Broadband Operation of Class-E Power Amplifier with Shunt Filter

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***Abstract*—This work proposes a new approach for designing broadband class-E power amplifier (PA) with shunt filter. The approach is based on the double reactance compensation technique. Using this technique reactance variation of loaded Q-factor of a shunt filter and parameters of L-shaped matching circuit are adjusted to minimize variation of load impedance at the device drain across frequency range. Based on this concept, a 10W output power class-E PA was designed, optimized in circuit simulator Keysight ADS and fabricated using GaN HEMT transistor. The manufactured PA has compact output circuit and provides drain efficiency over 65% across frequency range 1.7 - 2.8 GHz and over 60% drain efficiency across frequency range 1.4 - 2.8 Hz. The measured output power variation is 2 dB.**

I. Introduction

Increasing demand for wireless channel capacity in emerging communication systems has led to the use of wide frequency bands. Using such wide frequency ranges in turn requires design of PAs that are capable of providing high efficiency across given frequency band. Besides, using large-scale antenna arrays with fully digital or hybrid beamforming involves an additional constraint on the PA dimensions. Switch-mode power amplifiers are of particular interest since they can provide high drain efficiency and are widely used in Doherty amplifiers, outphasing amplifiers and envelope tracking transmitters.

The behavior of the class-E PA was described in [1]. Compared to the previously known class-D amplifier it offered better drain efficiency by minimizing the power dissipation during the transistor switching. In order to increase operational bandwidth several structures of the class-E PA have been proposed [2], [3], [4]. However, the maximum frequency range of such a PA is limited by the parasitic drain capacitance of transistor. Another approach to achieve high efficiency across wide frequency range is called continuous class-F PA [5], [6]. Using this technique broadband operation is achieved by proper impedance adjustment at fundamental, 2nd and 3rd harmonics across the required frequency range. However, this approach requires complicated output circuit.

In order to overcome these problems several modified class-E PA structures have been proposed including class-E PA with shunt capacitance and shunt filter [7], [8]. The general structure of such a PA is shown in Fig. 1. The output network consists of a parallel capacitance C, series inductance L, parallel filter L_0C_0, reactance X, which can be inductive or capacitive, and an active load R. In [8] it was shown that optimum parameters of the load network are uniquely defined from the following parameters: output power, operating frequency, supply drain voltage and parameter q defined as:

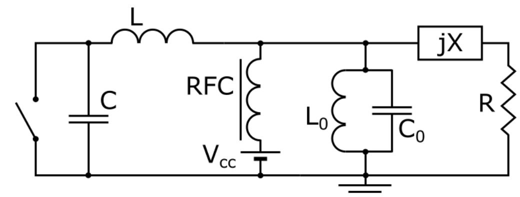

Fig. 1. General structure of a class-E PA with shunt capacitance and shunt filter.

$$q = \frac{1}{\omega\sqrt{LC}} \tag{1}$$

where $\omega = 2\pi f$ is the operating angular frequency. However, the demonstrated PA provides high efficiency across a limited frequency range.

In this paper we demonstrate a class-E PA with shunt capacitance and shunt filter operating across a wide frequency band. The small variation of load network impedance is achieved by means of a double reactance compensation technique. The input and output circuits were simulated using Keysight ADS simulation tool. The proposed PA was implemented using a GaN HEMT transistor CGH40010F.

II. Reactance compensation technique

The reactance compensation technique was initially proposed in [9] as a way of improving gain-frequency response of diode parametric amplifiers. It was shown that the bandwidth of a shunt resonator can be maximized if the first derivative of input susceptance becomes zero at the resonant frequency [10]:

$$\left.\frac{dB}{d\omega}\right|_{\omega=\omega_0} = 0 \tag{2}$$

In a similar manner, the bandwidth of a series resonator is maximized if the first derivative of input reactance becomes zero:

$$\left.\frac{dX}{d\omega}\right|_{\omega=\omega_0} = 0 \tag{3}$$

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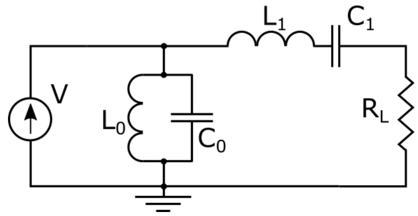

Fig. 2. Reactance compensation of a shunt filter resonator.

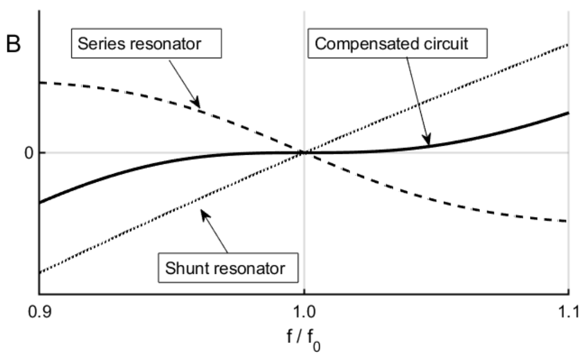

Fig. 3. Input susceptance of a shunt resonator, series resonator and combined compensated circuit.

Fulfilling the condition (2) can be achieved by adding another series resonance circuit to a shunt resonator as shown in Fig. 2. It can be shown that input susceptance of a series resonator increases with frequency whereas susceptance of a shunt resonator decreases. Combined together these two circuits compensate each other providing zero slope of the input susceptance as shown in Fig. 3. This technique was successfully used to improve the bandwidth of class-E PA with finite DC-feed inductance [11] and class-E power amplifiers with shunt filter [7], [12].

In [10] it was shown that the bandwidth of a resonant circuit can be further increased by adding two or more resonant circuits. The potential to improve the bandwidth of class-E power amplifiers was shown in [11]. In this paper the application of the double reactance compensation technique to class-E power amplifier with shunt capacitance and shunt filter is demonstrated.

III. Proposed Broadband PA

As shown in Fig 1, the output circuit of a class-E PA with shunt filter consists of a shunt capacitance C, series inductance L, shunt resonator L_0C_0 and output matching circuit. The shunt capacitance C is usually represented by the output capacitance of a packaged device, and the inductance L is partially represented by the bondwire inductance. The output matching circuit transforms the output load impedance (usually 50 Ohm) to the load impedance required to provide necessary output power. At high frequencies all lumped components are usually replaced with transmission lines. The output matching circuit can be realized as quarter-wavelength transmission line (Fig 4a) or as an L-shaped impedance transformer (Fig 4b). In the former case a transmission line simply provides impedance transformation and therefore only a single reactance compensation can be achieved. In the latter case, the L-shaped circuit is essentially an LC-resonant circuit and therefore can be used to realize double reactance compensation technique and improve the broadband performance of the amplifier.

In the general case the circuit parameters for double reactance compensation technique can be found by solving a system of two equations given by conditions [10]:

$$\left.\frac{dB}{d\omega}\right|_{\omega_0} = 0 \qquad \left.\frac{d^3B}{d\omega^3}\right|_{\omega_0} = 0 \tag{4}$$

However, since the implementation of the output circuit has many additional constraints (providing required impedance, harmonics suppression, width of the microstrip lines, etc.), it is easier to simulate the load circuit using a circuit simulator and to minimize both the first and third derivatives of the input susceptance.

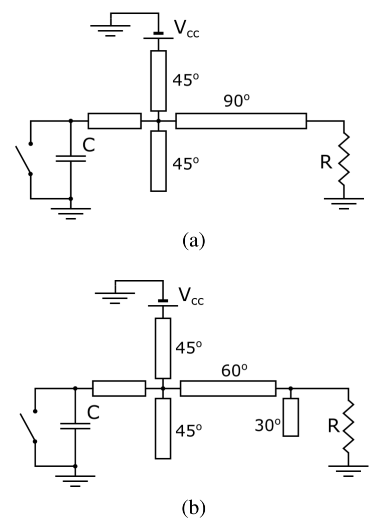

Fig. 4. Output circuit of class-E PA with shunt filter: (a) - with quarter wavelength transmission line; (b) - with L-shaped matching circuit

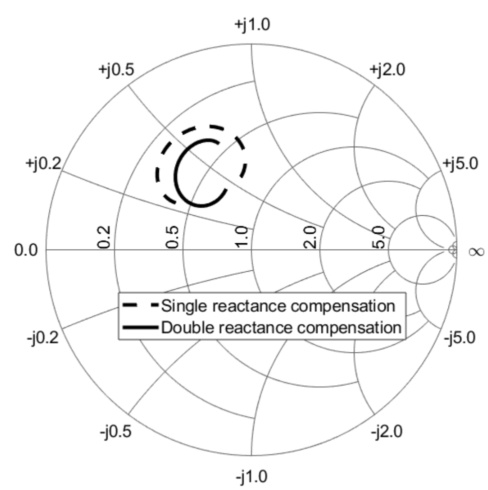

Fig. 5. Simulated load impedance for single reactance compensation and double reactance compensation.

As a result, two output circuits have been simulated: with single reactance compensation technique (as shown in Fig. 4a) and with double reactance compensation technique (as shown in Fig. 4b). Both of the circuits were optimized for broadband operation and simulated for frequency range 1.4 - 3.1 GHz. The results for simulated load impedance for both circuits are presented in Fig. 5. From these results it can be seen that using double reactance compensation it is possible to provide better load impedance across a wide frequency range.

IV. Implementation and Measured Results

The optimized PA structure was simulated using the harmonic balance solver from Keysight ADS simulation tool. In the simulation a model of GaN HEMT device CGH40010F was used which enabled the optimization of the input and output circuits of the PA taking into account device parasitic reactance. The simulated results for output power and drain efficiency are shown in Fig. 6. The voltage and current waveforms at the 1.8 GHz and 2.7 GHz are presented in Fig 7 and Fig 8. From these plots one can see, that high drain efficiency is provided by minimizing current and voltage waveforms intersection across the frequency range.

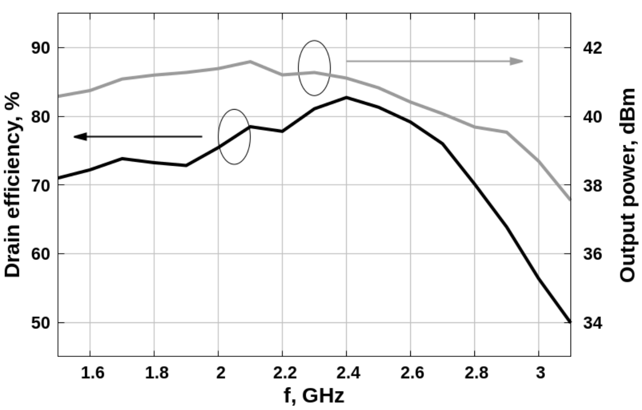

Fig. 6. Drain efficiency and output power of simulated PA.

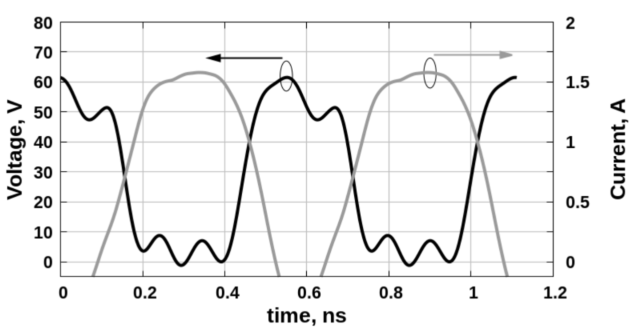

Fig. 7. Simulated drain and current waveforms at 1800 MHz.

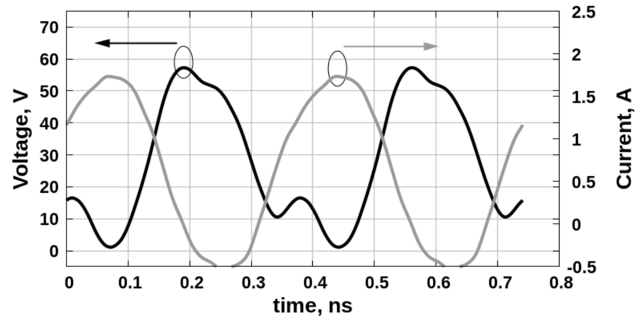

Fig. 8. Simulated drain and current waveforms at 2700 MHz.

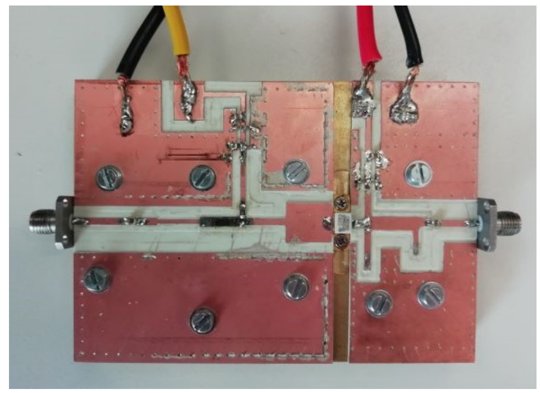

Fig. 9. Fabricated wideband class-E PA.

The optimized PA was manufactured using CGH40010F GaN HEMT packaged transistor as shown in Fig. 9. The input and output circuits were implemented on Rogers RO4350B substrate with dielectric constant 3.66 and thickness 0.762 mm. The fabricated PA has a very compact output circuit ($0.164\lambda \times 0.164\lambda$ mm), which makes it suitable for highly integrated transmitters. The input single-tone signal was generated from HP83712B generator and preamplified to the level of 30 dBm using a linear PA EMPOWER CA90301. The frequency of the input signal was swept from 1.4 to 3.1 GHz keeping the power 1 W. The output power was measured using Rohde&Schwarz NRP-Z23 power meter.

TABLE I
Switch-mode PA comparison.

PA	Class of operation	Frequency	Output power	Drain efficiency
[2]	Class-E	1.9-2.4 GHz	35-38.7 dBm	$> 54\%$
[3]	Class-E	2.1-2.7 GHz	39.7-41 dBm	$> 56\%$
[3]	Class-E	2.0-2.5 GHz	38.5-41.1 dBm	$> 75\%$
[6]	Class-F	2.15-2.65 GHz	40.6-41.8 dBm	$> 65\%$
[7]	Class-E	1.4-2.7 GHz	39.7-41.5 dBm	$> 63\%$
This work	**Class-E**	**1.7-2.8 GHz**	**40.3-42.3 dBm**	$> 65\%$

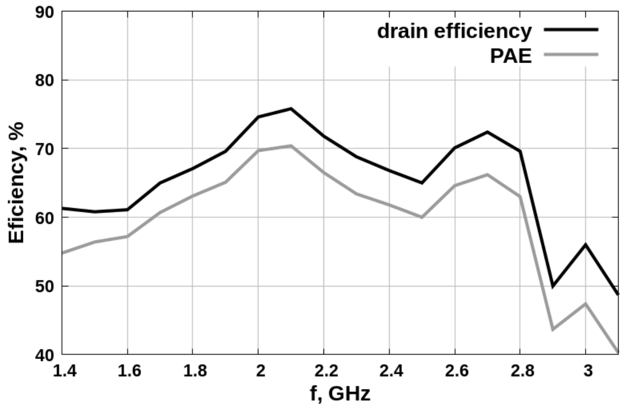

Fig. 10. Measured efficiency of the fabricated PA

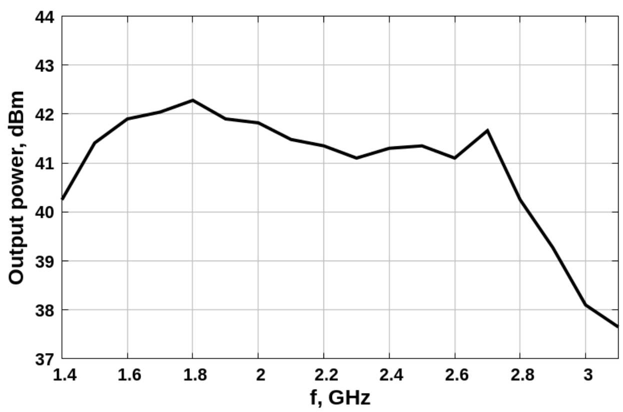

Fig. 11. Measured output power of the fabricated PA

The measured output power and drain efficiency are shown in Fig. 10 and Fig. 11. From these plots one can see that the proposed PA provides over 65% drain efficiency across frequency band 1.7 - 2.8 GHz and over 60% drain efficiency across frequency band 1.4 - 2.8 GHz. The variation of output power is 2 dB across frequency range 1.4 - 2.8 GHz.

V. Conclusion

A broadband class-E PA with shunt capacitance and shunt filter has been described. In the proposed design an L-shaped output matching section and shunt resonator are used to compensate the reactance variation of LC-circuit. The proposed technique has been demonstrated on a PA built using a GaN HEMT transistor. The fabricated PA shows over 65% drain efficiency across frequency range 1.7-2.8 GHz, 60% drain efficiency across frequency range 1.4-2.8 GHz, and 2 dB variation of output power. The fabricated PA has a very compact output circuit which makes it suitable for highly integrated 5G transmitters.

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