ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015

Design of p-HEMT based Low Noise Amplifier for RF applications in 'C' Band

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Abstract*— This paper explains the design of an LNA (Low Noise Amplifier) with sub 1-dB noise figure based on p-HEMT technology for RF applications in 'C' Band. The proposed design attempts to minimize the noise figure while maintaining considerable power gain and good input/ output matching. The LNA is designed to operate at 6 GHz which lies in the IEEE C-band. This band is suitable for satellite communications, some wireless communication applications, and radiolocation applications. The main aim of designer is to minimize the low noise figure while maintaining considerable gain with the help of p-HEMT technology by using single stage low noise amplifier. The LNA is designed using a p-HEMT GaAs FET from Sirenza Microdevices. The basic architecture of LNA comprises a RF amplifier in the middle of input matching network and the output matching network. The designed LNA exhibits low noise figure, good input and output impedance matching and high gain and stability. We have used ADS RF Design software tool for optimization& simulation of results. The design uses micro strip open shunt matching networks fabricated on a Duroid RO3006 substrate circuit board. The DC biasing network utilizes surface mount inductors and capacitors. The simulation results show (at 6 GHz) a gain of 13.121 dB, noise-figure of 0.811 dB and VSWRin =1.527 , VSWRout =1.508, where the circuit operates at 20 mA drain current, supply voltage of 3.0 V and biasing voltage of 2.0 V.

Index Terms— **Biasing, HEMT, LNA, Matching networks, Micro strip, Noise Figure, Stability factor.**

I. INTRODUCTION

The most important part of the radio frequency receiver is the front-end as the determination of the gain and minimum noise figure of the system is affected by this section. Perfect design enables the system gets the necessary gain with minimal noise, as well as meet the needs of the signal to noise ratio (SNR). A typical RF front-end receiver consists of preselecting filter, low noise amplifier (LNA) and mixer as shown in Fig 1[7]. One of the key components in RF front-end is a low noise amplifier (LNA). A low noise amplifier (LNA) is in the first stage dominating the noise, gain and sensitivity performance of the RF front-end receiver. In order to increase the system sensitivity, an excellent low noise amplifier (LNA) in front of the receiver is mandatory, especially in an environment with very weak signal strength and because of the insertion loss of the single-pole-double-throw (SPDT) switch and the Band pass Filter (BPF) or diplexer.

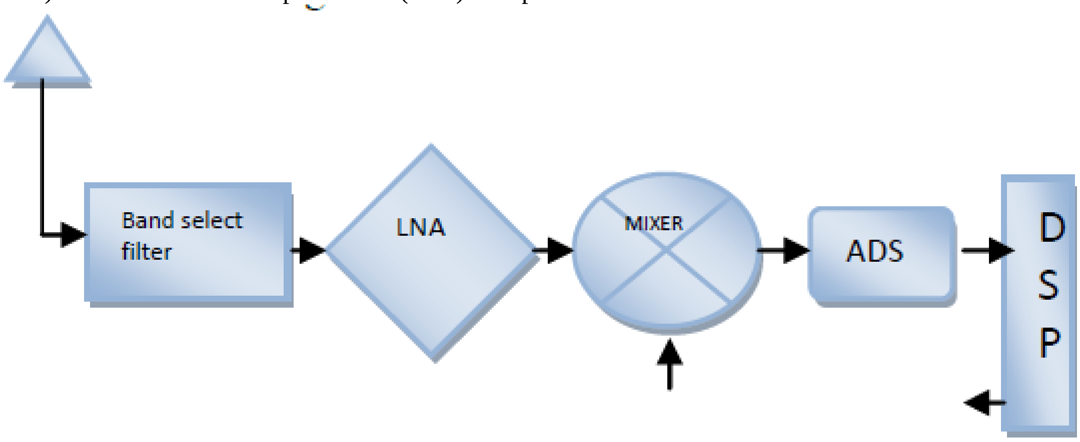

Fig 1. Typical RF front end assembly

The typical allowed receiver chain Noise Figure (NF) of approx. 2 dB can only be achieved by using a high-gain low noise amplifier (LNA). In addition, strong signal environment can exist when the equipment is next to a transmitter. In that case, the LNA must be linear enough, i.e. have high 1dB compression point. This avoids saturation, degradation of the gain and increased noise figure. The various parameters like Noise figure, gain,

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input/output VSWR, stability & linearity are dependent on each other but there is a trade-off involved to optimize the overall design wherein we have to sacrifice on one parameter to maximize other. In this design, we probe the dependency of the above factors like gain, noise figure, stability, bandwidth on the design parameters so as to come up with the most optimal combination. The methodology adopted for tuning the LNA for optimal behavior can be extended to any other circuit design.

II. AMPLIFIER DESIGN

A. General Design Procedure for an Amplifier

The LNA have mainly three sections to be designed in complete circuit namely the Input matching network, Main transistor section & the Output matching network. The input matching network is used to make the input return loss (S_{11}) minimized without introducing additional noise. The input matching circuit that terminates the transistor to gamma optimum (Γout) which represents the impedance at the input of the transistor for the optimum noise matches. It is observed that attenuation is lowest at 77 Ω and power handling capability is highest at 30 Ω hence, a compromise between these two parameters gives 50 Ω resistive input impedance to design a LNA.

Main transistor section ensures a high gain, high linearity and low noise factor at the input and output of the amplifier. The final step in design of LNA is the design of output matching network. The input and output impedance matching is required to maximize the power transfer and minimize the reflections. Smith chart is used for impedance matching. According to maximum power transfer theorem, maximum power delivered to the load when the impedance of load is equal to the complex conjugate of the impedance of source ($Z_S = Z_L^*$).

The various parameters like noise figure, Gain, input/output VSWR, Stability and Linearity are all dependent on each other. The parameter are equally important and hence a tradeoff is needed to be exercised among them to optimize the final design. At microwave frequencies, impedance and admittance parameters of a transistor cannot be directly measured, whereas the scattering matrix parameters of a transistor can be measured easily. Therefore, a design methodology based on using the Sij parameters is widely used. Many of the relationship that occurs in amplifier design involve S-parameters.

B. Selection of Active device

The selection of a suitable active device i.e Transistor is the first step in the design process of an LNA. The selection of the transistor should be carefully undertaken, keeping in mind the important LNA parameters trade-offs in mind. The selected device must exhibit high gain, low noise figure, and offer high IP3performance at the low current consumption, while providing easy matching at frequency of operation. Based on the primary objective of achieving sub-1dB noise figure, a p-HEMT GaAs FET from Sirenza Microdevices (SPF-2086TK) is selected which exhibits a minimum noise figure of 0.7 dB.

C. Stability considerations

The conditions for amplifier stability are established by requiring that the reflected power from the amplifier ports be smaller than the incident power. This means that the reflection coefficients looking into the amplifier ports must have a magnitude <1 for all passive source and load impedances. Although an LNA design may be unconditionally stable at the operating frequency, there will be no guarantee that the LNA will not oscillate at some other frequency unless a stability analysis is performed. The analysis should be performed at all frequencies over which the device has gain. An out-of-band oscillation could possibly be at a large enough amplitude to cause a reduction in in-band gain or an increase in noise figure. Although it is not necessary that an LNA be unconditionally stable at all frequencies, stability should be analyzed so that the areas of potential instability can be evaluated and problem source and load impedances can be avoided. When embarking on any amplifier design it is very important to spend time checking on the stability of the device chosen, otherwise the amplifier may well turn into an oscillator. The main way of determining the stability of a device is to calculate the Rollett's stability factor (K) [1], which is calculated using a set of S-parameters for the device at the intended operating frequency of 6 GHz

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}.S_{21}|} \rangle 1, \, where\, |\Delta| = |S_{11}.S_{22} - S_{12}.S_{21}| \langle 1 \quad (1)$$

K & |Δ| values provide information that whether a device is likely to be conditionally/unconditionally stable or whether it is likely to oscillate. The parameters must satisfy K > 1 and |Δ| < 1for a transistor to be unconditionally

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stable. *The Rollett stability factor, K, and delta were calculated for the transistor. K was found to be 1.05 and delta was found to be 0.25, making it unconditionally stable with* $K > 1$ *and* $|\Delta| < 1$.

D. Minimum Noise figure based design

The minimum noise figure of 0.7 dB at 6GHz and an optimal reflection coefficient of $\Gamma_S = 0.28\angle 179^o$ was obtained from the datasheet of the selected transistor. The achievable gain of the LNA at 6GHz was then considered. The maximum stable gain and maximum transducer gain were calculated. The maximum gains are given below.

$$MSG = 15.69dB$$

$$G_{T,max} = G_{P,max} = G_{A,max} = 14.27\ dB$$

The constant gain circles were then plotted on the smith chart. The available power gain circles were plotted in the Γ_S plane as shown in Fig. 2 and Fig. 4 in order to better understand the tradeoffs between gain and noise. The operating power gain circles were plotted in the Γ_L plane as shown in Fig. 3 and Fig. 5 in order to get a better understanding of the trade-offs between gain and VSWR.

As the primary objective of the design was to achieve sub 1dB noise figure hence the same was the starting point for the design. The optimal source reflection coefficient, Γ_{OPT}, was selected for Γ_S. Then a conjugate match was selected at the output to set Γ_L. The performance of this configuration was calculated and is shown below.

$$\Gamma_S = \Gamma_{OPT} = 0.280\angle 179^\theta$$

$$\Gamma_L = \Gamma_{ML,OPT} = 0.364\angle 118^\theta$$

$$NF = NF_{min} = 0.7dB$$

$$G_p = 13.55\ dB,\ G_A = 12.42\ dB,\ G_r = 12.42\ dB$$

$$VSWR_{in} = 2.84,\ VSWR_{out} = 1.00$$

It was observed that in this configuration there was a high mismatch between input & output VSWR. To rectify the same constant output VSWR circles were plotted for a $VSWR_{OUT}$ of 1.6, 1.8, and 2.0 as shown in Fig.3. Along each of these constant $VSWR_{OUT}$ circles the $VSWR_{IN}$ was calculated for 8 choices of Γ_L evenly spaced along each circle. The minimum $VSWR_{IN}$ of the 8 points along each circle was calculated and indicated on the Smith chart by a green-colored marker. These calculations were carried out using MATLAB Smith chart Toolbox [4]. Detailed results of the calculations are given in Appendix A. Finally a Γ_L that had a balanced $VSWR_{IN}$ and $VSWR_{OUT}$ was selected. The performance of this configuration was calculated and is shown below.

$$\Gamma_S = \Gamma_{OPT} = 0.280\angle 179^\theta$$

$$\Gamma_L = \Gamma_{ML,OPT} = 0.155\angle -179^\theta$$

$$NF = NF_{min} = 0.7dB$$

$$G_p = 13.55\ dB,\ G_A = 12.42\ dB,\ G_r = 12.42\ dB$$

$$VSWR_{in} = 1.95,\ VSWR_{out} = 2.00$$

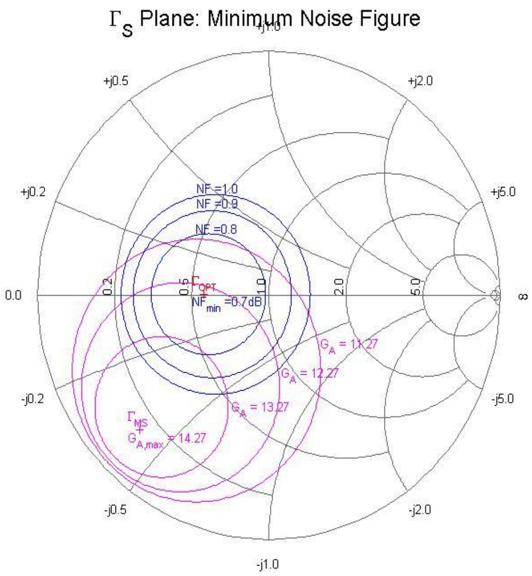

Fig 2. Γ_S **plane design for Minimum noise figure with** $\Gamma_S = \Gamma_{OPT}$

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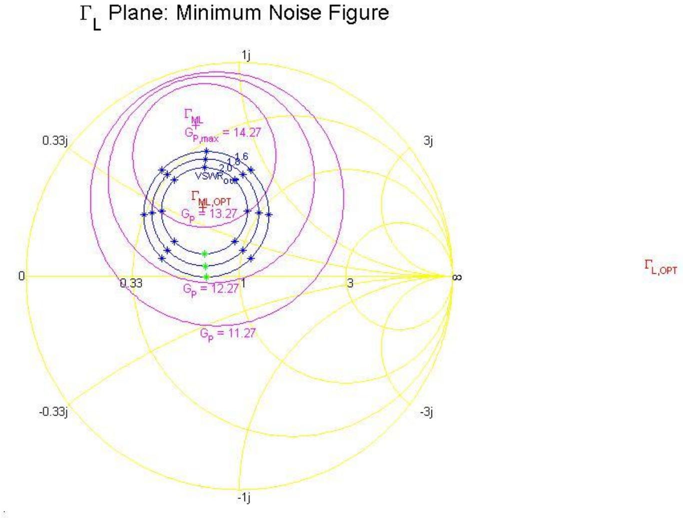

Fig 3. Γ_L plane design for Minimum noise figure with $\Gamma_L = \Gamma_{OPT}$

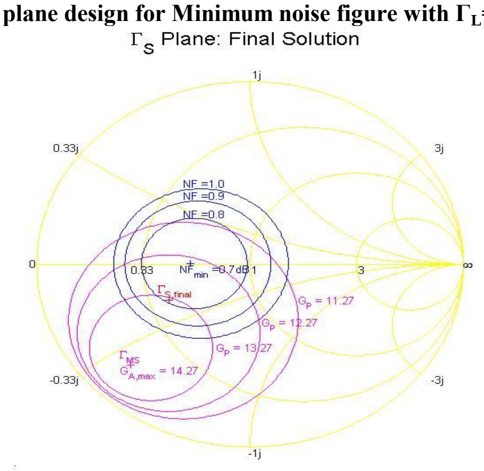

Fig 4. Γ_S plane final design after NF & GAIN trade off

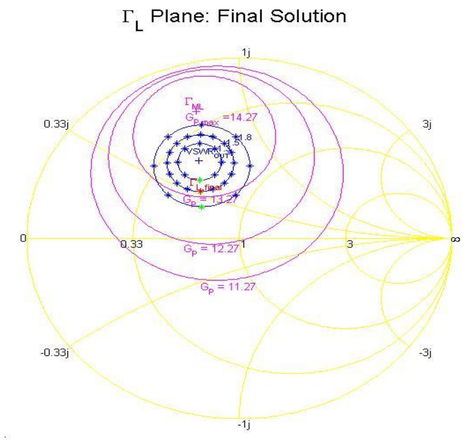

Fig 5. Γ_L plane final design

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E. Gain vs Noise figure trade off

A close look at the noise figure circles & power gain circles in the smith chart reveled that although choosing Γ_{OPT} for Γ_S produces a minimum noise figure , a whole 1dB of gain can be added at the expense of only 0.1 dB higher noise figure. Any further compromise in the noise figure provides a significantly smaller increase in gain. Hence Γ_S was selected to have a noise figure of 0.8dB, instead of the minimum possible value of 0.7 dB which improved the power gain value by almost 1 dB above the maximum power gain as derived in the earlier configuration. Once Γ_S was re-selected to the new value, again the input and output VSWR matching process was repeated. For this constant $VSWR_{OUT}$ circles at a $VSWR_{OUT}$ of 1.8, 1.5, and 1.3 were plotted in the Γ_L plane shown in Fig. 5 and $VSWR_{IN}$ was calculated at 8 points around each circle. The minimum $VSWR_{IN}$ on each constant $VSWR_{OUT}$ circle was found and highlighted in green on the Γ_L plane. Once Γ_L had been selected for a balanced VSWR, the number of points for which $VSWR_{IN}$ was calculated was doubled to see if a smaller $VSWR_{IN}$ could be achieved, but the original selected Γ_L remained the minimum. Γ_L was selected for a good VSWR that balanced a $VSWR_{OUT}$ of 1.5 and $VSWR_{IN}$ of 1.58. The performance of the final design was calculated as:

$$\Gamma_S = 0.427\angle{-153^0}$$
$$\Gamma_L = 0.318\angle{125^0}$$
$$NF=NF_{min} = 0.786dB$$
$$G_p = 13.36\text{ dB},\ G_A= 13.31\text{ dB},\ G_r = 13.14\text{ dB}$$
$$VSWR_{in} = 1.58,\ VSWR_{out} = 1.50$$

F. Matching network design

The need for matching network arises because amplifiers, in order to deliver maximum power to a load, or to perform in a certain desired way, must be properly terminated at both the input and output ports. The matching network is ideally lossless to avoid unnecessary loss power and is usually designed so that looking into the matching network is Z_0. Several types of matching network are available, however factors likes complexity, bandwidth, implementation and adjustability need to be considered in the matching network selection. Suitable mathematical expressions or graphical aid in form of smith charts is available for designing the impedance matching networks. The amplifier could be matched for *Optimum Noise Match*. The matching for lowest possible noise figure over a band of frequencies requires that particular source impedance be presented to the input of the transistor. The noise optimizing source impedance is called as Γopt, and is obtained from the manufacturer's data sheet [2]. The corresponding load impedance is obtained from the cascade load impedance formula [1]:

$$\Gamma_L = \left(\frac{S_{22} - \Gamma_{opt} * .\Delta}{1 - \Gamma_{opt} * .S_{11}} \right) \qquad (2)$$

The input and output matching network in the design have been realized using the micro strip lines. The Micro strip lines have become the best known and most widely used planar transmission line for RF and Microwave circuits. This popularity and widespread use are due to its planar nature, ease of fabrication using various processes, easy integration with solid-state devices, good heat sinking, and good mechanical support.
The electrical lengths of the required open shunt and series micro strip lines were first calculated by hand in smith chart. The ADS Smith chart matching network utility was also used to calculate the electrical lengths and matched the hand calculations. The electrical lengths can be seen in Fig. 6[8].

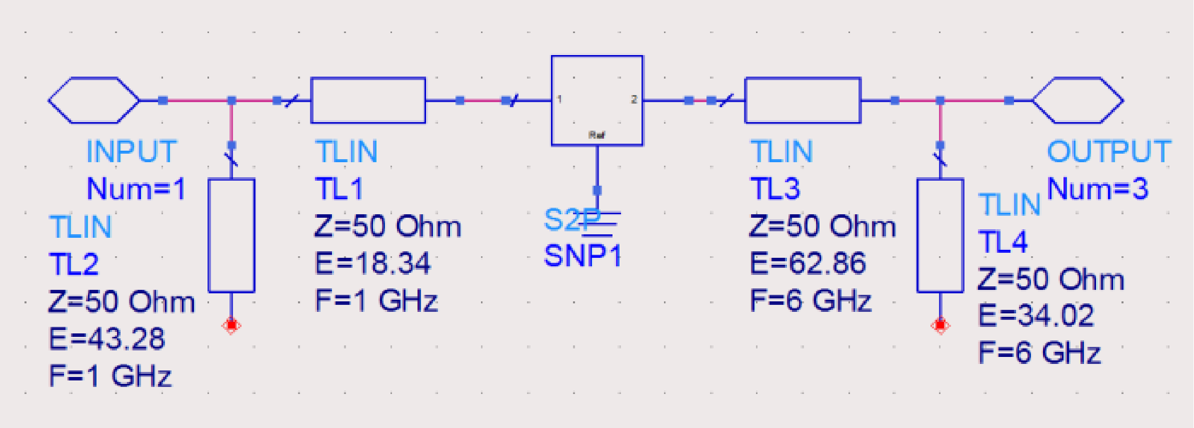


Fig 6. Electrical length calculation for input & output micro strip matching lines network

G. DC biasing circuit Design

S-parameter data for two unique biasing conditions were procured from the datasheet of the provided GaAs pHEMT FET [2]. The quiescent point of V_{DS} = 3.0v and I_{DS} = 20mA was selected for its lower minimum noise figure. The DC biasing network is aimed at supplying a constant DC gate voltage, drain voltage and drain current to the transistor while keeping the RF signals from corrupting the supply. A simple DC biasing scheme utilizing two RF chokes to bias the drain and gate is shown in the final schematic in fig. 14 was selected from [2]. The gate voltage is selected to set the drain current to 20 mA while the drain voltage is set directly to 3.0v. The values of the RF choke inductors need to be large enough to ensure good isolation of the DC bias source from the RF input and output. The DC decoupling capacitors on the supply lines also need to be large enough to filter out noise and any remaining RF on the supplies.

H. Simulation & Optimization of the Design

Agilent Advanced Design System (ADS) was used to simulate the LNA using micro strip transmission line models. Micro strip transmission lines model were used to get a more accurate simulation of the performance of the actual amplifier design. The circuit board is designed using Duroid 3006 substrate & the electrical and mechanical properties of the substrate were found in the substrate's datasheet [3]. Then these properties were entered into the simulator and LineCalc was utilized to calculate the widths and lengths of the micro strip lines. A test bench was created in ADS as shown in Fig. 7[8]. This test bench was used to test the gain, noise figure and the input and output VSWRs. The performance of this design is summarized in Fig. 8[8]. The noise and gain were degraded slightly with the micro strip T-lines; however the VSWRIN and VSWROUT were improved slightly.

The optimization of the design was done using ADS test bench and the optimization cockpit to adjust the length of the micro-strip lines. It was used to make only very subtle trade-offs in the design. The optimization was able to slightly increase the power gain at the expense of a slight (0.005 dB) increase in noise figure. It was also able to better balance the input and output VSWR by increasing the VSWRIN slightly and decreasing the VSWROUT slightly.

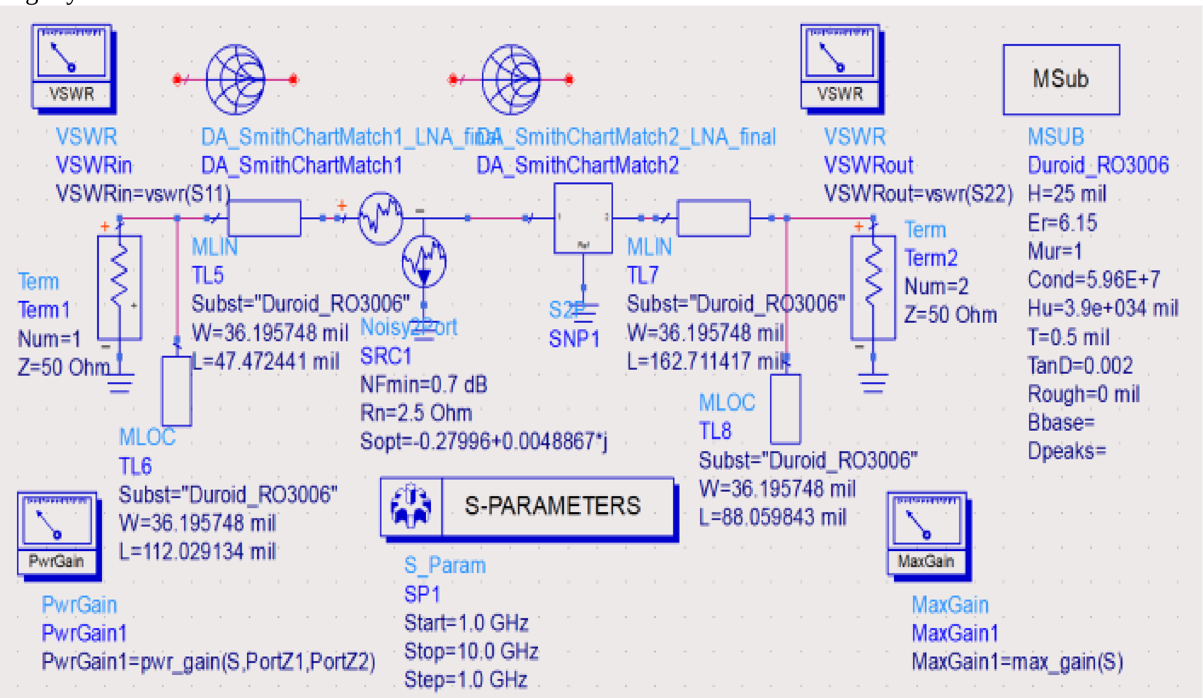


Fig 7. ADS Test bench for micro strip transmission line network

NF_6GHz	PwrGain	VSWRin_6GHz	VSWRout_6GHz
0.806	13.100	1.556	1.495

Fig 8. Simulated results of micro strip matching line network

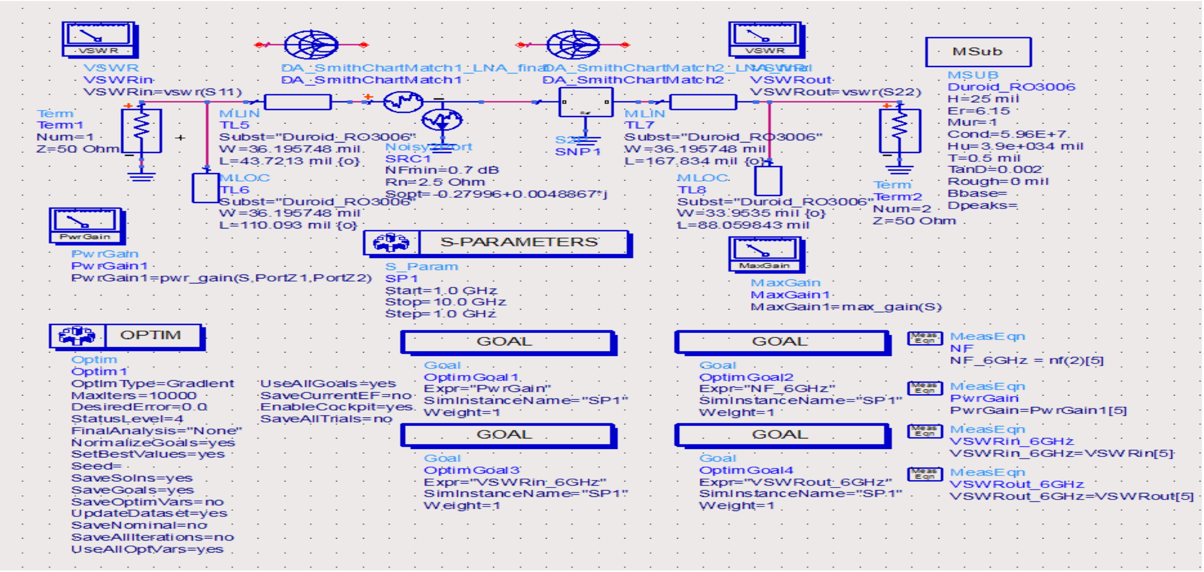
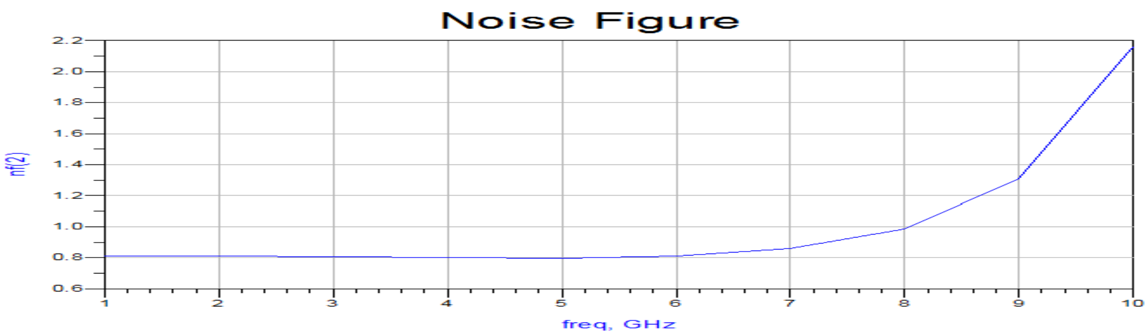
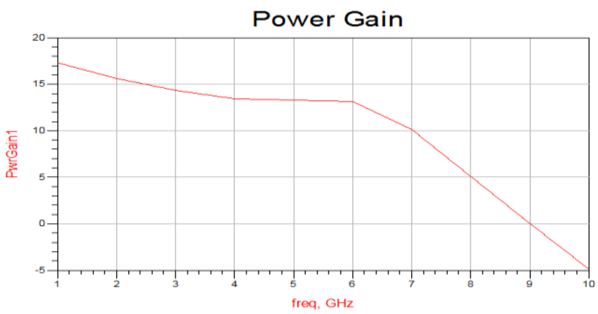


Fig 9. ADS Optimization Test bench



freq	nf(2) optIter=109
1.000 GHz	0.811
2.000 GHz	0.809
3.000 GHz	0.804
4.000 GHz	0.799
5.000 GHz	0.798
6.000 GHz	0.811
7.000 GHz	0.858
8.000 GHz	0.985
9.000 GHz	1.307

Fig 10. Simulated noise figure performance of the final design



freq	PwrGain1 optIter=109
1.000 GHz	17.251
2.000 GHz	15.618
3.000 GHz	14.347
4.000 GHz	13.419
5.000 GHz	13.282
6.000 GHz	13.124
7.000 GHz	10.166
8.000 GHz	5.133
9.000 GHz	0.020

Fig 11. Simulated Gain performance of the final design

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ISO 9001:2008 Certified
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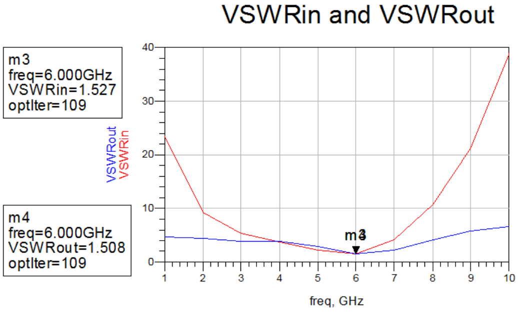

freq	VSWRin optIter=109	VSWRout optIter=109
1.000 GHz	23.579	4.699
2.000 GHz	9.214	4.369
3.000 GHz	5.399	3.876
4.000 GHz	3.739	3.833
5.000 GHz	2.235	2.935
6.000 GHz	1.527	1.508
7.000 GHz	4.077	2.153
8.000 GHz	10.660	4.097
9.000 GHz	21.242	5.779

Fig 12. Simulated Gain performance of the final design

Final Design Performance results at 6 GHz	
Parameter	Simulated Value
Noise figure (dB)	0.811
Gain (dB)	13.12
Input VSWR	1.527
Output VSWR	1.508

Fig 13. Summary of final design performance at 6 GHz

III. RESULTS

The final simulated performance was measured using the optimization test bench shown in Fig. 9[8]. The noise figure performance is shown in fig. 10[8], the gain performance in fig. 11 [8] and the VSWR performance in fig. 12[8]. A summary of the performance at 6 GHz is given in fig. 13[8]. The final schematic incorporating the transistor, DC bias network and matching networks is shown in fig. 14 [8].

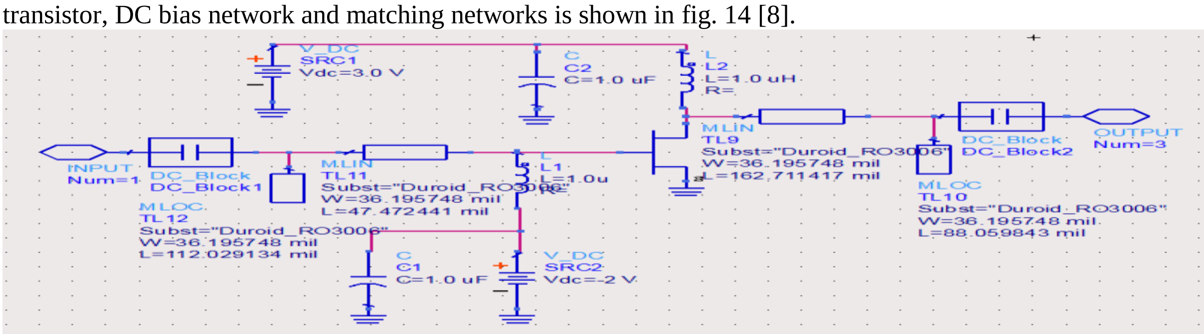

Fig 14. Final schematic of the proposed LNA

The comparison of the proposed design with results achieved by earlier designs is as follows:

Parameter	Proposed design	By ZHANG H (Ref 6)	By Yi-Jing Lin(Ref 5)
Technology	p-HEMT	CMOS	CMOS
Frequency (GHz)	1-8	3.1 – 10.6	3.1- 10.6
Noise Figure (dB)	0.798- 0.985	4-9.2	3.3-6
Gain (dB)	10.166 – 17.251	10.4	13.5-16

IV. CONCLUSION & FUTURE SCOPE OF WORK

A low-noise amplifier has been designed at 6.0 GHz. A noise figure of 0.811dB has been achieved with a gain of 13.12dB. The VSWRIN of 1.527 was balanced with the VSWROUT of 1.508. The DC biasing network has been implemented with RF chokes isolating the DC voltage supplies from RF corruption. Further scope of work may include improving of the linearity and bandwidth of the amplifier. In order to simulate the linearity a device model for the GaAs FET would need to be obtained. The 1-dB compression point and third order intercept values could then be simulated in ADS. The design simulation accuracy could also be improved by including a model of the input, output and ground pads along with the associated bond wires inductance & stray capacitances.

APPENDIX

Appendix A – Detailed calculation results from smith chart toolbox

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AUTHOR BIOGRAPHY

Yashpal Yadav has completed his B Tech degree in Electronics engineering from Jawaharlal Nehru University, New Delhi. He is currently undergoing his post-graduation from Defense institute of advanced technology, Pune. His area of interest includes radar & wireless communication systems.

Dr CRS Kumar ME, PhD is currently posted in Defense institute of advanced technology as HOD Electronics Engineering department. He has professional membership of institution of engineers (India), Institution of Electronics & Telecommunication engineers, senior member of computer society of India, senior member IEEE & member of society of technical education. He is recipient of 3i & Icube awards for innovation and has multiple papers, conference proceedings & one patent to his name. His area of research includes wireless communication & networking, network security, jamming/ant jamming and cognitive radio networks.

APPENDIX A – MATLAB DETAILED CALCULATIONS

Stability: Unconditionally Stable
k = 1.0545, |del| = 0.24529
MSG = 15.6937dB
Γ_{ML} = 0.73451 < 106.1876
Gp,max = Gt,max = Ga,max = 14.2659 dB
Plotted Gp values (dB):
13.2659 ,12.2659, 11.2659
Plotted Ga values (dB):
13.2659, 12.2659, 11.2659
Plotted NF values (dB):
0.8000, 0.9000. 1.0000
Minimum Noise figure ($\Gamma_S = \Gamma_{OPT}$ & $\Gamma_L = \Gamma_{ML\_opt}$)
Γ_S = 0.28 < 179, Γ_L = 0.36413 < 118.0992
VSWRin = 2.835, VSWRout = 1
NF = 0.7dB

ISSN: 2319-5967
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Gp = 13.5493Db, Ga = 12.4201dB, Gt = 12.4201dB

Try VSWRout = 2

VSWRin = 2.1106 ΓL = 0.37146 < 167.2023 theta = -0.75 pi rad
VSWRin = 1.9525 ΓL = 0.15477 < -178.6412 theta = -0.5 pi rad
VSWRin = 2.1941 ΓL = 0.097755 < 57.3223 theta = -0.25 pi rad
VSWRin = 2.7799 ΓL = 0.32129 < 64.4181 theta = 0 pi rad
VSWRin = 3.6996 ΓL = 0.50009 < 83.9418 theta = 0.25 pi rad
VSWRin = 4.4675 ΓL = 0.60342 < 104.8576 theta = 0.5 pi rad
VSWRin = 3.92 ΓL = 0.61524 < 126.0699 theta = 0.75 pi rad
VSWRin = 2.779 ΓL = 0.53371 < 147.1141 theta = 1 pi rad
min VSWRin = 1.9525
Choose theta = -pi/2
ΓS = ΓOPT = 0.28 < 179
ΓS = 0.28 < 179 , ΓL = 0.15477 < -178.6412
VSWRin = 1.9525, VSWRout = 2
NF = 0.7dB
Gp = 12.3859dB, Ga = 12.4201dB, Gt = 11.9086dB

Try VSWRout = 1.8

VSWRin = 2.2037 ΓL = 0.35751 < 160.2077 theta = -0.75 pi rad
VSWRin = 2.0516 ΓL = 0.16621 < 163.3319 theta = -0.5 pi rad
VSWRin = 2.2655 ΓL = 0.12238 < 81.5737 theta = -0.25 pi rad
VSWRin = 2.7911 ΓL = 0.31188 < 72.9752 theta = 0 pi rad
VSWRin = 3.5711 ΓL = 0.47572 < 87.8396 theta = 0.25 pi rad
VSWRin = 4.1572 ΓL = 0.57139 < 106.1806 theta = 0.5 pi rad
VSWRin = 3.7272 ΓL = 0.58236 < 125.2841 theta = 0.75 pi rad
VSWRin = 2.7964 ΓL = 0.5068 < 143.9542 theta = 1 pi rad
min VSWRin = 2.0516

Try VSWRout = 1.6

VSWRin = 2.3154 ΓL = 0.34711 < 151.8579 theta = -0.75 pi rad
VSWRin = 2.1754 ΓL = 0.19416 < 147.3769 theta = -0.5 pi rad
VSWRin = 2.3556 ΓL = 0.16506 < 97.3015 theta = -0.25 pi rad
VSWRin = 2.8032 ΓL = 0.30862 < 82.9145 theta = 0 pi rad
VSWRin = 3.424 ΓL = 0.44931 < 92.676 theta = 0.25 pi rad
VSWRin = 3.8388 ΓL = 0.53354 < 107.848 theta = 0.5 pi rad
VSWRin = 3.5227 ΓL = 0.54325 < 124.2925 theta = 0.75 pi rad
VSWRin = 2.8124 ΓL = 0.47656 < 140.0097 theta = 1 pi rad
min VSWRin = 2.1754
Give up a little NF for a larger increase in gain , Lose 0.1dB of NF, add 1dB of gain
Choose ΓS = 0.42713 < -152.8189
Plotted Gp values (dB):
13.2659 12.2659 11.2659
Plotted Ga values (dB):
13.2659 12.2659 11.2659
Plotted NF values (dB):
0.8000 0.9000 1.0000

Try VSWRout = 1.8

VSWRin = 1.5453 ΓL = 0.4152 < 144.338 theta = -0.75 pi rad
VSWRin = 1.4267 ΓL = 0.24941 < 135.2243 theta = -0.5 pi rad
VSWRin = 1.6305 ΓL = 0.24264 < 93.9614 theta = -0.25 pi rad
VSWRin = 2.0458 ΓL = 0.4054 < 82.968 theta = 0 pi rad
VSWRin = 2.6146 ΓL = 0.56289 < 91.7065 theta = 0.25 pi rad
VSWRin = 3.0288 ΓL = 0.65347 < 105.7201 theta = 0.5 pi rad
VSWRin = 2.6997 ΓL = 0.65602 < 120.9454 theta = 0.75 pi rad

VSWRin = 2.0076 ΓL = 0.56999 < 135.0981 theta = 1 pi rad
min VSWRin = 1.4267
Solution:
ΓS = 0.42713 < -152.8189, ΓL = 0.24941 < 135.2243
VSWRin = 1.4267, VSWRout = 1.8
NF = 0.78634dB
Gp = 13.08dB, Ga = 13.3135dB, Gt = 12.9436dB

Try VSWRout = 1.5

VSWRin = 1.8197 ΓL = 0.48486 < 132.6655 theta = -0.875 pi rad
VSWRin = 1.6758 ΓL = 0.42437 < 133.949 theta = -0.75 pi rad
VSWRin = 1.5939 ΓL = 0.36467 < 131.8954 theta = -0.625 pi rad
VSWRin = 1.5776 ΓL = 0.31773 < 125.2462 theta = -0.5 pi rad
VSWRin = 1.623 ΓL = 0.2981 < 114.4113 theta = -0.375 pi rad
VSWRin = 1.721 ΓL = 0.31394 < 103.2956 theta = -0.25 pi rad
VSWRin = 1.8616 ΓL = 0.35856 < 96.1031 theta = -0.125 pi rad
VSWRin = 2.0359 ΓL = 0.41751 < 93.5917 theta = 0 pi rad
VSWRin = 2.2323 ΓL = 0.47837 < 94.5708 theta = 0.125 pi rad
VSWRin = 2.4295 ΓL = 0.53276 < 97.7886 theta = 0.25 pi rad
VSWRin = 2.5903 ΓL = 0.57527 < 102.3662 theta = 0.375 pi rad
VSWRin = 2.6663 ΓL = 0.60247 < 107.7188 theta = 0.5 pi rad
VSWRin = 2.6219 ΓL = 0.61242 < 113.4302 theta = 0.625 pi rad
VSWRin = 2.4648 ΓL = 0.60446 < 119.1599 theta = 0.75 pi rad
VSWRin = 2.2438 ΓL = 0.5791 < 124.5709 theta = 0.875 pi rad
VSWRin = 2.0158 ΓL = 0.53816 < 129.2595 theta = 1 pi rad
min VSWRin = 1.5776
Solution:
ΓS = 0.42713 < -152.8189, ΓL = 0.31773 < 125.2462
VSWRin = 1.5776, VSWRout = 1.5
NF = 0.78634dB
Gp = 13.3599dB, Ga = 13.3135dB, Gt = 13.1362dB

Try VSWRout = 1.3

VSWRin = 1.7908 ΓL = 0.43726 < 126.3086 theta = -0.75 pi rad
VSWRin = 1.7169 ΓL = 0.37268 < 120.0804 theta = -0.5 pi rad
VSWRin = 1.8126 ΓL = 0.37055 < 108.0259 theta = -0.25 pi rad
VSWRin = 2.0312 ΓL = 0.43288 < 101.296 theta = 0 pi rad
VSWRin = 2.2841 ΓL = 0.50968 < 103.0015 theta = 0.25 pi rad
VSWRin = 2.4155 ΓL = 0.55865 < 109.534 theta = 0.5 pi rad
VSWRin = 2.2959 ΓL = 0.56006 < 117.536 theta = 0.75 pi rad
VSWRin = 2.0205 ΓL = 0.51342 < 124.2287 theta = 1 pi rad
min VSWRin = 1.7169
Solution:
ΓS = 0.42713 < -152.8189, ΓL = 0.37268 < 120.0804
VSWRin = 1.7169, VSWRout = 1.3
NF = 0.78634dB
Gp = 13.5524dB, Ga = 13.3135dB, Gt = 13.239dB

FINAL SOLUTION:
ΓS = 0.42713 < -152.8189, ΓL = 0.31773 < 125.2462
VSWRin = 1.5776, VSWRout = 1.5
NF = 0.78634dB
Gp = 13.3599dB, Ga = 13.3135dB, Gt = 13.1362dB