Design and Simulation of Wideband High-Efficiency X-band MMIC Power Amplifier based on GaN HEMT Technology

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ABSTRACT:
High output power, good efficiency, sufficient power gain, compact size, and low cost are essential parameters of high-frequency integrated microwave power amplifiers. Due to its unique characteristics, gallium nitride is considered a good choice for realizing high-frequency power amplifiers. This article presents an integrated microwave power amplifier with high efficiency and wide bandwidth in 0.25 µm GaN technology. Input and output matching networks are realized using spiral inductors, on-chip resistors, on-chip capacitors, and appropriate transmission line structures. The optimal values of the elements have been determined using the random and hybrid optimizer in the ADS simulator. Large on-chip inductors in the drain and gate bias circuits were used for biasing. They were designed in such a way that no ac signal leaks into the bias circuit. The proposed circuit works at 6.8 GHz to 11 GHz frequency, while its maximum PAE is 60%. The small signal gain at the frequency of 9.8 GHz is 12.45 dB, whereas the saturated output power is 32.68 dBm.

KEYWORDS: Power Amplifier, Output Power, Power Added Efficiency, GaN HEMT, Bandwidth, Gain.

1. INTRODUCTION

With the advancements in GaN HEMT technology, they have become an appropriate option for realizing high-frequency Power Amplifiers (PAs). They provide high power density (more than ten times its similar gallium arsenide), small size, low parasitic elements, good power gain, and high efficiency. Therefore, they can meet the future needs for the high-power wideband design.

The realization of high-power amplifiers has many challenges, one of which is their limited bandwidth. Due to the large dimensions of power transistors, their parasitic capacitors are significant, and as a result, access to wide bandwidths in high-power amplifiers is not simply possible. Therefore, it is necessary to use appropriate circuit techniques to increase the bandwidth of the amplifier.[1-10]

Class AB, B, and C amplifiers in which the conduction angle is less than 360 degrees are known as reduced conduction angle power amplifiers. Decreasing the conduction angle of the amplifier improves PA's efficiency. It increases the harmonics in the amplifier's output current, and as a result, the amplifier becomes more non-linear. It also reduces the output power of the amplifier [11].

If the transistor current enters the saturation region, the transistor current does not increase even as the input ac voltage increases. In this case, as the input power increases, the amplifier's output power increases slightly, but the amplifier's power consumption remains almost constant. As a result, the efficiency of the amplifier increases. The power amplifier in over-driven mode has been investigated in detail in [12].

Class E, D, and S amplifiers are switching PAs. In switching classes, the transistor is used as a switch by controlling the output current and voltage of the transistor. In a class F amplifier, the load impedance seen by the transistor output is open-circuited at odd harmonics and short-circuited at even harmonics. As a result, the output voltage and current of the transistor will have square and half-sine waveforms, respectively. Ideally, the efficiency of this class would be 100%. However, since it is only possible to create an open circuit and a short circuit in a few harmonics, it is practically impossible to reach an efficiency of 100%. In addition, class F has limited bandwidth [13].

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This article will explain the design steps of a high-efficiency wideband integrated power amplifier in X-band frequency based on the GaN HEMTs. The second section will discuss the methods, challenges, and stages of designing high-power amplifiers. In section three, the proposed circuit will be discussed. The simulation results will be examined in the fourth section, and finally, the conclusion will be expressed in section five.

2. STEPS AND CHALLENGES OF DESIGNING INTEGRATED HIGH-POWER AMPLIFIERS

This part will review the stages and challenges of designing integrated high-frequency power amplifiers.[1-10]

2.1. Implementation Methods of High-Frequency Circuits

High-frequency PAs can divide into two different categories: integrated PAs and hybrid PAs. Integrated PAs can be suitable for mass production. They have microscopic dimensions, while internal circuit connections have negligible parasitic elements, and thus they can use for very high-frequency design. However, using different materials in the manufacturing process is impossible in integrated PAs. As a result, all elements must be realized based on a specific material, such as gallium nitride or gallium arsenide.

Hybrid circuits have a much simpler manufacturing technology. They usually use very cheap substrate materials. In this technology, various elements from different materials can be assembled to realize the PA. This technology is suitable for implementing high-power amplifiers. Nevertheless, the repeatability and manufacturing accuracy is lower than integrated PAs. The proposed power amplifiers will be implemented based on integrated GaN HEMT technology.[1-10]

2.2. Design Steps of Integrated Power Amplifiers

The implementation of power amplifiers becomes more complicated by increasing the amplifier's working frequency and output power. The designer must have sufficient technical knowledge of high-frequency, non-linear, and thermal design and high-frequency measurements. [1-10]

The design of integrated high-frequency power amplifiers has different stages. These steps include choosing the appropriate technology and transistor, characterizing the selected transistor, checking the linear and non-linear transistor model, conducting small signal and large signal simulations of the PA at the schematic level, simulating the designed circuit at the Layout level, designing an appropriate bias circuit, thermal analysis of the PA, and designing a suitable heat sink, which will be briefly described below.[1-10]

2.2.1. Choosing an appropriate transistor

In high-power and high-frequency amplifiers, the transistor must have high working voltage, suitable thermal characteristics, long lifetime, sufficient output power, sufficient power gain, and high power efficiency. The characteristics of the substrate on which the transistor is implemented must be considered to choose an appropriate transistor. A suitable semiconductor for high-frequency PA implementation should have high breakdown voltage, band gap, electron saturation speed, electron mobility, and thermal conductivity.

Gallium nitride high electron mobility transistors with a high power density and small size are a unique option for implementing high power amplifiers in the X-band and higher frequency bands. They have a breakdown voltage of higher than100 volts, high efficiency, suitable output power, high reliability, and low thermal resistance. Therefore, they can meet the future needs of designing high-power and high-frequency amplifiers.[1-10]

2.2.2. Design and simulation of matching circuits

Although the linear model of the transistor gives essential information about the performance of the transistor, access to the non-linear model of the transistor is necessary for the PA design. Referring to the linear model of the transistor and by drawing the diagrams of the maximum stable gain, the maximum available gain, and the stability diagrams, it is possible to determine the frequency stability bandwidth and the transistor's small signal gain. If the selected transistor is not unconditionally stable (it becomes unstable due to some input or output impedances), it is necessary to design a stabilization circuit to stabilize the transistor. [1-10].

For PA's large-signal simulation and calculating the output power, efficiency and power added efficiency (PAE), it is necessary to use a non-linear transistor model. In the proposed circuit, the non-linear model of Hiwafer transistors has been used, in which all non-linear effects, including non-linear capacitors, non-linear transconductance, and thermal effects, are modeled.

The most critical part of high-frequency power amplifier design is the design and simulation of matching circuits. Accurate PA design cannot be achieved except by having an accurate model of the active and passive elements of the circuit, including transistors and all the elements in matching networks. In these frequency ranges, parasitic elements can destroy the circuit's performance. Therefore, accurate high-frequency analyses of various circuit elements are necessary. In the proposed amplifier, the elements used in the input and output matching circuits are modeled using high-frequency 3-D momentum simulation in an ADS simulator with a meshing frequency of 14 GHz[1-

10]. Simulated matching circuit is shown in figure 5,6. In the input matching circuit, series and shunt resistor is used for stabilization. The combination of series inductor-shunt capacitor topology and multi-stub configuration were used in both input and output matching networks to increase the PA's bandwidth.

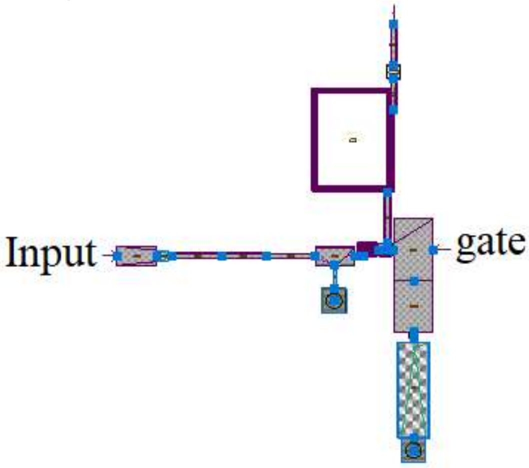

Fig. 1. Input matching circuit.

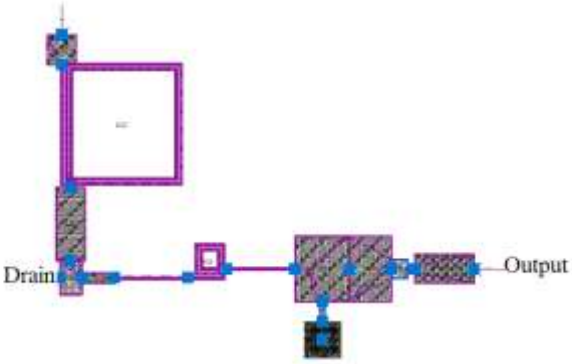

Fig. 2. Output matching circuit.

2.2.3. Thermal Design

One of the essential parts of solid-state PA design is thermal analysis. In this part, the designer must find a suitable way with minimum thermal resistance to transfer heat from the power components to the environment. A transistor's 10 degrees Celsius increase in junction temperature will halve its lifetime. An excellent thermal design can increase the amplifier's lifetime and improve its electrical performance.[1-10]

2.2.4. Bias circuit design

The voltage applied to the GaN HEMTs for turning on and off the transistors must have proper timing. As a result, it is necessary to design appropriate bias circuits. PAs are dealing with high currents and voltages. Therefore, the bias circuit must have low losses. Otherwise, high losses can affect the overall PA's efficiency. The designed bias circuit has the minimum loss and can stimulate the transistor both in pulse and continuous form[1-10]. Large on-chip inductors in the drain and gate bias circuits ensure that no ac signal leaks into the bias circuit. There is a resistor in the gate bias path, which increases the stability at low frequencies.

3. THE PROPOSED PA

The proposed integrated PA was designed based on Hi-Wafer's GaN HEMT technology with a minimum gate length of 0.25 micrometers. The transistor size is 4 x 125. The maximum voltage that can be tolerated is 100 volts, while the working frequency is up to 50 GHz. Hi-wafer NPA25 technology is implemented on gallium nitride substrate with a 100-micron thickness. This technology uses two layers of M1 and M2 gold metallization with thicknesses of 1 and 4 mm for microstrip lines and Bridges. It enables the implementation of metal-insulator-metal (MIM) capacitors with a capacitance density of 280 pF/mm2, thin film resistors (TFR), and spiral/square inductors.

In the proposed PA, in order to achieve the optimum efficiency and bandwidth, a suitable wideband structure, which includes various elements such as inductors and capacitors on the chip and transmission lines, has been used to match the input and output impedances of the transistor. The dimensions of the various elements of the circuit have been determined by multi-objective random and hybrid optimization in ADS software in such a way that all the PA characteristics, including efficiency, gain, bandwidth, output power, and S-parameters, are optimized. The dimensions of the proposed PA are 3.181 mm x 2.04 mm.

The proposed PA is biased in class AB while the bias current of the transistor is 580 mA. This class provides appropriate linearity and efficiency. The bias circuit provides a drain voltage of 28V and a source voltage of -2.8V. The layout of the proposed PA is shown in Fig. 3.

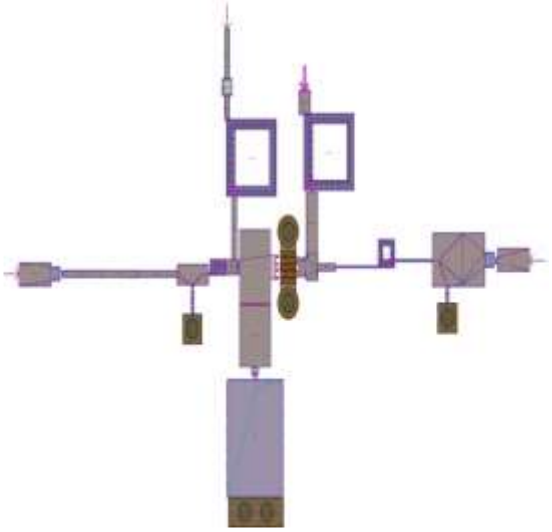

Fig. 3. The proposed PA layout.

4. SIMULATION RESULTS

The simulations have been performed in Momentum ADS software using the non-linear model of the transistor. The result of the large signal simulation of the proposed PA at the frequency of 9.5 GHz is shown in Fig. 4. At the 1-dB power compression point, the PA efficiency is 60% , while the output power is 32.68 dB mW (1.854 W) and the power gain is 10dB.

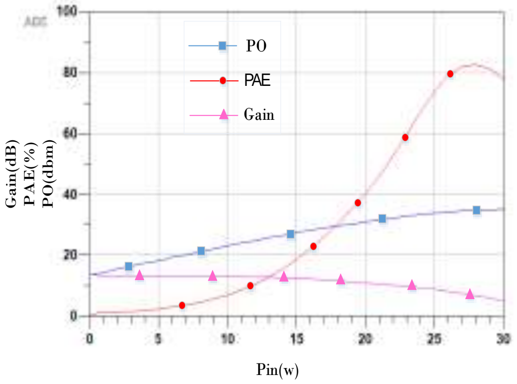

Fig. 4. Simulation of power gain, output power, and power added efficiency of the proposed PA at 9.5 GHz.

Fig. 5 shows the simulated S-parameters of the proposed PA. The maximum value of S_{21} is 12.451 dB, whereas S_{11} in the frequency range of 8.5 GHz to 11.7 GHz and S_{22} in the frequency range of 7.3 GHz to 14.05 GHz is less than -10 dB.

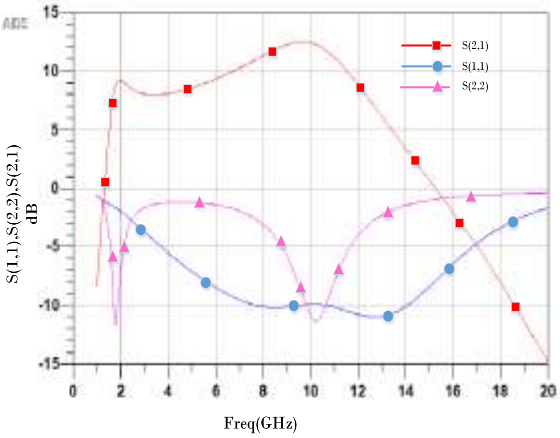

Fig. 5. Simulated S-parameters of the proposed amplifier.

The µ stability coefficient of the proposed PA is shown in Fig. 6. As it is clear, the stability coefficient is greater than one in all frequencies, and the PA is unconditionally stable.

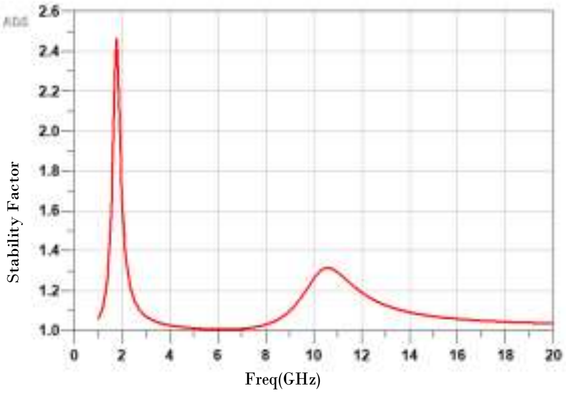

Fig. 6. Simulated stability coefficient of the proposed PA.

In Table 1, the results of the proposed amplifier are compared with other similar PAs implemented using GaN HEMT technology in the X-band. As shown, the proposed amplifier has higher bandwidth and efficiency than other similar PAs.

Table. 1. Comparison of simulation results of the proposed PA with other similar PAs.

Size (mm^2)	power added efficiency) (/.	Power gain (db)	Output power (dBm)	Bandwidth (GHz)	Ref
2.❋3.18104	60	12.45	32.68	6.8-11	Proposed PA
4.5❋4	38	18.5	41.5	8.8-10.4	(23)
3.5❋3.8	45	22.7	47.7	8-12	(24)
4.5❋4	38	14.6	47.7	8.5-9.5	(25)
3.7❋2.5	33	16	42	8.6-10.6	(26)

5. CONCLUSION

This paper presents the design steps of a high-efficiency GaN HEMT integrated microwave power amplifier in HiWafer NPA25 technology. By using the appropriate structure selected for the input and output matching circuits and optimizing the values of the circuit elements, wide bandwidth, high efficiency, and sufficient power gain have been achieved. The proposed PA provides an output power of 32.68 dBm, 60% efficiency and 12.45 dB gain, and bandwidth of 6.8GHz to 11 GHz.

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