# Design of class-E GaN HEMT power amplifier using elliptic low pass matching network with 86% efficiency

**Oguzhan Kızılbey**[a)]

*The Scientific and Technological Research Council of Turkey, Tubitak Bilgem, 41470, Gebze, Kocaeli, Turkey*

a) *oguzhan.kizilbey@tubitak.gov.tr*

**Abstract:** In this paper, a highly efficient prototype of Gallium Nitride high electron mobility transistor (GaN HEMT) power amplifier using elliptic low pass filter output network is proposed, fabricated and measured. A fifth-order elliptic low-pass filter network is designed and implemented for the output matching, which provides optimized fundamental and harmonic impedances. Simulation and experimental results show that a Class-E PA is realized from 2.7 to 2.9 GHz with 10-W (40 dBm) output power, 10 dB gain and a measured efficiency of 86%, which is the highest reported today for such a frequency band and output power.

**Keywords:** GaN HEMT, high efficiency, power amplifier

**Classification:** Microwave and millimeter wave devices, circuits, and systems

## 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, June 1975.

[2] F. H. Raab, "Class-F power amplifiers with maximally flat waveforms," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 11, pp. 2007–2012, Nov. 1997.

[3] S. D. Kee, et al., "The class-E/F family of ZVS switching amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 6, pp. 1677–1690, June 2003.

[4] A. Adahl and H. Zirath, "A 1 GHz class E LDMOS power amplifier," *33rd Eur. Microw. Conf.*, vol. 1, pp. 285–288, Oct. 2003.

[5] H. Zirath and D. B. Rutledge, "An LDMOS VHF class-E power amplifier using a high- Q novel variable inductor," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 12, pp. 2534–2538, Dec. 1999.

[6] H. Xu, S. Gao, S. Heikman, S. I. Long, U. K. Mishra, and R. A. York, "A high-efficiency class-E GaN HEMT power amplifier," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 1, pp. 22–24, Jan. 2006.

[7] K. J. Cho, W. J. Kim, J. H. Kim, and S. P. Stapleton, "40 W gallium nitride microwave doherty power amplifier," *IEEE MTT-S Int. Dig.*, pp. 1895–1898, 2006.

[8] W. Nagy, J. Brown, R. Borges, and S. Singhal, "Linearity characteristics of microwave-power GaN HEMTs," *IEEE Trans. Microw. Theory Tech.*,


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013

IEICE Electronics Express, Vol.10, No.2, 1–6

vol. 51, no. 2, pp. 660–664, Feb. 2003.
[9] D. M. Pozar, *Microwave Engineering*, 3rd ed., Wiley, Boston, 2005.
[10] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, 2nd ed., Artech House, Norwood, 2006.
[11] Y. Lee and Y. Jeong, "A high-efficiency class-E GaN HEMT power amplifier for WCDMA applications," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 8, pp. 622–624, Aug. 2007.
[12] P. Saad, C. Fager, H. Cao, H. Zirath, and K. Andersson, "Design of a highly efficient 2–4-GHz octave bandwidth GaN-HEMT power amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 7, pp. 1677–1685, July 2010.
[13] M. P. van der Heijden, M. Acar, and J. S. Vromans, "A compact 12-watt high-efficiency 2.1–2.7 GHz class-E GaN HEMT power amplifier for base stations," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 657–660, June 2009.

## 1 Introduction

In wireless communication systems, a microwave power amplifier (PA) with high efficiency & linearity is required. In recent years, highly efficient PAs are also required for wireless power transmission applications to achieve high-reliable operation. Many types of amplifiers have been reported to improve efficiency, such as class E [1], class F [2], class E/F [3] so far. Among these types of PAs, the class E structure requires an extra shunt capacitor at the output side of the transistor in order to cancel the dissipation power at the active element. However, because every capacitor has a self-resonance frequency, the dissipation power cancellation at higher-order harmonics is rather challenging. Non-ideal series $L_S$-$C_S$ resonant filter in ideal class-E structure causes unwanted harmonics at the output, which results in degradation of the amplifier performance. Also output capacitor of the transistor has extra amount of required capacitance for class-E operation. To overcome these practical design problems, effect of this excess capacitor must be eliminated and $L_S$-$C_S$ resonant circuit must be replaced with elliptic low-pass matching network. By this way, all harmonic signals are reflected before the resistive load. For the input circuit, the second harmonic is treated. Based on this method, a high-efficiency PA was developed with elliptic low-pass matching output network at the 2.7–2.9 GHz band using a GaN HEMT.

## 2 GaN HEMT

For the switching mode PA topologies in the class-E, Si LDMOS devices have been frequently used around 1 GHz, but the large output capacitance limits the operation of the class-E amplifier over the 1 GHz using these transistors [4, 5]. Therefore, wide-bandgap devices have been recently developed for high power and high efficiency PAs at frequencies over 1 GHz. Because of the fact that the peak drain voltage of the transistor in the class-E amplifier reaches a maximum of two and a half times the dc drain voltage, high breakdown voltage is compulsory. Among wide band gap transistors, the GaN HEMT has been regarded as a major alternative device for Si LDMOS [6, 7, 8]. These devices have low and voltage-


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013

IEICE Electronics Express, Vol.10, No.2, 1–6

independent output capacitance, high thermal conductivity, high break-down voltage and high electron saturation velocity. Especially, low and voltage independent output capacitor of the GaN transistor provides to replace the shunt capacitor in the ideal class-E structure. These characteristics are very important to realize high-efficiency PAs.

## 3 Class-E PA using elliptic-low-pass output matching network

### 3.1 Design of elliptic low-pass matching network

From the ladder-based networks only the low-pass and band-pass behaviors are useful. However, a conventional low-pass filter or a conventional band-pass filter do not lead to the optimal behavior because of the restrictions imposed in their out of band behaviors, which do not yield the minimum possible in-band ripple and faster transition in gain between the pass-band and the stop-band. Consequently, the elliptic low-pass matching network approach is selected instead of Chebyshev or Butterworth low-pass filters to realize this Class-E PA.

To compare these 3 filter types, iFilter wizard of AWR Microwave Office CAD tool was used. Design parameters are as follows: Degree of filter is 5, ripple in pass band is 0.01 dB, corner frequency is 3000 MHz, source and load impedances are 19 Ω which is necessary for maximum power transfer. These types of filters with mentioned specifications are designed and insertion loss parameter is compared with each other in Fig 1.

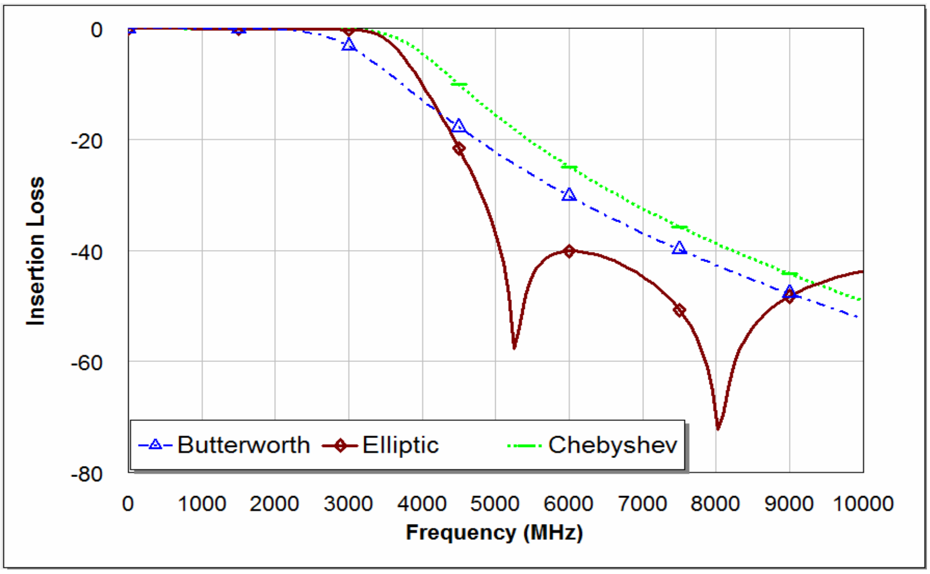


**Fig. 1.** Insertion loss of elliptic, butterworth and chebyshev filters.

As shown in Fig 1. elliptic filter has the fastest transition between pass-band and stop band. According to the simulation results, $2^{nd}$ and $3^{rd}$ harmonics are suppressed approximately 60 and 70 dBc with elliptic filter. Butterworth and Chebyshev type filters suppressed these harmonics 25 dBc, 40 dBc and 15 dBc, 35 dBc, respectively. Suppressing $2^{nd}$ and $3^{rd}$ harmonics enough will lead the whole PA structure to high efficiency. Among mentioned filter structures, the elliptic structure is the best one to improve the efficiency by suppressing harmonics.


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013

IEICE Electronics Express, Vol.10, No.2, 1–6

### 3.2 Realization of elliptic low-pass matching network with micro-strip lines

The most preferred way to implement the designed elliptic low-pass matching network is to build it with lumped elements, as shown in the Fig 2. The filter design is conducted and optimized with iFilter tool of AWR Microwave Office. The desired output impedance of the GaN transistor has a real part from 18 to 20 Ω and an imaginary part varying from 9 to 7 Ω. Because the imaginary part has small amplitude, matching will only be considered as 19 to 50 Ω.

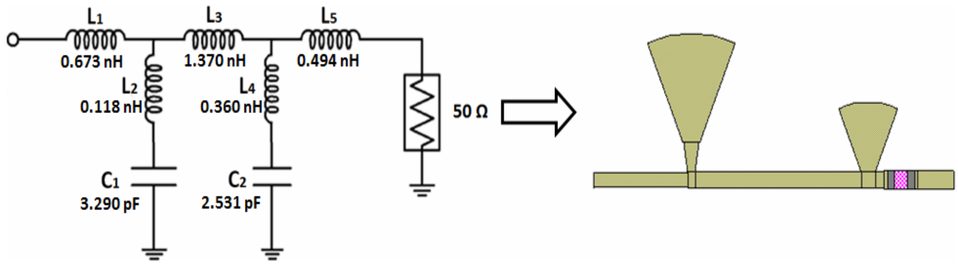


**Fig. 2.** Lumped and distributed equivalent of elliptic low-pass matching network.

However, getting high-quality inductors and capacitors at the desired frequency range is very difficult. So, the elliptic low-pass matching network is implemented with distributed elements in this paper. The inductors are replaced by high impedance transmission lines and the capacitors are replaced by low impedance open circuit radial stubs by using short line approximation theory expressed in [9, 10]. This theory provides a starting point to run a computer aided based optimization. The parameters of this matching network are optimized using AWR Microwave Office together with the CREE CGH40010P transistor to achieve an optimal Class-E PA performance. At last stage, 19 Ω is matched to 50 Ω with 30 Ω, $\lambda/4$ transmission line.

## 4 Implementation and experimental results

To validate the proposed topology, a prototype board of the PA circuit is realized on a Rogers 5880 PCB material which has 10 mil thickness and 2.2 dielectric constant. A photograph of the prototype board is shown in Fig. 3. Drain and gate voltages were set to 28 V and −3.6 V, respectively. In the measurement, the RF signal is generated from a Rohde Schwarz SMIQ06B signal generator and amplified by the Mini-Circuits, ZHL-16W-43+ preamplifier to supply a sufficiently large driving power for the PA block around 30 dBm. Input and output RF powers were measured by using a Rohde Schwarz power meter. As the results of the various simulations a maximum power added efficiency (PAE) of 82%, maximum drain efficiency ($\eta_D$) of 85% and a saturation power of 40 dBm were estimated. The maximum PAE of 83% and a maximum drain efficiency of 86% were obtained from the measurements which were carried out over the 2.7–2.9 GHz band. It was also observed that the 2$^{nd}$ and 3$^{rd}$ order harmonics were suppressed as −40 dBc.

Measured and simulated frequency response of the PA is shown in Fig. 4. A quite substantial correlation between the simulation and


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013

IEICE Electronics Express, Vol.10, No.2, 1–6

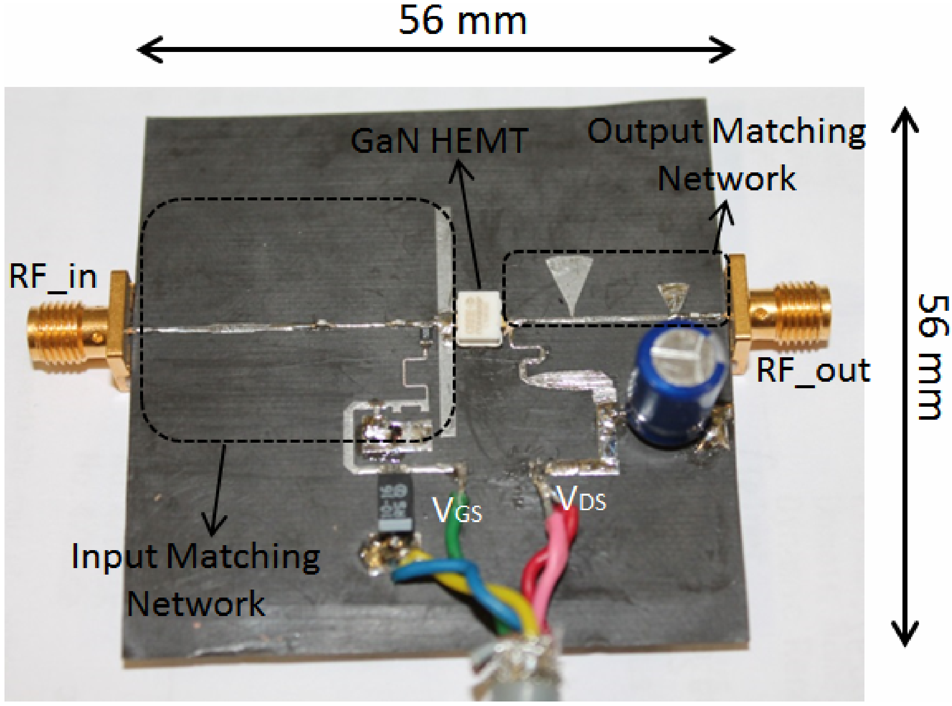


**Fig. 3.** Photograph of a fabricated class-E GaN HEMT PA.

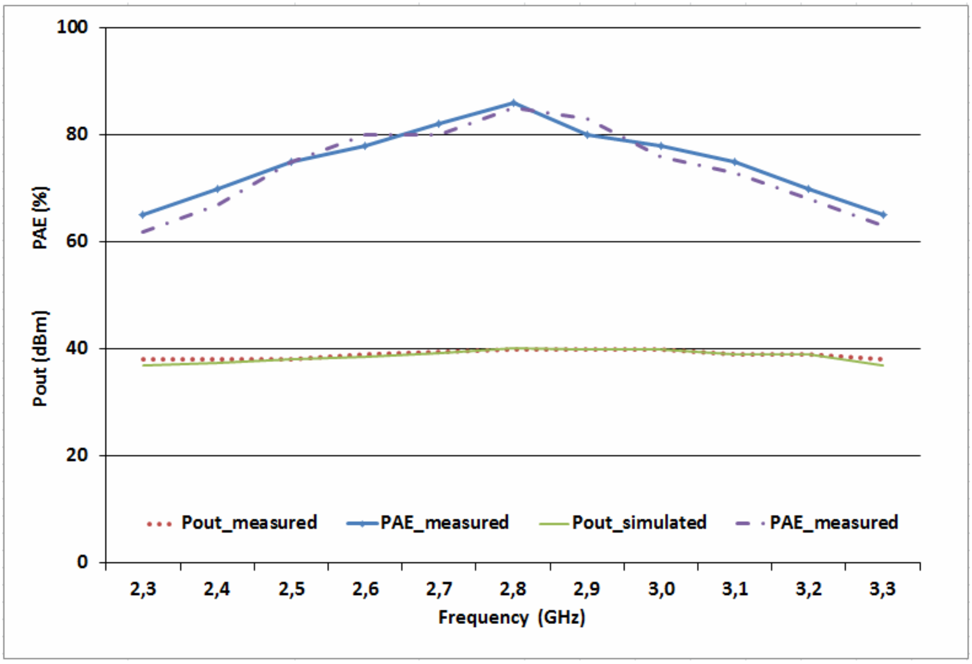


**Fig. 4.** Measured and simulated frequency response.

measurements is achieved through AWR modeling of complete layout structure.

Measured and simulated input-output power response and efficiency is shown in Fig. 5.

Table I shows a summary of the measured results compared with other high-efficiency amplifiers that have so far been reported in the literature.


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013

ELectronics EXpress



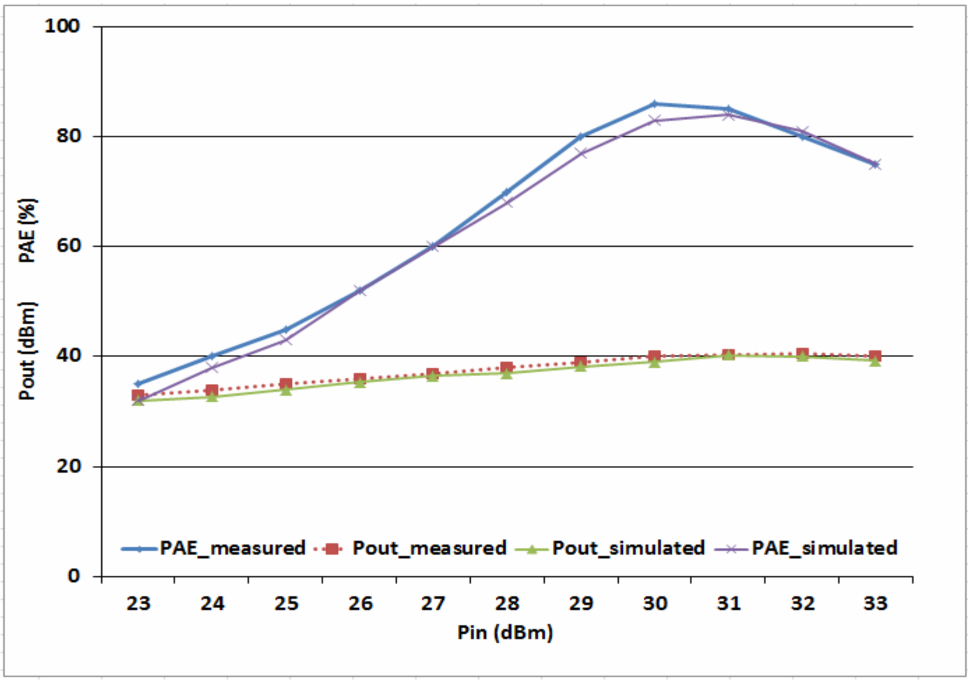


**Fig. 5.** Measured and simulated input-output power response and efficiency.

**Table I.** Comparison of characteristics.

| Ref. | Frequency (GHz) | PAE (%) | $\eta_D$ (%) | Transistor |
|---|---|---|---|---|
| [11] | 2.14 | 70 | 75 | GaN HEMT |
| [12] | 2-4 | 62 | 72 | GaN HEMT |
| [13] | 2.1-2.7 | 74 | 77 | GaN HEMT |
| [4] | 1 | 67 | 73 | Si LDMOS |
| This work | 2.7-2.9 | 83 | 86 | GaN HEMT |

## 5 Conclusion

In this letter, a highly efficient class-E PA using a GaN HEMT was designed and fabricated. To improve output power and efficiency by suppressing harmonic powers, an output circuit using the elliptic low pass matching network was used. For a single tone, harmonic power levels were maintained below −40 dBc over the output power range of 40 dBm. The peak PAE of 86% with a power gain of 10 dB was achieved at a $P_{out}$ of 40.2 dBm at 2.8 GHz. The broadband performance with a power gain over 10 dB and PAE over 80% was maintained through 200 MHz. From the measured results, it is worth noting that the elliptic low-pass output matching network can make the class-E switching-mode amplifier deliver high output power and high efficiency over 2.7–2.9 GHz band.


DOI: 10.1587/elex.10.20120960
Received December 21, 2012
Accepted December 26, 2012
Published January 29, 2013