[0039]

[0040] One embodiment selects a tuning range of roughly +/-5 percent of the chosen operating frequency, so as to cover variations in the capacitance and detuning from external factors. The varactor's tuning range could be approximately +/-10 percent the fixed capacitance value. Components used preferably have a high Q, so that they degrade the overall Q of the circuit as little as possible.

[0041] In one embodiment, tuning is carried out solely at the transmitter. In this embodiment, no varactor diode need be located at the receiver and the transmitter tracks the receiver resonant frequency. This is dependent on how much resonant frequency of the receiver loop is affected by changes in the environment near the loop. The opposite configuration can also be used.

[0042] At higher frequencies, or with larger loop dimensions, or with more loop turns, a very small capacitance may be required to bring the loop to resonance. In an embodiment, only a varactor diode or only a fixed capacitor would be used without the other.

[0043] Another effect to be considered is the self-resonance of the loop, especially at higher frequencies. This effect will occur as inter-winding capacitance and stray capacitances on the loop antenna come into resonance with the inductance of the winding itself. This decreases as frequency increases.

[0044] At a lower operating frequency such as 1.3 MHz, a larger fixed capacitor will be required. For example, the loop antenna with the dimensions given in Figure 3 with 5 turns of loop antenna would require a fixed capacitance of about 3 nF. Capacitance variations of +/-1 percent (30 pF) are typical for these types of capacitors. As will be shown, this exceeds the tuning range of most available tunable capacitors. Therefore, at low frequencies, one embodiment locates the adaptive tuning only in the transmitter.

[0045] Increasing the operating frequency or increasing the number of turns allows reducing the size of the fixed capacitance. A larger number of turns may make the packaging more difficult. Therefore, with a large number of turns, practical implementation for certain types of applications could become difficult. A higher frequency therefore might allow certain benefits in applications where this factor might otherwise be limiting.

[0046] However, at frequencies of 250 MHz and above, the size of fixed capacitor required is extremely small - e.g. on the order of 1 pF for N = 1, and even less for more turns. At these frequencies, the fixed capacitor can be eliminated altogether in some cases, and only a very small tuning capacitor used. This physical limit on capacitor size also places a limit on the frequencies that can be used, for given loop dimensions. A smaller receiver loop size would allow a higher frequency or more loops to be used.

[0047] Exemplary high Q/low ESR capacitors with capacitances from the low picofarad to the low nanofarad range can be obtained commercially, e..g, from AVX Corp. Details of some potentially suitable AVX capacitors are tabulated in Table 3, although any number of other devices may be used.

[0048] Table 3

Table 3

Capacitor Family (all AVX)	*Capacitance Range of Family*	*Tolerance*	*Q*	*ESR*	*Voltage Rating*	*Dimensions*
HQ series, E case	3.3 pF to 6800 pF	+/-0.25 pF to +/-1%	Varies according to capacitance and frequency - see Figure 19	Varies according to capacitance and frequency - see Figure 20	600V to 7200 V	9.4 mm x 9.9 mm x 3.3 mm
SQ, AQ or CDR[1] series, style 13 or 14	0.1 pf to 5100 pF	+/-1%	Claimed greater than 10000 at 1 MHz	Approx 0.004 at 1 MHz	50 V	2.79 mm x 2.79 mm x 2.59 mm

[0049]

[0050] Note that in general, Q ESR and C are related by the following equation:

$$C = \frac{1}{\omega R_{esr} Q}$$

[0051]

[0052] Another embodiment uses MEMS (Microelectromechanical Systems) varactors. This may lower the power consumption.

[0053] The circuit of Figure 4 at resonance is analyzed to evaluate performance. In a first approach, the varactor will be replaced by a fixed value capacitor one-tenth the size of the main fixed capacitor. The AVX data will be used for both capacitors. The tuning circuit 100 in Figure 4 is modeled as a single R/C impedance. Values used are:

[0054] I_{rx} is the current in the receiver loop

[0055] P_{rx} is the power at the load resistor

[0056] C_{ser} is the equivalent series capacitance of the fixed capacitor and varactor, and

[0057] R_{ser} is the equivalent series resistance of the fixed capacitor and varactor.

[0058] At resonance, the reactances can be neglected since XL = -Xc. Only the resistive (real) losses in the circuit are considered.

[0059] The inventors found that when the resistances of the tuned antenna are matched to the load resistance, the maximum amount of power P_{rx} is available at the load. In other words, the optimum condition is when

[0060] $RL\_{rx} + Rr\_{rx} + R_{ser} = Rload\_{rx}$. The values may vary by 20% while still staying within "optimum" resonance.

[0061] In the embodiment, therefore, the transmitter circuit is modeled as a resonant loop where the loop is power-matched to the source. An exemplary air loop antenna with maximum dimensions of 20cm (i.e. a radius r of 10cm), a wire radius of 1 mm and a single turn (N = 1) is used for an embodiment, although other types, sizes and dimensions of antenna may be used for the transmitter in other embodiments.

[0062] In one embodiment, the transmitter antenna could, for example, sit vertically on a bench or a table inside a home, within a wall, around a wall power outlet, on or within a garage floor, behind a refrigerator, etc. To simplify calculations, the loop will be assumed circular, as Figure 3. A single wire loop transmitting antenna of Figure 3, having a wire diameter of 10 cm radius, wire radius of 1mm, has an inductance of approximately 840 nH. Different frequencies will require different capacitance values for resonance with this antenna. For example, 1.3 Mhz will require a capacitor of 17.85 nF; 13.56 Mhz will require 164.1 pF; 64 Mhz will require 7.365 pF; 250 Mhz will require .483 pF and 500 Mhz will require 0.121 pF.

[0063] A number of different antennas are described as embodiments herein. For testing of the embodiments, the antennas were built of 1.5 mm^2 copper wire and fixed onto a wooden frame.

[0064] The transmit antenna has a radius of 0.2 m, 6 turns, and 3Mhz operating frequency. The matching is realized with two tunable capacitors. The receiving antenna has a radius of 0.1 m. Before considering power transfer/pathgain, the antennas were tuned and measured independently. The resulting characteristics are summarized in Table 6.

Table 6

	Transmitting antenna (TX)	Receiving antenna (RX)
Measured unmatched characteristics @ 3 MHz		
R [Ω]	23	1.7
L [μH]	43	12.5
Used matching network		
C_S [pF]	36.5	33
C_P [pF]	27.6	187
Match [dB]	-24	-24
3 dB-bandwidth [kHz]	34	90
Quality factor Q	89	33

[0065] A quality factor increase may further increase power transfer. The quality factor, for example, can be increased using a Matlab simulation. The mathematical investigations done for the simulation, leads to the following approximation for the path gain:

$$\eta(x) = \frac{\pi^2 a^6 Q_{ul}^2}{16 x^6 \left[\ln\left(8\frac{a}{b} - 2 \right) \right]^2}$$

where:
a = loop radius [m]
b = wire radius [m]
Q_{ul} = unloaded quality factor
x = distance between transmitter and receiver antenna [m]

[0066]

[0067] The Equation above shows that for a practical antenna, the loop radius has a high impact on the path gain.

[0068] Second Embodiment Antennas

[0069] Figure 5 illustrates a second embodiment of the antennas. This embodiment obtains a maximized power transfer between a coupling loop 500 to which the transmitted power 502 is delivered. The coupling loop radiates to a resonator 510 with optimized Q. This embodiment uses a coupling loop which acts as a resonator instead of a coupling network made of two capacitors. This reduces losses by omitting a matching network. The coupling between the coupling loop and the antenna can be conceptualized as an ideal transformer.

[0070] The antenna may be made out of e.g., copper tube or the like in order to decrease the loss resistance by increasing the wire surface. In addition, the surface may be plated with silver (Ag) or another such high conductance material well known in the art. With this type of construction, a quality factor in the order of 10^3 is achieved, as described in greater detail below. The resonator part of the antenna may also be optimized for a high quality factor (Q). This is done by increasing the number of turns, increasing the surface of the wire and reducing dielectric losses due to isolation or the mounting of the antenna.

[0071] To tune the resonance frequency of the antennas, tunable capacitors 504, 512 may be integrated at the bottom of both antennas. The capacitors may be metal plates that are tunable by using three screws 514 to change the distance between the two plates of the capacitor. The capacitors dominate the self-capacitance (CS) of the antennas. Table 6A illustrates the characteristics of these antennas.

	Transmitting antenna (TX)	Receiving antenna (RX)
Radius [m]	0.085	0.085
Length [m]	0.078	0.078
Number of turns	7	7
Operating frequency [MHz]	Resonance	Resonance

Table 6A

[0072] The exemplary embodiments of the antennas are built of copper tube with an outer diameter of 6.0 mm. The surface is silver-plated. This protects the copper from corrosion and slightly increases the conductivity of the surface.

[0073] With an exemplary plate-distance of the tuneable capacitor of 8 mm, the resulting calculated resonance frequency is 14.4 MHz.

[0074] Using a Q of 1300, pathgain is approx. -10 dB, at 1 m, which corresponds to a factor of 0.1. In other words, a transmitting power of 10 watts must be used to receive 1 W at the receiver.

[0075] The system should be defined around the unloaded Q ($Q_{u\ell}$) of the antennas. starting with:

$$Q_{ui} = \frac{1}{R} \cdot \sqrt{\frac{L}{C}},$$ Equation 1-1

The total loss resistance of either the Tx or Rx antenna can be defined by:

$$R = \frac{1}{Q_{ui}} \cdot \sqrt{\frac{L}{C}}.$$ Equation 1-2

At resonance, it can be written as

$$P_{in} = I^2 \cdot R.$$ Equation 1-3

The resulting current in the TX-antenna can now be specified by

$$I = \sqrt{\frac{P_{in}}{R}}.$$ Equation 1-4

Using Equation 1-2, the current can be rewritten as

$$I = \sqrt{P_{in} \cdot Q_{ui} \cdot \sqrt{\frac{C}{L}}}.$$ Equation 1-5

The magnitude of the H-field generated by the current in the TX-antenna in a distance x is

$$H(x) = \frac{r_A^2 \cdot I \cdot N}{2 \cdot \sqrt{(r_A^2 + x^2)^3}},$$ Equation 1-6

and induces a voltage

$$U_{ind}(x) = 2\pi f_{res} \cdot N \cdot \pi r_A^2 \cdot \mu_0 \cdot H(x)$$ Equation 1-7

in the RX-antenna. The parameter r_A is the radius, N the number of turns of the loop-antenna. The available output power P_{out} can now be calculated with

$$P_{out}(x) = \frac{U_{ind}(x)^2}{4 \cdot R},$$ Equation 1-8

$$P_{out}(x) = U_{ind}(x)^2 \cdot \frac{Q_d}{4} \cdot \sqrt{\frac{C}{L}}, \qquad \text{Equation 1-9}$$

Finally, pathgain is defined as

$$\eta(x)_{dB} = 10 \cdot \log_{10}\left(\frac{P_{out}(x)}{P_{in}}\right). \qquad \text{Equation 1-10}$$

To further simplify and understand the behaviour of Equation 1-10 and Equation 1-9, models for L and C are needed. The capacitance can simply be defined over the resonance frequency

$$C = \frac{1}{\omega_0^2 \cdot L}. \qquad \text{Equation 1-11}$$

For the inductivity, an empiric formula was found to be the most accurate for the type of antenna used in this system.

$$L = \frac{\mu_0 \pi \cdot N^2 r_A^2}{0.9 r_A + l_A} \qquad \text{Equation 1-12}$$

The parameter l_A is the width of the antenna.

[0076] Under the assumption that the separation x between the antennas is large compared to the radius of the antennas rA (x > rA), and with Equation 1-11 and Equation 1-12, Equation 1-10 can be written as:

$$\eta(x)_{dB} = 10 \cdot \log_{10}\left(\frac{r_A^4 \cdot Q_{id}^2 (0.9 r_A + l_A)^2}{16 x^6}\right). \qquad \text{Equation 1-13}$$

[0077] The term in brackets in 1-13 is the linear pathgain. Note that this linear pathgain is not a direct function of the frequency or the number of turns, although these parameters are implicitly contained in the quality factor. The pathgain is approximately proportional to loop radius rA^6, if the loop radius is much larger than the loop length ℓ_A. It is inversely proportional to the separation x^6 between the antennas. It is also proportional to the quality factor $Q_{u\ell}^2$.

[0078] For a given antenna dimension, as the quality factor is increased, the pathgain is improved. This is validated in an embodiment via simulation. The above equations were simulated using Matlab® to test antennas with different sizes and quality factors. The following parameter set was defined to run the script:

[0079] % Parameter definitions

[0080] Q = 1000; % target unloaded quality factor [1]

[0081] N = 7;% number of turns [1]

[0082] r_loop = 85e-3; % radius of loop antenna [m]

[0083] r_wire = 3e-3; % radius of wire [m]

[0084] pitch = 12e-3; % distance between two turns (center to center) [m]

[0085] freq = 13.0e6; % system frequency [Hz]

[0086] dist =1: 0.1 : 3; % distance ofantennas [m]

[0087] P_in = 1% input power [W]

[0088] The resulting simulation showed a pathgain variation

[0089] of -60 dB per decade which is caused by the term x^6 in Equation 1-13. If Q is doubled, for example from 1000 to 2000, pathgain increases by 6 dB. If the distance is doubled, pathgain decreases by 18 dB. The exemplary defined parameters are valid for both TX-and RX-antennas, and hence can assist with forming an optimal antenna for the parameters.

[0090] The simulation also calculates the reactive voltages. The reactive voltages occurring at the inductance and the capacitance are directly proportional to the quality factor and proportional to the square root of the transmitting power as set forth in Equation 1-14.

$$U_{L,C} = Q_{ui}\sqrt{P_{in} \cdot R} \qquad \text{Equation 1-14}$$

[0091] Both reactive voltages will be very high in a practical implementation, thus planning for those voltages becomes more critical. With a Q of 1000 and a transmitting power of 10 W, the voltages may be 2.7 kV. If a plate capacitor is used with a plate distance of 0.01 m, the resulting field strength is 270 kV/m. Capacitors that can withstand these high voltages become critical. For example, it may be necessary to use 2000 v or 3000 V or higher voltage withstanding capacitors. It is believed that at least one reason why systems of this type did not operate properly in the past is that they were not properly sized for the amount of reactive voltage at was actually present. In fact, the unexpectedly high voltage above 2KV is found as part of these reactive voltages even when much smaller voltages are being transmitted. This unexpectedly high voltage needs to be handled by the circuit components.

[0092] Definition of the Quality Factor also becomes important, because a major focus of the antenna design process is on optimizing the quality factor. Accordingly, the following describes an in-depth analysis of Q.

[0093] The fundamental equation about the quality factor is given by Equation 1-1 above.

$$Q_{ul} = \frac{1}{R} \cdot \sqrt{\frac{L}{C}}, \qquad \text{Equation 1-1}$$

[0094] Figure 6 illustrates a plot of Q vs frequency for a number of different frequencies.

[0095] Note that the proportion of L and C is important in this equation. For a given resonance frequency, there are an infinite number of possible L-C combinations. However, higher Q is obtained when the inductance L is as high as possible compared to the capacitance.

[0096] The quality factor is also inversely proportional to the resistance R. This resistance consists of a loss resistance (R_l) and a radiation resistance (R_r). Both should be minimized in order to increase the quality factor.

[0097] The loss resistance is dependent of the material used to build the antenna, and due to the skin effect of frequency used for the system. A highly conductive material with good skin effect is preferable.

[0098] A high resonance frequency increases losses and hence decreases the quality factor. This is why the curve of Figure

6 decreases at the upper end of the frequency-scale. However, a lower resonance frequency is obtained by increasing the capacitance. This decreases the L/C ratio, and since L is independent of the frequency, this lowers Q. Hence, the Figure 6 curve shows how Q decreases at both the upper and lower end of the frequency-scale, making an ideal quality factor around a frequency of 29 MHz for the given antenna dimensions.

[0099] This shows an ideal frequency or frequency range for each antenna geometry.

[00100] The resonance frequency of 13 MHz used during testing described herein is below this ideal frequency. This is because self resonance, which is the resonance frequency without the tunable capacitor , below the resonator of the antennas is around 35 MHz. If the resonator is used at this frequency without the tunable capacitor, the sensitivity of the antenna against close-by objects may become significant.

[00101] An embodiment minimizes this effect and at the same time makes it possible to change the resonance frequency. A tunable capacitor of a value which dominates the self-capacitance of the resonator is used for this purpose. The added capacitance lowers the resonance frequency of the antenna.

[00102] Quality factor typically cannot be measured directly. Instead, the definition

$$Q = \frac{\omega_0}{\Delta\omega}$$ Equation 2-1

[00103]

may be used as a starting point, where ω_0 is the center or resonance frequency and $\Delta\omega$ corresponds to the 3 dB-bandwidth. Q can therefore be found by measuring the two parameters ω_0 and $\Delta\omega$.

[00104] The 3 dB-bandwidth can be found as follows. The impedance Z of a first order series RLC-circuit is given by

$$\underline{Z} = R + j\omega L + \frac{1}{j\omega C}.$$ Equation 2-2

With the help of

$$\omega_0 = \frac{1}{\sqrt{LC}}$$ Equation 2-3

and

$$Q = \frac{1}{R}\cdot\sqrt{\frac{L}{C}},$$ Equation 2-4

the inductance L and capacitance C can be written in terms of Q and ω_0.

$$L = \frac{QR}{\omega_0}$$ Equation 2-5

$$C = \frac{1}{QR\cdot\omega_0}$$ Equation 2-6

If Equation 2-5 and Equation 2-6 is used in Equation 2-2, impedance can be expressed with

$$\underline{Z} = R + j\cdot QR\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right).$$ Equation 2-7

The quality factor Q can also be used to define the bandwidth (like in Equation 2-1)

$$\frac{\Delta\omega}{2} = \frac{\omega_0}{2Q}$$ Equation 2-8

[00105]

[00106] The impedance phase is given by the inverse tangent of the imaginary part of Z, divided by the real part of Z. In this division, R cancels out. If in addition Equation 2-8 is used and the function is evaluated at the upper cut-off frequency, then the phase is given by

$$\varphi\left(\omega_0+\frac{\Delta\omega}{2}\right)=\tan^{-1}\left(Q\left(\frac{\omega_0+\frac{\omega_0}{2Q}}{\omega_0}-\frac{\omega_0}{\omega_0+\frac{\omega_0}{2Q}}\right)\right). \quad \text{Equation 2-9}$$

If the expression in the bracket is simplified, the phase gets dependent only from Q.

$$\varphi\left(\omega_0+\frac{\Delta\omega}{2}\right)=\tan^{-1}\left(Q+\frac{1}{2}-\frac{Q}{1+\frac{1}{2Q}}\right). \quad \text{Equation 2-10}$$

If Q increases, the function in the bracket tends to 1.

$$\varphi\left(\omega_0+\frac{\Delta\omega}{2}\right)=\tan^{-1}(1)=\frac{\pi}{4}. \quad \text{Equation 2-11}$$

[00107]

[00108] The result from Equation 2-11 corresponds to an angle of 90 degrees which implies that the imaginary part of Z is equal to the real part of Z. Those two points can then be found with a network analyzer, and then Equation 2-1 can be used to calculate Q. Hence, using this framework, the Q value of such an antenna can be actually determined.

[00109] A second embodiment of the antenna is shown in Figure 7. A coupling loop 700 is placed approximately 0.1 m away from the main part of the antenna 710. A plate capacitor is formed between two copper plates 721, 722. Screws 723, 724, 725 are formed of a capacitively-inert material such as polyimide. These screws are used to adjust the capacitance provided by the tuneable capacitor 720 and in turn adjust the resonance frequency of the antenna.

[00110] A glass body 730 or other dielectric may be below the antenna to minimize losses due to obstacles below the antenna.

[00111] Moreover, as described above, surface conduction is important to maximize Q. A silver plating or other non-corrosive material, may be applied to protect the copper from corrosion.

[00112] The coupling loop 700 may be formed of the same copper tube material, but has only one turn and about half the diameter of the antenna. The coupling loop is placed around 0.1 m away from the antenna to get a 50 W matching.

[00113] The following explains how the resonance frequency of the antenna parts can be determined. In the following equations, L is the inductance of the resonator itself, Cs is the self-capacitance of the resonator and CT is the tuneable capacitor associated with the resonator, Rr is the radiation resistance, Rℓ the loss resistance of the resonator.

$$L = \frac{\mu_0 \pi \cdot N^2 r_A^2}{0.9 r_A + l_A}$$ Equation 3-1

where:

r_A = loop radius
N = number of turns
l_A = length of antenna
μ_0= 1.2566 · 10^{-6}

$$C_S = \frac{\pi^2 \cdot 2r_A \cdot \varepsilon_0}{\ln\left(\frac{p}{2r_A} + \sqrt{\left(\frac{p}{2r_A}\right)^2 - 1}\right)}$$ Equation 3-2

where:

p = pitch of the antenna, corresponds to the distance between two turns plus the diameter of a turn
ε_0 = 8.8542 · 10^{-12}
Note: see [GRA] for a derivation of this formula.

$$C_T = \frac{\varepsilon_0 \cdot A}{d}$$ Equation 3-3

where:

A = area of the plate capacitor
d = distance between the plates
Note: this is an approximate formula because fringing is neglected. The real capacitance is higher than the calculated.

$$f_0 = \frac{1}{2\pi \cdot \sqrt{L \cdot (C_T + C_S)}}$$ Equation 3-4

$$R_r = 320\pi^4 N^2 \left(\frac{\pi \cdot r_A^2}{\lambda^2}\right)^2$$ Equation 3-5

[00114]

where:

λ = wavelength at the frequency f_0

$$R_l = 1.25 \cdot \frac{N \cdot \pi \cdot r_A}{r_w} \cdot \sqrt{\frac{f_0 \cdot \mu_0}{\sigma \cdot \pi}}$$ Equation 3-6

where:

σ = conductivity of the metal used for the antenna, 45 · 10^6 S/m used for calculations
r_w = radius of the copper tube

[00115]

[00116] Table 8 shows the values obtained for the current values of antenna parameters.

L [µH] (calculated value)	9.05
C_S [pF] (calculated value)	1.9
C_T [pF] (calculated value with the plate-distance varying from 5 mm – 15 mm)	6.2 - 18.6
R_r [Ohm]	0.0028
R_l [Ohm]	0.264
f_{Res} [MHz] (measured)	12.5
Quality factor Q (calculated)	2780
Quality factor Q (measured)	1300

Table 8

[00117]

An exemplary test arrangement for the pathgain-measurement may be carried out to obtain the actual values. This measurement may completely decouple the transmitter from the receiver, to avoid power transfer on the surface of the coaxial shields and on the power lines. A signal generator and a battery powered spectrum analyzer may be used on the transmitter and the receiver side respectively.

[00118] To measure the quality of the matching, the energy returning from the transmitting antenna is measured with a power meter which was connected through a directional coupler. The forward coupling port of the directional coupler was terminated with a 50 W load. During the measurements, the matching was at least 20 dB. Matching can be varied by adjusting the distance between the antenna and the coupling loop.

[00119] On the receiver side, the spectrum analyzer iss directly connected to the receiving antenna.

[00120] The same resonance frequencies are used for both antennas. Detuning results in a dramatically reduced power transfer. The receiving antenna may use a tuning aid, e.g., a Teflon bar that is selectively insertable into the tunable capacitor of the antenna, resulting in a resonance-shift of approximately 40 kHz, or may use an adjustable capacitor as previously described. For each distance measured, the receiving antenna is tuned to receive the maximum power available. The transmitting antenna is tuned by slightly adjusting the signal generator's frequency.

[00121] Table 9 shows the resulting measured pathgains.

Distance [m]	Level at receiver [dBm]	Level at transmitter [dBm]	Pathgain [dB]
1.1	3.3	12.5	-9.2
1.5	-3.7	12.5	-16.2
2.0	-10.5	12.5	-23.0
2.5	-18.5	12.5	-31.0
3.0	-25.3	12.5	-37.8

[00122] Table 9

[00123] Moreover, since the reactive voltage can easily exceed several kV, it may be useful to test the antenna prototypes to determine that reactive voltage, in order to allow determination of proper sizing for the capacitors. An electrically decoupled system may be used. A source signal from the signal generator is amplified by a 50 dB RF amplifier. The 20 dB attenuator in-between is used to limit the available power on the TX antenna.

[00124] The 3 dB attenuator after the amplifier is used to protect the amplifier in case of a mismatched antenna. To measure the quality of the matching, a power meter is used to show the energy returning from the antenna. On the receiver side, a small light bulb (50 W / 3 W) may be used to indicate the received power. Tuning and matching was realized by using the tuning aid, by varying the frequency of the signal generator and by varying the distance between the antennas and the coupling loop.

[00125] The results are summarized in the Table 10:

Distance [m]	1.2
Pathgain in dB	-11
Transmitting power [W]	10
Receiving power [W]	0.8
Approximate reactive voltage [kV]	3.1
Approximate field strength in the tuneable capacitor [kV / m]	310

[00126] Table 10

[00127] In one embodiment, sensitivity to close-by objects or humans may cause a shift of the resonance frequency due to e.g., stray capacitance. This may be mitigated by a shield, e.g., a slotted or other shield, disposed around the antenna.

[00128] In another embodiment, a piece of mica which has a high dielectric strength and very good isolating capabilities is used in place of the polyimide screws noted above. This also raises the quality factor. It is postulated suggesting that less energy is absorbed by the mica compared to the polymer.

[00129] In another configuration, very thin pieces of mica or Teflon are used to hold the capacitor and limit transmitting power.

[00130] There is a tradeoff between Q and bandwidth. Due to the high quality factor, the bandwidth of the exemplary second antennas is somewhat narrow, e.g., around 9 kHz at a resonance frequency of 13 MHz. This results in certain tuning requirements, because both antennas have to work on almost exactly the same resonance frequency. Hence, in another embodiment, the antenna sensitivity to approaching objects as described above is reduced using the shield described above. An electronic tuning circuit may be used to automatically tune the antenna circuit(s) to maintain coherence. The detuning issue becomes especially important in a system like this where the Q is very narrow. This narrow Q implies narrow bandwidth, which requires that the tuning be closer.

[00131] To further evaluate the effects of various external or design factors on Q, various aspects of the experimental setup are considered, including e.g. the glass body under the antenna, the piece of mica in the capacitor, the losses of the coupling loop, and the losses of all the objects within the near field of the antenna.

[00132] To evaluate these factors, the environment of the antenna should be as ideal as possible. Therefore, the exemplary antenna was suspended with two thin nylon strings. Two coupling loops are used to measure transmission (S 12 / S21) instead of reflection (S 11). The coupling loops were placed on both sides of the antenna, about 0.6 m away from the antenna, to achieve an undercritical coupling. That is, when an equal amount of power is dissipated in the external circuit as in the resonator itself, the coupling is said to be critical (and the antenna is matched). An undercritical coupling means that more power is dissipated in the resonator than in the external circuit, while an overcritical coupling means that more power is lost in the external circuit than in the resonator.

[00133] The theoretically expected Q for this embodiment is 2877. The realized Q of 2263 is 78.6% of the theoretical value. The theoretical value was almost reached in this test. It was also noted that higher Q, however, may make the antenna more susceptible to influence by its environment. Thus, in practice, the Q will likely always be lower than the theoretical value.

[00134] A second measurement showed another characteristic of the quality factor. The loaded quality factor QL should be half of the unloaded quality factor (Quℓ) under the condition when the resonator is critically coupled.

[00135] The foregoing transmitter and receiver apparatus (e.g., antenna. and any associated electronic or electrical components) may also be combined in another embodiment as a transceiver: i.e. a device adapted to both transmit and receive power. This may comprise for example a common form factor (e.g., a single unit or "box" having both transmit and receive antennas and circuitry disposed therein). Moreover, the device may be used as a repeater to receive energy from one source via the receive antenna, and then transmit the received power to another source (or back to the same on) using the transmit antenna. These events (transmission and reception) may occur at the same time or with one delayed relative to each other. Values can be modified depending on the polarization, strength, geometry, relative spacing and placement, and other factors associated with the transmit and receive antennas, or may also be conducted according to any number of well known multiple access schemes such as e.g., frequency division or FDMA (e.g.. wherein the resonant frequency of the first antenna (receiver or transmitter) is different or separated from that of the second antenna (transmitter or receiver). As yet another option, the two antennas may use the same or different frequency, and be time-divided or slotted as to their operation (e.g., TDMA).

[00136] In another alternative, a "CSMA" like approach may be used (whether with our without "collision detection"), such as where one device actively or passively detects or senses the activity of the other, and adjusts its behavior accordingly. In one such embodiment, the transmitter, before transmitting, detects the state of the receiver (e.g., whether in resonance, generating current, etc.) and uses this as a gating criterion for transmission).

[00137] Another embodiment uses a "resonant frequency hopping" approach, wherein multiple access or other aims, such as defeating or mitigating Rayleigh or antenna diversity fading or other such issues, is accomplished by way of periodically or deterministically or psuedorandomly hopping the resonant frequency as a function of time. For example, the transmitter and receiver may "seed" corresponding deterministic algorithms so as to mutually generate a common hop sequence that allows them to maintain synchronized. Alternatively. "in-band" (e.g., modulated power signal) signaling may be used to transmit the hop sequence in advance (or as it proceeds) to the receiver from the transmitter; e.g .. "I will hop to frequency X at next interval, and frequency X+Y after that. .. .", and so forth. A separate low power transmitter, e.g., RF or Bluetooth, can be used to synchronize the specific information. Clocking information may also be sent in an analogous way.

[00138] In another embodiment, a passive "collision detection" or CD approach is used, such as where the transmitter attempts to transmit, and determines whether an interfering operation is occurring at the same time. For example, the determination may be by detecting a resonant frequency, a transmission efficiency, a feedback from a receiver, or some other detection. This interfering operation may be caused by the

operation of the receiver, a parasitic or stray capacitance effect, a loss of tuning, or other similar effect.

[00139] The transmitter may take an action at that point to avoid the issue.

[00140] In an embodiment, since the interference is typically temporary, the transmitter can terminate the ongoing transmission and retry a later time. One example of this is via a random backoff via an anti-collision algorithm. One embodiment allows the power has transmitted to be stored in a storage part such as a battery. Because of this, the device can the power transmission can be stopped temporarily; while still allowing the powered device to operate.

[00141] The transmitter can attempt to tune itself to a different resonant frequency so as to mitigate the interference and/or attempt to tune or otherwise vary the operation of the receiver.

[00142] Another option is to increase the gain so as to increase an energy transfer rate. This may operate to "blast through" the interference as it were).

[00143] A system of adjusting polarization or orientation of transmitter and/or receiver can be used, such as via a motor drive or similar mechanism that physically alters the position of the antenna(s).

[00144] Any combination of the above can alternatively be used. These features can be implemented at the transmitter, and/or at the receiver basis, or in tandem or coordination between the transmitter and receiver.

[00145] Another embodiment uses signaling information between the devices that relates to the level or rate of power transfer as determined by the receiver (e.g., "here's what I'm actually receiving, so you can compare this to what you are actually sending to tune yourself, transmitter"). Moreover, the aforementioned multiple access schemes can be implemented in this fashion; e.g., backoff or CD based on a drop in receiver received power as communicated back to the transmitter via a communication channel.

[00146] As yet another alternative embodiment, multiple transmitters and/or receivers may be used, and the aforementioned features implemented as between the multiple transmitters (and/or receivers). For example, the FDMA, TDMA, CSMA or CD techniques may be applied as between two potentially conflicting transmitters.

[00147] The foregoing functions may be implemented at an electrical or electronic component level; e.g., via simple gate logic or the like implemented as anything from discrete components through highly integrated circuits, as computer programs or applications running on e.g., a micro-controller or digital processor, via firmware disposed on a IC, manually, or in hardware to the degree applicable (e.g .. electromechanical tuners, motors, etc.).

[00148] Moreover, the present application contemplates the dynamic alteration or variation of one or more antenna or circuit parameters by environmental characteristics. For example, this can change antenna characteristics. The characteristics that can be changed can include tuning capacitance, resistance value, radius of the loop or coil, e.g. via a thermal effect that causes elongation or contraction of the material used to form the antenna loop(s), thereby changing its effective radius, the properties of the antenna or components in proximity thereto (e.g .. by selectively applying a particular electric field or magnetic field, alignment of dipoles within the material or components might be selectively altered, thereby affecting the properties of the antenna), as well as electrical or electronic processing such as power signal processing, filtration, modulation, and others.

[00149] For example, in one embodiment, the (predominantly) magnetic field of the transmitter is modulated or impressed with information so as to transfer information, along with power.

[00150] In another embodiment this information comprises control signaling between the receiver and transmitter, thereby obviating any separate data or communications link (and hence simplifying the system and making it more robust). For instance, the transmitter may modulate the transmitted narrowband signal as a function of time, e.g., via an amplitude modulation, phase modulation. sideband or frequency modulation; e.g., GMSK or sideband shift up or down to encode a data "0" or "1", pseudo-noise modulation. or other technique. This allows transfer of information relating to inter alia transmitter parameters (such as resonant frequency. polarization, etc. that might otherwise allow the receiver to better "lock on" to the transmitter to optimize power transfer. Duty cycle, clock, or timing information might also be encoded: e.g., windows during which the transmitter will be operational, to synchronize time frames of reference etc.

[00151] The theoretical limits on antenna performance are explained herein. Aspects such as the antenna efficiency, quality factor (bandwidth) and size are considered. In addition, a model for the radio wave propagation in the near-field and in the far-field is established.

[00152] An electrically small antenna is an antenna that can be fitted into a fraction of a radiansphere, which is a sphere of radius rmax

$$r_{max} = \frac{1}{k} = \frac{\lambda}{2\pi} = \frac{c}{2\pi f} = \frac{d_{max}}{2}$$

[00153] (eq A-1)

[00154] where: k is the wavenumber in m-1

[00155] ℓ 1is the wavelength in m

[00156] c is the speed of light 299792458 ms-1

[00157] f is the frequency in Hz, and

[00158] dmax is the diameter of the radiansphere

[00159] The antennas used for this application will be electrically small in almost all cases (i.e. kr < 1), where kr =d/ℓo.

[00160] Electrically small antennas are not typically self-resonant. For low frequencies, the antennas are either capacitive (dipole antenna) or inductive (loop antenna). They can be approximated for example by a first-order series RC or parallel RL circuit. They are brought to resonance by tuning with a reactor of an opposite kind.

[00161] The equivalent circuit of such an antenna is shown in Figure 8 for the capacitive case. One main element of the antenna is the radiation resistance Rr. In the equivalent circuit, this resistor models the radiated power. The loss resistor RL accounts for the conduction and dielectric losses of the antenna. The capacitor C represents the reactive component of the antenna. This, together with the external matching inductor L forms a resonant circuit, which is tuned to the operating frequency. This circuit can also be modeled as an equivalent representation as a parallel resonant circuit.

$$R_s + j\omega_o L = \left(\underbrace{R_L + R_r}_{R_a}\right) - j\frac{1}{\omega_o C},\ \omega_o = \frac{1}{\sqrt{LC}}$$

where:

R_s is the source resistance in Ω

R_a is the antenna resistance in Ω

R_L is the loss resistance in Ω

R_r is the radiation resistance in Ω

ω_o is the resonance frequency in rads^{-1}

L is the matching inductance in H

C is the antenna capacitance in F

[00162]

(eq A-2) For maximum power transfer, the antenna and matching network impedance is complex conjugate matched at resonance to the antenna impedance.

[00163] A similar circuit can be derived for the case of an inductive antenna.

[00164] Applicants believe that there are fundamental limits on the efficiency and quality Factor of such an antenna. If a certain antenna performance is required, the size of an antenna cannot be reduced to an arbitrary value. Like the well-known Shannon limit in communication theory, which relates channel capacity to bandwidth and dynamic range, there is also a fundamental limit in antenna theory that relates minimum antenna size to the radiation quality factor.

[00165] There have been many attempts to calculate the theoretical limits on antenna size. The fundamental work was done by Chu [CHU] and Harrington [HAR]. Their theory states that the antenna is completely enclosed by a sphere of radius r, The field outside the sphere, can be expressed as a sum of weighted spherical waves propagating radially outward. Each wave (mode) exhibits power orthogonality and therefore carries power independently from the others.

[00166] It can be mathematically proven that a particular field outside the sphere can be generated with an infinite number of different source distributions. The field outside the sphere is therefore independent from a particular implementation of the antenna. From Chu's calculation it has been shown that an antenna that excites only one mode (either TE01 or TM01) achieves the lowest possible radiation quality factor of any linearly polarized antenna. Based on the above-described fundamental work. Hansen derived an approximate analytical expression for this quality factor Qr [HAN], which has been cited many times in the literature. Mclean further developed and corrected the work from Hansen [MLE], giving an exact expression for the radiation quality factor Qr of a linear polarized antenna:

$$Q_r = \left\{ \begin{array}{l} 2\omega \frac{W_e}{P_r}, W_e > W_m \text{ (capacitive antenna)} \\ 2\omega \frac{W_m}{P_r}, W_m > W_e \text{ (inductive antenna)} \end{array} \right\} = \frac{1}{(kr)^3} + \frac{1}{kr}$$ Equation 3

where:
Q_r is the radiation quality factor (unitless)
ω is the radian frequency in rads^{-1}
W_e is the time-averaged, non-propagating, stored electric energy in J
W_m is the time-averaged, non-propagating, stored magnetic energy in J
P_r is the radiated power in W

[00167]

This equation shows that the dominant term for electrically small antennas (k; « 1) is the cubic term. However, for large antennas (k; » 1) the radiation quality factor will be governed by the linear term.

[00168] A physical implementation of an antenna exhibits losses, i. e. its radiation efficiency is smaller than unity due to non-ideal conductors and dielectrics. The reduction of the efficiency has an impact on the overall quality factor, called the antenna quality factor. Assuming the antenna is power-matched to the source, the antenna quality factor Qa results in:

$$Q_a = \eta_r Q_r$$

where:
Q_a is the antenna quality factor (unitless)

[00169] Eq A4

[00170] where:

[00171] Q" is the antenna quality factor (unitless)

[00172] Three important relations can be derived from Equation A3 and Equation A4:

- For small antennas the efficiency is proportional to the cube of the relative antenna size and therefore also proportional to the cube of the antenna size and to the cube of the frequency:

$$\eta_r \propto (kr)^3 \propto r^3 \propto f^3 \quad \text{Equation 5}$$

- For large antennas the efficiency is proportional to the relative antenna size and therefore also proportional to the antenna size and the frequency:

$$\eta_r \propto kr \propto r \propto f \quad \text{Equation 6}$$

- In general, the radiation efficiency is proportional to the antenna quality factor:

$$\eta_r \propto Q_a \quad \text{Equation 7}$$

For the antenna models in Figure 4 and Figure 5 the values for radiation quality factor Q_r and radiation efficiency η_r are given as:

$$Q_{r,cap} = \frac{\mathrm{Im}\{Z_a\}}{\mathrm{Re}\{Z_a\}} = \frac{1}{\omega_o R_r C} \quad \text{Equation 8}$$

$$Q_{r,ind} = \frac{\mathrm{Im}\{Y_a\}}{\mathrm{Re}\{Y_a\}} = \frac{R_r}{\omega_o L} \quad \text{Equation 9}$$

$$\eta_r = \frac{P_r}{P_{in}} = \frac{R_r}{R_r + R_L} \quad \text{Equation 10}$$

where:
η_r is the radiation efficiency (unitless)
Z_a is the antenna input impedance in Ω
Y_a is the antenna input admittance in Ω^{-1}
P_r is the radiated power at resonance in W
P_{in} is the power input to the antenna at resonance in W

[00173]
This shows that for a given radiation efficiency, reducing antenna size leads to increased antenna quality factor. For a given antenna size, decreasing radiation efficiency results in lower antenna quality factor. Consequently, for a given radiation efficiency, a higher antenna quality factor is the penalty for a small antenna size.

[00174] The antenna quality factor decreases with increasing frequency and increasing antenna size when the radiation for the wireless powering and charging system the antenna efficiency is the most important criterion, as this determines how much power can be transmitted between two antennas. Equation 5 illustrates that the antenna efficiency is proportional to the cube of the relative antenna size and therefore also proportional to the cube of the absolute antenna size. Increasing the size by a factor of 10 results in an improvement of antenna efficiency of 30dB (factor 1000), assuming that the antenna quality factor is kept constant.

[00175] Equation 7 shows that the antenna quality factor is proportional to the antenna efficiency. Increasing by 10 times the antenna quality factor yields an increase of the antenna efficiency of 10dB (factor 10), assuming a constant relative antenna size. Antenna efficiency is proportional to the cube of the frequency. An increase by a factor of 10 in the frequency leads to an improvement of the antenna efficiency by 30dB (factor 1000), assuming that the antenna size and the antenna quality factor are kept constant.

[00176] Unlike the fundamental limits on efficiency and quality factor that have been described above, the gain does not present a physical limit. However, as opposed to the gain, there is a good knowledge of the directivity that can be achieved with certain antenna types. The directivity is linked to the gain as follows:

[00177] $G=hD$ …. (A11)

[00178] According to Balanis [BAL], the directivity of a small dipole is D=1.5. The same directivity applies also to a small loop. This similarity becomes clear when the principle of duality of the electric and magnetic field is applied, as a small loop can be described with the help of a magnetic dipole.

[00179] Higher directivities can be expected from antennas that are not electrically small. This is the case e.g. for the dipole as can be seen from Figure A1. If the maximum antenna dimension is in the order of a wavelength, the directivity is higher than that of the small dipole. However, for the wireless powering and charging system this is only the case for frequencies above 1 GHz.

[00180] Radio Wave Propagation

[00181] The characteristics of an antenna show a strong dependence on the point (in terms of distance) where their fields are observed. A distinction between near field and far field is often made. In the near-field region, the electromagnetic energy is mainly stored and not radiated (stationary wave). The boundary for this region is usually defined as:

- Near-field: In the near-field region the electromagnetic energy is mainly stored and not radiated (stationary wave). The boundary for this region is usually defined as:
  $kr << 1 \leftrightarrow r << \frac{\lambda}{2\pi}$,
  where:
  k is the wave number, and
  r the observation distance to the antenna.

[00182]

In the far-field region most of the electromagnetic energy is radiated and not stored. The boundary for this area is usually defined as:

- Far-field: In the far-field region most of the electromagnetic energy is radiated and not stored. The boundary for this area is usually defined as:
  $kr >> 1 \leftrightarrow r >> \frac{\lambda}{2\pi}$.

[00183]

[00184] Between the near-field and the far-field a transition from a stationary into a propagating wave occurs. This is the so-called transition region.

[00185] For a distance of 0.5 to 5m to the antenna the boundary between the near-field and the far-field is in the frequency range of 10 to 100MHz.

[00186] All radio waves propagate in a very different manner in the near-field and in the far-field. From radio communication theory the Friis transmission equation is well known. It describes the ratio of received power to power of a transmit antenna. assuming a certain receive and transmit antenna gain, as well as a certain separation between these antennas:

$$\frac{P_{Rx}}{P_{Tx}} = G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi r} \right)^2$$ **Equation 12**

[00187]

[00188] This equation is only valid in the Far-field. For a more general treatment of energy transmission between two antennas, a new equation is developed that also covers the near-field.

[00189] The radiated fields of an electrically small dipole will be considered As a basis for this general radio wave propagation model. The dipole can also be used to model a loop antenna because of the principle of duality of the electric and magnetic field. Because of this, the electric field component of a dipole corresponds to the magnetic field component of the loop and vice versa.

[00190] Equation 13 and Equation 14 show the components of the electric and the magnetic field of a small dipole. The radial component of the electric field has been omitted, as it accounts only for the reacti ve energy that is stored in the near-field.

$$E_\theta = j\eta \frac{kI_o l \sin\theta}{4\pi r}\left[1 + \frac{1}{jkr} - \frac{1}{(kr)^2}\right] \cdot e^{-jkr}$$ Equation 1

$$H_\phi = j\frac{kI_o l \sin\theta}{4\pi r}\left[1 + \frac{1}{jkr}\right] \cdot e^{-jkr}$$ Equation 1

[00191]

In these equations, r is the distance to the antenna and not the antenna radius. After some algebraic manipulations, the following simplified equations for the field magnitude can be obtained:

$$|E_\theta|^2 \propto \frac{1}{(kr)^2} - \frac{1}{(kr)^4} + \frac{1}{(kr)^6} \propto P_{RX,E}$$ **Equation 15**

$$|H_\phi|^2 \propto \frac{1}{(kr)^2} + \frac{1}{(kr)^4} \propto P_{RX,H}$$ **Equation 16**

[00192]

[00193] The received power from a co-polarized antenna, that is, one in which the transmit and the receive antenna are parallel to each other, is proportional to the time averaged value of the incident field squared as described above. Thus, the path gain can be calculated as follows

$$G_{path,E_\theta} = \frac{P_{RX,E}}{P_{TX}} = \frac{G_{Tx}G_{Rx}}{4}\left[\frac{1}{(kr)^2} - \frac{1}{(kr)^4} + \frac{1}{(kr)^6}\right]$$ **Equation 1**

$$G_{path,H_\phi} = \frac{P_{RX,H}}{P_{TX}} = \frac{G_{Tx}G_{Rx}}{4}\left[\frac{1}{(kr)^2} + \frac{1}{(kr)^4}\right]$$ **Equation 1**

[00194]

Equation 17 is the propagation law for like antennas (propagation from a dipole to another co-polarized dipole or propagation from a loop to another co-polarized loop). Equation 18 is the propagation law for unlike antennas (propagation from a dipole to a co-polarized loop or propagation from a loop to a co-polarized dipole). The path gain in the near-field is much higher than what would be expected by applying the far-field theory (Friis equation). For the transmission between like antennas in the near-field a path loss of 60dB/decade can be seen, whereas the transmission between unlike antennas in the near-field has a path loss of

40dB/decade. This is contrasted to the path loss of 20dB/decade that is seen in the far-field.

[00195] These equations can be used to determine additional antennas and characteristics that can be used for this purpose.

[00196] Although only a few embodiments have been disclosed in detail above, other embodiments are possible and the inventors intend these to be encompassed within this specification. The specification describes specific examples to accomplish a more general goal that may be accomplished in another way. This disclosure is intended to be exemplary, and the claims are intended to cover any modification or alternative which might be predictable to a person having ordinary skill in the art.

[00197] For example, other antenna forms and selections can be used. The term "power" as used herein can refer to any kind of energy, power or force transfer of any type. The receiving source can be any device that operates from stored energy, including a computer or peripheral, communicator, automobile, or any other device. Myriad applications of the foregoing transmitter, receiver and transceiver apparatus of the invention are recognized. By way of example and without limitation, such applications include: (i) powering or charging portable computers. PMDs. client devices. cellular phones. etc.; (ii) powering or charging flat screen or wall-mounted televisions or displays; (iii) powering or charging

refrigerators (e.g., by placing a transmitter on the wall behind the refrigerator. and a receiver in the refrigerator proximate to the transmitter); (iv) powering or charging electric cars; e.g., by placing or building in a transmitter in the floor of a garage, and placing a receiver on the bottom of the car: (v) powering or charging home or office lighting: e.g.. incandescent, fluorescent or LED¬based lamps with no cords: (vi) powering or charging home or office appliances such as toasters, blenders, clocks, televisions, microwave ovens, printers, computers, etc.: (vii) powering or charging multiple devices simultaneously (e.g., through the use of a substantially omni-directional transmitter arrangement); and (viii) powering or charging devices where the presence of electrical conductors with voltage would represent a hazard; e.g., near water, near children, etc.

[00198] As used herein, the terms "electrical component" and "electronic component" are used interchangeably and refer to, without limitation, components adapted to provide some electrical or electronic function, including without limitation inductive reactors ("choke coils"), transformers, filters, gapped core toroids, inductors, capacitors, resistors, operational amplifiers, varactors, MEMS devices, FETs and other transistors and diodes, whether discrete components or integrated circuits, whether alone or in combination.

[00199] As used herein, the term "integrated circuit (IC)" refers to any type of device having any level of integration (including without limitation ULSI, VLSI, and LSI) and irrespective of process or base materials (including, without limitation Si, SiGe, CMOS and GAs). ICs may include, for example, memory devices (e.g., DRAM, SRAM, DDRAM, EEPROM/Flash, ROM), digital processors, SoC devices, FPGAs, ASICs, ADCs, DACs and other devices, as well as any combinations thereof.

[00200] As used herein, the term "digital processor" is meant generally to include all types of digital processing devices including, without limitation, digital signal processors (DSPs), reduced instruction set computers (RISC), general-purpose (CISC) processors, microprocessors, gate arrays (e.g., FPGAs), Reconfigurable Compute Fabrics (RCFs), and application-specific integrated circuits (ASICs). Such digital processors may be contained on a single unitary IC die, or distributed across multiple components.

[00201] As used herein, the terms "computing device", "client device", and "end user device" include, but are not limited to, personal computers (PCs) and minicomputers, whether desktop, laptop, or otherwise, set-top boxes such as the Motorola DCT2XXXl5XXX and Scientific Atlanta Explorer 2XXXl3XXX/4XXXl8XXX series digital devices, personal digital assistants (PDAs) such as the Blackberry® or "Palm®" family of devices, handheld computers, personal communicators, J2ME

equipped devices, cellular telephones, or literally any other device capable of using power, or interchanging data with a network.

[00202] As used herein, the term "memory" includes any type of integrated circuit or other storage device adapted for storing digital data including, without limitation, ROM, PROM, EEPROM, DRAM, SDRAM, DDR/2 SDRAM, EDOIFPMS, RLDRAM, SRAM, "flash" memory (e.g., NANDINOR), and PSRAM.

[00203] Also, the inventors intend that only those claims which use the words "means for" are intended to be interpreted under 35 USC 112, sixth paragraph. Moreover, no limitations from the specification are intended to be read into any claims, unless those limitations are expressly included in the claims.

[00204] The operations and/or flowcharts described herein may be carried out on a computer, or manually. If carried out on a computer, the computer may be any kind of computer, either general purpose, or some specific purpose computer such as a workstation. The computer may be an Intel (e.g., Pentium or Core 2 duo) or AMD based computer, running Windows XP or Linux, or may be a Macintosh computer. The computer may also be a handheld computer, such as a PDA, cellphone, or laptop. Moreover, the method steps and operations described herein can be carried out on a dedicated machine that does these functions.

[00205] The programs may be written in C or Python, or Java, Brew or any other programming language. The programs may be resident on a storage medium, e.g., magnetic or optical, e.g. the computer hard drive, a removable disk or media such as a memory stick or SD media, wired or wireless network based or Bluetooth based Network Attached Storage (NAS), or other removable medium or other removable medium. The programs may also be run over a network, for example, with a server or other machine sending signals to the local machine, which allows the local machine to carry out the operations described herein.

[00206] Where a specific numerical value is mentioned herein, it should be considered that the value may be increased or decreased by 20%, while still staying within the teachings of the present application, unless some different range is specifically mentioned. Where a specified logical sense is used, the opposite logical sense is also intended to be encompassed.

WHAT IS CLAIMED IS:

1. A method, comprising:

inducing power into a near field magnetic field of a transmitting antenna; and

operating the transmitting antenna along with a receiving antenna, to couple the power magnetically to a receiving antenna that has at least one characteristic that is matched to the transmitting antenna; and

tuning at least one of said antennas to improve a matching therebetween.

2. A method as in claim 1, wherein said matching comprises matching impedances between said antennas.

3. A method as in claim 2, wherein said tuning comprises using an adjustable capacitor in the at least one of said antennas and electrically adjusting a capacitance value of the adjustable capacitor to a desired value.

4. A method as in claim 3, wherein said tuning comprises adjusting a distance between plates in a capacitor.

5. A method as in claim 4, wherein said adjusting comprises using screws made of a non-electrical material.

6. A method as in claim 3, wherein said adjustable capacitor comprises an electrically adjustable capacitor, and said tuning comprises automatically tuning.

7. A method as in claim 6, wherein said electrically adjustable capacitor comprises a varactor diode.

8. A method as in claim 3, further comprising a fixed value capacitor in addition to said adjustable capacitor.

9. A method as in claim 8, wherein said variable capacitor has 10% of a capacitance value of the fixed value capacitor.

10. A method as in claim 2, further comprising detecting a temporary situation that reduces matching between the transmitter and receiver, and carrying out at least one operation responsive to said detecting.

11. A method as in claim 10, wherein said detecting is carried out at the transmitter.

12. A method as in claim 11, wherein said least one operation comprises terminating power transmission until the temporary situation is terminated.

13. A method as in claim 2 wherein said tuning comprises using an electrically adjustable capacitor in the at least one antenna and electrically adjusting a capacitance value of the electrically-adjustable capacitor to a desired value and wherein said at least one operation comprises changing a value of said adjustable capacitor.

14. A method as in claim 1, wherein said transmitter and said receiver are both formed of antennas made of circular shaped loops of electrically conductive material.

15. A method as in claim 1, wherein said operating comprises storing energy in and near field of the transmitting antenna and inducing said energy into the receiving antenna.

16. A method as in claim 1, wherein each of said antennas have a Q of at least 1000.

17. A method as in claim 1, wherein each of said antennas are magnetic antennas which are tuned to within 10% of their resonant values.

18. A method as in claim 2, wherein said antennas include capacitors therein, and further comprising sizing said capacitors to withstand at least 2KV of reactive voltage.

19. A wireless power transmitter, comprising:

a power transmitter, that produces power to be transmitted wirelessly over a magnetic link; and

an inductive loop antenna part, having at least one capacitive part connected to said inductive loop part, wherein said capacitive part is sized to withstand at least 2KV of reactive voltage.

20. A transmitter as in claim 19, further comprising a receiver with a receiving antenna that is matched to the transmitting antenna.

21. A transmitter as in claim 19, further comprising a tuning part that allows tuning said antenna.

22. A transmitter as in claim 21, wherein said tuning part comprises an adjustable capacitor.

23. A transmitter as in claim 22, wherein said adjustable capacitor comprises a capacitor with plates whose distance can be adjusted.

24. A transmitter as in claim 23, wherein said capacitor has screws made of a non-electrical material.

25. A transmitter as in claim 21, wherein said tuning part comprises an electrically adjustable capacitor.

26. A transmitter as in claim 25, wherein said tuning part comprises a varactor diode.

27. A transmitter as in claim 25, further comprising a fixed value capacitor in addition to said adjustable capacitor.

28. A transmitter as in claim 27, wherein said variable capacitor that has 10% of a capacitance value of the fixed value capacitor.

29. A transmitter as in claim 20, further comprising a part that detects a reduction of matching between the transmitter and receiver, and carries out at least one operation responsive to the detecting.

30. A transmitter as in claim 29, wherein said device terminates power transmission until the temporary situation is terminated.

31. A transmitter as in claim 29, further comprising an adjustable capacitor in at least one antenna and said device electrically adjusts a capacitance value of the electrically-adjustable capacitor to a desired value to change a value of said adjustable capacitor to improve said matching.

32. A transmitter as in claim 19, wherein said antenna is made of circular shaped loop of electrically conductive material.

33. A transmitter as in claim 19, wherein said antenna has a Q of at least 1000.

34. A transmitter as in claim 19, wherein said antenna is a magnetic antenna which is tuned to within 10% of its resonant value.

35. A transmitter as in claim 19, wherein said antenna has a first part, connected to the power transmitter, and forming a coupling loop, and a second part, electrically unconnected to said coupling loop, into which power is electrically induced.

36. A transmitter as in claim 19, wherein at least part of said antenna is electrically decoupled from said power transmitter.

37. A transmitter as in claim 19, wherein at least part of said antenna is coated with an anti corrosion material.

38. A wireless power receiver, comprising:

an inductive loop antenna part, having at least one capacitive part connected to said inductive loop part, wherein said capacitive part is sized to withstand at least 2KV of reactive voltage; and

a power receiver, coupled to receive power from said inductive loop antenna part, that has been transmitted wirelessly over a magnetic link.

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39. A receiver as in claim 38, wherein said inductive loop antenna part forms a receiving antenna, and further comprising a transmitter with a transmitting antenna that is matched to the receiving antenna.

40. A receiver as in claim 38, further comprising a tuning part that allows tuning said antenna.

41. A receiver as in claim 40, wherein said tuning part comprises an adjustable capacitor.

42. A receiver as in claim 41, wherein said adjustable capacitor comprises a capacitor with plates whose distance can be adjusted.

43. A receiver as in claim 42, wherein said capacitor has screws made of a non-electrical material.

44. A receiver as in claim 40, wherein said tuning part comprises an electrically adjustable capacitor.

45. A receiver as in claim 44, wherein said tuning part comprises a varactor diode.

46. A receiver as in claim 44, further comprising a fixed value capacitor in addition to said adjustable capacitor.

47. A receiver as in claim 46, wherein said variable capacitor that has 10% of a capacitance value of the fixed value capacitor.

48. A receiver as in claim 39, further comprising a part that detects a reduction of matching between the receiver and transmitter, and carries out at least one operation responsive to the detecting.

49. A receiver as in claim 48, wherein said device terminates power transmission until the temporary situation is terminated.

50. A receiver as in claim 48, further comprising an adjustable capacitor in at least one antenna and said device electrically adjusts a capacitance value of the electrically-adjustable capacitor to a desired value to change a value of said adjustable capacitor to improve said matching.

52. A receiver as in claim 38, wherein said antenna is made of a circular shaped loop of electrically conductive material.

53. A receiver as in claim 38, wherein said antenna has a Q of at least 1000.

54. A receiver as in claim 38, wherein said antenna is a magnetic antenna which is tuned to within 10% of its resonant value.

55. A receiver as in claim 38, wherein at least part of said antenna is coated with an anti corrosion material.

56. A wireless power transmitter, comprising:

a power transmitter connection, that receives energy to be transmitted wirelessly over a magnetic link;

a first coupling antenna part, electrically connected to receive said energy; and

a second antenna part, electrically disconnected from said first coupling part and from said power transmitter connection, and operating to transmit, magnetically, said energy.

57. A transmitter as in claim 56, wherein at least one of said antenna parts includes an inductive loop antenna part, having at least one capacitive part connected to said inductive loop part, wherein said capacitive part is sized to withstand at least 2KV of reactive voltage.

58. A transmitter as in claim 56, further comprising a tuning part that allows tuning said antenna.

59. A transmitter as in claim 58, wherein said tuning part comprises an adjustable capacitor.

60. A transmitter as in claim 56, wherein said adjustable capacitor comprises a capacitor with plates whose distance can be adjusted.

61. A transmitter as in claim 58, wherein said tuning part comprises an electrically adjustable capacitor.

62. A transmitter as in claim 61, wherein said tuning part comprises a varactor diode.

63. A transmitter as in claim 61, further comprising a fixed value capacitor in addition to said adjustable capacitor.

64. A transmitter as in claim 63, wherein said variable capacitor that has 10% of a capacitance value of the fixed value capacitor.

65. A method, comprising:

transmitting power from a transmitting antenna to a receiving antenna;

automatically detecting a detuning event that detunes a relationship between said transmitting antenna and receiving antenna; and

responsive to said detecting, automatically taking an action to change a characteristic of said transmitting.

66. A method as in claim 65, wherein said action comprises terminating device power transmission during a time of the detuning event.

67. A transmitter as in claim 65, wherein said action comprises electronically tuning one of said antennas to a different resonance value.

68. A wireless power transmitter, comprising:

a power transmitter connection, that receives energy to be transmitted wirelessly over a magnetic link;

at least one antenna part formed of a single loop of conductive material; and

a capacitor part, having a value to match an L and C value of the antenna to a frequency of said power transmitter.

69. A transmitter as in claim 68, wherein said antenna includes a first coupling antenna part, electrically connected to receive said energy; and

a second antenna part, electrically disconnected from said first coupling part and from said power transmitter connection, and operating to transmit, magnetically, said energy.

70. A transmitter as in claim 68, wherein said capacitor part is sized to withstand 2KV of reactive voltage.

71. A method, comprising:

magnetically transmitting power from a transmitting antenna to a receiving antenna, where each of said antennas has a Q value for a specified frequency, greater than 1000; and

tuning said antennas to maintain resonance at said specified frequency.

72. A method comprising:

forming a radiated magnetic field with energy therein using a transmitting antenna with a Q value greater than 1000;

extracting energy from the radiated field of the transmitting antenna, at a receiving antenna location that is unconnected to said transmitting antenna by any wires; and

using said energy in an electronic device that is unconnected to said transmitting antenna by any wires.

73. A method as in claim 72, further comprising adaptively tuning circuit one of said antennas.

74. A method as in claim 73 wherein said adaptive tuning is carried out automatically by an electric circuit associated with at least one of said antennas.

75. A method as in claim 72, further comprising matching a resistance of a receiving antenna to the load resistance.

76. A method as in claim 72, further comprising shielding at least one of said antennas against external influences to resonance.

77. A method as in claim 76, wherein said shield is against stray capacitance.

78. An apparatus comprising:

a receiving antenna, operative to extract energy from a radiated field at a receiving antenna location that is unconnected to any transmitting antenna by any wires; and

a power system, using said energy in an electronic device that is unconnected to said transmitting antenna by any wires.

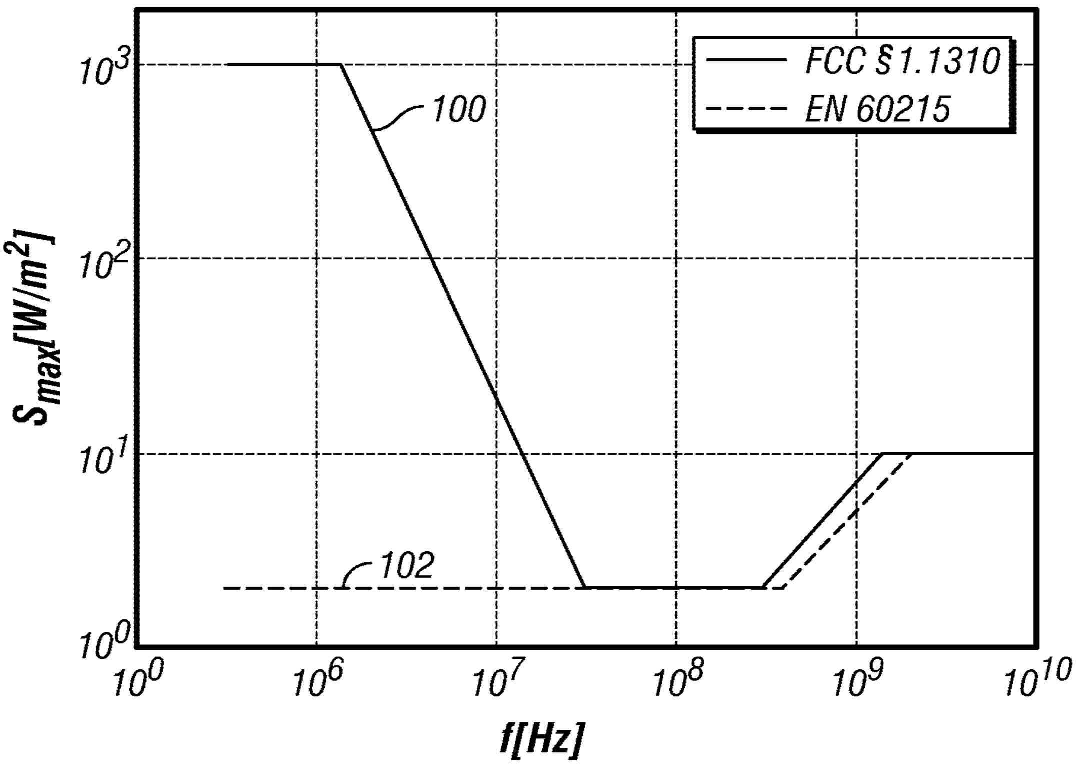
79. An apparatus as in claim 78, further comprising an adaptive tuning circuit, changing a tuning value of one of said antennas.

80. An apparatus as in claim 79 wherein said adaptive tuning circuit is an automatic tuning circuit associated with at least one of said antennas.

81. An apparatus as in claim 78, further comprising a matching circuit that matches a resistance of a receiving antenna to the load resistance.

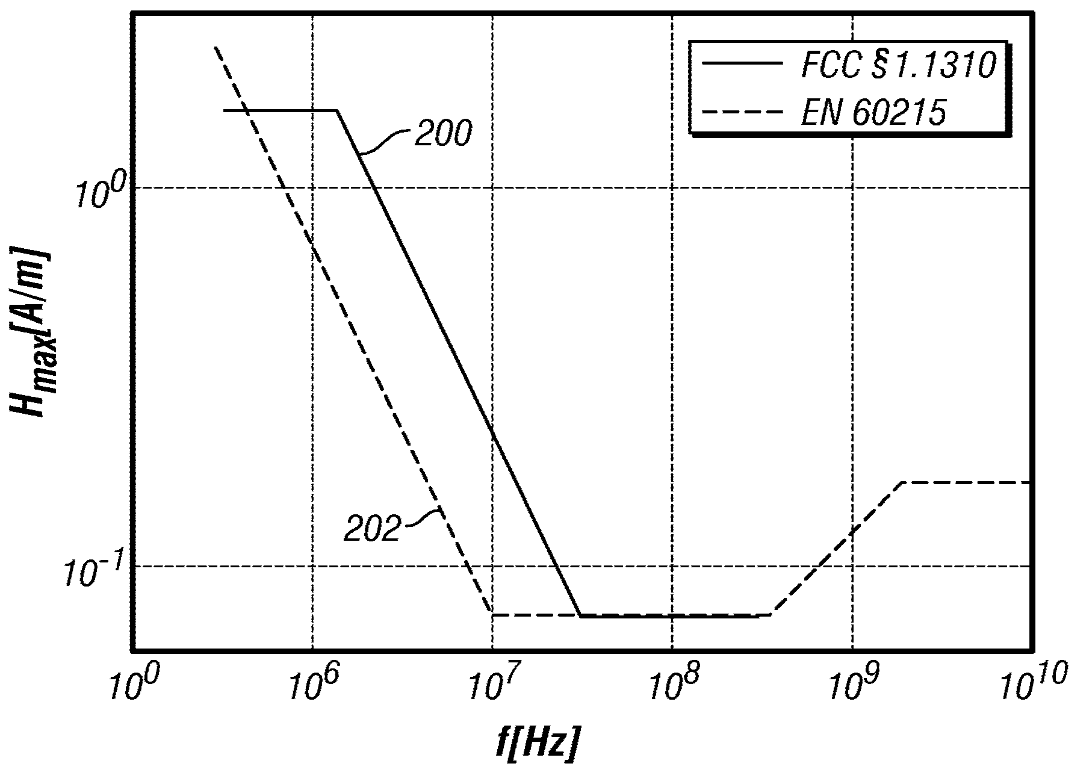
82. An apparatus as in claim 78, further comprising a shield that shields at least one of said antennas against external influences to resonance.

83. An apparatus as in claim 82, wherein said shield is a slotted shield.



FCC §1.1310
EN 60215
100
102
10^3
10^2
10^1
10^0
$S_{max}[W/m^2]$
10^0
10^6
10^7
10^8
10^9
10^{10}
f[Hz]

FIG. 1



FCC §1.1310
EN 60215
200
202
10^0
10^{-1}
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10^6
10^7
10^8
10^9
10^{10}
f[Hz]

FIG. 2

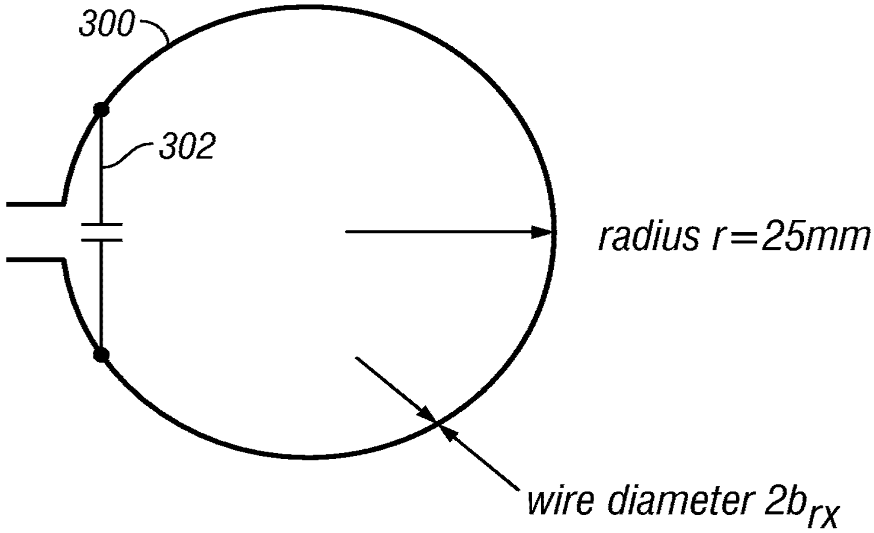
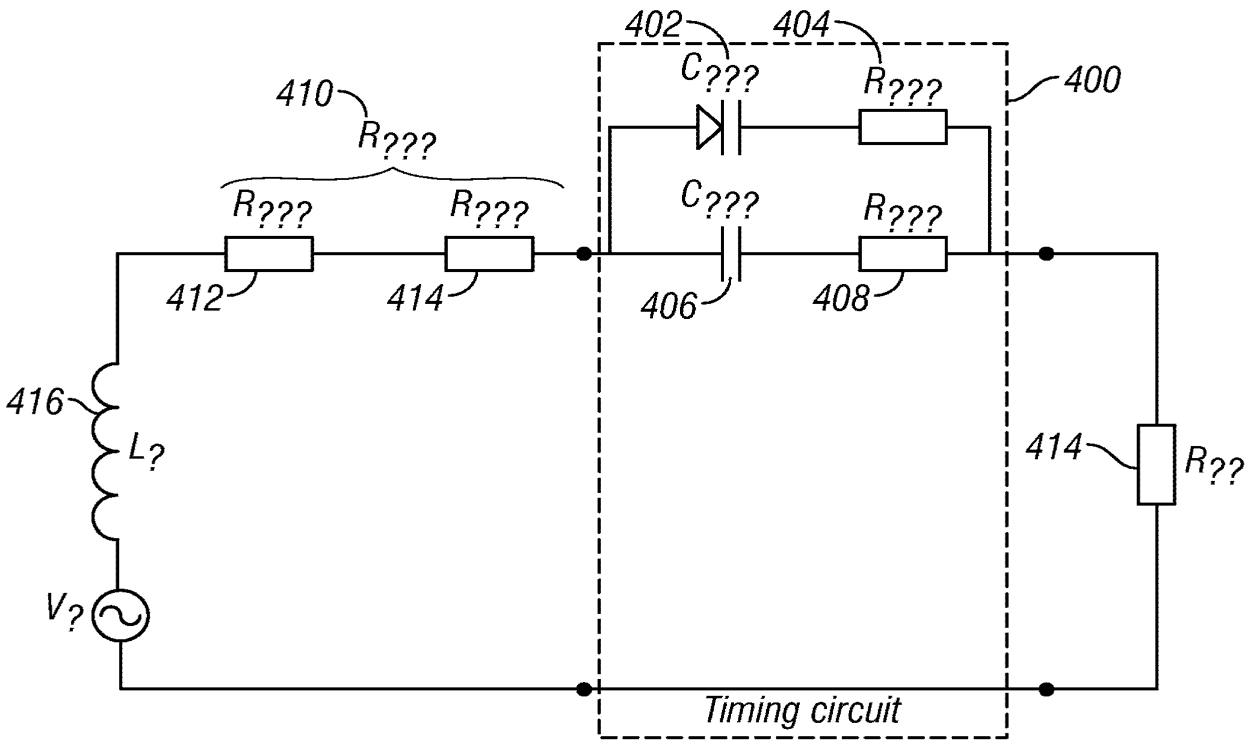

300
302
radius r=25mm
wire diameter $2b_{rx}$

FIG. 3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404
400
410
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$R_{???}$
$R_{???}$
$R_{???}$
$R_{???}$
$C_{???}$
$R_{???}$
412
414
406
408
416
$L_?$
414
$R_{??}$
$V_?$
Timing circuit

FIG. 4

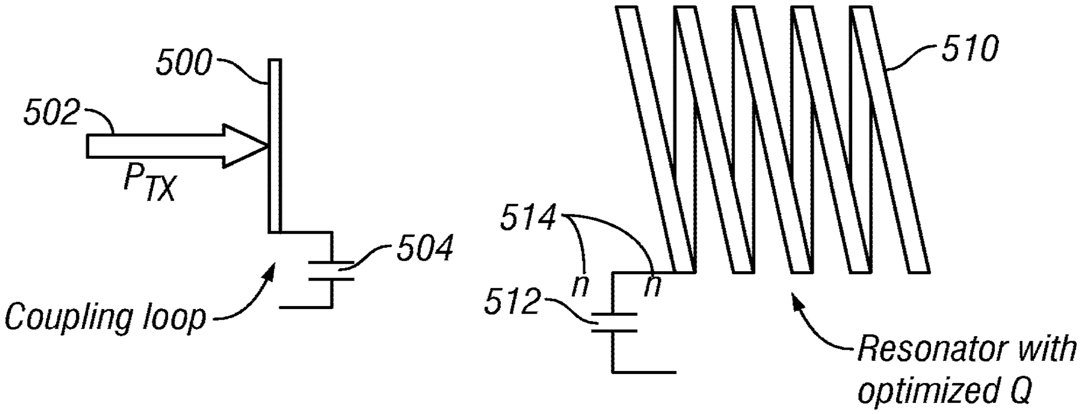

FIG. 5

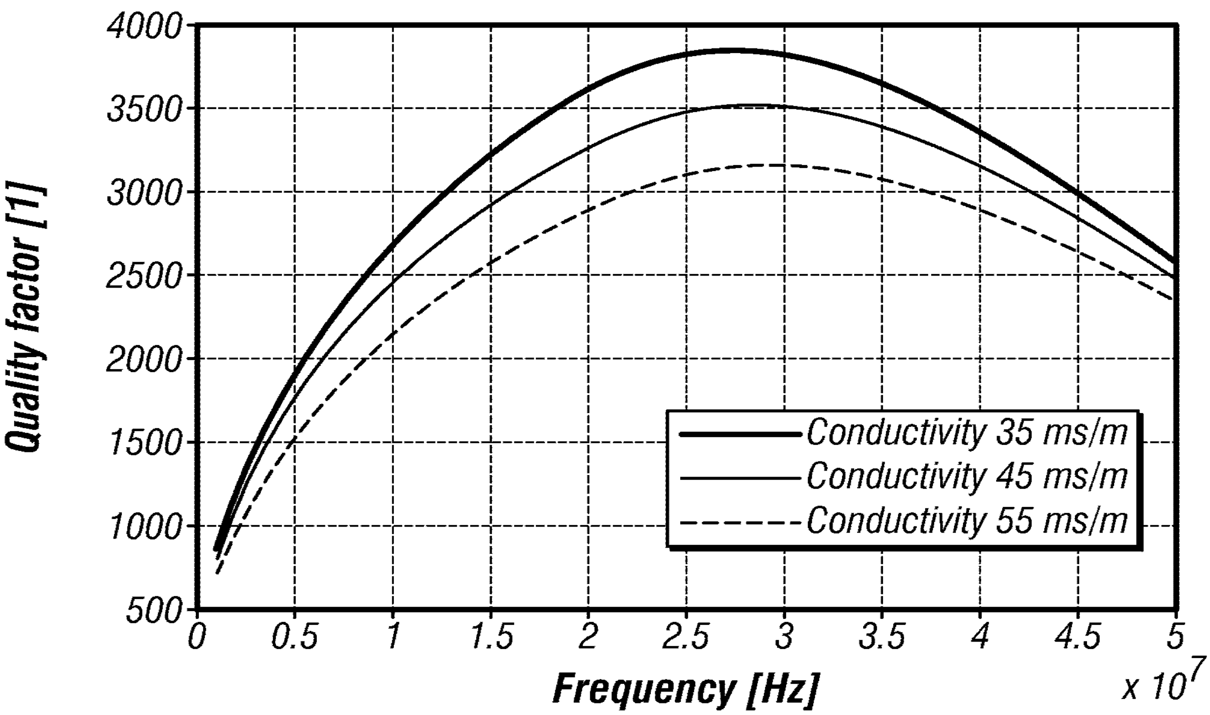

FIG. 6

SUBSTITUTE SHEET (RULE 26)

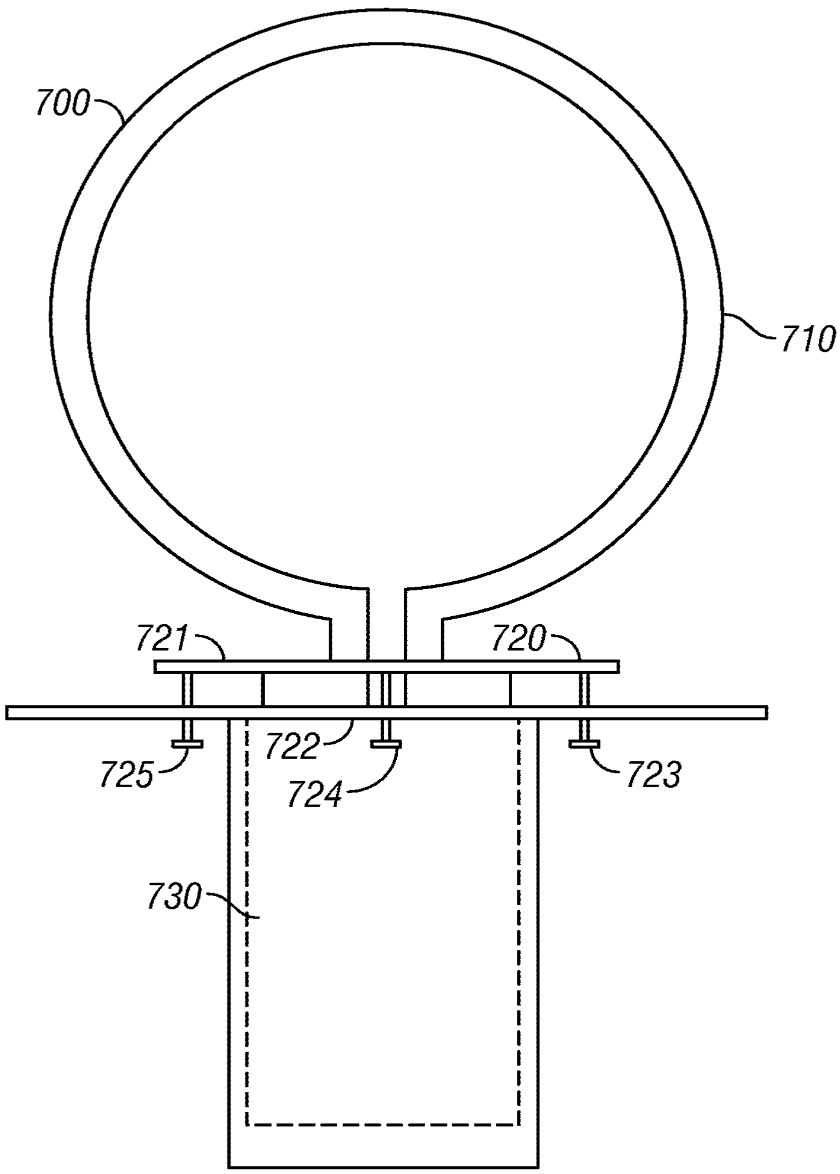

FIG. 7

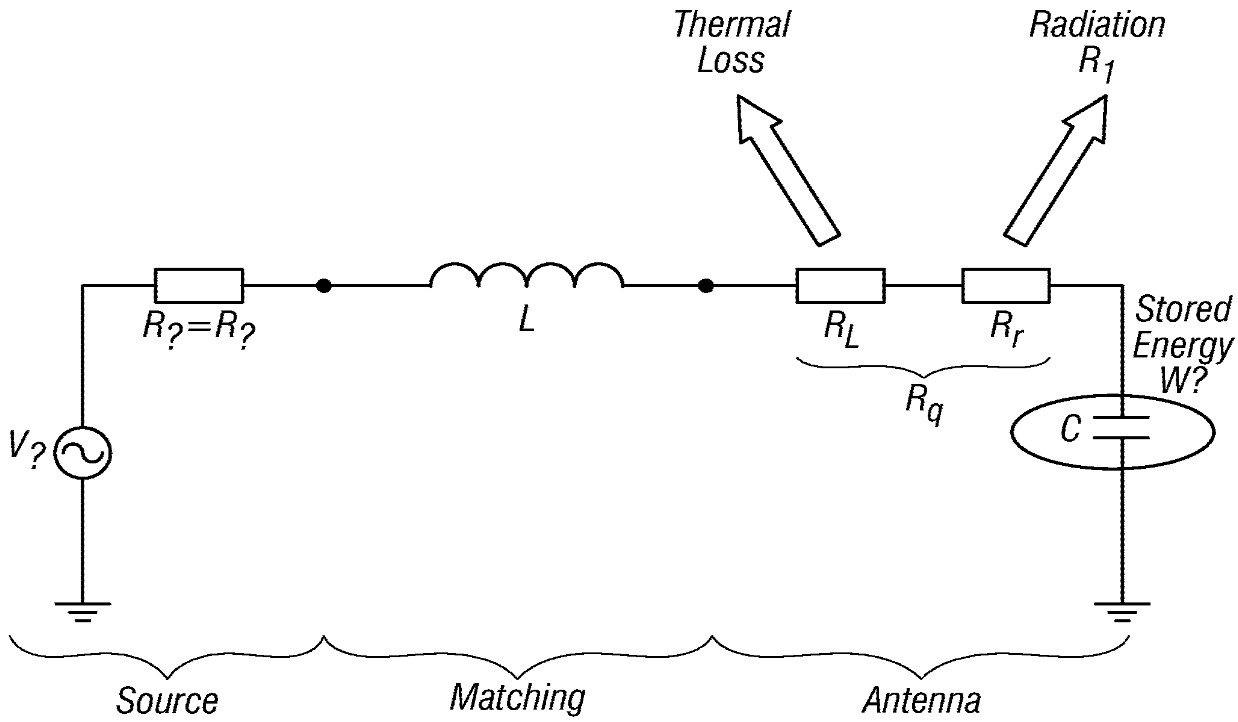

FIG. 8

SUBSTITUTE SHEET (RULE 26)

PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION CONCERNING TRANSMITTAL OF COPY OF INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY (CHAPTER I OF THE PATENT COOPERATION TREATY)

(PCT Rule 44bis.1(c))

To:

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ETATS-UNIS D'AMERIQUE

Date of mailing *(day/month/year)* 07 February 2008 (07.02.2008)	
Applicant's or agent's file reference MIT.11757PCT	**IMPORTANT NOTICE**

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2006/026480	05 July 2006 (05.07.2006)	12 July 2005 (12.07.2005)

Applicant

MASSACHUSETTS INSTITUTE OF TECHNOLOGY et al

The International Bureau transmits herewith a copy of the international preliminary report on patentability (Chapter I of the Patent Cooperation Treaty)

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Agnes Wittmann-Regis e-mail: pt06.pct@wipo.int

Form PCT/IB/326 (January 2004)

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 MIT.11757PCT	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/US2006/026480	International filing date (*day/month/year*) 05 July 2006 (05.07.2006)	Priority date (*day/month/year*) 12 July 2005 (12.07.2005)
International Patent Classification (8th edition unless older edition indicated) See relevant information in Form PCT/ISA/237		
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

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 7 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 January 2008 (29.01.2008)
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Agnes Wittmann-Regis e-mail: pt06.pct@wipo.int

Form PCT/IB/373 (January 2004)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY
(PCT Rule 43*bis*.1)

Date of mailing
(day/month/year) see form PCT/ISA/210 (second sheet)

Applicant's or agent's file reference
see form PCT/ISA/220

FOR FURTHER ACTION
See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2006/026480	05.07.2006	12.07.2005

International Patent Classification (IPC) or both national classification and IPC
INV. H02J17/00

Applicant
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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 usually 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 notifed 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:	Date of completion of this opinion	Authorized Officer
European Patent Office - P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Tx: 31 651 epo nl Fax: +31 70 340 - 3016	see form PCT/ISA/210	Lund, Michael Telephone No. +31 70 340-2388

Form (PCT/ISA/237) (Cover Sheet) (April 2005)

Box No. I Basis of the 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 43bis.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

   ☐ a sequence listing

   ☐ table(s) related to the sequence listing

   b. format of material:

   ☐ on paper

   ☐ in electronic form

   c. time of filing/furnishing:

   ☐ contained in the international application as filed.

   ☐ filed together with the international application in electronic form.

   ☐ furnished 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 and/or table relating thereto 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:

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)	Yes:	Claims	2-5 7 9-13 15-19 21
	No:	Claims	1 6 8 14 20
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-21
Industrial applicability (IA)	Yes:	Claims	1-21
	No:	Claims	

2. Citations and explanations

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

Reference is made to the following documents:
D1: EP1335477
D2: US2133494
D3: WO9217929
D4: US5528113

1. The present application does not meet the criteria of Article 33(1) PCT, because the subject-matter of claim 1 is not new in the sense of Article 33(2) PCT.

1.1 The document D1 discloses (the references in parentheses applying to this document):
A method of transferring energy comprising:
providing a first resonator structure **(resonating cable 201)** *receiving energy from an external power supply, said first resonator structure having a first resonant frequency omega1, and a first Q- factor Q1, and characteristic size L1, and providing a second resonator structure* **(secondary inductance and capacitance 401,402)** *being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency omega2, and a second Q-factor Q2, and characteristic size L2 wherein the two said frequencies omega1 and omega2 are close to within the narrower of the two resonance widths gamma1, and gamma2* **(see section 1.3a)**,
transferring energy non-radiatively **(see section 1.3b)** *between said first resonator structure and said second resonator structure, said energy transfer being mediated through coupling of their resonant-field evanescent tails* **(see section 1.3c)**, *and the rate of energy transfer between said first resonator and said second resonator being denoted by kappa, wherein non-radiative means D* **(see section 1.3d)** *is smaller than each of the resonant wavelengths Lambda1 and Lambda2* **(the wavelength at 100KHz is 3000 Meters; the wavelength at 1MHz is 300 Meters; the wavelength at 10MHz is 30 Meters; the wavelength at 100MHz is 3 Meters; the wavelength at 1GHz is 30 Centimeters)**, *wherein c is the propagation speed of radiation in the surrounding medium.*

1.2 The same reasoning applies, mutatis mutandis, to the subject-matter of the corresponding independent claim 6, which therefore is also not considered new and inventive.

1.3 Clarity issues: More issues of clarity relate to claim 1 and need to be addressed in order to judge upon the content of claim 1.
1.3a The wording *"...are close to within the narrower of the two resonance widths..."* was understood for the search as both the two frequencies being chosen such that both the first and second resonating structures display a high quality factor. Else the advantage of resonant coupling would be lost. Re-phrasing should be considered.
1.3b The wording *"...transferring energy non-radiatively..."* is not considered to be clear per ce for two reasons: firstly, as energy is transferred from one resonator to the other in an electromagnetic or dielectric manner the energy appears to be "radiated" from the first resonator to the second (the non-radiatively seems to replace the confined radiation described at the start of page 2), secondly, non-radiatively must be interpreted as that no radiation can be observed and not as that a field that is much weaker than the field between the two resonators exists.
1.3c The wording *"...energy transfer being mediated through coupling of their resonant-field evanescent tails..."* contains the word "mediated" that was interpreted for the search as "promoted", which is in line with what is written in the two first lines of page 3 of the description. The coupling of the "evanescent fields", i.e. the out-skirt of the coupling field, is of non-specified nature such that any inherent coupling resulting from the resonant coupling will perform coupling of the "evanescent fields".
In D1, column 11, lines 46-50 the observation of such coupling, that causes a weakening of the field outside the resonant coupling, is disclosed. This phenomena is likewise disclosed in other of the prior art documents and appears to be linked to the observation of improved energy transfer at mutual resonance.
1.3d "D" is used both to designate a "closest distance" and "non-radiative means". What appears to be a double use of a single reference symbol must be clarified.

1.4 A number of prior art documents that describe energy transfer over distances, using resonant coupling between two resonators and operating in the KHz, MHz or GHz range, were retrieved The documents disclose that improved energy transfer is possible that way, and more of the documents describe that at resonance the fields are to a large extend

confined between the two resonators such that other resonators outside only tend to see little field strength.
Though the present application is carrying out an analysis based on mathematics, the qualitative results appears to be the same as those observed in the prior art.

2. Dependent claims 2-5 claim the use of resonators with high quality factor. Though the quality factors mentioned here are above what is often seen in the prior art, the improvement in energy transfer with raise in quality factor is known from the prior art; as example see D3, page 16, lines 32-34. The high quality factors appear rather to be "goals to be achieved" (desiderata), and not the means to achieve these goals, and it may appear surprising to the person skilled in the art that such high quality factors of above 1000 can be maintained in resonators when transferring significant amount of energy.
For these reasons the subject matter of claims 2-5 and 7 cannot be considered as involving an inventive step (Article 33(3) PCT).

3. Dependent claims 8-21 appear to be a listing of a large number of resonator-types and characteristics that may be useful for the energy transfer. Some of these resonator types are known from the prior art that is cited, others not. The listing in claims 8-21 leaves the impression that these resonators and characteristics only will perform as expected, and that none are clearly preferable as none will exhibit particularly good or surprising performance. They provide a mere choice between a number of ordinary alternatives.
For these reasons the subject matter of claims 8-21 cannot be considered as involving an inventive step (Article 33(3) PCT).

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To:

GAUTHIER & CONNORS, LLP
Attn. Connors, Matthew E.
225 Franklin Street, Suite 2300
Boston, MA 02110
ETATS-UNIS D'AMERIQUE

RECEIVED
DEC 26 2007
GAUTHIER & CONNORS LLP

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)* 21/12/2007
Applicant's or agent's file reference MIT.11757PCT	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2006/026480	International filing date *(day/month/year)* 05/07/2006
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY	

1. [X] 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, Fascimile No.: (41-22) 338.82.70

   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 International Searching Authority	Authorized officer
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	Susanne Gundlach

Form PCT/ISA/220 (October 2005) *(See notes on accompanying sheet)*

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*, a publication of WIPO.

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*, Volume I/A, Annexes B1 and B2).

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*, Volume I/A, 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 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 must be submitted for each sheet of the claims which, on account of an amendment or amendments, differs from the sheet originally filed.

All the claims appearing on a replacement sheet must be numbered in Arabic numerals. 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 (Section 205(b)).

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.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference MIT.11757PCT	**FOR FURTHER ACTION** see Form PCT/ISA/220 as well as, where applicable, item 5 below.	
International application No. PCT/US2006/026480	International filing date *(day/month/year)* 05/07/2006	(Earliest) Priority Date *(day/month/year)* 12/07/2005
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

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 4 sheets.

[X] 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:
      [X] 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. [ ] 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**,
   [X] 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**,
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established, according to Rule 38.2(b), 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
      [X] 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) (April 2005)

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

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* 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 document 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	Date of mailing of the international search report
11 December 2007	21/12/2007

Name and mailing address of the ISA/	Authorized officer
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	Lund, Michael

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/026480

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 92/17929 A (JAMES PIPER) 15 October 1992 (1992-10-15) abstract page 2, line 33 - line 35 page 4, line 25 - line 31 page 5, line 1 - line 5 page 16, line 22 - line 35 page 18, line 26 - line 30 -----	1-21
X	US 5 528 113 A (JOHN T. BOYS ET AL.) 18 June 1996 (1996-06-18) abstract column 1, line 12 - line 18 column 4, line 65 - column 5, line 21 column 7, line 60 - column 8, line 1 -----	1-21
X	WO 94/28560 A (ERA PATENTS LIMITED) 8 December 1994 (1994-12-08) page 2, line 33 - page 3, line 6 page 4, line 1 - line 10 page 7, line 16 - line 20 -----	1,6
X	WO 93/23908 A (AUCKLAND UNISERVICES LIMITED) 25 November 1993 (1993-11-25) page 1, line 11 - line 14 page 1, line 20 - line 24 page 1, line 26 - line 27 page 2, line 21 - line 28 page 4, line 7 - line 15 claim 1 -----	1,6
X	DE 38 24 972 A (ROLAND HIERING) 12 January 1989 (1989-01-12) abstract claims 1,2,15,17,20 column 3, line 67 - column 4, line 4 column 4, line 39 - line 43 column 4, line 49 - line 54 column 4, line 67 - column 5, line 4 column 5, line 14 - line 23 column 5, line 64 - column 6, line 4 column 6, line 36 - line 39 figures 1-3 -----	1,6

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2006/026480

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 1335477	A	13-08-2003	NONE			
US 2133494	A	18-10-1938	NONE			
WO 9217929	A	15-10-1992	AU	1237392	A	02-11-1992
			ES	2125256	T3	01-03-1999
			MX	9201100	A1	01-09-1992
			US	5293308	A	08-03-1994
US 5528113	A	18-06-1996	AU	8006494	A	08-05-1995
			AU	8006594	A	08-05-1995
			DE	4498007	T0	21-11-1996
			DE	69432262	D1	17-04-2003
			EP	0727105	A1	21-08-1996
			JP	3630452	B2	16-03-2005
			JP	7170681	A	04-07-1995
			WO	9511544	A1	27-04-1995
			WO	9511545	A1	27-04-1995
			US	5821638	A	13-10-1998
WO 9428560	A	08-12-1994	AU	6725694	A	20-12-1994
			DE	69404655	D1	04-09-1997
			DE	69404655	T2	27-11-1997
			EP	0700574	A1	13-03-1996
WO 9323908	A	25-11-1993	AU	4093493	A	13-12-1993
			DE	69330516	D1	06-09-2001
			DE	69330516	T2	25-04-2002
			EP	0640254	A1	01-03-1995
			ES	2163409	T3	01-02-2002
			JP	3512798	B2	31-03-2004
			JP	8501435	T	13-02-1996
			US	5898579	A	27-04-1999
DE 3824972	A	12-01-1989	NONE			

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY
(PCT Rule 43*bis*.1)

	Date of mailing (*day/month/year*) see form PCT/ISA/210 (second sheet)
Applicant's or agent's file reference see form PCT/ISA/220	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date (*day/month/year*)	Priority date (*day/month/year*)
PCT/US2006/026480	05.07.2006	12.07.2005

International Patent Classification (IPC) or both national classification and IPC
INV. H02J17/00

Applicant
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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 usually 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 notifed 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:	Date of completion of this opinion	Authorized Officer
European Patent Office - P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Tx: 31 651 epo nl Fax: +31 70 340 - 3016	see form PCT/ISA/210	Lund, Michael Telephone No. +31 70 340-2388

Form (PCT/ISA/237) (Cover Sheet) (April 2005)

Box No. I Basis of the 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 43bis.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

      ☐ a sequence listing

      ☐ table(s) related to the sequence listing

   b. format of material:

      ☐ on paper

      ☐ in electronic form

   c. time of filing/furnishing:

      ☐ contained in the international application as filed.

      ☐ filed together with the international application in electronic form.

      ☐ furnished 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 and/or table relating thereto 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:

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)	Yes:	Claims	2-5 7 9-13 15-19 21
	No:	Claims	1 6 8 14 20
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-21
Industrial applicability (IA)	Yes:	Claims	1-21
	No:	Claims	

2. Citations and explanations

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

Reference is made to the following documents:
D1: EP1335477
D2: US2133494
D3: WO9217929
D4: US5528113

1. The present application does not meet the criteria of Article 33(1) PCT, because the subject-matter of claim 1 is not new in the sense of Article 33(2) PCT.

1.1 The document D1 discloses (the references in parentheses applying to this document): *A method of transferring energy comprising:*
providing a first resonator structure **(resonating cable 201)** *receiving energy from an external power supply, said first resonator structure having a first resonant frequency omega1, and a first Q- factor Q1, and characteristic size L1, and providing a second resonator structure* **(secondary inductance and capacitance 401,402)** *being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency omega2, and a second Q-factor Q2, and characteristic size L2 wherein the two said frequencies omega1 and omega2 are close to within the narrower of the two resonance widths gamma1, and gamma2* **(see section 1.3a),**
transferring energy non-radiatively **(see section 1.3b)** *between said first resonator structure and said second resonator structure, said energy transfer being mediated through coupling of their resonant-field evanescent tails* **(see section 1.3c)**, *and the rate of energy transfer between said first resonator and said second resonator being denoted by kappa, wherein non-radiative means D* **(see section 1.3d)** *is smaller than each of the resonant wavelengths Lambda1 and Lambda2* **(the wavelength at 100KHz is 3000 Meters; the wavelength at 1MHz is 300 Meters; the wavelength at 10MHz is 30 Meters; the wavelength at 100MHz is 3 Meters; the wavelength at 1GHz is 30 Centimeters)**, *wherein c is the propagation speed of radiation in the surrounding medium.*

1.2 The same reasoning applies, mutatis mutandis, to the subject-matter of the corresponding independent claim 6, which therefore is also not considered new and inventive.

1.3 Clarity issues: More issues of clarity relate to claim 1 and need to be addressed in order to judge upon the content of claim 1.
1.3a The wording *"...are close to within the narrower of the two resonance widths..."* was understood for the search as both the two frequencies being chosen such that both the first and second resonating structures display a high quality factor. Else the advantage of resonant coupling would be lost. Re-phrasing should be considered.
1.3b The wording *"...transferring energy non-radiatively..."* is not considered to be clear per ce for two reasons: firstly, as energy is transferred from one resonator to the other in an electromagnetic or dielectric manner the energy appears to be "radiated" from the first resonator to the second (the non-radiatively seems to replace the confined radiation described at the start of page 2), secondly, non-radiatively must be interpreted as that no radiation can be observed and not as that a field that is much weaker than the field between the two resonators exists.
1.3c The wording *"...energy transfer being mediated through coupling of their resonant-field evanescent tails..."* contains the word "mediated" that was interpreted for the search as "promoted", which is in line with what is written in the two first lines of page 3 of the description. The coupling of the "evanescent fields", i.e. the out-skirt of the coupling field, is of non-specified nature such that any inherent coupling resulting from the resonant coupling will perform coupling of the "evanescent fields".
In D1, column 11, lines 46-50 the observation of such coupling, that causes a weakening of the field outside the resonant coupling, is disclosed. This phenomena is likewise disclosed in other of the prior art documents and appears to be linked to the observation of improved energy transfer at mutual resonance.
1.3d "D" is used both to designate a "closest distance" and "non-radiative means". What appears to be a double use of a single reference symbol must be clarified.

1.4 A number of prior art documents that describe energy transfer over distances, using resonant coupling between two resonators and operating in the KHz, MHz or GHz range, were retrieved The documents disclose that improved energy transfer is possible that way, and more of the documents describe that at resonance the fields are to a large extend

confined between the two resonators such that other resonators outside only tend to see little field strength.
Though the present application is carrying out an analysis based on mathematics, the qualitative results appears to be the same as those observed in the prior art.

2. Dependent claims 2-5 claim the use of resonators with high quality factor. Though the quality factors mentioned here are above what is often seen in the prior art, the improvement in energy transfer with raise in quality factor is known from the prior art; as example see D3, page 16, lines 32-34. The high quality factors appear rather to be "goals to be achieved" (desiderata), and not the means to achieve these goals, and it may appear surprising to the person skilled in the art that such high quality factors of above 1000 can be maintained in resonators when transferring significant amount of energy.
For these reasons the subject matter of claims 2-5 and 7 cannot be considered as involving an inventive step (Article 33(3) PCT).

3. Dependent claims 8-21 appear to be a listing of a large number of resonator-types and characteristics that may be useful for the energy transfer. Some of these resonator types are known from the prior art that is cited, others not. The listing in claims 8-21 leaves the impression that these resonators and characteristics only will perform as expected, and that none are clearly preferable as none will exhibit particularly good or surprising performance. They provide a mere choice between a number of ordinary alternatives.
For these reasons the subject matter of claims 8-21 cannot be considered as involving an inventive step (Article 33(3) PCT).

Possible steps after receipt of the international search report (ISR) and written opinion of the International Searching Authority (WO-ISA)

General information	For all international applications filed on or after 01/01/2004 the competent ISA will establish an ISR. It is accompanied by the WO-ISA. Unlike the former written opinion of the IPEA (Rule 66.2 PCT), the WO-ISA is not meant to be responded to, but to be taken into consideration for further procedural steps. This document explains about the possibilities.
Amending claims under Art. 19 PCT	Within 2 months after the date of mailing of the ISR and the WO-ISA the applicant may file amended claims under Art. 19 PCT directly with the International Bureau of WIPO. The PCT reform of 2004 did not change this procedure. For further information please see Rule 46 PCT as well as form PCT/ISA/220 and the corresponding Notes to form PCT/ISA/220.
Filing a demand for international preliminary examination	In principle, the WO-ISA will be considered as the written opinion of the IPEA. This should, in many cases, make it unnecessary to file a demand for international preliminary examination. If the applicant nevertheless wishes to file a demand this must be done before expiry of 3 months after the date of mailing of the ISR/WO-ISA or 22 months after priority date, whichever expires later (Rule 54bis PCT). Amendments under Art. 34 PCT can be filed with the IPEA as before, normally at the same time as filing the demand (Rule 66.1 (b) PCT). If a demand for international preliminary examination is filed and no comments/amendments have been received the WO-ISA will be transformed by the IPEA into an IPRP (International Preliminary Report on Patentability) which would merely reflect the content of the WO-ISA. The demand can still be withdrawn (Art. 37 PCT).
Filing informal comments	After receipt of the ISR/WO-ISA the applicant may file informal comments on the WO-ISA directly with the International Bureau of WIPO. These will be communicated to the designated Offices together with the IPRP (International Preliminary Report on Patentability) at 30 months from the priority date. Please also refer to the next box.
End of the international phase	At the end of the international phase the International Bureau of WIPO will transform the WO-ISA or, if a demand was filed, the written opinion of the IPEA into the IPRP, which will then be transmitted together with possible informal comments to the designated Offices. The IPRP replaces the former IPER (international preliminary examination report).
Relevant PCT Rules and more information	Rule 43 PCT, Rule 43bis PCT, Rule 44 PCT, Rule 44bis PCT, PCT Newsletter 12/2003, OJ 11/2003, OJ 12/2003

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 01997-358WO2	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/US2007/070892	International filing date *(day/month/year)* 11 June 2007 (11.06.2007)	Priority date *(day/month/year)* 27 March 2007 (27.03.2007)
International Patent Classification (8th edition unless older edition indicated) See relevant information in Form PCT/ISA/237		
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

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 14 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:

   - [X] 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
   - [X] 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 September 2009 (29.09.2009)
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 338 82 70	Authorized officer Philippe Becamel e-mail: pt12.pct@wipo.int

Form PCT/IB/373 (January 2004)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY
(PCT Rule 43*bis*.1)

	Date of mailing (*day/month/year*) see form PCT/ISA/210 (second sheet)
Applicant's or agent's file reference see form PCT/ISA/220	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date (*day/month/year*)	Priority date (*day/month/year*)
PCT/US2007/070892	11.06.2007	28.03.2007

International Patent Classification (IPC) or both national classification and IPC
INV. H02J17/00

Applicant
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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 usually 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 notifed 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:	Date of completion of this opinion	Authorized Officer
European Patent Office - P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Tx: 31 651 epo nl Fax: +31 70 340 - 3016	see form PCT/ISA/210	Lund, Michael Telephone No. +31 70 340-2388

Form (PCT/ISA/237) (Cover Sheet) (April 2005)

Box No. I Basis of the 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 43bis.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

      ☐ a sequence listing

      ☐ table(s) related to the sequence listing

   b. format of material:

      ☐ on paper

      ☐ in electronic form

   c. time of filing/furnishing:

      ☐ contained in the international application as filed.

      ☐ filed together with the international application in electronic form.

      ☐ furnished 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 and/or table relating thereto 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:

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)	Yes:	Claims	7-41 44-58 60-71 74-141 143-156 158-170 179 186 192 193 200-234 237-251 253-264 267-334 336-345 347-349 351-363 366
	No:	Claims	1-6,42 43 59 72 73 142 157 171-178 180-185 187-191 194-199 235 236 252 265 266 335 346 350 364 365
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-366
Industrial applicability (IA)	Yes:	Claims	1-366
	No:	Claims	

2. Citations and explanations

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

Reference is made to the following documents:
D1: DE3824972
D2: DE102005036290
D3: WO92/17929
D4: US2133494
D5: US2005/0085873
D6: US2002/0032471
D7: WO96/02970
D8: US5528113
D9: WO93/23908
D10: WO2007008646
D11: US2003/0199778
D12: US6798716
D13: DE10304584
D14: DE10029147

1. The application contains a large number of claims and a substantial number of issues that appear to lack clarity, that seems to be contradictory and claim "goals to be achieved" (desiderata) instead of the tangible technical features that achieve the goals. Therefore the scope of the application is not clear and confined. The basic concept of wireless power transfer using resonant coupling between resonators is clear but well known from the prior art. Further than what is known from the prior art a large number of claims appears to be based on various selection of values in trivial ranges and desiderata without clearly specifying tangible, technical features. This leaves the person skilled in the art in doubt if an improved wireless power transfer system has been found, compared to what is already known from the prior art, and which technical features that cause such improved performance. Here the mentioning of a huge number of possible features leaves the impression that none of these are known in particular to cause an unexpected and surprising effect and that none of these will involve an inventive step. The application is not

concise in the sense of Article 6, PCT and Rule 6, PCT.
For these reasons the application is considered to be complex of nature and not fulfilling the requirements of Article 6 PCT.

The examiner has chosen from his understanding of a number of claims and consideration of the nature of the further claims to include the following analysis and comments as it is considered expedient for the further procedure:

2. The present application does not meet the criteria of Article 33(1) PCT, because the subject-matter of claim 1 is not new in the sense of Article 33(2) PCT.

2.1 The document D1 discloses (the references in parentheses applying to this document):
An apparatus for use in wireless energy transfer **(Fig.1)**, *the apparatus comprising:*
a first resonator structure **(7,8,9)** *configured to transfer energy non-radiatively with a second resonator structure* **(2)** *over a distance D greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L1 of the first resonator structure and greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L2 of the second resonator structure,*
wherein the non-radiative energy transfer **(See paragraph 4. with comments on "non-radiative")** *is mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the second resonator structure* **(the "field evanescent tail" is inherent and the coupling is not specified to be of a particular type)**.

2.2 The document D14 discloses (the references in parentheses applying to this document):
An apparatus for use in wireless energy transfer **(Fig.0)**, *the apparatus comprising:*
a first resonator structure **(2)** *configured to transfer energy non-radiatively with a second resonator structure* **(7/8)** *over a distance D greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L1 of the first resonator structure and greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L2 of the second resonator structure,*
wherein the non-radiative energy transfer **(See paragraph 4. with comments on "non-radiative")** *is mediated by a coupling of a resonant field evanescent tail of the first*

resonator structure and a resonant field evanescent tail of the second resonator structure **(the "field evanescent tail" is inherent and the coupling is not specified to be of a particular type)**.

2.3 The same reasoning applies, mutatis mutandis, to the subject-matter of the corresponding independent claims 171, 174, 180, 187 and 194 which therefore are also considered not new and inventive.

3. Dependent claims:

Claims 2, 175, 181, 188, 195: The resonant structure transferring the energy may be called the "first resonant structure".

Claims 3, 182, 196: The resonant structure transferring the energy may be called the "second resonant structure".

Claims 4, 176, 183, 189, 197: The second resonant structure is included in the independent claim.

Claims 5, 172, 177, 184, 190, 198: Definition of parameters that are inherent.

Claims 6, 173, 178, 185, 191, 199: Operation at the common resonance frequency is described in the prior art.

Claims 7-13, 23-25, 78, 131, 165, 166 , 200-206, 216-218, 271, 324, 358, 359: The quality factor of the resonators is claimed to be high (>100; >1000; >10000): whereas it is known from the prior art that the coupling of energy increases with an increase in the quality factor of the resonators and that a high quality factor is desirable, it is not obvious for the person skilled in the art how such quality factors can be maintained in a system for transfer of significant power when the second resonator is considerably loaded. A clarification of this is needed.

Claims 14-22, 26-28, 45-58, 64-71, 74-77, 79-112, 114-126, 130, 132-141, 143-152, 158-164, 179, 186, 192, 193, 207-215, 219-221, 238-251, 253-264, 267-270, 272-305, 307-319, 323, 325-334, 336-345, 351-357: A large number of claims are describing characteristics of the system with values that appear to be varied in trivial ranges and do not appear to cause an unexpected and surprising effect. The fact that the applicant chooses to include claims with each a part of a range leaves the impression that the applicant is not aware of a particular effect caused by a particular value compared to the other values that are contained in the claims, such that none of these values will involve an inventive step.

Claims 29-33, 60-63, 222-226: A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features themselves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such claims attempt to define the subject-matter in terms of the result to be achieved, which merely amounts to a statement of the underlying problem, without providing the technical features necessary for achieving this result.
One such property is the efficiency that is claimed in a number of claims to include the range from 1% to 100%. An apparatus for use in wireless energy transfer is very likely to have an efficiency in the range of 1%-100%. The efficiency achieved does not involve an inventive step whereas the means that causes the efficiency to be at a certain level may involve an inventive step.
Low efficiency levels in the order of 1% or 10% appear to be an indication that a significant part of the energy transmitted from the first resonator structure is not picked up by the second resonator structure but lost before. This indicates that a significant part of the energy is radiated outside the fields interacting between the two resonator structures and that the system described is not performing "non-radiative energy transfer".

Claims 34-37, 227-230 : A radiation loss that is measurable is contradicting the fact that the system is stated to perform "non-radiative energy transfer".
A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features themselves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such properties do not involve an inventive step.

Claims 38-41, 231-234 : The loss to a human does not comply with the system being stated to perform "non-radiative energy transfer", further does the loss to a human appear to be heavily dependent on the particular human and the situation of this human with respect to the system.
A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features them selves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such properties do not involve an inventive step.

Claims 42, 43, 59, 142, 235, 236, 252 : Inherent in a system as claimed in the independent claim.

Claims 44, 237, 366: The objective problem points at the solution.

Claims 72, 73, 157, 265, 266, 335, 346, 350, 364, 365 : Known from the prior art.

Claims 113, 153-155, 306, 347, 348: The prior art acknowledge that other energy transfer than electromagnetic may be employed. Examples of systems employing other energy transfer than electromagnetic are mentioned in US2003/0199778 (D11). US6798716 (D12) is describing an example using ultrasound for power transmission and DE10304584 (D13) an example of electrostatic coupling.
Resonators that are compliant with such other type of energy transfer will need to be used. It is not obvious to the person skilled in the art how dielectric energy transfer with tenths of watts and over significant distances can be achieved.

Claims 127-129, 320-322: Use of "self resonant conducting wire coils", meaning coils with the capacitive part formed by the intrinsic capacitance between the windings is known from the prior art.

Claims 156, 349: A "whispering gallery mode" is a term that appears related to optical resonators and waveguides The use of light in general is foreseen in US2003/0199778 (D11). The frequency of light seems to extend beyond the frequencies proposed in other claims. Further, the examining division is not sure if a "whispering gallery mode" is compatible with other characteristics claimed in the dependent claims. However, the use of a "whispering gallery mode" is not known from the prior art that is considered the closest for the technical concept of claim 1. The examining division would appreciate a statement from the applicant if the applicant considers that the "whispering gallery mode" is a technical feature that will cause the effects described in the application and allow tenths of watt to be transferred wirelessly through air. It should be reminded that a large number of claims refer to the use of resonantly coupled coils such that a change of the technology necessary to solve the problem may cause an objection of unity to be raised.

Claims 167-170, 360-363: It is trivial that a third resonant structure of the same type may couple with the first or second resonant structure as the mechanism for coupling remains the same. This is further known from the prior art.

4. The following general comments should be considered by the applicant:

4.1 More of the claims, hereunder claim 1, uses the term "characteristic size" of a resonator. "Characteristic size" is not well defined in the field and may refer to a physical dimension of the resonator without making which dimension clear, or for instance refer to a wavelength that may be radiated by the resonator. The "characteristic size" is used in dependent claim to describe further characteristics.
"Characteristic size" is found not to comply with Article 6 PCT due to lack of clarity.

4.2 The term "non-radiative" is used in a number of claims. "Non-radiative" must be interpreted such that no significant radiation can be observed outside of the path connecting the first and second resonators. This appears not to be the case in the present situation for the reason that a number of the claims containing "non-radiative" do not include features that clearly will focus fields from the first resonator towards the second resonator. Therefore only the resonant interaction is a feature that may influence the distribution of the field. Further, more dependent claims mention an efficiency in the order of 1% such that this must be taken as an indication that a considerable part of the field is not interacting with the energy receiving resonator but is radiated elsewhere. This is supported by dependent claims mentioning "a radiation loss".
"Non-radiative" may be a term attributed by the applicant in order to praise the probably reduced level of radiation compared to a situation with no second resonator, such as

described in the prior art, but with a general misleading interpretation. As "non-radiative" would be a result of technical features and not in itself a tangible technical feature of the system, "non-radiative" is a result to be achieved (desideratum) that lacks clarity in how it is being achieved.

4.3 A number of dependent claims describe the quality factor of the resonators to be high (even more than 10000). Whereas it is known from the prior art that the coupling of energy increases with an increase in the quality factor of the resonators, it is not obvious for the person skilled in the art how such quality factors can be maintained in a system for transfer of significant power when the second resonator is considerably loaded. A clarification of this is needed.

4.4 A large number of claims are describing characteristics of the system with values that appear to varied in trivial ranges and do not appear to cause an unexpected and surprising effect. The fact that the applicant chooses to include claims with each a part of a range leave the impression that the applicant is not aware of a particular effect caused by a particular value compared to the other values that are contained in the claims, such that none of these values will involve an inventive step.

4.5 The application at present can only be treated to the extend that it is clear and unambiguous. A large number of the claims appear to contain elements that lack clarity and results to be achieved as replacement of tangible technical features. When such a situation is remedied and the proper technical features of each claim are clear, the features may lack unity in the sense of Rule 13 PCT. In the regional phase of the application a number of different technical concepts may be found after clarification and corresponding objections of lack of unity raised.

4.6 Whereas the basic concept of wireless power transfer using resonant coupling between resonators is clear, but known from the prior art, the applicant should be aware that "scientific theories" are exempted from patenting (Rule 39 PCT). If the applicant has a further understanding of the mechanism that makes the systems known from the prior art work, but no further tangible technical features that causes an unexpected and surprising effect are added to the system, the further enlightenment of the applicant may be characterised as elaborating on a scientific theory.

5. In order to clarify eventual differences between the prior art and the present application a short description of examples and statements in the prior art and a summary of the prior art may be expedient:

D1 (DE3824972): Wireless power transfer system with lamps containing resonant secondary coils that are coupling with a resonant primary at the resonance frequency. Distances up to 5 metres are mentioned.

D2 (DE102005036290): RFID device with power transferred wirelessly from a resonant primary to a resonant secondary over a distance that is larger than the wavelength.

D3 (WO92/17929): A contact less power distribution system with resonant primary- and pick-up circuit and with high quality factor because more power can be extracted this way. It is experienced that low loading of the pick-up circuit can prevent power from reaching other pick-up circuits. This is believed to be caused by high circulating currents in the pick-up coil interacting with the primary coil.

D4 (US2133494): System for transmitting electrical power without wire connection employing resonant conditions in both the energy transmitting and receiving circuits, tuned to the generator frequency whereby the losses in the system are reduced to a minimum.

D5 (US2005/0085873): Resonantly tuned, high quality factor energy transfer system with coils. More efficient energy transfer is known to take place with a high quality factor in the coupling.

D6 (US2002/0032471): A primary and secondary (implanted) coil operating at tuned resonance for efficient power transfer. It is known that a high Q resonant circuit promotes efficient power transfer.

D7 (W096/02970): An inductively powered lamp unit preferably operating in resonance. It is known that transmission of electrical power over significant gaps is feasible with resonant primary and secondary conductors. It is experienced that the resonant secondary currents tends to block the primary current from reaching past this secondary coil and reach other secondary coils.

D8 (US5528113): A loosely coupled inductive power transfer system with a statement that electric power can be transferred "across a significant space". Use of resonant or tuned primary and secondary inductive elements for the sake of greatly improved effectiveness prevents proper transfer to other consumers further away than the secondary inductive element.

D9 (WO93/23908): A non-contact power distribution system with resonant primary and secondary circuits operating at the same resonant frequency in order to maximise the quality factor and enhance coupling and power transfer.

D10 (WO2007/008646): Wireless non-radiative energy transfer system, from the same applicant, that is forming part of the prior art.

Examples of systems employing other energy transfer than electromagnetic are mentioned in US2003/0199778 (D11). US6798716 (D12)is describing an example using ultrasound for power transmission and DE10304584 (D13) an example of electrostatic coupling.

5.1 In conclusion a large number of prior art documents describe power transfer using mutually coupled resonators operating in the vicinity of the resonant frequency. It is well known that the higher the quality factor of the resonators are, the better the energy is coupled. It is also an observed fact in the prior art that the field around the energy receiving resonator is influenced by the resonant coupling such that little field is observed around the energy receiving resonator. The coupling may be near-field or remote-field and the field may be focussed in the direction of the other resonator. It is known from the prior art that not only electromagnetic coupling may be employed but also other type of coupling. A wide range of frequencies from the KHz-range to the GHz-range is employed.

5.2 The part of the application with tangible technical features, though containing some terms that are considered to lack clarity, appears to be known from the prior art. A huge number of dependent claims are listing characteristics and desiderata of the system and it is at present not clear to the examining division if any of these characteristics may relate to a special technical feature that cause unexpected and surprising effects.

It is the hope of the examining division that the above description of the prior art may help the applicant in identifying which one of the many different characteristics that can be argued to be a special technical feature and involve an inventive step (Article 33(3) PCT).

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

PCT

To:
FISH & RICHARDSON P.C.
Attn. Wefers, Marc
P.O. Box 1022
Minneapolis MN 55440-1022
ETATS-UNIS D'AMERIQUE

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*) 03/03/2008
Applicant's or agent's file reference 01997-358WO2	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US2007/070892	International filing date (*day/month/year*) 11/06/2007
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY	

1. [x] 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, Fascimile No.: (41-22) 338.82.70

   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 International Searching Authority	Authorized officer
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	Babara van Rooijen

Form PCT/ISA/220 (October 2005)

(See notes on accompanying sheet)

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*, a publication of WIPO.

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*, Volume I/A, Annexes B1 and B2).

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*, Volume I/A, 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 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 must be submitted for each sheet of the claims which, on account of an amendment or amendments, differs from the sheet originally filed.

All the claims appearing on a replacement sheet must be numbered in Arabic numerals. 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 (Section 205(b)).

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.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 01997-358W02	**FOR FURTHER ACTION**	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US2007/070892	International filing date *(day/month/year)* 11/06/2007	(Earliest) Priority Date *(day/month/year)* 28/03/2007
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

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 5 sheets.

[X] 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:
      [X] 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,**
   [X] 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,**
   [X] the text is approved as submitted by the applicant
   [ ] the text has been established, according to Rule 38.2(b), 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
      [X] 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) (April 2007)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/070892

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	DE 38 24 972 A (ROLAND HIERING ET AL.) 12 January 1989 (1989-01-12) abstract claims 2,20 column 3, line 64 - column 4, line 2 column 5, line 14 - line 23 column 6, line 36 - line 39 figure 1	1-366
X	DE 100 29 147 A (ULF TIEMENS) 20 December 2001 (2001-12-20) abstract paragraphs [0001], [0006] claims 1,4	1-366

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* 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 document 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	Date of mailing of the international search report
26 February 2008	03/03/2008

Name and mailing address of the ISA/	Authorized officer
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	Lund, Michael

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 10 2005 036290 A (GEBRÜDER FREI GMBH) 15 February 2007 (2007-02-15) paragraphs [0010], [0011], [0014], [0032], [0036] claims 5-7 figure 2	1-366
X	WO 92/17929 A (JAMES WILLIAM PIPER) 15 October 1992 (1992-10-15) abstract page 16, line 32 - line 34 page 18, line 26 - line 30	1-366
X	US 2 133 494 A (H.F.WATERS) 18 October 1938 (1938-10-18) column 2, line 10 - line 52 column 6, line 1 - line 11	1-366
X	US 2005/085873 A1 (JOHN C. GORD ET AL.) 21 April 2005 (2005-04-21) abstract figure 1 paragraphs [0014], [0016]	1-366
X	US 2002/032471 A1 (SCOTT M. LOFTIN ET AL.) 14 March 2002 (2002-03-14) abstract figure 1 paragraphs [0006], [0007], [0022], [0029], [0031]	1-366
X	WO 96/02970 A (AUCLAND UNISERVICES LIMITED) 1 February 1996 (1996-02-01) abstract page 1, line 18 - line 21 page 2, line 22 - line 23 page 5, line 29 page 8, line 31 - line 32 page 9, line 16 page 10, line 2 - line 5 page 14, line 11 - line 13 page 15, line 8 - line 10	1-366
X	US 5 528 113 A (JOHN T. BOYS ET AL.) 18 June 1996 (1996-06-18) column 1, line 12 - line 18 column 7, line 60 - column 8, line 3	1-366
X	WO 93/23908 A (AUCKLAND UNISERVICES LIMITED) 25 November 1993 (1993-11-25) page 1, line 11 - line 14 page 1, line 20 - line 27 page 2, line 21 - line 28 page 4, line 6 - line 15 claim 1	1-366
	-/--	

3

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 535 543 A (C.C. DAILEY) 20 October 1970 (1970-10-20) column 1, line 12 - line 22 column 1, line 41 - line 46	1
A	WO 2007/008646 A (MASSACHUSETTS INSTITUTE OF TECHNOLOGY) 18 January 2007 (2007-01-18) the whole document	1-366
A	US 2003/199778 A1 (MARLIN MICKLE ET AL.) 23 October 2003 (2003-10-23) abstract figure 1 paragraphs [0014], [0052]	113, 153-155, 306,347, 348
A	US 6 798 716 B1 (ARTHUR CHARYCH) 28 September 2004 (2004-09-28) figure 1 column 1, line 6 - line 10 column 1, line 25 - line 45 column 1, line 65 - column 2, line 6 column 2, line 19 - line 27 column 4, line 35 - line 38 column 4, line 48 - line 52 column 4, line 67 - column 5, line 12	113, 153-155, 306,347, 348
A	DE 103 04 584 A (ABB RESEARCH LTD) 19 August 2004 (2004-08-19) abstract paragraph [0014]	113, 153-155, 306,347, 348

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2007/070892

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
DE 3824972	A	12-01-1989	NONE			
DE 10029147	A	20-12-2001	NONE			
DE 102005036290	A	15-02-2007	NONE			
WO 9217929	A	15-10-1992	AU	1237392	A	02-11-1992
			ES	2125256	T3	01-03-1999
			MX	9201100	A1	01-09-1992
			US	5293308	A	08-03-1994
US 2133494	A	18-10-1938	NONE			
US 2005085873	A1	21-04-2005	NONE			
US 2002032471	A1	14-03-2002	US	7079901	B1	18-07-2006
			US	7092762	B1	15-08-2006
WO 9602970	A	01-02-1996	AU	682120	B2	18-09-1997
			AU	2810395	A	16-02-1996
			EP	0786165	A1	30-07-1997
US 5528113	A	18-06-1996	AU	8006494	A	08-05-1995
			AU	8006594	A	08-05-1995
			DE	4498007	T0	21-11-1996
			DE	69432262	D1	17-04-2003
			EP	0727105	A1	21-08-1996
			JP	3630452	B2	16-03-2005
			JP	7170681	A	04-07-1995
			WO	9511544	A1	27-04-1995
			WO	9511545	A1	27-04-1995
			US	5821638	A	13-10-1998
WO 9323908	A	25-11-1993	AU	4093493	A	13-12-1993
			DE	69330516	D1	06-09-2001
			DE	69330516	T2	25-04-2002
			EP	0640254	A1	01-03-1995
			ES	2163409	T3	01-02-2002
			JP	3512798	B2	31-03-2004
			JP	8501435	T	13-02-1996
			US	5898579	A	27-04-1999
US 3535543	A	20-10-1970	NONE			
WO 2007008646	A	18-01-2007	AU	2006269374	A1	18-01-2007
US 2003199778	A1	23-10-2003	NONE			
US 6798716	B1	28-09-2004	NONE			
DE 10304584	A	19-08-2004	NONE			

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY
(PCT Rule 43*bis*.1)

Date of mailing
(day/month/year) see form PCT/ISA/210 (second sheet)

Applicant's or agent's file reference
see form PCT/ISA/220

FOR FURTHER ACTION
See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US2007/070892	11.06.2007	28.03.2007

International Patent Classification (IPC) or both national classification and IPC
INV. H02J17/00

Applicant
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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 usually 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 notifed 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:	Date of completion of this opinion	Authorized Officer
European Patent Office - P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk - Pays Bas Tel. +31 70 340 - 2040 Tx: 31 651 epo nl Fax: +31 70 340 - 3016	see form PCT/ISA/210	Lund, Michael Telephone No. +31 70 340-2388

Form (PCT/ISA/237) (Cover Sheet) (April 2005)

Box No. I Basis of the 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 43bis.1(a))

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

   ☐ a sequence listing

   ☐ table(s) related to the sequence listing

   b. format of material:

   ☐ on paper

   ☐ in electronic form

   c. time of filing/furnishing:

   ☐ contained in the international application as filed.

   ☐ filed together with the international application in electronic form.

   ☐ furnished 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 and/or table relating thereto 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:

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)	Yes:	Claims	7-41 44-58 60-71 74-141 143-156 158-170 179 186 192 193 200-234 237-251 253-264 267-334 336-345 347-349 351-363 366
	No:	Claims	1-6,42 43 59 72 73 142 157 171-178 180-185 187-191 194-199 235 236 252 265 266 335 346 350 364 365
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-366
Industrial applicability (IA)	Yes:	Claims	1-366
	No:	Claims	

2. Citations and explanations

see separate sheet

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

Reference is made to the following documents:
D1: DE3824972
D2: DE102005036290
D3: WO92/17929
D4: US2133494
D5: US2005/0085873
D6: US2002/0032471
D7: WO96/02970
D8: US5528113
D9: WO93/23908
D10: WO2007008646
D11: US2003/0199778
D12: US6798716
D13: DE10304584
D14: DE10029147

1. The application contains a large number of claims and a substantial number of issues that appear to lack clarity, that seems to be contradictory and claim "goals to be achieved" (desiderata) instead of the tangible technical features that achieve the goals. Therefore the scope of the application is not clear and confined. The basic concept of wireless power transfer using resonant coupling between resonators is clear but well known from the prior art. Further than what is known from the prior art a large number of claims appears to be based on various selection of values in trivial ranges and desiderata without clearly specifying tangible, technical features. This leaves the person skilled in the art in doubt if an improved wireless power transfer system has been found, compared to what is already known from the prior art, and which technical features that cause such improved performance. Here the mentioning of a huge number of possible features leaves the impression that none of these are known in particular to cause an unexpected and surprising effect and that none of these will involve an inventive step. The application is not

concise in the sense of Article 6, PCT and Rule 6, PCT.
For these reasons the application is considered to be complex of nature and not fulfilling the requirements of Article 6 PCT.

The examiner has chosen from his understanding of a number of claims and consideration of the nature of the further claims to include the following analysis and comments as it is considered expedient for the further procedure:

2. The present application does not meet the criteria of Article 33(1) PCT, because the subject-matter of claim 1 is not new in the sense of Article 33(2) PCT.

2.1 The document D1 discloses (the references in parentheses applying to this document):
An apparatus for use in wireless energy transfer **(Fig.1)**, *the apparatus comprising:*
a first resonator structure **(7,8,9)** *configured to transfer energy non-radiatively with a second resonator structure* **(2)** *over a distance D greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L1 of the first resonator structure and greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L2 of the second resonator structure,*
wherein the non-radiative energy transfer **(See paragraph 4. with comments on "non-radiative")** *is mediated by a coupling of a resonant field evanescent tail of the first resonator structure and a resonant field evanescent tail of the second resonator structure* **(the "field evanescent tail" is inherent and the coupling is not specified to be of a particular type)**.

2.2 The document D14 discloses (the references in parentheses applying to this document):
An apparatus for use in wireless energy transfer **(Fig.0)**, *the apparatus comprising:*
a first resonator structure **(2)** *configured to transfer energy non-radiatively with a second resonator structure* **(7/8)** *over a distance D greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L1 of the first resonator structure and greater than a characteristic size* **(See paragraph 4. with comments on "characteristic size")** *L2 of the second resonator structure,*
wherein the non-radiative energy transfer **(See paragraph 4. with comments on "non-radiative")** *is mediated by a coupling of a resonant field evanescent tail of the first*

resonator structure and a resonant field evanescent tail of the second resonator structure **(the "field evanescent tail" is inherent and the coupling is not specified to be of a particular type)**.

2.3 The same reasoning applies, mutatis mutandis, to the subject-matter of the corresponding independent claims 171, 174, 180, 187 and 194 which therefore are also considered not new and inventive.

3. Dependent claims:

Claims 2, 175, 181, 188, 195: The resonant structure transferring the energy may be called the "first resonant structure".

Claims 3, 182, 196: The resonant structure transferring the energy may be called the "second resonant structure".

Claims 4, 176, 183, 189, 197: The second resonant structure is included in the independent claim.

Claims 5, 172, 177, 184, 190, 198: Definition of parameters that are inherent.

Claims 6, 173, 178, 185, 191, 199: Operation at the common resonance frequency is described in the prior art.

Claims 7-13, 23-25, 78, 131, 165, 166 , 200-206, 216-218, 271, 324, 358, 359: The quality factor of the resonators is claimed to be high (>100; >1000; >10000): whereas it is known from the prior art that the coupling of energy increases with an increase in the quality factor of the resonators and that a high quality factor is desirable, it is not obvious for the person skilled in the art how such quality factors can be maintained in a system for transfer of significant power when the second resonator is considerably loaded. A clarification of this is needed.

Claims 14-22, 26-28, 45-58, 64-71, 74-77, 79-112, 114-126, 130, 132-141, 143-152, 158-164, 179, 186, 192, 193, 207-215, 219-221, 238-251, 253-264, 267-270, 272-305, 307-319, 323, 325-334, 336-345, 351-357: A large number of claims are describing characteristics of the system with values that appear to be varied in trivial ranges and do not appear to cause an unexpected and surprising effect. The fact that the applicant chooses to include claims with each a part of a range leaves the impression that the applicant is not aware of a particular effect caused by a particular value compared to the other values that are contained in the claims, such that none of these values will involve an inventive step.

Claims 29-33, 60-63, 222-226: A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features themselves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such claims attempt to define the subject-matter in terms of the result to be achieved, which merely amounts to a statement of the underlying problem, without providing the technical features necessary for achieving this result.
One such property is the efficiency that is claimed in a number of claims to include the range from 1% to 100%. An apparatus for use in wireless energy transfer is very likely to have an efficiency in the range of 1%-100%. The efficiency achieved does not involve an inventive step whereas the means that causes the efficiency to be at a certain level may involve an inventive step.
Low efficiency levels in the order of 1% or 10% appear to be an indication that a significant part of the energy transmitted from the first resonator structure is not picked up by the second resonator structure but lost before. This indicates that a significant part of the energy is radiated outside the fields interacting between the two resonator structures and that the system described is not performing "non-radiative energy transfer".

Claims 34-37, 227-230 : A radiation loss that is measurable is contradicting the fact that the system is stated to perform "non-radiative energy transfer".
A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features themselves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such properties do not involve an inventive step.

Claims 38-41, 231-234 : The loss to a human does not comply with the system being stated to perform "non-radiative energy transfer", further does the loss to a human appear to be heavily dependent on the particular human and the situation of this human with respect to the system.
A number of claims refer to properties of the system that are results of technical features used in the system but are not technical features them selves. These properties are often results to be achieved by the technical features and are inherent effects that has values that depend on the technical features. Such properties do not involve an inventive step.

Claims 42, 43, 59, 142, 235, 236, 252 : Inherent in a system as claimed in the independent claim.

Claims 44, 237, 366: The objective problem points at the solution.

Claims 72, 73, 157, 265, 266, 335, 346, 350, 364, 365 : Known from the prior art.

Claims 113, 153-155, 306, 347, 348: The prior art acknowledge that other energy transfer than electromagnetic may be employed. Examples of systems employing other energy transfer than electromagnetic are mentioned in US2003/0199778 (D11). US6798716 (D12) is describing an example using ultrasound for power transmission and DE10304584 (D13) an example of electrostatic coupling.
Resonators that are compliant with such other type of energy transfer will need to be used. It is not obvious to the person skilled in the art how dielectric energy transfer with tenths of watts and over significant distances can be achieved.

Claims 127-129, 320-322: Use of "self resonant conducting wire coils", meaning coils with the capacitive part formed by the intrinsic capacitance between the windings is known from the prior art.

Claims 156, 349: A "whispering gallery mode" is a term that appears related to optical resonators and waveguides The use of light in general is foreseen in US2003/0199778 (D11). The frequency of light seems to extend beyond the frequencies proposed in other claims. Further, the examining division is not sure if a "whispering gallery mode" is compatible with other characteristics claimed in the dependent claims. However, the use of a "whispering gallery mode" is not known from the prior art that is considered the closest for the technical concept of claim 1. The examining division would appreciate a statement from the applicant if the applicant considers that the "whispering gallery mode" is a technical feature that will cause the effects described in the application and allow tenths of watt to be transferred wirelessly through air. It should be reminded that a large number of claims refer to the use of resonantly coupled coils such that a change of the technology necessary to solve the problem may cause an objection of unity to be raised.

Claims 167-170, 360-363: It is trivial that a third resonant structure of the same type may couple with the first or second resonant structure as the mechanism for coupling remains the same. This is further known from the prior art.

4. The following general comments should be considered by the applicant:

4.1 More of the claims, hereunder claim 1, uses the term "characteristic size" of a resonator. "Characteristic size" is not well defined in the field and may refer to a physical dimension of the resonator without making which dimension clear, or for instance refer to a wavelength that may be radiated by the resonator. The "characteristic size" is used in dependent claim to describe further characteristics.
"Characteristic size" is found not to comply with Article 6 PCT due to lack of clarity.

4.2 The term "non-radiative" is used in a number of claims. "Non-radiative" must be interpreted such that no significant radiation can be observed outside of the path connecting the first and second resonators. This appears not to be the case in the present situation for the reason that a number of the claims containing "non-radiative" do not include features that clearly will focus fields from the first resonator towards the second resonator. Therefore only the resonant interaction is a feature that may influence the distribution of the field. Further, more dependent claims mention an efficiency in the order of 1% such that this must be taken as an indication that a considerable part of the field is not interacting with the energy receiving resonator but is radiated elsewhere. This is supported by dependent claims mentioning "a radiation loss".
"Non-radiative" may be a term attributed by the applicant in order to praise the probably reduced level of radiation compared to a situation with no second resonator, such as

described in the prior art, but with a general misleading interpretation. As "non-radiative" would be a result of technical features and not in itself a tangible technical feature of the system, "non-radiative" is a result to be achieved (desideratum) that lacks clarity in how it is being achieved.

4.3 A number of dependent claims describe the quality factor of the resonators to be high (even more than 10000). Whereas it is known from the prior art that the coupling of energy increases with an increase in the quality factor of the resonators, it is not obvious for the person skilled in the art how such quality factors can be maintained in a system for transfer of significant power when the second resonator is considerably loaded. A clarification of this is needed.

4.4 A large number of claims are describing characteristics of the system with values that appear to varied in trivial ranges and do not appear to cause an unexpected and surprising effect. The fact that the applicant chooses to include claims with each a part of a range leave the impression that the applicant is not aware of a particular effect caused by a particular value compared to the other values that are contained in the claims, such that none of these values will involve an inventive step.

4.5 The application at present can only be treated to the extend that it is clear and unambiguous. A large number of the claims appear to contain elements that lack clarity and results to be achieved as replacement of tangible technical features. When such a situation is remedied and the proper technical features of each claim are clear, the features may lack unity in the sense of Rule 13 PCT. In the regional phase of the application a number of different technical concepts may be found after clarification and corresponding objections of lack of unity raised.

4.6 Whereas the basic concept of wireless power transfer using resonant coupling between resonators is clear, but known from the prior art, the applicant should be aware that "scientific theories" are exempted from patenting (Rule 39 PCT). If the applicant has a further understanding of the mechanism that makes the systems known from the prior art work, but no further tangible technical features that causes an unexpected and surprising effect are added to the system, the further enlightenment of the applicant may be characterised as elaborating on a scientific theory.

5. In order to clarify eventual differences between the prior art and the present application a short description of examples and statements in the prior art and a summary of the prior art may be expedient:

D1 (DE3824972): Wireless power transfer system with lamps containing resonant secondary coils that are coupling with a resonant primary at the resonance frequency. Distances up to 5 metres are mentioned.

D2 (DE102005036290): RFID device with power transferred wirelessly from a resonant primary to a resonant secondary over a distance that is larger than the wavelength.

D3 (WO92/17929): A contact less power distribution system with resonant primary- and pick-up circuit and with high quality factor because more power can be extracted this way. It is experienced that low loading of the pick-up circuit can prevent power from reaching other pick-up circuits. This is believed to be caused by high circulating currents in the pick-up coil interacting with the primary coil.

D4 (US2133494): System for transmitting electrical power without wire connection employing resonant conditions in both the energy transmitting and receiving circuits, tuned to the generator frequency whereby the losses in the system are reduced to a minimum.

D5 (US2005/0085873): Resonantly tuned, high quality factor energy transfer system with coils. More efficient energy transfer is known to take place with a high quality factor in the coupling.

D6 (US2002/0032471): A primary and secondary (implanted) coil operating at tuned resonance for efficient power transfer. It is known that a high Q resonant circuit promotes efficient power transfer.

D7 (W096/02970): An inductively powered lamp unit preferably operating in resonance. It is known that transmission of electrical power over significant gaps is feasible with resonant primary and secondary conductors. It is experienced that the resonant secondary currents tends to block the primary current from reaching past this secondary coil and reach other secondary coils.

D8 (US5528113): A loosely coupled inductive power transfer system with a statement that electric power can be transferred "across a significant space". Use of resonant or tuned primary and secondary inductive elements for the sake of greatly improved effectiveness prevents proper transfer to other consumers further away than the secondary inductive element.

D9 (WO93/23908): A non-contact power distribution system with resonant primary and secondary circuits operating at the same resonant frequency in order to maximise the quality factor and enhance coupling and power transfer.

D10 (WO2007/008646): Wireless non-radiative energy transfer system, from the same applicant, that is forming part of the prior art.

Examples of systems employing other energy transfer than electromagnetic are mentioned in US2003/0199778 (D11). US6798716 (D12)is describing an example using ultrasound for power transmission and DE10304584 (D13) an example of electrostatic coupling.

5.1 In conclusion a large number of prior art documents describe power transfer using mutually coupled resonators operating in the vicinity of the resonant frequency. It is well known that the higher the quality factor of the resonators are, the better the energy is coupled. It is also an observed fact in the prior art that the field around the energy receiving resonator is influenced by the resonant coupling such that little field is observed around the energy receiving resonator. The coupling may be near-field or remote-field and the field may be focussed in the direction of the other resonator. It is known from the prior art that not only electromagnetic coupling may be employed but also other type of coupling. A wide range of frequencies from the KHz-range to the GHz-range is employed.

5.2 The part of the application with tangible technical features, though containing some terms that are considered to lack clarity, appears to be known from the prior art. A huge number of dependent claims are listing characteristics and desiderata of the system and it is at present not clear to the examining division if any of these characteristics may relate to a special technical feature that cause unexpected and surprising effects.

It is the hope of the examining division that the above description of the prior art may help the applicant in identifying which one of the many different characteristics that can be argued to be a special technical feature and involve an inventive step (Article 33(3) PCT).

Possible steps after receipt of the international search report (ISR) and written opinion of the International Searching Authority (WO-ISA)

General information	For all international applications filed on or after 01/01/2004 the competent ISA will establish an ISR. It is accompanied by the WO-ISA. Unlike the former written opinion of the IPEA (Rule 66.2 PCT), the WO-ISA is not meant to be responded to, but to be taken into consideration for further procedural steps. This document explains about the possibilities.
Amending claims under Art. 19 PCT	Within 2 months after the date of mailing of the ISR and the WO-ISA the applicant may file amended claims under Art. 19 PCT directly with the International Bureau of WIPO. The PCT reform of 2004 did not change this procedure. For further information please see Rule 46 PCT as well as form PCT/ISA/220 and the corresponding Notes to form PCT/ISA/220.
Filing a demand for international preliminary examination	In principle, the WO-ISA will be considered as the written opinion of the IPEA. This should, in many cases, make it unnecessary to file a demand for international preliminary examination. If the applicant nevertheless wishes to file a demand this must be done before expiry of 3 months after the date of mailing of the ISR/WO-ISA or 22 months after priority date, whichever expires later (Rule 54bis PCT). Amendments under Art. 34 PCT can be filed with the IPEA as before, normally at the same time as filing the demand (Rule 66.1 (b) PCT). If a demand for international preliminary examination is filed and no comments/amendments have been received the WO-ISA will be transformed by the IPEA into an IPRP (International Preliminary Report on Patentability) which would merely reflect the content of the WO-ISA. The demand can still be withdrawn (Art. 37 PCT).
Filing informal comments	After receipt of the ISR/WO-ISA the applicant may file informal comments on the WO-ISA directly with the International Bureau of WIPO. These will be communicated to the designated Offices together with the IPRP (International Preliminary Report on Patentability) at 30 months from the priority date. Please also refer to the next box.
End of the international phase	At the end of the international phase the International Bureau of WIPO will transform the WO-ISA or, if a demand was filed, the written opinion of the IPEA into the IPRP, which will then be transmitted together with possible informal comments to the designated Offices. The IPRP replaces the former IPER (international preliminary examination report).
Relevant PCT Rules and more information	Rule 43 PCT, Rule 43bis PCT, Rule 44 PCT, Rule 44bis PCT, PCT Newsletter 12/2003, OJ 11/2003, OJ 12/2003

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:
MARC M. WEFERS
FISH & RICHARDSON P.C.
PO BOX 1022
MINNEAPOLIS, MN 55440-1022

PCT

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing *(day/month/year)* 14 JUL 2009		
Applicant's or agent's file reference 019970364WO1	FOR FURTHER ACTION See paragraph 2 below	
International application No. PCT/US 09/43970	International filing date *(day/month/year)* 14 May 2009 (14.05.2009)	Priority date *(day/month/year)* 14 May 2008 (14.05.2008)
International Patent Classification (IPC) or both national classification and IPC IPC(8) - H01P 7/00 (2009.01) USPC - 333/219		
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

1. This opinion contains indications relating to the following items:

- [x] 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
- [x] 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	07 July 2009 (07.07.2009)	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (April 2007)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

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Box No. I **Basis of this opinion**

1. With regard to the **language**, this opinion has been established on the basis of:
   - [X] 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. type of material
      - [ ] a sequence listing
      - [ ] table(s) related to the sequence listing

   b. format of material
      - [ ] on paper
      - [ ] in electronic form

   c. time of filing/furnishing
      - [ ] contained in the international application as filed
      - [ ] filed together with the international application in electronic form
      - [ ] furnished 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 and/or table(s) relating thereto 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:

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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 - 63	YES
	Claims	None.	NO
Inventive step (IS)	Claims	None.	YES
	Claims	1 - 63	NO
Industrial applicability (IA)	Claims	1 - 63	YES
	Claims	None.	NO

2. Citations and explanations:

Claims 1-8 lack an inventive step under PCT Article 33(3) as being obvious over US 2007/0222542 A1 to Joannopoulos et al. (hereinafter 'Joannopoulos').

Regarding claim 1, Joannopoulos discloses an apparatus for use in wireless energy transfer, the apparatus comprising: a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L1 of said first resonator structure and larger than a characteristic size L2 of said second resonator structure (para [0005]), wherein the energy transfer has a rate kappa and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 at least larger than 300 (para [0027]), and said resonant field of the first resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 at least larger than 300 (para [0027]), wherein the absolute value of the difference of said angular frequencies omega1 and omega2 is smaller than the broader of said resonant widths gamma1 and gamma2 (para [0016]), and further comprising a power supply coupled to the first structure and configured to drive the first resonator structure or the second resonator structure at an angular frequency away from the resonance angular frequencies and shifted towards a frequency corresponding to an odd normal mode for the resonator structures (para [0024]) to reduce radiation from the resonator structures by destructive far-field interference (para [0029]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]).

Regarding claim 2, Joannopoulos discloses the apparatus of claim 1, wherein the power supply is configured to drive the first resonator structure or the second resonator structure at the angular frequency away from the resonance angular frequencies and shifted towards the frequency corresponding to an odd normal mode for the resonator structures (para [0024]) to substantially suppress radiation from the resonator structures by destructive far-field interference (para [0029]).

Regarding claim 3, Joannopoulos discloses a method for wireless energy transfer involving a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L1 of said first resonator structure and larger than a characteristic size L2 of said second resonator structure (para [0005]), wherein the energy transfer has a rate kappa and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 at least larger than 300 (para [0027]), and said resonant field of the first resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 at least larger than 300 (para [0027]), wherein the absolute value of the difference of said angular frequencies omega1 and omega2 is smaller than the broader of said resonant widths gamma1 and gamma2 (para [0016]), the method comprising: driving the first resonator structure or the second resonator structure at an angular frequency away from the resonance angular frequencies and shifted towards a frequency corresponding to an odd normal mode for the resonator structures (para [0024]) to reduce radiation from the resonator structures by destructive far-field interference (para [0029]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]).

Regarding claim 4, Joannopoulos discloses the method of claim 3, wherein the first resonator structure or the second resonator structure is driven at the angular frequency away from the resonance angular frequencies and shifted towards the frequency corresponding to an odd normal mode for the resonator structures (para [0024]) to substantially suppress radiation from the resonator structures by destructive far-field interference (para [0029]).

-Please see Supplemental Pages.-

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Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
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Box V.2. Citations and explanations:

Regarding claim 5, Joannopoulos discloses an apparatus for use in wireless energy transfer, the apparatus comprising: a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L1 of said first resonator structure and larger than a characteristic size L2 of said second resonator structure (para [0005]), wherein the energy transfer has a rate kappa and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 at least larger than 300 (para [0027]), and said resonant field of the first resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 at least larger than 300 (para [0027]), wherein the absolute value of the difference of said angular frequencies omega1 and omega2 is smaller than the broader of said resonant widths gamma1 and gamma2 (para [0016]), wherein for a desired range of the distances D, the resonance angular frequencies for the resonator structures increase transmission efficiency T by accounting for radiative interference, wherein the increase is relative to a transmission efficiency T calculated without accounting for the radiative interference (para [0042]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]).

Regarding claim 6, Joannopoulos discloses the apparatus of claim 5, wherein the resonance angular frequencies for the resonator structures are selected by optimizing the transmission efficiency T to account for both a resonance quality factor U and an interference factor V (para [0035]).

Regarding claim 7, Joannopoulos discloses a method for designing a wireless energy transfer apparatus, the apparatus including a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L1 of said first resonator structure and larger than a characteristic size L2 of said second resonator structure (para [0005]), wherein the energy transfer has a rate kappa and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 at least larger than 300 (para [0027]), and said resonant field of the first resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 at least larger than 300 (para [0027]), wherein the absolute value of the difference of said angular frequencies omega1 and omega2 is smaller than the broader of said resonant widths gamma1 and gamma2 (para [0016]), the method comprising: selecting the resonance angular frequencies for the resonator structures to substantially optimize the transmission efficiency by accounting for radiative interference between the resonator structures (para [0042]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]). Joannopoulos does not specifically disclose wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20. However, it does disclose wherein the quantity kappa is much greater than the quantity sqrt(gamma1gamma2) (para [0028]). It would have been obvious to one of ordinary skill in the art to provide wherein the quantity kappa/sqrt(gamma1gamma2) is at least larger than 20 based on experiment and design to give the quantities their optimum values (para [0028]).

Regarding claim 8, Joannopoulos discloses the method of claim 7, wherein the resonance angular frequencies for the resonator structures are selected by optimizing the transmission efficiency T to account for both a resonance quality factor U and an interference factor V (para [0035]).

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In case **the space in any of the preceding boxes is not sufficient.**
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Box V.2. Citations and explanations:

Claims 9-14, 26-36, 48-56, 59, 60 and 63 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos, in view of US 2004/0113847 A1 to Qi et al. (hereinafter 'Qi').

Regarding claim 9, Joannopoulos discloses an apparatus for use in wireless energy transfer, the apparatus comprising: a first resonator structure configured for energy transfer with a second resonator structure over a distance D (para [0005]), wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 (para [0027]), with an associated radiation quality factor Q1,rad >= Q1 (para [0022]), said resonant field of the second resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 (para [0027]), with an associated radiation quality factor Q2,rad >= Q2 (para [0022]), wherein an absolute value of a difference of said angular frequencies omega1 and omega2 is smaller than broader of said resonant widths gamma1 and gamma2 (para [0016]), and an average resonant angular frequency is defined as omegao = sqrt(omega1omega2) (para [0024]), corresponding to an average resonant wavelength lambdao = 2pic/omegao, where c is the speed of light in free space (para [0026]), and a strong-coupling factor being defined as U = ksqrt(Q1Q2) (para [0028]). Joannopoulos does not specifically disclose wherein said resonant field of the first resonator structure is radiative in the far field, wherein said resonant field of the second resonator structure is radiative in the far field, and wherein the apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference, a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)). However, Qi does disclose wherein said resonant field of the first resonator structure is radiative in the far field (para [0015]), wherein said resonant field of the second resonator structure is radiative in the far field (para [0015]), and wherein the apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator (para [0015]), with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference (para [0023]), a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)) (para [0015]). It would have been obvious to one of ordinary skill in the art to combine the apparatus of Joannopoulos with the element of Qi because Qi discloses that its element addresses an ongoing need in the art for improving operating characteristics (Qi para [0015]).

Regarding claim 10, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.01 and Q2/Q2,rad >= 0.01 (para [0027]).

Regarding claim 11, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.1 and Q2/Q2,rad >= 0.1 (para [0027]).

Regarding claim 12, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein D/lambdao is larger than 0.001 (para [0024]) and the strong-interference factor V is larger than 0.01 (para [0027]).

Regarding claim 13, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein D/lambdao is larger than 0.001 (para [0024]) and the strong-interference factor V is larger than 0.1 (para [0027]).

Regarding claim 14, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses the second resonator structure (para [0005]).

Regarding claim 26, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein at least one of the first and second resonator structures comprises a capacitively loaded loop of a conducting wire (para [0019]).

Regarding claim 27, the combination of Joannopoulos and Qi discloses the apparatus of claim 26, and Joannopoulos further discloses where the characteristic size of said loop is less than 30 cm and the width of said conducting wire is less than 2 cm (para [0027]).

Regarding claim 28, the combination of Joannopoulos and Qi discloses the apparatus of claim 26, and Joannopoulos further discloses where the characteristic size of said loop is less than 1 m and the width of said conducting wire is less than 2 cm (para [0027]).

Regarding claim 29, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses a feedback mechanism for maintaining the resonant frequency of one or more of the resonant objects (para [0031]).

Regarding claim 30, the combination of Joannopoulos and Qi discloses the apparatus of claim 29, and Joannopoulos further discloses wherein the feedback mechanism comprises an oscillator with a fixed driving frequency and is configured to adjust the resonant frequency of the one or more resonant objects to be detuned by a fixed amount with respect to the fixed frequency (para [0031]).

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Continuation of:

Box V.2. Citations and explanations:

Regarding claim 31, Joannopoulos discloses an apparatus for use in wireless energy transfer, the apparatus comprising: a first resonator structure configured for energy transfer with a second resonator structure over a distance D (para [0005]), wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 (para [0027]), with an associated radiation quality factor Q1,rad >= Q1 (para [0022]), said resonant field of the second resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 (para [0027]), with an associated radiation quality factor Q2,rad >= Q2 (para [0022]), wherein an absolute value of a difference of said angular frequencies omega1 and omega2 is smaller than broader of said resonant widths gamma1 and gamma2 (para [0016]), and an average resonant angular frequency is defined as omegao = sqrt(omega1omega2) (para [0024]), corresponding to an average resonant wavelength lambdao = 2pic/omegao, where c is the speed of light in free space (para [0026]), and a strong-coupling factor being defined as U = ksqrt(Q1Q2) (para [0028]). Joannopoulos does not specifically disclose wherein said resonant field of the first resonator structure is radiative in the far field, wherein said resonant field of the second resonator structure is radiative in the far field, and wherein the apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference, a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)). However, Qi does disclose wherein said resonant field of the first resonator structure is radiative in the far field (para [0015]), wherein said resonant field of the second resonator structure is radiative in the far field (para [0015]), and wherein the apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator (para [0015]), with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference (para [0023]), a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)) (para [0015]). It would have been obvious to one of ordinary skill in the art to combine the apparatus of Joannopoulos with the element of Qi because Qi discloses that its element addresses an ongoing need in the art for improving operating characteristics (Qi para [0015]).

Regarding claim 32, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.05 and Q2/Q2,rad >= 0.05 (para [0027]).

Regarding claim 33, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.5 and Q2/Q2,rad >= 0.5 (para [0027]).

Regarding claim 34, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein D/lambdao is larger than 0.01 (para [0024]) and the strong-interference factor V is larger than 0.05 (para [0027]).

Regarding claim 35, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein D/lambdao is larger than 0.01 (para [0024]) and the strong-interference factor V is larger than 0.5 (para [0027]).

Regarding claim 36, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses the second resonator structure (para [0005]).

Regarding claim 48, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein at least one of the first and second resonator structures comprises a capacitively loaded loop of a conducting wire (para [0019]).

Regarding claim 49, the combination of Joannopoulos and Qi discloses the apparatus of claim 48, and Joannopoulos further discloses where the characteristic size of said loop is less than 30 cm and the width of said conducting wire is less than 2 cm (para [0027]).

Regarding claim 50, the combination of Joannopoulos and Qi discloses the apparatus of claim 48, and Joannopoulos further discloses where the characteristic size of said loop is less than 1 m and the width of said conducting wire is less than 2 cm (para [0027]).

Regarding claim 51, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses a feedback mechanism for maintaining the resonant frequency of one or more of the resonant objects (para [0031]).

Regarding claim 52, the combination of Joannopoulos and Qi discloses the apparatus of claim 51, and Joannopoulos further discloses wherein the feedback mechanism comprises an oscillator with a fixed driving frequency and is configured to adjust the resonant frequency of the one or more resonant objects to be detuned by a fixed amount with respect to the fixed frequency (para [0031]).

Regarding claim 53, the combination of Joannopoulos and Qi discloses the apparatus of claim 51, and Joannopoulos further discloses where the feedback mechanism is configured to monitor an efficiency of the energy transfer, and adjust the resonant frequency of the one or more resonant objects to maximize the efficiency (para [0031]).

Regarding claim 54, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein the resonance angular frequencies for the resonator structures are selected to optimize the energy-transfer efficiency by accounting for both the strong-coupling factor U and the strong-interference interference factor V (para [0016]).

-Please see continuation sheet-

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

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Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Box V.2. Citations and explanations:

Regarding claim 55, the combination of Joannopoulos and Qi discloses a method for wireless energy transfer, the method comprising: providing a first resonator structure configured for energy transfer with a second resonator structure over a distance D (para [0005]), wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 (para [0027]), with an associated radiation quality factor Q1,rad >= Q1 (para [0022]), said resonant field of the second resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 (para [0027]), with an associated radiation quality factor Q2,rad >= Q2 (para [0022]), wherein an absolute value of a difference of said angular frequencies omega1 and omega2 is smaller than broader of said resonant widths gamma1 and gamma2 (para [0016]), and an average resonant angular frequency is defined as omegao = sqrt(omega1omega2) (para [0024]), corresponding to an average resonant wavelength lambdao = 2pic/omegao, where c is the speed of light in free space (para [0026]), and a strong-coupling factor being defined as U = ksqrt(Q1Q2) (para [0028]). Joannopoulos does not specifically disclose wherein said resonant field of the first resonator structure is radiative in the far field, wherein said resonant field of the second resonator structure is radiative in the far field, and employing interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference, a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)). However, Qi does disclose wherein said resonant field of the first resonator structure is radiative in the far field (para [0015]), wherein said resonant field of the second resonator structure is radiative in the far field (para [0015]), and employing interference between said radiative far fields of the resonant fields of the first and second resonator (para [0015]), with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference (para [0023]), a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)) (para [0015]). It would have been obvious to one of ordinary skill in the art to combine the method of Joannopoulos with the element of Qi because Qi discloses that its element addresses an ongoing need in the art for improving operating characteristics (Qi para [0015]).

Regarding claim 56, the combination of Joannopoulos and Qi discloses the method of claim 55, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.01 and Q2/Q2,rad >= 0.01 (para [0027]).

Regarding claim 59, the combination of Joannopoulos and Qi discloses a method for wireless energy transfer, the method comprising: providing a first resonator structure configured for energy transfer with a second resonator structure over a distance D (para [0005]), wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k (para [0006]), wherein said resonant field of the first resonator structure has a resonance angular frequency omega1 (para [0015]), a resonance frequency-width gamma1 (para [0015]), and a resonance quality factor Q1 = omega1/2gamma1 (para [0027]), with an associated radiation quality factor Q1,rad >= Q1 (para [0022]), said resonant field of the second resonator structure has a resonance angular frequency omega2 (para [0015]), a resonance frequency-width gamma2 (para [0015]), and a resonance quality factor Q2 = omega2/2gamma2 (para [0027]), with an associated radiation quality factor Q2,rad >= Q2 (para [0022]), wherein an absolute value of a difference of said angular frequencies omega1 and omega2 is smaller than broader of said resonant widths gamma1 and gamma2 (para [0016]), and an average resonant angular frequency is defined as omegao = sqrt(omega1omega2) (para [0024]), corresponding to an average resonant wavelength lambdao = 2pic/omegao, where c is the speed of light in free space (para [0026]), and a strong-coupling factor being defined as U = ksqrt(Q1Q2) (para [0028]). Joannopoulos does not specifically disclose wherein said resonant field of the first resonator structure is radiative in the far field, wherein said resonant field of the second resonator structure is radiative in the far field, and employing interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference, a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)). However, Qi does disclose wherein said resonant field of the first resonator structure is radiative in the far field (para [0015]), wherein said resonant field of the second resonator structure is radiative in the far field (para [0015]), and employing interference between said radiative far fields of the resonant fields of the first and second resonator (para [0015]), with an interference factor Vrad, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference (para [0023]), a strong-interference factor being defined as V = Vradsqrt((Q1/Q1,rad)(Q2/Q2,rad)) (para [0015]). It would have been obvious to one of ordinary skill in the art to combine the method of Joannopoulos with the element of Qi because Qi discloses that its element addresses an ongoing need in the art for improving operating characteristics (Qi para [0015]).

Regarding claim 60, the combination of Joannopoulos and Qi discloses the method of claim 59, and Joannopoulos further discloses wherein Q1/Q1,rad >= 0.01 and Q2/Q2,rad >= 0.05 (para [0027]).

Regarding claim 63, the combination of Joannopoulos and Qi discloses the method of claim 59, and Joannopoulos further discloses wherein the resonance angular frequencies for the resonator structures are selected to optimize the energy-transfer efficiency by accounting for both the strong-coupling factor U and the strong-interference interference factor V (para [0016]).

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Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Box V.2. Citations and explanations:

Claims 15-25, 37-47, 57, 58, 61 and 62 lack an inventive step under PCT Article 33(3) as being obvious over Joannopoulos in view of Qi and in further view of US 5,437,057 A to Richley et al. (hereinafter 'Richley').

Regarding claim 15, the combination of Joannopoulos and Qi discloses the apparatus of claim 9, and Joannopoulos further discloses wherein, during operation, a power generator is coupled to one of the first and second resonant structure (para [0005]), with a coupling rate kappag (para [0006]), wherein Ug is defined as kappag/gamma1, if the power generator is coupled to the first resonator structure and defined as kappag/gamma2 if the power generator is coupled to the second resonator structure (para [0024]). Neither specifically discloses wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif. However, Richley does disclose wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif (col 9, ln 6-18). It would have been obvious to one of ordinary skill in the art to combine the apparatus of Joannopoulos and Qi with the element of Richley because Richley teaches that its element addresses an ongoing need in the art for driving the resonators (Richley col 9, ln 6-18).

Regarding claim 16, the combination of Joannopoulos, Qi and Richely discloses the apparatus of claim 15, and Joannopoulos further discloses wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures (para [0024]), wherein the detuning of the first resonator from the driving frequency is defined as D1 = (omega - omega1)/gamma1 and the detuning of the second resonator structure from the driving frequency is defined as D2 = (omega - omega2)/gamma2 (para [0024]).

Regarding claim 17, the combination of Joannopoulos, Qi and Richely discloses the apparatus of claim 16, and Qi further discloses wherein D1 is approximately equal to UVrad and D2 is approximately equal to UVrad (para [0015]).

Regarding claim 18, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 15, and Joannopoulos further discloses wherein Ug is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency (para [0012]).

Regarding claim 19, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 17, and Joannopoulos further discloses wherein Ug is approximately equal to sqrt(1 + U^2 - Vrad^2 U^2 + V^2 - 2VVrad) (para [0028]).

Regarding claim 20, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 17, and Joannopoulos further discloses wherein f is at least larger than 100 kHz and smaller than 500MH (para [0027]).

Regarding claim 21, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 17, and Joannopoulos further discloses wherein f is at least larger than 1MHz and smaller than 50MHz (para [0027]).

Regarding claim 22, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 15, and Joannopoulos further discloses the power generator (para [0005]).

Regarding claim 23, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 15, and Joannopoulos further discloses wherein, during operation, a power load is coupled to the resonant structure to which the power generator is not coupled, with a coupling rate kappa1 (para [0021]), and is configured to receive from the resonator structure, to which it is coupled, a usable power (para [0005]), wherein U1 is defined as kappa1/gamma1, if the power load is coupled to the first resonator structure and defined as kappa1/gamma2 if the power load is coupled to the second resonator structure (para [0024]).

Regarding claim 24, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 23, and Joannopoulos further discloses wherein U1 is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency (para [0012]).

Regarding claim 25, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 24, and Joannopoulos further discloses wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures (para [0024]), wherein the detuning of the first resonator from the driving frequency is defined as D1 = (omega - omega1)/gamma1 and is approximately equal to UVrad and the detuning of the second resonator structure from the driving frequency is defined as D2 = (omega - omega2)/gamma2 and is approximately equal to UVrad (para [0024]), wherein U1 is approximately equal to sqrt(1 + U^2 - Vrad^2 U^2 + V^2 - 2VVrad) (para [0028]).

Regarding claim 37, the combination of Joannopoulos and Qi discloses the apparatus of claim 31, and Joannopoulos further discloses wherein, during operation, a power generator is coupled to one of the first and second resonant structure (para [0005]), with a coupling rate kappag (para [0006]), wherein Ug is defined as kappag/gamma1, if the power generator is coupled to the first resonator structure and defined as kappag/gamma2 if the power generator is coupled to the second resonator structure (para [0024]). Neither specifically discloses wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif. However, Richley does disclose wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif (col 9, ln 6-18). It would have been obvious to one of ordinary skill in the art to combine the apparatus of Joannopoulos and Qi with the element of Richley because Richley teaches that its element addresses an ongoing need in the art for driving the resonators (Richley col 9, ln 6-18).

-Please see continuation sheet-

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

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Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of:
Box V.2. Citations and explanations:

Regarding claim 38, the combination of Joannopoulos, Qi and Richely discloses the apparatus of claim 37, and Joannopoulos further discloses wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures (para [0024]), wherein the detuning of the first resonator from the driving frequency is defined as D1 = (omega - omega1)/gamma1 and the detuning of the second resonator structure from the driving frequency is defined as D2 = (omega - omega2)/gamma2 (para [0024]).

Regarding claim 39, the combination of Joannopoulos, Qi and Richely discloses the apparatus of claim 38, and Qi further discloses wherein D1 is approximately equal to UV and D2 is approximately equal to UV (para [0015]).

Regarding claim 40, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 37, and Joannopoulos further discloses wherein Ug is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency (para [0012]).

Regarding claim 41, the combination of Joannopoulos, Qi and Richely discloses the apparatus of claim 39, and Joannopoulos further discloses wherein Ug is approximately equal to sqrt((1 + U^2)(1 - V^2)) (para [0028]).

Regarding claim 42, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 37, and Joannopoulos further discloses wherein f is at least larger than 100 kHz and smaller than 500MH (para [0027]).

Regarding claim 43, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 37, and Joannopoulos further discloses wherein f is at least larger than 1MHz and smaller than 50MHz (para [0027]).

Regarding claim 44, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 37, and Joannopoulos further discloses the power generator (para [0005]).

Regarding claim 45, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 37, and Joannopoulos further discloses wherein, during operation, a power load is coupled to the resonant structure to which the power generator is not coupled, with a coupling rate kappa1 (para [0021]), and is configured to receive from the resonator structure, to which it is coupled, a usable power (para [0005]), wherein U1 is defined as kappa1/gamma1, if the power load is coupled to the first resonator structure and defined as kappa1/gamma2 if the power load is coupled to the second resonator structure (para [0024]).

Regarding claim 46, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 45, and Joannopoulos further discloses wherein U1 is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency (para [0012]).

Regarding claim 47, the combination of Joannopoulos, Qi and Richley discloses the apparatus of claim 46, and Joannopoulos further discloses wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures (para [0024]), wherein the detuning of the first resonator from the driving frequency is defined as D1 = (omega - omega1)/gamma1 and is approximately equal to UV, and the detuning of the second resonator structure from the driving frequency is defined as D2 = (omega - omega2)/gamma2 (para [0024]) and is approximately equal to UV, wherein U1 is approximately equal to sqrt((1 + U^2)(1 - V^2)) (para [0028]).

Regarding claim 57, the combination of Joannopoulos and Qi discloses the method of claim 55, and Joannopoulos further discloses wherein, during operation, a power generator is coupled to one of the first and second resonant structure (para [0005]), with a coupling rate kappag (para [0006]), wherein Ug is defined as kappag/gamma1, if the power generator is coupled to the first resonator structure and defined as kappag/gamma2 if the power generator is coupled to the second resonator structure (para [0024]). Neither specifically discloses wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif. However, Richley does disclose wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif (col 9, ln 6-18). It would have been obvious to one of ordinary skill in the art to combine the method of Joannopoulos and Qi with the element of Richley because Richley teaches that its element addresses an ongoing need in the art for driving the resonators (Richley col 9, ln 6-18).

Regarding claim 58, the combination of Joannopoulos, Qi and Richley discloses the method of claim 57, and Joannopoulos further discloses wherein, during operation, a power load is coupled to the resonant structure to which the power generator is not coupled, and is configured to receive from the resonator structure, to which it is coupled, a usable power (para [0005]).

Regarding claim 61, the combination of Joannopoulos and Qi discloses the method of claim 59, and Joannopoulos further discloses wherein, during operation, a power generator is coupled to one of the first and second resonant structure (para [0005]), with a coupling rate kappag (para [0006]), wherein Ug is defined as kappag/gamma1, if the power generator is coupled to the first resonator structure and defined as kappag/gamma2 if the power generator is coupled to the second resonator structure (para [0024]). Neither specifically discloses wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif. However, Richley does disclose wherein a power generator is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency omega = 2pif (col 9, ln 6-18). It would have been obvious to one of ordinary skill in the art to combine the method of Joannopoulos and Qi with the element of Richley because Richley teaches that its element addresses an ongoing need in the art for driving the resonators (Richley col 9, ln 6-18).

Regarding claim 62, the combination of Joannopoulos, Qi and Richley discloses the method of claim 61, and Joannopoulos further discloses wherein, during operation, a power load is coupled to the resonant structure to which the power generator is not coupled, and is configured to receive from the resonator structure, to which it is coupled, a usable power (para [0005]).

Claims 1 - 63 have industrial applicability as defined by PCT Article 33(4) because the subject matter can be made or used in industry.

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. PCT/US 09/58499	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 (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:

- [X] 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
- [X] 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:
   - [X] 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 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)---

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.

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:
"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	Date of mailing of the international search report
24 November 2009 (24.11.2009)	10 DEC 2009

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	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: 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. PCT/US 09/58499	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 (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:
   - [X] 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)---

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.

PATENT COOPERATION TREATY

From the INTERNATIONAL SEARCHING AUTHORITY

To: MARC M. WEFERS FISH & RICHARDSON P.C. P.O. BOX 1022 MINNEAPOLIS, MN 55440-1022	**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)* 07 DEC 2009
Applicant's or agent's file reference 019970366WO1	**FOR FURTHER ACTION** See paragraphs 1 and 4 below
International application No. PCT/US 09/59244	International filing date *(day/month/year)* 01 October 2009 (01.10.2009)
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY	

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 22 740 14 35

   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	Authorized officer:
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/220 (January 2004) *(See notes on accompanying sheet)*

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference 019970366WO1	FOR FURTHER ACTION	see Form PCT/ISA/220 as well as, where applicable, item 5 below.
International application No. PCT/US 09/59244	International filing date *(day/month/year)* 01 October 2009 (01.10.2009)	(Earliest) Priority Date *(day/month/year)* 01 October 2008 (01.10.2008)
Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY		

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 3 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(b), 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) (April 2007)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/59244

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 5, 7-12, 14-19, 25-27, 33-49 and 54-79
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (April 2007)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 09/59244

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01P 7/00 (2009.01)
USPC - 333/219
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 - 333/219

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 333/219; 307/126; 455/522 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
pubwest (DB=PGPB,USPT,EPAB,JPAB), Google Scholar
Terms - wireless energy, coupling rate, resonate, energy accumulation, near-field, transfer, intermediate

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), abstract, para [0013], [0015], [0016], [0026], [0027], [0035]	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
Y	US 3,517,350 A (Beaver) 23 June 1970 (23.06.1970), col 2, ln 69-72; col 7, ln 22-39	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
X, P	US 2009/0153273 A1 (Chen) 18 June 2009 (18.06.2009), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
X, P	WO 2008/118178 A1 (Karalis et al.) 02 October 2008 (02.10.2008), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 6,960,968 B2 (Odendaal et al.) 01 November 2005 (01.11.2005), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 7,069,064 B2 (Gevorgian et al.) 27 June 2006 (27.06.2006), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81
A	US 1,119,732 A (Tesla) 01 December 1914 (01.12.1914), entire document	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81

☐ 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
16 November 2009 (16.11.2009)

Date of mailing of the international search report
07 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) (April 2007)

PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:
MARC M. WEFERS
FISH & RICHARDSON P.C.
P.O. BOX 1022
MINNEAPOLIS, MN 55440-1022

PCT

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

Date of mailing *(day/month/year)*	07 DEC 2009

Applicant's or agent's file reference	FOR FURTHER ACTION
019970366WO1	See paragraph 2 below

International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/US 09/59244	01 October 2009 (01.10.2009)	01 October 2008 (01.10.2008)

International Patent Classification (IPC) or both national classification and IPC
IPC(8) - H01P 7/00 (2009.01)
USPC - 333/219

Applicant MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1. This opinion contains indications relating to the following items:

- [x] Box No. I Basis of the opinion
- [ ] Box No. II Priority
- [x] Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- [ ] Box No. IV Lack of unity of invention
- [x] 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
- [x] 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	24 November 2009 (24.11.2009)	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/237 (cover sheet) (April 2007)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/US 09/59244

Box No. I Basis of this opinion

1. With regard to the **language**, this opinion has been established on the basis of:
   - [X] 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. type of material
      - [ ] a sequence listing
      - [ ] table(s) related to the sequence listing

   b. format of material
      - [ ] on paper
      - [ ] in electronic form

   c. time of filing/furnishing
      - [ ] contained in the international application as filed
      - [ ] filed together with the international application in electronic form
      - [ ] furnished 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 and/or table(s) relating thereto 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) (April 2007)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/US 09/59244

Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability

The questions whether the claimed invention appears to be novel, to involve an inventive step (to be non obvious), or to be industrially applicable have not been examined in respect of

☐ the entire international application

☒ claims Nos. 5, 7-12, 14-19, 25-27, 33-49, 54-79

because:

☐ the said international application, or the said claims Nos. ______ relate to the following subject matter which does not require an international search *(specify)*:

☒ the description, claims or drawings *(indicate particular elements below)* or said claims Nos. See below. are so unclear that no meaningful opinion could be formed *(specify)*:

Claims 5, 7-12, 14-19, 25-27, 33-49 and 54-79 are unsearchable because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

☐ the claims, or said claims Nos. ______ are so inadequately supported by the description that no meaningful opinion could be formed *(specify)*:

☒ no international search report has been established for said claims Nos. 5, 7-12, 14-19, 25-27, 33-49, 54-79

☐ a meaningful opinion could not be formed without the sequence listing; the applicant did not, within the prescribed time limit:

- ☐ furnish a sequence listing on paper complying with the standard provided for in Annex C of the Administrative Instructions, and such listing was not available to the International Searching Authority in a form and manner acceptable to it.
- ☐ furnish a sequence listing in electronic form complying with the standard provided for in Annex C of the Administrative Instructions, and such listing was not available to the International Searching Authority in a form and manner acceptable to it.
- ☐ pay the required late furnishing fee for the furnishing of a sequence listing in response to an invitation under Rule 13*ter*.1(a) or (b).

☐ a meaningful opinion could not be formed without the tables related to the sequence listings; the applicant did not, within the prescribed time limit, furnish such tables in electronic form complying with the technical requirements provided for in Annex C-*bis* of the Administrative Instructions, and such tables were not available to the International Searching Authority in a form and manner acceptable to it.

☐ the tables related to the nucleotide and/or amino acid sequence listing, if in electronic form only, do not comply with the technical requirements provided for in Annex C-*bis* of the Administrative Instructions.

☐ See Supplemental Box for further details.

Form PCT/ISA/237 (Box No. III) (April 2007)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/US 09/59244

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	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81	YES
	Claims	None.	NO
Inventive step (IS)	Claims	None.	YES
	Claims	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81	NO
Industrial applicability (IA)	Claims	1-4, 6, 13, 20-24, 28-32, 50-53, 80, 81	YES
	Claims	None.	NO

2. Citations and explanations:

Claims 1-4, 6, 13, 20-24, 28-32, 50-53, 80 and 81 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 3,517,350 A (Beaver).

As per claim 1, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose transferring energy wirelessly from a first resonator structure to an intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is K_1B; transferring energy wirelessly from the intermediate resonator structure to a second resonator structure, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is K_B2; and during the wireless energy transfers, adjusting at least one of the coupling rates K_1B and K_B2 to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure. Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos wireless energy transfer with two resonator structures with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have the optimization of the coupling rate to minimize losses by Joannopoulos be such that adjusting at least one of the coupling rates K_1B and K_B2 to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure, in order to improve wireless energy transfer.

As per claims 2-4, dependent on claim 1, neither Joannopoulos nor Beaver specifically disclose wherein the adjustment of at least one of the coupling rates K_1B and K_B2 minimizes energy accumulation in the intermediate resonator structure and causes wireless energy transfer from the first resonator structure to the second resonator structure; maintains energy distribution in the field of the three resonator system in an eigenstate having substantially no energy in the intermediate resonator structure; and further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure. However, Joannopoulos discloses coupling rates being optimized (Abstract, para [0015], [0016]). It would have been obvious to a person of ordinary skill in the art to have the optimization of Joannopoulos be such that the adjustment of at least one of the coupling rates K_1B and K_B2 minimizes energy accumulation in the intermediate resonator structure and causes wireless energy transfer from the first resonator structure to the second resonator structure; maintains energy distribution in the field of the three resonator system in an eigenstate having substantially no energy in the intermediate resonator structure, and further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure as a means of optimizing energy transfer and coupling rates.

As per claim 6, dependent on claim 1, Joannopoulos further discloses wherein the resonator structures each have a quality factor larger than 10 (para [0026], [0027]).

As per claim 13, dependent on claim 1, Joannopoulos further discloses wherein the first and second resonator structures are substantially identical (para [0013]).

-------------(continued on supplemental pages)-------------

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/US 09/59244

Box No. VI Certain documents cited

1. Certain published documents (Rules 43*bis*.1 and 70.10)

Application No. Patent No.	Publication date *(day/month/year)*	Filing date *(day/month/year)*	Priority date (valid claim) *(day/month/year)*
US 2009/0153273 A1	18/06/2009	19/06/2008	14/12/2007

2. Non-written disclosures (Rules 43*bis*.1 and 70.9)

Kind of non-written disclosure	Date of non-written disclosure *(day/month/year)*	Date of written disclosure referring to non-written disclosure *(day/month/year)*

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.

PCT/US 09/59244

Box No. VIII Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:

Box V.2. Citations and explanations:

As per claim 20, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is K_1B and a coupling rate between the intermediate resonator structure and the second resonator structure is K_B2; and means for adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure. Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos's wireless energy transfer with two resonator structures with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have the optimization of the coupling rate by Joannopoulos be such that adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to reduce energy accumulation in the intermediate resonator structure and improve wireless energy transfer from the first resonator structure to the second resonator structure through the intermediate resonator structure, thereby optimizing energy transfer.

As per claims 21-23, dependent on claim 20, neither Joannopoulos nor Beaver disclose wherein the means for adjusting comprises a rotation stage for adjusting the relative orientation, a translation stage for moving, or a mechanical, electro-mechanical or electrical staging system for adjusting of the intermediate resonator structure with respect to the first and second resonator structures. However, such configurations were well known in the art at the time of the invention and could have been provided as a means of positioning the resonators for optimizing energy transfer.

As per claim 24, dependent on claim 4, neither Joannopoulos nor Beaver disclose wherein the adjustment of at least one of the coupling rates K_1B and K_B2 causes peak energy accumulation in the intermediate resonator structure during the wireless energy transfers to be less than ten percent (10%) of the peak total energy in the three resonator structures. It would have been obvious to a person of ordinary skill in the art to have the adjustment of at least one of the coupling rates K_1B and K_B2 causes peak energy accumulation in the intermediate resonator structure during the wireless energy transfers to be less than ten percent (10%) of the peak total energy in the three resonator structures, based on the requirements of the system.

As per claim 28, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is K_B1; transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure is K_B2; and during the wireless energy transfers, adjusting at least one of the coupling rates K_1B and K_B2 to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure. Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos's wireless energy transfer with two resonator structure with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have the optimization of the coupling rate to minimize losses by Joannopoulos be such that during the wireless energy transfers, adjusting at least one of the coupling rates K_1B and K_B2 to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure since it would optimize energy flow between primary and secondary resonator, in order to improve wireless energy transfer.

——————(continued on next page)——————

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 09/59244

Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of:

Box V.2. Citations and explanations:

As per claim 29, dependent on claim 28, neither Joannopoulos nor Beaver disclose wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfer. However, this configuration could have been determined based on routine experimentation and provided based on the requirements of the system.

As per claim 30, dependent on claim 28, neither Joannopoulos nor Beaver disclose wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfer. IHowever, this configuration could have been determined based on routine experimentation and provided based on the requirements of the system.

As per claim 31, dependent on claims 28 to 30, neither Joannopoulos nor Beaver disclose wherein the adjustment of at least one of the coupling rates K_1B and K_B2 maintains the energy distribution in the field of the three resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure. However Joannopoulos discloses coupling rates being optimized to minimize losses (Abstract, para [0015], [0016]). It would have been obvious to a person of ordinary skill in the art to have the coupling rate optimization of Joannopoulos be such that the adjustment of at least one of the coupling rates K_1B and K_B2 maintains energy distribution in the field of the three resonator system in an eigenstate having substantially no energy in the intermediate resonator structure, in order to improve energy transfer.

As per claim 32, dependent on 31, neither Joannopoulos nor Beaver disclose wherein the adjustment of at least one of the coupling rates K_1B and K_B2 further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure. However Joannopoulos discloses coupling rates being optimized to mimimize losses (Abstract, para [0015], [0016]). It would have been obvious to a person of ordinary skill in the art to have the coupling rate optimization of Joannopoulos be such that the adjustment of at least one of the coupling rates K_1B and K_B2 further causes the eigenstate to evolve substantially adiabatically from an initial state with substantially all energy in the resonator structures in the first resonator structure to a final state with substantially all of the energy in the resonator structures in the second resonator structure, in order to improve energy transfer.

As per claim 50, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is K_1B and a coupling rate between the intermediate resonator structure and the second resonator structure is K_B2; and means for adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure. Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos's wireless energy transfer with two resonator structure with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have the optimization of the coupling rate by Joannopoulos be such that adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to cause an energy distribution in the field of the three-resonator system to have substantially no energy in the intermediate resonator structure while wirelessly transferring energy from the first resonator structure to the second resonator structure through the intermediate resonator structure since it maximizes energy transferred from first resonator to second resonator, in order to improve energy transfer.

As per claim 51, dependent on claim 50, neither Joannopoulos nor Beaver disclose wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than ten percent (10%) of the peak total energy in the three resonator structures throughout the wireless energy transfer. However, this configuration could have been determined based on routine experimentation and provided based on the requirements of the system.

As per claim 52, dependent on claim 50, neither Joannopoulos nor Beaver disclose wherein having substantially no energy in the intermediate resonator structure means that peak energy accumulation in the intermediate resonator structure is less than five percent (5%) of the peak total energy in the three resonator structures throughout the wireless energy transfer. However, this configuration could have been determined based on routine experimentation and provided based on the requirements of the system.

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WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/US 09/59244

Supplemental Box

In case **the space in any of the preceding boxes is not sufficient.**
Continuation of:

Box V.2. Citations and explanations:

As per claim 53, dependent on claims 50 to 52, neither Joannopoulos nor Beaver disclose wherein the means for adjusting is configured to maintain the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure. However Joannopoulos discloses coupling rates being optimized (Abstract, para [0015], [0016]). It would have been obvious to a person of ordinary skill in the art to combine the teacheing os Joannopoulos and Beaver to have the optimization of Joannopoulos be such that the adjusting is configured to maintain the energy distribution in the field of the three-resonator system in an eigenstate having the substantially no energy in the intermediate resonator structure, thereby improving energy transfer..

As per claim 80, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose transferring energy wirelessly from a first resonator structure to a intermediate resonator structure, wherein the coupling rate between the first resonator structure and the intermediate resonator structure is K_1B; transferring energy wirelessly from the intermediate resonator structure to a second resonator, wherein the coupling rate between the intermediate resonator structure and the second resonator structure with a coupling rate is K_B2; and during the wireless energy transfers, adjusting at least one of the coupling rates K_1B and K_B2 to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate K'_1B for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate K'_B2 for wireless energy transfer from the intermediate resonator structure to the second resonator structure with K'_1B and K'_B2 each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates K_1B and K_B2 in the first mode of operation satisfies K_1B, K_2B<SQRT((K'_1B^2+K'_2B^2)/2). Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos's wireless energy transfer with two resonator structure with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have adjusted at least one of the coupling rates K_1B and K_B2 to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation of wireless energy transfer among the three resonator structures having a coupling rate K'_1B for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate K'_B2 for wireless energy transfer from the intermediate resonator structure to the second resonator structure with K'_1B and K'_B2 each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates K_1B and K_B2 in the first mode of operation satisfies K_1B, K_2B<SQRT((K'_1B^2+K'_2B^2)/2), where SQRT((K'_1B^2+K'_2B^2)/2) is just the Root-Mean-Square of the coupling rate for the second mode of operation and the magnitude of K_1B and K_B2 in the first mode is less than the RMS value of the coupling rates K'_1B and K'_B2 in the second mode. It would have been obvious to one skilled in the art to combine the teachings of Joannopoulos with those of Beaver in order to improve energy transfer.

As per claim 81, Joannopoulos discloses a method for transferring energy wirelessly (Abstract, para [0013]), and a first resonator structure and a second resonator structure with coupling rates being optimized for low loss rates (Abstract, para [0015], [0016], [0035]), but does not disclose first, intermediate, and second resonator structures, wherein a coupling rate between the first resonator structure and the intermediate resonator structure is K_1B and a coupling rate between the intermediate resonator structure and the second resonator structure is K_B2 ; and means for adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation for wireless energy transfer among the three resonator structures having a coupling rate K'_1B for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate K'_B2 for wireless energy transfer from the intermediate resonator structure to the second resonator structure with K'_1B and K'_B2 each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates K_1B and K_B2 in the first mode of operation satisfies K_1B, K_2B<SQRT((K'_1B^2+K'_2B^2)/2). Beaver discloses wireless energy transfer (col 2, ln 69-72) and utilizing intermediate resonators (col 7, ln 22-39). It would have been obvious to a person of ordinary skill in the art to utilize Joannopoulos's wireless energy transfer with two resonator structure with optimized coupling rate and Beaver's intermediate resonator for transferring wireless energy from primary to secondary resonator since it creates a device that allows for the wireless transfer of energy from a primary to a secondary resonator via an intermediate resonator and acts as a filter. It also would have been obvious to a person of ordinary skill in the art to have the means for adjusting at least one of the coupling rates K_1B and K_B2 during wireless energy transfers among the resonator structures to define a first mode of operation in which energy accumulation in the intermediate resonator structure is reduced relative to that for a second mode of operation for wireless energy transfer among the three resonator structures having a coupling rate K'_1B for wireless energy transfer from the first resonator structure to the intermediate resonator structure and a coupling rate K'_B2 for wireless energy transfer from the intermediate resonator structure to the second resonator structure with K'_1B and K'_B2 each being substantially constant during the second mode of wireless energy transfer, and wherein the adjustment of the coupling rates K_1B and K_B2 in the first mode of operation satisfies K_1B, K_2B<SQRT((K'_1B^2+K'_2B^2)/2), where SQRT((K'_1B^2+K'_2B^2)/2) is just the Root-Mean-Square of the coupling rate for the second mode of operation and the magnitude of K_1B and K_B2 in the first mode is less than the RMS value of the coupling rates K'_1B and K'_B2 in the second mode. It would have been obvious to one skilled in the art to combine the teachings of Joannopoulos with those of Beaver in order to improve energy transfer.

Claims 1-4, 6, 13, 20-24, 28-32, 50-53, 80 and 81 have industrial applicability as defined by PCT Article 33(4) because the subject matter can be made or used in industry.

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First Named Inventor/Applicant Name:	Andre B. Kurs
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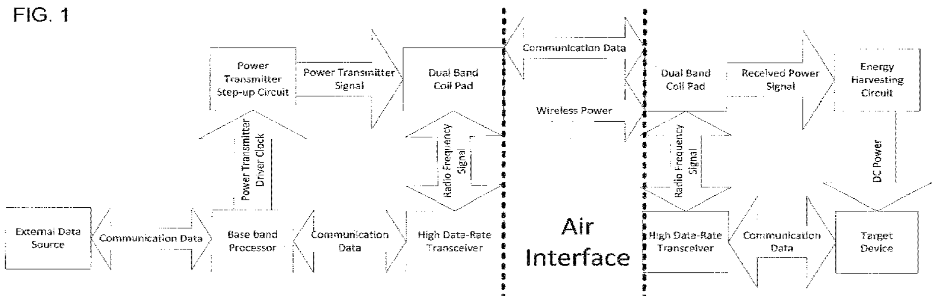
(54) Title: PLANAR NEAR-FIELD WIRELESS POWER CHARGER AND HIGH-SPEED DATA COMMUNICATION PLATFORM

FIG. 1



(57) Abstract: In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications. In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component. An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not changing.

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DESCRIPTION

PLANAR NEAR-FIELD WIRELESS POWER CHARGER AND HIGH-SPEED DATA COMMUNICATION PLATFORM

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 60/970,201, filed September 5, 2007, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Portable electronic equipment, such as mobile phones, handheld computers, and personal data assistants, are normally powered by batteries. In many cases, rechargeable batteries are preferred because of environmental and economical concerns. The most common way to charge rechargeable batteries is to use a conventional charger, which normally includes an AC-DC power supply when the AC mains are used, or a DC-DC power supply when a car battery is used. Conventional chargers normally use an electric cable to connect the charger circuit to the battery located in the portable electronic equipment.

In large part due to the inconvenience of conventional chargers, wireless power solutions have been presented. Examples of wireless power solutions include electric toothbrushes and electric razors. Current wireless power solutions have limitations such as requiring a particular alignment of the device being charged to the charging unit, or other inconveniences such as the need for the device being charged to be within a certain distance of a certain section of the charging unit.

Thus, there remains a need for a system for wireless charging of portable electronic devices in an efficient manner.

BRIEF SUMMARY

In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications.

In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component.

An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not charging. In exemplary embodiments, the mechanical connection can be a flip or slide mechanism that allows the receiver coil to be positioned such that a vertical magnetic field does not need to pass through the portable device in order to pass through the receiver coil during charging, but allows the receiver coil to reside adjacent to the device when not charging in order to make the device with receiver coil easier to carry and store.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows one embodiment of a system architecture of a planar near-field wireless power charger and high-speed data communication platform.

Figure 2 shows an embodiment of a planar wireless power charger platform in accordance with the present disclosure.

Figure 3 shows a diagram of one embodiment of a multiple-transmitter power delivery system.

Figure 4 shows a system block diagram of a multiple-transmitter power delivery system.

Figures 5A-5B show embodiments of a single transmitter coil for a wireless power system.

Figure 6 shows an existing technology using a horizontal field to charge the portable device.

Figure 7 shows a cell phone incorporating an embodiment of a power charging receiver in accordance with the present disclosure.

Figures 8A-8B show a power charging receiver attached to a cell phone using a flip mechanism.

Figure 9 shows a power charging receiver attached to a cell phone using the a slide mechanism.

DETAILED DISCLOSURE

In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. Embodiments of the wireless power charging system can allow powering devices at close proximity. In an embodiment, a charging efficiency of greater than 75% can be achieved. In a further embodiment, a charging efficiency of greater than 85% can be achieved. Specific embodiments can allow charging to occur at a distance of, for example, up to about 5 inches above the pad. The ability to charge the device with up to a 5 inch separation between the device and the charging unit, or portion thereof, allows versatility as to where devices can be positioned during the charging process. In a specific embodiment, a receiver coil as small as 10% of the transmitting coil can be utilized. In an exemplary embodiment, the system is capable of charging multiple devices at the same time.

In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications. In a specific embodiment, a power signal for charging can have a frequency less than or equal to 1MHz. in a further embodiment, the data signal for communications can have a frequency in the ultra wide band (UWB) of 3.1GHz-10.6GHz and use a carrier-less signal with pulses, or a carrier based signal with a carrier frequency in the WiFi band, e.g., at 2.4GHz.

Figure 1 shows one embodiment of a system architecture of a planar near-field wireless power charger and high-speed data communication platform. The system architecture can include a power transmitter, power receiver and energy harvesting circuit, and transmitting coil pad. In an exemplary embodiment, the subject platform is designed for short range applications using near field coupling. This embodiment can achieve high data rates using a simple transceiver architecture. In various embodiments, the base station can: transmit a power signal; transmit a power signal and transmit a data signal; transmit a power signal, transmit a data signal, and receive a data signal; or transmit a power signal and receive a data signal. The base station can break the various transmit and/or receive functions into separate transmitters and receivers, or combine such functions into one or more transceivers. By using a single coil to transmit and receive costs and space can be saved. Likewise, the receiver can: receive a power signal; receive a power signal and transmit a data signal; receive a power signal, transmit a data signal, and receive a data signal; or receive a power signal and transmit a data signal. The transmit power, transmit data, receive power, and receive data functions can be performed sequentially or simultaneously.

The wireless transfer of power and data can allow a variety of configurations. An embodiment can use a first pad and a second pad, each having a base station, and a television having a receiver, with the TV on the first pad and a DVD player having a receiver on a second pad. Power is provided to the DVD player and data can be received by the second pad from the DVD player. The received data can then be transferred from the second pad to the first pad and then from the data transmitter in the first pad to the receiver in the TV. Other embodiments can use a pad and an audio device, such as and MP3 player, where power is supplied to the audio device and music data is received by the pad from the audio device. The received audio data can then be delivered to, for example, speakers or some sort of device to further utilize the audio data. The pad can be networked to a home or office network, such that received data can be distributed as needed. The data can also include information about the charging state of the receiver device. In a specific embodiment, the data can be transmitted at a rate of 50Mb-500Mb. In another specific embodiment, the data can be transmitted at a rate up to 1Gbps.

Figure 2 shows an embodiment of a platform in accordance with the present disclosure. Exemplary applications of this system include its use as a platform for wireless power charging and high data rate communication for portable devices, such as mobile phones and mp3 players. The system can be implemented in various locations, such as homes, airports, and hotel rooms. This adds convenience as it provides a universal charging interface and can reduce, or eliminate, the need to bring multiple chargers. In addition, it can serve as a high speed data link between devices so that data can be exchanged on the same platform, instead of separate ones. This can be integrated with a smart home or smart office space. The system can have simple hardware architecture so as to achieve low cost for mass production. In one embodiment, a wireless near-field high-speed data communication capability is implemented as part of the system.

Preferably, the magnetic flux generated by the transmitting coil pad is substantially uniform over at least a major part of the planar charging surface. In this way, the impact that the precise position and orientation of the electronic device on the charging surface has on the charging efficiency is reduced. The system illustrated in Figure 2 includes a power transmitter **4** that powers a power-transmitting coil pad **6**. The power transmitter **4** is powered by power source **2**. The transmitting coil pad **6** wirelessly sends power to a power receiver and energy harvesting circuit **8**. The power receiver is connected to the target electronic device **10**. In alternative embodiments, the power receiver and energy harvesting circuit can be attached or integrated with the target device, such that the target device can be placed on or near the coil pad for charging. In an exemplary embodiment, discussed later, the power receiver is formed as a back cover of the electronic device. In an exemplary embodiment, the equipment is charged simply by placing the power receiver on, or near, the transmitting coil pad surface.

In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. In a specific embodiment, the size of each lower powered transmitter can be reduced up to 80-90% compared with a single high-powered transmitted, such that the large transformer typically used to step up the voltage to a high voltage can be eliminated from the system. Removing the large transformer can enhance safety. Figure 3 shows a diagram of one embodiment incorporating a multiple-transmitter power delivery system for a multiple coil design having seven coils. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Figure 4 shows a system block diagram of a multiple-transmitter power delivery system that can be used with a coil design having eight coils.

Figures 5A -5B show embodiments of a single transmitter coil for a wireless power system. The coils can have a variety of shapes. This coil can be integrated with a pad, or other object, for placing devices to be charged on or near the pad. In an embodiment, the coils are positioned such that the resulting magnetic field is normal to a surface of the pad, such that receiver coils can be located on the pad's surface to receive the magnetic fields. In a specific embodiment, the transmitter coil, such as the coil shown in Figure 5, can be driven by multiple transmitters, which can each be selectively turned on or off, and tuned. In a specific embodiment incorporating a stacked set of coils, each transmitter can be tuned independently, thereby achieving a wide tuning range. Individual tuning of the coils can be performed in near real time and increase energy transfer efficiency for different charging circumstances. Power control can be achieved by individually turning on and off the individual transmitters depending on the charging load, making it more energy efficient. The multiple-transmitter design enables the transmitter system to be more flexible and adaptive to a wider range of environmental situations while consuming less power. Thus, a significant improvement in efficiency can be attained. In a specific embodiment, each transmitter for the stacked set of coils is identical, or each transmitter for the multiple transmitters driving a single coil, allowing low cost for mass production. Since the transmitters are the same, additional transmitters can be easily added to the system to boost the maximum output, thereby offering a great advantage for scalability. Having multiple transmitters also gives the system many extra degrees of freedom for achieving a higher dynamic range. In a specific embodiment, the coils in the stacked configurations are driven in place by the plurality of transmitters.

Referring to Figure 6, a device incorporating a coil design to receive power from surface magnetic fields that are substantially horizontal is shown. In accordance with current wireless power charging technology that uses horizontal magnetic fields for coupling of energy to charge portable electronic devices. The receiver coil used with the device to be charged receives magnetic field flux that is substantially parallel with the surface of the pad the device is placed on and does not extend very far above the surface of the pad. Such use of horizontal magnetic fields is inefficient because the cross sectional area of the receiver coil is limited; thus, the coupling factor is low. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component. Examples of transmitter coil design that can be used to produce magnetic fields that have a substantial vertical component are shown in Figure 3 and Figure 5. Other designs can also be used in accordance with the invention.

Using a vertical field for coupling of energy can be more efficient. However, by mounting the receiver on the back of a portable device, the efficiency of such coupling can be reduced as the magnetic field must pass through the portable device in order to pass through the receiver coil. An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not charging. In specific embodiments, the receiver coil can be positioned so that the magnetic fields pass through less than one half of the body of the device. In exemplary embodiments, the mechanical connection can be a flip or slide mechanism that allows the receiver coil to be positioned such that a vertical magnetic field does not need to pass through the portable device in order to pass through the receiver coil during charging, but allows the receiver coil to reside adjacent to the device when not charging in order to make the device with receiver coil easier to carry and store. The use of such a mechanical connection can enable efficient charging of the device without significant modification to the device's form factor, as shown in Figure 7.

The receiver can be designed as an add-on device or as part of a portable electronic device such as a mobile phone. In an exemplary application, a user need not replace an entire phone to take advantage of the new technology. For example, the user can replace the back panel or the battery cover of a phone or device to make the device compliant to this technology.

Figures 8A and 8B show a power charging receiver coil attached to a cell phone using a flip mechanism. In one embodiment, the flip mechanism includes a catch at one end of the device and a hinge on the other end of the device for allowing the receiver coil to flip open. The receiver coil can flip out, as shown by arrows in Figure 8B, such that the receiver coil is rotated 180 degrees and is parallel with the surface of the device from where it rotated from. In an alternative embodiment, the receiver coil can rotate 90 degrees and be used to receive horizontal magnetic fields for charging the device. Figure 9 shows a power charging receiver attached to a cell phone using a slide mechanism. In this embodiment, the receiver coil is slid out away from the phone body and placed on the charging pad so that the receiver coil is substantially parallel with the surface of the charging pad so as to allow the vertical portion of the magnetic field to pass through the receiver coil. Other mechanisms can be incorporated with embodiments of the invention to coordinate the relative position of the device body and the receiver coil.

The large cross-sectional area of the receiver coil provides for increased coupling for use with a near-field planar wireless power charger system. Positioning the receiver coil, for example, via the flip mechanism or the slide mechanism, such that the magnetic field flux does not pass through the body of the device enhances the charging efficiency. The device can be charged in the pre-flip or pre-slide position, but at a slower rate. To fully realize the benefits of the subject receiver coil design, the wireless power charger system can incorporate a vertical magnetic field for coupling of energy to the receiver coil. Such a vertical magnetic field achieves a higher efficiency coupling and, therefore, higher efficiency charging. Further, embodiments using vertical fields can allow the receiver coil to be positioned higher off of the pad having the transmitted coils than with systems using horizontal fields, while achieving the same coupling efficiency. In a specific embodiment, the receiver coil can be up to 5 inches above the pad.

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 wireless power transfer system, comprising:

a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter, wherein the power transmitter is capable of driving the transmitter coil such that a first magnetic field is produced; and

a data receiver,

a receiver station, wherein the receiver station comprises:

a receiver coil, wherein the receiver coil inductively couples the first magnetic field to produce a received power signal; and

a data transmitter, wherein the data transmitter drives the receiver coil to produce a transmitted data signal,

wherein the transmitter coil inductively couples the transmitted data signal to produce a received RF data signal, wherein the data receiver receives the received RF data signal and outputs a received data signal.

2. The wireless power transfer system according to claim 1, where in the receiver station further comprises an energy harvesting circuit, wherein the energy harvesting circuit receives the received power signal and outputs DC power.

3. The wireless power transfer system according to claim 1, wherein the receiver station further comprises a target device, wherein the target device provides a data input signal to the data transmitter, wherein the data input signal is used by the data transmitter to produce the data signal.

4. The wireless power transfer system according to claim 1, wherein the base station further comprises:

a second data transmitter, wherein the second data transmitter drives the transmitter coil to produce a second transmitted data signal, wherein the receiver station further comprises a second data receiver, wherein the receiver coil inductively couples the second transmitted data signal to produce a second received RF data signal.

5. The wireless power transfer system according to claim 1, wherein the power transmitter and the data receiver are integrated as a first transceiver.

6. The wireless power transfer system according to claim 4, wherein the data transmitter and the second data receiver are integrated as a second transceiver.

7. The wireless power transfer system according to claim 4, wherein the second data transmitter is integrated with the power transmitter and the data receiver as the first transceiver.

8. The wireless power transfer system according to claim 4, wherein the second data receiver is integrated with the data transmitter and the second data receiver as the second transceiver.

9. The wireless power transfer system according to claim 4, wherein the power transmitter and the second data transmitter are capable of simultaneously driving the transmitter coil, wherein the power transmitter drives the transmitter coil at a first wavelength and the second data transmitter drives the transmitter coil at a second wavelength.

10. A wireless power transfer system, comprising:

a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter, wherein the power transmitter is capable of driving the transmitter coil such that a first magnetic field is produced; and

a data transmitter,

a receiver station, wherein the receiver station comprises:

a receiver coil, wherein the receiver coil inductively couples the first magnetic field to produce a received power signal; and

a data receiver, wherein the data transmitter drives the transmitter coil to produce a transmitted data signal,

wherein the reciever coil inductively couples the transmitted data signal to produce a received RF data signal, wherein the data receiver receives the received RF data signal and outputs a received data signal.

11. A method of wireless power transfer, comprising:

providing a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter; and

a data receiver,

providing a receiver station, wherein the receiver station comprises:

a receiver coil; and

a data transmitter,

driving the transmitter coil with the power transmitter such that a first magnetic field is produced;

inductively coupling the first magnetic field to the receiver coil to produce a received power signal;

driving the receiver coil with the data transmitter to produce the transmitted data signal;

inductively coupling the transmitted data signal to the transmitter coil to produce a received RF data signal;

receiving the received RF data signal by the data receiver; and

outputting a received data signal by the data receiver.

12. The method according to claim 11, where in the receiver station further comprises an energy harvesting circuit, further comprising receiving the received power signal by the energy harvesting circuit and outputting DC power by the energy harvesting circuit.

13. The method according to claim 11, wherein the receiver station further comprises a target device, further comprising providing a data input signal from the target device to the data transmitter, wherein the data input signal is used by the data transmitter to produce the data signal.

14. The method according to claim 11, wherein the base station further comprises:

a second data transmitter and the receiver station further comprises

a second data receiver, the method further comprising:

driving the transmitter coil with the second data transmitter to produce a second transmitted data signal; and

inductively coupling the second transmitted data signal to the receiver coil to produce a second received RF data signal.

15. The method according to claim 11, wherein the power transmitter and the data receiver are integrated as a first transceiver.

16. The method according to claim 14, wherein the data transmitter and the second data receiver are integrated as a second transceiver.

17. The method according to claim 14, wherein the second data transmitter is integrated with the power transmitter and the data receiver as the first transceiver.

18. The method according to claim 14, wherein the second data receiver is integrated with the data transmitter and the second data receiver as the second transceiver.

19. The method according to claim 14, wherein the power transmitter and the second data transmitter are capable of simultaneously driving the transmitter coil, wherein the power transmitter drives the transmitter coil at a first wavelength and the second data transmitter drives the transmitter coil at a second wavelength.

20. A method of wireless power transfer, comprising:

providing a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter; and

a data transmitter,

providing a receiver station, wherein the receiver station comprises:

a receiver coil; and

a data receiver,

driving the transmitter coil with the power transmitter such that a first magnetic field is produced;

inductively coupling the first magnetic field to the receiver coil to produce a received power signal;

driving the transmitter coil with the data transmitter to produce the transmitted data signal;

inductively coupling the transmitted data signal to the receiver coil to produce a received RF data signal;

receiving the received RF data signal by the data receiver; and

outputting a received data signal by the data receiver.

21. A wireless power transfer system, comprising:

a plurality of transmitters;

a corresponding plurality of transmitter coils, wherein each transmitter delivers power to a corresponding transmitter coil, so as to produce a corresponding plurality of magnetic fields, wherein the plurality of transmitter coils are positioned such that corresponding plurality of magnetic fields are substantially coextensive.

22. The system according to claim 21, wherein the plurality of transmitter coils are positioned such that the plurality of magnetic fields are normal to a surface.

23. The system according to claim 22, further comprising at least one receiver coil, wherein the at least one receiver coil is positionable with respect to the surface such that the at least one receiver coil is substantially parallel with the surface.

24. The system according to claim 22, wherein the plurality of transmitter coils are integrated in a pad, wherein the surface is on the pad.

25. The system according to claim 21, wherein each of the plurality of transmitters can be tuned independently.

26. The system according to claim 21, wherein the plurality of transmitters can be individually turned on and off depending on a needed charging load.

27. The system according to claim 21, wherein the plurality of transmitters drive the plurality of transmitter coils in phase.

28. An electronic device, comprising:

a body;

a receiver coil; and

a connector, wherein the connector moveably connects the receiver coil to the body such that the receiver coil can transition between at least two positions relative to the body, wherein at least one of the at least two positions the receiver coil can receive magnetic fields normal to the receiver coil without the received magnetic fields passing through a substantial portion of the body.

29. The device according to claim 28, wherein the connector allows the receiver coil to slide relative to the body to transition between the at least two positions.

30. The device according to claim 28, wherein the connector allows the receiver coil to rotate relative to the body to transition between the at least two positions.

31. The device according to claim 28, wherein in at least one other of the at least two positions the receiver coil is adjacent the body such that magnetic fields normal to the receiver coil pass through a substantial portion of the body.

32. The device according to claim 31, wherein the connector comprises a hinge locateded at an end of the body, wherein the hinge allows the receiver coil to rotate from a first position adjacent the body to a second position that is an approximately 180° rotation of the receive coil with to the hinge.

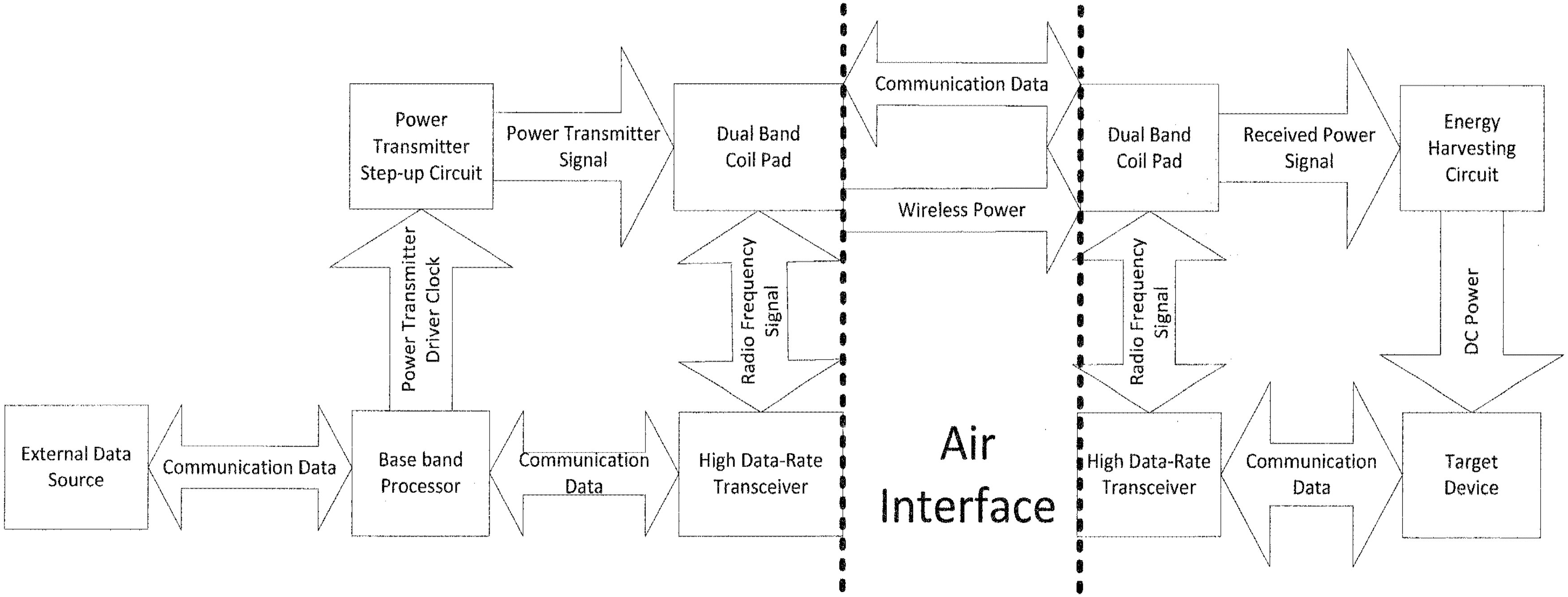
Power Transmitter Step-up Circuit
Power Transmitter Signal
Dual Band Coil Pad
Communication Data
Wireless Power
Dual Band Coil Pad
Received Power Signal
Energy Harvesting Circuit
Power Transmitter Driver Clock
Radio Frequency Signal
Radio Frequency Signal
DC Power
External Data Source
Communication Data
Base band Processor
Communication Data
High Data-Rate Transceiver
Air Interface
High Data-Rate Transceiver
Communication Data
Target Device

FIG. 1

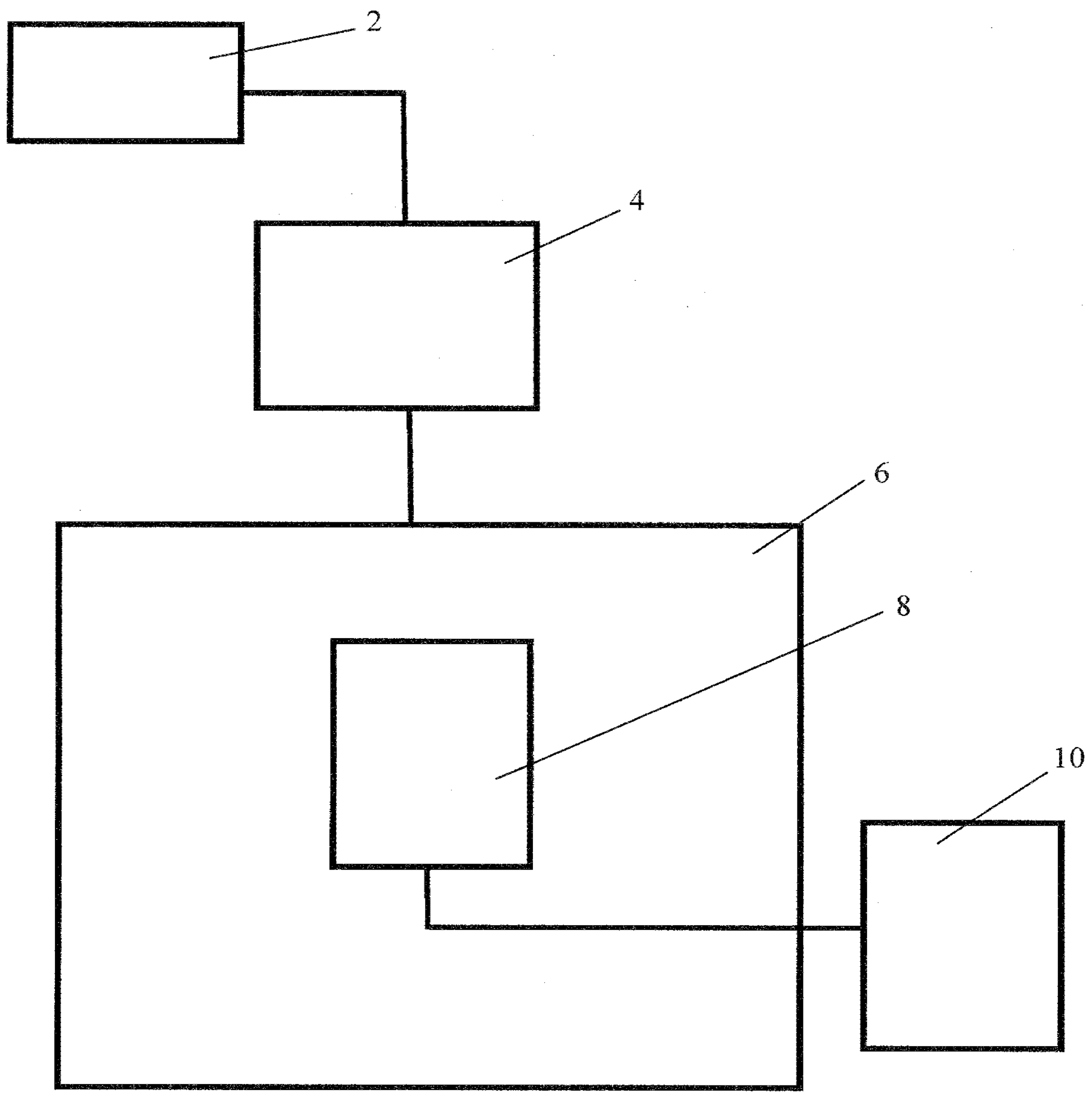

FIG. 2

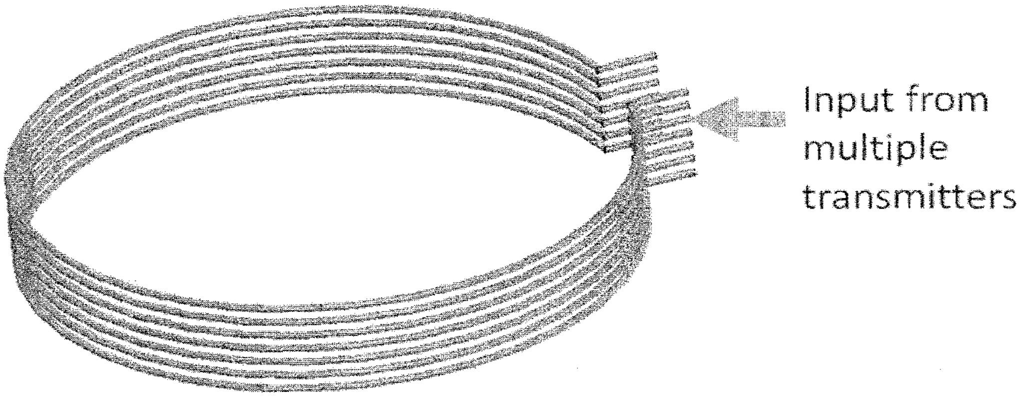
Input from
multiple
transmitters

FIG. 3

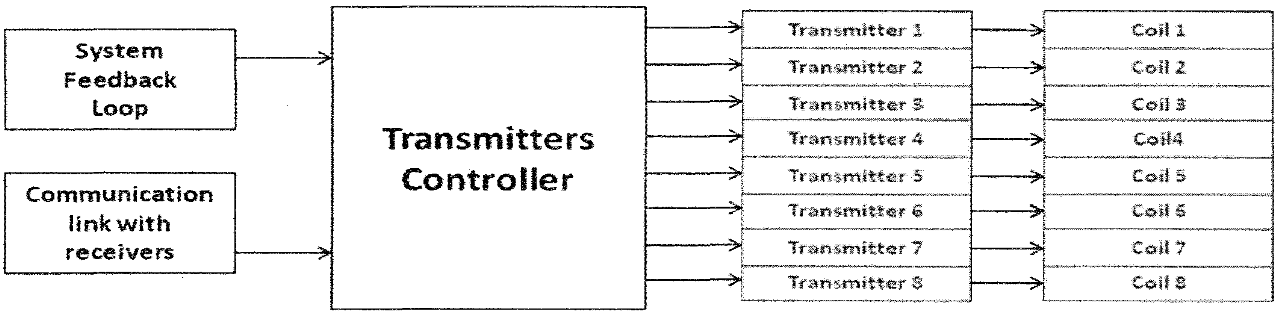
System
Feedback
Loop
Communication
link with
receivers
Transmitters
Controller
Transmitter 1
Transmitter 2
Transmitter 3
Transmitter 4
Transmitter 5
Transmitter 6
Transmitter 7
Transmitter 8
Coil 1
Coil 2
Coil 3
Coil4
Coil 5
Coil 6
Coil 7
Coil 8

FIG. 4

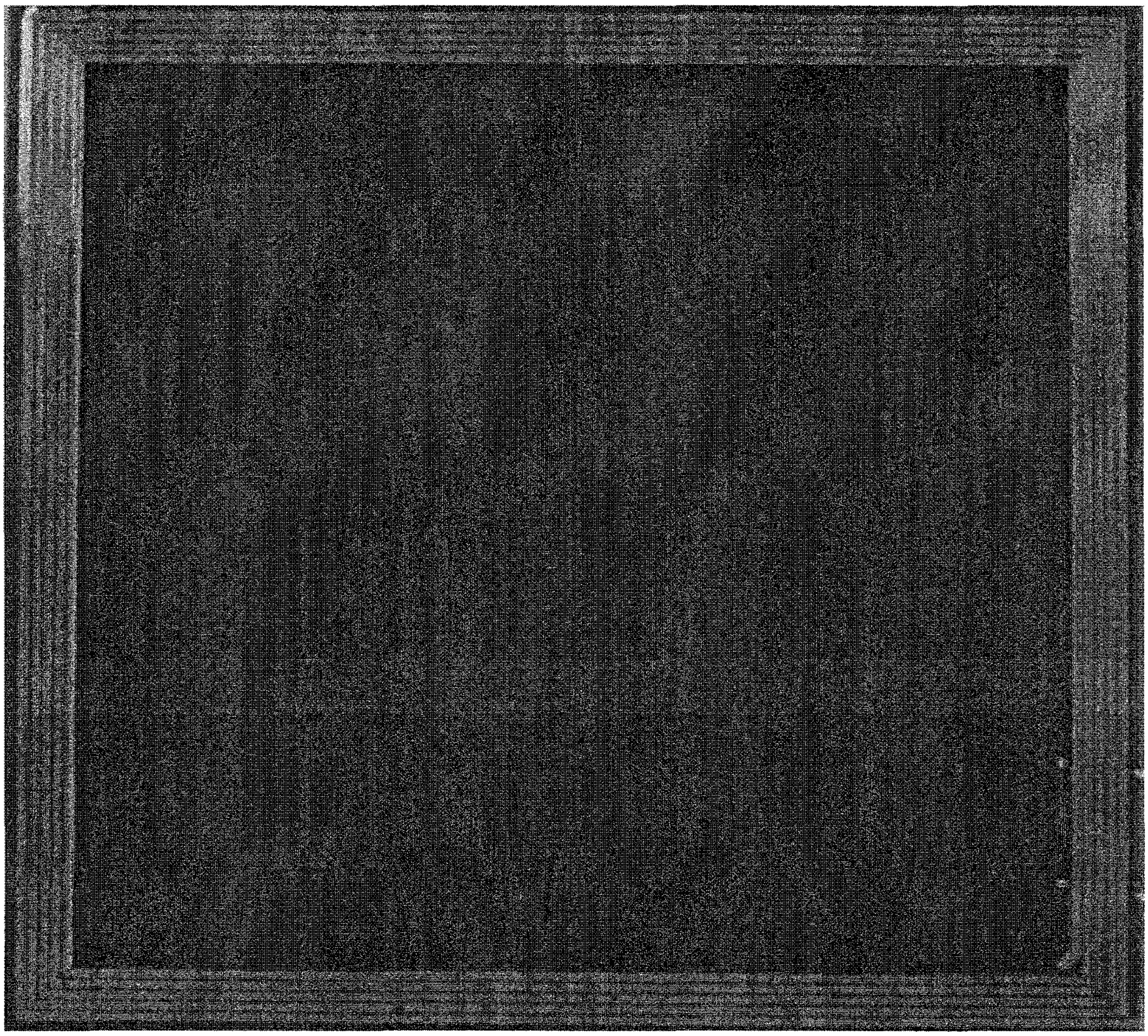

FIG. 5A

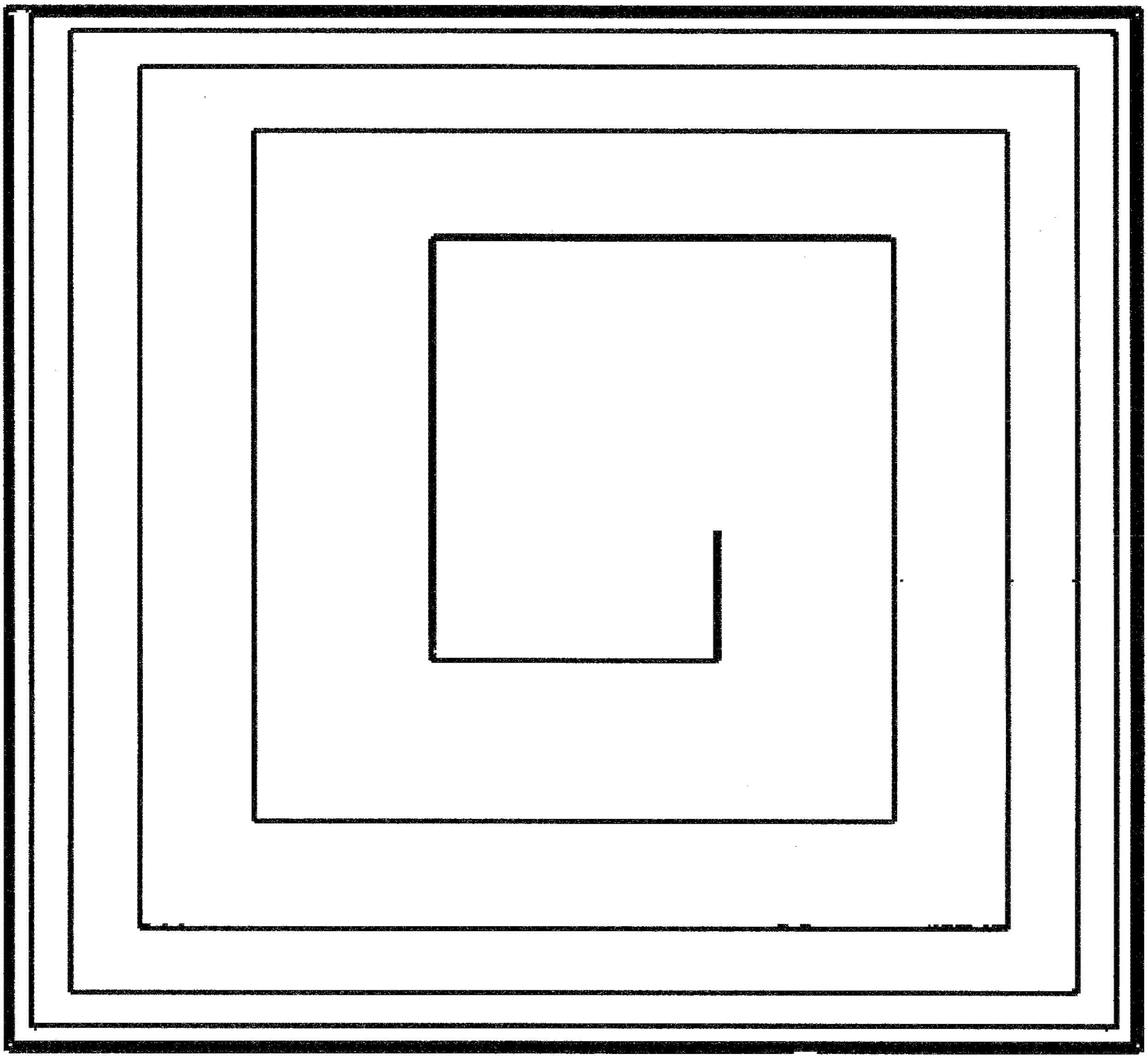

FIG. 5B

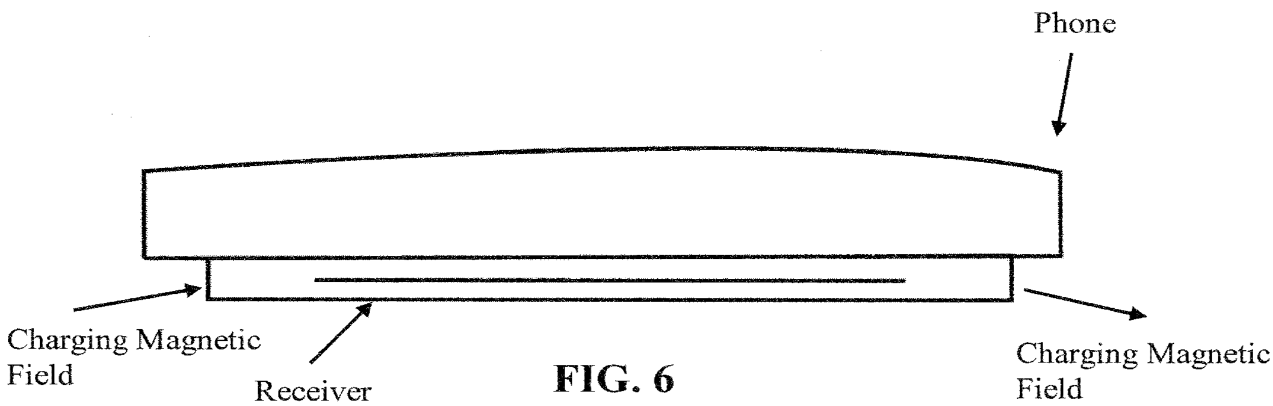

FIG. 6

(Prior Art)

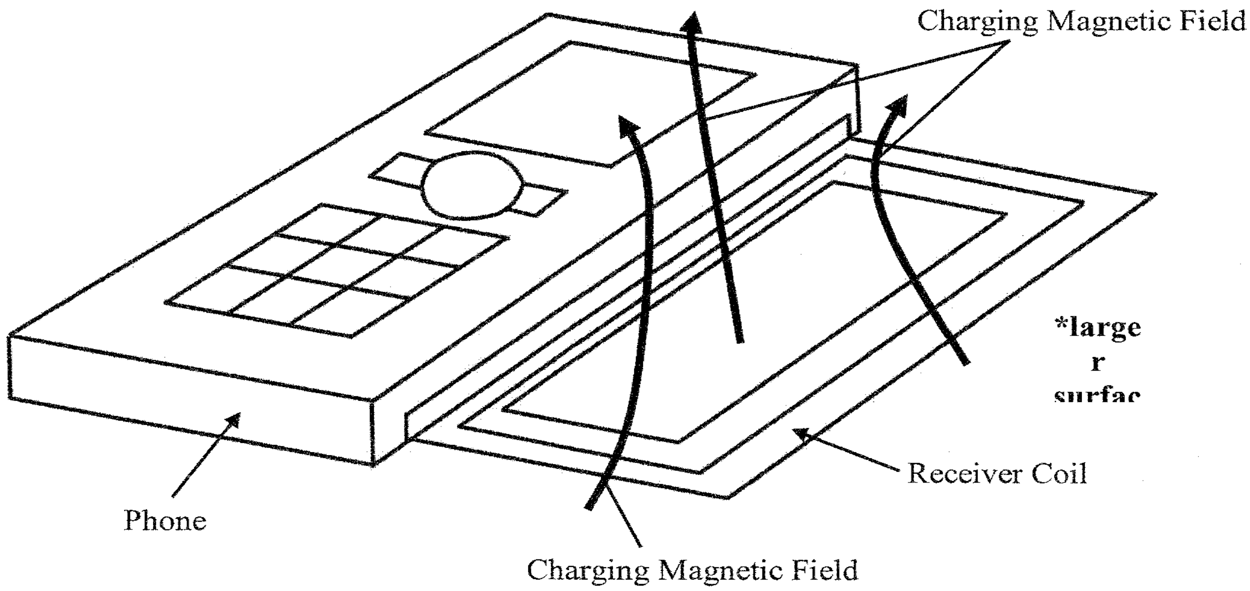

FIG. 7

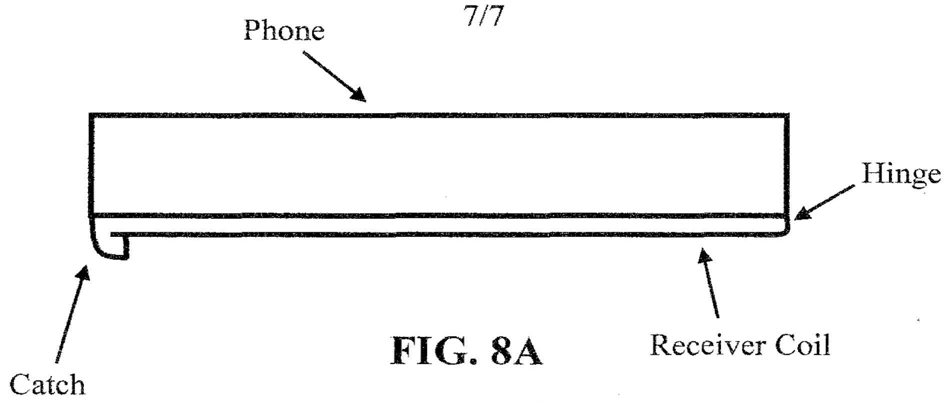

FIG. 8A

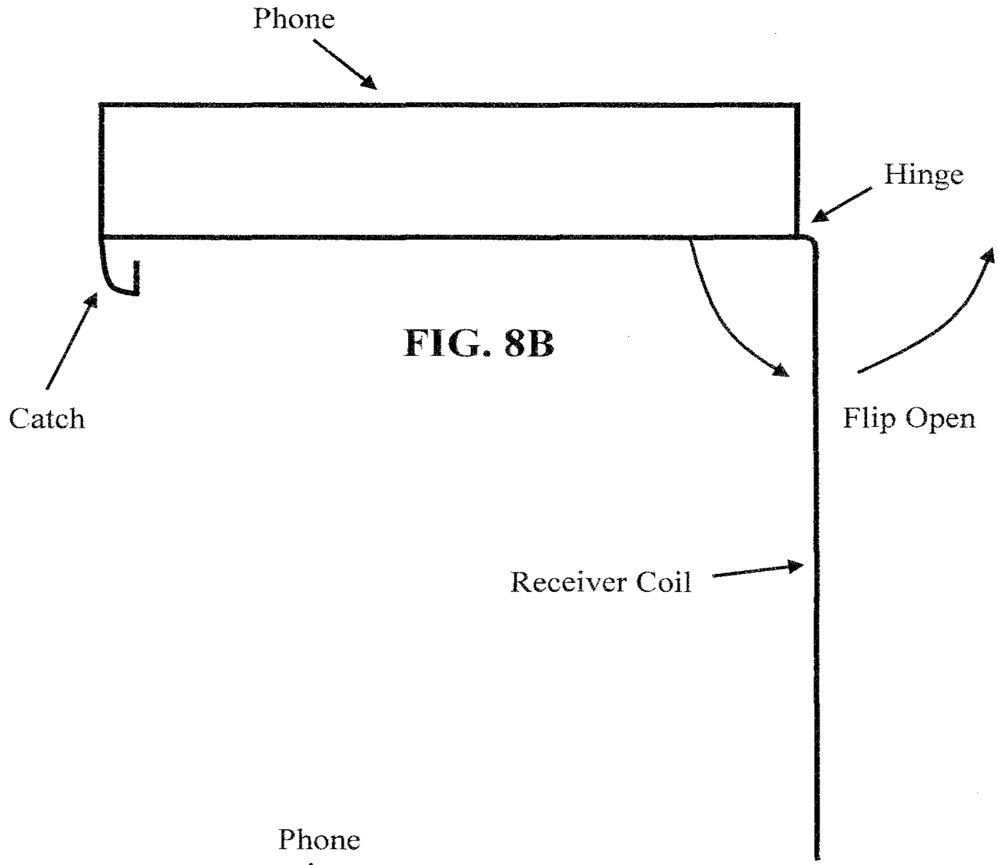

FIG. 8B

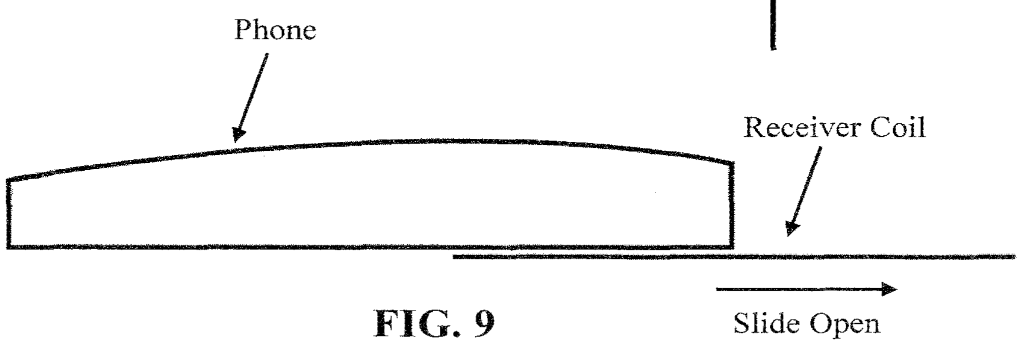

FIG. 9

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[Continued on next page]

(54) Title: PLANAR BATTERY CHARGING SYSTEM

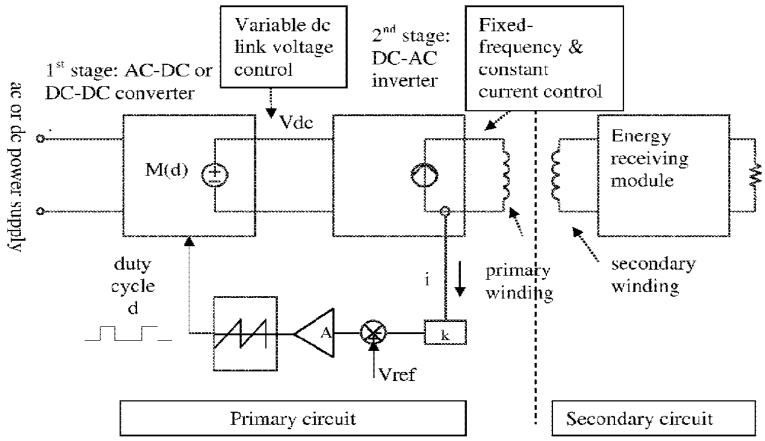

FIG.1

(57) Abstract: A planar battery charging system. The planar battery charging system comprises a primary power transmission side formed of an array of primary windings (1) adapted to generate magnetic flux substantially perpendicular to a charging surface, a secondary power receiving side comprising a secondary winding connected to a battery and being adapted to receive the magnetic flux when the secondary winding is placed on the charging surface, and a control circuit. The control circuit includes a first-stage power converter by which a variable DC link voltage (Vdc) is provided, and a second-stage power inverter by which the variable DC link voltage (Vdc) is converted to a fixed-frequency constant AC current and the fixed-frequency constant AC current is provided to the primary windings (1).

WO 2009/062438 A1

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— *with international search report*

PLANAR BATTERY CHARGING SYSTEM

FIELD OF THE INVENTION

This invention relates to methods and apparatus for the control of a planar battery charging apparatus.

BACKGROUND OF THE INVENTION

The increasing popularity of portable consumer electronic products such as mobile phones, MP3 players and PDAs has prompted new concerns on the huge variety and number of battery chargers that are required and which are costly, inconvenient and eventually lead to electronic waste problems. Inductive or wireless charging apparatus that can charge more than one electronic product have been proposed. Two different approaches to the generation of ac magnetic flux have been proposed, namely "horizontal flux" and "vertical flux" methods.

PRIOR ART

Inductive electronic chargers with a direct connection have been developed for use with some types of portable electronic equipment such as electric toothbrushes. Inductive chargers have also been proposed in a number of documents such as US6,356,049, US6,301,128, US6,118,249. These inductive chargers, however, use traditional transformer designs with windings wound around ferrite magnetic cores and the main magnetic flux between the primary winding and secondary winding has to go through the magnetic core materials. Other contactless chargers proposed (eg "Chang-Gyun Kim; Dong-Hyun Seo; Jung-Sik You; Jong-Hu Park; Cho, B.H., 'Design of a contactless battery charger for cellular phone', IEEE Transactions on Industrial Electronics, Volume:48, Issue:6 , Dec. 2001 Page(s): 1238 –1247.") also use magnetic cores as the main structure for the coupled transformer windings. However, these battery chargers do not use a planar structure and each charger is only able to charge one item of electronic equipment at a time.

Recent research in the field of planar magnetics and planar transformer technology has prompted the development of planar contactless battery charging systems for portable electronic equipment. Among them, two proposals are particularly of interest, because they allow one or more items of electronic equipment to be placed and charged simultaneously on the charging surface, regardless of the orientation of the electronic equipment.

The first type of planar battery charger modifies the rotating machine concept by flattening the "round shape" of the motor into a "pancake shape", as described in GB2399225A, GB2398176A, WO2004/038888A, GB2388716A, US2003-210106-A1, GB2392024A, and GB2399230A. The magnetic flux lines flow horizontally along (roughly in parallel to) the planar charging surfaces. The portable electronic equipment to be charged by the charging device needs a secondary winding wound on preferably a soft magnetic core. An ac voltage will be induced in this secondary winding for charging the battery, usually via a battery charging circuit.

A fundamental and inherent limitation of this type of battery charger is that this charging device must have a good electromagnetic flux guide to confine the flux along the lower surface. Otherwise, if such a charging device is placed on a metallic table or a conductive surface, induced current will circulate in the metallic table or conductive surface, resulting in heat generation and power loss in the metallic table or conductive surface. One imperfect way to solve this problem is to place a piece of soft-magnetic material (such as a layer of ferrite, iron power or amorphous soft magnetic alloy) as a magnetic flux guide under the lower surface. However, if the electromagnetic flux is large, a fairly thick layer of soft-magnetic material is needed, defeating the purpose of designing a "thin" charging platform and increasing the cost due to the large amount of soft magnetic material required. In addition, the electromagnetic shielding effect of using one layer of soft magnetic material may not be sufficient for electromagnetic compatibility (EMC) requirements. Some flux may still penetrate through the soft magnetic layer and induce current in any conductive surface below the charging platform.

A better solution to shield the magnetic field in the lower surface is to use a combination of a layer of soft magnetic material and a conductive material as disclosed in US2003-095027-A1. It is important to note that the addition of a thin layer of conductive material can significantly increase the shielding effectiveness as reported in US-2003-095027-A1, US 6,501,364 and Tang S.C., Hui S.Y.R and Chung H., 'Evaluation of the Shielding Effects on Printed-Circuit-Board Transformers using Ferrite Plates and Copper Sheets', *IEEE Transactions on Power Electronics*, Vol.17, No.6, Nov. 2002, pp.1080-1088.

The second approach described in WO03/105308A, GB2389720A, GB2399446A, GB2389767A, GB2389767A, WO2007/019806 is to create an ac magnetic field with the flux lines flowing substantially vertically out of the planar charging surfaces, ie in a direction substantially perpendicular to the plane of the charging platform. Since the lines of flux enter and leave the planar charging surface vertically, a very thin secondary coil can be used to pick up the magnetic flux. This results in the possibility of a slim design for the secondary module that can be embedded in the portable electronic load.

SUMMARY OF THE INVENTION

According to the present invention there is provided a planar battery charging system comprising a primary power transmission side formed of an array of primary windings adapted to generate magnetic flux substantially perpendicular to a charging surface, and a secondary power receiving side comprising a secondary winding associated with a battery to be charged and being adapted to receive said magnetic flux when a said secondary winding is placed on said charging surface, wherein a said primary winding is energized by a control circuit comprising a first-stage power converter and a second-stage power inverter, wherein the first-stage power converter provides a variable dc link voltage and wherein the second-stage power inverter generates a fixed-frequency constant ac current to said primary winding.

The first-stage power converter may be either current controlled or voltage-controlled. Preferably the current fed to said primary winding is monitored to provide a feedback control of the variable dc link voltage.

In some embodiments of the invention a step-down transformer may be provided between the output of said second-stage power inverter and the primary winding.

The second-stage power inverter may comprise a resonant tank that sets the frequency of said ac current supplied to said winding. In such embodiments the second-stage power inverter is switched at a constant frequency that is equal to the frequency of the resonant tank.

Preferably the secondary side is adapted to receive power optimally at the said excitation frequency of the primary winding.

The first-stage power converter may be a boost converter, or a buck converter, or a flyback converter, or a Cuk converter or a Sepic converter. The second-stage power inverter may be a full-bridge type, or a half-bridge type, or a Class D type or a Z-source type inverter.

Preferably when excited each primary winding is excited at the same frequency and generates the same ac magnetic flux. The ac current supplied to the primary winding is preferably sinusoidal.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention will now be described by way of example and with reference to the accompanying drawings, in which:-

FIG.1 is a schematic showing the control methodology according to an embodiment of the invention,

FIG.2 is a schematic of a boost converter,

FIG.3 is a schematic of a flyback-type ac-dc power converter,

FIG.4 is a schematic of a full-bridge power inverter with a primary winding and a dc-blocking capacitor,

FIG.5 is a schematic of a half-bridge power inverter with a primary winding and a dc-blocking capacitor,

FIG.6 shows a typical winding array in a planar battery charging platform,

FIG.7 shows an AC-DC voltage-mode controlled first-stage flyback converter feeding constant current source to a second-stage full-bridge fixed frequency inverter,

FIG.8 shows an AC-DC current-mode controlled first-stage flyback converter feeding constant current source to a second-stage full-bridge fixed frequency inverter,

FIG.9 shows an AC-DC voltage-mode controlled first-stage boost converter feeding constant current source to a second-stage full-bridge fixed frequency inverter,

FIG.10 shows an AC-DC current-mode controlled first-stage boost converter feeding constant current source to a second-stage full-bridge fixed frequency inverter,

FIG.11 shows an AC-AC current-mode controlled first-stage flyback converter feeding a full-bridge inverter that provides a step-down current source through a transformer, and

FIG.12 shows an AC-AC voltage-mode controlled first-stage flyback converter feeding a full-bridge inverter that provides a step-down current source through a transformer.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

For such planar battery charging systems it is important that a standard charging pad can be used to charge inductively a wide range of portable electronic products. In order to meet this requirement, preferably several conditions must be met.

(1) The windings of the charging pad that are excited must be able to generate sufficient energy for charging these electronic products.

(2) Since the inductive charging method relies on the near-field magnetic coupling of the charging pad (primary energy-transmitting circuit or simply primary circuit) and the energy-receiving module (secondary circuit) inside the electronic products, it is necessary for the charging pad to generate an ac magnetic flux of a controllable magnitude that can satisfy a wide range of portable electronic loads to be charged.

(3) Since a range of electronic loads may be charged on the same charging pad, there should be a standard operating frequency and a set of basic secondary circuit design features. In other words, the secondary circuits in a wide range of electronic loads must be compatible with the magnetic flux generated by the charging pad.

In the following, methods and apparatus that can provide power control and ac flux control for the inductive charging pad are described. In order to meet the criteria mentioned previously, the following design and operating conditions are set so that the charging pad can be used to charge a wide range of electronic loads and to enable the flux that is generated by the excited windings to be controlled.

(1) One or more windings of the charging pad are excited and may be termed as an "active group". A common magnitude of ac magnetic flux may be set for each coil on the charging pad so that the ac magnetic field created by each energized coil would be identical. This allows the electronic products to be charged in the same manner anywhere over the charging surface of the charging pad.

(2) Such magnetic flux must provide sufficient energy to charge the electronic products.

(3) The ac magnetic flux generated by the charging pad must be set at a specific frequency. The secondary energy-receiving circuits of all electronic loads must be designed to pick up the flux at the same frequency. This ensures that the secondary circuits are compatible with the charging pad.

(4) Since the magnetic flux is a function of the excitation current in the windings of an active group, the power inverter that drives the windings in the charging pad should be current controlled.

(5) In order to control the power delivered to the inverter and hence the windings of the active group, the front-stage power converter should have a controllable output voltage. Since the second-stage power inverter is controlled to inject a constant ac current into the windings of the active group, the control of the output voltage of the first-stage power converter can be used to control the power of the active group.

(6) In order to reduce harmonic losses in the windings and EMI radiation, it is necessary to ensure that the current in the primary winding is sinusoidal. Therefore a capacitor should be added to the primary winding to form a resonant tank. The second-stage inverter should be operated at this resonant frequency to ensure that the current in the winding is sinusoidal.

FIG.1 shows an embodiment of an electronic control system for an inductive charging pad (primary system) and comprising the two power stages that drive a primary winding that forms part (or all) of an active group of the charging pad. The front or first-stage power converter depends on the nature of the input power supply. If the power supply is an ac mains, this first-stage power converter should be an ac-dc power converter. If there is a dc power supply, then the first-stage power converter should be a dc-dc power converter. In either case, the output voltage (i.e. dc link voltage V_{dc} in FIG.1) should be a controllable variable.

If the input power supply is a dc voltage source, the front-stage dc-dc power converter can be, but not restricted to, a flyback converter, boost converter, buck converter, Cuk converter and Sepic converter. An example of boost converter is given in FIG.2. If the input power supply is an ac voltage source (such as the ac mains), an ac-dc power converter with or without power factor correction can be used as the front-stage power converter. An ac-dc converter typically consists of a diode rectifier and a dc-dc converter. An example of a flyback type ac-dc converter is shown in FIG.3. The second-stage power inverter can be a full-bridge inverter (FIG.4), a half-bridge inverter (FIG.5) or a z-source inverter.

The primary winding(s) of the charging pad may consist of a single coil or an array of coils 1 connected in series as shown in FIG.6 where hexagonal coils are shown as an example. The array of coils can be of single-layer or multi-layer structures. The array of coils may be re-configurable into groups in order to achieve localized charging such that, if necessary, only those coils through which energy transfer is required are energized.

The control principle is now explained with reference to FIG.1. The front-stage power converter controls its output voltage (Vdc) by varying the duty-cycle of the converter switch. Typically, a pulse-width modulation (PWM) technique is used to control the duty-cycle of the converter switch, which in turn, controls the output voltage of the power converter. The duty-cycle function is denoted as M(d) in FIG.1. The first-stage power converter that provides a controllable dc-link voltage (Vdc) can be controlled either in "voltage control" mode or in "current control" mode.

The second-stage power inverter adopts a fixed frequency control. Generally, the diagonal pairs of switches in the full-bridge inverter are switched together and the two pairs are switched in a complementary manner so that an ac voltage can be generated at the output of the inverter. If necessary, a small dead time can be introduced in the switching instants of the two switches in the same inverter leg in order to achieve soft switching, thus reducing the switching loss and EMI radiation. The inverter is switched at a constant frequency, which should preferably be the same as the resonant frequency of the resonant tank in the primary circuit. Since the current fed from the first-stage power converter is kept constant, the second-stage inverter generates a fixed-frequency constant ac current into the winding(s) of an active group. The fixed-frequency operation is important because the secondary circuits of the electronic loads will be designed to receive power transfer at this frequency. This frequency should preferably be chosen so that the radiated electromagnetic interference (EMI) should not violate international electromagnetic compatibility (EMC) requirements.

Under voltage-control mode, the first-stage power converter feeds dc-link voltage to the second-stage power inverter. Under current-control mode, the first-stage power converter feeds a dc current to the second-stage power inverter. In both operating modes, the objective is to maintain a constant current feeding the second-stage power inverter. That is, under voltage-control mode, the power converter will vary its output voltage (Vdc) in order to keep constant the current feeding the second-stage inverter. Under the current-control mode, the power converter is controlled to provide a current of a desired value to the second-stage inverter.

The current feeding the second-stage power inverter is monitored by a current sensor which can be a small resistor or a hall-effect current sensor. If the power absorbed by the secondary load increases (decreases), this current may be reduced (increased). A feedback current is compared with a preset reference (Vref) that represents the desired current feeding the primary winding, which can be set by users, or according to some standard or to flux, power or other requirements communicated back from the load. The error signal is then amplified by amplifier A and compared by a comparator C with a triangular carrier reference of a fixed frequency that determines the switching frequency of the first-stage power converter. The duty cycle will be dynamically adjusted to control the dc link voltage (Vdc) so as to keep the current feeding the second-stage inverter to the desired current value within a small tolerance.

FIG.7 shows an embodiment of the invention. In this example, the charging pad is powered by an ac mains. An ac-dc flyback converter is used to feed an dc-ac inverter that drives the primary winding(s) inside an active group of the charging pad. An ac-dc flyback converter comprising (diode bridge 2 and gate driver 3) operating under a voltage-control mode is illustrated here. Sensing resistor Rsen is used to monitor the current feeding the inverter. This sensed current signal is filtered by a resistive-capacitive filter and then compared with a reference value (Vref – which is arbitrarily set at 2.5V and represents the desired current value in the inverter) in an error amplifier 4, which generates an error signal in its output. This current error signal (Ve) is then fed to a comparator 5 and compared with a sawtooth reference signal (Vsw) that is set at a specific frequency which determines the switching frequency of the first-stage ac-dc flyback converter. The output of this comparator provides the PWM signal for switching the power converter. The duty cycle of this PWM signal controls the output voltage of the flyback converter (i.e. the dc-link voltage Vdc). Vdc is controlled in a manner that keeps the current flowing into the inverter to the desired value within a certain small tolerance. The second-stage inverter is simply driven at constant frequency (at the resonant frequency of the resonant tank in the primary circuit) to inject an ac current of constant magnitude into the primary circuit of the charging pad. The resonant tank of the primary circuit ensures that current in the primary winding(s) of an active group is sinusoidal in order to reduce harmonic losses and EMI radiation.

FIG.8 shows a typical implementation of the invention, where the first-stage power converter is operated under current-control mode. In this implementation, the current sensor Rsen is used to sense the current feeding into the inverter. The sensed current signal is filtered and then compared with a desired current reference (Vref – arbitrarily set at 2.5V) in an error amplifier 14. The current error signal (Ve) is the output of this error amplifier. Another current sensor Rs is used to monitor the current in the power switch of the flyback converter. This switch current is the same as the current in the primary winding of the coupled inductor in the flyback converter. The sensed switch current (Vipk) is filtered and then compared with Ve at comparator 15 in order to generate the PWM signal for driving the switch of the flyback converter. The objective is to for the first-stage converter to feed a desired level of current into the second-stage inverter. The second-stage inverter is simply driven at constant frequency (at the resonant frequency of the resonant tank in the primary circuit) to inject an ac current of constant magnitude into the primary circuit of the charging pad. The resonant tank of the primary circuit ensures that current in the primary winding is sinusoidal in order to reduce harmonic losses and EMI radiation.

The same principle can be implemented using a boost converter as the first-stage under voltage-control mode and current-control mode as shown in FIG.9 and FIG.10, respectively.

An alternative way to inject a sinusoidal current into the winding(s) of an active group of the charging pad is to use a second-stage power inverter to drive a resonant tank formed by a capacitor and the primary winding of a step-down transformer 20. Typical circuit schematics are shown in FIG.11 and FIG.12. The use of a step-down transformer has the advantage that the dc-link voltage of the inverter can be set to a higher value so that the current injected into the capacitor and the primary winding of the transformer can be kept to a relatively low value. This facilitates the choice of components in the circuit by avoiding the need for components such as capacitors that are suitable for use with large currents. The sinusoidal current in the secondary winding of this step-down transformer is then fed into the winding(s) of the active group.

In summary, in order to develop a battery charging pad that meets the criteria mentioned previously for compatibility with a wide range of portable electronic products, there is proposed the use of a first-stage power converter to control directly or indirectly the current to a desired value (within a small tolerance) fed into the second-stage inverter either under voltage-control or current-control mode so that the current injected by the second-stage inverter into the primary winding(s) of an active group of the charging pad can maintain an ac magnetic flux (which is a function of the current) of identical magnitude in all coils energized in the group. In this way, the first-stage power converter also controls the power of the active group.

A resonant tank may be used in the primary circuit in order to ensure that the current in the winding is sinusoidal. Sinusoidal current in the primary winding, which creates the ac magnetic flux, ensures that the harmonic losses and EMI radiation are minimized. The use of a second-stage power inverter that is switched at a constant frequency equal to the resonant frequency of the primary circuit further assists in ensuring that the current in the primary winding is sinusoidal.

The secondary energy-receiving circuit is preferably designed to work optimally at the operating frequency set in the second-stage power inverter of the charging pad to ensure the compatibility of the secondary energy-receiving modules in all loads for this charging pad.

The first-stage power converter may be selected from boost, buck, flyback, Cuk and Sepic type converters but is not restricted thereto. The second-stage power inverter can be a full-bridge, half-bridge, or Class-D and Z-source type converter but again is not restricted. The second-stage power inverter can use a step-down transformer so that a relatively high dc-link voltage can be used in order to reduce the current in the resonant capacitor for a given power requirement.

CLAIMS

1. A planar battery charging system comprising a primary power transmission side formed of an array of primary windings adapted to generate magnetic flux substantially perpendicular to a charging surface, and a secondary power receiving side comprising a secondary winding associated with a battery to be charged and being adapted to receive said magnetic flux when a said secondary winding is placed on said charging surface, wherein a said primary winding is energized by a control circuit comprising a first-stage power converter and a second-stage power inverter, wherein the first-stage power converter provides a variable dc link voltage and wherein the second-stage power inverter generates a fixed-frequency constant ac current to said primary winding.

2. A battery charging system as claimed in claim 1 wherein the first-stage power converter is current controlled.

3. A battery charging system as claimed in claim 1 wherein the first-stage power converter is voltage-controlled.

4. A battery charging system as claimed in claim 1 wherein the current fed to said primary winding is monitored to provide a feedback control of said variable dc link voltage.

5. A battery charging system as claimed in claim 1 wherein a step-down transformer is provided between the output of said second-stage power inverter and the primary winding.

6. A battery charging system as claimed in claim 1 wherein said second-stage power inverter comprises a resonant tank that sets the frequency of said ac current supplied to said winding.

7. A battery charging system as claimed in claim 6 wherein said second-stage power inverter is switched at a constant frequency that is equal to the frequency of the resonant tank.

8. A battery charging system as claimed in claim 1 wherein the secondary side is adapted to receive power at the said excitation frequency of the primary winding.

9. A battery charging system as claimed in claim 1 wherein the first-stage power converter is a boost converter, or a buck converter, or a flyback converter, or a Cuk converter or a Sepic converter.

10. A battery charging system as claimed in claim 1 wherein the second-stage power inverter is a full-bridge type, or a half-bridge type, or a Class D type or a Z-source type inverter.

11. A battery charging system as claimed in claim 1 wherein when excited each primary winding is excited at the same frequency and generates the same ac magnetic flux.

12. A battery charging system as claimed in claim 1 wherein the ac current supplied to the primary winding is sinusoidal.

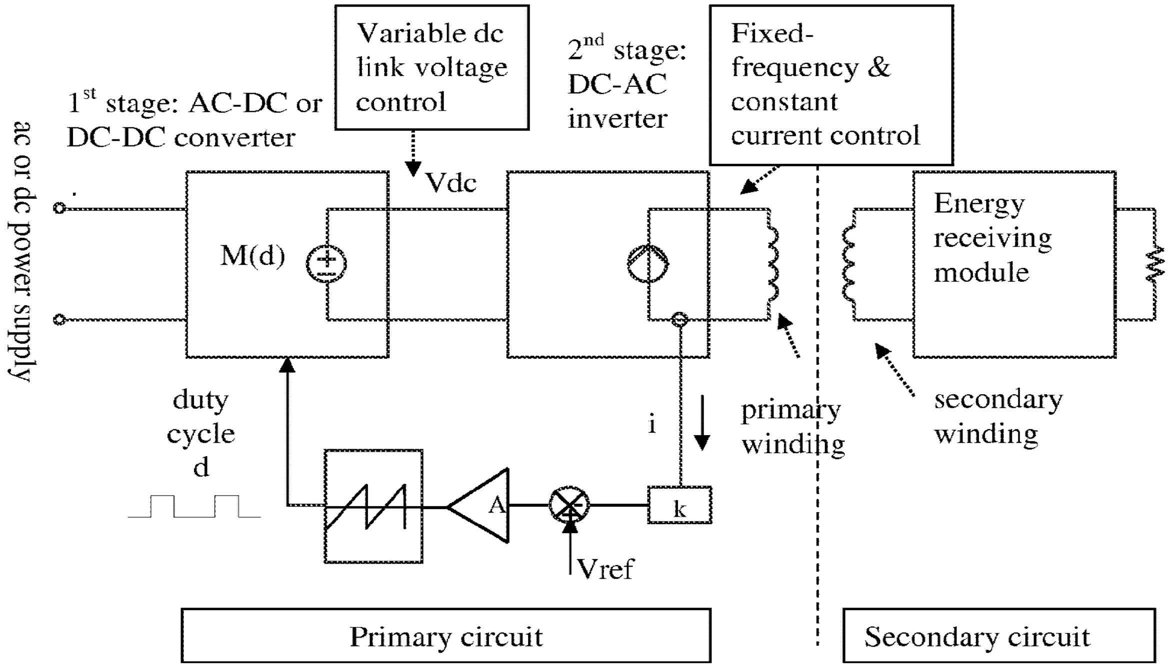
Variable dc link voltage control
2nd stage: DC-AC inverter
Fixed-frequency & constant current control
1st stage: AC-DC or DC-DC converter
ac or dc power supply
Vdc
M(d)
Energy receiving module
duty cycle d
i
primary winding
secondary winding
A
k
Vref
Primary circuit
Secondary circuit

FIG.1

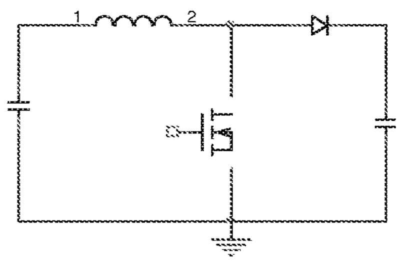
1
2

FIG.2

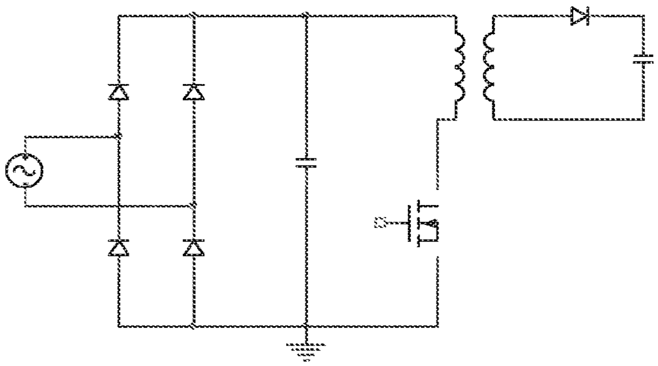

FIG.3

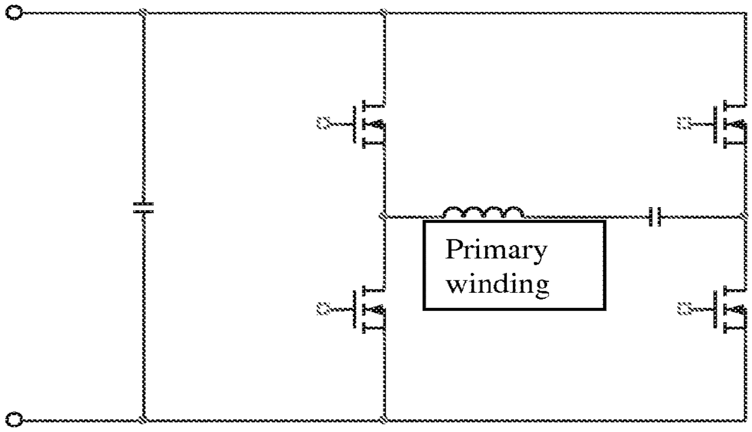

FIG.4

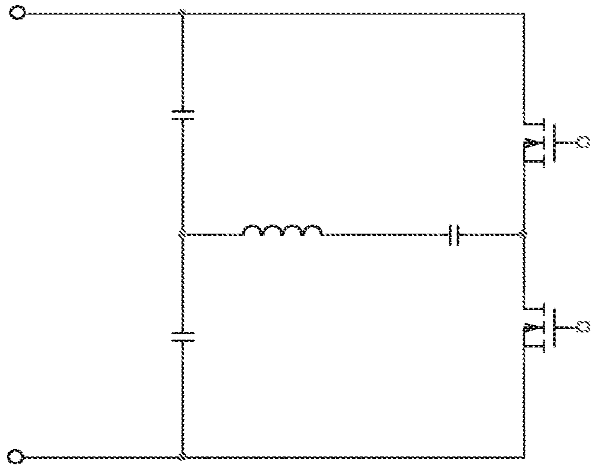

FIG.5

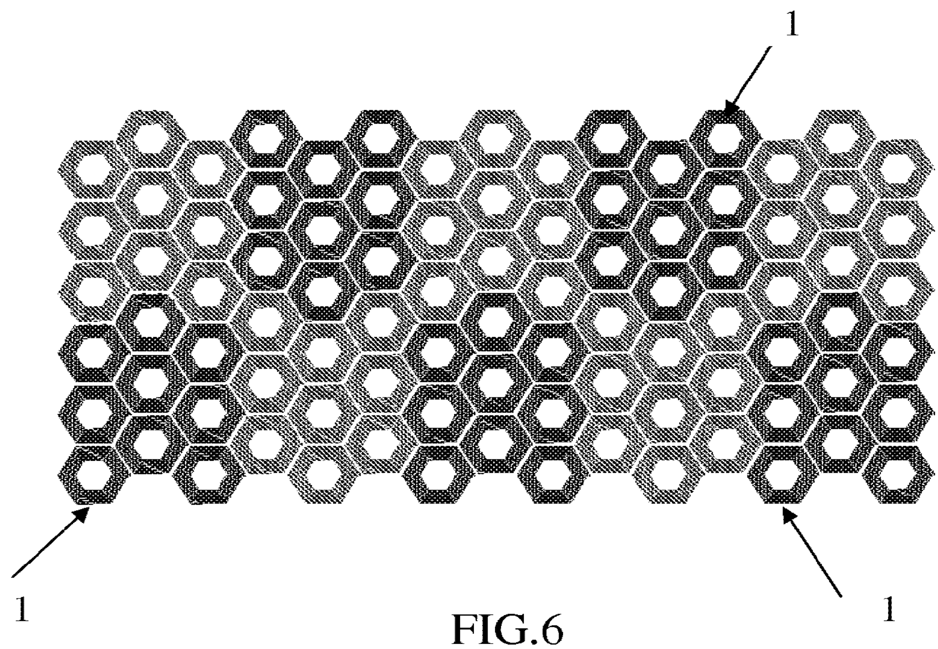

FIG.6

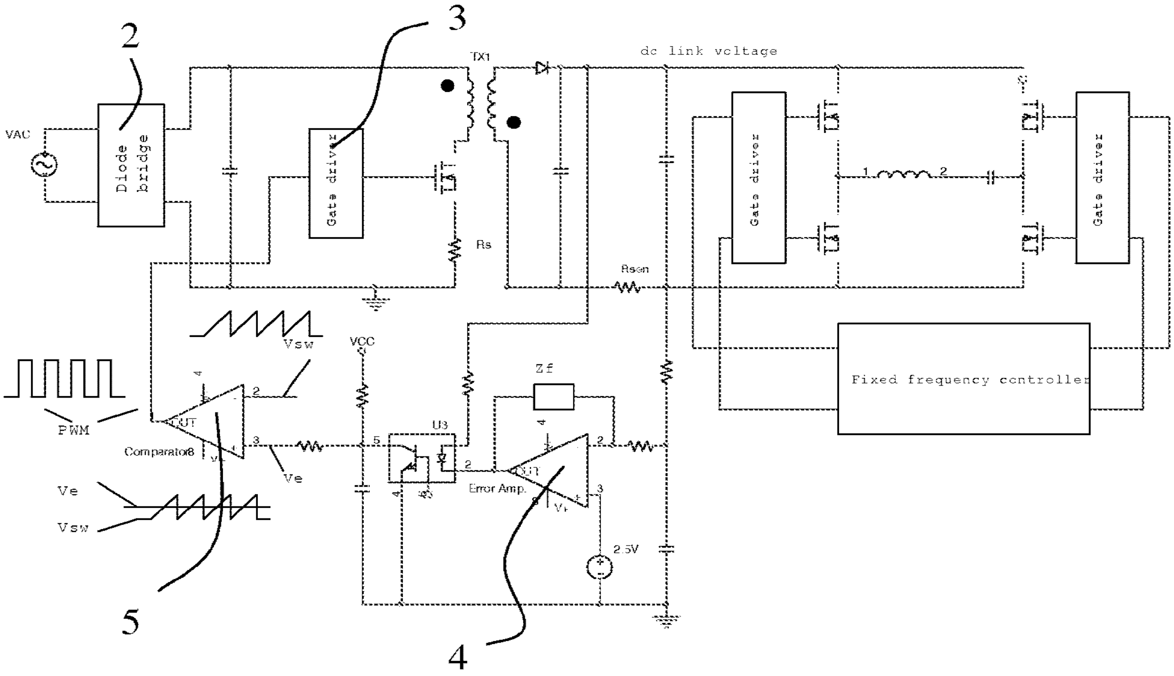
2
3
VAC
Diode bridge
Gate driver
TX1
dc link voltage
Rs
Rsen
Gate driver
Gate driver
Vsw
VCC
Zf
PWM
Comparator8
Ve
Vsw
U3
Error Amp.
2.5V
Fixed frequency controller
5
4

FIG.7

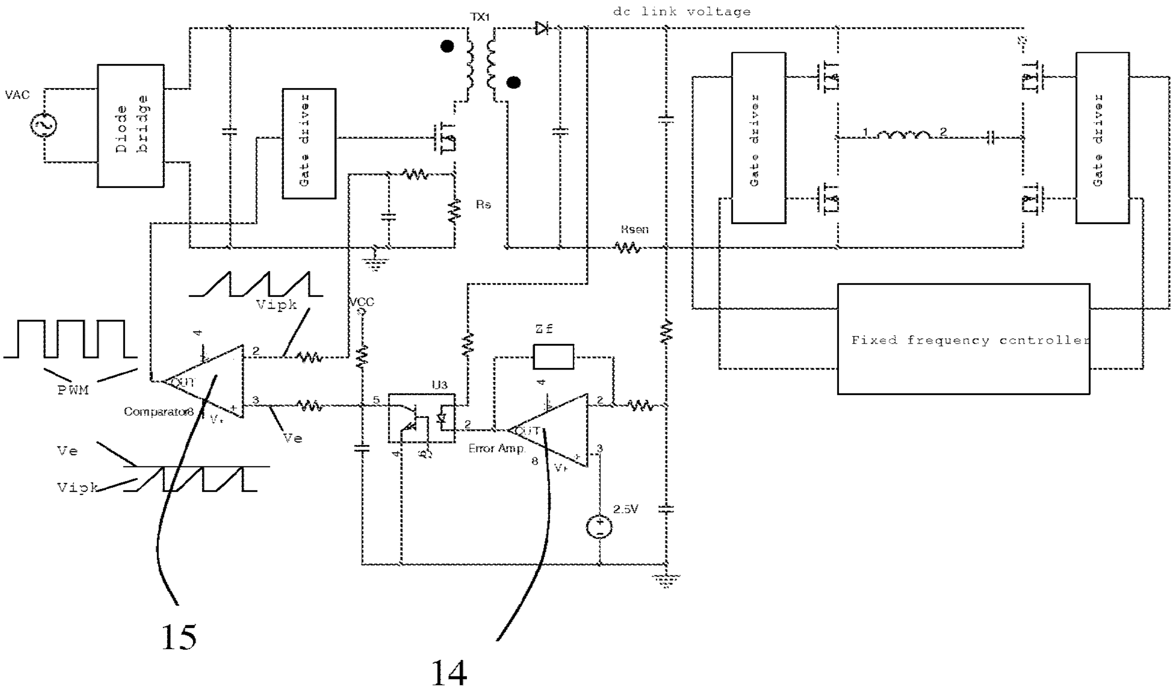
VAC
Diode bridge
Gate driver
TX1
dc link voltage
Rs
Rsen
Gate driver
Gate driver
Vipk
VCC
Zf
PWM
Comparator8
Ve
Vipk
U3
Error Amp.
2.5V
Fixed frequency controller
15
14

FIG.8

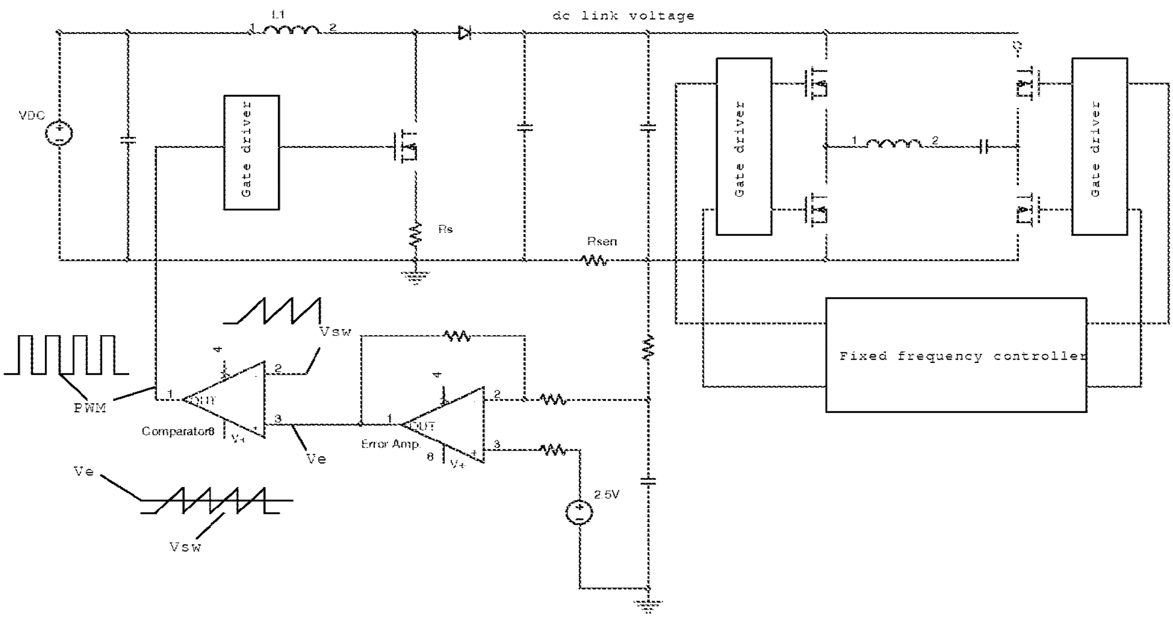
L1
dc link voltage
VDC
Gate driver
Rs
Rsen
Gate driver
Gate driver
Vsw
PWM
Comparator8
Ve
Error Amp.
2.5V
Fixed frequency controller
Ve
Vsw

FIG.9

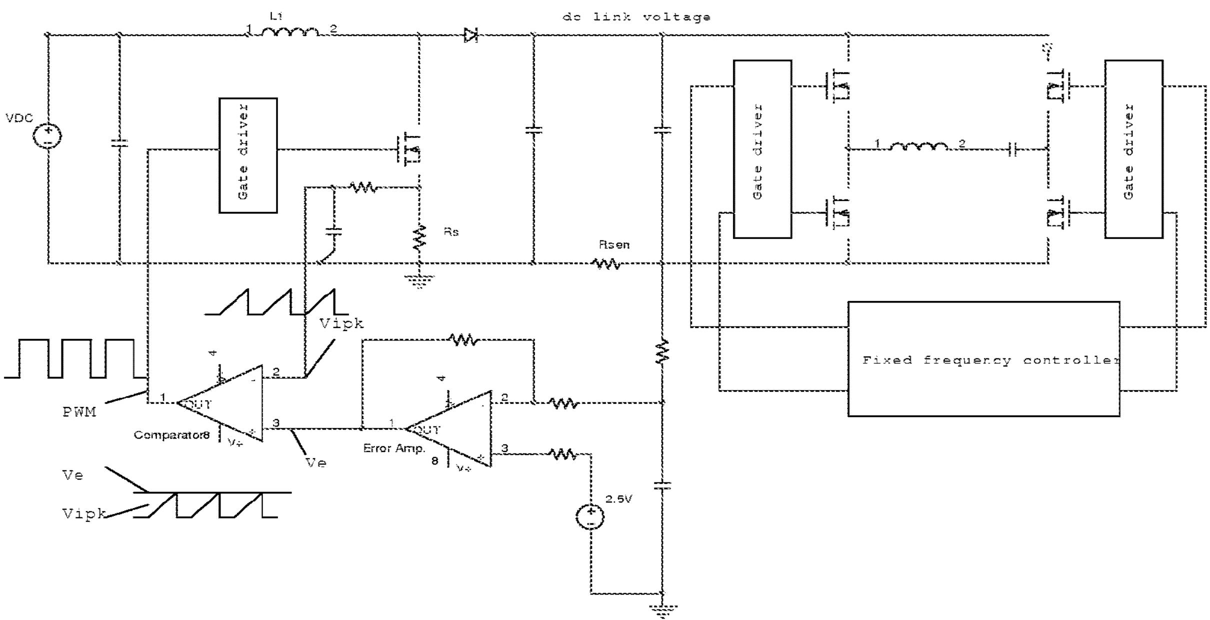
L1
dc link voltage
VDC
Gate driver
Rs
Rsen
Gate driver
Gate driver
Vipk
PWM
Comparator8
Ve
Error Amp.
2.5V
Fixed frequency controller
Ve
Vipk

FIG.10

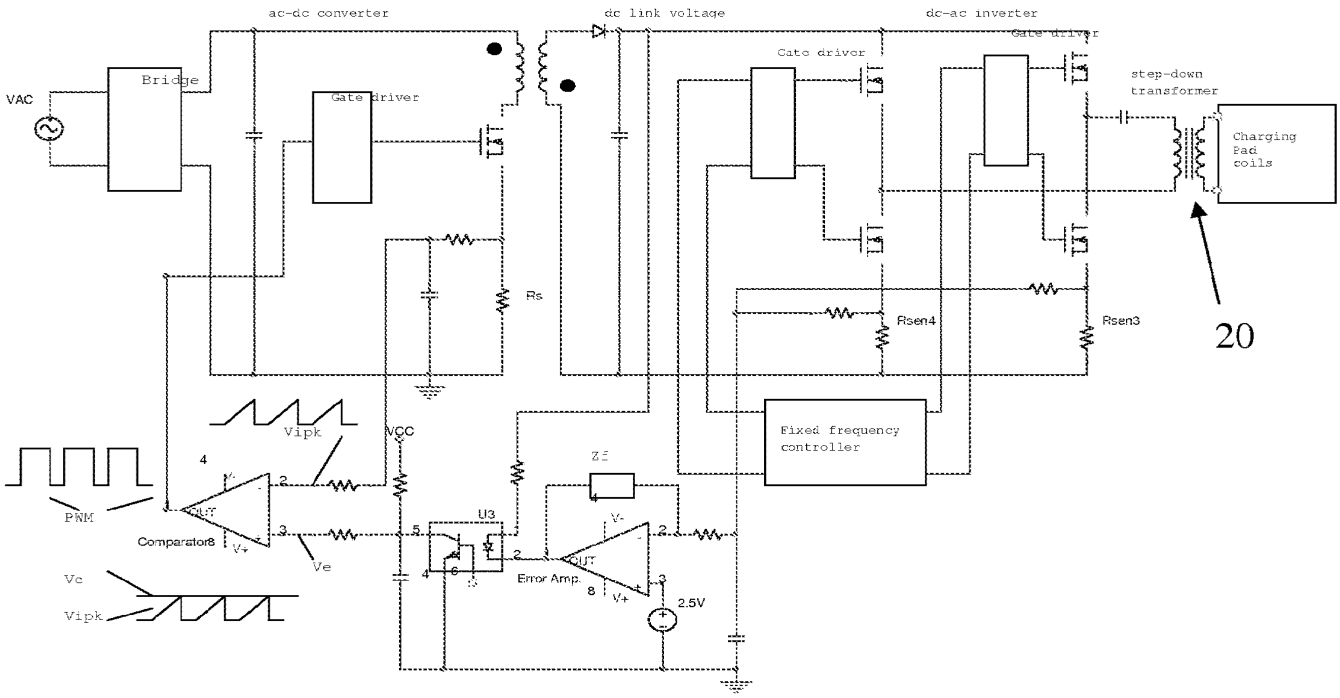
ac-dc converter
dc link voltage
dc-ac inverter
Gate driver
Gate driver
Gate driver
Bridge
VAC
step-down
transformer
Charging
Pad
coils
Rs
Rsen4
Rsen3
20
Fixed frequency
controller
Vipk
VCC
PWM
Comparator8
Ve
U3
Error Amp.
2.5V
Vc
Vipk

FIG.11

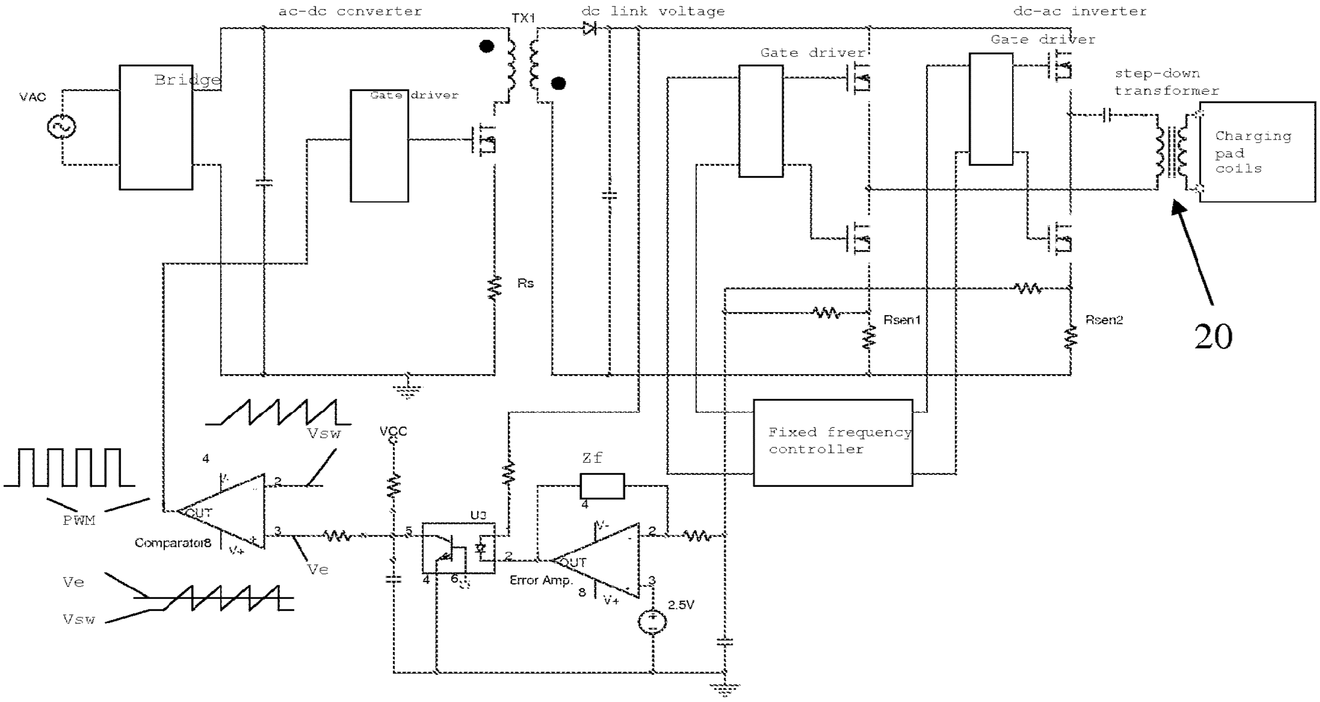
ac-dc converter
TX1
dc link voltage
dc-ac inverter
Gate driver
Gate driver
Gate driver
Bridge
VAC
step-down
transformer
Charging
pad
coils
Rs
Rsen1
Rsen2
20
Fixed frequency
controller
Vsw
VCC
Zf
PWM
Comparator8
Ve
U3
Error Amp.
2.5V
Ve
Vsw

FIG.12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2008/072898

A. CLASSIFICATION OF SUBJECT MATTER

H02J 17/00 (2006.01) i

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: H02J 17/-

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)

CNPAT, WPI, EPODOC, PAJ

Contactless, power transfer, charge, induct

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2007/089086 A1 (LS CABLE LTD et al.) 09 August 2007 (09.08.2007) see paragraph [13] to paragraph [73] of the description, Figs.1-5	1-12
X	WO 2007/015599 A1 (LS CABLE LTD et al.) 08 February 2007 (08.02.2007) see paragraph [38] to paragraph [74] of the description, Figs. 1-3	1-12

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* 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	Date of mailing of the international search report
23 December 2008 (23.12.2008)	**08 Jan. 2009 (08.01.2009)**

Name and mailing address of the ISA/CN	Authorized officer
The State Intellectual Property Office, the P.R.China 6 Xitucheng Rd., Jimen Bridge, Haidian District, Beijing, China 100088 Facsimile No. 86-10-62019451	HUANG, Jun Telephone No. (86-10)62411799

Form PCT/ISA/210 (second sheet) (April 2007)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2008/072898

Patent Documents referred in the Report	Publication Date	Patent Family	Publication Date
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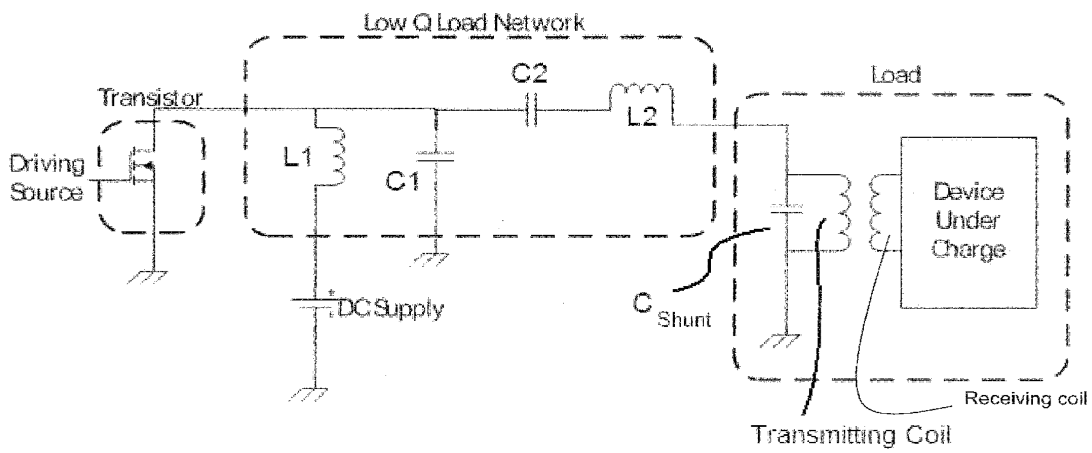

FIG. 1

(57) Abstract: Wireless power transfer systems are provided. A wireless power transmitter can include a transistor block providing a switching mode amplifier, and a low-Q output network including a tunable supply voltage. The transistor block can be scalable. Multiple scalable transistor blocks can be incorporated in a power transfer system using a single tunable supply voltage and transmitting coil. The tunable supply voltage can be controlled by an adaptive power supply tuning circuit to accommodate for a range of loading conditions. Embodiments of the subject invention are capable of achieving high efficiency across a wide range of output power levels.

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DESCRIPTION

METHOD AND APPARATUS FOR HIGH EFFICIENCY SCALABLE NEAR-FIELD WIRELESS POWER TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 60/990,377, filed November 27, 2007, 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.

For charging of portable electronic devices and/or powering the portable electronic devices at close proximity, radio frequency charging appears to be a viable option. Recent improvements in efficiency have made it possible to consider radio frequency charging technology for commercial applications. However, there still exists a need in the art for a high efficiency low cost wireless power charging platform and components.

BRIEF SUMMARY

Embodiments of the present invention relate to a method and apparatus for wireless power transfer. Wireless power transfer systems in accordance with embodiments of the invention are capable of transmitting power to devices under charge through radio frequency charging. According to an embodiment, the wireless power transfer system of the present invention includes a switching mode amplifier and a low-Q output network. Embodiments of the present invention can follow class E amplifier designs while focusing on providing a low Q load.

In one embodiment of the present invention, a wireless transmitter includes a transistor block, a supply voltage block, and a transmitting coil block. The transistor block can include a transistor, load network capacitor, and a load network inductor. The transistor block can be scalable. The supply voltage block can include an RF choke inductor and a DC supply voltage. The supply voltage can provide tunable output power. The transmitting coil block can include a second load network capacitor, a transmitting coil, and a coil shunt capacitor.

In a further embodiment, multiple transistor blocks sharing the same load current can be used. Advantageously, the multiple transistor blocks can use a single DC supply voltage and transmitting coil block. Additional RF choke inductors can be added for each transistor block. The multiple transistor blocks can be incorporated to increase output power.

In yet another embodiment, the DC supply voltage can be tuned to achieve high efficiency for a wide range of load conditions through adaptive power supply tuning. This can be accomplished though a feedback circuit involving a current monitor network, a voltage monitor network, and a receiver for receiving charging data of a device under charge.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a planar wireless power transfer system according to an embodiment of the present invention.

Figure 2 shows ideal voltage and current waveforms to prevent simultaneous high voltage and high current in a transistor of a planar wireless power transfer system according to an embodiment of the present invention.

Figure 3 shows a schematic of a transmitter according to an embodiment of the present invention with three scalable transistor blocks.

Figure 4 shows a power delivery and efficiency plot of a two-scalable transistor block transmitter according to an embodiment of the present invention at 24 V, 36 V and 48 V supply voltage.

Figure 5 shows a power delivery and efficiency plot of a two-scalable transistor block transmitter according to an embodiment of the present invention with adaptive power control.

Figure 6A shows a system block diagram of a planar wireless power transfer system using adaptive power supply tuning according to an embodiment of the present invention.

Figure 6B shows a planar wireless power transfer system according to an embodiment of the present invention including current and voltage monitoring.

Figures 7A and 7B show measurement results with different loads according to an embodiment of the present invention, where Figure 7A shows efficiency vs. power delivered to a load, and Figure 7B shows power supply voltage vs. power delivered to a load.

Figure 8 shows the efficiency at different power levels at a fixed power supply voltage of 48 V according to an embodiment of the present invention with no adaptive power supply tuning.

DETAILED DISCLOSURE

Embodiments of the present invention provide a method and apparatus for wireless power transfer. Specific embodiments of the present invention utilize radio frequency (RF) charging techniques. According to an embodiment of the present invention, a wireless power transmitter includes a transistor block providing a switching mode amplifier, and a low-Q output network including a tunable supply voltage. The combination of a switching mode amplifier and the low-Q output network provides high efficiency for power charging.

Potential uses for the subject invention include, but are not limited to, high efficiency and low cost wireless power charging platform for all portable devices such as laptop computers, LCD digital photo frames, mobile phones, mp3 players. With its high efficiency, energy loss via heating could be reduced. Further, embodiments of the subject invention can be implemented at home, in airports, and in hotel rooms. This would bring great convenience to general consumers, especially frequent travelers, as it would provide a universally charging interface and eliminate the need to bring multiple chargers. In addition, the scalable transmitter and power control design enables the transmitter system to be more flexible and adaptive to wider range of environmental situations while maintaining high energy efficiency.

Further, impedance tuning design enables the transmitter system to be more flexible and adaptive to wider range of loading conditions while maintaining high efficiency.

Figure 1 shows a schematic for a planar wireless power transfer system according to an embodiment of the present invention. Referring to Figure 1, a transmitter of the power transfer system includes a transistor block and a low Q load network. A transmitting coil with shunt capacitor is connected to the low Q load network to transmit the signal from the power transfer system to a device under charge. The device under charge should include a receiving coil for receiving the signal transmitted by the transmitter. Advantageously, the low Q network is insensitive to a change in load. In particular, the transmitter is capable of providing a range of frequencies for the transmitted signal without causing a problem with respect to load matching.

The transistor block can receive a driving power source as input. For example, a wall outlet providing ac power can provide the driving power to the transistor block. In an embodiment, the transistor block can receive the input at the gate of a transistor. A variety of transistors can be utilized in the transistor block in accordance with embodiments of the invention. In a specific embodiment, the transistor can be an n-channel metal oxide semiconductor field effect transistor (NMOSFET). In another specific embodiment, an NPN BJT transistor can be used. The transistor block can amplify an input signal and operate as an on/off switch. The output network shapes the voltage and current waveforms to prevent a simultaneous high voltage and high current in the transistor. Figure 2 shows the ideal voltage and current waveforms to prevent simultaneous high voltage and high current in the transistor. This effect minimizes power dissipation, especially during the switching transitions. Unlike a conventional amplifier using a high-Q output network to reduce harmonics in wireless communications systems, embodiments of the present invention can use a low-Q output network to provide successful operation regardless of load condition. In a specific embodiment, the low-Q output network can also be dynamic.

According to embodiments of the present invention, a maximum value for Q can be about 10. In one embodiment, Q can be selected to be less than or equal to 10. In other embodiments, Q can be selected to be less than or equal to 8 or less than or equal to 5. In further embodiments, Q can be a range of 10-20, 2-4, or 1.8-5.

In one embodiment a single transistor is used for the transistor block. The single-transistor amplifier can be used to significantly reduce the circuit complexity. Although a single transistor is illustrated in the embodiment shown in Figure 1, multiple transistors can also be used.

Embodiments of the subject invention may ensure that a low cost amplifier is able to operate at a wide dynamic range of frequency and load impedance. This is important because the load condition of the planar wireless power transfer system varies over a huge range depending on the device or devices it is powering/charging as well as the charging stage. Embodiments of the present invention have very simple hardware architecture and are able to work for a wide dynamic range of load impedance variation.

Embodiments of the subject invention provide a planar wireless power transfer system that is capable of charging portable devices as well as powering them at close proximity attaining 78% efficiency while delivering 68 W of power to an ideal load. A peak power of 132 W has been achieved using a planar wireless power transfer system according to an embodiment of the present invention. Another specific embodiment has achieved a peak power of 300W. Further, an embodiment can incorporate litz wire and achieve an efficiency of about 80%. Current existing products have not been able to achieve this level of efficiency and power output. The power capability with high efficiency makes the wireless power transmission system of the present invention suitable for charging laptop computers wirelessly.

According to an embodiment of the present invention, as illustrated in Figure 1, the transmitter is designed in a hybrid class-E parallel amplifier topology.

The class E amplifier design equations provide:

$$P = 0.576801\left(\frac{V_{CC}^{2}}{R}\right)\left(1.001245 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^{2}}\right)$$

$$R = 0.576801\left(\frac{V_{CC}^{2}}{P}\right)\left(1.001245 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^{2}}\right)$$

$$C1 = \frac{1}{34.2219 fR}\left(0.99866 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^{2}}\right) + \frac{0.6}{(2\pi f)^2 L1}$$

$$C2 = \frac{1}{2\pi fR}\left(\frac{1}{Q_L - 0.104823}\right)\left(1.00121 + \frac{1.01468}{Q_L - 1.7879}\right) + \frac{0.2}{(2\pi f)^2 L1}$$

$$L2 = \frac{Q_L R}{2\pi f}$$

$$Q_L = \frac{2\pi f L2}{R},$$

where P is the power delivered to the load of resistance R, R is the load resistance (related to the transmitting coil and shunt capacitor), V_{CC} is the supply voltage, Q_L is the load quality factor, and f is the operating frequency.

Assuming that the amplifier is ideal,

$$P = V_{CC} \times I_{DD}$$

$$PeakV_{DS} = \frac{3.56 \times V_{CC}}{SF}$$

$$PeakI_{DS} = \frac{2.86 \times I_{DD}}{SF}$$

$$\frac{t_{f/r}}{T} = \frac{\sqrt{12\left(\frac{P_{Dissipiation\ of\ f}}{P}\right)}}{2\pi\left(1 + \frac{0.82}{Q_L}\right)},$$

where I_{DD} is the supply current, V_{CC} is the supply voltage, Q_L is the load quality factor, SF is the safety factor for the off nominal load condition range (typical value 0.75), $\frac{P_{Dissipiation\ of\ f}}{P}$ is the fraction of turn off power dissipation (typically < 1%), T is the period of the operating frequency, $PeakV_{DS}$ is the peak drain to source voltage (the rating of the transistor), $PeakI_{DS}$ is the peak drain to source current (the rating of the transistor), and $t_{f/r}$ is the fall time and rise time of the transistor (typically of similar value or order of magnitude).

Depending on the requirements, the transmitter can be designed for various maximum power output. In addition, by varying the supply voltage, the transmitter can tune its instantaneous power output to maintain its high efficiency while powering smaller devices such as PDA or cellular phone.

In a further embodiment of the present invention, the transistor block and low Q network of the power transfer system can be modified to achieve higher power output. In particular, the transistor block and low Q network can be provided as a scalable transistor block, tunable supply voltage block, and coil block, where the scalable transistor block ›ck and C1 and L2 from the low Q load network, the tunable supply voltage block incorporates the DC supply and L1 from the low Q load network, and the coil block incorporates C2 from the low Q load network, the coil shunt capacitor, and the transmitting coil. Although the coil block is described as including the capacitor C2 from the low Q load network, the capacitor C2 can be considered part of the load network. The transmitting coil block, not including a receiver coil for a device under charge, can be viewed as part of the load network of the transmitter.

According to embodiments of the present invention, the power supplied from the transmitter can be increased by increasing the number of scalable transistor blocks while lower cost can be achieved by decreasing the number of scalable transistor blocks. Advantageously, a single tunable supply voltage block and coil block can be used for multiple scalable transistor blocks. For example, 2-5 scalable transistor blocks can be used, sharing the load current, with a single tunable supply voltage, load network capacitor (C2), transmitting coil and coil shunt capacitor.

Figure 3 shows a schematic of a transmitter with three scalable transistor blocks according to an embodiment of the present invention. Each scalable transistor block includes a transistor, a load capacitor C1, and a load inductor L1. The transistor can be a NMOSFET. In one embodiment the NMOSFET can be an active device IRFP264NPbF. The load capacitor C1 can have a value of, for example, 3.3 nF, and the load inductor can have a value of, for example, 100 μH. A single variable DC supply can be used for tunable output power. The tunable supply voltage block includes the DC supply and an inductor for each scalable transistor block acting as an RF choke. The inductor acting as an RF choke can have a value of, for example, 500 μH.

A single coil block is connected to the three scalable transistor blocks. The coil block includes a transmitting coil, a coil shunt capacitor, and a load network capacitor C2. The load network capacitor C2 and the coils shunt capacitor can each have a value of, for example, 100 nF. In the embodiment shown in Figure 3, a buffer and input clock oscillator can be included as input to the scalable transistor blocks.

Although each scalable transistor block illustrated in Figure 3 is indicated as having an RF choke inductor, embodiments of the present invention are not limited thereto. For example, a single RF choke inductor can be shared by the scalable transistor blocks to reduce cost.

As indicated by Figure 3, the DC supply can provide tunable output power. The can be affected by the voltage of the DC supply voltage. Figure 4 shows a power delivery and efficiency plot of a two scalable block transmitter at 24 V, 36 V and 48 V supply voltage. In particular, in Figure 4, the lower curve shows the 48V supply voltage results, the middle curve shows the 36V supply voltage results, and the upper left curve shows the 24V supply voltage results. As illustrated by the plots of Figure 4, an efficiency of about 78% is possible over a range of supply voltage. Figure 5 shows a power delivery and efficiency plot of a two scalable block transmitter according to an embodiment of the present invention with tunable power control. As illustrated by the plot shown in Figure 5, a high efficiency is possible over a large range of power.

This system has simple hardware architecture and each scalable block is a duplicate of each other that maintains the architecture of the transmitter. In addition, the power control enables high efficiency across a wide band power level. Therefore, it is able to achieve low cost for future custom design to meet various needs. Embodiments can also incorporate blocks that have different parameters, and that can be utilized together in various combinations. In this way, power delivery can be unevenly distributed.

Further embodiments of the present invention can include adaptive power supply tuning. The adaptive power supply tuning can be performed on a modified switching-mode amplifier with low-Q output network. According to one embodiment of the present invention, the power supply voltage of a wireless transmitter is tuned based on the feedback from a receiver load, which is the device under charge, to optimize the efficiency. Referring back to Figures 1 and 3, since the power supply (labeled as DC supply) has a direct path to the transmitting coil via the switching mode amplifier, the input impedance of the transmitter seen by the power supply is related to the impedance of the transmitting coil. The impedance of the transmitting coil is related to the coupling coefficient of the coils as well as the receiver load impedance. The receiver load impedance varies with the input voltage to the receiver load's voltage regulator. By adjusting the load impedance, by tuning the power supply voltage, the load impedance seen by the transmitter can be closer to an optimal value. Accordingly, varying the DC supply in the embodiments shown in Figures 1 and 3, the voltage at the input of the receiver's voltage regulator will change, so as to change the impedance looking into the input port of the voltage regulator. According to embodiments of the present invention incorporating an adaptive power supply, the tuning system measures the voltage and current delivered to the receiver load and attempts to tune its impedance via varying the power supply voltage. Therefore, by tuning the power supply voltage, power control as well as impedance tuning can be achieved. The adaptive tuning method can be implemented using a low cost microprocessor as well as a programmable switching regulator.

A block diagram of a planar wireless power transfer system using adaptive power supply tuning according to an embodiment of the present invention is shown in Figure 6A. Referring to Figure 6A, a wireless charger according to any embodiment of the present invention can be connected to an adaptive power control circuit. The adaptive power control circuit can include a programmable regulator and feedback network to set programmable regulator output voltage; a voltage monitor network and current monitor network that each receive the output voltage as input; and a microprocessor that receives input from the current monitor network and the voltage monitor network, and provides feedback to the feedback network. The microprocessor can also receive charging data from a device under charge. Examples of charging data that can be provided from the device under charge includes, but is not limited to, charge status, voltage provided to receiver, and/or current into the receiver. The device under charge can provide receiver charging data to a wireless transmitter. In other embodiments, other types of data links than wireless can be used. The charging data can then be received by a receiver of the adaptive power supply tuning circuit and provided to the microprocessor. The current monitor network can provide the power supply to the wireless charger. As examples, the output of the current monitor network in Figure 6A can be the DC supply of Figure 1 or the DC supply variable of Figure 3.

In an embodiment, tuning of the transmitter can be accomplished using voltage and current monitoring. For example, as illustrated in Figure 6B, the voltage across the drain of the transistor and the voltage and current across the transmitting coil can be monitored. These monitored values can be used as input in a feedback system for tuning control. In another specific embodiment, the supply DC current and the voltage across the transmitting coil can be monitored and provided for tuning of the power supply, such as a DC power supply. The power supply can then be tuned by, for example, inputting the monitored data into a lookup table created based on a determination of desired efficiency and the output of the power supply tuned accordingly.

Figures 7A and 7B show measurement results for the embodiment of Figure 6A with different loads. Referring to Figure 7A, it is possible to maintain efficiency at over 75% in all conditions. Figure 7B shows power supply voltage vs. power delivered to the load. Power supply voltage is tuned to achieve high efficiency at each load condition.

As a comparison, Figure 8 shows the efficiency at different power levels when no adaptive power supply tuning is included. Here the power supply voltage is fixed at 48 V.

Previous planar wireless power transfer systems tend to suffer low efficiency at low output power, even though the efficiency at higher output power is higher. In contrast, embodiments of the present invention are capable of maintaining a high efficiency of over 75% across a wide range of output power levels. Current existing products cannot achieve this level of efficiency and power output. The adaptive power supply tuning according to embodiments of the present invention enables high efficiency across a wide range of output power levels. Therefore, embodiments of the present invention are able to achieve low cost for future custom designs to meet various needs.

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

What is claimed is:

1. A wireless power transfer system, comprising:

a transistor, wherein the transistor has an on state and an off state;

an output network, wherein the output network is low Q; and

a transmitting coil block, wherein the transmitting coil block is coupled to the output network, wherein the transmitting coil block comprises a transmitting coil,

wherein when the transistor is in the on state the transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the transistor is in the on state the transistor has a low voltage and high current across the transistor, wherein when the transistor is in the off state the transistor has a low current and high voltage across the transistor.

2. The system according to claim 1, wherein Q is less than 20.

3. The system according to claim 1, wherein Q is less than 10.

4. The system according to claim 1, wherein Q is less than 8.

5. The system according to claim 1, wherein Q is in the range of 10-20.

6. The system according to claim 1, wherein Q is in the range of 1.8-5.

7. The system according to claim 1, wherein Q is in the range of 2-4.

8. The system according to claim 1, further comprising:

a receiver coil, wherein the receiving coil is inductively coupled to the transmitting coil, wherein the receiver coil is capable of delivering power to a load.

9. The system according to claim 1, further comprising: a first choke inductor coupled between the drain of the transistor and a power supply, wherein the output network comprises:

a first load network capacitor coupled between a drain of the transistor and ground;

a first load network inductor, wherein the first load inductor is in series between the drain of the transistor and the transmitting coil block.

10. The system according to claim 9, wherein the power supply is a DC power supply.

11. The system according to claim 9, wherein the transmitting coil block comprises a series capacitor in series with the transmitting coil.

12. The system according to claim 11, wherein the transmitting block comprises a shunt capacitor in parallel with the transmitting coil.

13. The system according to claim 9, wherein the output network comprises a series capacitor in series with the first load network inductor.

14. The system according to claim 10, wherein the DC power supply is a variable DC supply.

15. The system according to claim 14, further comprising a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning of the variable DC supply.

16. The system according to claim 9, wherein the output network further comprises:

a second transistor, wherein the second transistor has a second on state and a second off state;

a second load network capacitor coupled between a drain of the second transistor and ground; and a second load network inductor, wherein the second load network inductor is in series between the drain of the second transistor and the transmitting coil block

wherein when the second transistor is in the second on state the second transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the second transistor is in the second on state the second transistor has a low voltage and high current across the second transistor, wherein when the second transistor is in the second off state the second transistor has a low current and high voltage across the second transistor.

17. The system according to claim 16, further comprising:

a second choke inductor coupled between the drain of the second transistor and the DC supply.

18. The system according to claim 9, wherein the output network further comprises:

at least one additional transistor, wherein the at least one additional transistor has an at least one additional on state and an at least one additional off state;

at least one additional load network capacitor coupled between a drain of a corresponding at least one additional transistor and ground; and

at least one additional load network inductor, wherein the at least one additional load network is in a series between the drain of the at least one additional transistor and the transmitting coil block,

wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor has a low voltage and high current across the at least one additional transistor, wherein when the at least one additional transistor is in the at least one additional off state, the at least one additional transistor has a low current and high voltage across the at least one additional transistor.

19. The system according to claim 18, further comprising:

at least one additional choke inductor coupled between the drain of the corresponding at least one additional transistor and the DC supply.

20. The system according to claim 1, wherein the transmitting coil block further comprises:

a coil shunt capacitor coupled in parallel with the transmitting coil.

21. The system according to claim 1, further comprising a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning.

22. The system according to claim 1, further comprising a tuning circuit capable of receiving voltage and current data from across the transmitting coil and voltage data from across the transistor as input for adaptive power supply tuning.

23. The system according to claim 9, further comprising a tuning circuit capable of receiving output current of the power supply and voltage across the transmitting coil for adaptive supply tuning.

24. The system according to claim 1, further comprising:

a driving source coupled to a gate of the transistor.

25. The system according to claim 24, wherein the driving source is an ac power source.

26. A method for wireless power transfer, comprising:

providing a transistor, wherein the transistor has an on state and an off state;

providing an output network, wherein the output network is low Q;

providing a transmitting coil block, wherein the transmitting coil block is coupled to the output network, wherein the transmitting coil block comprises a transmitting coil; and

driving a gate of the transistor with a driving source, wherein when the transistor is in the on state the transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the transistor is in the on state the transistor has a low voltage and high current across the transistor, wherein when the transistor is in the off state the transistor has a low current and high voltage across the transistor.

27. The method according to claim 26, wherein Q is less than 20.

28. The method according to claim 26, wherein Q is less than 10.

29. The method according to claim 26, wherein Q is less than 8.

30. The method according to claim 26, wherein Q is in the range of 10-20.

31. The method according to claim 26, wherein Q is in the range of 1.8-5.

32. The method according to claim 26, wherein Q is in the range of 2-4.

33. The method according to claim 26, further comprising:

providing a receiver coil, wherein the receiving coil is inductively coupled to the transmitting coil, wherein the receiver coil is capable of delivering power to a load.

34. The method according to claim 26, further comprising: providing a first choke inductor coupled between the drain of the transistor and a power supply, wherein the output network comprises:

a first load network capacitor coupled between a drain of the transistor and ground;

a first load network inductor, wherein the first load inductor is in series between the drain of the transistor and the transmitting coil block.

35. The method according to claim 34, wherein the power supply is a DC power supply.

36. The method according to claim 34, wherein the transmitting coil block comprises a series capacitor in series with the transmitting coil.

37. The method according to claim 36, wherein the transmitting block comprises a shunt capacitor in parallel with the transmitting coil.

38. The method according to claim 34, wherein the output network comprises a series capacitor in series with the first load network inductor.

39. The method according to claim 35, wherein the DC power supply is a variable DC supply.

40. The method according to claim 39, further comprising providing a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning of the variable DC supply; and

tuning the variable DC supply base on the received charging data.

41. The method according to claim 34, wherein the output network further comprises:

providing a second transistor, wherein the second transistor has a second on state and a second off state;

providing a second load network capacitor coupled between a drain of the second transistor and ground;

providing a second load network inductor, wherein the second load network inductor is in series between the drain of the second transistor and the transmitting coil block; and

driving a second gate of the second transistor with the driving source,

wherein when the second transistor is in the second on state the second transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the second transistor is in the second on state the second transistor has a low voltage and high current across the second transistor, wherein when the second transistor is in the second off state the second transistor has a low current and high voltage across the second transistor.

42. The method according to claim 41, further comprising:

providing a second choke inductor coupled between the drain of the second transistor and the DC supply.

43. The method according to claim 34, wherein the output network further comprises:

providing at least one additional transistor, wherein the at least one additional transistor has an at least one additional on state and an at least one additional off state;

providing at least one additional load network capacitor coupled between a drain of a corresponding at least one additional transistor and ground;

providing at least one additional load network inductor, wherein the at least one additional load network is in a series between the drain of the at least one additional transistor and the transmitting coil block; and

driving the at least one additional gate of the at least one additional transistor with the driving source,

wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor has a low voltage and high current across the at least one additional transistor, wherein when the at least one additional transistor is in the at least one additional off state, the at least one additional transistor has a low current and high voltage across the at least one additional transistor.

44. The method according to claim 43, further comprising:

providing at least one additional choke inductor coupled between the drain of the corresponding at least one additional transistor and the DC supply.

45. The method according to claim 26, wherein the transmitting coil block further comprises:

a coil shunt capacitor coupled in parallel with the transmitting coil.

46. The method according to claim 26, further comprising providing a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning; and

tuning the power supply based on the received charging data.

47. The method according to claim 26, further comprising providing a tuning circuit capable of receiving voltage and current data from across the transmitting coil and voltage data from across the transistor as input for adaptive power supply tuning; and

tuning the power supply based on the voltage and current data from across the transmitting coil and voltage data from across the transistor.

48. The method according to claim 34, further comprising providing a tuning circuit capable of receiving output current of the power supply and voltage across the transmitting coil for adaptive supply tuning; and

tuning the power supply based on the output current of the power supply and voltage across the transmitting coil.

49. The method according to claim 26, wherein the driving source is an ac power source.

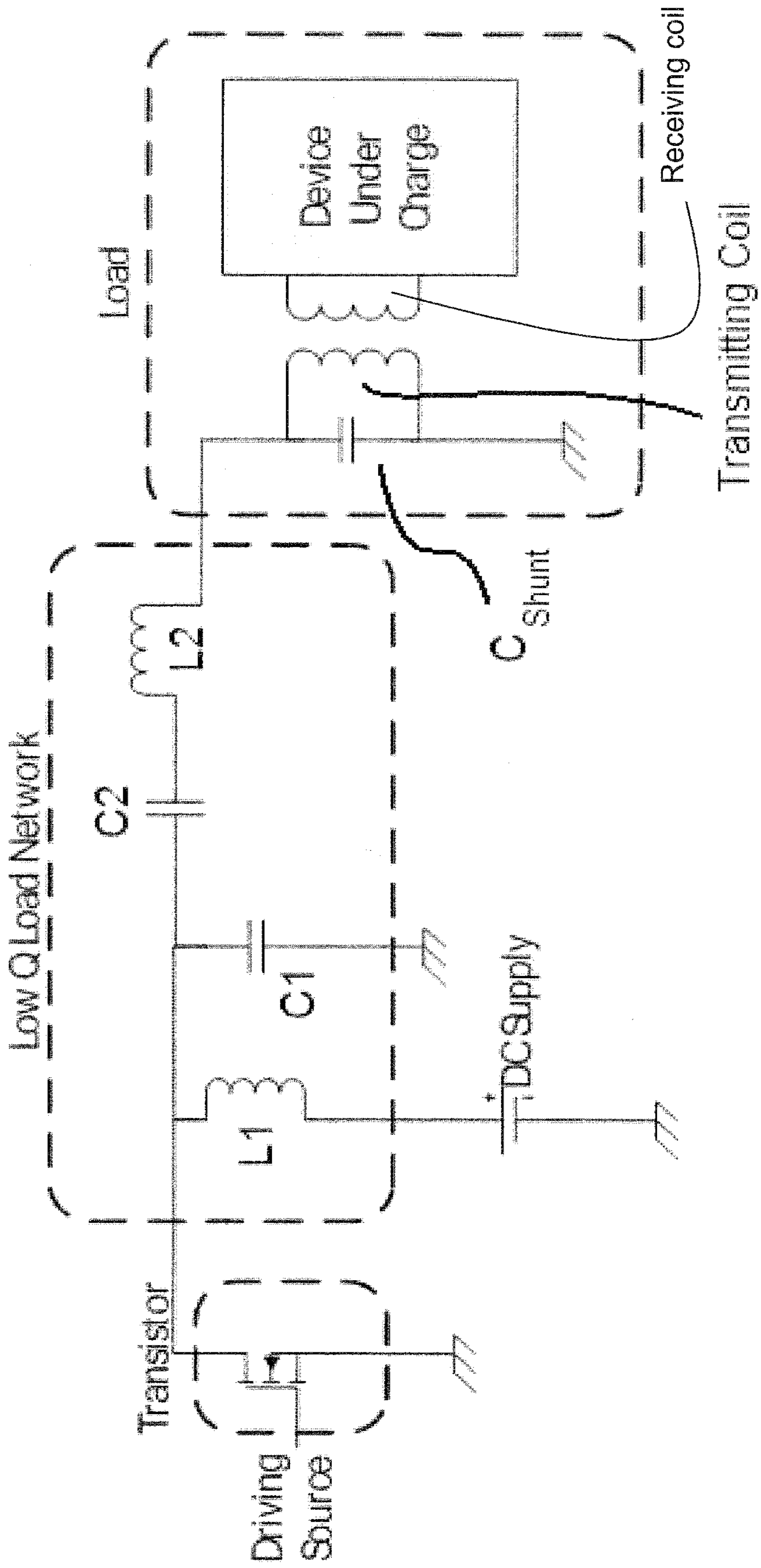
Load
Device Under Charge
Receiving coil
Transmitting Coil
C Shunt
Low Q Load Network
C2
L2
C1
L1
DC Supply
Transistor
Driving Source

FIG. 1

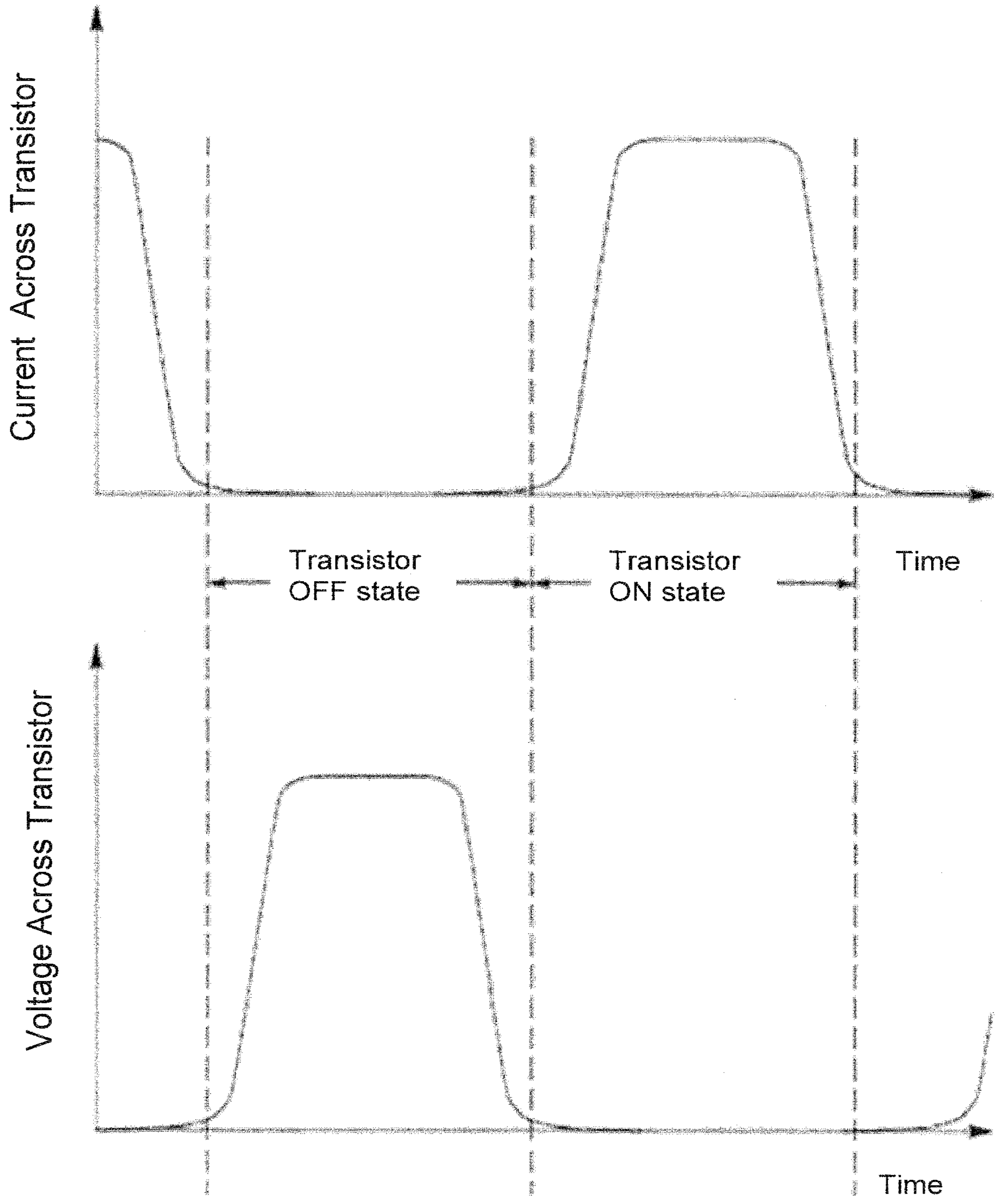
Current Across Transistor
Transistor
OFF state
Transistor
ON state
Time
Voltage Across Transistor
Time

FIG. 2

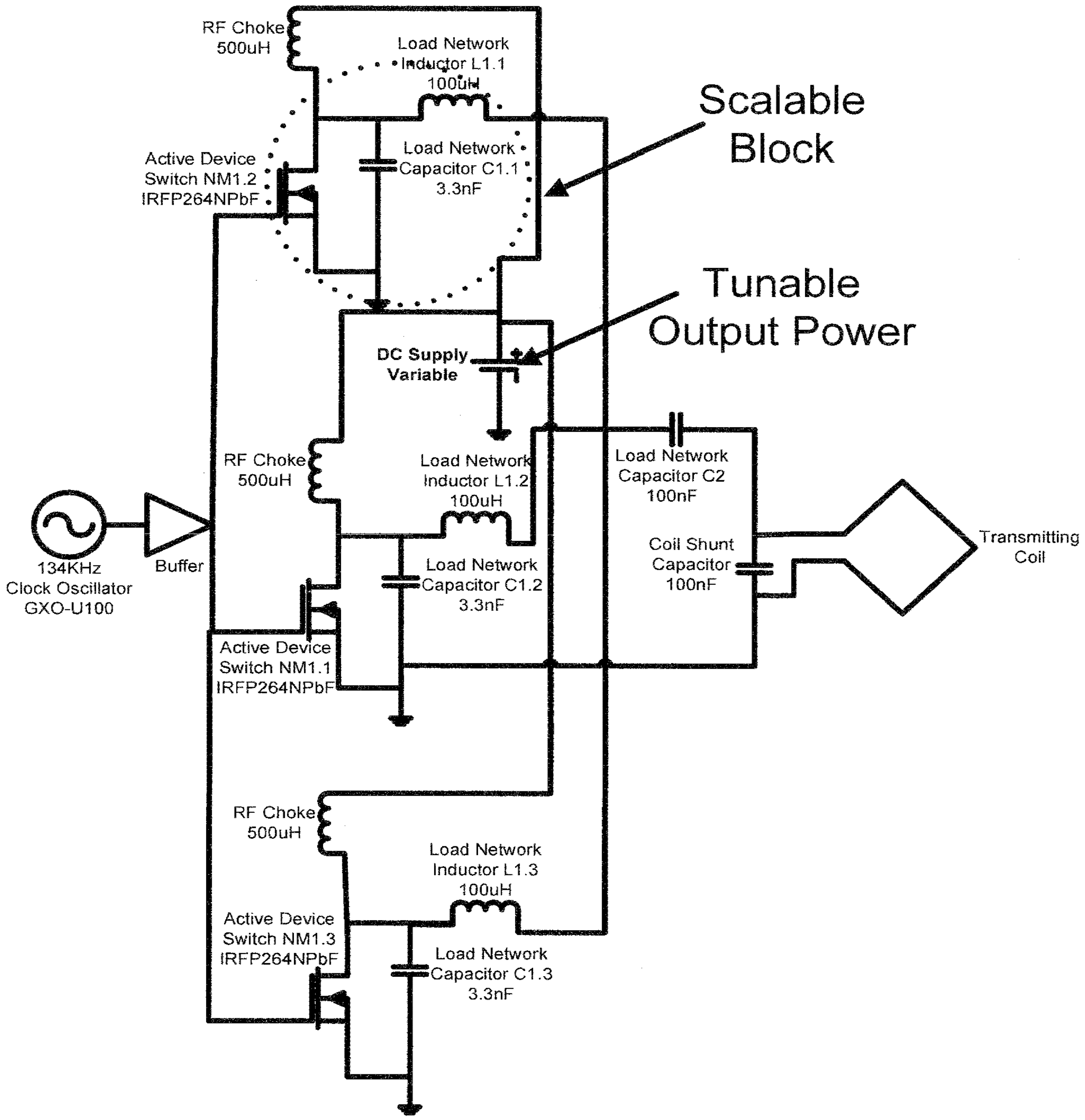
RF Choke
500uH
Load Network
Inductor L1.1
100uH
Scalable
Block
Active Device
Switch NM1.2
IRFP264NPbF
Load Network
Capacitor C1.1
3.3nF
Tunable
Output Power
DC Supply
Variable
RF Choke
500uH
Load Network
Inductor L1.2
100uH
Load Network
Capacitor C2
100nF
Coil Shunt
Capacitor
100nF
Transmitting
Coil
134KHz
Clock Oscillator
GXO-U100
Buffer
Load Network
Capacitor C1.2
3.3nF
Active Device
Switch NM1.1
IRFP264NPbF
RF Choke
500uH
Load Network
Inductor L1.3
100uH
Active Device
Switch NM1.3
IRFP264NPbF
Load Network
Capacitor C1.3
3.3nF

FIG. 3

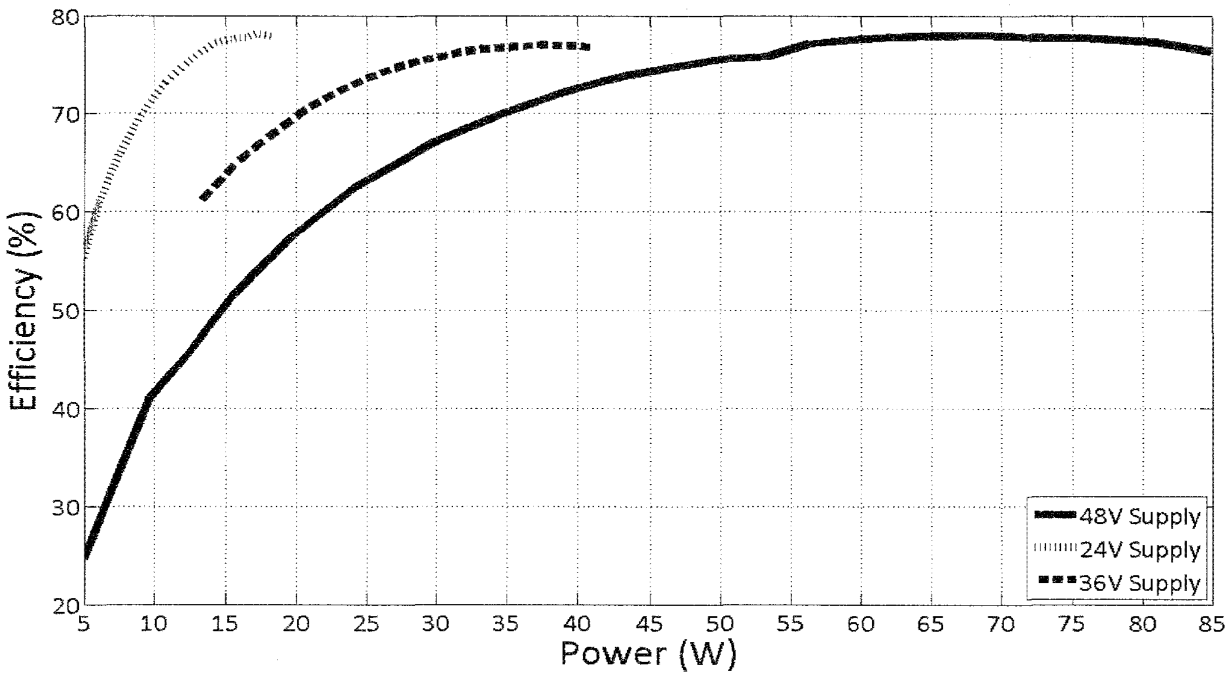
80
70
60
50
40
30
20
Efficiency (%)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Power (W)
48V Supply
24V Supply
36V Supply

FIG. 4

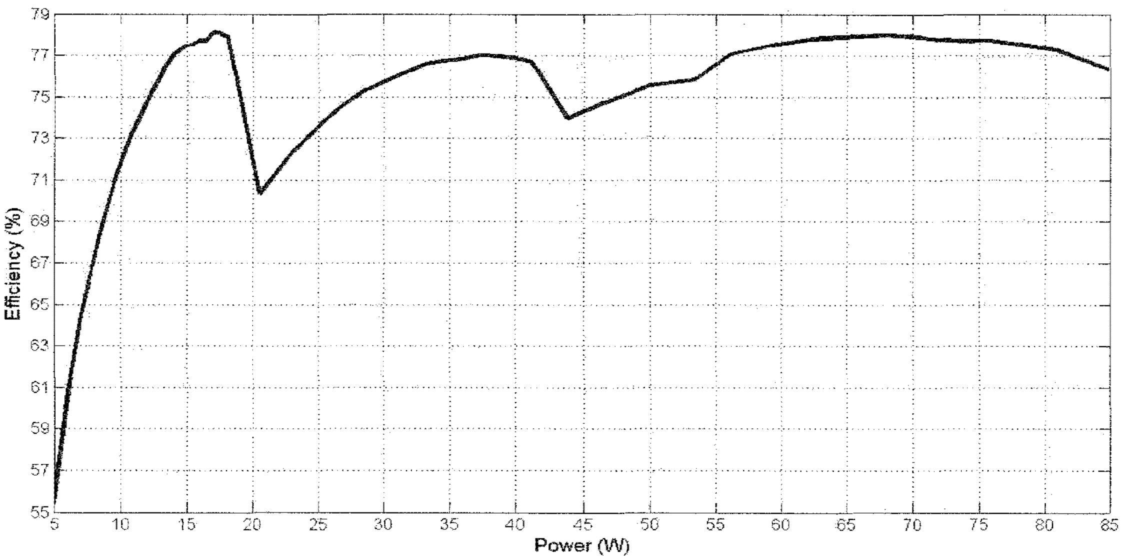
79
77
75
73
71
69
67
65
63
61
59
57
55
Efficiency (%)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Power (W)

FIG. 5

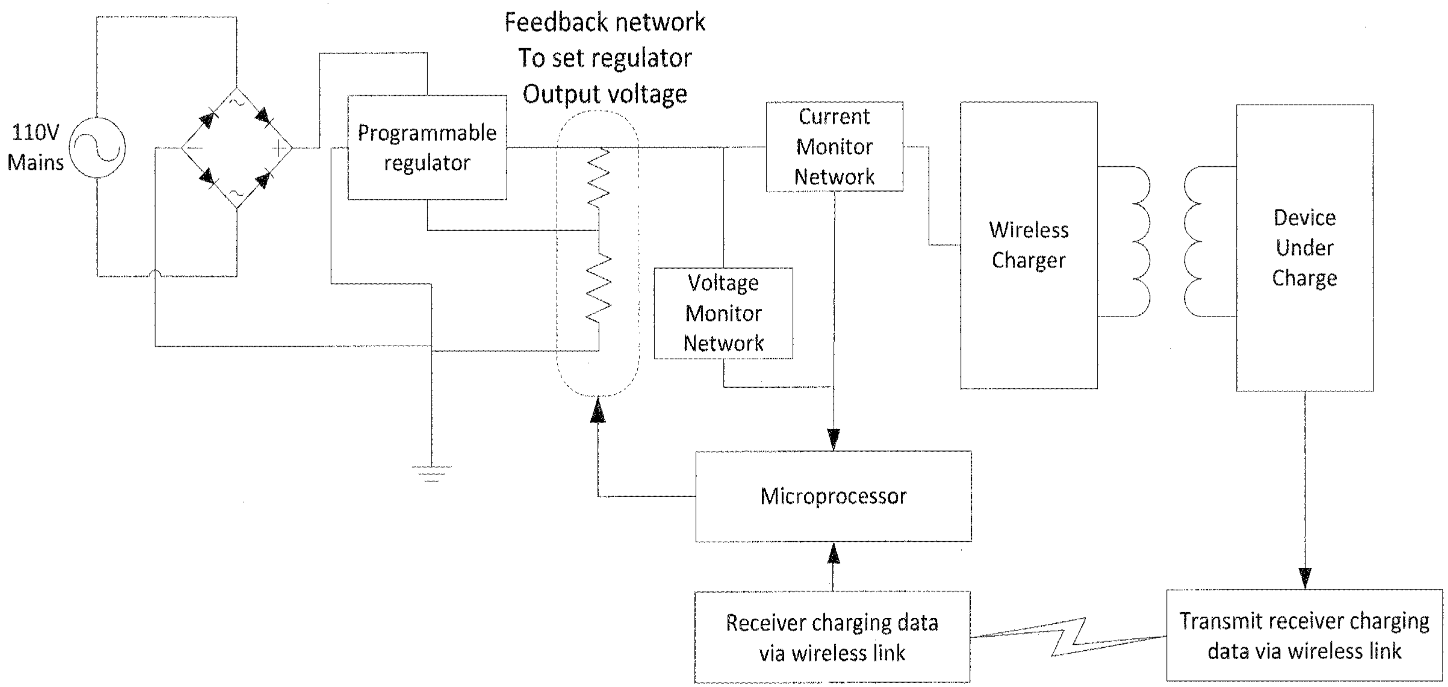
110V
Mains
Programmable
regulator
Feedback network
To set regulator
Output voltage
Current
Monitor
Network
Voltage
Monitor
Network
Wireless
Charger
Device
Under
Charge
Microprocessor
Receiver charging data
via wireless link
Transmit receiver charging
data via wireless link

FIG. 6A

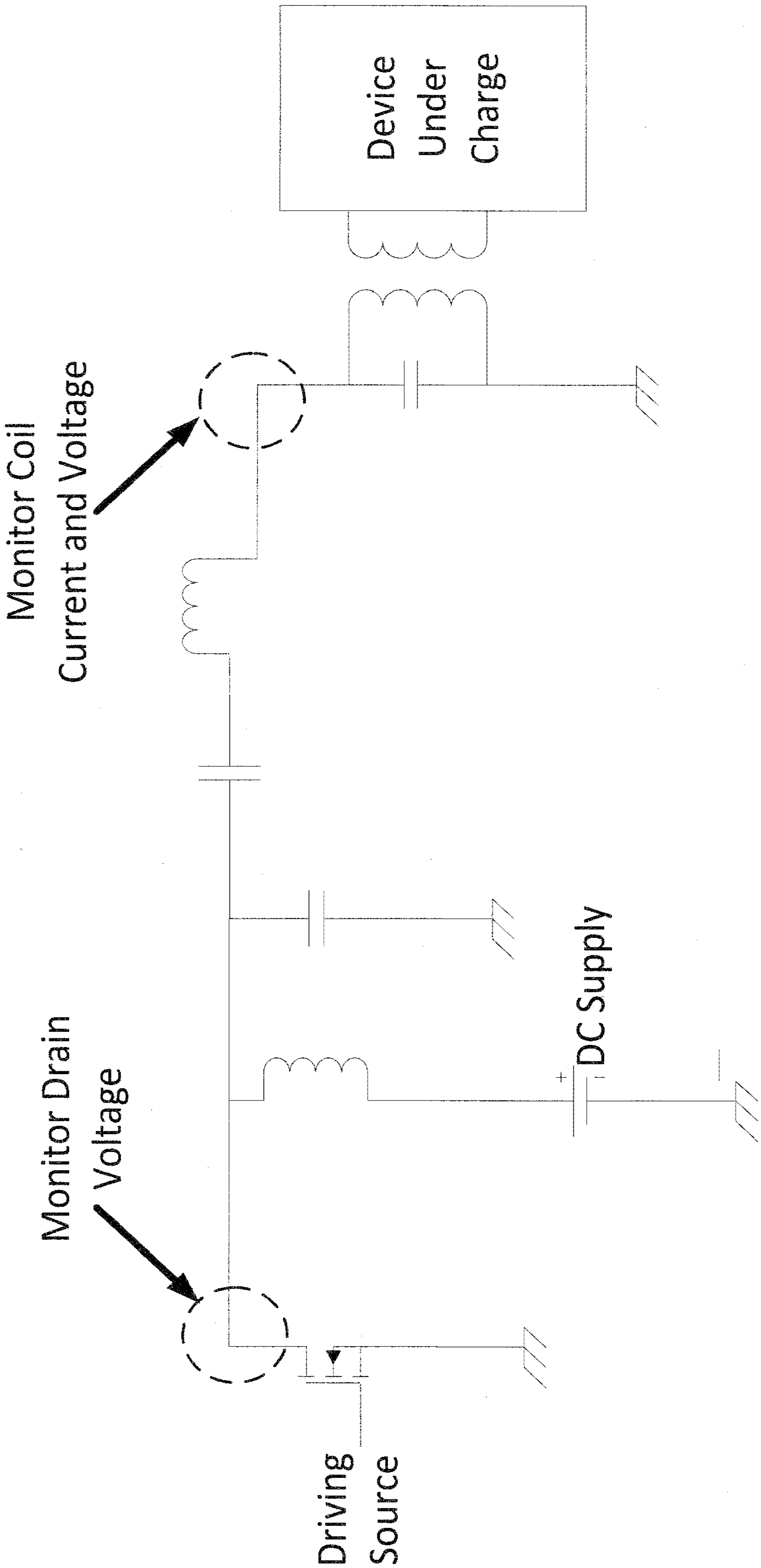
Device
Under
Charge
Monitor Coil
Current and Voltage
Monitor Drain
Voltage
DC Supply
Driving
Source

FIG. 6B

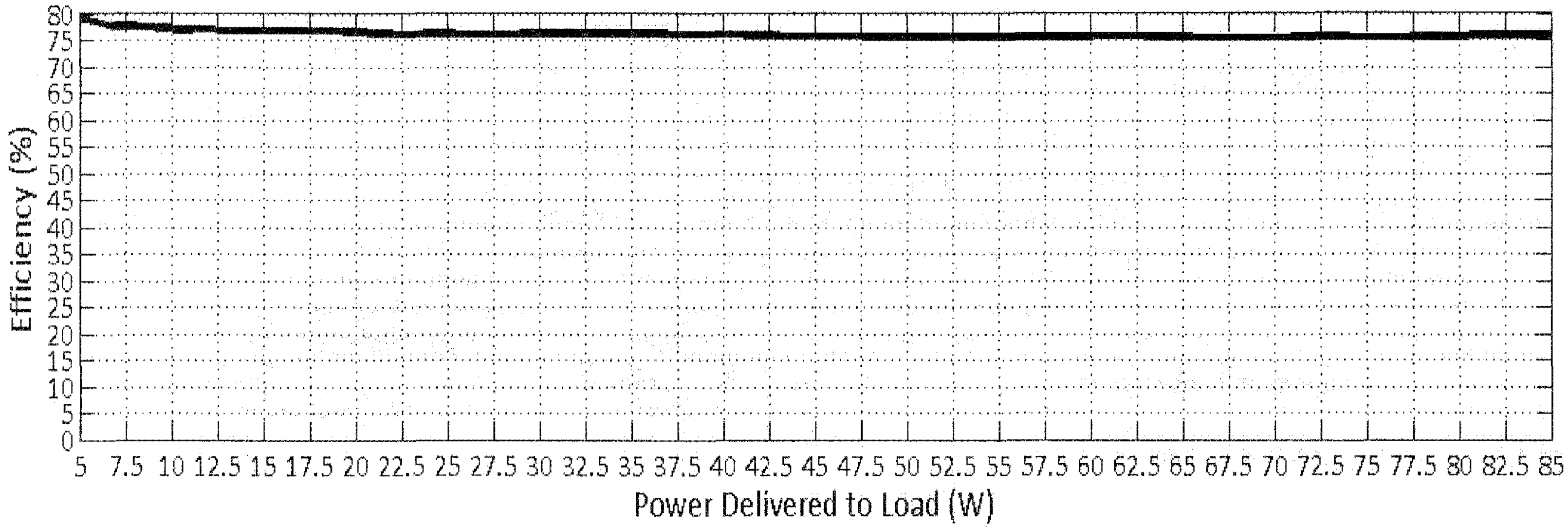
Efficiency (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
5 7.5 10 12.5 15 17.5 20 22.5 25 27.5 30 32.5 35 37.5 40 42.5 45 47.5 50 52.5 55 57.5 60 62.5 65 67.5 70 72.5 75 77.5 80 82.5 85
Power Delivered to Load (W)

FIG. 7A

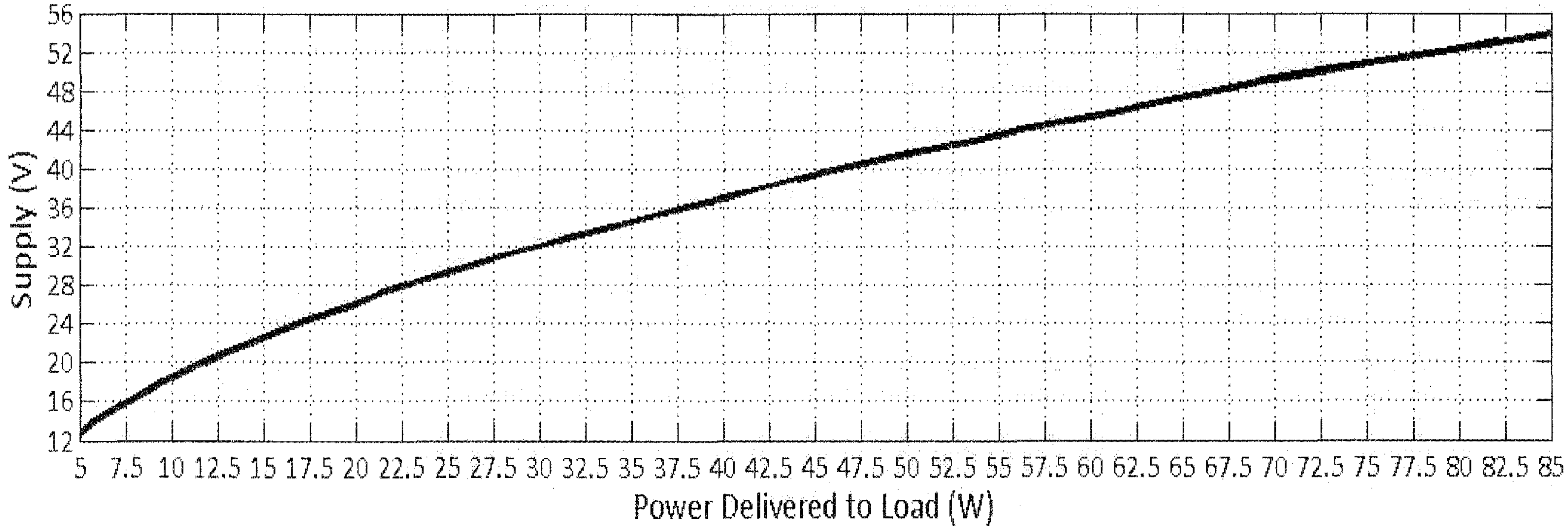
Supply (V)
56
52
48
44
40
36
32
28
24
20
16
12
5 7.5 10 12.5 15 17.5 20 22.5 25 27.5 30 32.5 35 37.5 40 42.5 45 47.5 50 52.5 55 57.5 60 62.5 65 67.5 70 72.5 75 77.5 80 82.5 85
Power Delivered to Load (W)

FIG. 7B

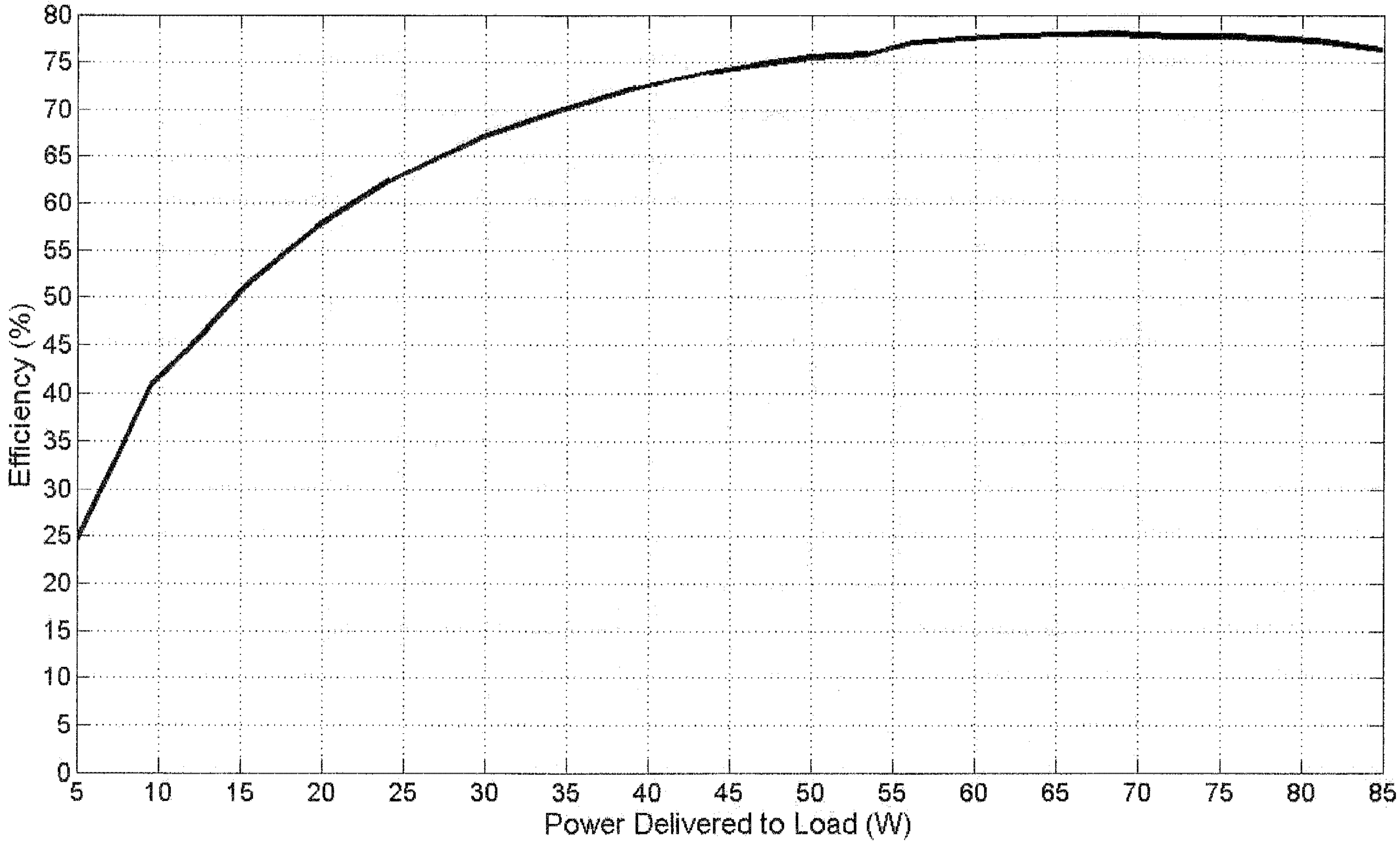
Efficiency (%)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Power Delivered to Load (W)
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85

FIG. 8

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(54) **Title**: POWER CONTROL DUTY CYCLE THROTTLING SCHEME FOR PLANAR WIRELESS POWER TRANSMISSION SYSTEM

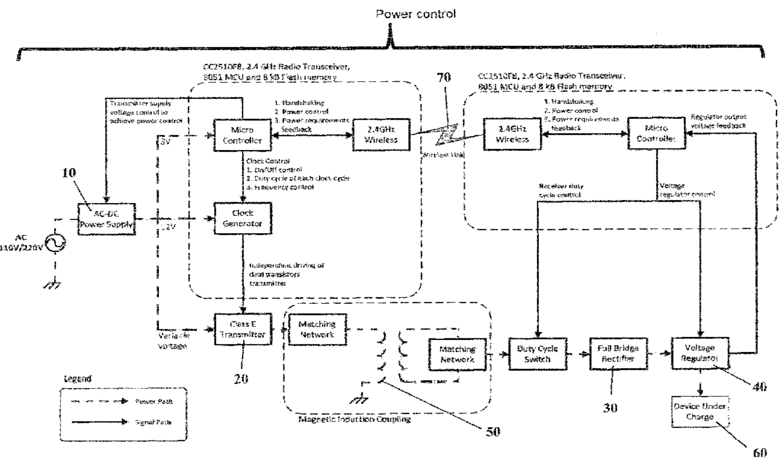

FIG. 1

(57) **Abstract**: Embodiments of a power transmission system and power control scheme are provided. The power control scheme utilizes the power requirements for each receiver of a device on a charging pad for highly efficient charging of multiple devices. According to an embodiment, each receiver transmits its power requirement to the transmitter, and based on this power requirement, the most power hungry device is used to set the duty cycle of the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. Once all the devices are fully charged, the transmitter can be powered off or have its duty cycle reduced to performance trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the charging pad.

WO 2009/126963 A2

DESCRIPTION

POWER CONTROL DUTY CYCLE THROTTLING SCHEME FOR PLANAR WIRELESS POWER TRANSMISSION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/044,327, filed April 11, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Wireless power transmission is an emerging technology as trends move toward completely wireless devices. Currently, power control can be achieved via changing the operating frequency of a transmitter, tuning the transmitter's matching network, and changing the transmitter's supply voltage. However, limited dynamic range can be attained by changing the operating frequency. It can be difficult and costly to find tunable components to operate at such high power level. In addition, system performance tends to degrade when the supply voltage deviates too far from it nominal operating voltage.

BRIEF SUMMARY

Embodiments of the present invention relate to a method and apparatus for power control in wireless power transmission. According to an embodiment, multiple receivers can be used with a single transmitter. In an embodiment, a low cost microprocessor can be used to perform timing control for the transmitter output. Embodiments of the present invention have a significantly wider power dynamic range than other competing solutions. In addition, it is possible to scale the timing control technique to charge a large number of devices concurrently, thus becoming more flexible.

In an embodiment, an intelligent power control technique is implemented that attends to the power requirement for the receiver of each device on a charging pad. According to an embodiment, each receiver transmits the power requirement of the receiver to the transmitter, and based on this power requirement, the most power hungry device is used to set the duty cycle of the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. Once all the devices are fully charged, the transmitter can be powered off or have its duty cycle reduced to perform trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the charging pad.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a system overview according to an embodiment of the present invention.

Figure 2 shows a duty cycling throttling scheme according to an embodiment of the present invention.

Figure 3 shows a timing scheme according to an embodiment of the present invention for three receivers of significantly different per-unit area power requirement (75W, 25W, 5W) placed on a 100W transmitting pad.

Figure 4 shows an optimum duty cycling throttling scheme according to an embodiment of the present invention.

DETAILED DISCLOSURE

Embodiments of the present invention provide a method and apparatus for power control in wireless power transmission. Embodiments of the subject invention can be utilized in a planar power transmission system that is capable of charging multiple portable devices as well as powering them at close proximity. Since different devices have different power requirements that can span across a large dynamic range, embodiments of the present invention provide an intelligent power control scheme that allows contemporaneous charging of multiple devices that may span across a large dynamic range. According to an embodiment, multiple receivers can be used with a single transmitter. Certain embodiments of the present invention can attain 81% efficiency while delivering 68W of power to an ideal load. A peak power of 132W has been achieved using a specific embodiment of the present invention. In a further embodiment, a peak power of 300W has been achieved.

Figure 1 illustrates a power transmission system according to an embodiment of the present invention that can utilize one or more power control schemes. The power-related systems of this example are shown, following a power path. Power control techniques according to embodiments of the present invention can be applied to the power-related systems. In the transmitter portion of the system, the amplifier supply voltage **10** and the duty cycle can be tuned. In a specific embodiment, a duty cycle of driving square pulses can be tuned. In addition, in a system where the class E transmitter portion **20** includes two transistors, one of the two transmitting transistors can be shut down to reduce power output.

In one embodiment, two independent clocks can be used to separately drive the two transistors, such that a power control scheme is capable of shutting down one transistor when the power requirement is low. Synchronization between the independent clocks can be provided.

In an embodiment of the power control scheme, the system duty cycle for the transmitter can be controlled. On the receiver end, the system duty cycle can also be controlled as part of a power scheme according to an embodiment of the present invention. In an embodiment, receivers from different devices can have different duty cycles. Receivers from different devices can communicate with each other and coordinate such that the receivers reduce the amount of the duty cycle where no receiver is receiving power and/or the more than one, or more than two, receivers are receiving power, so as to enhance the charging of the two or more devices.

In one embodiment, the system duty cycle of a receiver can be controlled using, for example, discrete rectifying diodes **30** with a voltage regulator **40**. For example, the voltage regulator part LM5574 for 500mA output current and part LM5576 for 3A output current can be used. In another example, voltage regulation can be performed by a microprocessor having an RF receiver such as the Chipcon CC2510F8.

Figure 2 shows a power control scheme according to an embodiment of the present invention. As shown in Figure 2, the transmitter (e.g., reference **20** of Figure 1) excites the coil (e.g., reference **50** of Figure 1) for a short period of time (X/Y seconds) to access a pad's load condition so as to determine if any device (e.g., reference **60** of Figure 1) is on or near the pad and to power down for X seconds if no load is detected. Values of X and Y are determined by the settling time of the system and the response time requirement once the receiver(s) is/are placed on the pad. In a specific embodiment, X can be about one second and X/Y can be from about 500 μsec to about 1 msec, so as to promptly start charging a device placed in appropriate position and avoid wasting power.

The load condition can be monitored, in order to determine when a device to be charged is put in an appropriate position by, for example, comparing one or more of the following with values that occur when no load is present: transmitter supply current, transmitter coil voltage, and transmitter coil current. The transmitter is also able to detect a device on the pad via a near field wireless communication link (e.g., reference **70** of Figure 1) if there is still charge left in the receiver's battery. However, if there is not sufficient charge left in the battery, the transmitter can power up at full 100% duty cycle to transmit power to the power depleted receiver(s). In another embodiment, the transmitter is powered up to at least 50% duty cycle. Upon receiving sufficient power to power the near field communication module, the receiver can then transmit its power requirement to the transmitter. Based on the power requirement of the receiver(s), the transmitter can then determine a duty cycle that is, for example, sufficient to power the most power hungry device without wasting extra energy. In specific embodiments, the selected duty cycle can optimize the efficiency of charging.

When there is a single device to be charged the transmitter can detect the presence of the device to be charged by detecting load conditions, and can then adjust the duty cycle of the transmitter appropriately. In embodiments having two or more devices to be charged the transmitter can detect the devices to be charged by detecting load conditions and then receiving communications from the receiver(s) of the device(s) to be charged as to the charging requirements. In a specific embodiment, the devices to be charged can communicate with each other as to what portions of the transmitters duty cycle to receive power.

The receiver can determine the transmitter duty cycle. In a specific embodiment, the receiver can determine the transmitter duty cycle via the envelope detect technique. In addition, clock synchronization can also be performed during the process of determining the transmitter duty cycle. Depending on the power requirement of the receiver, the receiver can transmit its requirement if insufficient power is being transmitted or perform further duty cycling on the transmitter duty cycled power transmission to obtain the required power level. In a specific embodiment, a device placed on charging pad is recognized by the transmitter as a change in load. If a battery is drained, then the near field communication module is powered-up using power from the transmitter.

Figure 3 shows a duty cycle scheme according to an embodiment of the present invention. In a specific embodiment, a duty cycle scheme for a 100 W per unit area transmitter is provided with examples of three receivers' per unit area power requirement of 75 W, 25 W and 5 W respectively. The shaded portions show when the transmitter is transmitting or when the receivers are receiving, while the dark line shows when the receivers are on. The transmitter is shown as having a 75% duty cycle, as turning the transmitter off for a portion of the cycle can be helpful. Other percentage duty cycles can also be used. Each receiver can determine its duty cycle and turn on charging in accordance with its power requirement. Other than the most power hungry device, which is reflected in the scheme shown by receiver 1 in Figure 3, all other receivers (receiver 2 and receiver 3 of Figure 3) can stop receiving power by disengaging the coil during the beginning of the next cycle of power transmission from the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. The scheme is capable of seamlessly letting any device receive power even if there are other devices under charge.

In another specific embodiment, the duty cycling scheme can be optimized as shown in Figure 4. The difference between the scheme illustrated by Figure 4 and the scheme illustrated by Figure 3 is the change in the window position of receiver 2. This change in window position can provide improved distribution of power transmission between lower power devices by reducing overlapping of receivers being on. However, synchronization between receivers can be important. If desired, the receivers can be turned off while the transmitter is off. In addition, the window of when the receivers are turned on can be moved to reduce the amount of overlapping of receiver charging in order to further improve charging efficiency.

Then, once all the devices are fully charged, which can be determined via feedback from the receiver(s), the transmitter can be powered off or its duty cycle can be reduced to performance trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the transmitting pad.

Through using a duty cycle scheme according to embodiments of the present invention, it is possible to provide a high efficiency and low cost wireless power charging platform that is capable of concurrent charging/powering of one or more portable devices such as mobile phones, mp3 players, and laptop computers. Embodiments of the present invention can be implemented, for example, at home, at airports, hotel rooms, or any public location. Accordingly, this would bring great convenience to general consumers, especially frequent travelers, as it would provide a universally charging interface and eliminate the need to carry multiple chargers. In addition, the user is able to charge all of his portable devices at the same time without significant impact on charge time.

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

What is claimed is:

1. A method for wireless power transmission, comprising:

(a) exciting a transmitter coil of a transmitter of a wireless power transmission system for X/Y seconds, wherein the transmitter coil transmits an RF magnetic field when the transmitter coil is excited;

(b) determining a load condition so as to determine if a device is positioned to be charged, wherein each device to be charged comprises a receiver coil inductively coupled to the transmitter coil when the device is positioned to be charged and a receiver for receiving a receiver current from the receiver coil, wherein if there is no device positioned to be charged, then after a delay of X seconds returning to (a);

(c) if there is a device positioned to be charged, then exciting the transmitter coil so as to transmit power to the device positioned to be charged.

2. The method according to claim 1, further comprising receiving at the transmitter a power requirement for the device positioned to be charged provided by the receiver of the device positioned to be charged.

3. The method according to claim 2, wherein when there are two or more devices positioned to be charged, receiving at the transmitter the power requirement for each device positioned to be charged provided by the receiver of each device positioned to be charged.

4. The method according to claim 2, wherein the receiver comprises a near field communication module for providing the power requirement, wherein when a battery of the device positioned to be charged is not sufficiently charged to power the near field communication module of the receiver to provide the power requirement the receiver of the device positioned to be charged provides the power requirement to the transmitter upon receiving sufficient power from the transmitter to power the near field communication module of the receiver.

5. The method according to claim 3, further comprising:
detecting at the receiver a transmitter duty cycle.

6. The method according to claim 5, wherein the transmitter duty cycle is detected by using an envelope detect technique.

7. The method according to claim 5, wherein each of the two or more devices positioned to be charged detects the transmitter duty cycle and charges according to the power requirement of the device.

8. The method according to claim 1, wherein X is less than or equal to 1 second.

9. The method according to claim 1, wherein X/Y is in the range of 500 μsec to 1 msec.

10. The method according to claim 1, further comprising adjusting a duty cycle of the transmitter based on the load condition.

11. The method according to claim 2, further comprising adjusting a duty cycle of the transmitter based on the power requirement provided by the receiver of the device positioned to be charged.

12. The method according to claim 1, wherein determining the load condition comprises determining a transmitter supply current.

13. The method according to claim 1, wherein determining the load condition comprises determining a transmitter coil voltage.

14. The method according to claim 1, wherein determining the load condition comprises determining a transmitter coil current.

15. A system for wireless power transmission, comprising:

a transmitter having a transmitter coil, wherein the transmitter coil transmits an RF magnetic field when the transmitter coil is excited;

a device having a receiver and a receiver coil, wherein the receiver coil is inductively coupled to the transmitter coil when the device is positioned to be charged, wherein the receiver receives a receiver current from the receiver coil;

a means for exciting the transmitter coil for X/Y seconds; and

a means determining a load condition after exciting the transmitter coil for X/Y seconds so as to determine if the device is positioned to be charged, wherein if the device is not positioned to be charged, then after a delay of X seconds initiating the means for exciting the transmitter coil for X/Y seconds, wherein if the device is positioned to be charged, then exciting the transmitter coil so as to transmit power to the device positioned to be charged.

16. The system according to claim 15, wherein the receiver further comprises a means for transmitting to the transmitter a power requirement for the device.

17. The system according to claim 16, wherein the system comprises two or more devices.

18. The system according to claim 16, wherein the means for transmitting to the transmitter the power requirement comprises a near field communication module for providing the power requirement, wherein when a battery of the device is not sufficiently charged to power the near field communication module to provide the power requirement the receiver of the device positioned to be charged provides the power requirement to the transmitter upon receiving sufficient power from the transmitter to power the near field communication module of the receiver.

19. The system according to claim 17, wherein at least one device further comprises:

a means for detecting a transmitter duty cycle.

20. The system according to claim 19, wherein the transmitter duty cycle is detected by using an envelope detect technique.

21. The system according to claim 19, wherein each of the two or more devices detect the transmitter duty cycle and charges according to the power requirement of the device.

22. The system according to claim 15, wherein X is less than or equal to 1 second.

23. The system according to claim 15, wherein X/Y is in the range of 500 μsec to 1 msec.

24. The system according to claim 15, wherein the transmitter further comprises a means for adjusting a duty cycle of the transmitter based on the load condition.

25. The system according to claim 16, wherein the transmitter further comprises a means for adjusting a duty cycle of the transmitter based on the power requirement provided by the receiver of the device.

26. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter supply current.

27. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter coil voltage.

28. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter coil current.

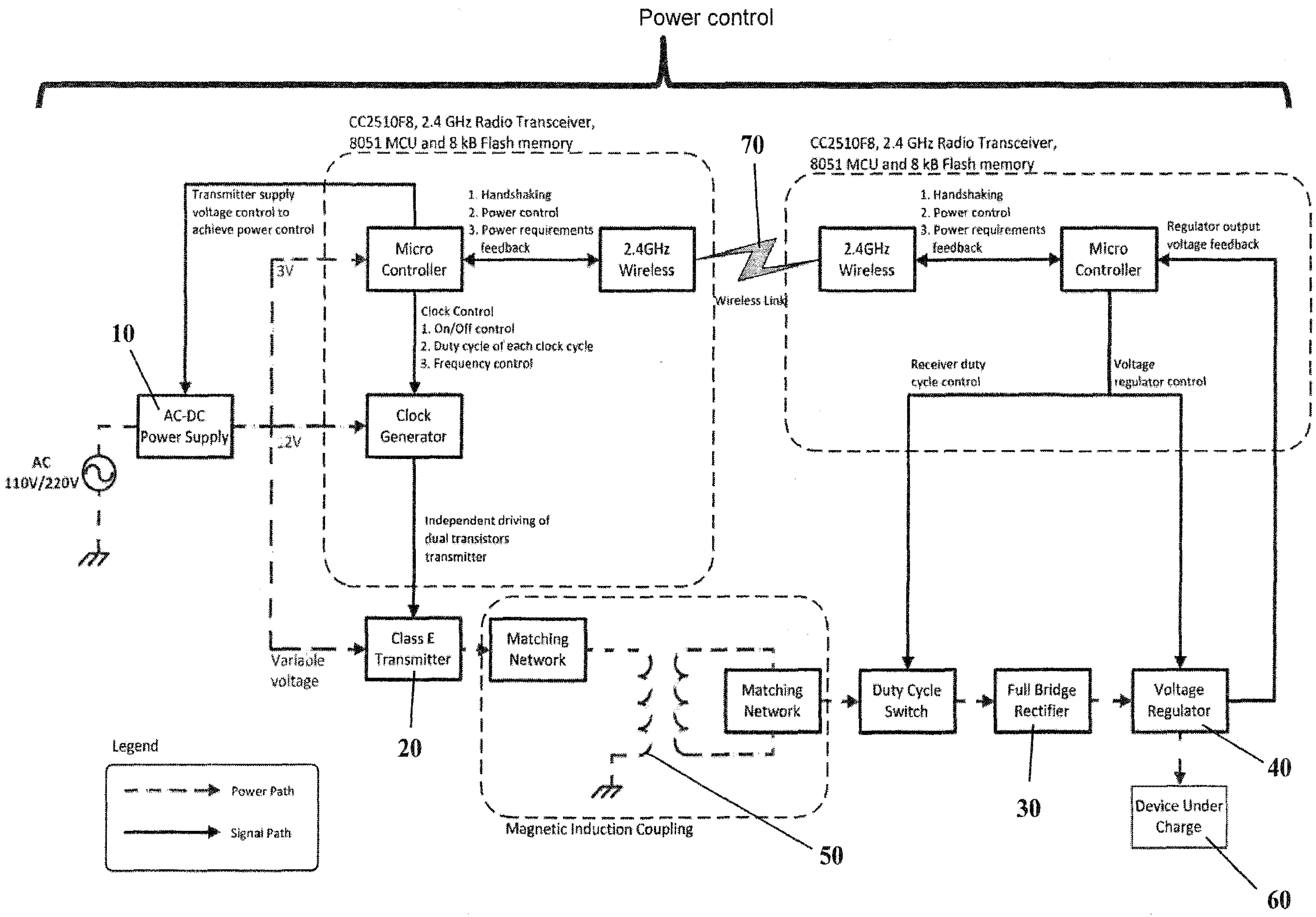
Power control
CC2510F8, 2.4 GHz Radio Transceiver, 8051 MCU and 8 kB Flash memory
70
CC2510F8, 2.4 GHz Radio Transceiver, 8051 MCU and 8 kB Flash memory
Transmitter supply voltage control to achieve power control
1. Handshaking
2. Power control
3. Power requirements feedback
Micro Controller
2.4GHz Wireless
2.4GHz Wireless
1. Handshaking
2. Power control
3. Power requirements feedback
Micro Controller
Regulator output voltage feedback
3V
Wireless Link
Clock Control
1. On/Off control
2. Duty cycle of each clock cycle
3. Frequency control
10
Receiver duty cycle control
Voltage regulator control
AC-DC Power Supply
Clock Generator
12V
AC 110V/220V
Independent driving of dual transistors transmitter
Class E Transmitter
Matching Network
Variable voltage
Matching Network
Duty Cycle Switch
Full Bridge Rectifier
Voltage Regulator
20
40
Legend
Power Path
Signal Path
30
Device Under Charge
Magnetic Induction Coupling
50
60

FIG. 1

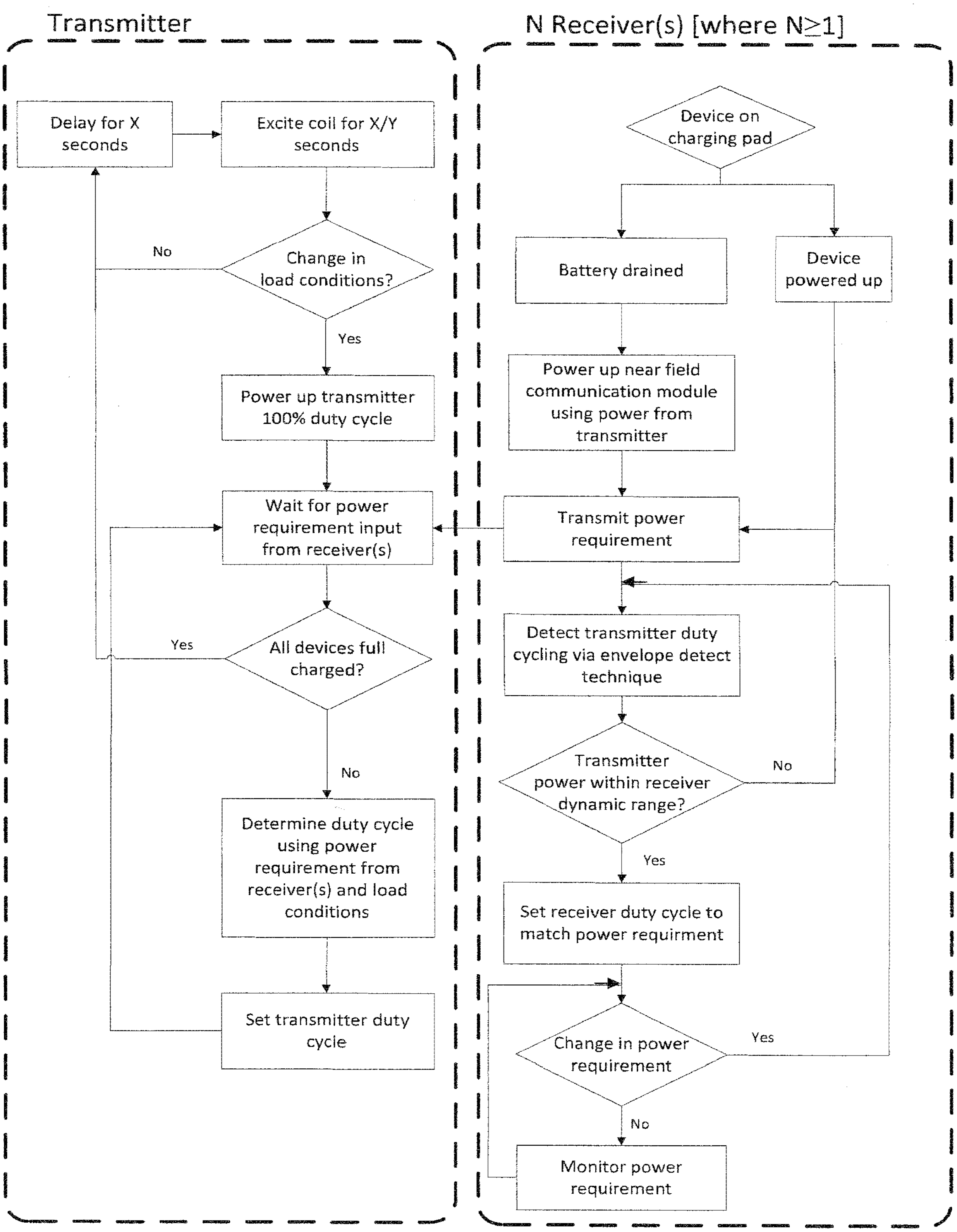
Transmitter
N Receiver(s) [where N≥1]
Delay for X seconds
Excite coil for X/Y seconds
Change in load conditions?
No
Yes
Power up transmitter 100% duty cycle
Wait for power requirement input from receiver(s)
All devices full charged?
Yes
No
Determine duty cycle using power requirement from receiver(s) and load conditions
Set transmitter duty cycle
Device on charging pad
Battery drained
Device powered up
Power up near field communication module using power from transmitter
Transmit power requirement
Detect transmitter duty cycling via envelope detect technique
Transmitter power within receiver dynamic range?
No
Yes
Set receiver duty cycle to match power requirment
Change in power requirement
Yes
No
Monitor power requirement

FIG. 2

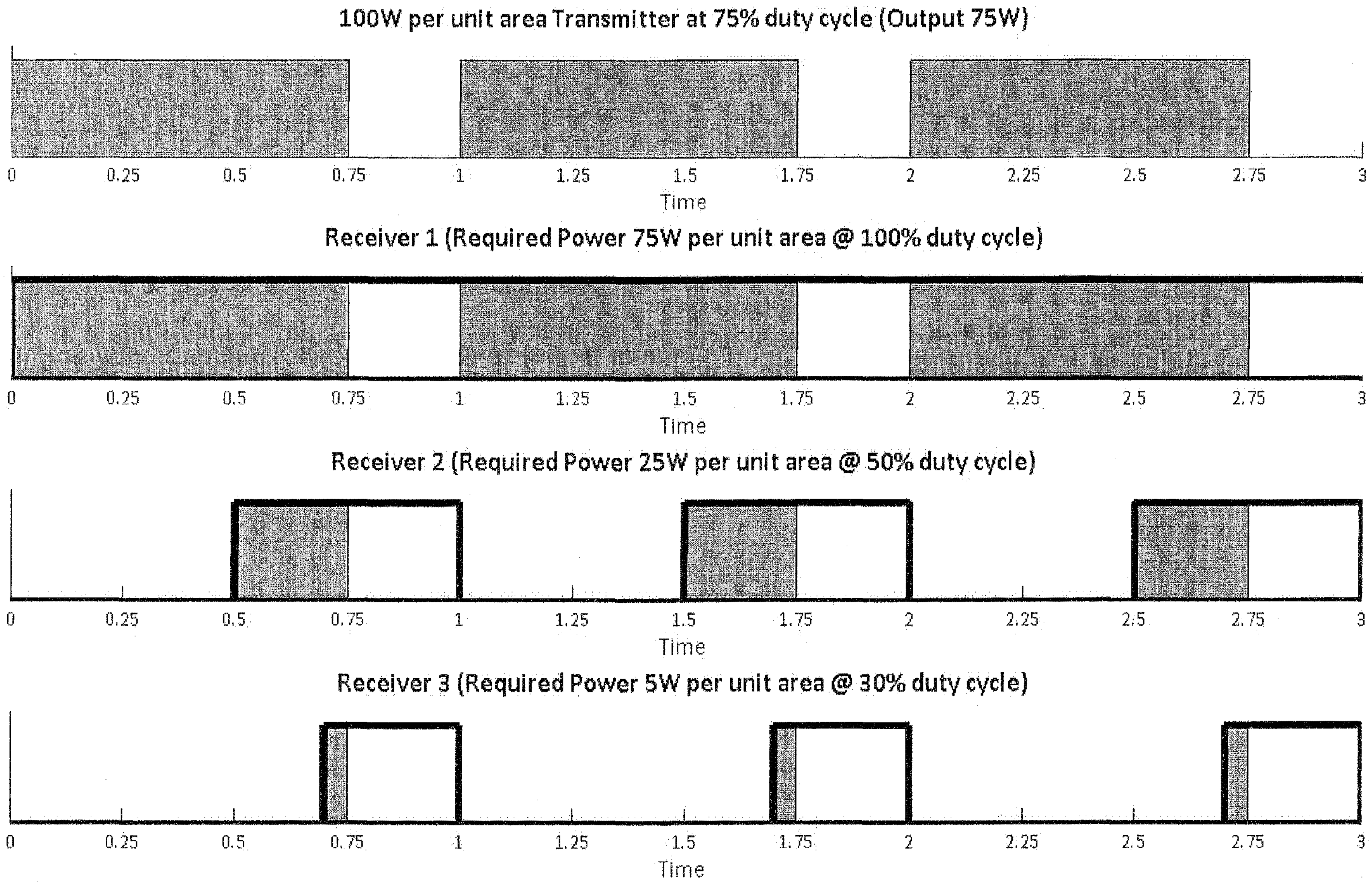
100W per unit area Transmitter at 75% duty cycle (Output 75W)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 1 (Required Power 75W per unit area @ 100% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 2 (Required Power 25W per unit area @ 50% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 3 (Required Power 5W per unit area @ 30% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time

FIG. 3

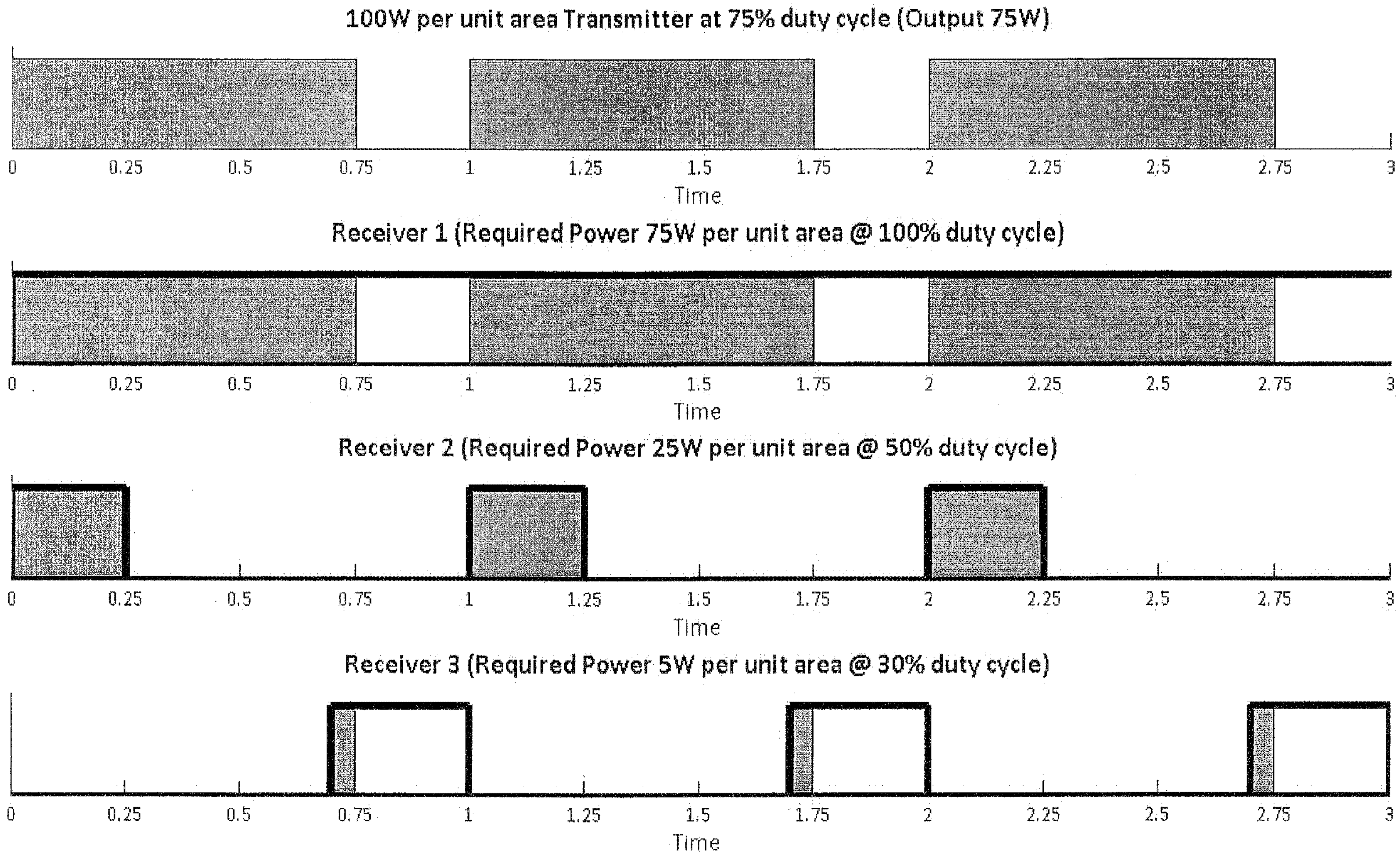
100W per unit area Transmitter at 75% duty cycle (Output 75W)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 1 (Required Power 75W per unit area @ 100% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 2 (Required Power 25W per unit area @ 50% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time
Receiver 3 (Required Power 5W per unit area @ 30% duty cycle)
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3
Time

FIG. 4

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(54) **Title**: WIRELESS ENERGY TRANSFER, INCLUDING INTERFERENCE ENHANCEMENT

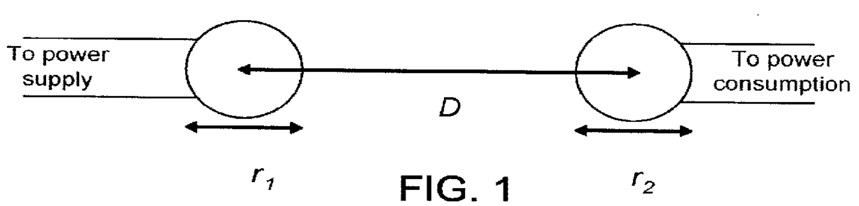

FIG. 1

(57) **Abstract**: Disclosed is an apparatus for use in wireless energy transfer, which includes a first resonator structure configured for energy transfer with a second resonator structure over a distance D larger than characteristic sizes, [insert formula] and [insert formula], of the first and second resonator structures. A power generator is coupled to the first structure and configured to drive the first resonator structure or the second resonator structure at an angular frequency away from the resonance angular frequencies and shifted towards a frequency corresponding to an odd normal mode for the resonator structures to reduce radiation from the resonator structures by destructive far-field interference.

WIRELESS ENERGY TRANSFER, INCLUDING INTERFERENCE ENHANCEMENT

CROSS REFERENCE TO RELATED APPLICATIONS

Pursuant to U.S.C. § 119(e), this application claims priority to U.S. Provisional Application Serial No. 61/127,661, filed May 14, 2008.

This application is also related by subject matter to the following commonly owned applications: U.S. Utility Patent Application Serial No. 12/055,963, filed March 26, 2008; U.S. Utility Patent Application Serial No. 11/481,077, filed July 5, 2006; U.S. Provisional Application Serial No. 60/698,442, filed July 12, 2005; U.S. Provisional Application Serial No. 60/908,383, filed March 27, 2007; U.S. Provisional Application Serial No. 60/908,666, filed March 28, 2007; and International Application No. PCT/US2007/070892, filed June 11, 2007.

The contents of the prior applications are incorporated herein by reference in their entirety.

BACKGROUND

The disclosure relates to wireless energy transfer. Wireless energy transfer can for example, be useful in such applications as providing power to autonomous electrical or electronic devices.

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 and/or the source), but require existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects. Some transfer schemes rely on induction, but are typically restricted to very close-range ($L_{TRANS} \ll L_{DEV}$) or low power (~mW) energy transfers.

The rapid development of autonomous electronics of recent years (e.g. laptops, cell-phones, house-hold robots, that all typically rely on chemical energy storage) has led to an increased need for wireless energy transfer.

SUMMARY

Efficient wireless energy-transfer between two resonant objects can be achieved at mid-range distances, provided these resonant objects are designed to operate in the 'strong-coupling' regime. We describe an implementation of a method to increase the efficiency of energy-transfer or to suppress the power radiated, which can be harmful or a cause of interference to other communication systems, by utilizing destructive interference between the radiated far-fields of the resonant coupled objects. 'Strong coupling' is a necessary condition for efficient energy-transfer, in the absence of far-field interference. 'Strong coupling' can be demonstrated in the case of realistic systems: self-resonant conducting coils, capacitively-loaded conducting coils, inductively-loaded conducting rods and dielectric disks, all bearing high-Q electromagnetic resonant modes. Also, an analytical model can be developed to take far-field interference into account for wireless energy-transfer systems. The analytical model can be used to demonstrate the efficiency enhancement and radiation suppression, in the presence of interference. In an example implementation, we describe improved performance based on the above principles in the case of two realistic systems: capacitively-loaded conducting coils and dielectric disks, both bearing high-Q electromagnetic resonant modes and far-field interference.

In an aspect, an apparatus for use in wireless energy transfer includes a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L_1 of said first resonator structure and larger than a characteristic size L_2 of said second resonator structure. The energy transfer has a rate κ and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure. The resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$ at least larger than 300, and the said resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$ at least larger than 300. The absolute value of the difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and

Γ_2, and the quantity $\kappa/\sqrt{\Gamma_1\Gamma_2}$ is at least larger than 20. The apparatus also includes a power supply coupled to the first structure and configured to drive the first resonator structure or the second resonator structure at an angular frequency away from the resonance angular frequencies and shifted towards a frequency corresponding to an odd normal mode for the resonator structures to reduce radiation from the resonator structures by destructive far-field interference.

In some examples, the power supply is configured to drive the first resonator structure or the second resonator structure at the angular frequency away from the resonance angular frequencies and shifted towards the frequency corresponding to an odd normal mode for the resonator structures to substantially suppress radiation from the resonator structures by destructive far-field interference.

In an aspect, a method for wireless energy transfer involves a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L_1 of said first resonator structure and larger than a characteristic size L_2 of said second resonator structure, wherein the energy transfer has a rate κ and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, said resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$ at least larger than 300, and said resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$ at least larger than 300, the absolute value of the difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and Γ_2, and the quantity $\kappa/\sqrt{\Gamma_1\Gamma_2}$ is at least larger than 20. The method includes driving the first resonator structure or the second resonator structure at an angular frequency away from the resonance angular frequencies and shifted towards a frequency corresponding to an odd normal mode for the resonator structures to reduce radiation from the resonator structures by destructive far-field interference.

In some examples, the first resonator structure or the second resonator structure is driven at the angular frequency away from the resonance angular frequencies and shifted towards the frequency corresponding to an odd normal mode for the resonator structures to substantially suppress radiation from the resonator structures by destructive far-field interference.

In an aspect, an apparatus for use in wireless energy transfer includes a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L_1 of said first resonator structure and larger than a characteristic size L_2 of said second resonator structure. The energy transfer has a rate κ and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure. The resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$ at least larger than 300, and the resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$ at least larger than 300. The absolute value of the difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and Γ_2, and the quantity $\kappa / \sqrt{\Gamma_1 \Gamma_2}$ is at least larger than 20. For a desired range of the distances D, the resonance angular frequencies for the resonator structures increase transmission efficiency T by accounting for radiative interference, wherein the increase is relative to a transmission efficiency T calculated without accounting for the radiative interference.

In some examples, the resonance angular frequencies for the resonator structures are selected by optimizing the transmission efficiency T to account for both a resonance quality factor U and an interference factor V.

In an aspect, a method involves designing a wireless energy transfer apparatus, the apparatus including a first resonator structure configured for energy transfer with a second resonator structure, over a distance D larger than a characteristic size L_1 of said first resonator structure and larger than a characteristic size L_2 of said second resonator structure, wherein the energy transfer has a rate κ and is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, wherein said resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$ at least larger than 300, and said resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$ at least larger than 300, wherein the absolute value of the difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and Γ_2, and the quantity $\kappa / \sqrt{\Gamma_1 \Gamma_2}$ is at least larger than 20. The method includes selecting the resonance angular frequencies for the resonator structures to substantially optimize the transmission efficiency by accounting for radiative interference between the resonator structures.

In some examples, the resonance angular frequencies for the resonator structures are selected by optimizing the transmission efficiency T to account for both a resonance quality factor *U* and an interference factor *V*.

In an aspect, an apparatus for use in wireless energy transfer includes a first resonator structure configured for energy transfer with a second resonator structure over a distance *D*. The energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor *k*. The resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$, and is radiative in the far field, with an associated radiation quality factor $Q_{1,\text{rad}} \geq Q_1$, and the resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$, and is radiative in the far field, with an associated radiation quality factor $Q_{2,\text{rad}} \geq Q_2$. An absolute value of a difference of said angular frequencies ω_1 and ω_2 is smaller than broader of said resonant widths Γ_1 and Γ_2, and an average resonant angular frequency is defined as $\omega_o = \sqrt{\omega_1 \omega_2}$, corresponding to an average resonant wavelength $\lambda_o = 2\pi c / \omega_o$, where c is the speed of light in free space, and a strong-coupling factor being defined as $U = k\sqrt{Q_1 Q_2}$. The apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor V_{rad}, to reduce a total amount of radiation from the apparatus compared to an amount of radiation from the apparatus in the absence of interference, a strong-interference factor being defined as $V = V_{\text{rad}}\sqrt{(Q_1 / Q_{1,\text{rad}})(Q_2 / Q_{2,\text{rad}})}$.

The following are examples within the scope of this aspect.

The apparatus has $Q_1 / Q_{1,\text{rad}} \geq 0.01$ and $Q_2 / Q_{2,\text{rad}} \geq 0.01$. The apparatus has $Q_1 / Q_{1,\text{rad}} \geq 0.1$ and $Q_2 / Q_{2,\text{rad}} \geq 0.1$. The apparatus has D / λ_o larger than 0.001 and the strong-interference factor V is larger than 0.01. The apparatus has D / λ_o larger than 0.001 and the strong-interference factor V is larger than 0.1. The apparatus includes the second resonator structure.

During operation, a power generator is coupled to one of the first and second resonant structure, with a coupling rate κ_g, and is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency $\omega = 2\pi f$, wherein U_g is defined as κ_g / Γ_1, if the power generator is coupled to the first resonator structure and defined as κ_g / Γ_2, if the power generator is coupled to the second resonator structure. The driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures, wherein the detuning of the first resonator from the driving frequency is defined as $D_1 = (\omega - \omega_1) / \Gamma_1$ and the detuning of the second resonator structure from the driving frequency is defined as $D_2 = (\omega - \omega_2) / \Gamma_2$.

D_1 is approximately equal to UV_{rad} and D_2 is approximately equal to UV_{rad}. U_g is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency. U_g is approximately equal to $\sqrt{1 + U^2 - V_{\text{rad}}^2 U^2 + V^2 - 2VV_{\text{rad}}}$. f is at least larger than 100 kHz and smaller than 500MHz. f is at least larger than 1MHz and smaller than 50MHz. The apparatus further includes the power generator. During operation, a power load is coupled to the resonant structure to which the power generator is not coupled, with a coupling rate κ_l, and is configured to receive from the resonator structure, to which it is coupled, a usable power, wherein U_l is defined as κ_l / Γ_1, if the power load is coupled to the first resonator structure and defined as κ_l / Γ_2, if the power load is coupled to the second resonator structure. U_l is chosen to maximize the ratio of the energy-transfer efficiency to the radiation efficiency. The driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures, wherein the detuning of the first resonator from the driving frequency is defined as $D_1 = (\omega - \omega_1)/\Gamma_1$ and is approximately equal to UV_{rad}, and the detuning of the second resonator structure from the driving frequency is defined as $D_2 = (\omega - \omega_2)/\Gamma_2$ and is approximately equal to UV_{rad}, and U_l is approximately equal to $\sqrt{1+U^2-V_{\text{rad}}^2U^2+V^2-2VV_{\text{rad}}}$.

At least one of the first and second resonator structures comprises a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon. The characteristic size of said loop or coil is less than 30 cm and the width of said conducting wire or Litz wire or ribbon is less than 2cm. The characteristic size of said loop or coil is less than 1m and the width of said conducting wire or Litz wire or ribbon is less than 2cm.

The apparatus further includes a feedback mechanism for maintaining the resonant frequency of one or more of the resonant objects. The feedback mechanism comprises an oscillator with a fixed driving frequency and is configured to adjust the resonant frequency of the one or more resonant objects to be detuned by a fixed amount with respect to the fixed frequency.

In an aspect, an apparatus for use in wireless energy transfer includes a first resonator structure configured for energy transfer with a second resonator structure over a distance *D*. The energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k. The resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$, and is radiative in the far field, with an associated radiation quality factor $Q_{1,\text{rad}} \geq Q_1$, and the resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$, and is radiative in the far field, with an associated radiation quality factor $Q_{2,\text{rad}} \geq Q_2$. An absolute value of a difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and Γ_2, and an average resonant angular frequency is defined as $\omega_o = \sqrt{\omega_1\omega_2}$, corresponding to an average resonant wavelength $\lambda_o = 2\pi c / \omega_o$, where c is the speed of light in free space, and a strong-coupling factor is defined as $U = k\sqrt{Q_1 Q_2}$. The apparatus is configured to employ interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor V_{rad}, to increase efficiency of energy transfer for the apparatus compared to efficiency for the apparatus in the absence of interference, the strong-interference factor being defined as $V = V_{\text{rad}}\sqrt{(Q_1 / Q_{1,\text{rad}})(Q_2 / Q_{2,\text{rad}})}$.

The following are examples within the scope of this aspect.

The apparatus has $Q_1 / Q_{1,\text{rad}} \geq 0.05$ and $Q_2 / Q_{2,\text{rad}} \geq 0.05$. The apparatus has $Q_1 / Q_{1,\text{rad}} \geq 0.5$ and $Q_2 / Q_{2,\text{rad}} \geq 0.5$. The apparatus has D / λ_o larger than 0.01 and the strong-interference factor V is larger than 0.05. The apparatus has D / λ_o larger than 0.01 and the strong-interference factor V is larger than 0.5. The apparatus further includes the second resonator structure.

During operation, a power generator is coupled to one of the first and second resonant structure, with a coupling rate κ_g, and is configured to drive the resonator structure, to which it is coupled, at a driving frequency f, corresponding to a driving angular frequency $\omega = 2\pi f$, wherein U_g is defined as κ_g / Γ_1, if the power generator is coupled to the first resonator structure and defined as κ_g / Γ_2, if the power generator is coupled to the second resonator structure. The driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures, wherein the detuning of the first resonator from the driving frequency is defined as $D_1 = (\omega - \omega_1)/\Gamma_1$ and the detuning of the second resonator structure from the driving frequency is defined as $D_2 = (\omega - \omega_2)/\Gamma_2$.

D_1 is approximately equal to UV and D_2 is approximately equal to UV. U_g is chosen to maximize the energy-transfer efficiency. U_g is approximately equal to $\sqrt{(1+U^2)(1-V^2)}$. f is at least larger than 100 kHz and smaller than 500MHz. f is at least larger than 1MHz and smaller than 50MHz. The apparatus further includes the power generator.

During operation, a power load is coupled to the resonant structure to which the power generator is not coupled, with a coupling rate κ_l, and is configured to receive from the resonator structure, to which it is coupled, a usable power, wherein U_l is defined as κ_l / Γ_1, if the power load is coupled to the first resonator structure and defined as κ_l / Γ_2, if the power load is coupled to the second resonator structure. U_l is chosen to maximize the energy-transfer efficiency. The driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures, wherein the detuning of the first resonator from the driving frequency is defined as $D_1 = (\omega - \omega_1)/\Gamma_1$ and is approximately equal to UV, and the detuning of the second resonator structure from the driving frequency is defined as $D_2 = (\omega - \omega_2)/\Gamma_2$ and is approximately equal to UV, and U_l is approximately equal to $\sqrt{(1+U^2)(1-V^2)}$.

At least one of the first and second resonator structures comprises a capacitively loaded loop or coil of at least one of a conducting wire, a conducting Litz wire, and a conducting ribbon. The characteristic size of said loop or coil is less than 30 cm and the width of said conducting wire or Litz wire or ribbon is less than 2cm. The characteristic size of said loop or coil is less than 1m and the width of said conducting wire or Litz wire or ribbon is less than 2cm. The apparatus includes a feedback mechanism for maintaining the resonant frequency of one or more of the resonant objects. The feedback mechanism comprises an oscillator with a fixed driving frequency and is configured to adjust the resonant frequency of the one or more resonant objects to be detuned by a fixed amount with respect to the fixed frequency. The feedback mechanism is configured to monitor an efficiency of the energy transfer, and adjust the resonant frequency of the one or more resonant objects to maximize the efficiency. The resonance angular frequencies for the resonator structures are selected to optimize the energy-transfer efficiency by accounting for both the strong-coupling factor U and the strong-interference interference factor V.

In an aspect, a method for wireless energy transfer includes providing a first resonator structure configured for energy transfer with a second resonator structure over a distance D, wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor k, wherein said resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$, and is radiative in the far field, with an associated radiation quality factor $Q_{1,\text{rad}} \geq Q_1$, and resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$, and is radiative in the far field, with an associated radiation quality factor $Q_{2,\text{rad}} \geq Q_2$, wherein an absolute value of a difference of said angular frequencies ω_1 and ω_2 is smaller than broader of said resonant widths Γ_1 and Γ_2, and an average resonant angular frequency is defined as $\omega_o = \sqrt{\omega_1\omega_2}$, corresponding to an average resonant wavelength $\lambda_o = 2\pi c / \omega_o$, where c is the speed of light in free space, and the strong-coupling factor is defined as $U = k\sqrt{Q_1 Q_2}$, and employing interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor V_{rad}, to reduce a total amount of radiation from the first and second resonator compared to an amount of radiation from the first and second resonator in the absence of interference, a strong-interference factor being defined as

$V = V_{\mathrm{rad}}\sqrt{\left(Q_1 / Q_{1,\mathrm{rad}}\right)\left(Q_2 / Q_{2,\mathrm{rad}}\right)}$.

The following are examples within the scope of this aspect.

The method has $Q_1 / Q_{1,\mathrm{rad}} \geq 0.01$ and $Q_2 / Q_{2,\mathrm{rad}} \geq 0.01$. During operation, a power generator is coupled to one of the first and second resonant structure and is configured to drive the resonator structure, to which it is coupled, at a driving frequency *f*, corresponding to a driving angular frequency $\omega = 2\pi f$, wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures. During operation, a power load is coupled to the resonant structure to which the power generator is not coupled and is configured to receive from the resonator structure, to which it is coupled, a usable power.

In an aspect, a method for wireless energy transfer includes providing a first resonator structure configured for energy transfer with a second resonator structure over a distance *D*, wherein the energy transfer is mediated by evanescent-tail coupling of a resonant field of the first resonator structure and a resonant field of the second resonator structure, with a coupling factor *k*, wherein said resonant field of the first resonator structure has a resonance angular frequency ω_1, a resonance frequency-width Γ_1, and a resonance quality factor $Q_1 = \omega_1 / 2\Gamma_1$, and is radiative in the far field, with an associated radiation quality factor $Q_{1,\mathrm{rad}} \geq Q_1$, and said resonant field of the second resonator structure has a resonance angular frequency ω_2, a resonance frequency-width Γ_2, and a resonance quality factor $Q_2 = \omega_2 / 2\Gamma_2$, and is radiative in the far field, with an associated radiation quality factor $Q_{2,\mathrm{rad}} \geq Q_2$, wherein an absolute value of the difference of said angular frequencies ω_1 and ω_2 is smaller than the broader of said resonant widths Γ_1 and Γ_2,and an average resonant angular frequency is defined as $\omega_o = \sqrt{\omega_1\omega_2}$, corresponding to an average resonant wavelength $\lambda_o = 2\pi c / \omega_o$, where *c* is the speed of light in free space, and the strong-coupling factor is defined as $U = k\sqrt{Q_1 Q_2}$, and employing interference between said radiative far fields of the resonant fields of the first and second resonator, with an interference factor V_{rad}, to increase efficiency of energy transfer between the first and second resonator compared to efficiency of energy transfer between the first and second resonator in the absence of interference, a strong-interference factor being defined as $V = V_{\text{rad}}\sqrt{(Q_1/Q_{1,\text{rad}})(Q_2/Q_{2,\text{rad}})}$.

The following are examples within the scope of this aspect.

The method has $Q_1/Q_{1,\text{rad}} \geq 0.05$ and $Q_2/Q_{2,\text{rad}} \geq 0.05$. During operation, a power generator is coupled to one of the first and second resonant structure and is configured to drive the resonator structure, to which it is coupled, at a driving frequency *f*, corresponding to a driving angular frequency $\omega = 2\pi f$, wherein the driving frequency is different from the resonance frequencies of the first and second resonator structures and is closer to a frequency corresponding to an odd normal mode of the system of the two resonator structures. During operation, a power load is coupled to the resonant structure to which the power generator is not coupled and is configured to receive from the resonator structure, to which it is coupled, a usable power. The resonance angular frequencies for the resonator structures are selected to optimize the energy-transfer efficiency by accounting for both the strong-coupling factor *U* and the strong-interference interference factor *V*.

Various examples may include any of the above features, alone or in combination. Other features, objects, and advantages of the disclosure will be apparent from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic of an example wireless energy transfer scheme.

Figs. 2(a)-(b) show the efficiency of power transmission η_{P} for (a) $U = 1$ and (b) $U = 3$, as a function of the frequency detuning D_o and for different values of the loading rate U_o.

Fig. 2(c) shows the optimal (for zero detuning and under conditions of impedance matching) efficiency for energy transfer $\eta_{\text{E*}}$ and power transmission $\eta_{\text{P*}}$, as a function of the coupling-to-loss figure-of-merit U.

Fig. 3 shows an example of a self-resonant conducting-wire coil.

Fig. 4 shows an example of a wireless energy transfer scheme featuring two self-resonant conducting-wire coils

Fig. 5 is a schematic of an experimental system demonstrating wireless energy transfer.

Fig. 6 shows a comparison between experimental and theoretical results for the coupling rate of the system shown schematically in Fig. 5.

Fig. 7 shows a comparison between experimental and theoretical results for the strong-coupling factor of the system shown schematically in Fig. 5.

Fig. 8 shows a comparison between experimental and theoretical results for the power-transmission efficiency of the system shown schematically in Fig. 5.

Fig. 9 shows an example of a capacitively loaded conducting-wire coil, and illustrates the surrounding field.

Fig. 10 shows an example wireless energy transfer scheme featuring two capacitively loaded conducting-wire coils, and illustrates the surrounding field.

Fig. 11 illustrates an example circuit model for wireless energy transfer.

Fig. 12 shows the efficiency, total (loaded) device Q, and source and device currents, voltages and radiated powers (normalized to 1Watt of output power to the load) as functions of the resonant frequency, for a particular choice of source and device loop dimensions, wp and N_s and different choices of N_d=1,2,3,4,5,6,10 (red, green, blue, magenta, yellow, cyan, black respectively).

Fig.13 shows the efficiency, total (loaded) device Q, and source and device currents, voltages and radiated powers (normalized to 1Watt of output power to the load) as functions of frequency and wp for a particular choice of source and device loop dimensions, and number of turns N_s and N_d.

Fig. 14 shows an example of an inductively-loaded conducting-wire coil.

Fig. 15 shows (a) an example of a resonant dielectric disk, and illustrates the surrounding field and (b) a wireless energy transfer scheme featuring two resonant dielectric disks, and illustrates the surrounding field.

Figs. 16(a)-(b) show the efficiency of power transmission η_P for (a) U = 1, V = 0.5 and (b) U = 3, V = 0.5, as a function of the frequency detuning Do and for different values of the loading rate U_o. (The dotted lines show, for comparison, the results when there is no interference, as shown in Fig.2(a)-(b).) and Figs. 16(c)-(d) show the optimal (for optimal detuning and under conditions of impedance matching) efficiency for energy transfer (only in (c)) and power transmission, as a function of the strong-coupling factor U and the strong-interference factor V.

Fig. 17 shows coupled-mode theory (CMT) results for (a) the coupling factor k and (b) the strong-coupling factor U as a function of the relative distance D/r between two identical capacitively-loaded conducting single-turn loops, for three different dimensions of the loops. Note that, for conducting material, copper ($\sigma = 5.998 \cdot 10^7 \, \mathrm{S/m}$) was used.

Fig. 18 shows AT results for the interference factor V_{rad} as a function of the distance D (normalized to the wavelength λ) between two capacitively-loaded conducting loops.

Fig. 19 shows CMT results for the strong-coupling factor U and AT results for the interference factor V_{rad} and strong-interference factor V as a function of the resonant eigenfrequency of two identical capacitively-loaded conducting single-turn loops with $r = 30\mathrm{cm}$ and $a = 2\mathrm{cm}$, at a relative distance $D / r = 5$ between them. Note that, for conducting material, copper ($\sigma = 5.998 \cdot 10^7 \, \mathrm{S/m}$) was used.

Fig. 20 shows the power-transmission efficiency as a function of the resonant eigenfrequency of two identical capacitively-loaded conducting single-turn loops. Results for two different loop dimensions are shown and for two relative distances between the identical loops. For each loops dimension and distance, four different cases are examined: without far-field interference (dotted), with far-field interference but no driving-frequency detuning (dashed) and with driving-frequency detuning to maximize either the efficiency (solid) or the ratio of efficiency over radiation (dash-dotted).

Fig. 21 shows the driving-frequency detunings required in the presence of far-field interference as a function of the resonant eigenfrequency of two identical capacitively-loaded conducting single-turn loops of Fig. 20 to maximize either the efficiency (solid) or the ratio of efficiency over radiation (dash-dotted).

Fig. 22(a) shows the resonant eigenfrequencies f_{U} and f_{η}, where the strong-coupling factor U and the power-transmission efficiency η peak respectively, as a