A High Efficiency and Multi-Band/Multi-Mode Power Amplifier using a Distributed Second Harmonic Termination

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***Abstract*— This paper proposes a new broadband saturated power amplifier (SPA) with a distributed second harmonic termination supporting multi-band/multi-mode operation. The proposed network is composed of a fundamental matching circuit and multiple second harmonic termination circuits. Due to the multiple harmonic terminations, the proposed PA improves the frequency range where the PA can achieve a high efficiency. The proposed PA is fabricated using a 45 W Cree CGH40045 GaN HEMT. Drain efficiencies of greater than 60% (average 66%) are achieved between about 1.8 GHz and 2.3 GHz (500 MHz bandwidth). When driven with long term evolution (LTE) and two carrier wideband code division multiple access (WCDMA) signals at DCS1800, PCS1900, and WCDMA bands, the linearity specifications of the corresponding standards are satisfied using the digital predistortion linearization technique, and it attains an efficiency of greater than 30%.**

I. INTRODUCTION

The constant proliferation of wireless standards is bringing about various challenges to the design and operation of wireless networks. These challenges concern the different stakeholders from base stations and handsets manufactures, to the final service providers. In the particular case of base station and handset manufactures, the demand for co-existence and interoperability of the different standards, imposed by different specifications, serves to complicate the design, fabrication and management of the corresponding systems. Indeed, although simple in principle, the trivial solution of assigning specific hardware to cope with the requirements of a given standard is not the most favorable in terms of cost and size minimization. This mainly is attributed to the low component reuse when multiple radios are used to cope with multiple standards. Using a single radio to cope with multiple standards would be a very interesting solution as it will address the previously mentioned problems; however, this idea poses a new set of challenges. In fact, radio systems involve a number of frequency-dependent circuits; therefore, multi-standard radio requires multi-band circuits. Among these circuits, the power amplifiers (PAs) will need to achieve good RF performance (RF gain, output power and power efficiency) over a range of operating frequencies. Knowing that optimizing these performance metrics at one band is a challenging task, designing a high power amplifier that maintains a high efficiency at multiple frequencies is very complicated [1], [2]. Alternatively, one can target the design of a PA that would maintain a high efficiency over a broad range of frequencies used by a number of standards.

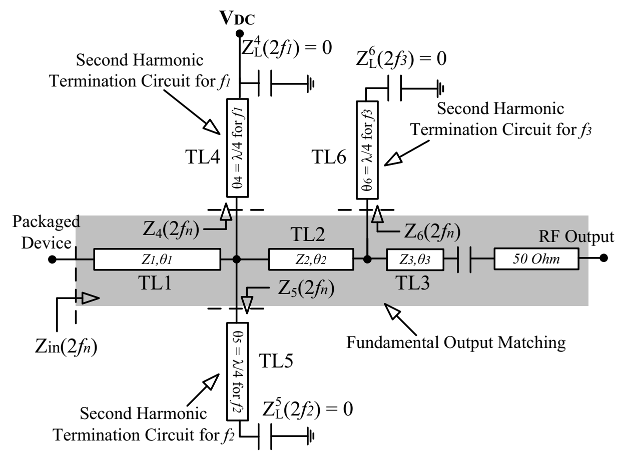

Fig. 1. Simplified block diagram of the output matching network with the distributed second harmonic termination circuit.

Among the high-efficiency PA topologies suggested in the literature [3], a class-F (or inverse class-F) PA, can achieve a peak power efficiency of greater than 70%. Interestingly, this efficiency can only be achieved over a narrow band of frequency due to the required resonator-like harmonic terminations in this topology. A class-J PA has been recently suggested as a good candidate for a broadband high-efficiency PA topology [3]. It has the potential to maintain an excellent efficiency over large bandwidth thanks to the continuity of the high efficiency for both inductive and capacitive second harmonic terminations [4], [5]. Furthermore, a saturated PA (SPA), which relies on self-generated harmonic currents, allows for high efficiency over about 10% bandwidth with only fundamental load matching [6].

In this paper, a new broadband SPA with distributed second harmonic termination is proposed to expand the range of frequencies where high efficiency can be achieved to lay the foundation for multi-band and multi-standard radios. The block diagram and the reasoning of the distributed second harmonic matching networks are explained in Section II. Section III expounds on the design of the broadband and high efficiency PA, which is designed to operate in the frequency range spanning from 1.8 GHz to 2.3 GHz, providing support for the DCS1800, PCS1900, and wideband code division multiple access (WCDMA) bands. In Section IV, the fabricated PA prototype, obtained under continuous-wave (CW), long term evolution (LTE), and 2-carrier (2C) WCDMA signals, is presented.

II. A Distributed Second Harmonic Termination Circuit

As explained in [6], the transistor in SPA operation incorporates the knee region of the I-V curves. This results in highly nonlinear behavior, which generates large currents at the harmonics. The extent of the harmonics currents is controlled by the load impedance at the fundamental, which affects the depth of operation in the knee region. Hence, adequate and simple harmonic terminations to the transistor enables the generation of rectangular current and half-sinusoidal voltage waveforms, thus achieving a higher efficiency. Although emerging transistor technologies such as Gallium Nitride (GaN) HEMT are known to be favorable for broadband operation, (as they maintain high efficiency over broad frequency ranges) they require not only broadband fundamental termination but also adequate harmonic terminations over the entire band. It is particularly challenging to achieve the proper harmonic terminations because of the high frequency dispersion of the optimum harmonic impedance over frequency. Thus, it is relatively difficult to achieve the required waveforms for high efficiency operation with conventional matching networks.

To mitigate this problem, this paper proposes a novel distributed harmonic termination circuit as depicted in Fig. 1. This proposed circuit can manipulate the second harmonic component over broad bandwidth, preventing null second harmonic impedance at the drain current source. As packaged devices inherently have an inductive impedance, due to wire bonding, capacitive harmonic terminations should be avoided to prevent the null harmonic impedance conditions (Fig. 2). The proposed network is composed of two separate blocks: i) a fundamental matching circuit, and ii) a second harmonic inductive termination circuit. The fundamental matching circuit is kept relatively simple as the optimum impedance versus frequency is relatively not very scattered. However, as per the Fig. 2, the optimum second harmonic termination versus frequency is very dispersive. To mitigate this problem

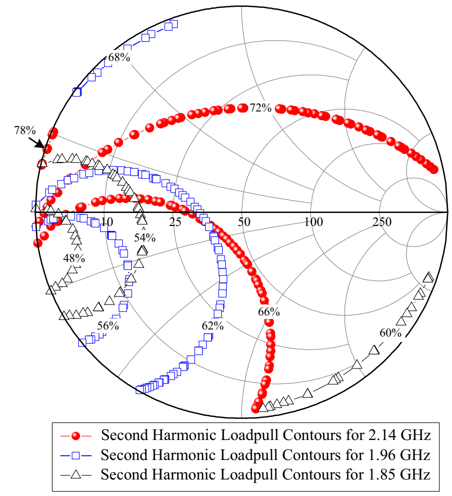

Fig. 2. Simulated second-order harmonic impedance loadpull contours of PAE at a given operating frequency.

a distributed topology, where multiple discrete harmonic terminations are included, was obtained. From Fig. 1, second harmonic impedances are expressed as

$$Z_{in}(2f_n) = Z_1 \frac{Z_L^{(n+3)} + jZ_1 tan[2\theta_1(2f_n)]}{Z_1 + jZ_L^{(n+3)} tan[2\theta_1(2f_n)]}, \quad (1)$$

$$= jZ_1 tan[2\theta_1(2f_1)], n = 1 \quad (2)$$

$$= jZ_1 tan[2\theta_1(2f_2)], n = 2 \quad (3)$$

where

$$Z_L^4(2f_1) = 0$$

$$Z_L^5(2f_2) = 0$$

and, because of the restricted layout, the second harmonic impedance at the third operating frequency f_3 is given by

$$Z_{in}(2f_3) = Z_1 \frac{Z_P + jZ_1 tan[2\theta_1(2f_3)]}{Z_1 + jZ_P tan[2\theta_1(2f_3)]}, n = 3 \quad (4)$$

where

$$Z_P = jZ_2 tan[2\theta_2(2f_3)] // Z_4(2f_3) // Z_5(2f_3)$$

$$Z_L^6(2f_3) = 0$$

This made possible individual control over the second harmonic for each targeted frequency.

A. Simulation Results

To assess the outcome of the proposed distributed harmonic termination based matching network, two SPAs, one with two second harmonic terminations and the other with three of them, were designed using a Cree CGH40045 GaN HEMT and simulated using the Agilent Advanced Design System (ADS). The fundamental matching impedance is optimized for 2.14 GHz. The second harmonic termination circuits are optimized for 1.85 GHz, 1.96 GHz, and 2.14 GHz operating frequencies. For comparison purposes, a conventional SPA [6] was also designed to operate at 2.14 GHz. In these PAs, the transistor

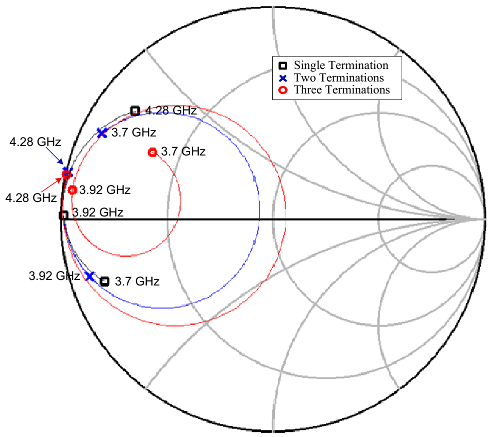

Fig. 3. Simulated second harmonic load impedance, at the three targeted frequencies: 1.85, 1.96, and 2.14 GHz, achieved using matching networks that involve single, two, or three harmonic terminations.

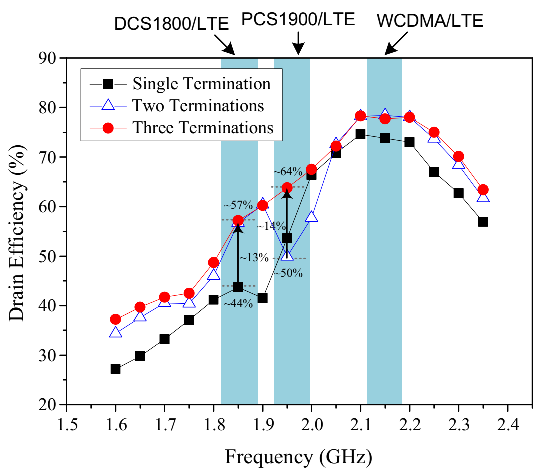

Fig. 4. Simulated drain efficiency according to the second harmonic termination.

is biased in deep class-AB mode (150 mA) with a drain voltage of 28 V. They all use the same input matching circuit.

Fig. 2 illustrates the second-order harmonic impedance loadpull PAE contours for the three considered frequencies. These contours confirm the non-ideal SPA operation caused by the variation of the operating frequency resulting in peak efficiency degradation. Fig. 3 shows the second harmonic impedances, according to the three targeted frequencies: 1.85, 1.96, and 2.14 GHz, achieved using matching networks that involve single, two or three harmonic terminations. Note that the second harmonic impedance is the matching impedance at the device package. The limited second harmonic termination in the conventional SPA is effectively ameliorated by the proposed distributed harmonic termination method.

The SPA with two second harmonic terminations shows a significant efficiency improvement for 1.85 GHz as shown in Fig. 4 (about 13% improvement), while the efficiency for 1.96 GHz is slightly degraded due to the corresponding second harmonic termination, as illustrated in Fig. 2. To improve the efficiency for 1.96 GHz, an additional second harmonic

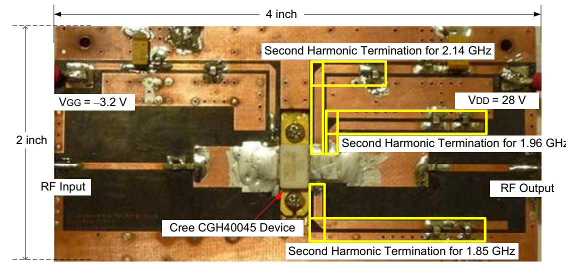

Fig. 5. Photographs of the proposed saturated PA.

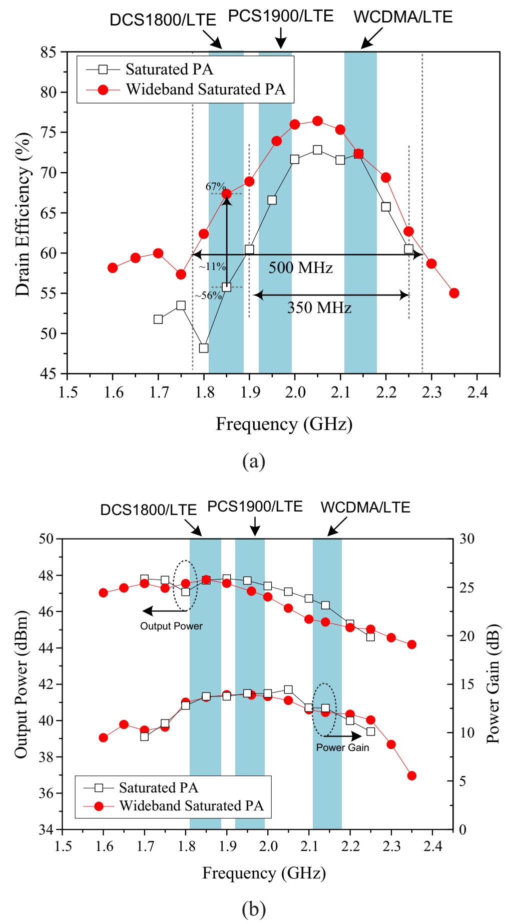

Fig. 6. Measured (a) drain efficiency and (b) output power and power gain of the conventional and proposed saturated PAs.

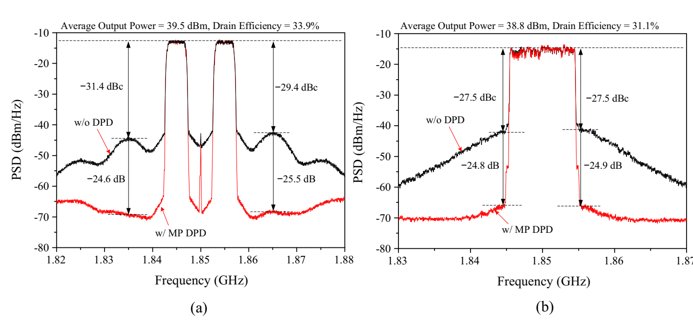

Fig. 7. Measured (a) 2C WCDMA and (b) LTE spectra before and after linearization at 1.85 GHz.

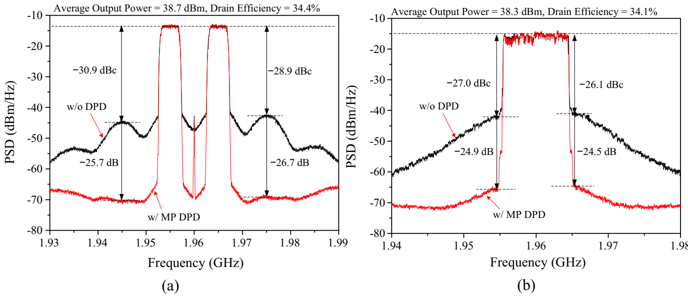

Fig. 8. Measured (a) 2C WCDMA and (b) LTE spectra before and after linearization at 1.96 GHz.

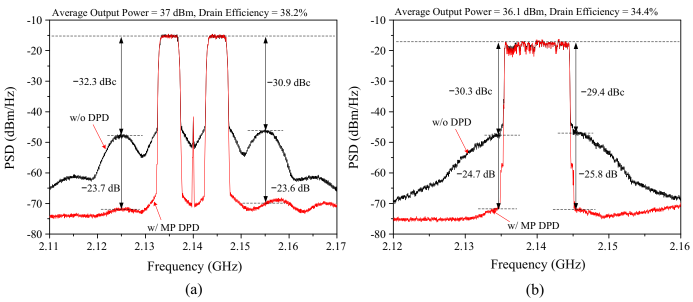

Fig. 9. Measured (a) 2C WCDMA and (b) LTE spectra before and after linearization at 2.14 GHz.

termination is added; thus, about 14% efficiency enhancement is obtained. This confirmed the strong dependency of the efficiency of the SPA on the second harmonic terminations, which were exploited to maintain high efficiencies over a large frequency band, using the distributed circuits.

III. Experimental Results

This section expounds on the measurement results used to validate the outcomes of the three second-harmonic termination-based broadband SPA, in terms of bandwidth broadening, when compared to conventional SPA. Fig. 5 shows the photograph of this PA prototype, which was designed using the 45 W GaN HEMT where the operation conditions are the same as those explained in the previous section.

Fig. 6 shows the measured drain efficiency, output power, and power gain versus frequency under CW stimulus. The proposed broadband SPA with the three second-harmonic terminations can achieve a significant efficiency improvement over the entire frequency range. About 11% and 7% enhancements for 1.85 GHz and 1.96 GHz, respectively, are obtained when compared to the conventional SPA. Drain efficiencies of greater than 60% (avg. 66%) are carried out between about 1.77 GHz and 2.27 GHz (a 500 MHz bandwidth). This result represents a 25% bandwidth at a center frequency of 2 GHz which is equivalent to 150 MHz bandwidth enhancement compared to the conventional SPA. The experimental results confirmed the simulation results with the exception of a slight frequency-shift. They are also the first-pass design results without any post fabrication PA tuning.

The appropriateness of the proposed PA in the context of multi-band/multi-mode application was validated using 2C WCDMA and LTE signals that were operated at 1.85 GHz, 1.96 GHz, and 2.14 GHz. The PAPR of these signals were 6.5 dB and 9.2 dB, respectively, at the 0.01% level in the complementary cumulative distribution function (CCDF). A memory polynomial digital predistortion (DPD) technique is used to linearize the proposed PA. Figs. 7, 8, and 9 show the measured 2C WCDMA and LTE spectra before and after linearization. These experimental results satisfy the linearity specification of the corresponding standards while achieving a high efficiency. This demonstrates the viability of a high efficiency and multi-band/multi-mode PA.

IV. Conclusions

In this paper, a new broadband SPA with distributed second harmonic termination is proposed to expand the frequency range where the SPA can achieve a maximum efficiency for multi-band/multi-mode applications. Unlike a broadband matching topology of a conventional broadband PA, the proposed matching topology reduces the frequency dispersion of the second harmonic termination with respect to frequency. It is a much simpler matching topology compared to a conventional broadband PA. The proposed PA is fabricated using the 45 W GaN HEMT device. Drain efficiencies of greater than 60% (avg. 66%) are achieved between about 1.77 GHz and 2.27 GHz (25% bandwidth). When driven with LTE and 2C WCDMA signals at DCS1800, PCS1900, WCDMA bands, the linearity specifications of the corresponding standards are satisfied using the DPD technique, and an efficiency of greater than 30% is obtained. We expect that the proposed PA can achieve a high average efficiency over 500 MHz when used with the envelope tracking technique.

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