RESEARCH ARTICLE

Engineering Reports Open Access

A Wideband 0.9-2.4 GHz 25 Watt High-Efficiency GaN RF Power Amplifier

Tanghid B. Rashid*[1] | Dr. Heather Song[2]

[1]Department of Electrical and Computer Engineering,University of Colorado at Colorado Springs,1420 Austin Bluffs Parkway, Colorado Springs, CO 80918 United States

[2]Department of Electrical and Computer Engineering,University of Colorado at Colorado Springs,1420 Austin Bluffs Parkway, Colorado Springs, CO 80918 United States

Correspondence
*Tanghid B. Rashid
Email: trashid@uccs.edu

Abstract

In this work, a 0.9-2.4 GHz, 25 Watt output power, radio frequency (RF) power amplifier based on Class-E switchmode topology has been analyzed. A load-pull simulations method is used to optimize the power performance in the operating band. To design input and output matching networks an optimized low pass filter network was used. Simulated results of the power amplifier (PA) demonstrate wideband behavior which covers a 0.9 GHz to 2.4 GHz band with an efficiency of 32-78%, and an output power of 25 W (44 dBm), and an average gain of 20 dB. The designed PA provides attractive features associated with a wider band, high gain, and efficiency, which makes it a proper candidate for the mobile transmitter and cellular infrastructure applications.

KEYWORDS

Power added efficiency, high gain, high power, wideband, class-E, switchmode, RF power amplifier, filter matching network, GaN-HEMT.

I. INTRODUCTION

RF power amplifiers (PAs) play a vital role in modern wireless communication systems specifically in system transceiver block. Due to the demand for ever-increasing bandwidth along with high output power and efficiency, efforts to enhance the power amplifier performance in the discrete subsystem will continue for foreseeable future. From an application perspective, cellular communications systems e.g. 4G/5G need to operate in multiband that means it's essential for designed PA to cover a wide frequency band and would also require a high data rate which defines increased signal bandwidth. In order to avoid the adjacent channel interference designed PA also need to operate at 6- dB backoff [1]. High-efficiency PAs are commonly narrowband ones since the optimum impedances to achieve maximum efficiency and maximum power would require narrowband matching networks. Thus, realizing high power, high gain, and efficient PAs design along with wideband response has become a challenging task and critical area of research.

In the course of the most recent year's RF GaN-HEMT, transistor technologies have been fully developed, it is now considered a reliable PA technology. Gallium Nitride (GaN) improves overall efficiency in the RF network by offering high power-added efficiency (PAE), gain, and ease in impedance matching [2].

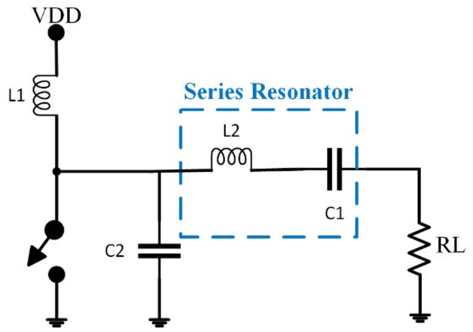
By far several techniques have been implemented by researchers and using switch-mode topologies Class-D, Class-E, and Class- F and inverse Class-F most of the high-efficiency PAs are designed [3-10]. An ultrawideband PA was designed in [11-12] using a broadband matching network that takes consideration of optimum input and output load conditions to increase PA power and efficiency. Though the design has significantly low efficiency which is less than 50%.

In this work, a broadband (0.9 GHz – 2.4 GHz), a 20 dB average gain, a highly efficient 25 W class E PA based on GaN High Electron Mobility Transistor (HEMT) has been designed using optimized matrching circuit. To meet the design requirement CG2H40025 25W, 28 V RF power GaN HEMT device manufactured by Wolfspeed [13] has been chosen. Based on the datasheet the transistor can operate up to 6 GHz with a 17 dB gain at 2.0 GHz and an operating drain voltage is 28 V. The proposed design was simulated using Keysight Advanced Design System (ADS) electromagnetic software with a 20mil Rogers RT/duroid 5880 high-frequency laminates. To achieve high gain and efficiency a distributed elements method has been used to design input matching network (IMN) and output matching network (OMN). The designed PA demonstrates PAE of 32-78% over a bandwidth of 1.5 GHz.

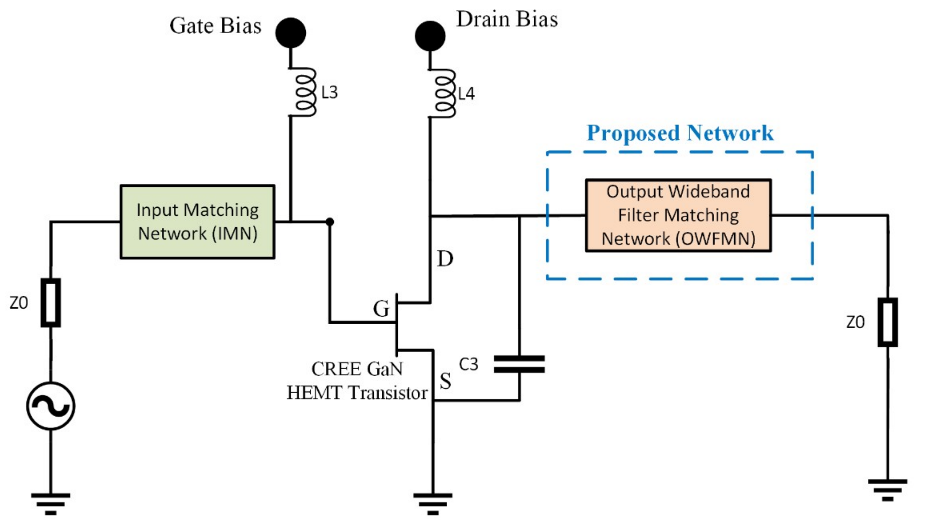
II. DESIGN AND OPTIMIZATION OF WIDEBAND PA

A. Broadband Class-E PA topology

Common broadband matching networks are small reflection theory, magnetic coupling structure, multistage low-pass ladder network, and multistage bandpass ladder network [14]. In this design, we followed a similar approach that was presented in [14] to design and optimize broadband input matching network and distributed element implementation of the low pass output matching network.



(a) Ideal Class-E power amplifier topology



(b) Proposed wideband Class-E PA topology with filter matching network in the output

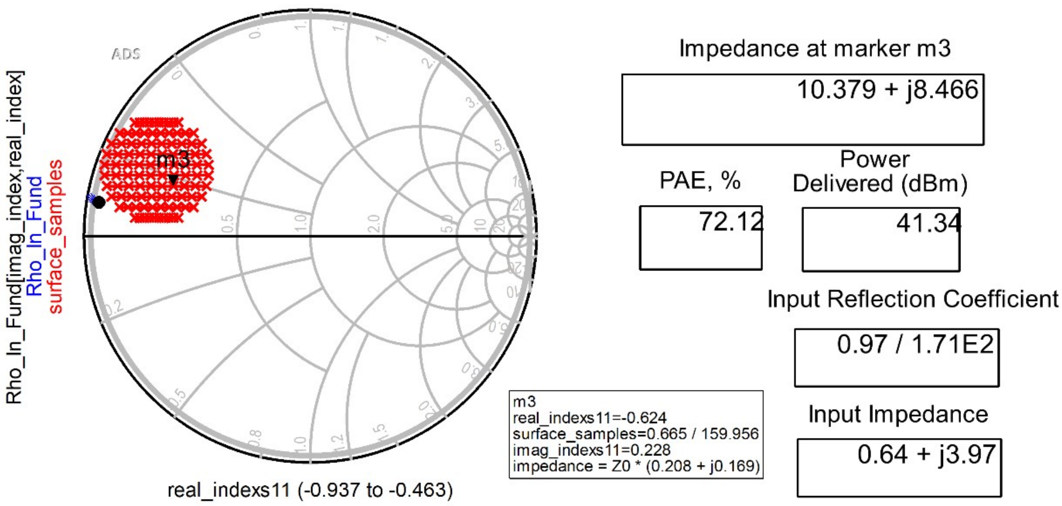
Figure-1: a) Ideal Class-E power amplifier topology b) Proposed wideband Class-E PA topology

Figure-1 (a) shows the ideal Class-E PA topology which contains frequency limiting series resonator. Figure-1 (b) shows the proposed wideband Class-E PA topology using optimized filter matching network in the output by replacing series resonator circuit from the ideal topology.

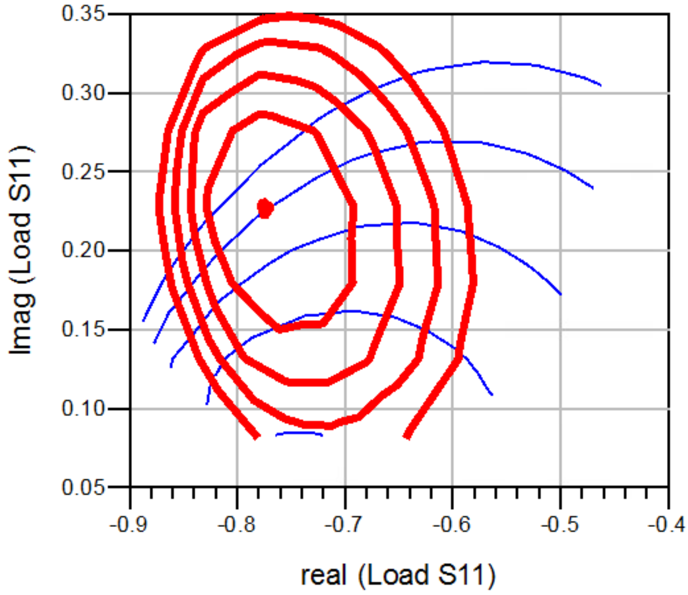
Broadband GaN HEMT-based RF power amplifiers is designed in several steps: (a) choose appropriate device biasing, (b) perform nonlinear analysis for output capacitance extraction (c) harmonic balance analysis to find optimal Z_L ¿ Z_s(d) harmonic load-pull analysis to find the target impedances (e) the synthesis of these impedances to design input and output matching network.

B. Load Pull Analysis

A comprehensive load-pull analysis has been performed to extract optimum source and load impedances using ADS, doing a load sweep at 2.4 GHz. The optimal impedance of the power amplifier is 10 Ω.



a) Load pull analysis to find the target load impedances



b) PAE (thick) and delivered power (thin) contours

Figure-2: a) Load pull analysis to find the target load impedances b) PAE (thick) and delivered power (thin) contours

The results of the load-pull simulation in figure-2 (a) show at 10.4+j8.5Ω, the PAE is 72 %, and the power level is 41.3 dBm. Figure-2 (b) shows the combined PAE and Pout contours on the Smith Chart using sweep frequencies. In terms of PAE, and output power selected impedances show excellent performance within the target frequency band.

C. Input matching network using low pass filter topology

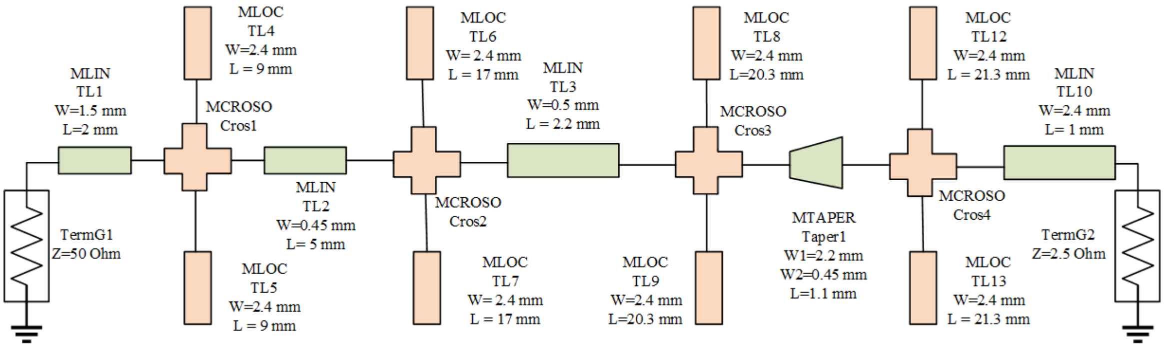
For the network topology, a classical approach utilizing lumped element lowpass Chebyshev network is used [15]. In order to design a multistage low pass matching network, few design steps have been followed. At step-1: A three-stage 5:1 low-pass transformer with a bandwidth of 80% is extracted from [15]. This prototype is scaled to the 50- system at a center frequency of f_0=1.7GHz by

$$L_n = g_{2n-1} \frac{\omega_0'}{\omega_0} \frac{50}{g_0} \tag{1}$$

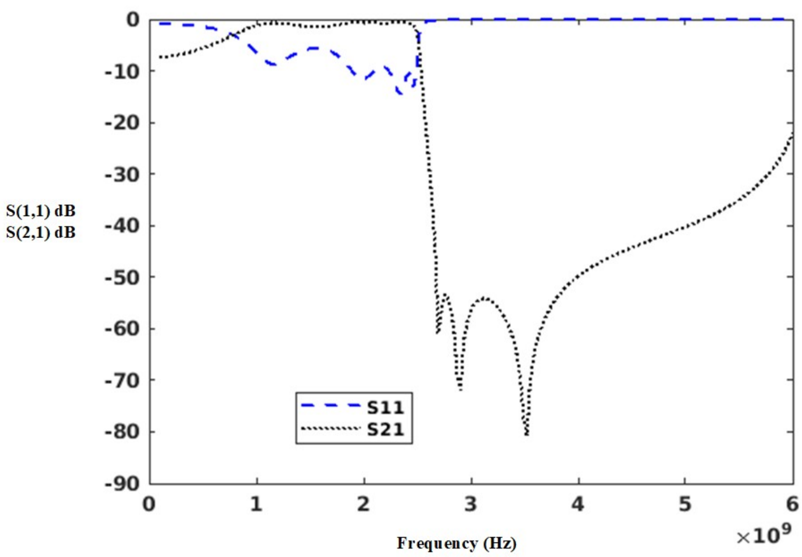
$$C_n = g_{2n} \frac{\omega_0^{'}}{\omega_0} \frac{g_0}{50} \quad (2)$$

where $\omega_0^{'}$ and g_0 represent the normalized angular frequency and impedance.

In step-2 post-optimization of the real-to-real transformer in the first step to form a real-to-complex transformer. In order to create a broadband input matching network, Chebyshev low-pass prototype of a 20:1 impedance transformer with 80% fractional bandwidth [15] and scaled to the desired frequency band and 50- system impedance. After that using the distributed element approach an input matching network has been produced shown in figure 3(a) and figure 3(b) shows the frequency response of the proposed wideband input matching network.



a) Design and implementation of input matching using transmission lines

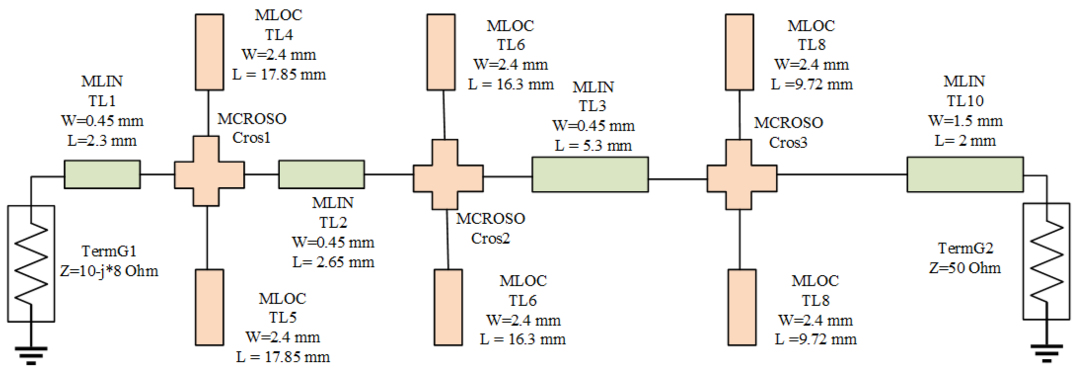


b) Frequency response of the input matching network

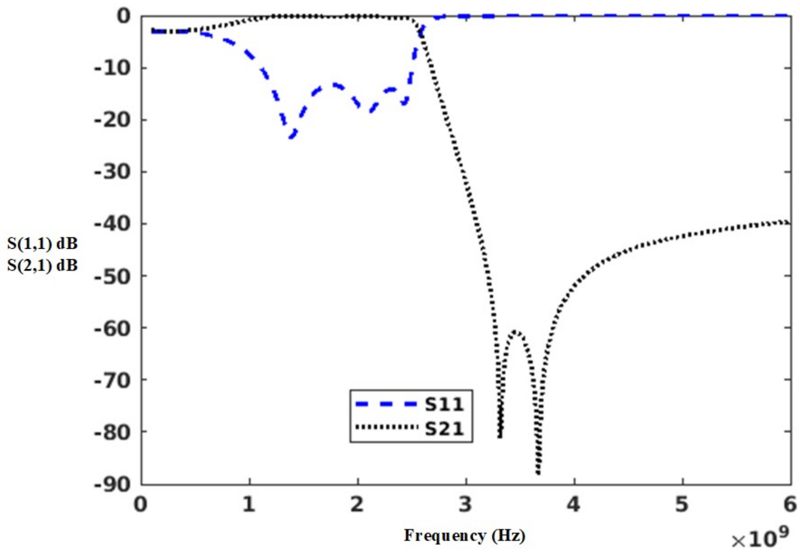
Figure-3: a) Design and implementation of input matching using transmission lines b) Frequency response of the input matching network

D. Output filter matching network

Using the same approach described in section-C a three-stage output filter was designed. Then using a distributed element method output matching network has been produced shown in figure 4(a). Figure 4 (b) shows the small-signal frequency response curve of the output matching network.



a) Design and implementation of output matching using transmission lines



b) Frequency response of the output matching network

Figure-4: a) Design and implementation of output matching using transmission lines b) Frequency response of the output matching network

III. RESULTS AND PERFORMANCE OF SIMULATED BROADBAND PA

A harmonic balance analysis has been implemented to simulate the designed amplifier. A frequency sweep is done to study the power-added efficiency in the band. Up to 5 harmonics of the fundamental frequency was considered.

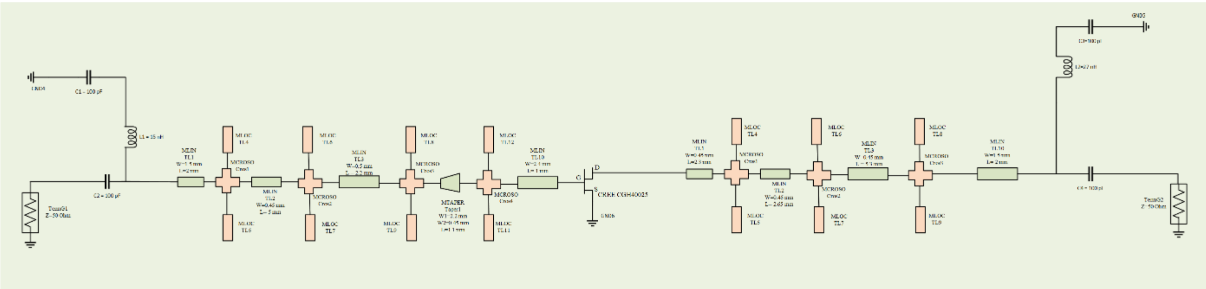
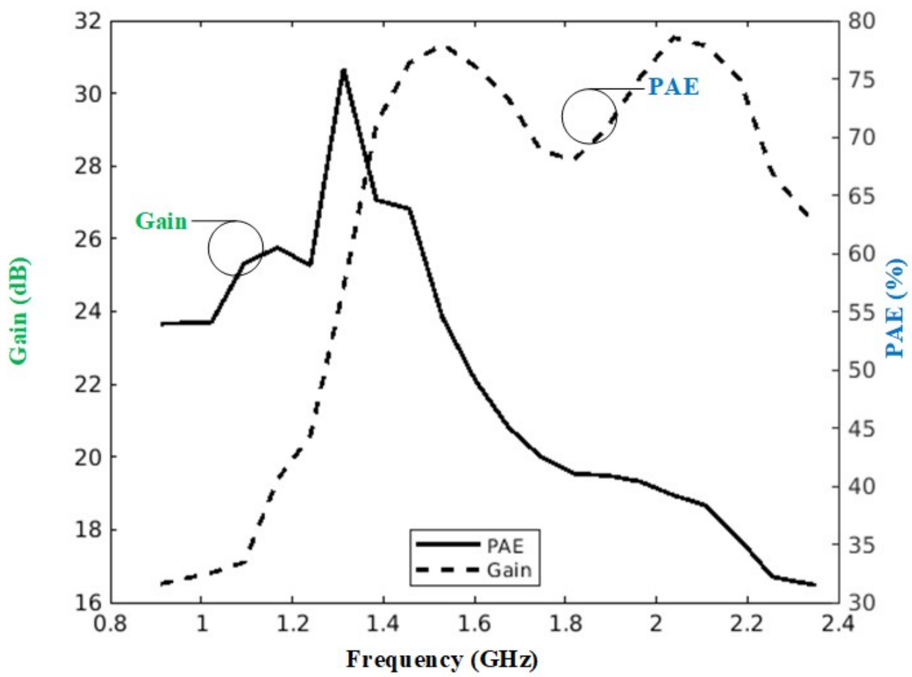
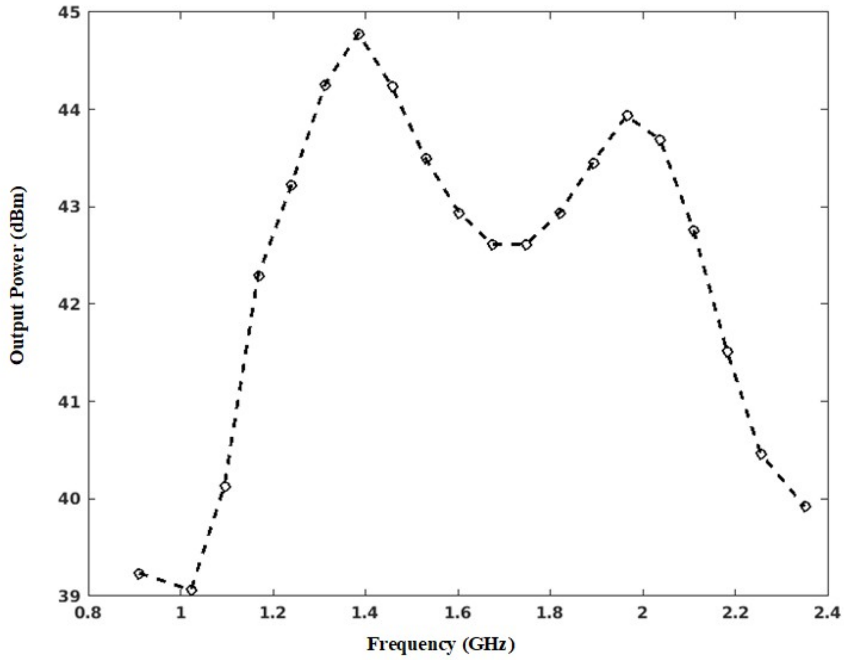


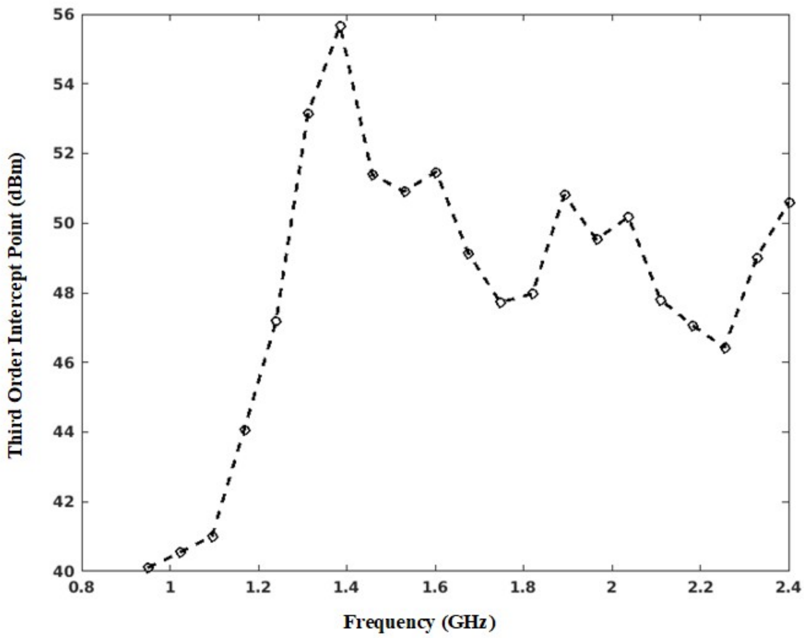
Figure-5: Designed Wideband Class-E PA schematic



a) Simulated gain, power added efficiency versus frequency



b) Simulated output power versus frequency



c) Simulated third-order intercept point versus frequency

Figure-6: a) Simulated gain, power added efficiency versus frequency b) Simulated output power versus frequency c) Simulated third-order intercept point

Figure 5 shows the final RF power amplifier schematic using a GaN transistor. The design produced a wideband performance (0.9-2.4 GHz), a high gain of 15-25 dB, high output power 43 ± 1 dBm, and power-added efficiency of 32-78%. Figure 6(a) shows simulated power added efficiency, gain versus frequency of the designed RF GaN power amplifier. Simulated PA efficiency is above 65% between 1.3-2.4 GHz and the highest efficiency achieved which is 78% fall between 1.4-1.6 GHz and 2-2.2 GHz band. Designed PA produced the highest gain of 30 dB at 1.3 GHz with an average gain of 20 dB within the whole operating band 0.9 GHz to 2.4 GHz. Figure 6(b) shows designed PA output power versus frequency. The PA output exhibits at least 40 dBm power between 0.9-2.4 GHz band. Finally, to check the PA linearities the third-order intercept characterizations were done using two tones, and figure 6(c) shows simulated third-order intercept (TOI) versus frequency.

Table I shows a comparison of the performance summary of wideband Class-E power amplifiers.

TABLE I PERFORMANCE SUMMARY OF WIDEBAND CLASS-E PAs

Reference	PA Topology	Bandwidth (GHz)	Gain (dB)	Output Power (W)	Efficiency (%)
2011 [14]	Class-E	0.9-2.2	10-13	10-20	63-89
2017 [10]	Class-E	0.9-2.3	7.5-13	12-30	57-88
2020 [16]	Class-E/F_3	0.35-0.73	12-13	10-12.5	74-77
2020 [17]	Class-E	1.7-2.8	NA	10-16.5	70-71
***This work**	**Class-E**	**0.9-2.4**	**15-25**	**10-25**	**32-78**

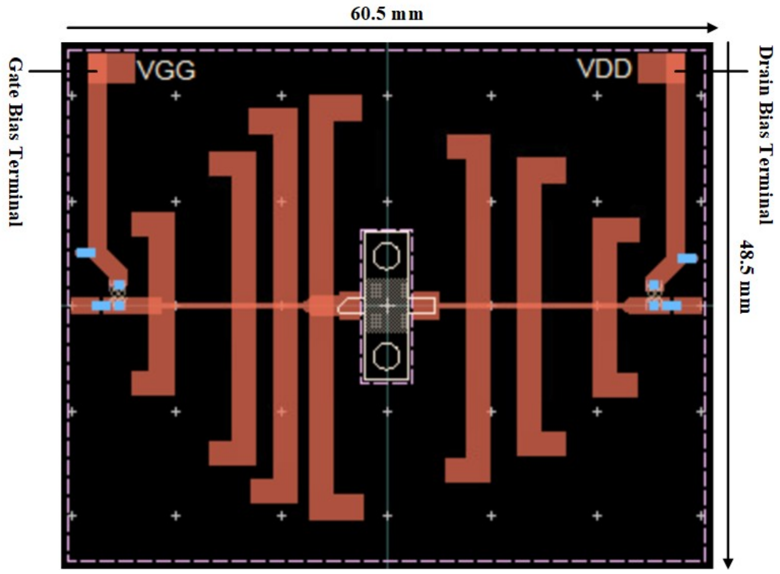


Figure-7: Designed power amplifier final layout

Figure-7 shows layout of the designed power amplifier. Designed power amplifier is compact in size and total dimension is 60.5 mm x 48.5 mm.

IV. CONCLUSION

In this work, wideband high gain, high power, high power-added efficiency class-E PA utilizing GaN HEMT technology has been investigated. A wideband filter based optimized output matching network was used by following the classical design approach resulting in a very good performance. Overall, the design presents wideband performance (0.9-2.4 GHz), exhibited a gain of 15-25 dB, output power 43 ± 1 dBm, and PAE (32-78%).

REFERENCES

[1] Andrei Grebennikov, James Wong, “A Dual-Band Parallel Doherty Power Amplifier for Wireless Applications” *IEEE Transactions on Microwave Theory and Techniques, (2012)*

[2] David Schnaufer,Bror Peterson, “Gallium Nitride (GaN): A Critical Technology for 5G” *Qorvo, (2019)*

[3] P. Boontamchauy, R. Phudpong, K. Wongthavarawat and S. Chalermwisutkul, "Wideband Class-E power amplifier with flat gain for FM radio transmitters," *2015 IEEE Conference on Antenna Measurements & Applications (CAMA), Chiang Mai, (2015).*

[4] E. Khansalee, K. Nuanyai and Y. Zhao, "Design and implementation of class E power amplifier with parallel circuit for wireless power transfer systems," *2017 International Electrical Engineering Congress (iEECON), Pattaya, (2017).*

[5] F. You, C. Huang and S. He, "A waveform-verified broadband class-E power amplifier design utilizing finite number of harmonics," *2017 IEEE Asia Pacific Microwave Conference (APMC), Kuala Lumpar, (2017).*

[6] T. Sharma, P. Aflaki, M. Helaoui and F. M. Ghannouchi, "Broadband GaN Class-E Power Amplifier for Load Modulated Delta Sigma and 5G Transmitter Applications*," in IEEE Access, vol. 6, pp. 4709-4719, (2018).*

[7] S. Lin, Y. Hsieh, S. Xu and J. Chen, "A Highly Efficient Pulse-Modulation Polar Transmitter Using Broadband Class E Power Amplifier for Femtocell Base Stations," *2018 Asia-Pacific Microwave Conference (APMC), Kyoto, (2018).*

[8] B. Merrick, J. King, T. Brazil, "A simplified procedure for the design of Continuous Class-F power amplifiers," *Microwave Integrated Circuits Conference, (2013).*

[9] M.P. Vander 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.*, *(2009).*

[10] F. Tamjid,A. Ghahremani, M. Richardson ,A. Fathy, "A novel approach to the design of a broadband high efficiency Class-E power amplifier with over 87% bandwidth" *IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications*, *(2017).*

[11] P. Colantonio, F. Giannini, R. Giofre, and L. Piazzon, “High efficiency ultra-wide-band power amplifier in GaN technology,” *Electron. Letters (2008).*

[12] A. Sayed, A. A. Tanany, and G. Boeck, “5 W, 0.35–8 GHz linear power amplifier using GaN HEMT,” *39rd Eur. Microw. Conf.*, *(2009)*

[13] www.cree.com/RF/Document-Library

[14] K. Chen, P. Peroulid, “Design of Highly Efficient Broadband Class-E Power Amplifier Using Synthesized Low-Pass Matching Networks” *IEEE Transcations on Microwave Theory and Technologies, (2011).*

[15] G. L. Matthaei, “Tables of Chebyshev impedance-transformation networksoflow-passfilterform,” *Proc.IEEE, (1964).*

[16] C. Liu, Q. Lin and F. M. Ghannouchi, "Highly efficient wideband parallel-circuit class-E/F3 power amplifier's design methodology," *in IET Microwaves, Antennas & Propagation, vol. 14, no. 10, pp. 1021-1026, (2020).*

[17] P. Afanasyev, A. Grebennikov, R. Farrell and J. Dooley, "Broadband Operation of Class-E Power Amplifier with Shunt Filter," *2020 18th IEEE International New Circuits and Systems Conference (NEWCAS), Montréal, QC, Canada, (2020).*