Broadband Class-F Power Amplifiers for Handset Applications

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***Abstract*— A broadband class-F power amplifier for handset application is developed covering 1.8 $\sim$ 2.1 GHz. The amplifier maintains constant fundamental impedance and the second and third harmonic impedances to be located at the high efficiency area. The second and third harmonic impedances are found for highly efficient class-F PA. The harmonic control circuits are immersed into the broadband output matching for the fundamental frequency. For demonstration, the PA is implemented using an InGaP/GaAs HBT process, and delivers 1 W output power ($<$ 1 dB variation) and over 48% PAE (54% peak PAE) across 300 MHz bandwidth with a continuous wave (CW) signal and a 3.4 V supply voltage. The broadband class-F PA is promising technique for the EER technique with high-efficiency and broadband.**

I. Introduction

Mobile phones become multi-functional devices, which carry voices, data, and broad-castings. Transmitters and receivers can be different for such functions due to frequency-bands and communication specifications. Another issue of wireless communication for multi-function is how to increase short battery life time. A power amplifier (PA) in a transmitter is the main hurdle for multi-functional wireless communication system. The PA has a limit in the operational frequency and consumes most of dc power in the transmitter [1].

Doherty and envelope elimination and restoration (EER) techniques have been researched for a high efficiency at a back-off power region [2], [3]. The efficiency at the back-off power region is the most important for the handset application because of the frequent use at that power. Doherty technique modulates the load according to power level. The load modulation is often achieved by a-quarter-wavelength transformer, which is sensitive to the frequency. Thus, Doherty PAs have a limit in broadband operation. The EER is modulating the bias voltage according to the power level of PA, and enhances efficiency at the back-off power region. The EER technique is comprised of a bias modulator and a PA. Only PA determines the the operating frequency band. Thus, the EER is more advantageous in broadband operation than the Doherty technique.

The EER technique often adopts class-E, -F, -D PAs for enhancing the efficiency overall power region. The class-E PAs achieve the 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 PAs control the voltage waveform shaped to the square, so that increase the magnitude of fundamental voltage, output power, and efficiency [4], [5]. The class-D PAs control the harmonics similarly to the class-F PAs, but are basically push-pull architectures.

Broadband approach for class-E PAs and class-F PAs are studied by [6] and [7]. However, they are for base station PAs, and use micro-strip lines for matching. The micro-strip lines are too bulky to be employed in PAs for handset application.

In this paper, we propose a broadband class-F PA for handset applications. The design topology of the broadband PA is implemented for the fundamental load. Harmonics impedances are searched for highly efficient class-F operation and matched at those points. Thus, the second and third harmonics enhance the efficiency across 300 MHz bandwidth. The harmonic circuits are realized using the elements used for the fundamental matching, reducing the size. The design concept has been verified by the fabricated chip. The broadband class-F PA is promising technique for the EER technique for high-efficiency and broadband transmitters.

II. Class-F Power Amplifier

A. Basic Concept

Class-F PAs control the voltage waveform shaped to the square, which increases the magnitude of fundamental voltage, output power, and efficiency. With a half sinusoidal current waveform, the theoretical calculation gives 100% of efficiency. The voltage waveform has only odd harmonics, the current waveform has only even harmonics. Practically, the control of all the harmonics is impossible, and limited harmonics are controlled.

When the voltage harmonic components have enough power to fulfill the proper ratio, the ratio of the maximum achievable fundamental-component to the maximum amplitude for the

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voltage waveform is defined to be $\delta_V(n)$ as a function of n [8]. The value of n indicates the highest odd harmonic present. The values of $\delta_V(n)$ are

$$\delta_V(1) = 1, \qquad \delta_V(3) = 1.155,$$
$$\delta_V(5) = 1.207, \quad \delta_V(\infty) = \frac{4}{\pi}. \tag{1}$$

Assuming a knee voltage V_k,output power is shown as functions of n,

$$P(n) \quad = \frac{1}{2} \cdot I_1 \cdot \delta_V(n) \cdot (V_{DC} - V_k). \tag{2}$$

The efficiency is

$$\eta(n) \quad = \frac{P(n)}{P_{DC}}. \tag{3}$$

The output power and efficiency increase by the control of odd harmonics as shown above.

B. Harmonic Impedances

For the class-F circuit, the second harmonic impedance should be small to eliminate the second harmonic voltage. The third harmonic impedance should be large but is not required to be infinite [1], [5]. A bit larger third harmonic impedance than the fundamental impedance can enhance the efficiency significantly. First, the fundamental and second harmonic impedances are matched properly, then the load-pull for third harmonic impedance is conducted as shown in Fig. 1(a). The PA is designed with two stages (idle currents are 3 mA and 19 mA for drive and power stages, respectively) and simulated including all the loss. Fig. 1(a) verifies that the 3rd harmonic impedance has a large tolerance for variation in PAE. Fig. 1(b) shows the second harmonic impedances load-pull for the efficiency, when the fundamental and third harmonic impedances are fixed by Fig. 1(a). The second harmonic impedance is more sensitive for PAE than the third harmonic impedance, but the variation is manageable within a few hundred MHz by the second harmonic short circuit. This load-pull results give us a design approach for the broadband class-F PA.

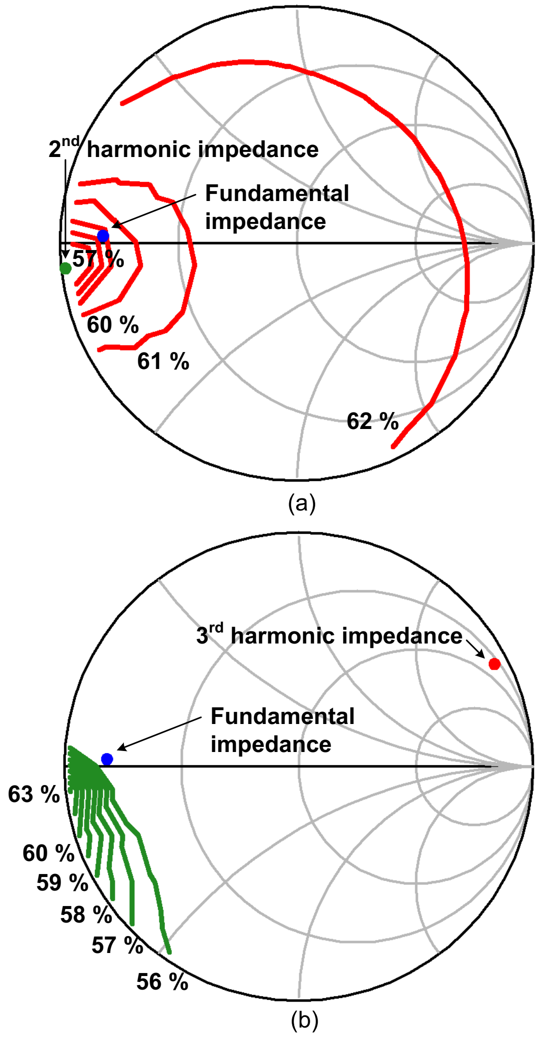

Fig. 1. Simulated load-pull results. (a) For 3rd harmonic impedance. The fundamenetal and 2nd harmonic impedances are fixed at 5+j1 and 0.5-j2.5, respectively. (b) For 2nd harmonic impedance. The fundamental and 3rd harmonic impedances are fixed at 5+j1 and 25+j200, respectively.

III. Broadband Class-F Power Amplifier

A. Broadband Matching

The LPF in Fig. 2(a) is transformed to the BPF in Fig. 2(b) using the low-pass to the bandpass filter transformation. The series L is transformed to a series LC and the shunt C to a parallel LC [9]. The BPF in Fig. 2(b) cannot transfer the impedance level. Thus, the capacitors can be converted as shown in Fig. 2(c), transforming the impedance level as well as maintaining the bandwidth.

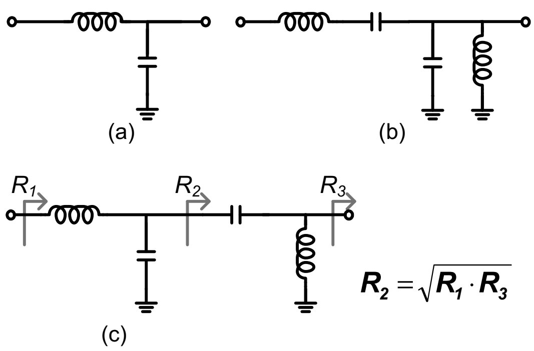

Fig. 2. (a) Low-pass filter. (b) Band-pass filter. (c) Band-pass filter with impedance transformation

B. Output and Input Matching

For the design of broadband class-F PA, the harmonic impedances should be located within high efficiency region in Fig. 1, and the fundamental impedance is constant across the bandwidth for driving the optimum power. The realized broad

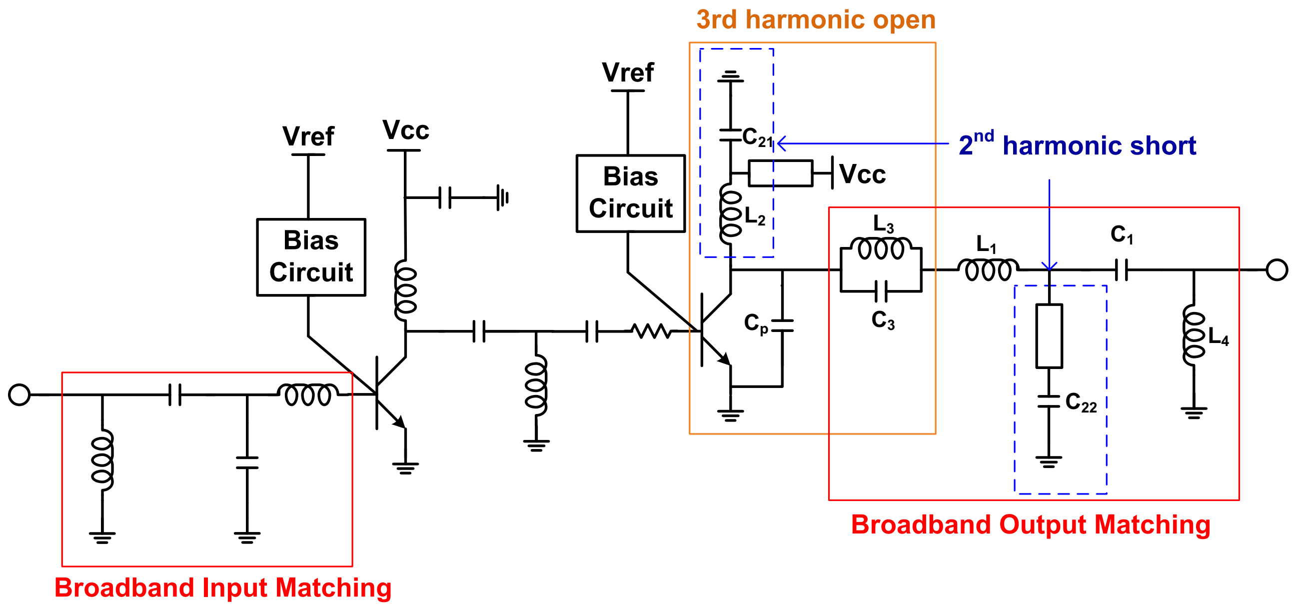

Fig. 3. Schematic of the broadband class-F PA

band mateched class-F PA is shown in Fig. 3. L_2C_{21} has near zero impedance at the upper-band of the second harmonic. C_{22} with a short micro-strip line has near zero impedance at the lower-band of the second harmonic. Thus, the voltage waveform of the second harmonics is eliminated across the broadband. The shunt L_3C_3 provides the high impedance at the third harmonic frequency. Since the device has a parasitic capacitance at the collector, the capacitance is resonated out at the third harmonic frequency by the inductance at the bias line. The fundamental impedance matching uses the BPF shown in Fig. 2(c). The shunt L_3C_3 is an inductance at the fundamental frequency, so this element with L_1 becomes the series inductor of the BPF. The simulated impedances including the device parasitics are shown in Fig. 4(a). The impedances across 1.8 to 2.1 GHz are constant. The impedances across 3.6 to 4.2 GHz (2nd harmonic impedances) are near zero, located at the high efficiency region in Fig. 1. The impedances across 5.4 to 6.3 GHz (3rd harmonic impedances) are high, also located at the high efficiency region in Fig. 1. Fig. 4(b) shows S21 with the broadband characteristic across 1.8 to 2.1 GHz. S21 has the two nulls in 3.6 and 4.2 GHz, which are produced by C_{22} with a short micro-strip line and L_2C_{21}, respectively. In this circuit topology, the harmonics circuits are merged into the fundamental matching elements, realizing a small size for handset applications. The input matching also employs the BPF of Fig. 2(c). The PA is comprised of a drive stage and a power stage, whose idle currents are 3 mA and 19 mA, respectively. To reduce the variation of input capacitance across the bandwidth and the power level, the bias point of power stage is determined higher than a normal PA design.

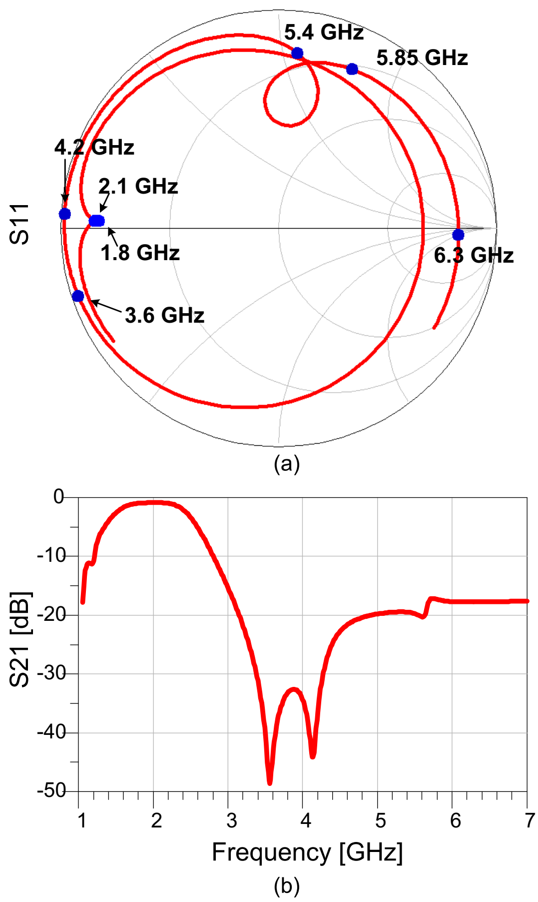

Fig. 4. Simulated S-parameters of output matching circuit including device parasitics.

IV. Implementation and Results

The broadband class-F PA is fabricated by an InGaP/GaAs 2 μm HBT process. The PA is integrated in a chip with

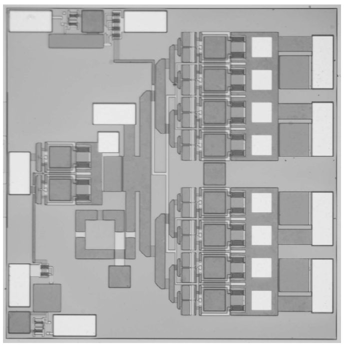

Fig. 5. A chip photograph.

the die size of 1.2 × 1.2 mm^2 except for four capacitors at the input and output matching circuit for tunability. All the inductors are implemented by bonding wires. All components can be integrated in die or package for handset application. The photograph is presented in Fig. 5. The inductor for the third harmonic circuit is implemented by a slab inductor instead of a spiral inductor. The slab inductor has a higher Q-factor than the spiral inductor, achieving higher third harmonic impedance and lower loss.

Measurement of the PA is conducted by comparing with simulated large signal S-parameters to confirm the precise control of the harmonics. Fig. 6(a) shows the gain and PAE at 1.95 GHz with a CW signal. Fig. 6(b) shows the measured performances as the function of frequencies. The output power and gain are within 1 dB, and the PAE is over 48% (54% peak PAE) from 1.8 to 2.1 GHz.

V. Conclusions

We have developed a broadband class-F PA for handset applications. The class-F topology is completely merged in the broadband fundamental output matching. The concept is demonstrated by the fabricated chip. The second and third harmonics enhance the efficiency up to 48% across 300 MHz bandwidth from 1.8 GHz to 2.1GHz. The broadband class-F PA is promising for the EER technique for high-efficiency and broadband.

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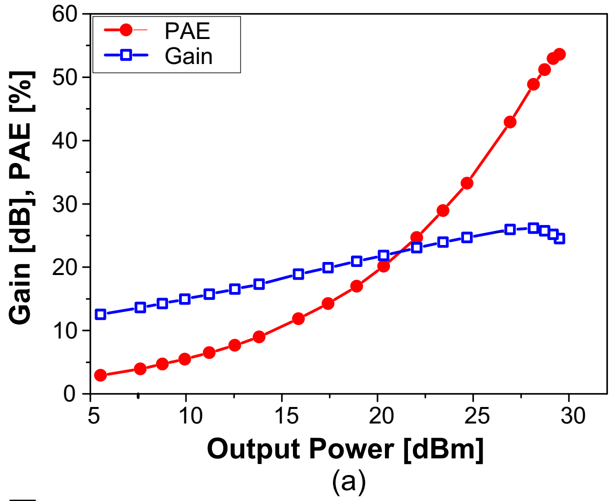

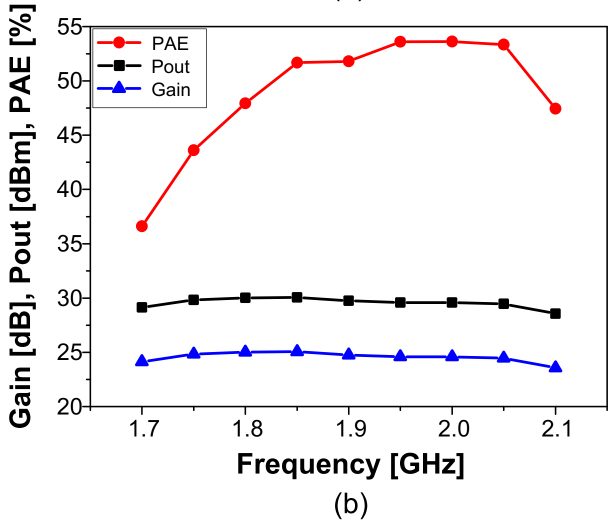

Fig. 6. (a) Measured CW performance at 1.95 GHz. (b) Measured output power and PAE from 1.7 GHz to 2.1 GHz at 3.4V supply voltage.

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