Design of a Microstrip Broadband LDMOS Class-E Power Amplifier

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This paper describes a 10 watt power amplifier for 1400-1600 MHz range, using an LDMOS FET device operating in Class-E, with broadband matching

The power amplifier (PA) consumes a majority of electrical power in a base station, thus high-efficiency amplification is necessary to reduce power consumption. High-efficiency switch mode PA design (class-E, class-F, etc.) has attracted a heated discussion.

The topology of class-E high-efficiency PA was first introduced by N.O. Sokal and A.D. Sokal in 1975 [1], the simple structure of which makes itself well accepted in high-efficiency amplification design. Many papers have been reported to analyze the operating principles of class-E PA [2-5]. Class-E working condition requires high load impedance at all the harmonics, which makes a wide-band class-E amplifier easier to design than a wide-band class-F amplifier [6]. Therefore, class-E is a good candidate to design a high-efficiency broadband PA.

Some researchers have made contributions that improve the bandwidth characteristic of a normal class-E PA. In [7], A. Grebennikov proposed a method called "reactance compensation technique" to broaden the bandwidth of class-E switch mode amplifier. This technique provides a constant admittance angle over a wide bandwidth at the fundamental frequency where the transistor is operating as a switch. Further research implemented this kind of technique. In [8], an LDMOS-based broadband class-E PA was designed, which indicated the feasibility of the "reactance compensation technique." The shortcoming of this design is its low frequency range (VHF band). LDMOS devices have been widely used in PA design for base stations due to their mature technology and relatively low cost. However, the large output capacitance of an LDMOS transistor limits its use for higher switching frequencies, especially in broadband designs.

Another technique to design a broadband class-E PA using LDMOS transistor is based on a modified load network [9]. It also works at a low frequency band of VHF, like the amplifier mentioned in [8].

In this article, the potential of using an LDMOS transistor for broadband class-E PA has been exploited. A class-E PA working at the frequency band from 1400 MHz to 1600 MHz was designed and implemented through an approach based on microstrip lines and broadband matching techniques. Test results show that the peak in-band PAE is 64.3% and the maximum output power reaches 40.3 dBm (10.7 watts).

Design Considerations

Figure 1 shows the circuit schematic of the proposed broadband class-E PA. The large signal model of the LDMOS transistor MRF21010 was obtained from the manufacturer (Freescale). Two kinds of broadband matching networks are used, a two-section Chebyshev for the input, and multi-section quarter wave networks for the output matching circuit. Both of the networks are based on microstrip lines.

The input impedance of LDMOS transistor MRF21010 is obtained through *S*-parameter simulation using Agilent's Advanced Design System (ADS). In this approach, a two-section Chebyshev low pass character broadband matching network (MN) is used to transform the transistor's conjugate input impedance

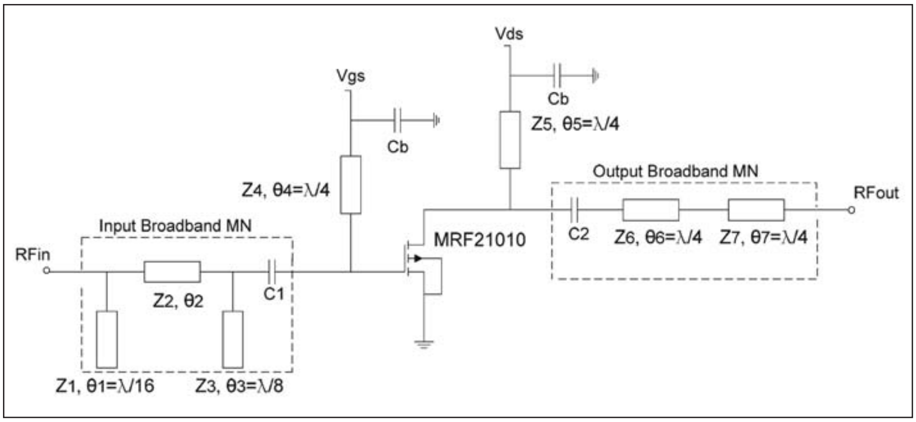

Figure 1 · Circuit schematic of the broadband class-E PA.

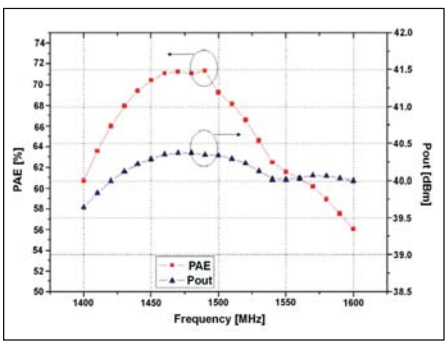

Figure 2 · Simulated PAE and output power versus frequency for this broadband LDMOS class-E PA with V_{ds} = 22 V and P_{in} = 26 dBm.

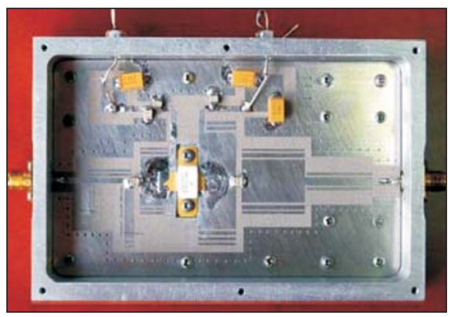

Figure 3 · Photo of broadband LDMOS class-E PA.

towards 50 ohms. By referring to the tables of Chebyshev impedance transforming networks [10], a refined broadband MN is designed. The return loss of this MN through the designed frequency band is better than 15 dB (VSWR <1.45). The capacitor C_1 in the MN compensates the inductive part of the input impedance which is partially formed by the packaging effects of the transistor. Also, this capacitor works as a DC block component.

Ideally, a class-E PA should be driven by a square wave signal at the gate of the transistor [2]. In the input network, we take steps to shape the gate voltage drive waveform. Two open stubs of two-section Chebyshev network, which are designed as electrical length of λ/8 and λ/16 respectively, help to short-circuit the second and fourth harmonic signal and therefore realize this requirement. The λ/4 feed line at the gate further assists to short-circuit the even harmonic voltage components.

The output capacitance of MRF21010 works as the shunt capacitor of class-E PA, so there is no need of any external shunt capacitor. According to Raab's design equations [2], different frequencies require different values of the shunt capacitor and it brings difficulty to design a broadband switch mode class-E PA. Load-pull simulation is adopted in this paper to help overcoming this shortcoming. A load impedance of 1.292 –j0.807 ohms is obtained by the load-pull method, regardless of the value of the shunt capacitor. The determined load impedance ensures the class-E PA achieves high PAE and high output power simultaneously through the whole designed frequency band.

The high *Q* series LC resonance circuit in the classic class-E topology is the main reason for the constrained bandwidth of class-E PA [1]. In this proposed approach, instead of the LC resonance circuit, a two-section quarter wave broadband MN is used to transfer the conjugate load impedance 1.292+j*0.807 ohms to 50 ohms. This MN presents a band-pass character, the return loss of which is always better than 15 dB (VSWR <1.45).

ADS's Harmonic Balance simulation is carried out after the whole topology determination of this broadband class-E PA. Figure 2 shows the simulation frequency response of the class-E PA. Simulation results show PAE greater than 56% and output power is greater than 39.6 dBm through the frequency band of 1400-1600 MHz. The peak PAE is greater than 70%, and the output power variation is less than 0.8 dB.

Measurement Results

In order to validate the design approach, a testing board of broadband LDMOS class-E PA was fabricated and measured. The substrate is selected as RF-35 from Taconic Co., which has a dielectric constant ε_r of 3.5 and a thickness of 30 mil. A photo of the constructes class-E PA is shown in Figure 3.

Figure 4 presents the measured PAE and output power characteristics according to frequency with an input power of 26 dBm, gate-source voltage of 3.4 V and drain-source voltage of 22 V. As shown in the figure, PAE is greater than 56%, output power is greater than 38.9 dBm and transducer power gain is greater than 12.9 dB for frequencies at the interested band from 1400 MHz to 1600 MHz (relative bandwidth over 13.3%). The peak in-band PAE is 64.3% and the maximum in-band output power is 40.3 dBm (10.7 watts). Over the entire 200 MHz bandwidth, the output power variation is 1.37 dB.

The simulated and measured

	Simulation	Measurement
Drain Voltage (V)	22	22
Frequency (MHz)	1400-1600	1400-1600
PAE (%)	>56	>56
Peak PAE (%)	71.3	64.3
Output Power (dBm)	>39.64	>38.93
Peak Output Power (dBm)	40.37	40.3
Power variation (dB)	0.73	1.37

Table 1 · Comparison of simulated and measured results.

results are compared in Table 1. According to this table, the results of experiment show good agreement with the simulation.

More measurement results of this broadband LDMOS class-E PA are shown in Figure 5. In Figure 5(a), the input power is swept with V_{ds} = 22 V and V_{gs} = 3.4 V. PAE and output power are strictly monotonic, increasing with input power. When the input power is driven at 23 dBm, the output power can go up to 37.6 dBm with a maximum transducer power gain of 14.6 dB.

In Figure 5(b), the drain-to-source voltage is swept with input power equal to 26 dBm and V_{gs} = 3.4 V. The output power monotonically and linearly increases when V_{ds} increases. This character can be utilized in supply tracking applications [11].

In Figure 5 (c), the gate-to-source voltage is swept with the input power equal to 26 dBm and V_{ds} = 22 V. When the gate of the transistor is biased at approximately 3.4 V, the amplifier achieves high PAE and high output power simultaneously. However, when V_{gs} increases above 3.6 V, PAE drops, although output power still increases.

Conclusion

In this paper, a broadband LDMOS class-E PA was presented based on two microstrip broadband MNs. The load-pull technique was used to determine the load impedance of this PA. The measured results showed the design approach successfully. This amplifier works at the frequency band of 1400-1600

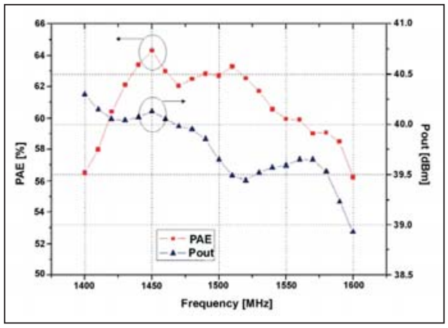

Figure 4 · Measured PAE and output power versus frequency for this broadband LDMOS class-E PA with V_{ds} = 22 V and P_{in} = 26 dBm.

MHz with PAE above 56% and output power greater than 38.9 dBm. The peak in-band PAE is 64.3% and the maximum output power is 40.3 dBm (10.7 watts). The output power variation is 1.37 dB.

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The authors would like to acknowledge Scott Li, Senior Engineer in the Freescale Co., for valuable discussions and opinions about LDMOS nonlinear model.

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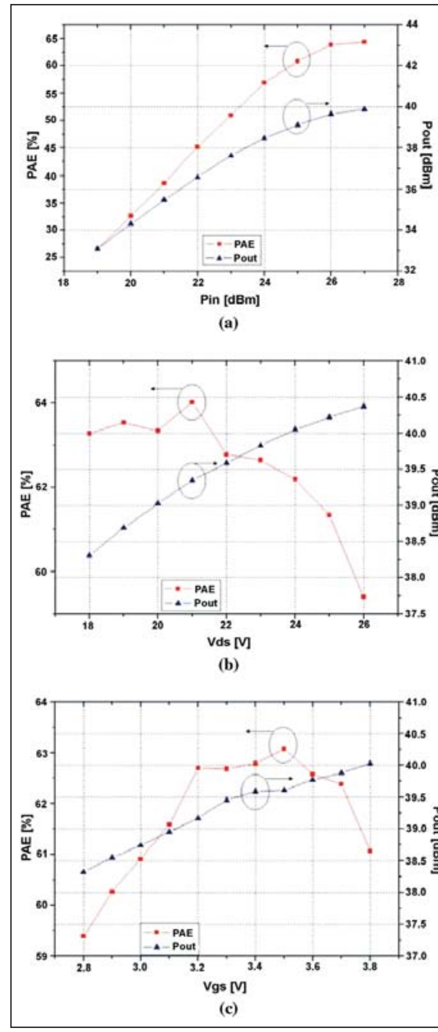

Figure 5 · Measured PAE and output power versus (a) input power, (b) drain-to-source voltage, (c) gate-to-source voltage for this broadband class-E LDMOS PA with f = 1510 MHz.

References

1. N. O. Sokal and A. D. Sokal, “Class E-A new class of high-efficiency tuned single ended switching power amplifiers,” *IEEE J. Solid-State Circuits,* vol. SC-10, no. 3, pp. 168–176, Jun. 1975.

2. F. H. Raab, “Idealized operation of the Class E tuned power amplifier,” *IEEE Trans Circuits Syst.,* vol. 24, pp. 725–735, Dec. 1977.

3. C.-H. Li and Y.-O. Yam, “Maximum frequency and optimum performance of Class E power amplifiers,” *IEEE Proceedings-Circuits, Devices and Systems,* pp. 174-84, Jun. 1994.

4. M. J. Chudobiak, “The use of parasitic nonlinear capacitors in Class E amplifier,” *IEEE Transactions on Circuits and Systems,* vol. 34, pp. 941-944, Dec. 1994.

5. N. O. Sokal, “Class-E switching-mode high-efficiency tuned RF microwave power amplifier: improved design equations,” *IEEE MTT-S,* pp. 779-782, 2000.

6. Saad Shahrani, *Design of Class-E Radio Frequency Power Amplifier,* Blacksburg, Virginia, July, 2001.

7. A. Grebennikov, *RF and Microwave Power Amplifier Design.* New York: McGraw-Hill, 2004.

8. N. Kumar, C. Prakash, A.

Grebennikov, and A. Mediano, "High-efficiency broadband parallel-circuit class E RF power amplifier with reactance-compensation technique," *IEEE Transactions on Microwave Theory and Techniques,* vol. 56, pp. 604-612, Mar. 2008.

9. F. You, S. B. He, T. Cao and X. H. Tang, "Class E power amplifier design with a modified load network," *International Conference on MTT Proceedings,* vol. 1, pp. 120-123, Apr. 2008.

10. G. L. Matthaei, "Tables of Chebyshev impedance–transforming networks of low-pass filter form," *Proceedings of the IEEE,* vol. 52, pp. 939-963, Aug. 1964.

11. C.-C. Chen, H.-Y. Ko, Y.-C. Wang, H.-W. Tsao, K.-Y. Jheng and A.-Y. Wu, "Polar transmitter for wireless communication system," *Proceedings of International Symposium on Intelligent Signal Processing and Communication Systems,* pp. 613-616, Dec. 2005.

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