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Design and Simulation of an X-band Solid State Power Amplifier

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Abstract— **In this paper design and simulation of an X-band Power Amplifier (9.3-9.9 GHz) has been carried out. This kind of amplifiers are used in various types of radars like weather warning radars, vehicle detection radars, frequency hopping radars and phased array radars. Different types of semiconductor devices are studied/ analyzed during solid state device selection phase; however both Gallium Nitride (GaN) and Gallium Arsenide (GaAs) devices are considered appropriate for this type of design. GaAs pseudomorphic induced high electron mobility transistor (pHEMT) has been used for our design. The amplifier has been optimized for low noise, moderate power output, small return loss (input & output) and low cost. The optimization has been carried out with Advance System Design software (ADS) by Agilent. Measured results at the design frequency show overall noise figure around 2.8 dB, a linear gain of 42 dB, input and output return loss over -12 dB with an associated power at 1dB gain compression point is in excess of 29-30 dBm. Using mixed elements (discrete and distributed) design technique it has been confirmed that such amplifiers are easy to build and provide cost effective solution.**

Keywords— **HEMTs, GaAs MMICs, Solid State Power Amplifier, Cascade, Radar applications**

1. INTRODUCTION

GaAs Monolithic Microwave Integrated Circuit (MMIC) technology has matured over the years. It is used for both microwave and millimeter wave applications [1][2]. The high power achievement at X-band frequencies is neither cheap nor easy to design. Design of input/output matching circuits and device stability used to be a critical issue but with advancements in semiconductor industry, amplifier designers today prefer to use MMIC devices [3]. This has not only made circuit design simple and less time consuming but also a lot of miniaturization is being achieved. Low noise amplifiers are vital part of almost all the receivers and can be used as driver amplifier in the transmitters. These are used in highly sensitive systems including Radars, Satellite communication systems and Radio communication systems. Travelling wave tubes are used as main power amplifiers in most of the Radars and Communication systems. These high power amplifiers are driven by medium power amplifiers like the one designed in this paper.

GaAs has dominated the world of wireless communication, military applications and space applications at high frequency since long. Late 1990's and early 2000 saw replacement of the GaAs MESFETS with improved higher performance GaAs HEMTS, which are building block of GaAs MMICs [4]. MMICs are packaged devices that have integrated radio frequency (RF) power devices with matching, coupling/decoupling elements like on chip capacitors, inductors, resistors and transmission lines etc. Due to refinement in semiconductor device manufacturing techniques, these discrete elements can be very easily and conveniently implemented by skillful manipulation of impurities and bulk (GaAs in this case). These discrete elements are placed in close proximity of the power device and packaged, so that the Input, Output and inter-device matching can be achieved.

Power aided efficiency and output power levels are identified as key specifications for amplifiers. However, using MMICs these may not be achieved at the same time. So for an optimum electrical performance following considerations are of paramount importance [5]:-

a. Heating sinking techniques
b. Power device grounding techniques
c. DC blocking techniques
d. Dc bias network design
e. Addition of microwave absorber blocks
f. Isolation blocks

ADS has been utilized for control of critical design parameters like noise figure , input/output return loss and available gain etc. More and more semiconductor device manufacturers have started manufacturing internally matched high power devices at X-band for RF/microwave design in order to reduce the amplifiers development time/cost. However, even if the power devices used are internally matched, ignoring above mentioned considerations may lead to the device breakdown or oscillations. The basic things that can result in degradations are insufficient device grounding and RF signal leakage to bias network.

2. CIRCUIT DESIGN

A. *Circuit Layout / Component Scheme*

This Power Amplifier circuit comprises of three GaAs devices, a microstrip coupled line band-pass filter and a microstrip isolator as shown in figure 1. The substrate is Rogers RO RO4003C, with a thickness 0.508mm, dielectric loss tangent 0.0027 and relative permittivity (ϵ_r) 5.5. First two low noise amplifiers (LNA) are low power/low noise, pHEMTS MMICs internally matched to 50Ω having noise figure of 2.5dB and gain of 13 dB and P1dB output power 14.5 dBm @ 10 GHz. These two devices are self-biased at VDD=5 volts & I_{DD}=66mA. In this biased condition; these two devices are unconditionally stable over the full X-band. The third power amplifier device is the high power device MMIC (FET) having gain of 26 dB and power output of 33 dBm at 9.5-13.3 GHz and it is also used to control the gain amplitude and output return loss. It is a distributed three staged amplifier which gives the cascade a final high gain at the frequency between 9.5-13.3GHz. The biasing has been done at VDD=10 Volts, VGG = -3 Volts and I_{DD} = 1500mA.

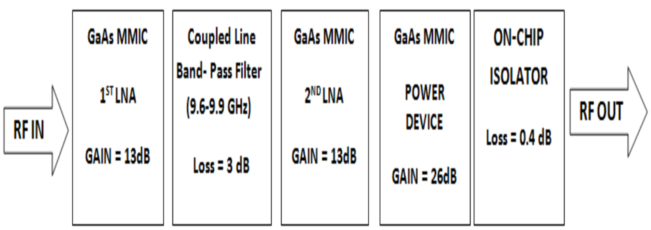


Figure 1. Block diagram of three stage X-Band amplifier showing gain/loss of each element in the cascade.

B. *Stability and Gain analysis*

Stability and Gain analysis has been carried out for this circuit at designed frequency (9.3-9.9 GHz), utilizing ADS from Agilent. The snap shot of layout in ADS is shown in Figure 2.

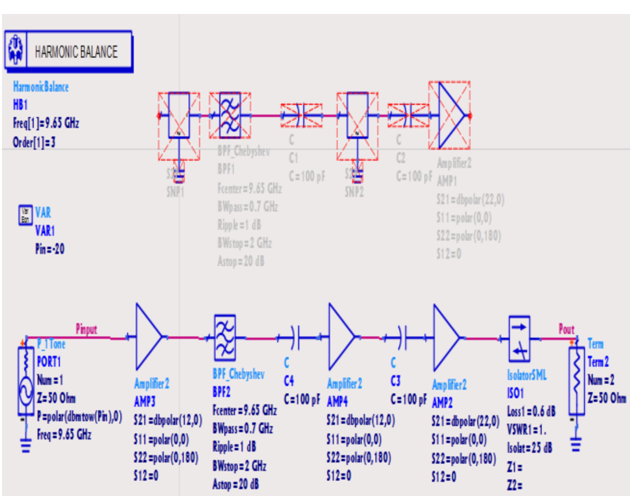


Figure 2. Amplifier Cascade Layout in ADS

C. *Stability Considerations*

The amplifier of our design is unconditionally stable if it passes K-Δ test (Rollet's condition) [6], defined as

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

And its auxiliary condition is

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1$$

The above two conditions can be combined to a new parameter, $\boldsymbol{\mu}$

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

So if $\boldsymbol{\mu > 1}$, the amplifier is unconditionally stable over the desired frequency range. The S-Parameters at the frequency (9.3-9.9 GHz) for the third and main power device are given in Table.1 (These values have been taken from manufacturer data sheet). At all the frequencies K and $\boldsymbol{\mu}$ values are greater than one and **Δ** values are less than unity, showing the unconditional stability of device at all frequencies of interest.

Table 1. S-Parameters from Device Data sheet (Power Device)

Freq (GHz)	*S11*		*S21*		*S12*		*S22*	
	MAG	*ANG*	*MAG*	*ANG*	*MAG*	*ANG*	*MAG*	*ANG*
9.3	*.299*	*-75.9*	22.37	-37.1	.001	-159.0	*.293*	*-24.1*
9.4	*.286*	*-79.8*	22.23	-51.7	.001	-171.2	*.296*	*-29*
9.5	*.272*	*-83.1*	22.10	-66.1	.001	-166.0	*.297*	*-33.3*
9.6	*.258*	*-86.8*	21.90	-80.0	.001	-174.2	*.300*	*-37.5*
9.7	*.243*	*-90.2*	21.78	-93.7	.000	-174.7	*.304*	*-40.9*
9.8	*.229*	*-93.7*	21.61	-107.1	.001	-162.9	*.305*	*-44.2*
9.9	*.217*	*-97.2*	21.47	-120.1	.001	-166.4	*.307*	*-47.4*
10	*.203*	*-99.4*	21.38	-133.1	.001	-170.5	*.308*	*-50.2*

D. *Cascade Noise Figure Calculations*

The noise figure of the cascade can be calculated by the formula [7]

$$F_{cas} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

The noise figure and gain of individual elements of the cascade are appended in table 2.The Noise Figure of the Cascade comes out to be around 2.85 dB using above mentioned formula.

Table 2. Noise Figure and gain details for different elements

s/no	Element name	Noise Figure dB	Gain dB
1	First LNA	2.5	13
2	Band pass filter	2	-2.3
3	Second LNA	2.5	13
4	Power Amplifier	2.5	26
5	Isolator	1	-0.4

E. Microstrip coupled line filter Implementation

After the first stage LNA, a microstrip coupled line band-pass filter is implemented. It is a 6 element bandpass filter with an insertion loss of 2.3 dB. The centre frequency of filter is 9.65 GHz. It allows frequencies between 9.6-9.96 GHz to pass without attenuation. The filter response is shown in Figure 3.

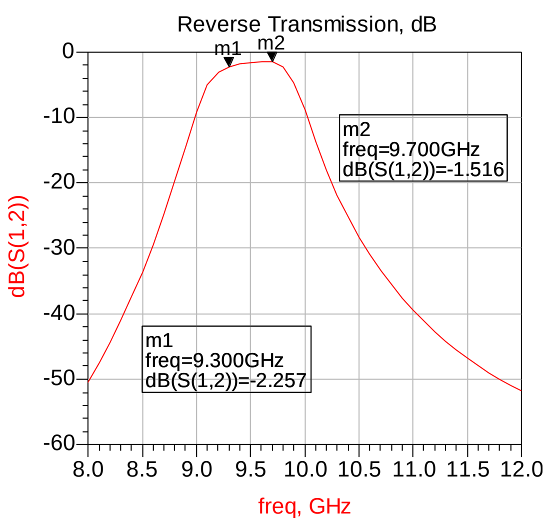


Figure 3. Filter response at 9.6-9.96 GHz

3. CIRCUIT DETAILS

The circuit details including biasing scheme are shown in Figure 4 and Figure 5. The power supply requirement of different devices has been met by utilizing DC-DC converter and voltage converter inverter.

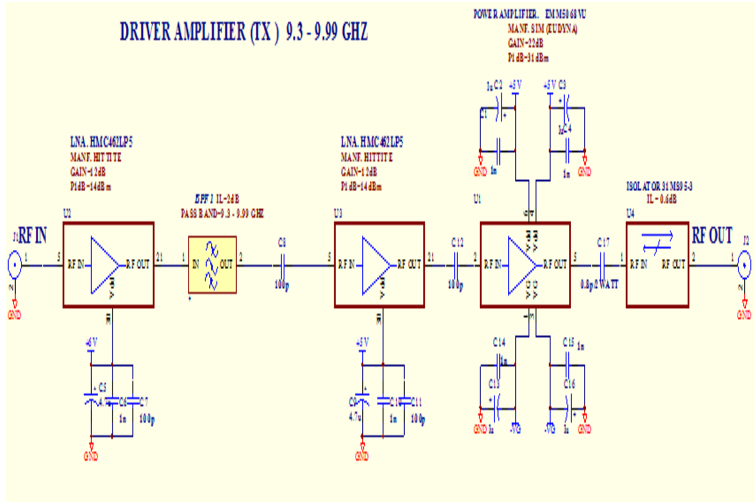


Figure 4. Circuit details including DC blocking and biasing circuit detail

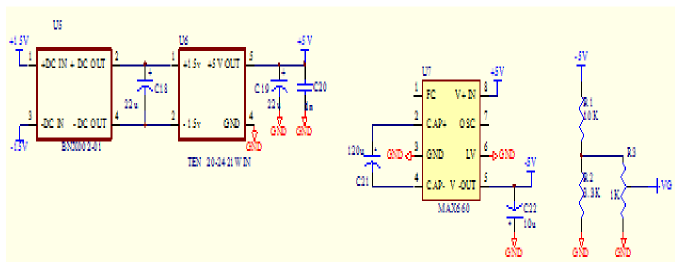


Figure 5. Power supply scheme

4. SIMULATION RESULTS

A. Amplifier Output

The amplifier provides power output between 30.8-31.9 dBm for an input power between -20 to -6 dBm. The simulation results are shown in Figure 6. This graph shows that at a given input of -11 to -6 dbm , corresponding output is around 30-31 dBm which is our desired goal in this design.

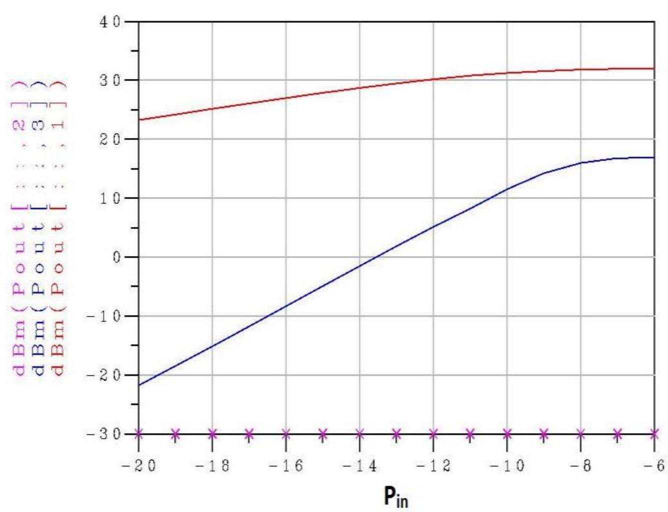


Figure 6. Power Output at desired Input (-11 to -6 dBm)

B. S-Parameters analysis

The S-Parameters at the designed frequency show a flat gain of approximately 42 dB as shown in Figure 7. This gain is kept as flat as possible to meet the specific requirement of application in which it is to be used [8][9].

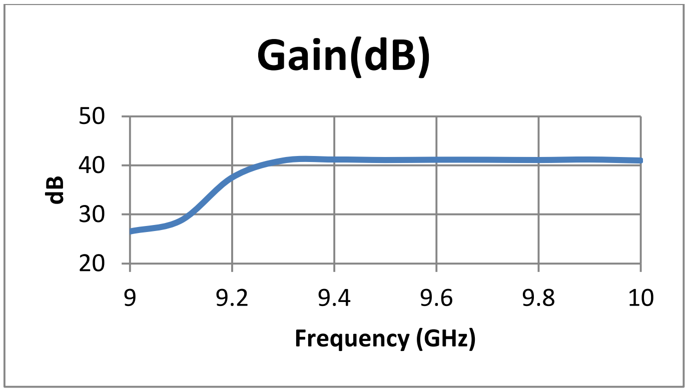


Figure 7. Simulation of S-Parameters at the frequency band between (9-10GHz) of amplifier in momentum (ADS)

C. Power Aided Efficiency (PAE) of the Amplifier

The power aided efficiency (PAE) of the amplifier at the desired frequency band (9.3-9.9 GHz) is simulated as shown in Figure 8. Simulated PAE comes out around 12%, due to linear nature of the amplifier (operated in class-A configuration).

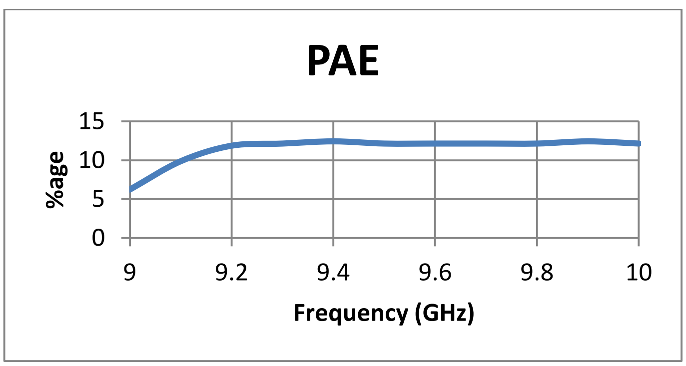


Figure 8. PAE of the amplifier

D. Simulated Noise figure of Amplifier

Snap shot of the simulated noise figure of the amplifier from ADS is shown in Figure 9. This reflects that the overall noise figure of the cascade is governed by noise figure of first stage and comes out around 2.85 dB.

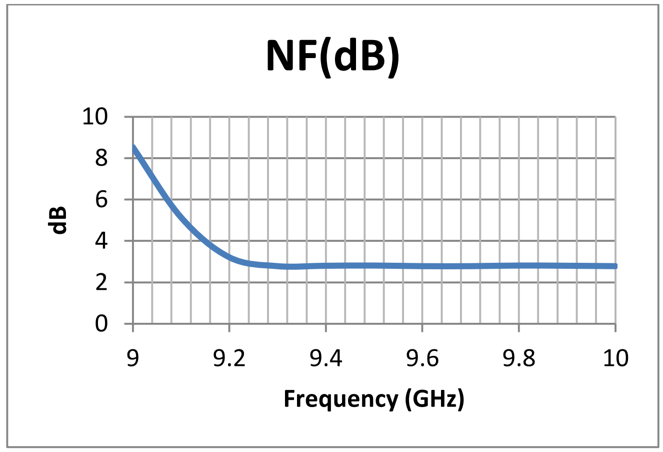


Figure 9. Simulated Noise figure of Cascade

E. Simulated μ parameter of Amplifier

Simulated μ parameter of the amplifier at the designed frequency is shown in Figure 10. It is pertinent to mention that at all the frequencies ***μ*** is greater than one, guaranteeing the unconditional stability throughout the frequency band.

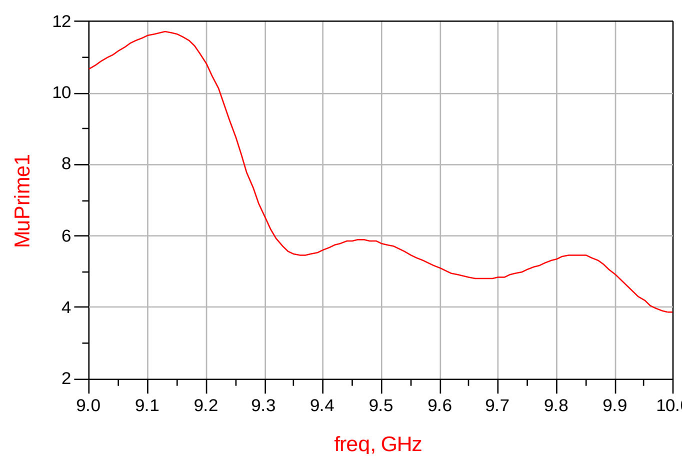
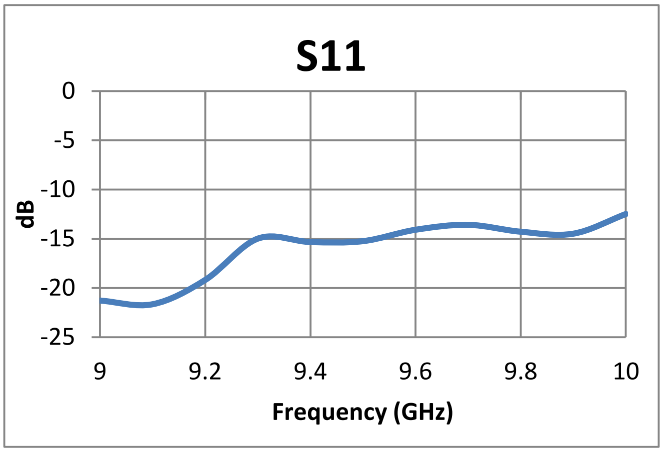


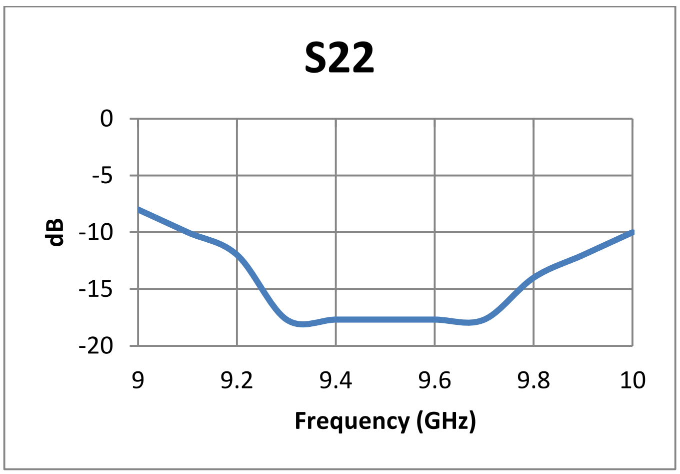
Figure 10. Snap shot of ***μ*** parameter

F. Input and output reflection co-efficient

The input/output reflection coefficient at the two ports of the cascade is shown in Figure 11(a&b). These plots show that due to good matching at both the ports, reflections have been minimized.



(a)



(b)

Figure 11. (a) Input Return loss (reflected power) (b) Output return loss (reflected power)

5. CONCLUSION

In this paper design and simulation of GaAs MMIC's based, 3 staged X-band power amplifier has been demonstrated. The amplifier is operated in class "A" configuration. The simulated results have confirmed the validity of our design and meet our targeted values. The X-band amplifier has achieved an overall linear gain of around 42 dB, a power output of around 29-31 dBm and a PAE (power aided efficiency) of the amplifier is around 12%. This low efficiency is due to excellent gain flatness, which was a prime requirement of our system. The use of GaAs MMIC's matched to 50Ω has provided us with cost effective design.

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