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DESIGN AND IMPLEMENTATION OF MMIC POWER AMPLIFIERS FOR MODERN WIRELESS COMMUNICATION SYSTEMS

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Abstract

Recent developments and demand for high data rate information in modern wireless communication systems have significantly increased the complexity in the infrastructures like power amplifier (PA) design. The PAs are the final stage in the transmitter chain of a communication system and their design needs careful planning and specialized techniques. This paper presents a monolithic microwave integrated circuit (MMIC) PA design that operates at the frequency of 2.4 GHz for wireless applications using 10 W CGH40010F gallium nitride (GaN) 0.18 µm HEMT transistor process. The simulated results of the layout MMIC PA design using ADS library package are acceptable to required design consideration at low biased quiescent current of less than 200 mA with a gate and drain voltages are -2.7 V and 28 V, respectively. The power added efficiency (PAE%) and gain are about 59% and 12 dB respectively at the operating frequency of 2.4 GHz and input source power 29 dBm. The proposed amplifier circuit design has a high linearity and stability, the simulated peak output power is about 41 dBm at the input power of 29 dBm. The upper and lower side of the third order intercept points (IP3) are greater than 40 dBc at 29 dBm.

Keywords: GaN HEMT, High gain and stability, MMIC design, Power added efficiency, Power amplifier.

1. Introduction

Recently, especially after the Covid-19 pandemic, the world is moving in the direction of online applications such as banking, meeting for business and lecturing, transportations, shopping, and autonomous cars, which depend on wireless data transfer [1]. New developments in modern communication systems including 5G for example, require a new technology for transmitters that can provide large data speeds, high accuracy, high linearity, and high energy efficiency [2]. As new communication standards have significantly revolutionized the complexity in the infrastructures of the design like monolithic microwave integrated circuit (MMIC) power amplifier circuit design [3].

The power amplifiers (PAs) are the one of the most important transmitter modules that playing a key role in several parameters such as linearity [4], dynamic range of the output power, power consumption, and quality of the signal which modulated and radiated in the portable electronic devices [5]. The fabrication process of the power amplifier is chosen based on depending on output power and operation frequency [6]. Therefore, there are many limitations and challenges in the PA design likes fabrication cost, chip area, power consumption, high gain, high linearity, and high power with efficiency.

In order to design PAs with high performances, high power Gallium Nitride (GaN) high electron mobility transistors (HEMT) have been used compared to GaAs [7], and CMOS technologies [8]. The LDMOS and GaN are the most important technologies that are suitable for high output power, for example, more than 10 W. Whereas, CMOS process is the one of the best selected for integrated circuit (IC) due to having several features such as low cost, simpler fabrication. However, high output power is not provided. In addition, there is a constant trade-off between linearity and efficiency [9].

In 2023 Ahmed et al. [10] presents a broadband power amplifier (PA) design for mobile base station applications using ATF13786 Gallium Arsenide (GaAs) transistor with DC biasing conditions like gate to source voltage (V_{GS}) is 2.2 V and drain to source voltage (V_{DS}) of 3.75 V. The simulate PA circuit design has been performed using ADS software. The operating frequency range used in this work is about (0.85 to 3) GHz. The simulated power added efficiency (PAE%) and maximum gain are about 32.41% and 11.93 dB at the peak output power of 25.425 dB and the input power is greater than 20 dBm.

Venkatesh Murthy, et al. [11] presents a new design of MMIC power amplifier that operates at mm-wave frequency about 27 GHz for communication systems applications in 2024. The MMIC PA is simulated and investigated using 0.15 µm GaN HEMT transistor in ADS software. The simulated results of the design achieve a PAE% and drain efficiency about 41% and 43% respectively at the peak delivered output power of 0.9 W.

In the same year, Zainol Murad et al. [12] suggested a two-stage power amplifier using 0.13 µm CMOS process for wireless communication applications. The class E PA operates at the WLAN frequency of 2.4 GHz. The input and output matched network were designed using LC lumped elements for harmonic filters at the operating frequency. The simulated layout design with a chip area of 1.05 mm^2 achieves a high PAE% and output power are about 45.2% and 19.19 dBm respectively when the biasing supply voltage of 2V.

In this work, presents a class AB GaN MMIC power amplifier that operates at the wireless frequency of 2.4 GHz for communication system applications. The DC biasing voltage and current of the amplifier circuit have been chosen based on particular application and operating frequency. The simulated layout EM-Co-simulation MMIC PA design based on Roger RO4350B substrate materials using ADS library package. The proposed amplifier utilized an input and output matched network with transmission line technique for harmonic rejection filters.

2. Power Amplifier Circuit Design

One of the most crucial components of wireless transceiver designs is the power amplifier (PA), which is often placed before the transmitting antenna. It usually determines the strength of the transmitted signal. As a result, the control in the overall performance of the wireless communication system like efficiency, gain, and output power [13]. The general schematic diagram of the power amplifier as shown in Fig. 1. It consists of CGH40010F 10 W gallium nitride (GaN) 0.18 µm HEMT transistor, input, and output matched networks (IMN and OMN), the low and high biasing circuits with voltages V_{GS} and V_{DS}, and finally, input and output sources (U_i, and U_o). In general, the operation of PA is to convert DC power fed by the biasing supply voltage to RF energy signal that is transmitted by antenna in the transmitter unit.

The main category of the general PAs are linear mode PAs and switching mode PA. There are many classes of the linear type named Class A, AB, B, C that depend on DC biasing current and determine the conduction angles and provide high linearity in theory. Whereas, the non-linear PAs named Class D, E, F, and et. switched mode that is turned ON and OFF periodically and achieves good efficiency. As a result, these classes are different in efficiency and linearity [14].

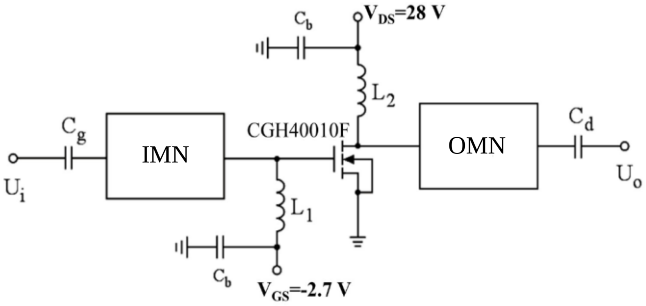


Fig. 1. Schematic diagram of RF power amplifier for communication systems.

Different considerations and challenges of the power amplifier design such as power consumption, linearity, efficiency, and modulation [15]. The power saving and linearity are the main challenges and especially in new applications like smart devices (Mobile phone and IoT). Whereas linearity is a key vital for controlling the quality of the transmitted signal via modern communication systems such as 5G, etc. For low output power up to 2 W, CMOS process is used for transistor technology due to having very little leakage current, availably, and simpler. In addition, the GaN and LDMOS are suitable for high output power and high frequency as shown in Fig. 2.

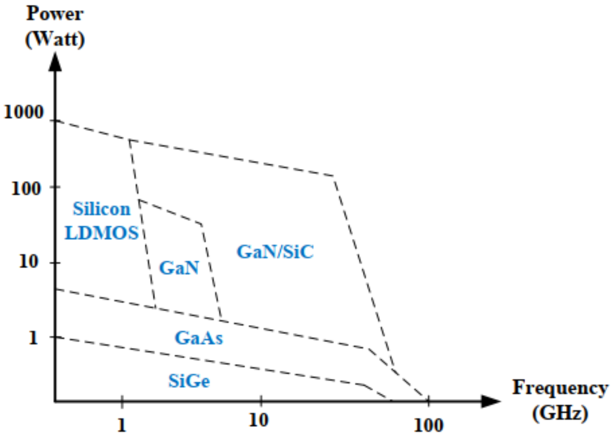


Fig. 2. Different technology of materials as a function of frequency [15].

In order to achieve an optimum design and simulate high power amplifier, the selection of materials and transistors are the most important parameters. Using ADS software, load pull, and source pull simulation are used to determine suitable impedances of output and input for the selected transistor, respectively. As consequently, input and output impedance matching networks (IMN, and OMN) are used to achieve linearity and high efficiency [16]. The design of PAs has many steps including the selection of an appropriate biasing for the 10 W CGH40010F HEMT GaN transistor, design of input and output matched circuits, and investigating the results via the performance characteristics like stability, efficiency, and linearity.

2.1. DC biasing and stability circuits

The first step of the design is the DC biasing circuit of the GaN transistor as shown in Fig. 3 to determine the quiescent point (Q-Point) and state operating region. The drain to source threshold voltage (V_{DS}) and Gate-Source voltage (V_{GS}) for GaN ranges from (0 to 70 V) and (-4 V to -2 V). The current-voltage characteristics are obtained and performed using an ADS tool at Q-point with V_{DS} is 28 V and V_{GS} of -2.7 V and drain current about 210 mA as shown in Fig. 4.

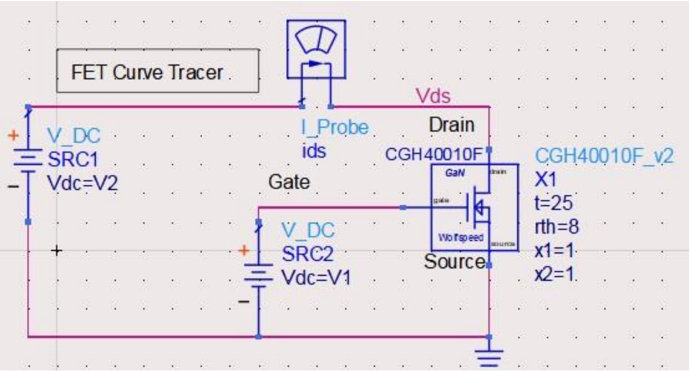


Fig. 3. The simulated DC bias circuit design for GaN HEMT transistor.

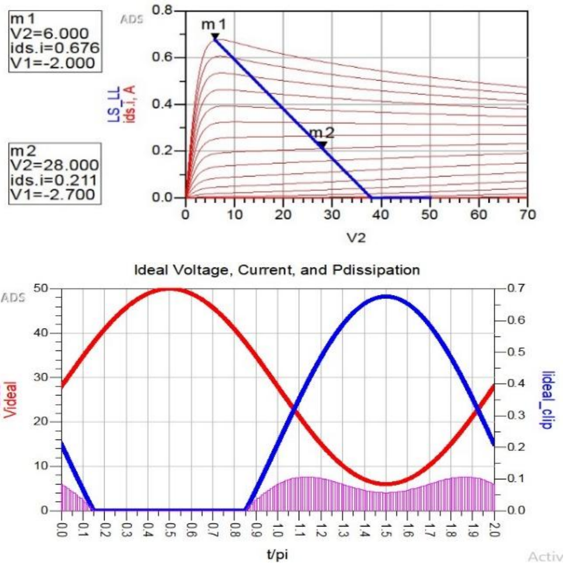


Fig. 4. The simulated I-V characteristic of the GaN power amplifier.

In order to design PAs that operate in a conditionally stable region, the Q-Point must be changed to V_{GS} voltage of -2.7 V and V_{DS} to 28 V. In this work, the stability factor (K) and delta factor (Δ) as expressed by Eqs. (1) and (2) have been selected less than 1 at frequency of 2.4 GHz. Where (S_{11}, S_{21}) are S-parameters like return loss in dB and gain, respectively. To improve the stability of the PAs, the transistor should be operated in the unconditionally stable region via connecting a series resistor at the input side of the transistor [17]. The value of series resistance R is about 5Ω is determined from a stability factor. The circuit of stability and the simulated result performed are shown in Figs. 5 and 6. It is observed that the K is increased to 2.243 after adding stability resistor with transistor.

$$K = \frac{1+|\Delta|^2-|S_{11}|^2-|S_{22}|^2}{2*|S_{21}|^2*|S_{12}|^2} \tag{1}$$

$$\Delta = S_{11} * S_{22} - S_{12} * S_{21} \tag{2}$$

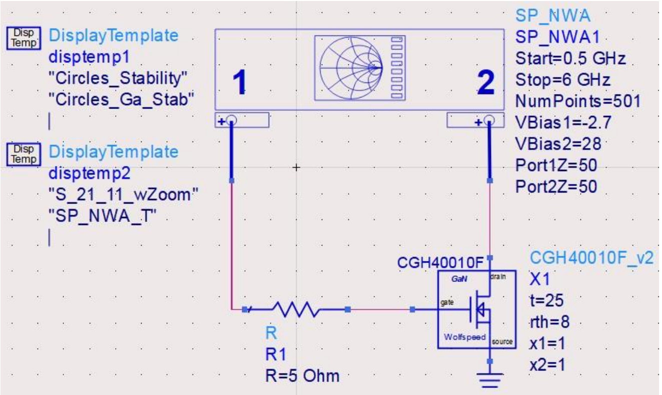


Fig. 5. The simulated stability circuit design of GaN power amplifier.

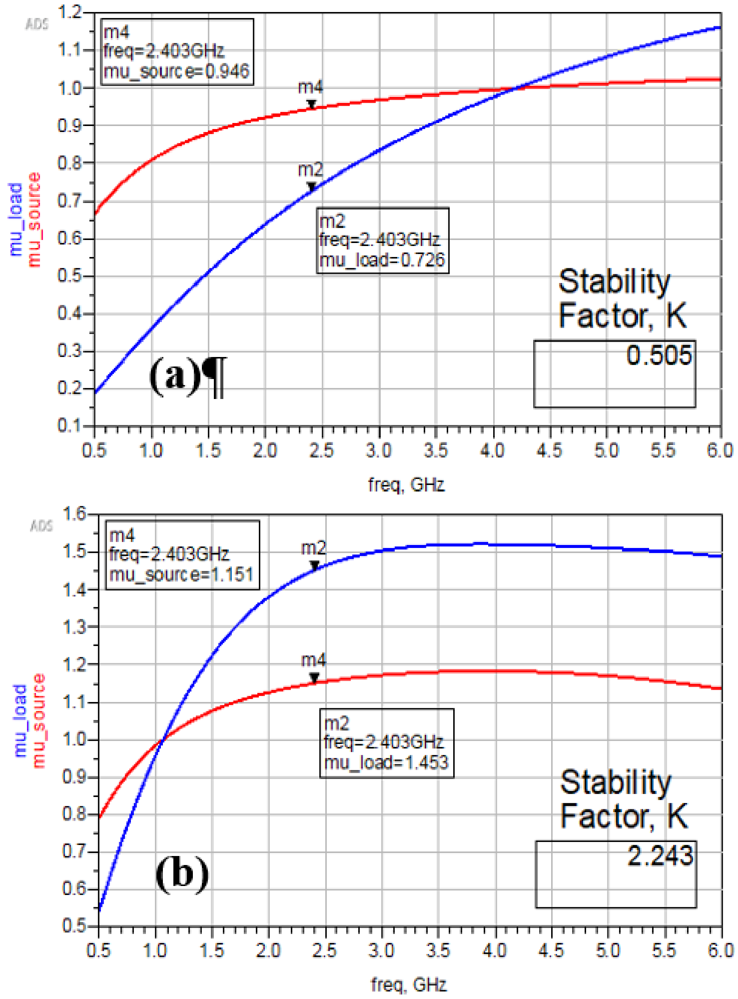


Fig. 6. The simulated results of the Mu.prime stability factor of GaN power amplifier: (a) without stability resistor, (b) with stability resistor of 5Ω simulated stability.

2.2. Input and output matching circuits

In order to obtain optimum design (high dynamic range and PAE%), input and output matched circuits have been designed at the operating frequency of 2.4 GHz using the ADS tool for improved stable zones of both the supply and the load as shown in Fig. 7. These circuits are implemented using microstrip transmission line (MTL) technique utilizing a Roger RO4350B material as substrate for layout PCB board. As a result, load pull, and source pull simulation have been used and performed to obtain optimum load and source impedance at 2.4 GHz fundamental frequency and maximum output power. The extracted source impedance (Zs) and load impedance (Z_L) are 5.742 + j*4.444 Ω and 14.249 + j*4.145 Ω, respectively. The simulated source pull and load pull of MMIC PAs circuit design and simulation results at the frequency of 2.4 GHz as shown in Figs. 8 and 9, respectively.

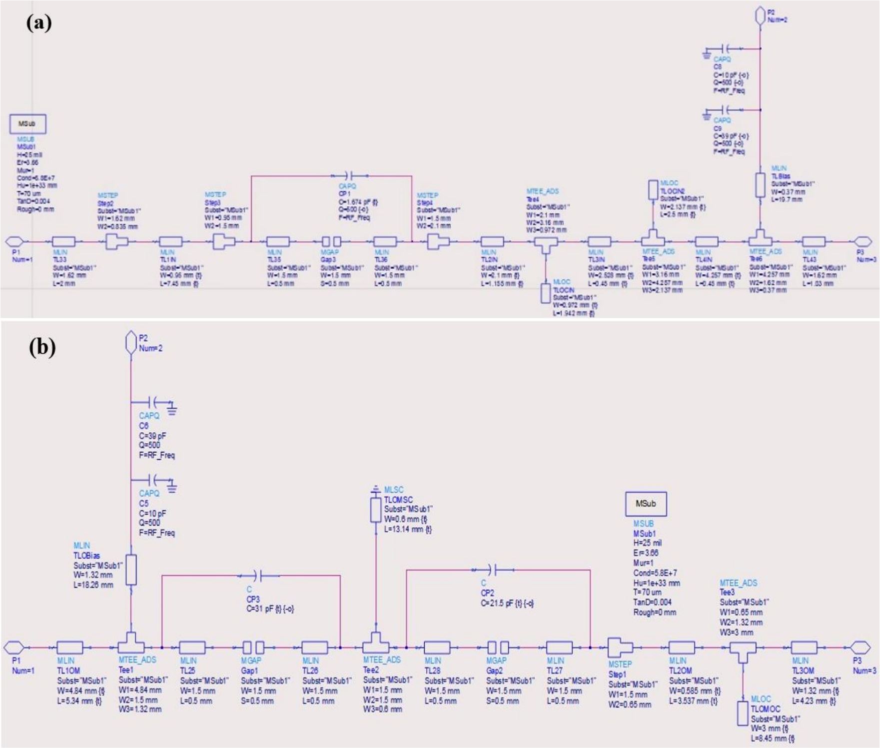


Fig. 7. The simulated MTL matched networks of MMIC PAs: (a) input IMNs, (b) output OMNs.

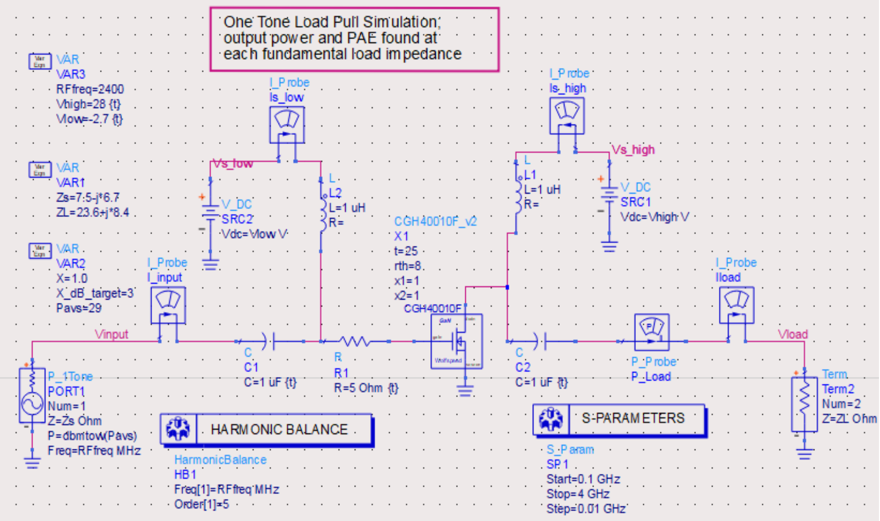
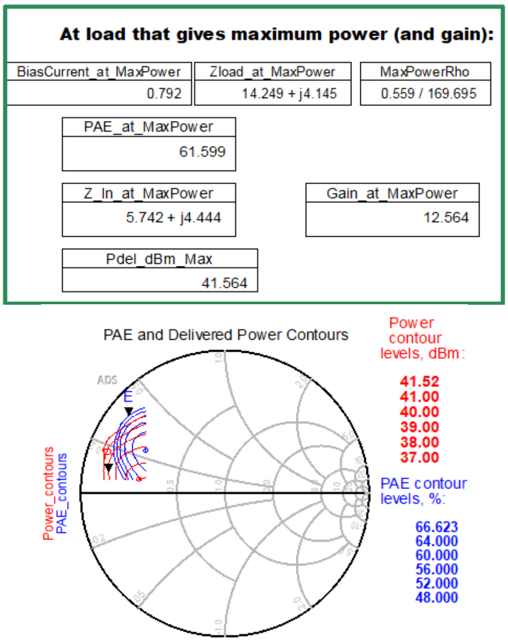


Fig. 8. The source and load pull simulation circuit design at the biasing conditions.



At load that gives maximum power (and gain):

BiasCurrent_at_MaxPower	Zload_at_MaxPower	MaxPowerRho
0.792	14.249 + j4.145	0.559 / 169.695

PAE_at_MaxPower: 61.599

Z_In_at_MaxPower: 5.742 + j4.444

Gain_at_MaxPower: 12.564

Pdel_dBm_Max: 41.564

Fig. 9. Load pull and source pull simulation results for MMIC Pas at the peak output power of 41.56 dBm and RF input power of 29 dBm.

3. Simulation Results and Discussion

The single stage MMIC high power GaN power amplifier has been designed and simulated at the operating frequency of 2.4 GHz using ADS software for communication systems applications. The layout PCB board of PAs with overall size area of (50 mm × 40 mm) has been designed and implemented using substrate material Rogers RO4350B and its specification explained in Table 1. The implemented PAs in this work achieves high linearity and output power ≥ 10 W using GaN HEMT CGH40010F transistor. The schematic circuit design of MMIC PA after connecting input and output matched networks as shown in Fig. 10.

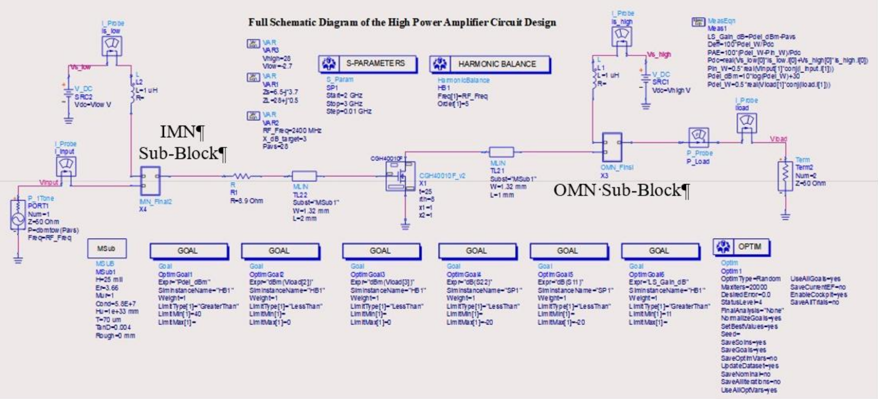


Fig. 10. The full design of the high-power amplifier at the operating frequency of 2.4 GHz including matching networks and GaN HEMT transistor.

Table 1. Roger RO4350B substrate specifications at the frequency of 2.4 GHz.

Parameters	Symbol	Value
Dielectric constant (Permittivity)	ε_r	**3.66**
Permeability	μ_r	**1**
Conductivity	σ	**$5.8\ E^{+7}$ S**
Thickness of conductor	**T**	**70 μm**
Thickness of substrate	**H**	**25 mil**

The EM Co-simulation layout MMIC GaN power amplifier has been performed in the ADS software using Roger RO4350B substrate material as shown in Fig. 11. The circuit design consists of input and output matched networks that are implemented using MTL technique. Finally, the (50 mm × 40 mm) PCB board of the proposed 10 W GaN MMIC PAs as shown in Fig. 12 for operating at 2.4 GHz and provide high power and gain about ≥ 40 dBm and ≥12 dB when the source power is 29 dBm. The simulation results can be divided to three-parts.

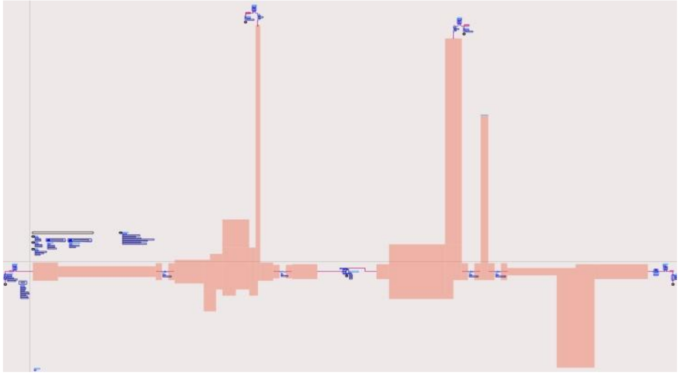


Fig. 11. The simulated EM layout power amplifier circuit design.

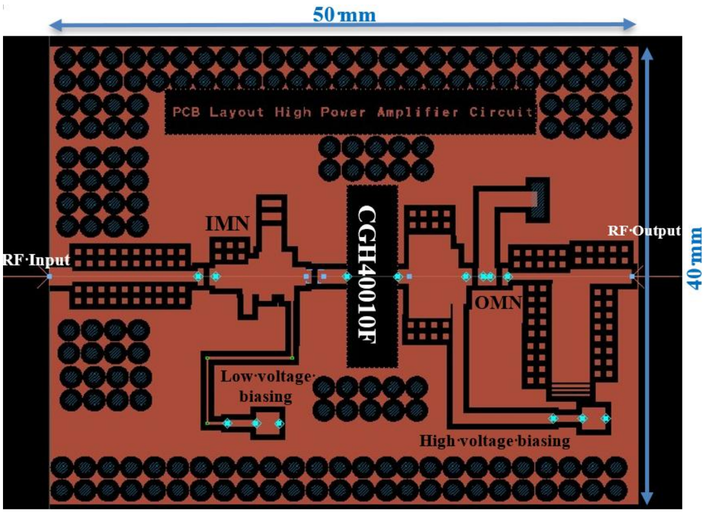


Fig. 12. The PCB MMIC power amplifier board with a size circuit about (50 mm × 40 mm).

3.1. S-parameters simulation and analysis

One of the most important parameters for evaluating the operation of the power amplifier at the fundamental frequency is S-parameter analysis that includes return loss (S_{11}) and gain (S_{21}) in dB for both. The simulated return loss and gain as a function of frequency have been explained by Fig. 13. It is observed that the proposed MMIC PA operates at 2.4 GHz and provides a high gain about greater than 12 dB. Also, the bandwidth of the amplifier can be calculated via 10-dB impedance, and it has been obtained about 0.5 GHz which is a ranging from (2.13 to 2.67 GHz).

3.2. Harmonic balance simulation

The proposed RF power GaN HEMT in this work is 10 W Cree's CGH40010 that operates at the high frequency like 2.4 GHz with a size package area about (50 mm × 40 mm) and made of Wolfspeed Cree company as shown in Fig. 14. GaN HEMT offers high gain, high linearity, and high efficiency with high output power. In addition, it provides a wide band for RF and microwave applications. The design considerations required in this work are that the transistor operates as a class AB with biasing conditions V_{DS}=28 V and V_{GS}=-2.7 V, efficiency ≥50%, and output power ≥ 40 dBm.

The harmonic balance (HB) simulation of the proposed amplifier consists of different results such as power added efficiency (PAE%), gain, fundamental harmonic, output power and current. The simulated PAE% and power gain have been obtained in this work as explained in Fig. 15. It observed that the PAE% is 58% and gain of about 12 dB at the source power of 29 dBm. The proposed amplifier design achieves high dynamic range of linearity as shown in Fig. 16. It observed that the peak output power of about 42 dBm has been obtained at the source power of 30 dBm. Also, the output current was obtained about 0.68 A at the power of 29 dBm.

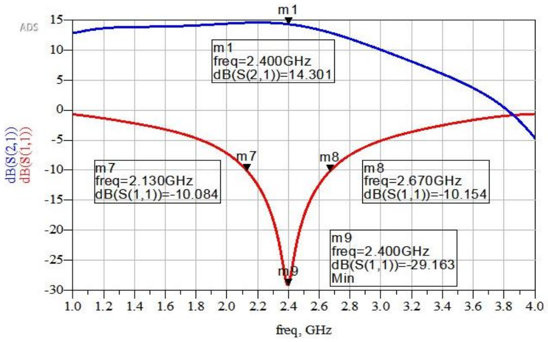


Fig. 13. The simulation return loss and gain of MMIC PAs at the source power of 29 dBm.

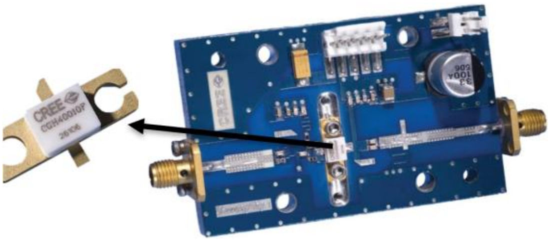


Fig. 14. 40 dBm CGH40010F GaN power amplifier circuit from Cree-company.

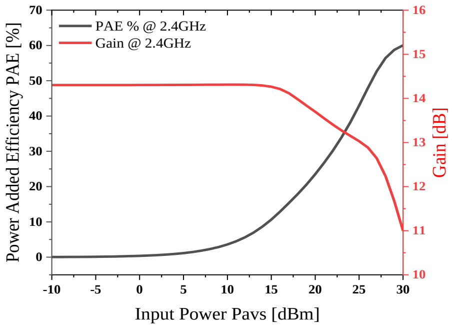


Fig. 15. The simulated PAE% and gain of the MMIC PA as a function of the source power.

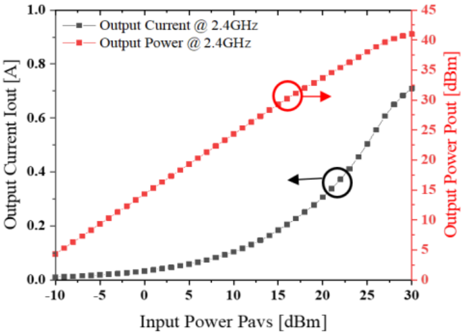


Fig. 16. The simulated output power and current of the proposed PAs as a function of input power.

The linearity is a key vital that can be used to evaluate the operation of the amplifier at the fundamental frequency. The MMIC PAs designed in this paper offer a high linearity via the output spectrum as shown in Fig. 17. The output power is about 41 dBm at the operating frequency of 2.4 GHz. Whereas the second and third harmonics are about -2.9 dBm and -2.6 dBm, respectively. The upper and lower side of third order intercept (IP3) for the proposed amplifier as shown in Fig. 18 which explains the relation between an available power source and harmonic fundamental with output spectrum. It is clear that when the input source power increases, the fundamental and third harmonic output spectra increase almost identically, indicating that the amplifier is appropriately linear.

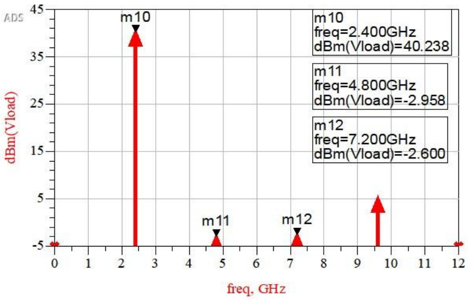


Fig. 17. The output power spectrum of the power amplifier.

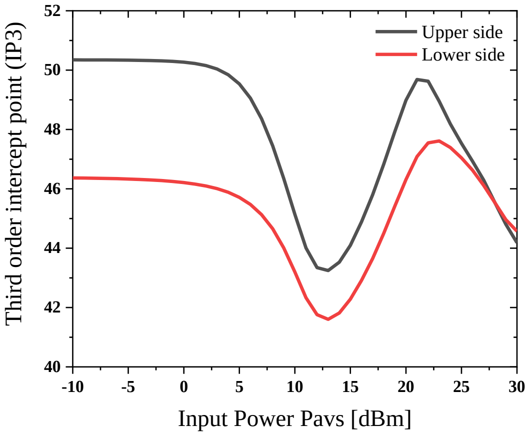


Fig. 18. The lower and upper side of the third order intercept point (IP3) of MMIC PAs.

3.3. Envelope and transient simulation

For more basic modulation systems, where two sinusoidal signals represent two active channels, intermodulation distortion characterizes the interference effects of a nearby active channel. It is not certain that the sinusoidal representation accurately captures adjacent channel interference as the modulation becomes more complex. For different modern communication systems such as WCDMA and OFDMA, adjacent channel power ratio (ACPR) is the most important parameter for evaluating how subsystems are distorted and whether a particular system could be interfering with a nearby radio. It is defined as the ratio of the average power in the adjacent channel to the power in the transmitted frequency channel. The high linearity of MMIC power amplifiers is indicated by ACPR better than 40 dBc. The simulated value of ACPR is dependent on the peak output power of about 41 dBm. The simulated result shows that the ACPR is about greater than 40 dBc, which is the output spectrum as a respect to the signal frequency (Bandwidth BW=50 kHz) as shown in Fig. 19. Table 2 provides an overview of the performance metrics showing better efficiency between the modified MMIC power amplifier and some other recent research used in the communication systems.

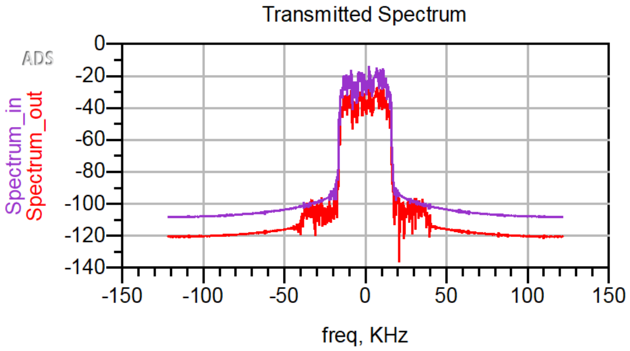


Fig. 19. The simulated value of ACPR of MMIC PAs.

Table 2. Performance comparison of the proposed MMIC power amplifier circuit with literature review.

Ref./ year	RF Device Process / Topology	Freq. [GHz]	Peak $P_{del.}$ [dBm]	PAE [%]	Gain [dB]	B.W [GHz]	Application
Ahmed et al. [10]	ATF13786 GaAs	0.8-3	25.42	32.41	11.9	---	Broadband Mobile base-station system
Zainol Murad et al. [12]	0.13 µm CMOS two stage PA/ Class E PA	2.4	19.19	45.2	11.2	---	WLAN communication systems
Dong-Wook [18]	0.25µm GaN / Distributed MMIC PAs	2-6	41	34	12.8	---	Wireless communication systems
Chen et al. [19]	GaAs HBT / 3-Stages broadband PAs	2.8	28	7.6	21.6	0.08	LTE-A communication systems
Rachakh et al. [20]	Si-LDMOS / Wide-band PAs	2	20	---	11	---	Wideband wireless communication systems
Gilasgar et al. [21]	0.18 µm CMOS / Class F PAs	2.4	19.2	26	11.5	---	Mobile communication systems
Bansal et al. [22]	CGH40010F GaN HEMT/ Broadband MMIC PAs	1.2-2.7	39.2	33	10	1.5	Electronic warfare and high-end security communication
[23] 2021	Two-stage 0.1µm GaN HEMT MMIC PAs / Broadband PAs	26	31.6	36.9	24	Wide	5G Broadband communication system
[24] 2023	10 W CG2H40010F GaN HEMT / MMIC PAs	2.2	38.4	50	14	0.4	Radar wireless communication systems
[25] 2023	0.18 µm CMOS / 2-Stage RF PAs	2.45	13.28	17.82	20	---	IoT applications
This Work	10 W CG2H40010F 0.18 GaN HEMT / MMIC PAs	2.4	41	58	12	0.5	Wireless communication systems

4. Conclusions

This paper presents an analysis and design with layout implementation of 10 W CG2H40010F 0.18 GaN HEMT MMIC power amplifier (PA) for wireless communication systems. The proposed MMIC PAs operate at the frequency of 2.4 GHz, and it is investigated and performed using ADS software. The input and output matched networks have been designed using microstrip transmission lines in order to transfer peak power at the load termination.

The design considerations required in this work are that the transistor operates as a class AB with biasing conditions V_{DS}=28 V and V_{GS}=-2.7 V, efficiency ≥50%, and output power ≥ 40 dBm. The simulated results and layout EM Co-simulation of the amplifier are better matched. The maximum power added efficiency (PAE%) is obtained about 58% at the RF input power of 29 dBm and 41 dBm for output power. The peak value of the power gain is about greater than 12 dB. The third order intercept point (IP3) (TOI) of the proposed MMIC PAs is greater than 40 dBc.

Therefore, this amplifier achieves high linearity, bandwidth, and its candidates for broadband wireless communication system applications. The simulated value of ACPR is dependent on the peak output power of about 41 dBm. The simulated result shows that the ACPR is about greater than 40 dBc, which is the output spectrum as a respect to the signal frequency (Bandwidth BW=50 kHz).

Nomenclatures

IP3	Third Order Intercept Points, dBc
V_{GS}	Gate to Source Voltage, V

Greek Symbols

ε_r	Dielectric constant (Permittivity), NC.
σ	Conductivity, S/m

Abbreviations

MMIC	Monolithic Microwave Integrated Circuit

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