RESEARCH ARTICLE

A wideband 0.9–2.4 GHz 25 W high-efficiency Gallium Nitride radio frequency power amplifier

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Abstract
In this work, a 0.9–2.4 GHz, 25 W output power, radio frequency (RF) power amplifier based on Class-E switchmode topology has been analyzed. A load-pull simulation 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 0.9–2.4 GHz band with an efficiency of 25%–78%, an output power of 25 W (44 dBm), and an average gain of 17 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
class-E, filter matching network, GaN-HEMT, high gain, high power, power-added efficiency, RF power amplifier, switchmode, wideband

1 | INTRODUCTION

Radio Frequency (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, for example, 4G/5G need to operate in multiband that means it is 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.

The emergence of Gallium Nitride (GaN) technology operating at 28–50 V on a low loss, high thermal conductivity substrate like silicon carbide (SiC) has opened up a range of new possibilities. In the course of the most recent year’s RF GaN-HEMT (High Electron Mobility Transistor), transistor technologies have been fully developed, it is now considered a reliable PA technology. 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-E, and Class-F, and inverse Class-F most of the high-efficiency PAs are designed.3–10 In Reference 3 a broadband Class-$E_M$ PA has been proposed using the double reactance compensation technique by adding a parallel resonator within the main circuit...
load network. This added parallel resonator has enhanced the bandwidth where 300 MHz PA bandwidth was achieved along with 20 dB gain and 70% PAE. In Reference 5 broadband Class-E/F PA was designed using a transmission line load network approach along with real frequency and the de-embedding technique matching method. In Reference 8 Class wideband E PA with non-foster matching network proposed where 200 MHz system bandwidth was achieved although average PAE across significantly low. An ultrawideband PA was designed in References 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 (0.9–2.4 GHz), a 17 dB average gain, a highly efficient 25 W Class E PA based on GaN HEMT has been designed using an optimized matching circuit. To meet the design requirement CG2H40025 25 W, 28 V RF power GaN HEMT device manufactured by Wolfspeed13 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/duriod 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 a PAE of 25%–78% over a bandwidth of 1.5 GHz.

2 DESIGN AND OPTIMIZATION OF WIDEBAND PA

2.1 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 Reference 14 to design and optimize broadband IMN and distributed element implementation of the low pass OMN.

Figure 1(A) shows the ideal Class-E PA topology which contains a frequency limiting series resonator. Figure 1(B) shows the proposed wideband Class-E PA topology using an optimized filter matching network in the output by replacing the 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 $Z_L$ and $Z_s$, (d) harmonic load-pull analysis to find the target impedances, and (e) the synthesis of these impedances to design input and OMN.

2.2 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.

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.

2.3 IMN using low pass filter topology

For the network topology, a classical approach utilizing lumped element lowpass Chebyshev network is used.15 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 Reference 15. This prototype is scaled to the 50-system at a center frequency of $f_0 = 1.7$ GHz by

$$L_n = g_{2n-1} \frac{\omega'_0}{\omega_0} \frac{50}{g_0} \quad (1)$$

$$C_n = g_{2n} \frac{\omega'_0}{\omega_0} \frac{g_0}{50} \quad (2)$$

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 IMN, Chebyshev low-pass prototype of a 20:1 impedance transformer with 80% fractional bandwidth and scaled to the desired frequency band and 50-ohm system impedance. After that using the distributed element approach an IMN has been produced shown in Figure 3(A) and Figure 3(B) shows the frequency response of the proposed wideband IMN.

2.4 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 OMN has been produced shown in Figure 4(A). Figure 4(B) shows the small-signal frequency response curve of the OMN.

3 RESULTS AND PERFORMANCE ANALYSIS OF BROADBAND PA

A harmonic balance analysis has been implemented to simulate the designed amplifier. A frequency sweep is done to study the PAE in the band. Up to five harmonics of the fundamental frequency was considered. Figure 5 shows the final RF power amplifier schematic using a GaN transistor.
**FIGURE 2**  (A) Load pull analysis to find the target load impedances. (B) PAE (thick) and delivered power (thin) contours

**FIGURE 3**  (A) Design and implementation of input matching using transmission lines. (B) Frequency response of the input matching network
Figure 4 (A) Design and implementation of output matching using transmission lines. (B) Frequency response of the output matching network.

Figure 5 Designed wideband Class-E PA schematic.

Figure 6 shows a layout of the designed power amplifier. The designed power amplifier is compact in size and the total dimension is 60.5 mm × 48.5 mm.

A prototype has been fabricated using LPKF protomat machine with 20 mil Rogers RT/duroid 5880 substrate. The SMA connectors and lumped components were soldered before adding CG2H40025 25 W, 28 V RF power GaN HEMT transistor on the board. The fabricated prototype of a designed broadband power amplifier is shown in Figure 7.

To measure the power amplifier performance (PAE, Gain, Output power) a 1-tone signal was excited at the input of the fabricated PA. The 1-tone signal setup was completed with HP83592B signal generator, HP6624A DC power supply, 20 dB attenuator, HP directional coupler, minicircuit amplifier for the preamplifier, adapters, test cables, and HP spectrum analyzer. Due to the high power density properties of the GaN transistor, a negative –3.5 V gate voltage was applied before increase the drain voltage to 28 V to ensure we do not damage the transistor. Figure 8 shows the measured PAE versus input power, while power is varied 5–35 dBm in 1 dBm increments. Measured PAE was plotted at five different frequencies of interest such as 1.5, 1.6, 1.9, 2.1, and 2.4 GHz where the highest 78% PAE was achieved at 2.4 GHz. Figure 9 shows the...
1 dB compression curve at various frequencies where input power was swept with 1 dBm increments. At 1.9 GHz 30 dBm input power the designed power amplifier reached 1 dB compression point while the output power was 44 dBm. Figure 10 shows measured PAE, gain versus frequency of the designed RF GaN power amplifier. The design produced a wideband performance (0.9–2.4 GHz), a high gain of 17–23 dB, high output power 43 ± 1 dBm, and PAE of 25–78%. Measured PA efficiency is above 65% between 1.3 and 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 an average gain of 17 dB and at least 40 dBm power within the operating band of 0.9 GHz to 2.4 GHz.

Table 1 shows a comparison of the performance summary of wideband Class-E power amplifiers.
**FIGURE 9** Measured output power (dBm) versus input power sweep (dBm) at 1.5, 1.6, 1.9, 2.1, and 2.4 GHz

**FIGURE 10** Measured output power (dBm), gain (dB), power added efficiency (%) versus frequency (GHz) at 28 dBm input power

**TABLE 1** Performance summary of wideband Class-E PAs

| Reference | PA topology | Bandwidth (GHz) | Gain (dB) | Output power (W) | Efficiency (%) |
|-----------|-------------|-----------------|-----------|------------------|----------------|
| 14        | Class-E     | 0.9–2.2         | 10–13     | 10–20            | 63–89          |
| 10        | Class-E     | 0.9–2.3         | 7.5–13    | 12–30            | 57–88          |
| 16        | Class-E/F_3 | 0.35–0.73       | 12–13     | 10–12.5          | 74–77          |
| 17        | Class-E     | 1.7–2.8         | NA        | 10–16.5          | 70–71          |
| *This work | Class-E     | 0.9–2.4         | 17–23     | 10–25            | 25–78          |

Abbreviation: PA, power amplifier.

## 4 CONCLUSION

In this work, wideband high gain, high power, high PAE class-E PA utilizing GaN HEMT technology has been investigated. A wideband filter-based optimized OMN 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 17–23 dB, output power $43 \pm 1$ dBm, and PAE (25%–78%).
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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest relevant to this article.

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