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High-Efficiency L-Band GaN Power Amplifier Employing Second and Third Harmonic Impedance Optimization

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Abstract:
This paper presents the design and evaluation of a high-efficiency harmonic tuned L-band power amplifier (PA) utilizing a Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT). To meet the demands of modern wireless communication and radar systems operating in the L-band, advanced harmonic tuning techniques were employed, specifically focusing on controlling the impedance terminations at the second ($2f_0$) and third ($3f_0$) harmonic frequencies. Through careful load-pull analysis and optimized output matching network design, precise harmonic terminations were achieved, along with optimal fundamental frequency impedance matching. The fabricated PA demonstrates state-of-the-art performance, delivering a saturated output power (Psat) of 46.4 dBm with a corresponding peak Power Added Efficiency (PAE) of 83%. Critically, the PA maintains high efficiency under back-off conditions, achieving 60% PAE at 3 dB output back-off (OBO). These results highlight the effectiveness of this combined second and third harmonic optimization approach with GaN HEMT technology, which enables both high peak efficiency and excellent back-off efficiency for demanding L-band applications.

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1. Introduction

The relentless growth of wireless communication systems (e.g., 5G, satellite communications) and the increasing sophistication of radar and electronic warfare systems operating in the L-band (1-2 GHz) necessitate the development of high-performance Radio Frequency (RF) power amplifiers (PAs).

PAs are often the most power-hungry components in these systems, directly impacting battery life in mobile devices, payload capacity in satellites, and overall system operating costs and thermal design complexity. Consequently, maximizing PA efficiency, particularly the PAE, is a critical design objective [1].

Traditional PA classes, such as Class A and Class AB, offer good linearity but suffer from relatively low theoretical maximum efficiencies (50% and 78.5%, respectively), which are often significantly lower in practice, especially when amplifying signals with high peak-to-average power ratios (PAPR) that require operation in back-off [2-4]. To overcome these limitations, various high-efficiency PA architectures have been developed, often relying on waveform engineering through harmonic impedance control [5]. Techniques such as Class F [6], Inverse Class F (Class F^{-1}) [7], and more advanced continuous modes [8, 9] manipulate the drain voltage and current waveforms by controlling the termination impedances at harmonic frequencies, thereby minimizing the overlap between voltage and current and reducing power dissipation within the active device.

While tuning the second harmonic ($2f_0$) is common in Class F/F^{-1} designs, controlling higher-order harmonics, such as the third harmonic ($3f_0$), can further refine the waveforms (e.g., creating a more square voltage waveform and/or flattened current waveform), potentially leading to even higher efficiencies or offering better trade-offs between efficiency, power, and bandwidth [10]. However, designing matching networks that simultaneously present optimal fundamental impedance and specific terminations at multiple harmonic frequencies (often reactive) presents significant challenges, especially over a desired bandwidth.

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This work focuses on the design and implementation of an L-band PA using the MACOM CG2H40035F GaN HEMT, specifically employing both second and third harmonic tuning to maximize efficiency, particularly under back-off conditions. The specific objectives of this research include achieving a high peak Power Added Efficiency (PAE), robust PAE under output back-off (OBO), and a high output power level suitable for demanding L-band applications. The design achieves a measured saturated output power of 46.4 dBm (>43 watts) with a peak PAE of 83% at the frequency band of 1.25 GHz to 1.65 GHz. Furthermore, it demonstrates excellent efficiency under back-off conditions, maintaining 60% PAE at 3 dB OBO, making it suitable for applications involving non-constant envelope signals.

This paper is organized as follows: Section 2 provides a review of harmonic tuning techniques and relevant state-of-the-art high-efficiency PAs, including a critical analysis of their limitations. Section 3 details the design methodology, load-pull analysis data, and matching network synthesis. Section 4 presents the measurement results, validating the design approach. Finally, Section 5 concludes the paper, summarizing the key findings and their significance as contributions to the field.

2. State-of-the-Art in Harmonic Tuned L-Band GaN PAs

GaN HEMTs are particularly well-suited for Harmonic Tuning techniques. Their high breakdown voltage allows for larger voltage swings (approaching the squared waveform ideal) [11, 12], and their relatively low output capacitance (Cds) compared to LDMOS devices [13], especially for a given power level, makes controlling harmonic frequencies up to $3f_0$ and beyond more feasible at L-band and higher frequencies. The high-power density also allows for compact high-power solutions. Numerous publications report high-efficiency GaN PAs in the L-band using harmonic tuning. For instance, Zaid et al. [14] achieved 65% PAE at 1.2-1.8 GHz using Class F^{-1}, while Zhang and Shi [15] demonstrated 70% PAE at 1.2-1.4 GHz using extended continuous Class F. Achieving peak PAE above 80% is indeed considered state-of-the-art [16, 17]. The PA reported by Hu et al. [18] covers 1.8–2.7 GHz with a drain efficiency ranging from 64% to 81%, showcasing the potential of harmonic tuning for broadband high-efficiency applications. However, for modulated signals, the efficiency of PA at the back-off power level (due to linearity performance) is a critical performance metric. Many high-efficiency designs suffer a rapid drop in PAE as the output power is backed off from saturation. For instance, designs like those of Zaid et al. [19] and Liu et al. [20] achieve high peak efficiencies, and similarly, Xuan et al. [21, 22] demonstrate broadband efficiency. Still, their primary focus is on broad frequency coverage rather than optimizing efficiency at back-off, particularly in the L-band. Techniques specifically targeting high back-off efficiency, like Outphasing PAs that optimize performance over a range of power levels, are an active area of research [23]. The unique contribution of this paper lies in achieving both a state-of-the-art high peak efficiency (83%) and a robust 60% PAE at 3 dB OBO. This simultaneous achievement represents a significant advancement, as it addresses the critical need for efficient operation under realistic signal conditions where PAs often operate away from saturation. This work builds upon these principles by applying targeted second and third harmonic impedance control to the CG2H40035F GaN HEMT, leveraging the device's capabilities to achieve both high peak efficiency and excellent efficiency at 3 dB output back-off in the L-band. The specific harmonic impedances were determined via extensive load-pull analysis to optimize the performance metrics reported in Table 1.

3. PA Design Methodology

The PA is biased in deep Class AB operation, with a quiescent drain current (Idq) of 60 mA and a drain-source voltage (VDS) of 28 V. This biasing approach is selected in accordance with the harmonic tuning strategy employed to optimize performance. Load-pull simulations were also carried out using Keysight ADS. The center frequency for the design was chosen as 1.45 GHz, where load-pull analysis was performed. The primary design goals include maximizing the PAE at the saturation power level, maximizing the PAE at 3 dB output OBO, and achieving a high output power level. From the load-pull data, the optimal fundamental load impedance (ZL_opt) and the target impedances for the second (Z_2f_0) and third (Z_3f_0) harmonics were extracted and shown in Figure 1 and their values summarized in Table 1.

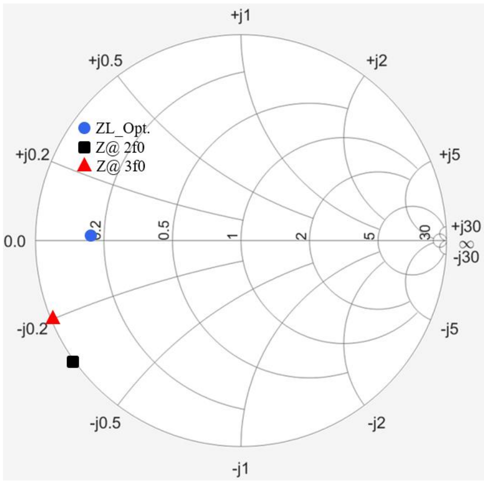

Figure 1. Optimal Load Impedances carried out from Load-pull analysis at 1.45 GHz

Table 1. Optimal Impedances value depicted in Figure 1

Impedance	Z (ohm)
ZL_opt	8.4+j1
Z_2f_0	-j16
Z_3f_0	-j10

The Output Matching Network (OMN) was designed to simultaneously present the optimal impedances for the fundamental and harmonic frequencies. A combination of microstrip transmission lines, lumped elements, and stepped impedance resonators was employed to facilitate multiharmonic impedance control efficiently. This topology enables the OMN to shape the impedance environment across a wide frequency range, thus enhancing the PA's efficiency.

The Input Matching Network (IMN) was also designed to ensure optimal power transfer and maximize gain at the operating frequency. Schematic diagrams of the OMN and IMN are provided to illustrate the network structures, as shown in Figure 2. Keysight ADS was utilized for the matching network synthesis, and electromagnetic (EM) simulations were performed using Keysight Momentum to verify the physical layout and account for parasitic effects. To prevent RF leakage and ensure reliable biasing, 1512SP-22N RF inductors from Coilcraft were used in both the gate and drain bias lines. In addition, multiple bypass capacitors, including resonant traps, were also placed strategically to maintain stability at low frequencies. Stability analysis was conducted using the Rollett stability factor (K-factor), and additional stabilization techniques such as parallel RC networks were implemented, as also shown in Figure 2.

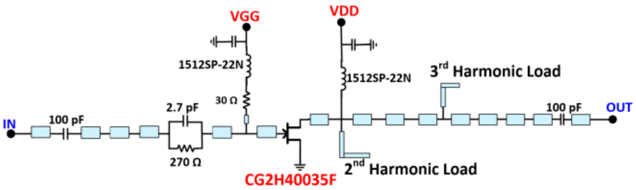

Figure 2. Schematic diagrams of the proposed PA

4. Measurement Results

The PA was fabricated on a 20-mil Rogers RO4003 substrate. A photograph of the fabricated PA is shown in Figure 3.

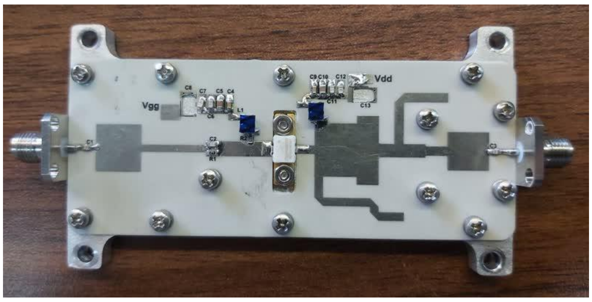

Figure 3. Photograph of the fabricated PA

Figure 4 illustrates the measured Psat and PAE versus frequency across the L-band, evaluated at an input power level corresponding to saturation (Psat).

The plot clearly shows the amplifier's performance across the desired frequency range, demonstrating consistent output power and efficiency. Figure 5 also presents the measured Gain, and PAE versus output power at the center frequency (1.45 GHz). This figure highlights the amplifier's gain compression characteristics and its efficiency profile as a function of output power, which is crucial for understanding its performance under varying signal conditions. The close agreement observed between the simulated design targets (as summarized in Table 1) and the experimentally measured performance (illustrated in Figures 4 and 5) provides strong empirical validation of the entire design approach and the achieved results.

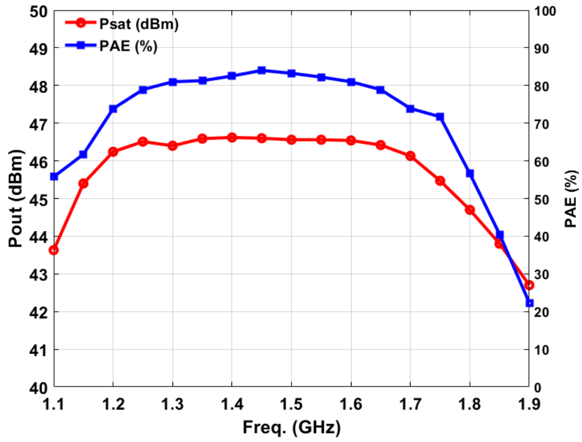

Figure 4. Measured Psat and PAE versus Frequency

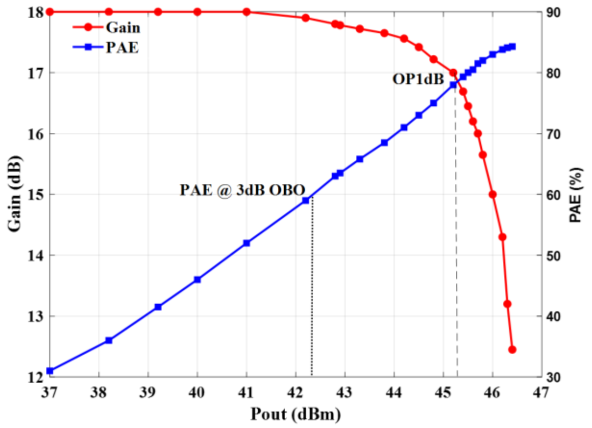

Figure 5. Measured Gain (dB) and PAE (%) vs output power at 1.45 GHz

A comprehensive comparison is also provided in Table 2, where the key performance metrics (Technique, Frequency, Psat, Peak PAE, and PAE at 3 dB OBO) of the proposed PA are benchmarked against other state-of-the-art designs reported in the section 2.

Table 2. Performance comparison between high-efficiency L-Band PAs

Ref.	Technique	Freq. (GHz)	Psat (dBm)	PAE @ Sat/ 3dB-OBO (%)
Mohadeskasaei and Zhou [24]	Tapered Microstrip Lines	1.2-1.4	45	64/50
Wu et al. [25]	Class F	1.575	50.1	66/55
Yang et al. [26]	Class-BJ	1.45 - 1.55	53	70/-
Mahdi et al. [27]	Optimized 3rd Harmonic	1-1.5	44.8	63/50

Furxhi et al. [28]	Hybrid PA	1.14-1.6	50	60/50
[This work]	Optimized 2nd and 3rd Harmonics	1.25-1.65	> 46.4	83/60

The data presented in Table 2 provides a comprehensive overview of recent advancements in high-efficiency L-band GaN PAs. Comparing the performance metrics reveals that the described PA design achieves a notably high peak PAE of 83% within its operating frequency band of 1.25 GHz to 1.65 GHz. This significantly surpasses the peak PAE reported in most of the analyzed publications [24-28], including the 66% achieved at 1.575 GHz [25] and 70% at 1.5 GHz [26], both of which also utilized switch mode schemes.

Crucially, the proposed PA's 60% PAE at 3 dB OBO surpasses or strongly competes with comparable works that report this metric. Specifically, the PAE of 50% at 3 dB OBO reported in [27] (a Class AB design with third harmonic optimization) is comparable to the 50% PAE at 3 dB OBO achieved by the hybrid PA in [28]. In contrast, our proposed PA achieves a significantly higher 60% PAE at 3 dB OBO, demonstrating superior performance under back-off conditions compared to these works. This simultaneous achievement of high peak efficiency and strong back-off performance represents a superior balance of performance, which is a direct consequence of the meticulously optimized combined second and third harmonic tuning strategy. This holistic efficiency, encompassing both peak and back-off performance, is a key distinguishing feature and a significant advantage of the proposed work.

5. Conclusion

This paper successfully demonstrated a high-efficiency L-band power amplifier based on the MACOM CG2H40035F GaN HEMT. By employing a targeted harmonic optimization strategy controlling both the second and third harmonic impedances, significant performance improvements were achieved. The design methodology involved careful load-pull analysis to identify optimal fundamental and harmonic terminations, followed by the synthesis of appropriate matching networks. The fabricated power amplifier delivered a saturated output power of 46.4 dBm and achieved a peak PAE of 83%. Notably, the PA maintained high efficiency under back-off conditions, exhibiting 60% PAE at 3 dB output back-off. These results validate the effectiveness of the combined second and third harmonic optimization approach for GaN devices and represent a significant contribution towards highly efficient RF amplification in the L-band, suitable for power-conscious radar and communication applications. Future work could investigate extending the bandwidth of the harmonic tuning or applying linearization techniques while maintaining high efficiency.

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