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DESIGN AND PERFORMANCE ANALYSIS OF AN X-BAND MMIC HPA WITH USING GAN-ON-SIC TECHNOLOGIES

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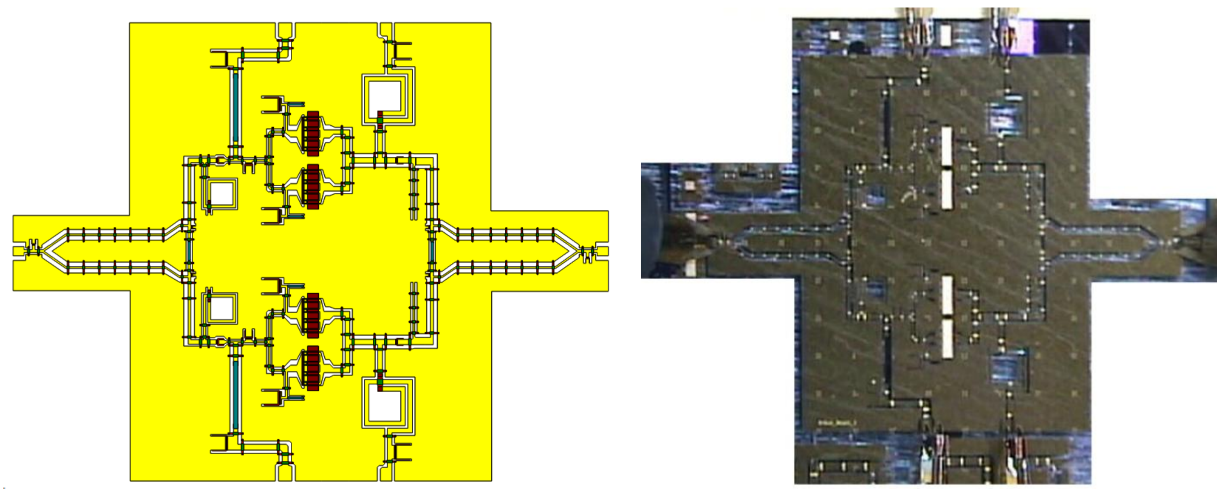
Highlights

- Designed X-band MMIC HPA with 4 parallel HEMTs (8×125 µm) for 7.6–10.3 GHz.
- Achieved max small-signal gain of 11.7 dB with 0.59 dB/GHz gain flatness.
- CPW structure with GaN-on-SiC tech improves matching and eliminates via-holes.
- Simulated saturated power of 41.21 dBm and peak PAE of 39.81%.
- Unconditional stability verified for satellite, radar, and EW applications.

Graphical Abstract



(a) (b)

(a) The layout of the X-band MMIC HPA and (b) Detailed Photography of the Fabricated X-band MMIC HPA

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ABSTRACT: This paper presents the design and performance analysis of an X-band monolithic microwave integrated circuit (MMIC) high-power amplifier (HPA) using four parallel high-electron-mobility transistors (HEMTs) with dimensions of $8 \times 125\ \mu m^2$. Operating in the frequency range of 7.6–10.3 GHz, the proposed amplifier achieves a maximum small-signal gain of 11.7 dB with a gain flatness of 0.59 dB/GHz, ensuring consistent performance across the operating band. The coplanar waveguide (CPW) structure, implemented using Gallium Nitride (GaN) on a Silicon Carbide (SiC) process, eliminates the need for via-holes, reducing manufacturing complexity while improving impedance matching and compactness. Stability analyses confirm unconditional stability, with the K-factor and μ-factor exceeding 1 and Delta remaining below 1 across the entire operating frequency range. Power simulations demonstrate a saturated output power of 41.21 dBm and a peak power-added efficiency (PAE) of 39.81%, highlighting the amplifier's high efficiency and robust performance. The measurement results exhibit a remarkable consistency with the simulated data. These results demonstrate the suitability of the amplifier for demanding X-band applications including satellite communications, radar systems, and electronic warfare.

Keywords: *X-band, High-Electron-Mobility Transistors (HEMTs), Monolithic Microwave Integrated Circuit (MMIC), High-Power Amplifier (HPA), Gallium Nitride (GaN) on a Silicon Carbide (SiC), Coplanar Waveguide (CPW)*

1. INTRODUCTION

The frequency bands above 8 GHz include X, Ku, K, and Ka bands. The various applications where these bands are used to include radar systems, satellite communication, and electronic warfare. Excellent propagation characteristics with the ability to support high-resolution, long-range operations make these bands suitable for these applications. Significant growth has been witnessed in the field of satellite communication technologies using X-Band, especially in military applications [1]. This has driven great demand for high-power amplifiers in recent years, hence the development of devices such as MMIC technologies that meet this demand. There is a high affinity for MMICs especially for their compact size and easy integration, as well as superior performance. These integrated circuits are designed to operate particularly within microwave frequencies between 300 MHz and 300 GHz. In other words, such circuits can find wide use in some fields like microwave mixers, power amplifiers, low-noise amplifiers, and high-frequency switching. Moreover, the input and output ports are always matched to the standard impedance levels. In this respect, they have considerable ease of integration into the different systems [2].

A major breakthrough in technology related to MMICs for high-frequency amplifiers is brought about by the use of a high-electron-mobility transistor (HEMTs). Normally, this kind of transistor is famous for its high mobility of electrons, which promises faster operations and higher efficiency compared with conventional ones [3]. In other words, this means they are almost idealistic for improving further the efficiencies and output powers of HPA. Recent works also showed astonishing improvements in performance, particularly in aspects of output power and PAE [4]-[6]. For example, one such GaN-based HEMT amplifier achieved an output power of 40.06 dBm with a better PAE than 44.53% in the frequency

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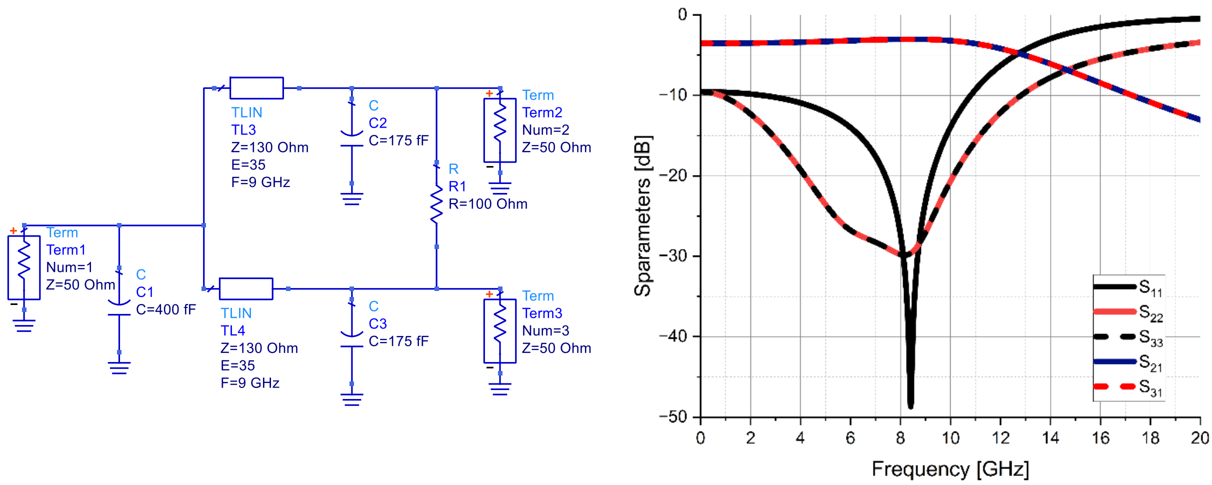
range from 8.5 to 10.5 GHz [7], while another design was able to provide 47.5-48.7 dBm with a PAE of 40-45% over the frequency band from 8 to 12 GHz [8]. This indeed reflects the very outstanding performance of HEMTs, in particular when used in compact configurations. The use of Gallium Nitride on Silicon Carbide substrates will further enhance the performance of HPA. Major advantages related to GaN-on-SiC technology are high efficiency, wide bandgap material, high power density, very wide frequency range, and excellent integration capabilities; hence, it is preferred for modern high-frequency applications. Some designs achieve a 3-stage X-band GaN MMIC power amplifier using Qorvo's 150 nm GaN-on-SiC technology [9] and wideband millimeter-wave power amplifiers using the GaN-on-SiC technology, specifically for frequencies of 24.5-29 GHz [10].

The other technique employed to enhance performance and manufacturability is the CPW structure. In contrast to microstrip designs, CPW eliminates the need for through-holes, thus minimizing fabrication processes and costs. The design using CPW also helps improve impedance matching due to reduced parasitic effects. These, in turn, permit easy integration and compact layouts. Such as: [11] focuses a two-stage CPW based E/W-band amplifier MMICs fabricated in a 60 nm GaN-on-Si process with a maximum gain of 16 dB. In the two-stage X-band MMIC amplifier, CPW was used to align the optimum noise matching and input matching of each element; in the three-stage W-band amplifier, because CPW can be used, each stage is able to be put close to each other for increasing the bandwidth [12]. Along this line, a compact Wilkinson power divider was designed in [13], using gallium-nitride-based CPW integrated passive device technology. It thus follows that the employment of CPW technology can be employed to advance both the functionality and manufacturability of microwave-integrated circuits [14]-[16].

In this paper, a novel design for the X-band MMIC HPA is presented; this includes four parallel HEMTs, each 8×125 μm² in size, to realize greater output power without detuning in operational frequency. A CPW structure is utilized that simplifies the manufacturing process, as it eliminates the need for via-holes, thereby enhancing the impedance matching. This HPA achieves a maximum small-signal gain of 11.7 dB with a flatness of 0.59 dB/GHz. Power simulations reveal a saturated output power of 41.21 dBm and peak PAE of 39.81%. The stability analysis confirms that the design is unconditionally stable across the entire frequency range, with both the K-factor and μ-factor exceeding 1 ($K > 1$, $\mu > 1$) and Delta remaining below 1. These results demonstrate the high efficiency and reliability of the amplifier. It aims to support advances in MMIC technology by presenting a study on the design of HPA for X-band applications.



(a) (b)

Figure 1. (a) Schematic and (b) S-parameter simulation results of the proposed compact WPD

2. DESIGN

In the design, commercially available Keysight's Advanced Design System (ADS) Momentum is employed, performing numerical analysis of electromagnetic problems using the Method of Moments (MoM). At the beginning of the design process, direct current (DC) and radio frequency (RF) analyses of HEMTs of different sizes are performed. The simulation results indicate that an HEMT with 8 fingers and a gate width of 125 μm is selected, operating under a bias condition of 28 V_{ds} and 240 mA for a single transistor. To increase the output power, the single MMIC HPA comprises two parallel HEMTs. Additionally, two identical Wilkinson power dividers are used for combining the two MMIC HPAs in proposed design.

The traditional WPD design consists of two $\lambda/4$ transmission lines and an isolation resistor (100 Ω) between output ports. However, $\lambda/4$ transmission lines become longer at lower frequencies. To minimize the traditional WPD, $\lambda/4$ transmission lines are replaced with a shunt capacitor, a series inductor, and another shunt capacitor, known as the π-type equivalent circuit method. As shown in Figure 1(a), the proposed Wilkinson power divider is designed using a shunt capacitor of 400 fF, a serially connected transmission line with a characteristic impedance of 130 Ω and an electrical length of 35°, and shunt capacitors of 175 fF. The TLIN impedance (130 Ω) was selected to match the even-mode impedance requirements of the divider, while the 35° electrical length (corresponding to ~$\lambda/8$ at 8.95 GHz) minimizes phase distortion. Shunt capacitors (400 fF/175 fF) were optimized via harmonic balance simulations in ADS Momentum to compensate for parasitic inductances and achieve broadband matching. Additionally, an isolation resistor of 100 Ω is placed between the output ports to maintain isolation and ensure proper power division.

In the S-parameter simulation results of the miniaturized WPD, it is observed that the input return loss (S_{11}) is better than -12 dB within the frequency range of 7.6-10.3 GHz. Additionally, the output return losses (S_{22} and S_{33}) are better than -19 dB in the same frequency range. The transmission coefficients (S_{21} and S_{31}) are less than -3.2 dB throughout the 7.6-10.3 GHz bandwidth. Figure 1(b) illustrates these results.

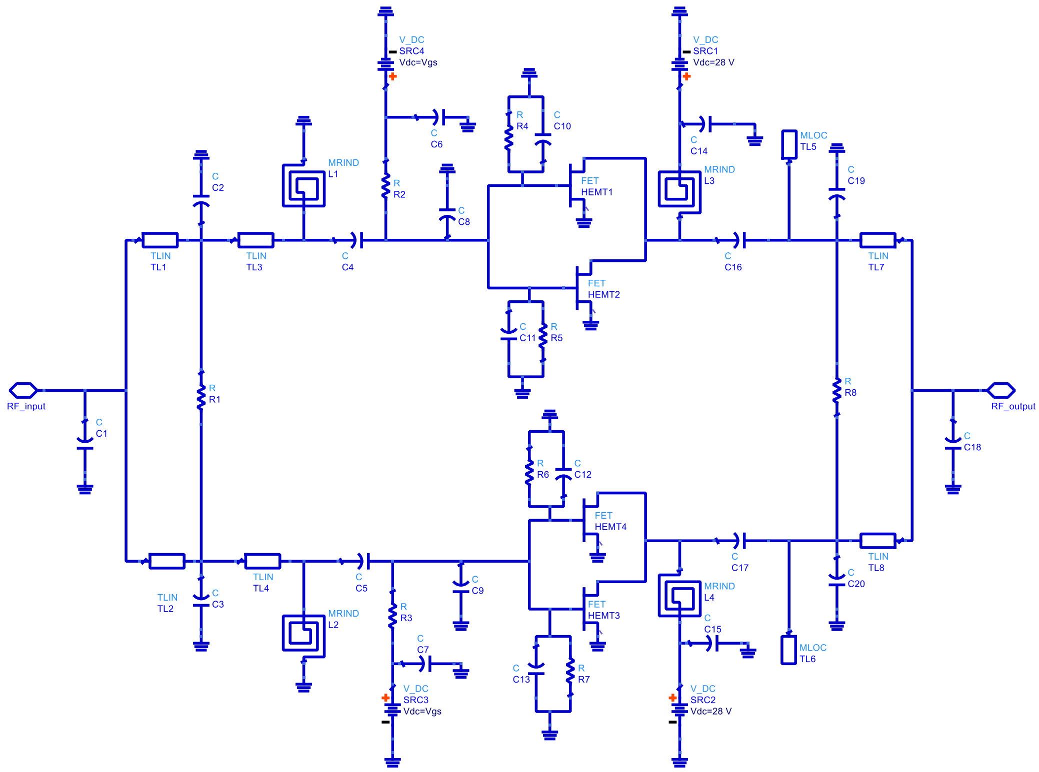


Figure 2. The Schematic of the X-band MMIC HPA

In the schematic depicted in Figure 2, ideal lumped elements are used in the design. Two WPDs are positioned at the input and output ports of the MMIC HPA to split and combine the RF signals without any phase difference. The design includes two parallel MMIC HPAs, each consisting of two 8×125 μm² HEMTs, resulting in a total of four 8×125 μm² HEMTs. To prevent DC flow through the RF input and output ports, serially connected DC block capacitors (C_4, C_5, C_{16}, and C_{17}) are included. The drain bias line incorporates serially connected resistors (R_2, R_3) to improve stability, while shunt capacitors (C_6, C_7) are added to the gate bias line to prevent undesired DC oscillations. Spiral inductors (L_3, L_4) are used in the drain bias line as choke inductors to block the RF signal flow into the DC supplies. Furthermore, parallel RC networks (R_4C_{10}, R_6C_{12}) are shunt-connected at the RF input ports of the transistors to enhance circuit stability. This configuration ensures the reliable and efficient operation of the amplifier.

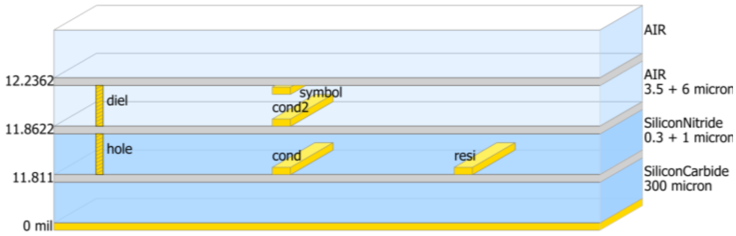
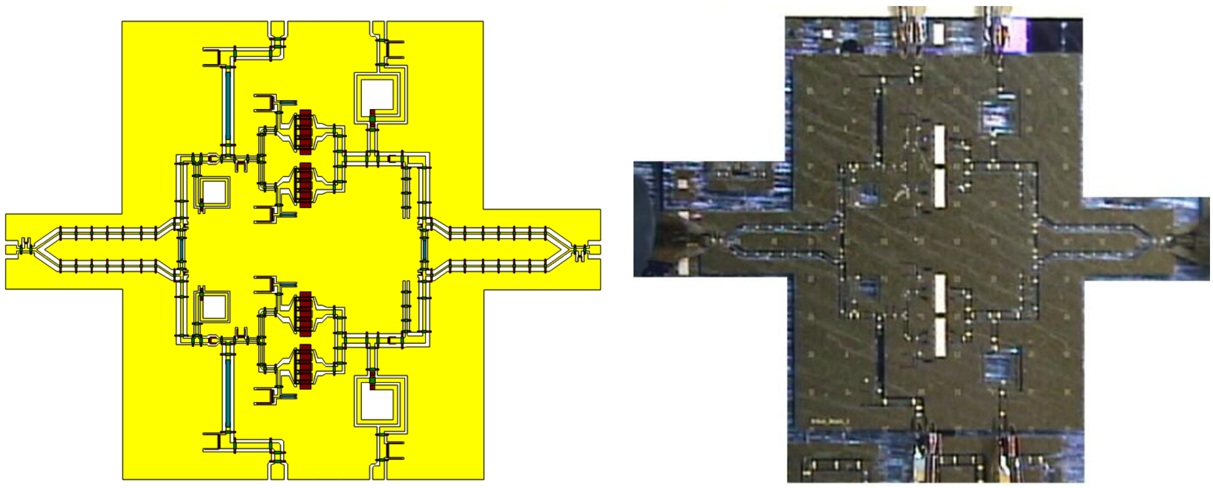


Figure 3. GaN on SiC MMIC technology

After the initial schematic design, the lumped elements are implemented using the GaN-on-SiC process, which features a dielectric constant of 9.6 and a thickness of 300 μm. CPW technology is employed to avoid the expensive and complex via-hole processes. The design includes four metallization layers: underpass (cond), second metal layer (cond2), Nickel Chrome (NiCr) resistor (resi), and airbridge metals (symbol), as illustrated in Figure 3. In the layout design, 2nd metal layer is utilized to carry both RF and DC signals. On the other hand, airbridge structure is utilized cross over the 2nd metal layer for electrical conductivity. To ensure the electrical conductivity of the ground planes, they are connected using an underpass metal at intervals of less than $\lambda/24$, where λ is the guided wavelength at the center frequency (8.95 GHz). This spacing ($\lambda/24 \approx 0.6$ mm for $\varepsilon_{eff} \approx 6.7$) was chosen to suppress parasitic resonances while maintaining a compact layout. The value derives from $\lambda = c / (f \sqrt{\varepsilon_{eff}})$, where c is the speed of light and ε_{eff} is the effective dielectric constant of the GaN-on-SiC CPW structure.



(a) (b)

Figure 4. (a) The Layout of the X-band MMIC HPA and (b) Detailed Photography of the Fabricated X-Band MMIC HPA

The final design of the X-band MMIC HPA incorporates four parallel HEMTs, each with dimensions of 8×125 μm². These transistors operate with a 28 V_{ds} bias, resulting in a total drain current of 960 mA and a DC power dissipation of 26.88 W. The HEMTs are chosen because of their high efficiency and performance at microwave frequencies. The design uses coplanar waveguide (CPW) technology, avoiding the need for costly via holes by placing the signal line and ground plane on the same layer. This approach results in a compact layout. To enhance circuit stability, the gate bias is fed through serially connected Nickel Chrome (NiCr) resistors, while shunt capacitors are used in both the gate and drain bias lines to suppress unwanted oscillations. Spiral inductors are employed in the drain bias line as choke inductors to block RF signals from reaching the DC supply. Additionally, serially connected DC block capacitors are placed at the input and output of each MMIC HPA to prevent DC flow through the RF paths. Small-value shunt capacitors are implemented using short stubs for compactness. The layout of the X-band MMIC HPA, showing these design elements, is presented in Figure 4(a).

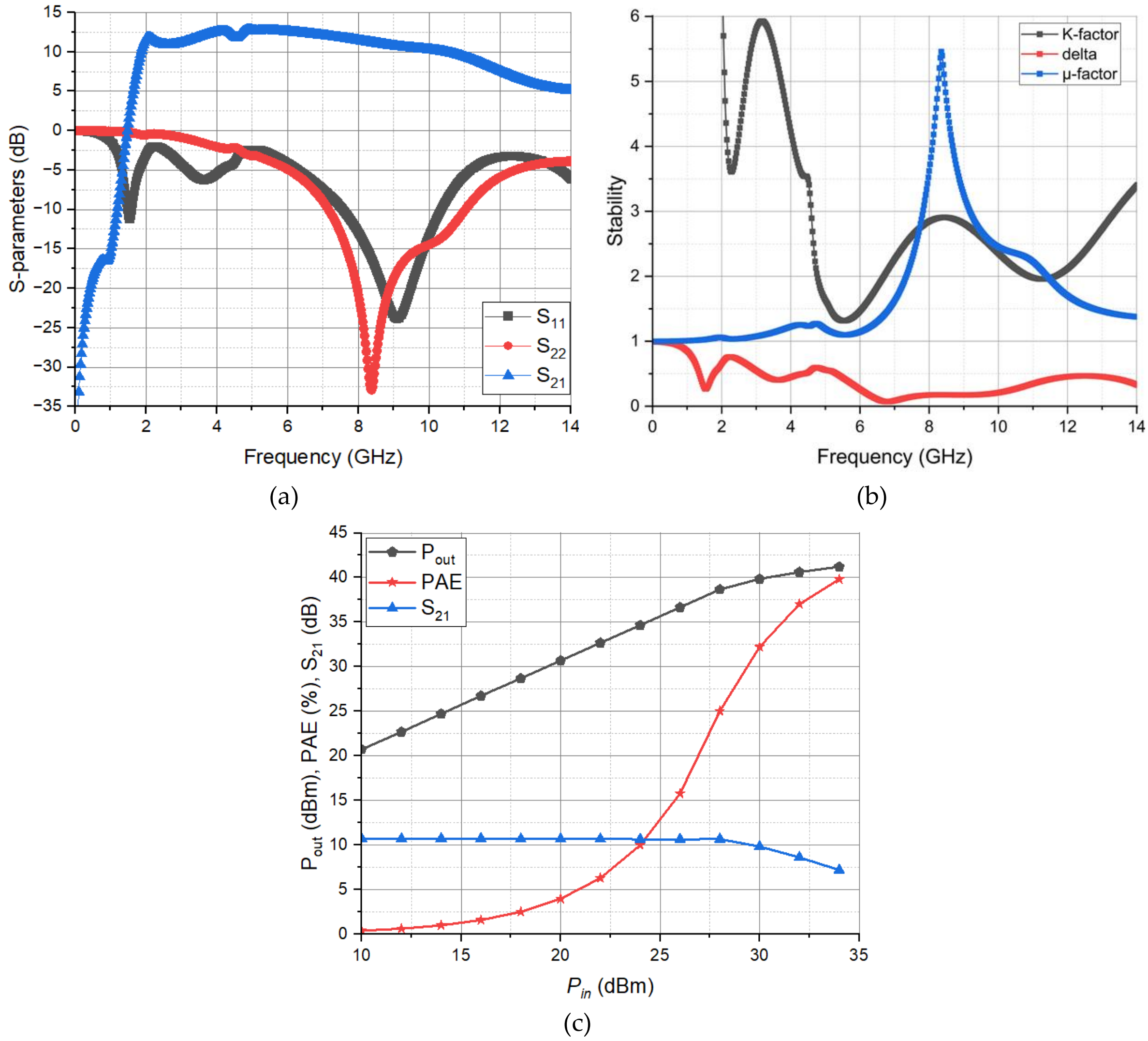


Figure 5. Simulation Results of the Proposed X-band MMIC HPA (a) S-parameter, (b) Stability, and (c) Power Simulation

3. ANALYSES AND DISCUSSION

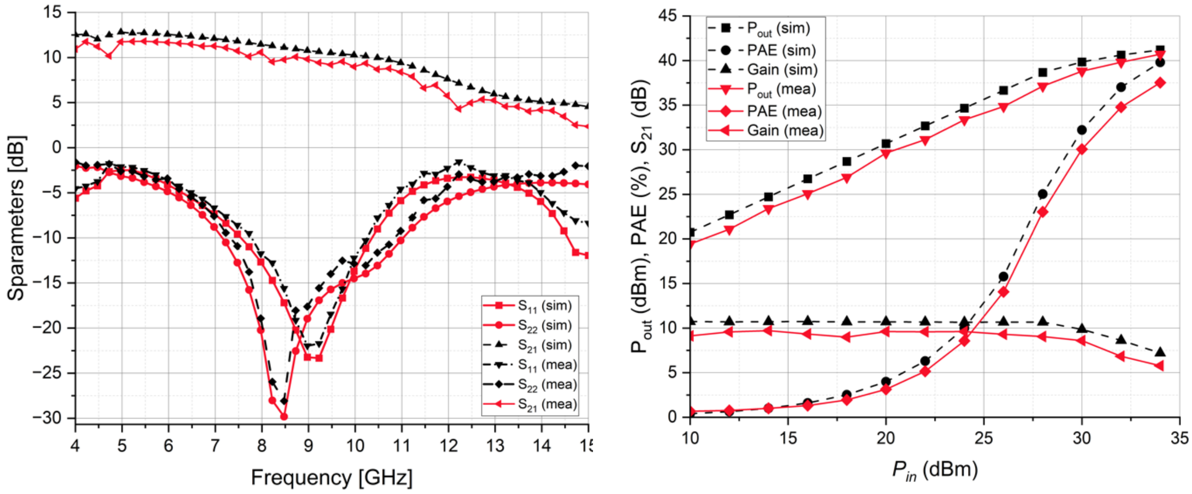
As Figure 5(a) is analyzed, the following conclusions are drawn. The forward gain (S_{21}) shows that the amplifier achieves a maximum small-signal gain of 11.7 dB and a minimum gain of 10.1 dB, resulting in a gain flatness of 0.59 dB/GHz within operating frequency range 7.6 - 10.3 GHz. This flatness indicates minimal gain variation across the operating frequency range, ensuring consistent performance for broadband applications. The input reflection coefficient (S_{11}) reaches a minimum value of -23.5 dB near the center of the operating frequency 7.6 - 10.3 GHz, indicating good impedance matching and minimal signal reflection at the input port. As to the output reflection coefficient (S_{22}), a similar trend to S_{11} is observed, with a minimum value approaching -20 dB near the center of the operating band. This signifies effective output matching, which is critical for maintaining high power transfer efficiency and minimizing signal distortion. Moreover, in Figure 5(b), it is observed that for both K-stability and μ-stability analyses, the proposed MMIC HPA is unconditionally stable. Furthermore, CPW structure contributes to the observed impedance matching by eliminating parasitic effects typically associated with via-holes, thus improving matching performance and reduces manufacturing costs by eliminating the need for costly via-holes to connect the ground plane to the substrate.

Table 1. Summary of Key Performance Metrics

Parameter	Value	Remarks
Frequency Bandwidth	7.6–10.3 GHz	Wideband X-band operation
Input Power	-10 dBm	Linear operation at low input power
Forward Gain	11.7 dB (max), 10.1 dB (min)	Stable gain with 0.59 dB/GHz flatness
Input Reflection Coefficient	-10 dB	Good input matching
Output Reflection Coefficient	-14 dB	Superior output matching
Power-Added Efficiency (PAE)	39.81%	High efficiency near saturation
Saturated Output Power, P_3dB	41.21 dBm	High output power for X-band applications
Power Dissipation, P_{dis}	26.88 W	Consistent with high-power operation
Stability	Unconditionally stable	Stable across all conditions and frequencies

The Figure 5(c) presents the relationships between input power (P_{in}), output power (P_{out}), power-added efficiency (PAE), and forward gain (S_{21}). P_{out} demonstrates a linear increase with P_{in} until approximately 25 dBm, then starts to saturate and reaches a value of about 41.21 dBm, indicating the maximum output power capability of the amplifier. PAE increases rapidly with input power, peaking at approximately 39.81% near the saturation point. This high PAE value highlights the efficiency of the proposed design. At lower input power levels (P_{in} < 20 dBm), the PAE is relatively low, which is typical for amplifiers as they operate with reduced efficiency in the linear region. S_{21} represents the amplifier's small-signal gain, remaining relatively constant at approximately 10 dB for input power levels below P_{in} ≈ 28 dBm. Beyond this point, S_{21} begins to degrade and the amplifier enters the non-linear region, characterized by gain compression and power saturation. The parameters and analysis results for the X-Band MMIC High Power Amplifier (HPA) design are summarized in Table-1.

The amplifier was fabricated via standard GaN-on-SiC processing: optical lithography defined the CPW (Ti/Al/Ni/Au metallization), followed by HEMT formation (mesa isolation, ohmic contacts, T-gates). NiCr resistors, MIM capacitors, and airbridges were integrated before final dicing. The electrical performance of the proposed structure was thoroughly evaluated using an Agilent Technologies E8364B PNA Network Analyzer (covering a frequency range of 10 MHz to 50 GHz) and a Cascade MPS150 RF probe station. RF signals were delivered through GGB RF probes, while DC biases were applied using multi-contact DC probes. The prototype, depicted in Figure 4(b), was tested to validate its operational capabilities over the intended frequency range. The results of the measurements, illustrated in Figures 6, demonstrate a high level of agreement with the simulated data, affirming the accuracy and robustness of the design methodology. Specifically, the measured small-signal gain, gain flatness, P_{out}, and PAE closely match the simulation results. The consistency between simulation and experimental outcomes confirms the reliability of the proposed design, emphasizing its potential for practical X-band applications within operating frequency range 7.6 - 10.3 GHz.



(a) (b)

Figure 6. Simulation vs. Measurement Results For (a) S-Parameters and (b) Power Characteristics

4. CONCLUSIONS

The proposed X-band MMIC HPA, designed using GaN-on-SiC technology, incorporates four parallel HEMTs with dimensions of 8×125 μm². Operating over the 7.6–10.3 GHz frequency range, the amplifier achieves unconditional stability, as confirmed by K-factor and μ-factor values exceeding 1 and Delta remaining below 1 across the entire band. Utilizing the GaN-on-SiC process enables the implementation of a coplanar waveguide (CPW) structure, eliminating the need for via-holes, thus simplifying the manufacturing process and enhancing both impedance matching and compactness. Power simulations reveal that the amplifier delivers a saturated output power of 41.21 dBm and achieves a peak power-added efficiency (PAE) of 39.81%, along with a small-signal gain of 11.7 dB with a flatness of 0.59 dB/GHz. The measurement results are in agreement with the simulation results. It is observed that this amplifier design shows a well-balanced optimization in terms of linearity, power handling, and efficiency, as demonstrated by its gain compression characteristics and the efficiency peak observed near saturation. These features position the design as a robust solution for challenging X-band applications including radar, satellite communications, and electronic warfare systems.

Declaration of Ethical Standards

The author confirms adherence to all ethical standards, including those related to authorship, proper citation, accurate data reporting, and the publication of original research.

Declaration of Competing Interest

The author states that there are no financial or personal relationships that could have influenced the findings presented in this paper.

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Data Availability

The data supporting the findings of this study will be provided upon request.

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