

Design and simulation of a high-efficiency class F power amplifier for 5G wireless energy transmission

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ABSTRACT

This paper presents the design and optimization of a high-efficiency class F power amplifier (PA) for 5G communication systems. The proposed design focuses on achieving optimal efficiency, output power P_{out} , and stability through precise harmonic control and waveform shaping. Using advanced simulation techniques, the PA achieves a power-added efficiency (PAE) of 80%, a P_{out} of 40.73 dBm, and a gain of 20 dB over a 120 MHz bandwidth centered at 3.5 GHz. Stability is ensured with a stability factor of 1.5 and a stability measure of 0.8 across the operating band. The first three harmonics are effectively managed to enhance efficiency, with the drain current (I_{DS}) shaped into a square waveform and the drain voltage (V_{DS}) into a quasi-sinusoidal waveform. These results demonstrate the capability of the proposed class F PA to meet stringent 5G requirements, offering high performance, strong stability, and efficient operation for sub-6 GHz applications.

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1. INTRODUCTION

The rapid evolution of wireless communications has reached a pivotal stage with the global deployment of 5G networks, offering unprecedented data rates, ultra-low latency, and massive connectivity to support applications such as the internet of things, autonomous systems, and high-definition multimedia streaming [1], [2]. These capabilities rely heavily on advancements in RF front-end components, particularly power amplifiers (PAs), which play a crucial role in ensuring efficient and reliable signal transmission in modern communication systems [3], [4].

Previous studies have demonstrated that achieving high power-added efficiency (PAE) while maintaining high output power (P_{out}) and linearity across broad frequency ranges is essential for meeting 5G requirements [5], [6]. Among various PA architectures, class F amplifiers have attracted considerable attention for their ability to maximize efficiency through harmonic tuning and waveform shaping techniques, enabling near-ideal switching conditions and reduced power dissipation [7]–[9].

Despite these advantages, most existing class F designs have been optimized for narrowband operation and face significant challenges when applied to broadband 5G systems. Conventional approaches often struggle to maintain efficiency, output power, and stability simultaneously across wide frequency ranges due to limitations in harmonic control and impedance matching networks [1]. Moreover, the adoption

of complex modulation schemes such as orthogonal frequency division multiplexing (OFDM) in 5G increases the demand for broadband, highly efficient PAs with precise harmonic management [10]. These limitations highlight a clear research gap in developing class F amplifiers that can sustain high efficiency, strong stability, and robust output performance over the broad bandwidths required by sub-6 GHz 5G applications [11], [12].

The primary challenge in 5G PA design lies in achieving an optimal balance between efficiency, output power, and linearity while maintaining stability across a broad bandwidth. Conventional class F amplifiers, while highly efficient in narrowband applications, often struggle to sustain their performance over wide frequency ranges due to limitations in harmonic control and impedance matching networks [13], [14].

Additionally, as 5G systems operate at higher frequencies and require complex modulation schemes such as OFDM, the need for highly efficient, broadband PAs with well-controlled harmonic performance becomes even more pressing [15], [16]. Addressing these limitations requires an advanced design methodology that ensures optimal harmonic shaping while preserving stability and high efficiency across the target bandwidth [17].

This work addresses this gap by presenting the design and optimization of a high-efficiency class F PA specifically tailored for 5G communication systems. Using advanced simulation techniques and meticulous harmonic control, the proposed amplifier achieves a PAE of 80%, an P_{out} of 40.73 dBm, and a gain of 20 dB over a 120 MHz bandwidth centered at 3.5 GHz. Stability is ensured with factors of 1.5 and 0.8 for the stability factor and stability measure, respectively. Key innovations include the effective control of the first three harmonics and the precise shaping of the drain current (semi-square waveform) and drain voltage (quasi-sinusoidal waveform), enabling optimal efficiency and performance [18], [19].

The significance of this study lies in demonstrating that, with proper harmonic shaping and impedance network optimization, class F amplifiers can meet the stringent requirements of 5G systems. The findings provide a valuable framework for the development of next-generation broadband PAs, offering a practical solution to the persistent trade-offs between efficiency, power, and stability in high-frequency wireless communication systems.

2. METHOD

2.1. Class F continuous mode theory

A conventional class F amplifier is considered ideal when ideal harmonic impedance conditions are met at the output node of the active device under test. In other words, for it to be ideal, it is necessary not only to have proper transistor biasing but also to include an infinite number of odd and even harmonic resonators in the amplifier's output network. In such a configuration, control over an infinite number of odd and even harmonics is achieved, ensuring that there is no overlap between the square current waveform and the half-sinusoidal voltage waveform across the active device [20], [21]. This ensures 100% efficiency, meaning no power is dissipated.

However, it's important to note that in practice, only a limited number of harmonics will be present at the transistor's load. This limitation is due to the bandwidth limitation behavior of the passive output network and chip size constraints. In reality, most class F amplifiers limit harmonic control up to one-third of the fundamental frequency, setting their maximum efficiency at 75% [21].

For class F amplifiers, the aforementioned waveforms are described as a Fourier series, where the harmonic components of both the voltage and current at the load are expressed as (1) and (2) [22]–[24]:

$$\frac{i(\omega t)}{I_0} = 1 - \frac{\pi}{2} \sin \omega t - 2 \sum_{n=2,4,6,\dots}^N \frac{\cos n \omega t}{n^2 - 1} \quad (1)$$

$$\frac{v(\omega t)}{V_0} = 1 + \frac{4}{\pi} \sin \omega t + \frac{4}{\pi} \sum_{n=3,5,7,\dots}^N \frac{\sin n \omega t}{n} \quad (2)$$

With $i(\omega t)$ and $v(\omega t)$ representing the square current waveform and the half-sinusoidal voltage waveform respectively, where ω is the angular frequency, I_0 and V_0 are the direct current (DC) components of current and voltage. The Figure 1 illustrates the ideal schematic of class F amplifier with an infinite number of harmonics.

For a class F PA with a finite number of three harmonics, it is assumed that the drain voltage waveform at the current generator reference plane is half-sinusoidal [25]:

$$V_D = 1 - \frac{2}{\sqrt{3}} \cos \theta + \frac{1}{3\sqrt{3}} \cos 3 \theta \quad (3)$$

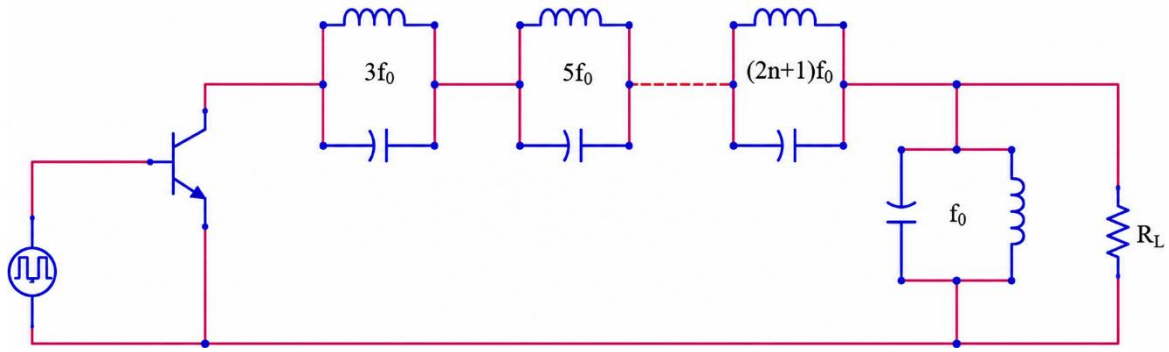


Figure 1. Ideal class F amplifier

On the other hand, the half-wave rectified waveform of a drain current i_D normalized by I_{max} can be expressed as (4), as indicated in [26]:

$$i_D = \frac{1}{\pi} + \frac{1}{2} \cos \theta + \frac{3}{2\pi} \cos 2\theta \quad (4)$$

with $\theta = \omega_0 t$, where ω_0 is the fundamental angular frequency.

2.2. Design and simulation of the class F power amplifier

Figure 2 depicts the overall schematic of our class F PA based on the GaN HEMT transistor CGH35030F. This setup ensures the necessary biasing condition for our PA to operate in the normal state. Optimization techniques under advanced design system (ADS) by Agilent Technologies, enabled us to achieve excellent 50-ohm matching, while initially setting the source impedance of the fundamental to ($Z_5 = 49.9 - j \times 4.9 \Omega$) [27], [28].

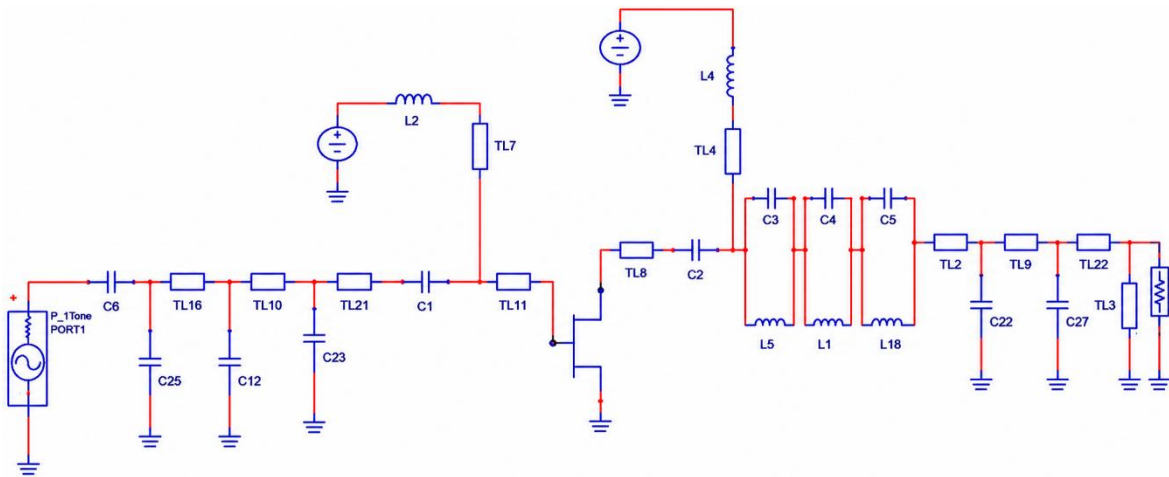


Figure 2. Global diagram of the class F PA

3. RESULTS AND DISCUSSION

3.1. Results and interpretations

Figure 3 respectively illustrates: (a) the reflection coefficients S_{11} and S_{22} , (b) the amplifier stability, (c) the time-domain variation of the drain-source voltage (V_{DS}), and drain-source current (I_{DS}), as well as the performance metrics: (d) PAE, (e) P_{out} , and (f) gain.

The simulation results indicate that the reflection coefficients $|S_{11}|$ and $|S_{22}|$ are below -10 dB at the resonance frequency of 3.5 GHz. In addition, the stability factor K is greater than 1 and the stability coefficient B is greater than 0, confirming that the proposed amplifier remains unconditionally stable across the entire 5G core band, 3.5–3.8 GHz.

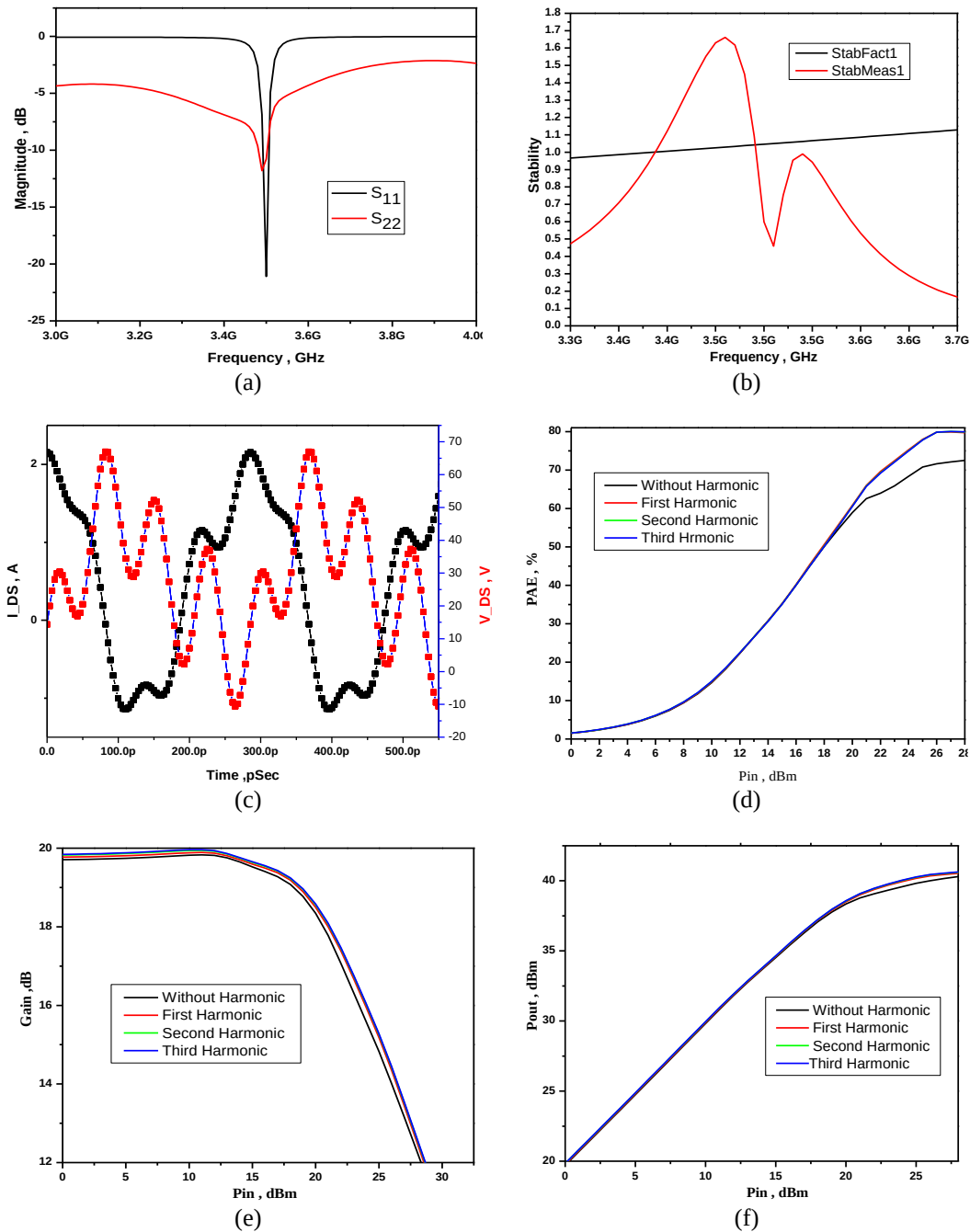


Figure 3. Simulated performance of the amplifier class F; (a) $|S_{11}|$ and $|S_{22}|$, (b) stability, (c) voltage and current waveforms of drain, (d) PAE, (e) P_{out} , and (f) gain

The analysis of the drain waveforms shows that the maximum amplitude of the drain current reaches 1.85 A, while the drain voltage waveform exhibits an approximately semi-sinusoidal shape with a very small third-harmonic component. These characteristics confirm the proper operation of the amplifier in class F mode. Furthermore, the gain remains nearly constant for the first three harmonics.

The simulation results also highlight the significant impact of impedance matching on the performance of the PA in terms of PAE and P_{out} . Initially, by fixing the source impedance at ($Z_S = -49.9 - j4.9 \Omega$) and adjusting the load impedance to ($Z_L = -50.35 + j0.05 \Omega$) at 3.5 GHz, the amplifier achieves a PAE of 72.61% with an P_{out} of 39.9 dBm.

After optimizing the load impedance at the fundamental harmonic ($Z_{L1} = -50.40 + j0.05 \Omega$), the PAE increases to 79.50% and the P_{out} reaches 40.46 dBm. Further adjustment of the load impedance at the

second harmonic ($Z_{L2} = -50.40 + j0.1 \Omega$) results in an additional improvement of the PAE, which reaches 79.97%. Finally, by applying the same load impedance at the third harmonic ($Z_{L3} = -50.42 + j0.1 \Omega$) [25], the PAE reaches 80.04% with an P_{out} of 40.73 dBm.

3.2. Discussion

These results demonstrate that impedance matching and harmonic control play a crucial role in improving the performance of class F PAs. The progressive increase in PAE observed during the optimization of the harmonic load impedances highlights the direct influence of harmonic management on power conversion efficiency [7], [20], [29].

In particular, the optimization at the fundamental harmonic provides the most significant improvement in efficiency, while the adjustment of the second and third harmonics contributes to further enhancing the overall performance and stabilizing the amplifier behavior. This confirms that harmonic control is essential for maintaining stable broadband operation, as also reported in [30]–[32].

Moreover, the obtained results are consistent with recent studies, which indicate that harmonic management up to the third order is necessary to fully maximize the power conversion efficiency of class F amplifiers. These findings emphasize the importance of properly designing harmonic matching networks in order to achieve high efficiency and high output power for sub-6 GHz 5G applications [7], [21], [33], [34]. The results of the simulations obtained are summarized in the Table 1.

Table 1. Comparison of the performance of our class F PA for the three harmonics

Harmonics	Load impedance	PAE (%)	Pout (dBm)	Gain (dB)
Thou	$Z_L = -50.35 + j \times 0.05 \Omega$	72.61	39.9	19.97
1	$Z_L = -50.40 + j \times 0.05 \Omega$	79.50	40.46	19.78
2	$Z_L = -50.40 + j \times 0.10 \Omega$	79.97	40.62	19.95
3	$Z_L = -50.42 + j \times 0.1 \Omega$	80.05	40.73	19.96

3.3. Comparison with state of the art

Table 2 presents a comparison of the performance of our gallium nitride high electron mobility transistor (GaN HEMT)-based PA with that of other results using the same technology. A comparison of our model's performance with other class F PAs presented in Table 2 highlights its superior PAE, while maintaining high output power and substantial gain. These results further underscore the suitability of GaN HEMT technology for the design of high-performance class F PAs tailored for 5G applications.

Table 2. Comparison with state of the art

References	Frequency (GHz)	Technology	Class	PAE (%)	Output power (dBm)	Gain (dB)
[35]	3–3.7	GaN	J	60–74	43–44.2	10–13
[36]	3.5	GaN	E ⁻¹	75–74.8	40.5–40.3	11–10.3
[37]	0.75–2.5	GaN	E	27	11.5	13.7
[38]	2.4	GaN	AB	54.15	40.05	13.63
[39]	3.5	GaN	F ⁻¹	66–74.6	42.6–43.3	13.5–16
[40]	1.4–2	GaN	F ⁻¹	70	40	13
[41]	3.5	GaN	F	79.25	16.54	13.03
[42]	3.3–4.3	GaN	F	67–80	41.3	10
This work	3.5	GaN	F	80.05	40.73	19.96

4. CONCLUSION

In this article, we detail the development and simulation of a class F PA tailored to the specific needs of 5G networks. Our results highlight a robust performance characterized by high stability, effective impedance matching, and optimal compatibility with the semi-square I_{DS} current and V_{DS} voltage characteristics. These findings indicate that the proposed architecture successfully meets the stringent requirements of 5G applications. Furthermore, this work paves the way for practical implementations aimed at enhancing the overall performance of 5G communication systems while reducing energy consumption and optimizing thermal management. Notably, the amplifier achieved a PAE of 80.05%, an P_{out} of 40.73 dBm, and a gain of 19.96 dB, underscoring the effectiveness of our approach in overcoming the challenges associated with next-generation communication technologies.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

Data availability is not applicable to this paper, as no new data were created or analyzed in this study.

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