A Compact 12-Watt High-Efficiency 2.1-2.7 GHz Class-E GaN HEMT Power Amplifier for Base Stations

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Abstract — **A compact broadband class-E power amplifier design is presented. High broadband power efficiency is observed from 2.0-2.5 GHz, where drain efficiency >74% and PAE >71%, when using 2nd-harmonic input tuning. The highest in-band efficiency performance is observed at 2.14 GHz from a 40V supply with peak drain-efficiency of 77.3% and peak PAE of 74.0% at 12W output power and 14dB gain. The best broadband output power performance is observed from 2.1-2.7 GHz without 2nd-harmonic input tuning, where the output power variation is within 1.5dB and power efficiency is between 53% and 66%.**

Index Terms — **Base station, broadband, class-E, gallium nitride (GaN), high electron mobility transistor (HEMT,) power-added efficiency (PAE), power amplifier (PA), RF circuit design.**

I. INTRODUCTION

In modern cellular base stations, power efficiency and linearity are the key requirements in the design of the power amplifier (PA). However, the increasing number of frequency bands and wider band standards (e.g. 3G-LTE) make RF bandwidth and modulation bandwidth equally important requirements for the complete transmitter and PA design. The main challenge to the designer is applying the right circuit design topology and choosing an appropriate semiconductor technology to enhance efficiency and linearity over a broad bandwidth. Among the high efficiency PA family (class D, E, and F), the class-E switch-mode amplifier is a good candidate for its rather simple matching network and it's well-described design methodology [1]-[5]. Although very high efficiencies have been recently reported for class-F PAs [6], the use of harmonic traps in the load network makes such PAs rather narrow band. In the family of class-D PAs, current-mode class-D can operate across a wide bandwidth, however a more complex input and output matching network is required, including baluns or hybrids [7]. Regarding the semiconductor technology for the switching device in a class-E PA, Si LDMOS devices have been the preferred choice up to 1 GHz, but the large output capacitance limits its use for higher switching frequencies. In recent years, wide band-gap and high electron mobility transistor (HEMT) technologies have gained more interest, such as gallium nitride (GaN). This technology enables high efficiency, high power density and wide band PAs due to its rather low input and output capacitance.

In this paper, a compact broadband class-E PA is presented that uses a dedicated power module design to implement the desired broadband class-E matching network. The PA design is aimed for 2.1-2.7GHz and uses a 3.6mm GaN HEMT die. The paper also shows the benefit of applying second-harmonic input tuning to improve the switching behavior and enhance the efficiency of the class-E PA. Finally, the experimental results are benchmarked against previously reported state-of-the-art results on broadband class-E GaN HEMT PA designs.

II. BROADBAND CLASS-E PA DESIGN AND IMPLEMENTATION

Fig. 1 shows the circuit schematic of our broadband class-E power amplifier. The output network consists of a parallel circuit of the finite dc-feed inductor L_f and the device output capacitance C_{DS}; and a series resonator circuit L_{f0}-C_{f0}, which form a broadband class-E matching network [2]. The use of a finite DC-feed inductance has advantages in terms of output power, maximum frequency of operation and results in a higher load resistance than the classical RF-choke class-E PA configuration [3], [4].

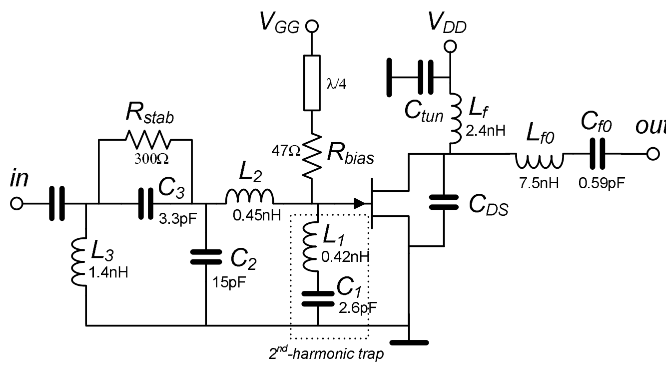

Fig. 1. Circuit schematic of the broadband class-E power amplifier. Second-harmonic input tuning is applied to approximate a square-wave gate drive.

Ideally, the class-E PA needs to be driven with a square-wave signal at the gate of the transistor [5]. However, since we did not implement a PA driver circuit, we make use of the nonlinear gate capacitance of the GaN HEMT to shape the gate voltage drive waveform. To do this, the second harmonic signal is short circuited at the gate by L_1 and C_1. The remaining circuit elements L_2-C_2 and L_3-C_3 form a band-pass input matching network towards the 50-Ω source. The resistors R_{stab} and R_{bias} make the PA unconditionally stable both at high and low frequencies and also form the gate bias network.

Fig. 2 shows a cross section of the prototype power amplifier module that was developed for our class-E PA. The module consists of a 2-layer Rogers laminate with ε_r = 3.5, mounted on a brass plate for cooling. The thickness of the upper laminate is 6.6 mils and nearly levels with the surface of the GaN die. This keeps the series drain bond-wire inductance as short as possible and minimizes its influence on the ideal parallel-tuned class-E operation. The thickness of the bottom laminate is 40 mils and matches with the thickness of our standard flange (SOT896).

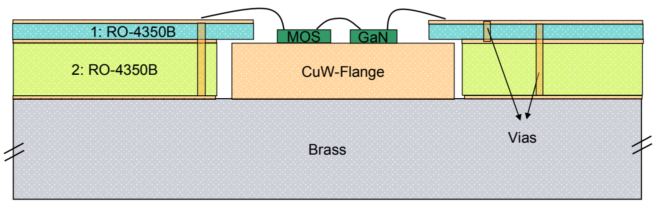

Fig. 2. Power module cross section.

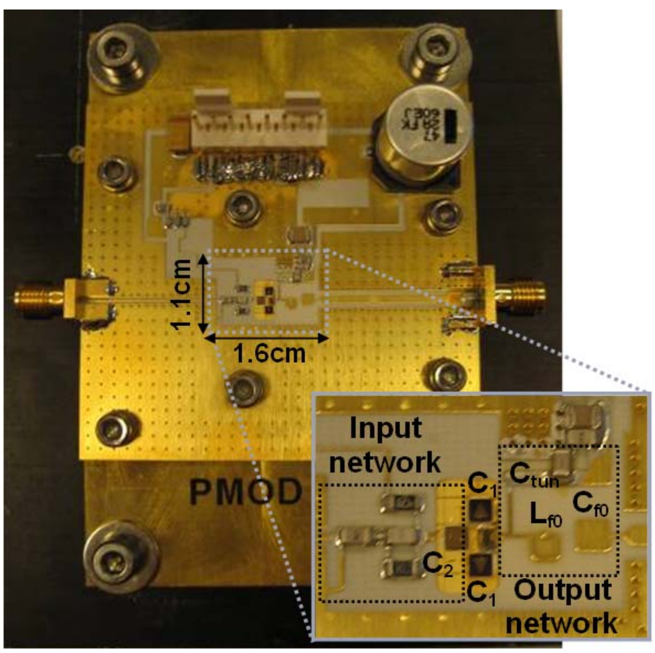

Fig. 3. Practical implementation of the compact broadband class-E GaN power amplifier module.

Fig. 3 shows the practical implementation of the power module. The actual size of the class-E PA including input and output matching is only 1.1cm x 1.6cm. At the input of the GaN device, inductors L_1 and L_2 are implemented with bond-wires and capacitors C_1 and C_2 are low-cost low-ESL MOS capacitors that are mounted on the flange next to the GaN transistor. The input 2nd-harmonic trap is placed perpendicular to L_2-C_2 to prevent magnetic coupling; and it is split into two parallel circuits to reduce the effect of spread in the bond-wire inductance. The feed inductor L_f and resonator (L_{f0}-C_{f0}) have been implemented by lumped components using both the top and bottom metal layers of the upper laminate. In this way, we try to prevent the use of bulky transmission-line techniques that are common practice in base-station amplifier design. This approach results in a compact module design that preserves better the resonator's required broadband class-E impedance properties at all harmonics.

In the following, we examine the properties of the series resonator more closely, since it is a critical circuit design element. Fig. 4a shows an equivalent circuit model of the resonator that is extracted from an EM simulation using Agilent's Momentum. The equivalent circuit can be used to analyze the unwanted resonances that are caused by parasitic shunt capacitive elements. Fig. 4b shows the impedance characteristic of the resonator, when node n_3 is tied to ground. The wanted resonance is at 2.2 GHz and a parasitic resonance appears at 5.9 GHz where the circuit presents an open at node n_1. The latter resonance is mainly attributed to the parasitic capacitors C_{p12} and C_{p1} that are low due to the resonator being electrically small. Therefore, the desired high impedance characteristic (>500Ω) is maintained from 4.2 to 8.1 GHz, which include the 2nd-harmonic and 3rd-harmonic of our desired 2.1-2.7GHz band.

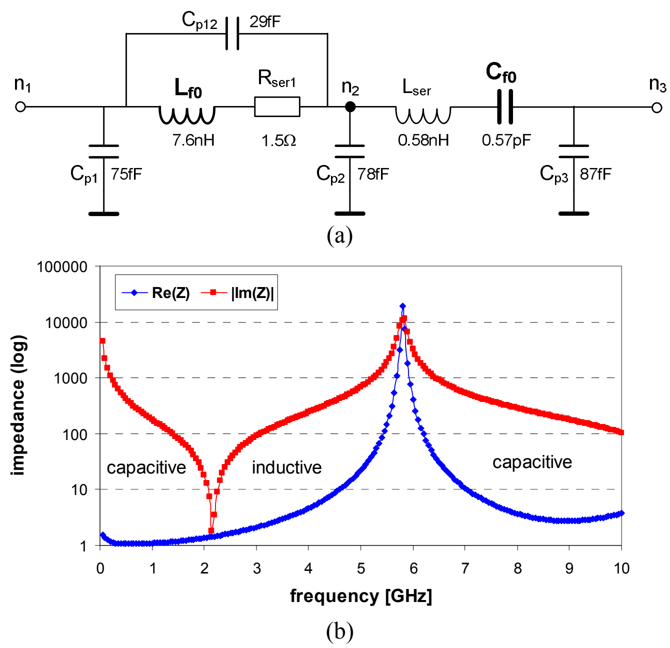

Fig. 4. (a) Equivalent circuit model of the output series resonator (L_{f0}-C_{f0}) of the class-E power amplifier with (b) its impedance characteristic. Note that the magnitude is taken for the imaginary part of the impedance to plot it on a log scale.

Fig. 5 shows the simulated frequency response of the class-E power amplifier when an ideal square-wave signal drives the gate of the transistor. To obtain these results, the complete output matching network was modeled based on EM simulations and appropriate component values were assumed for the SMD capacitors. Moreover, throughout the power amplifier design process we have made use of the supplied GaN HEMT large-signal models [8]. Simulations predict

>78% drain efficiency and >70% PAE across the 2.1-2.7GHz bandwidth and an output power variation of not more than 1.8dB. The estimated losses of the output matching network are around 0.25dB, which corresponds to a >82% device-level drain efficiency across the band of interest.

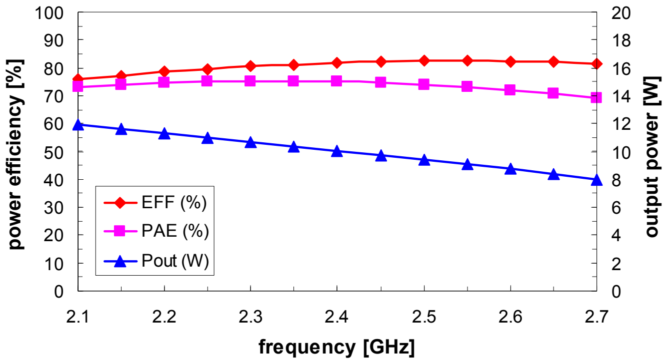

Fig. 5. Simulated drain efficiency, PAE, and output power versus frequency for the broadband class-E GaN SMPA, biased at V_{DD} = 35V with ideal square-wave gate drive. Simulations are based on the Momentum S-parameter dataset of the complete output network.

III. EXPERIMENTAL RESULTS

Fig. 6 shows the measured frequency response of the class-E PA at V_{DD} = 40V and a constant input power P_{IN} = 600mW.

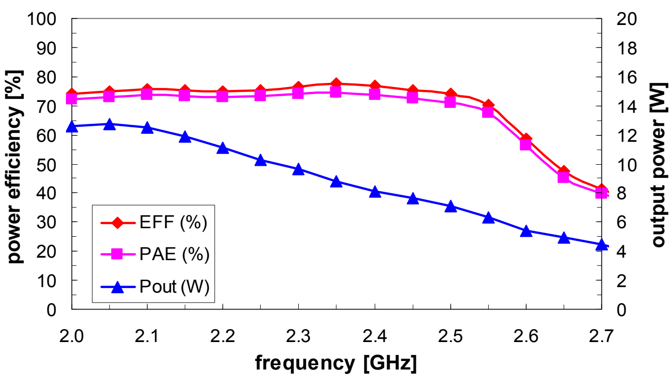

Fig. 6 Measured output power, drain efficiency, and PAE versus frequency with 2nd-harmonic input tuning. Supply voltage V_{DD} = 40V and input power excitation P_{IN} = 600mW.

The drain efficiency and PAE remain above 74% and 71% from 2.0-2.5 GHz, respectively, and drop down to 40% at 2.7GHz. The reason for that is a slight miss-tuning of the output matching network in combination with the 2nd-harmonic input resonator. We can partially restore the efficiency for the high-band by lowering the inductance of the DC-feed inductor by shifting the position of capacitor C_{tun}. Fig. 7 shows that power efficiency and output power improved considerably around 2.6GHz after re-tuning the finite DC-feed inductance.

To test the influence of *not* having the 2nd-harmonic input tuning input, we removed the bond-wires. The result in Fig. 8 shows that although the power efficiency dropped below 70%, the output power and efficiency variation is comparable to the simulation results in Fig. 5. This means that the bandwidth of the input and output matching network are according to our specification, but that the 2nd-harmonic input tuning is limiting our output power and efficiency bandwidth.

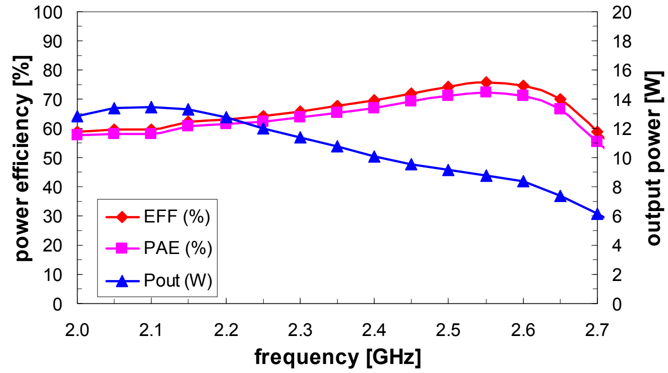

Fig. 7 Measured output power, drain efficiency, and PAE versus frequency with 2nd-harmonic input tuning and after re-tuning the finite DC-feed inductor for 2.6GHz. Supply voltage V_{DD} = 40V and input power excitation P_{IN} = 600mW.

We can, however, conclude that 2nd-harmonic input tuning or square-wave input drive is required for a correct switching behavior of the GaN device in a class-E PA. It results in a power efficiency improvement of more than 8 percentage points as indicated in Fig. 8. Note that the measured and simulated output power matches closest when the supply is increased from 35V to 40V.

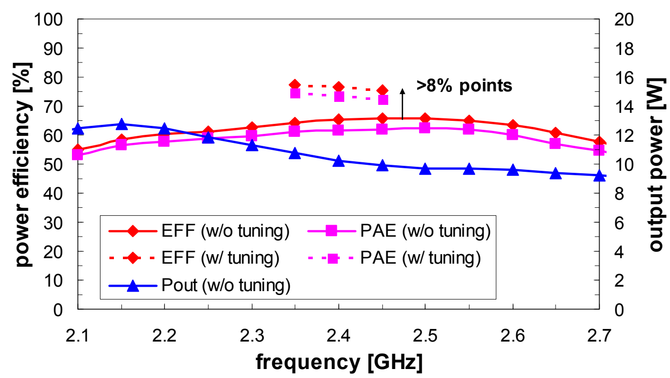

Fig. 8 Measured output power, drain efficiency, and PAE versus frequency after removing the 2nd-harmonic input tuning. Supply voltage V_{DD} = 40V and input power excitation P_{IN} = 600mW.

Note that the high power gain, high efficiency, and abrupt compression behavior at high supply voltages show the potential of GaN HEMT class-E PAs for switch-mode transmitter applications. For completeness, Figs. 9 and 10 also show the power efficiency and power gain plotted against output power for supply voltages ranging from 10V-45V at f_0 = 2.14 GHz. The PAE remains above 60% over 8dB power control range and above 50% over 12dB power control range, which is a good performance when the switch-mode PA is used in combination with average supply tracking.

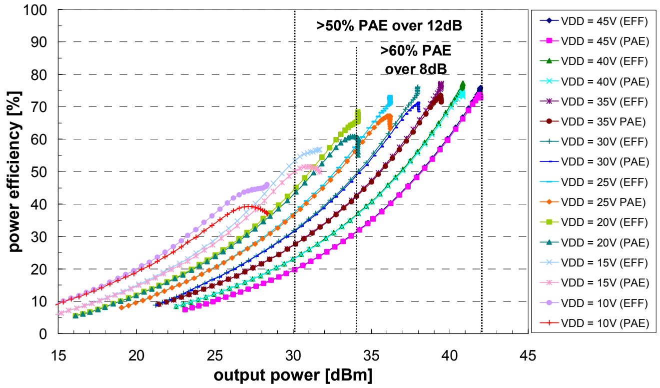

Fig. 9 Measured drain efficiency and PAE versus output power and supply voltage at f_0 = 2140MHz with 2nd-harmonic input tuning.

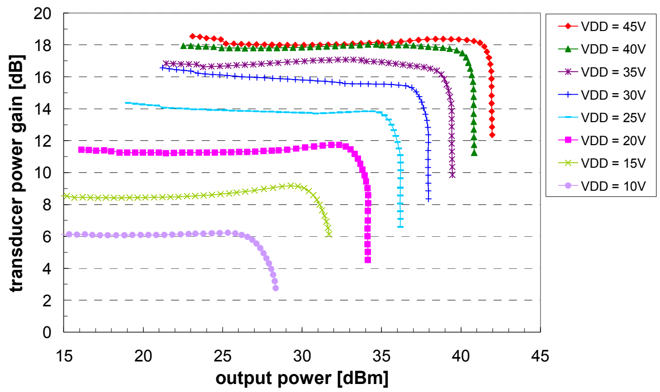

Fig. 10 Measured transducer power gain versus output power and supply voltage at f_0 = 2140MHz with 2nd-harmonic input tuning.

In conclusion, table I shows that this work outperforms the current state-of-the-art in terms of power efficiency of broadband class-E GaN HEMT power amplifiers [9]-[12].

TABLE I
COMPARISON OF CLASS-E GAN PAS

	BW [GHz]	P_{OUT} [W]	PAE [%]	PAE_{PK} [%]
[9]	1.9-2.4	<7.4	>50	57.0
[10]	0.8-4.0	>1.6	>40	55
[11]	2.05-2.25	<20	>60	71.3
[12]	0.7-1.5	<9.8	>30	35
This work	2.0-2.5	7.1-12.8	**>71**	**74**
This work*	2.1-2.7	9.3-12.7	>53	63

*without 2nd-harmonic input tuning

IV. CONCLUSION

In this paper, a compact broadband class-E power amplifier design is presented that uses a dedicated power module implementation. Without 2nd-harmonic input tuning, good broadband output power performance is observed in a 2.1-2.7 GHz band, for which the output power variation is only 1.5dB and power efficiency is between 53% and 66%. With 2nd-harmonic input tuning (approximate square-wave voltage drive), good broadband power efficiency is observed in a 2.0-2.5 GHz band, for which the drain efficiency η > 74% and PAE > 71%. In that case, the output power variation is 2.5dB. The highest in-band power efficiency performance is observed at 2.14 GHz and 40V supply voltage. That is, a peak drain efficiency of 77.3%, a peak PAE of 74.0%, an output power of 12W at 4dB gain compression, and a transducer power gain of 14 dB. Efficiency improvements of up to 8 percentage points are observed compared to having no 2nd-harmonic input tuning.

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REFERENCES

[1] A. Grebennikov and N. O. Sokal, *Switchmode RF Power Amplifiers*, Burlington MA: Elsevier, 2007.

[2] N. Kumar, *et al.*, "High-efficiency broadband parallel-circuit class E RF power amplifier with reactance compensation technique," *IEEE Trans. Microwave Theory & Tech.*, vol. 56, no. 3, pp. 604-612, March 2008.

[3] R. E. Zulinski and J. W. Steadman, "Class E power amplifiers and frequency multipliers with finite DC-feed inductance," *IEEE Trans. Circuits and Systems*, vol. CAS-34, pp. 1074-1087, September 1987.

[4] M. Acar, A. J. Annema, and B. Nauta, "Analytical design equations for class-E power amplifiers," *IEEE Trans. Circuits and Systems-I*, vol. 54, no. 12, pp. 2706-2717, December 2007.

[5] F. H. Raab, "Idealized operation of the class-E tuned power amplifier," *IEEE Trans. Circuits and Systems*, vol. CAS-25, no. 12, pp. 725-735, December 1977.

[6] P. Wright, *et al.*, "Highly efficient operation modes in GaN power transistors delivering upwards of 81% efficiency and 12W output power," *2008 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 1147-1150, June 2008.

[7] A. Al Tanany, *et. al.*, "A 2.14 GHz 50 Watt 60% power added efficiency GaN current mode class D power amplifier," *in Proc. 38th EuMC*, pp. 432-435, Oct. 2008.

[8] R. S. Pengelly, *et al.* (2008, June) Application of non-linear models in a range of challenging GaN HEMT power amplifier designs. [Online]. Available: http: //www.cree.com/products/wireless_docs.asp

[9] H. Xu, *et al.*, "A high-efficiency class-E GaN HEMT power amplifier at 1.9GHz," *IEEE Microwave Wireless Comp. Lett.*, vol. 16, no. 1, pp. 22-24, January 2006.

[10] P. Colantonio, F. Giannini, R. Giofre and L. Piazzon, "High-efficiency ultra-wideband power amplifier in GaN technology," *Electron. Lett.*, vol. 44, no.2, January 2008.

[11] Y.-S. Lee and Y.-H. Jeong, "A high-efficiency class-E GaN HEMT power amplifier for WCDMA applications," *IEEE Microwave Wireless Comp. Lett.*, vol. 17, no. 8, pp. 622-624, August 2007.

[12] S. Azam, R. Jonsson, and Q. Wahab, "Designing, fabrication and characterization of power amplifiers based on 10-Watt SiC MESFET & GaN HEMT at microwave frequencies," *in Proc. 38th EuMC*, pp. 444-447, October 2008.