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A Multimode/Multiband Power Amplifier With a Boosted Supply Modulator

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***Abstract*—A multimode/multiband power amplifier (PA) with a boosted supply modulator is developed for handset applications. A linear broadband class-F amplifier is designed to have a constant fundamental impedance across 1.7–2 GHz and its second and third harmonic impedances are located at the high-efficiency area. To reduce the circuit size for handset application, the harmonic control circuits are merged into the broadband output matching circuit for the fundamental frequency. An envelope-tracking operation delivers high efficiency for the overall power. The linearity is improved by envelope tracking (ET) through intermodulation-distortion sweet-spot tracking at the maximum output power level. The efficiency and bandwidth (BW) are enhanced by a boosted supply modulator. Multimode operation is achieved by an ET technique with a programmable hysteresis control and automatic switching current adaptation of the hybrid supply modulator. For demonstration purpose, the PA and supply modulator are implemented using an InGaP/GaAs heterojunction bipolar transistor and a 65-nm CMOS process. For a long-term evolution signal, the envelope-tracking (ET) PA delivers a power-added efficiency (PAE) and an error vector magnitude of 33.3%–39% and 2.5%–3.5%, respectively, at an average power of 27.8 dBm across 1.7–2 GHz. For a wideband code-division multiple-access signal across 1.7–2 GHz, the ET PA performs a PAE, an ACLR1, and an ACLR2 of 40%–46.3%, from −39 to −42.5 dBc, and −51 to −58 dBc, respectively, at an average output power of 30.1 dBm. The ET PA with an EDGE signal delivers a PAE, an ACPR1, and an ACPR2 of 37%–42%, from −56.5 to −59.3 dBc, and −63.5 to −69.5 dBc, respectively, at an average power of 28 dBm across the 300-MHz BW. These results show that the proposed design achieves highly efficient and linear power amplification for multimode/multiband wireless communication applications.**

***Index Terms*—Efficient, enhanced data rates for GSM evolution (EDGE), envelope tracking (ET), handset, heterojunction bipolar transistors (HBT), linear, long-term evolution (LTE), monolithic microwave integrated circuit (MMIC), power amplifier (PA), supply modulator, wideband code division multiple access (WCDMA).**

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I. Introduction

POWER amplifiers (PAs) for multifunctional smart mobile phones have become a very challenging area because the PA should handle voice, data, and broadcast with global roaming capability. Therefore, the PAs should have a multimode/multiband capability with high efficiency [1]. The input/output matching components of the transmitter are sensitive to frequency, thus preventing multiband operation. Low amplification efficiency leads to a short battery life and heat in mobile handsets. Moreover, as the information content increases, modulation systems need to have wider bandwidths (BWs) and a higher peak-to-average power ratio (PAPR), causing the PA to operate in a less efficient back-off region for linearity. To improve the low efficiency at the back-off power region, many efficiency enhancement techniques have undergone research for a long period of time.

The Doherty and the envelope elimination and restoration (EER) techniques have been investigated for high efficiency at the back-off power region. The efficiency at the back-off power region is important for handset applications because of frequent use of lower power levels and the high PAPR of the signals. The Doherty technique modulates the load according to the power level [2]–[5]. The load modulation is often achieved by a quarter-wavelength transformer, and linear operation is accomplished by third-order intermodulation (IM3) cancellation between the main and auxiliary amplifiers. Both of these are sensitive to the frequency of operation. Thus, the Doherty PAs have a limit for broadband operation.

The EER technique involves modulating the supply voltage according to the power level of a PA, and enhances efficiency at the back-off power region [6]–[16]. The EER structure comprises the supply modulator and the PA. Only the PA determines the RF operating frequency band. Thus, the EER technique is more advantageous for broadband operation than the Doherty technique.

The efficiency of the EER structure is determined by multiplication of the efficiencies of the supply modulator and the PA [12]. A highly efficient EER structure requires that both the supply modulator and PA be efficient. Thus, class-E, class-F, class-D, and class-J PAs can be candidates. The class-E PAs achieve high efficiency by turning on the transistor at the point when the drain–source (collector–emitter) capacitor does not have any charge. The class-F PA controls the voltage waveform to ensure it is square shaped, which increases the magnitude of class-F PA, using a push–pull structure. The class-J PA utilizes the phase shift between the output current and voltage waveforms to render the second harmonic termination to a purely reactive regime [19].

The broadband approaches for class-E PAs and class-F PAs have been studied in [20] and [21]. However, these concepts are for base-station PAs, and use microstrip lines for matching. The microstrip lines are too bulky to be employed in PAs for handset applications. In [22], we have proposed broadband class-F PAs, which control the second and third harmonic impedances across a broad BW, but linearity is not considered as we intend to use a digital pre-distortion (DPD) technique. Broadband class-J PAs for base-station PAs have been also investigated [19]. The researchers have found the optimum efficiency contour for class-J operation across a broad BW, and matched the load impedance to the contour, thus, a 50% fractional BW with high efficiency is achieved. A gallium–nitride (GaN) device with a high supply voltage has a low Q for the output impedances due to the small output capacitance, and its gain drops 3 dB per octave frequency (normally it is 6 dB/octave because of its operation at the maximum stable gain (MSG) region). Despite the advantageous characteristics of the GaN device, it is too expensive at the moment to be utilized for handset devices and it requires too high bias voltage.

The ideal EER structure would deliver a 100% efficiency using a highly efficient supply modulator, but the limited BW of switching amplifiers and the low efficiency of wideband linear amplifiers for the modulators degrades the ideal efficiency. Some researchers have utilized the advantages of the wide-BW linear amplifier and the high-efficiency switching amplifier [10]–[15]. The switching amplifier does not follow most of the high slew-rate load current, and operates as a quasi-constant current source. The linear amplifier supplies and sinks the current to regulate the load according to the envelope of the signal. This structure is suitable for the envelope signal of modern wireless communication systems, which has the most power in the low-frequency region. In [15], we have proposed a hybrid switching amplifier (HSA) for multistandard applications. Automatic switching current adaption from an HSA and programmable hysteresis control can achieve multimode operation.

In this paper, we propose a multimode/multiband PA with a boosted supply modulator for handset applications. For this multiband PA design, the fundamental load is maintained at a consistent level across the BW. Harmonic impedances are searched for highly efficient class-F operation. The harmonic circuits are merged into the broadband matching circuit, thereby reducing their size and increasing the available BW. In contrast to our previous paper [22], the PA matching is modified for linear class-AB bias. An HSA with a boost converter driving the linear stage increases the RF BW due to reduced output capacitance of the RF device at the higher operating voltages provided by the boost converter. The HSA also improves the efficiency due to envelope tracking (ET). Finally the HSA improves linearity due to intermodulation-distortion (IMD) sweet-

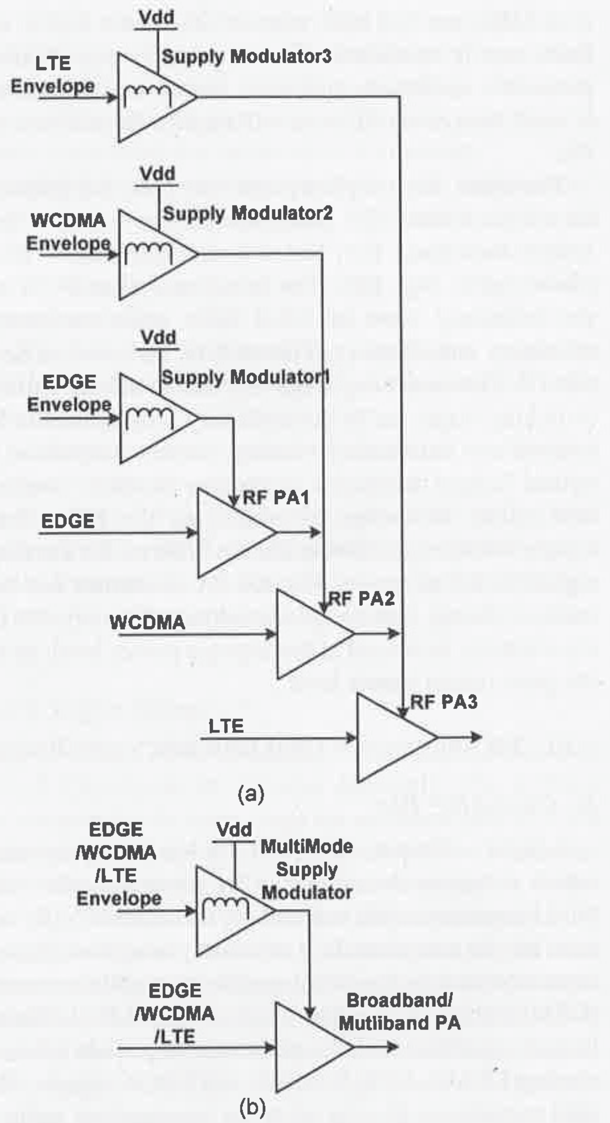

Fig. 1. (a) Conventional polar transmitter for multimode/multiband operation. (b) Proposed polar transmitter for multimode/multiband operation.

For demonstration purposes, the PA and supply modulator are implemented using an InGaP/GaAs HBT and a 65-nm CMOS processes, and are operated with signals of long-term evolution (LTE), wideband code division multiple access (WCDMA), and EDGE across frequencies of 1.7–2 GHz. The measured results prove that the proposed design achieves highly efficient and linear power amplification for multimode/multiband applications.

II. Multimode/Multiband Polar Transmitter

A conventional polar transmitter for multimode/multiband operation requires a PA and a supply modulator for each wireless communication standard, as shown in Fig. 1(a). For example, if we need transmitters operating for an LTE, a WCDMA, and an EDGE application across a 1.7–2.0-GHz frequency, supply modulators and PAs need to operate at different

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