X band GaN Based MMIC Power Amplifier with 36.5dBm $P_{1\text{-}dB}$ for Space Applications

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***Abstract*— An X-Band Monolithic Microwave Integrated Circuit (MMIC) High Power Amplifier (HPA) with coplanar waveguide (CPW) based on AlGaN/GaN on SiC technology is presented in this paper. Coplanar waveguide technology (CPW) is chosen for the simplicity and reduced cost of fabrication since CPW process has no via. High Electron Mobility Transistors (HEMTs) are matched for the 8 GHz-8.4GHz frequency band for maximum output power. The Amplifier has a small signal gain over 10 dB, output power of 36.5dBm at 1 dB gain compression point (P_{1dB}) and 40% power added efficiency (PAE) at (P_{1dB}) in the desired frequency band (8 GHz-8.4 GHz) with V_{ds} = 30V.**

***Keywords*— MMIC; Power Amplifier; GaN HEMTs; coplanar waveguide; AlGaN/GaN**

I. INTRODUCTION

Due to highly demanded physical and electrical properties of gallium nitride (GaN), AlGaN/GaN has become a promising material choice for wideband power amplification applications. GaN based High Electron Mobility Transistors (HEMTs) offer far superior features such as high current density, high breakdown voltage, and high saturation velocity compared to gallium arsenide (GaAs) based HEMTs which are widely used in conventional devices for amplification purposes [1], [2]. Morever, its excellent thermal and chemical stability furthermore makes it ideal material for high power space applications in harsh environments. Furthermore, GaN technology offers several key advantages such as higher efficiency in systems with limited prime energy, radiation hardness and higher linearity compared to other semiconductors. Linearity, efficiency and radiation hardness are quite crucial especially for X-band data downlink of low earth orbit (LEO) satellite applications where QPSK, 8PSK, etc. modulation schemes are used. Features described above makes GaN based power amplifiers to be the best solution for these applications.

In this paper, an X-band power amplifier has been designed, fabricated and summarized which is suitable for X-band LEO satellite downlink (8.0GHz-8.4GHz) applications. Presented amplifier is aimed to be used with 8PSK modulation scheme. Since spectral growth mask is an important constraint for such applications, the output power at 1dB gain compression (P_{1dB}) was given instead of the saturated output power. The fabrication details of the process are given in section II, the measured performance of the active device cell with eight gate-fingers, each 125 μm wide (8x125 μm) is presented in section III and the MMIC design considerations, design phase and comparison between simulated and measured amplifier performance is reported in section V.

II. FABRICATION TECHNOLOGY

X band power amplifier designed by using the GaN MMIC process by Bilkent University Nanotechnology Research Center (NANOTAM).

AlGaN/GaN HEMT epitaxial structure was grown on a semi-insulating SiC substrate by using metal organic chemical vapor deposition (MOCVD). The structure includes from bottom to top, an 15 nm-thick AlN nucleation layer, a 2 μm-thick undoped GaN buffer layer, an approximately 1.5 nm-thick AlN interlayer, a 20 nm-thick undoped $Al_{0.22}Ga_{0.78}N$ layer and a 2 nm-thick GaN cap layer on the top of the structure. The Hall mobility was measured as 1384 $cm^2V^{-1}s^{-1}$ whereas sheet carrier concentration was around $1.51\times10^{13}cm^{-2}$.

Fabrication process starts with mesa etching. Ohmic contacts were formed by using Ti/Al/Ni/Au metal stack with the thicknesses of 12, 120, 35 and 65 nm, respectively. Ohmic contact metals were deposited by e-beam evaporation method. After this step, electron beam lithography was used to define the gate region for Γ -gate region, for Γ-gate fabrication and these regions were deposited with Ni/Au metals. The gate structure of HEMTS is in the form of Γ- shaped gate (Fig.1) in order to increase the breakdown voltage and output power while having reasonable gain. Next step in fabrication, the devices were passivated with a 300 nm-thick Si_3N_4 layer grown by using plasma-enhanced chemical vapor deposition followed by the air bridge post formation to prevent any case of being short circuit of the metals. Finally, Ti/Au metal stack with a total thickness of 3μm had been deposited as an interconnection using e-beam evaporation. The details of the fabrication,DC and RF performance comparison of the fabricated devices were given in [3].

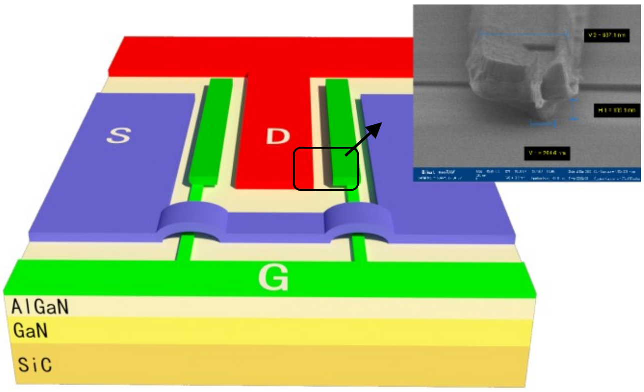


Figure 1. Modelled view of HEMT structure and SEM image of fabricated Γ-shaped gate

III. HEMTs Process

In order to observe the transistor performance; DC characterization, small signal and large signal characterizations were performed respectively for 8x125µm HEMT device which has 3µm drain-source spacing. Fabricated HEMT photo is shown in Fig.2. DC-IV and Gm characterization results can be seen in Fig.3.a. The fabricated HEMT has a drain current density of 970mA/mm and 310 mS/mm Gm.

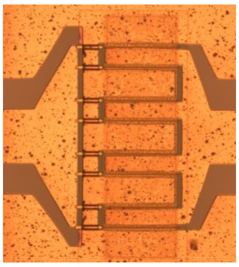
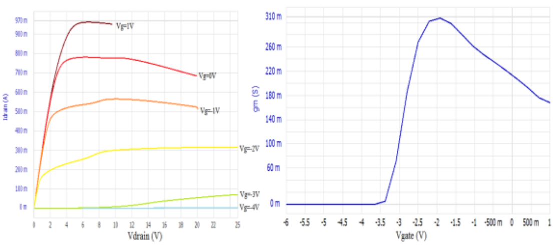
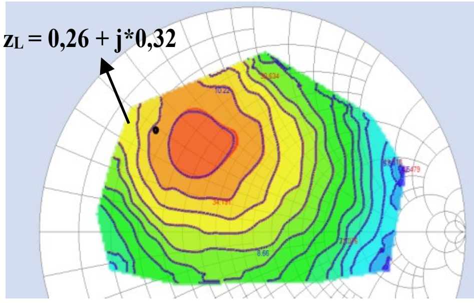


Figure 2. Image of fabricated HEMT

Load-pull measurements were performed to 8x125 µm HEMT devices under V_{DQ} = 30V and I_{DQ} = 100mA/mm. The load impedance contours are justified in Fig.3b. Output power of the transistor is 35dBm at 1dB compression point as seen in Fig.3c. Table 1 summarizes the optimum normalized source and load impedances of the presented HEMT device with respect to 50 ohm.



a)



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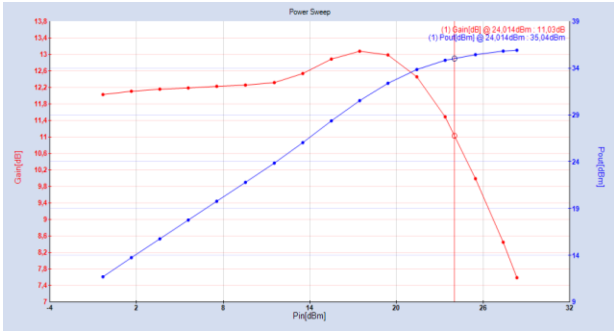

c)

Figure 3. Characterization results of HEMT a) DC-IV & Gm b) z_L contours c) Power sweep results at 8GHz

Table 1. Optimum Source and Load Impedances

Frequency (GHz)	z_S	z_L
8	0,20 + j*0,21	0,25 + j*0,31
8.4	0,17 + j*0,22	0,26 + j*0,32

IV. MMIC Design

The proposed single stage CPW HPA was designed by using parallel combination of two 8x125 µm HEMTs with 0.3 µm gamma-gate technology to increase the output power of the amplifier. The schematic of the design is depicted in Fig.4.

In the design process loop stability circuit was used to increase operation band of the amplifier by isolating the parallel transistors from each other. Unconditional stability was satisfied by using parallel R-C network (Input Stability Circuit) for the amplifier. After stabilization, drain biasing circuit was designed by using series high impedance CPW inductor which is equal to λ/4 length for 8GHz and shunt large Metal-Insulator-Metal (MIM) capacitor to isolate DC from RF signal. Gate biasing circuit consists of a large series resistor instead of CPW inductor which is different than drain biasing circuit, because large series resistor has benefits on gain flatness and stability of circuit which were already reported in [4].

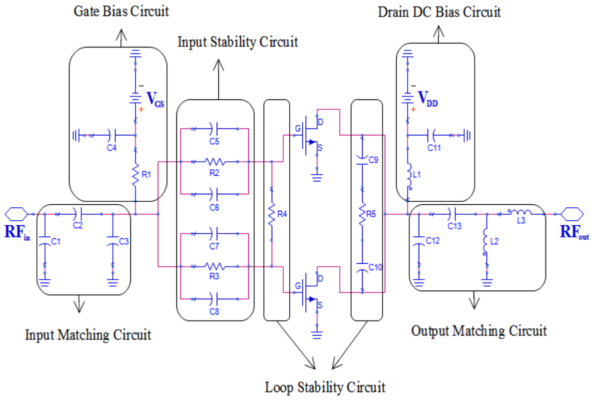

Figure 4. Layout of single stage MMIC amplifier

After implementing stabilization and bias circuits, input and output matching circuit networks were designed. In order to increase maximum power transfer, output matching circuit was implemented with four-reactance networks as optimum load impedance for 8x125 um HEMTs. Input matching circuit was designed using three-reactance matching network which includes DC blocking MIM capacitor. In order to increase P_{1dB} performance, input matching circuit impedance was also chosen from Load-pull measurements for the HEMTs.

V. Circuit Performance

The designed single stage power amplifier was fabricated using described process in section II. Real image of the fabricated PA is shown in Fig.5.

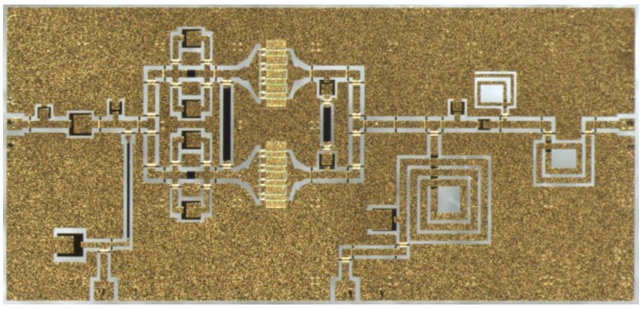

Figure 5. Fabricated single stage CPW MMIC (1.8mm x 4mm)

To characterize the performance of the fabricated CPW MMIC, small-signal measurements were conducted under drain voltage V_{DQ}=30V and operating current I_{DQ}=100mA/mm biasing conditions. According to small-signal measurements, the power amplifier has a small-signal gain (S21) of approximately 11dB at the beginning of the frequency band (8GHz). Gain is 1 dB lower at the end of the frequency band (8.4GHz) compared to 8GHz. Input return loss (S11) of the power amplifier is lower than -10dB and output return loss (S22) is lower than -10dB at the desired frequency band. Also, unconditional stability of the PA was satisfied at all frequencies. In Fig.6, measured and 3D EM simulated small-signal response is represented for 6-10GHz frequency band. As seen in Fig.6, simulated and measured performances shows quite good agreement.

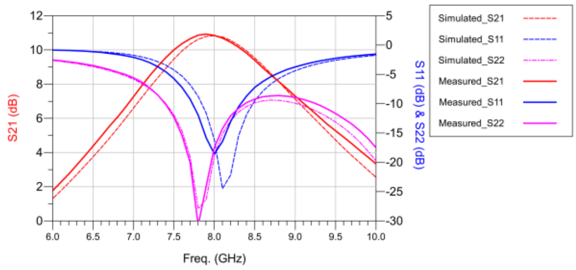

Figure 6. 3D EM simulation and Measurement S-parameters of the single stage MMIC amplifier

Large-signal measurements were applied to the PA under the same quiescent bias conditions with small-signal measurements. At 1dB gain compression point, aimed minimum output power 36.5 dBm, is achieved. These results show that parallel configuration of two HEMTs circuit in PA provides high output power at low gain compression point. Average power added efficiencies (PAE) is also around 40% at 1dB gain compression point. Large-signal measurement results are shown in Fig.7.

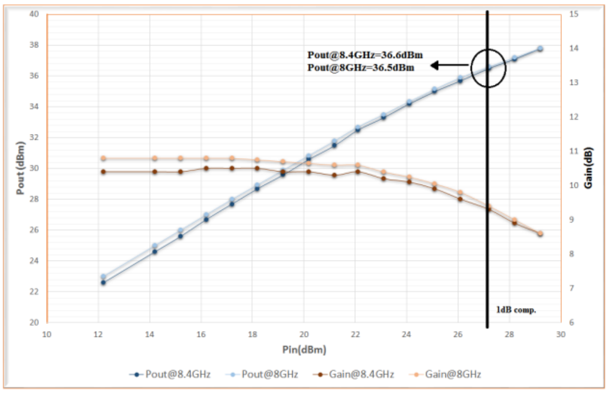

Figure 7. Large-Signal Measurements of the single stage MMIC amplifier at 8GHz and 8.4GHz

As far as the authors' knowledge, this work demonstrates quite good results for the output power at 1dB compression point. The comparison with similar works can be seen in Table 2.

Table 2. X-Band GaN PA Performance Comparison

Ref.	**Freq.** (GHz)	**Output Power** at 1dB comp.	**PAE**	**V_D** (V)	**operation**
This Work	8.4	36.6dBm	40	30	CW
[5]	8.8	29dBm	9	26	15%
[6]	8.5	28dBm	13	30	CW
[7]	9.6	33dBm	-	30	CW
[8]	8	31dBm	30	21	CW

VI. Conclusion

A study has been performed to obtain GaN based PA MMIC amplifier. 11dB gain and better than -10dB output and input return loss is achieved with the single stage PA using Γ-shaped gate HEMTs at the desired frequency. Using two HEMTs in parallel combination, minimum output power is reached as 36.5 dBm at 1dB gain compression point.

As a future work, three of these MMICs mentioned in sections IV and V, are planned to be paralleled by using a phase shifted three way Wilkinson Power Divider (WPD) presented in [9]. Layout of the phase shifted WPD and its simulation results are given in Fig.8 and Fig.9. Output power will be aimed to be more than 40dBm.

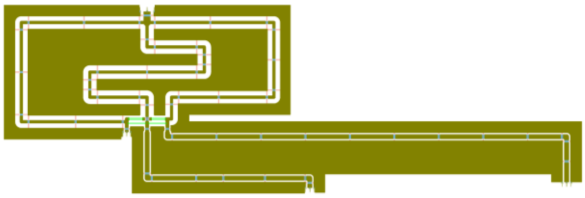

Figure 8. Layout of the phase shifted Wilkinson Power Divider

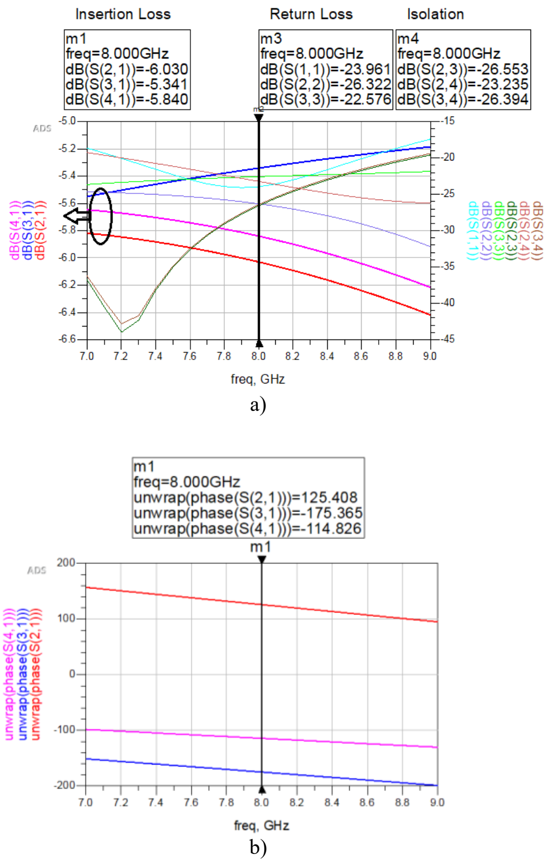

Figure 9. Simulation results of the phase shifted Wilkinson Power Divider a) Insertion Loss, Return Loss and Isolation b) Phase

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