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Design of Low Noise Amplifiers for 10 GHz Application

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***Abstract*—**This work deals with the designing of an efficient low noise amplifier for 10.00 GHz applications. The amplifier is designed using Gallium Arsenide High Electron Mobility Transistor (GaAs HEMT) ATF – 36077 with inductive source degeneration technique which is one of the techniques to improve the stability of the potentially unstable device and make it unconditionally stable. Also, different substrates are used for designing the LNA to identify the suitable substrate that gives optimum results. It is observed that the noise immunity is more in Low Noise Amplifier (LNA) designed using RT Duroid 5880 substrate. This design resulted in noise figure of 0.859 dB and power gain of 15.530 dB. The comparative analysis of the LNA design is discussed in this paper.

***Keywords*—**Low noise amplifier, substrate, distributed components, gain, noise figure.

I. Introduction

IN the microwave spectrum, the 10 GHz frequency is classified under the X band which ranges from 8 GHz to 12 GHz. There are various applications operating in this band like amateur radio location, radio navigation for aviation, ATC, scatter meter, vehicle speed detection, etc. [1]. Fallahnejad et al. designed different low noise amplifiers for 10 GHz applications using GaAs HEMT with lumped matching components and obtained a power gain of 15.049 dB and noise figure of 0.806 dB. To further improve the noise immunity, Radio Frequency (RF) chokes were used and could achieve less noise figure of 0.775 dB and gain of 14.77 dB [2]. Li et al. designed a CMOS ultra-wideband low noise amplifier for 3-12 GHz using the load effect of common gate configuration which is applied with the dual resonance load network for noise figure flatness and wide-band matching which resulted in the power gain of 13.8 dB and noise figure of 3.5 dB [3]. Zhao et al. designed Gm-boosted Flat Gain UWB two stage cascode Low Noise Amplifier with Noise Cancellation, self-body bias, and current reuse features to decrease the total power consumption, the noise generation and in turn the noise figure thereby achieving power gain of 22 dB and noise figure of 2.3 dB [4].

Vittori et al. designed three stage high-performance X-band low noise amplifiers with 0.25 µm GaN technology using different topologies w.r.t the output matching networks and obtained a power gain of 25.2 dB and noise figure of 1.3 dB [5]. Guo and Lin designed an ultra-wideband CMOS low noise amplifier using resistive feedback under forward body bias condition and obtained the noise figure of 3.95 dB, a gain of 10.55 dB [6]. Zeinadini et al. designed balanced low noise amplifier using HJFET for 9-11 GHz range and obtained a power gain of 12.75 dB and noise figure of 0.537 dB [7]. The main parameters of consideration for analysis of the efficient working of a low noise amplifier are power gain, noise figure, VSWR and scattering parameters.

Section I introduces the details of the frequency of operation of the application and various work that are already implemented in the same microwave bands. The design aspects of a low noise amplifier are described in Section II and the two proposed LNA designs are described in Section III. Section IV gives the results of the two designs which are being compared to determine the efficient and optimum low noise amplifier.

II. Design Aspects

The low noise amplifiers are designed with the help of the S - parameters of the active device being used. These parameters are responsible for determining the stability of the device and hence the amplifier. The step by step procedure for designing a low noise amplifier is described in [8]. Advanced Design System (ADS) is the simulation tool used for designing the LNA in this work. The active device used in this work is ATF – 36077 which is an ultra-low noise pseudomorphic high electron mobility transistor (pHEMT) of Hewlett Packard. The range of operation of this device is between 2 and 18 GHz.

In a low noise amplifier, the vital parameters to be considered for efficient operation are the maximum gain provided by the active device which is denoted as MAG (maximum available gain) and NF_{min} (minimum) intrinsic noise figure. These parameters depend on the S parameters of the device. The S parameters determine the stability criteria of the device at various biasing points which is mathematically shown in [9]. Theoretically, the stability of the device is checked using the K - |Δ| test where K said to be Rollet's Stability factor is given by,

$$K = \frac{1 - |s_{11}|^2 - |s_{22}|^2 + |\Delta|^2}{2\,|s_{12}s_{21}|} \quad (1)$$

Also, B is another parameter that is calculated for checking stability which should be positive for stable operation given by,

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$$B = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \quad (2)$$

and Δ is given by,

$$\Delta = S_{11}\,S_{22} - S_{12}\,S_{21} \quad (3)$$

The condition for stability is that if K > 1, $|\Delta| < 1$ and B = +ve, then the device is unconditionally stable and if K < 1 then device is potentially unstable. This condition generates oscillations in the device and the maximum available gain will be no more valid due to an unstable condition. Hence, the maximum gain produced by the device will now be said as MSG (maximum stable gain) which is mathematically expressed as,

$$MSG = \frac{|S_{21}|}{|S_{12}|} \quad (4)$$

If the device is unconditionally stable i.e. K > 1, then the gain obtained will be maximum available gain which is expressed as,

$$MAG = \frac{|S_{21}|}{|S_{12}|}(K \pm \sqrt{K^2 - 1}) \quad (5)$$

In later stages, there was another parameter introduced to check the stability of the active device for stable operation given by,

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}^*| + |S_{12}S_{21}|} \quad (6)$$

For the device to operate in the unconditionally stable region, the value of μ should be greater than 1 (μ > 1) and if it is less than 1 then the device is potentially unstable.

The LNA is designed using distributed Microstrip components because of the fact described in [10]. Proper selection of substrates for the Microstrip components is another important factor on which the performance of the LNA depends. There are two different substrates used in this work. The first substrate used for designing the Microstrip matching components is FR4 epoxy. Its properties are ε_r of 4.4, tanδ of 0.02, substrate height (h) of 1.6 mm, metal thickness (t) of 0.035 mm, metal being copper conductivity (σ) of 5.8 x e7. The second substrate used is RT Duroid 5880 of Rogers Corporation. Its properties are ε_r of 2.2, tanδ of 0.0009, of substrate height (h) of 1.6 mm, metal thickness (t) of 0.035 mm, metal being copper conductivity (σ) of 5.8 x e7. Also, for proper isolation between DC biasing and RF input signal, RF chokes are used [11]. Accordingly, two RF chokes one with FR4 substrate and another with RF Duroid substrate designed for LNA are shown in Figs. 1 and 2, respectively.

Voltage standing wave ratio (VSWR) is a parameter which determines the amount of reflections that occurs in a microwave circuit due to improper impedance matching. It is represented in the form of reflection coefficient which is mathematically represented as

$$VSWR = \frac{V\max}{V\min} \quad (7)$$

or

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (8)$$

where

$$\Gamma = \frac{Vr}{Vi}$$

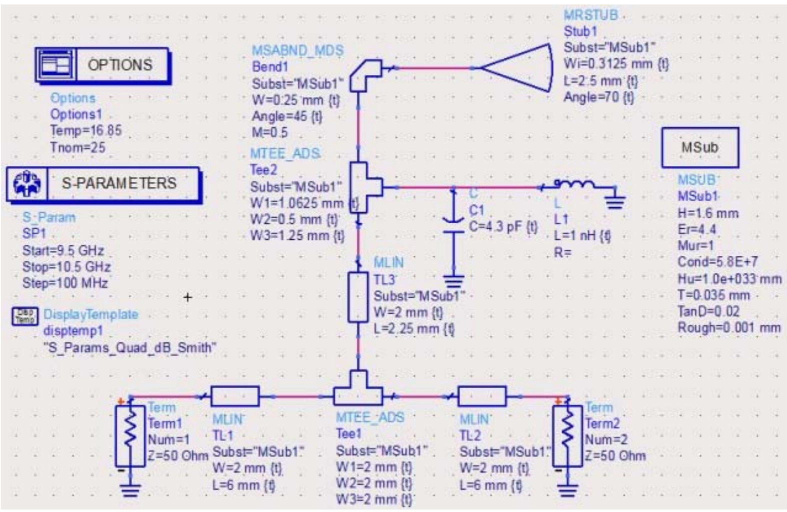

Fig. 1 RF choke with the FR4 substrate

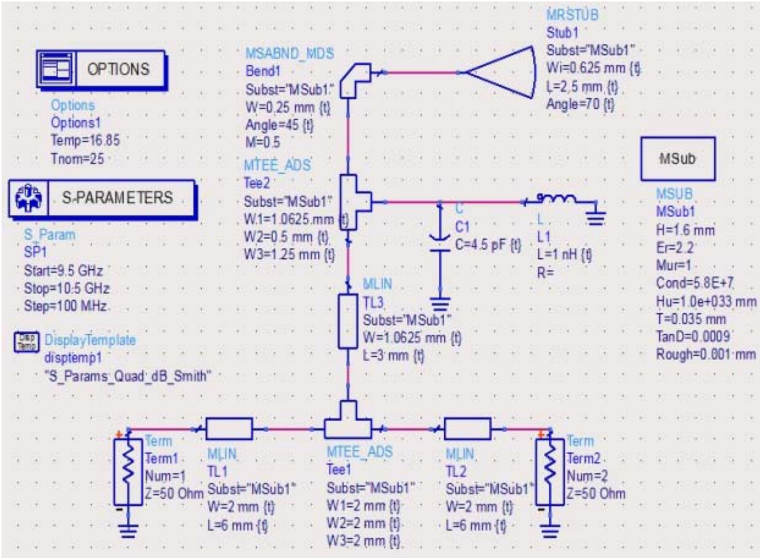

Fig. 2 RF choke with RT Duroid substrate

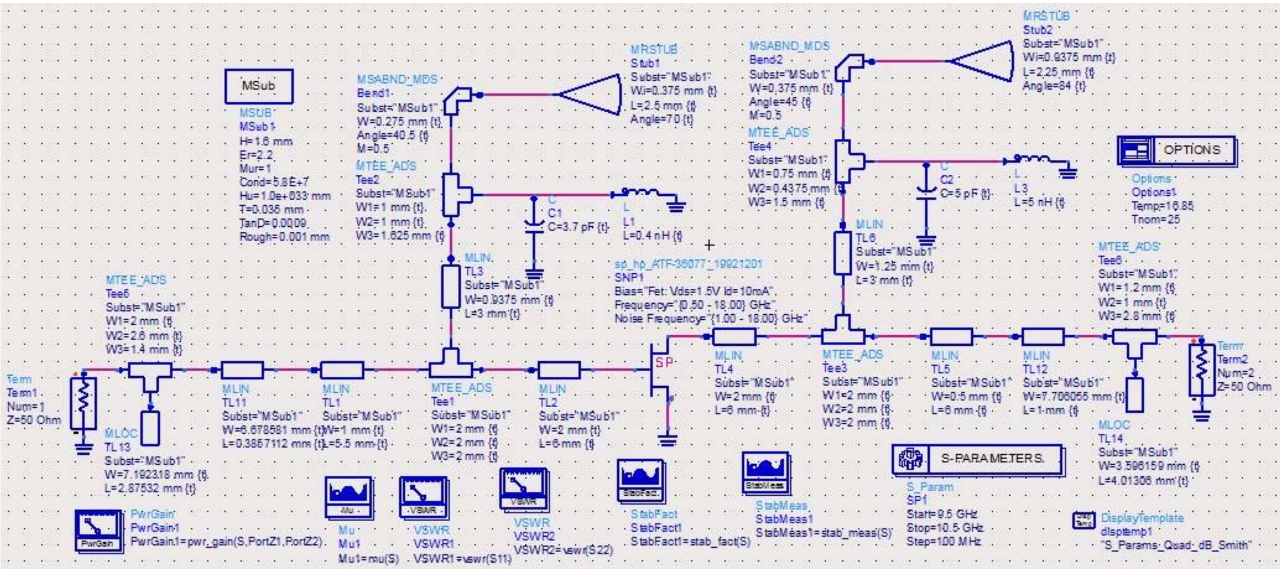

Fig. 3 Simple LNA Design

The VSWR values range from 1 < VSWR < ∞ for the corresponding reflection coefficient of 0 < Γ < 1.

III. Proposed Designs

The simple initial low noise amplifier is designed without any stability improvement technique for this application as shown in Fig. 3. The stability factor (K) denoted as stabfact1, delta (Δ) denoted as stabmeas1, factor (μ) denoted as Mu1 obtained for the designed LNA is shown in Fig. 4. The values obtained are K = 0.800, μ = 0.633, Δ = 0.118. These values show that the designed LNA is potentially unstable because of K < 1, μ < 1. Also, this inference is supported by another parameter obtained which is VSWR shown in Fig. 5. VSWR obtained for this LNA at the input and output side is 4.673 and 5.762 denoted as VSWR1 and VSWR2 respectively. These values show that reflections will be generated both at the input and output side of the active device and hence maximum power cannot be transferred from source to the load. Hence, to improve the stability of the active device, there are various techniques available which are described in [12]. One such technique is to connect an inductor in series to the source terminal of the active device i.e. here pHEMT and this technique is said to be inductive source degeneration technique. This technique improves not only the stability of the amplifier but also the power gain without affecting the noise immunity [13].

The LNA with source inductance on FR4 substrate is shown in Fig. 6.

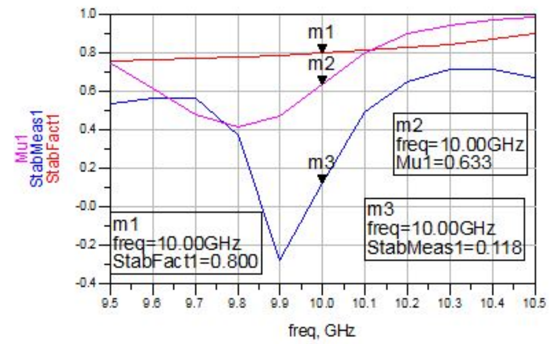

Fig. 4 Stability of Simple LNA

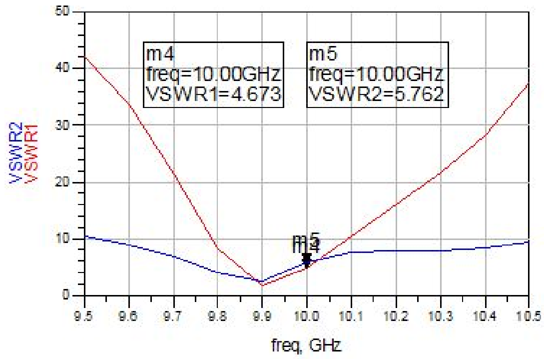

Fig. 5 VSWR of Simple LNA

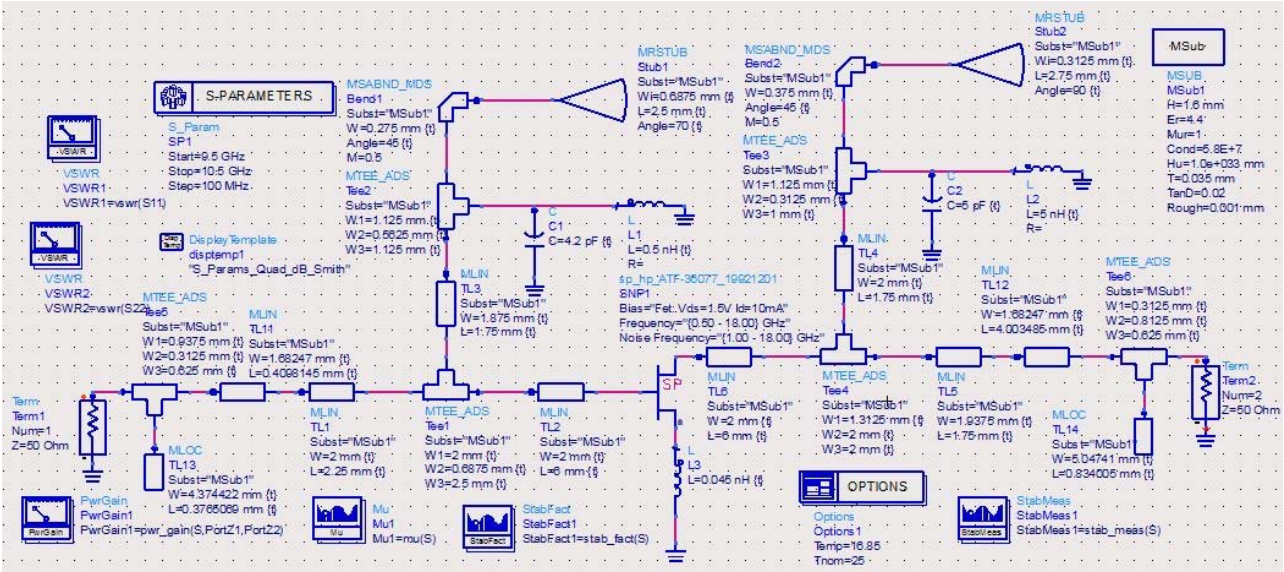

Fig. 6 FR4 LNA

K - |Δ| test, B and μ are calculated for the above design with the help of the obtained s parameters,

$S_{11} = 0.080\llcorner 169.192$, $S_{12} = 0.077\llcorner -114.723$

$S_{21} = 4.194\llcorner -107.917$, $S_{22} = 0.417\llcorner 18.435$

$\Delta = [(0.080\llcorner 169.192) \times (0.417\llcorner 18.435) - (0.077\llcorner -114.723) \times (4.194\llcorner -107.917)] = 0.301\llcorner -47.625$

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

$$K = \frac{1-|0.080|^2 - |0.417|^2 + |0.301|^2}{2*0.322} = 1.413$$

Hence, K > 1.

$$B = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 = 1 + |0.080|^2 - |0.417|^2 - |0.301|^2 = 0.923.$$

Hence, B is positive.

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

can be obtained as follows,

$\Delta S_{11}^* = [(0.301\llcorner -47.625) \times (0.080\llcorner -169.192)] = 0.02408\llcorner -216.817$

$|S_{22} - \Delta S_{11}^*| = 0.4305$

$$\mu = \frac{1-|0.080|^2}{0.4305+0.322} = 1.320 \text{ that's} > 1.$$

The various icons shown in Figs. 3, 6 are the parameters of measurement. S-parameter icon in the figure is used to measure the S-parameters of the amplifier which are S_{11}, S_{12}, S_{21}, and S_{22}. The MSUB icon is used to set the substrate parameters which include the substrate height, metal thickness, metal conductivity, loss tangent (tanδ), relative permittivity also called dielectric constant (εr), etc. Two VSWR icons namely VSWR1 and VSWR2 are used for calculating the VSWR at the input and output side of the amplifier after connecting the matching network which implies how perfectly the impedance is matched with the source and load. PwrGain is the function used to find the available power gain of the amplifier.

The Rollet's stability factor K, μ and |Δ| obtained for the designed FR4 LNA including the matching network is shown in Fig. 7 which are obtained as 1.409, 1.317 and 0.667 respectively. Therefore, the above obtained values of K > 1, B = +ve, |Δ| < 1 and μ > 1 proves that the device is unconditionally stable. The LNA with source inductance on RT Duroid substrate is shown in Fig. 8.

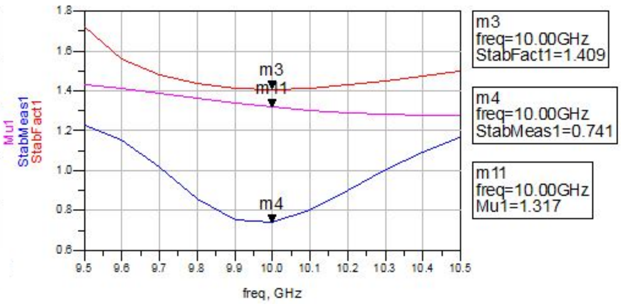

Fig. 7 Stability of FR4 LNA

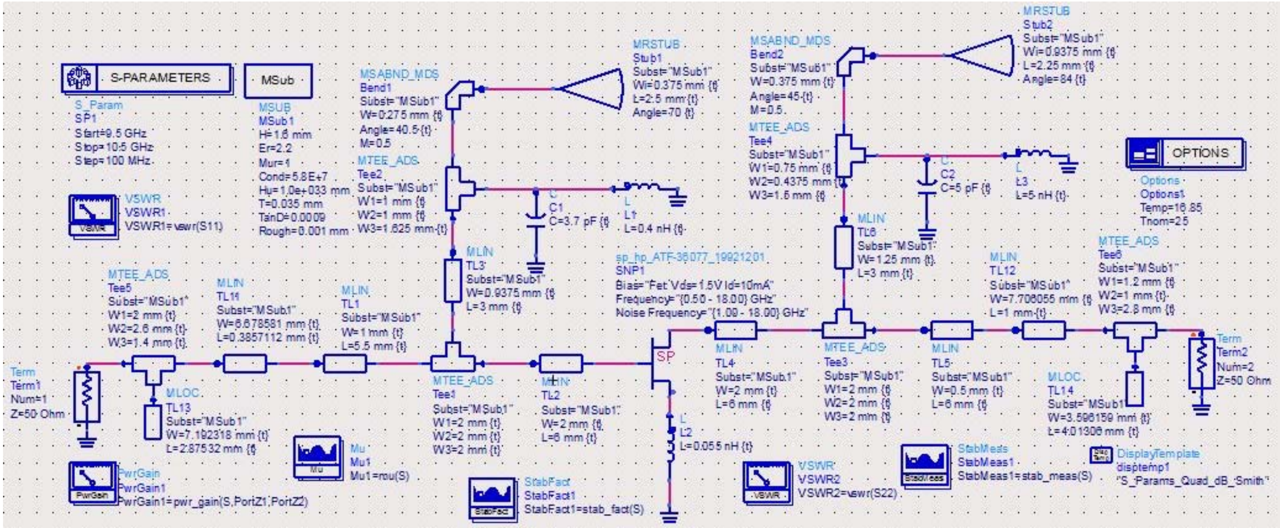

Fig. 8 RT Duroid LNA

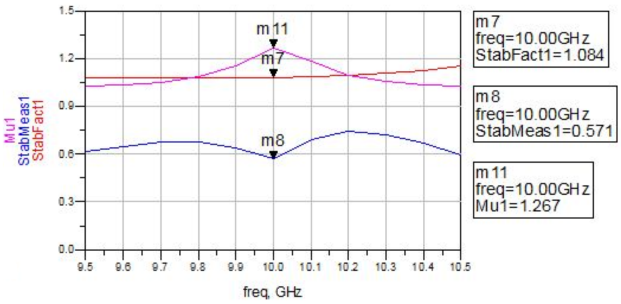

Fig. 9 Stability of RT Duroid LNA

K - |Δ| test, B and μ are calculated for the above design with the help of the obtained s parameters,

$S_{11} = 0.012\angle 59.279$, $S_{12} = 0.109\angle -179.716$

$S_{21} = 5.855\angle 177.803$, $S_{22} = 0.145\angle -9.454$

$\Delta = [(0.012\angle 59.279) \times (0.145\angle -9.454) - (0.109\angle -179.716) \times (5.855\angle 177.803)] = 0.635\angle 177.971$

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

$$K = \frac{1-|0.012|^2-|0.145|^2+|0.635|^2}{2*0.638} = 1.083$$

Hence, K > 1.

$$B = 1+|S_{11}|^2-|S_{22}|^2-|\Delta|^2 = 1 + |0.012|^2 - |0.145|^2 - |0.635|^2 = 0.575$$

Hence, B is positive.

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

can be obtained as follows,

$\Delta S_{11}^* = [(0.635\angle 177.971) \times (0.012\angle -59.279)] = 0.00762\angle 118.692$

$|S_{22} - \Delta S_{11}^*| = 0.149$

$$\mu = \frac{1-|0.012|^2}{0.149+0.638} = 1.270$$

Hence, μ > 1.

The Rollet's stability factor K, μ and |Δ| obtained for the designed RT Duroid LNA including the matching network is shown in Fig. 9 which are obtained as 1.084, 1.267 and 0.571 respectively. Therefore, the above obtained values of K > 1, B = +ve, |Δ| < 1 and μ > 1 prove that the device is unconditionally stable.

IV. Results

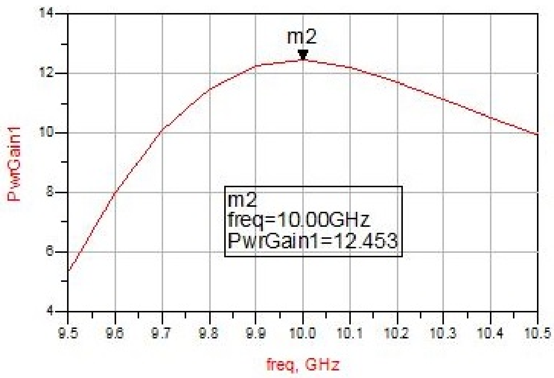

Fig. 10 Power Gain of FR4 LNA

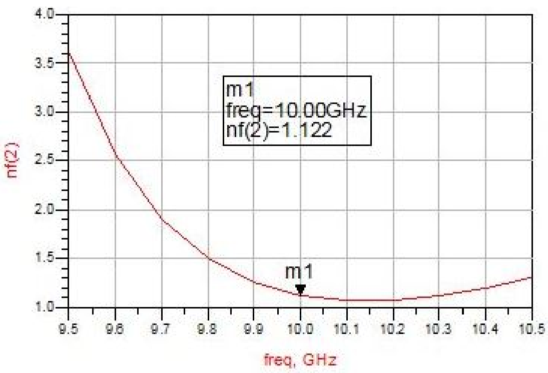

Fig. 11 Noise Figure of FR4 LNA

The power gain and noise figure obtained for the source degenerative LNA with FR4 substrate are 12.453 dB and 1.122 dB as shown in Figs. 10 and 11 respectively.

The VSWR obtained for the source (VSWR1) and load (VSWR2) matching are shown in Fig. 12 which are 1.173 and 2.428 at input and output side respectively. In this case, the input side VSWR is less i.e. near value 1. Hence, this signifies that the amount of reflections at the input side of amplifier is negligible. But the output side VSWR is more than value 2 which implies reflection of amplified signal at the output.

The S parameters of the designed FR4 LNA obtained are shown in Fig. 13. The S_{11} is -21.966 dB, S_{21} is 12.453 dB, S_{12} is-22.250 dB and S_{22} is -7.606 dB.

The power gain and noise figure obtained for the source degenerative LNA with FR4 substrate are 15.350 dB and 0.859 dB as shown in Figs. 14 and 15 respectively.

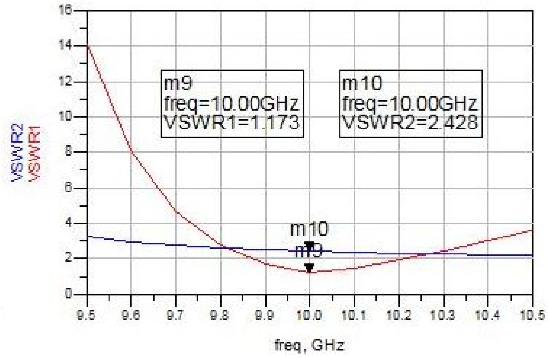

Fig. 12 VSWR of FR4 LNA

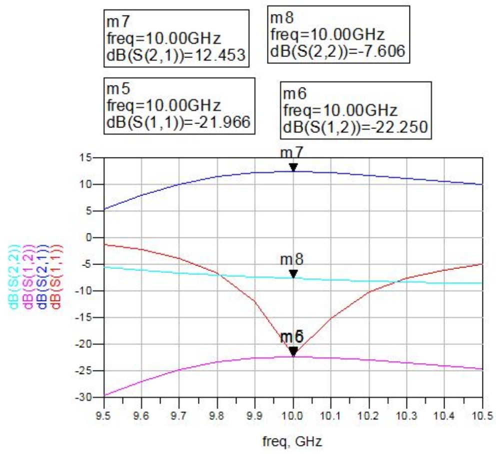

Fig. 13 S – parameters of FR4 LNA

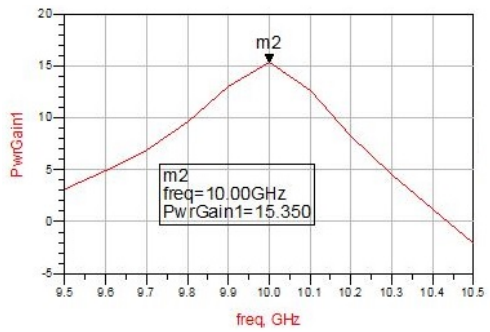

Fig. 14 Power Gain of RT Duroid LNA

The VSWR obtained for the source (VSWR1) and load (VSWR2) matching are shown in Fig. 16 which are 1.025 and 1.338 at input and output side respectively. The minimal values of VSWR i.e. nearby 1 signifies that the amount of reflections is very less i.e. negligible and hence maximum input power can be transferred to the output side of the amplifier.

The S parameters of the RT DuroidLNA obtained are shown in Fig. 17. The S_{11} is -38.210 dB, S_{21} is 15.350 dB, S_{12} is -19.230 dB and S_{22} is -16.795 dB.

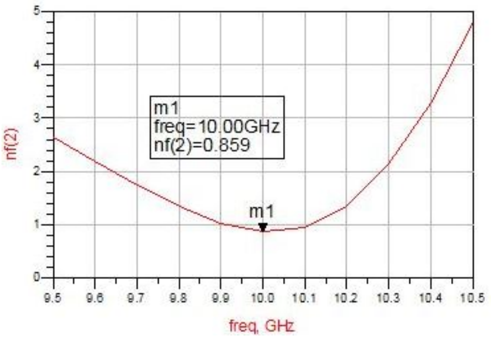

Fig. 15 Noise Figure of RT Duroid LNA

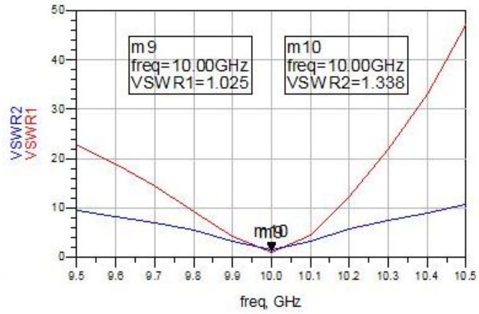

Fig. 16 VSWR of RT Duroid LNA

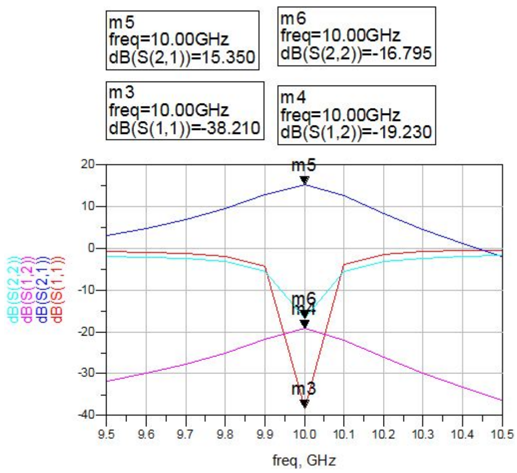

Fig. 17 S – parameters of RT Duroid LNA

TABLE I
COMPARATIVE ANALYSIS OF THE RESULTS

Parameter	[2]		Proposed Design FR4 LNA	Proposed Design RT Duroid LNA
K	0.951	0.951	1.409	1.084
μ	0.820	0.888	1.317	1.267
S_{11} (dB)	-9.101	-17.352	-21.966	-38.210
S_{21}(Gain) (dB)	15.049	14.77	12.453	15.350
S_{22}(dB)	-21.919	-10.246	-7.606	-16.795
NF(dB)	0.806	0.775	1.122	0.859
BW (MHz)	NM#	NM#	350	200
VSWR	NM#	NM#	1.173 (I) 2.428 (O)	1.025 (I) 1.338 (O)

NM#-Not measured, NF–Noise Figure, BW-Bandwidth

V. CONCLUSION

The design of low noise amplifiers are performed in ADS software and the results are obtained for both FR4 LNA and RT Duroid LNA. The comparative analysis shows that the amplifier designed using RT Duroid 5880 provides better results compared to FR4 with a power gain of 15.350 dB and optimum noise figure of 0.859 dB. The minimum values of VSWR i.e. 1.025 and 1.338 prove that the reflections are less both at the source and load side of the amplifier. The use of inductor at the source terminal not only improved the stability of the amplifier but also improved the power gain of the signal without affecting the noise immunity. But the bandwidth of the RT Duroid LNA is less compared to FR4. Hence to improve the bandwidth of the amplifier cascading can be implemented and multistage LNA's can be designed.

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