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Research Article

Low Noise Figure, High Gain Single LNA Cascaded with Cascoded LNA Amplifiers using Optimized Inductive Drain Feedback for Direct Conversion RF Front-end Receiver at Wireless Application

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Abstract: This study presents a design of low noise figure, high gain LNA at 5.8 GHz with cascaded and cascoded techniques using inductive drain feedback that is applicable for the WiMAX 802.16 standard. The amplifier uses Pseudomorphic High Electron Mobility Transistor FHX76LP super HEMT low noise FET. The Ansoft Designer SV as an Electromagnetic (EM) simulator was used during the design process. The LNA was designed using the inductive drain feedback, inductive generation to the source and the T-network as a matching technique was used at the input and output terminal. The cascaded and cascoded Low Noise Amplifier (LNA) produced a gain (S21) of 43.94 dB and the Noise Figure (NF) of 0.61 dB. The input reflection (S11), output reflection (S22) and return loss (S12) are -10.65, -20.02 and -52.23 dB, respectively. The measured 3 dB bandwidth of 1.24 GHz has been achieved. The input sensitivity is -84 dBm exceeded the standards required by IEEE 802.16 has been observed.

Keywords: Cascaded and cascoded LNA, IEEE 802.16, inductive drain feedback, RF front-end

INTRODUCTION

Over the past few years, wireless communication is an area that is growing rapidly and the latest technology applications created for the growth of the relationship between the progress of people or companies around the world. Where they can measure and control the entire work process, analyze data in real time, lower cost, improve reliability and requires a continuous and nonstop searching for new technologies with greater capacity (Fourty *et al*., 2005).

Expansion in coverage, increase data speed and capacity consumers is a challenge that must be addressed and it is always a requirement for on a different generation wireless communication systems. WiMAX is one of the new standards developed recently. It covers a large area and allows a huge data rate. Theoretically, WiMAX can achieve transmission rates up to 70 Mb/sec and a service area of around 50 km for fixed stations and 5-15 km for mobile stations (Roger, 2004). The construction of the RF front-end receiver for WiMAX application becomes an arduous task considering the complicated challenges of achieving the standard set.

Figure 1 shows the available RF bands that can be used for WiMAX. The system is based on IEEE 802.16 standards and uses several licensed and unlicensed bands (2.3-2.7, 3.4-3.6, 5.1-5.8 GHz, respectively) to transmit data (Roger, 2004). In this research, focus will be on the unlicensed spectrums at 5.8 GHz frequency.

To get the best performance in the RF front-end receiver, design optimization of Low Noise Amplifier (LNA) is needed to produce a good input impedance match, sufficient power gain and low noise figure at a predetermined band (Ruey *et al*., 2008). There are two types of amplifier topology used for LNA, i.e., the cascading and cascoding technique. The cascoded topology is the most famous since this technique introduces a higher gain, due to the increase in the output impedance and isolation that-occurs at the input and output ports which could be further reduced (Othman *et al*., 2012). While cascaded topology is used to increase the gain of the amplifier.

However, most of the researches that are focused on the single stage LNA or cascoded LNA only exhibit gain of around 20 dB (Othman *et al*., 2012). By taking consideration the extension of communication distance of up to 50 km, the increased in gain with low noise

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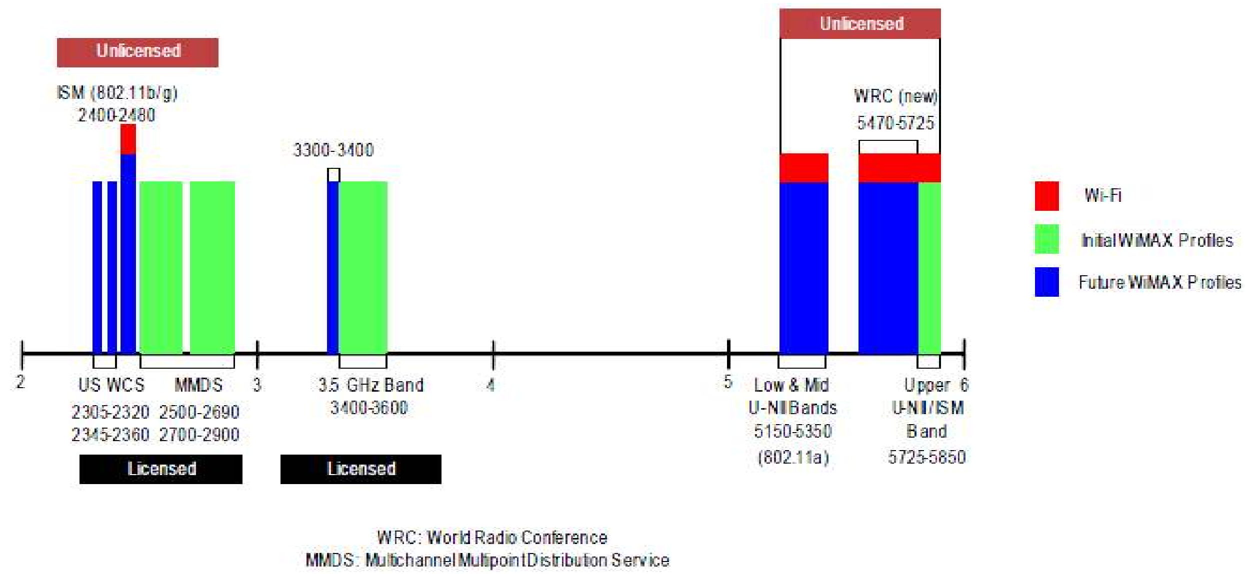

Fig. 1: 2 to 6 GHz centimeter bands available for BWA (Broadband Wireless Access), (Farahani and Ismail, 2005)

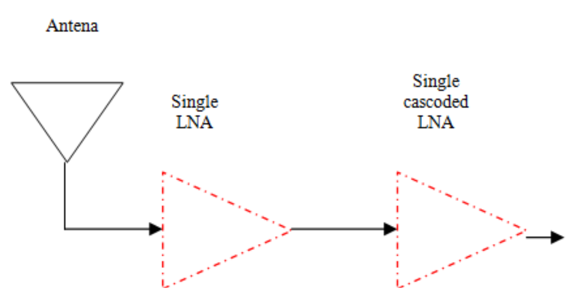

Fig. 2: Direct conversion RF front-end receiver using a single LNA cascaded with cascoded LNA configuration

figure is crucial to ensure the best signal generated. In this project, three transistors using PHEMT (LNA) were used under two different operating conditions. The first stage LNA is designed with the same parameters published in (Xuezhen and Robert, 2003). The second stage for two LNA is optimized to achieve a minimum noise figure with maximum gain available. This study describes the addition of inductive feedback in LNA to provide the higher gain and bandwidth of the RF front-end receiver.

In this study, a low noise amplifier with gain of more than 35 dB is proposed. A single LNA cascaded with cascoded LNA front-end amplifier is used. To achieve a gain more than 35 dB, a single LNA with cascoded amplifier for direct conversion RF front-end receiver architecture WiMAX at 5.8 GHz is introduced as shown in Fig. 2. The development of LNA at the front-end of the receiver will be focused.

METHODOLOGY

LNA theory: In designing the low noise amplifiers, analysis of the transistor stability, gain, noise figure, bandwidth, optimization and proper matching network selection will have to be carried out. The selection of the transistor for the LNA is based on input sensitivity and noise figure. Bipolar transistors are capable of high gain and power capacity at lower frequencies. GaAs is less expensive than bipolar devices and can operate at higher frequencies with better noise figures (Pozar, 2001). Table 1 shows the comparison between the FET and BJT transistors by Pozar (2001).

With reference to Table 1, the GaAs HEMT transistor is selected due to its low Noise Figure (NF) and reasonable gain at the required frequencies. For frequencies between 4 to 8 GHz, the GaAs HEMT could provide gains up to 20 dB while maintaining a minimum noise figure below 0.5 dB. However since the

Table 1: The comparison between FET and BJT transistors

	GaAs FET		GaAs HEMT		Silicon bipolar		GaAs HBT	
Freq GHz	Gain	Fmin	Gain	Fmin	Gain	Fmin	Gain	Fmin
4	20	0.5	20	0.3	15	2.5	-	-
8	16	0.7	18	0.4	9	4.5	-	-
12	12	1.0	22	0.5	6	8.0	20	4.0
18	8	1.2	16	0.9	-	-	16	-
36	8	1.2	16	0.9	-	-	16	-
60	-	-	12	1.7	-	-	10	-

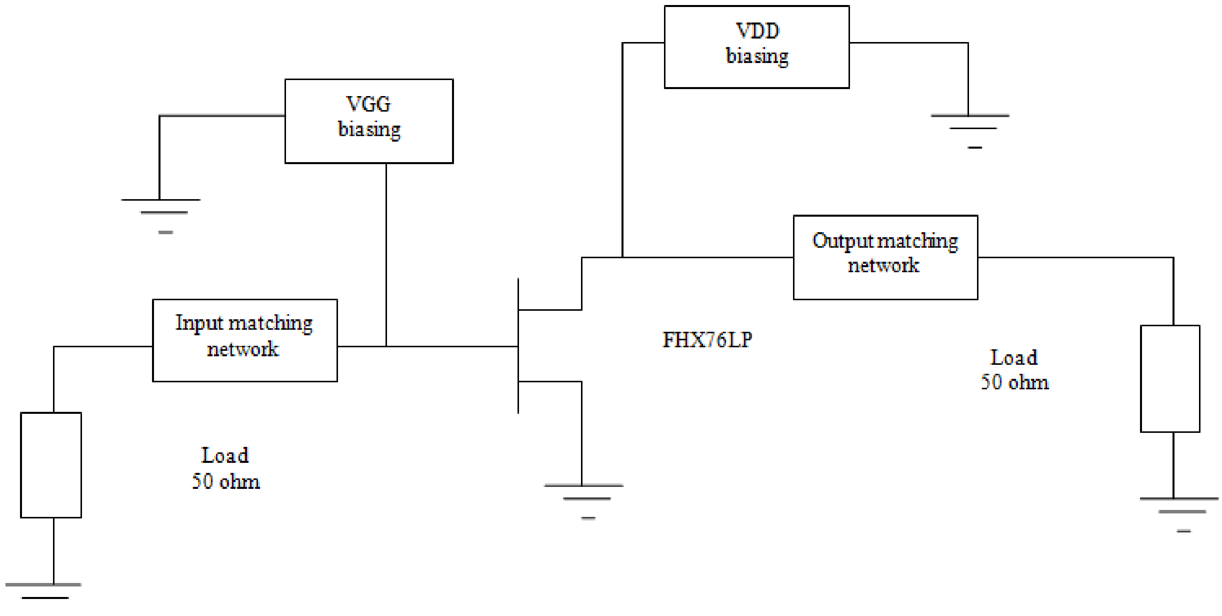

Fig. 3: Typical biasing circuit configurations

Table 2: Targeted S-parameters for a single LNA cascaded with cascoded LNA amplifier

S-parameter	Single LNA cascaded with cascoded LNA
Input reflection S11 (dB)	<-10 dB
Return loss S12 (dB)	<-35 dB
Forward transfer S21 (dB)	>+ 35 dB
Output reflection loss S22 (dB)	<-10 dB
Noise figure (dB)	<3 dB
Stability (K)	K>1
Bandwidth (MHz)	>1000

maximum gain available is only 20 dB, if we required more than 35 dB, a cascaded first stage is a reasonable solution.

Initially, the gain, bandwidth and noise figures were compared for different transistors. All the transistors satisfy the requirements of the design. The input sensitivity and bandwidth of the transistors are compliant with WiMAX standard. The stability of each transistor was then checked with reference to the data sheet. FHX76LP from Eudyna Devices Inc was found to have the best stability for the required frequency range of 5.2-6.5 GHz. This transistor is a super low noise HEMT and provides a low noise figure of 0.4 dB at 12 GHz and a high gain of 18 dB at 6 GHz. The transistor consumes very low current of 10 mA with drain-source voltage of 2 volts. Hence FHX76LP was selected for the LNA designed (Othman *et al*., 2010).

Figure 3 shows the basic concept of high frequency am plifierde sign. It shows there quired impedance to match the input and output impedance of the transistor at high frequencies. Using S-parameters, the frequency characteristics at a DC-bias point are set based on the source impedance and load impedance (Othman *et al*., 2010). The main purpose of obtaining input and output matching conditions is to avoid reflection and improve the efficiency of signal transmission from the source to the load.

The targeted S-parameter specification for the single LNA cascaded with cascoded LNA amplifier is shown in Table 2.

Minimum noise figure: One of the most critical steps in the LNA design procedure is the noise optimization (IEEE Computer Society and IEEE Microwave Theory Technique and Society, 2004). It can only be done using constant gain circles and circles of constant noise figure to select usable trade-off between noise figure and gain. Typically, noise figure of 2-port transistor has a minimum value at the specified admittance given by the Eq. (1), (Ibrahim *et al*., 2011):

$$F = F_{\min} + \frac{R_N}{G_S} | Y_s - Y_{opt} |^2 \tag{1}$$

For low noise transistors, manufacturers usually provide F_{min}, R_N, Y_{opt} by frequencies. N defined by formula for desired noise figure, shows in Eq. (2):

$$N = \frac{|\Gamma_s - \Gamma_{opt}|^2}{1 - |\Gamma_S|^2} = \frac{F - F_{\min}}{4R_N / Z_0} |1 + \Gamma_{opt}|^2 \tag{2}$$

After stability of the active device is determined, input and output matching circuits should be designed so

Table 3: S-parameter from transistor PHEMT FHX76LP datasheet

Frequency GHz	S_{11}	S_{12}	S_{21}	S_{22}
5.8 GHz	0.712	0.065	8.994	0.237
Angle	-86.54	33.88	178.66	-10.46

that reflection coefficient of each port can be correlated with conjugate complex number as given in Eq. (3) and (4):

$$\Gamma_{IN} = \Gamma_s^* = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} \tag{3}$$

And

$$\Gamma_{out} = \Gamma_L^* = S_{22} + \frac{S_{12}S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} \tag{4}$$

To get a minimum noise figure using 2-port transistor, the source reflection coefficient should match with Γ_{opt} and load reflection coefficient should match with Γ^*_{out} with a complex conjugate number as formulated in Eq. (5) and (6):

$$\Gamma_s = \Gamma_{opt} \tag{5}$$

$$\Gamma_L = \Gamma_{out}^* = \left(\frac{S_{22} + S_{12}S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} \right) \tag{6}$$

Power gain: Amplifier operation can be explained in more detail through the input/output circuit for two port networks. As shown in the Fig. 3, power gain of 2 port networks with circuit impedance or load impedance of the power amplifier are represented with scattering coefficient classified into Operating Power Gain, Power Transducer and Available Power Gain (Lorenzo and De Leon, 2010).

Operating power gain is the ratio of the power dissipated in the load Z_L (P_L) to the power delivered to the input (P_{in}) of the two-port network (Lorenzo and De Leon, 2010). The Operating Power Gain can be expressed as an Eq. (7), (Ibrahim *et al*., 2011):

$$G_P == \frac{P_L}{P_{in}} = \frac{|S_{21}|^2 \left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{in}|^2\right)|1 - S_{22}\Gamma_L|^2} \tag{7}$$

Transducer Power Gain is the ratio of P_{avs}, maximum power available from source to P_L, power delivered to the load. The maximum power cans be obtained, when the input impedance Γ_{in} of the network is terminated conjugately matched to the source impedance Γ_s., if $\Gamma_{in} = \Gamma_s$, Transducer Power Gain can be expressed in Eq. (8), (Ibrahim *et al*., 2011):

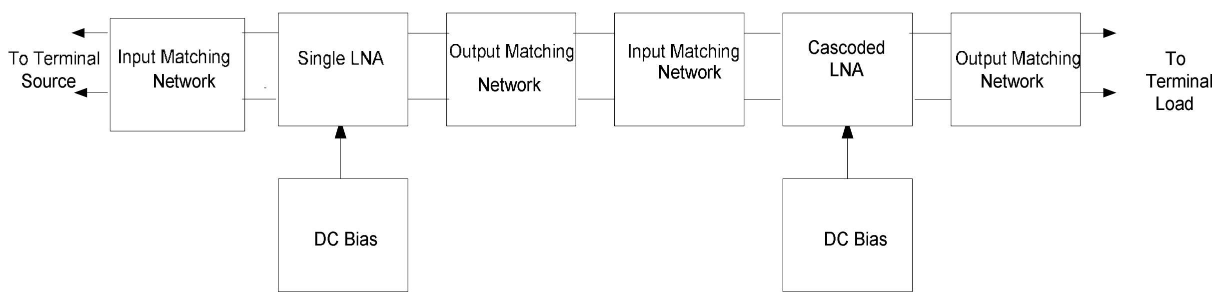

Fig. 4: Configuration diagram single LNA cascaded with cascoded LNA

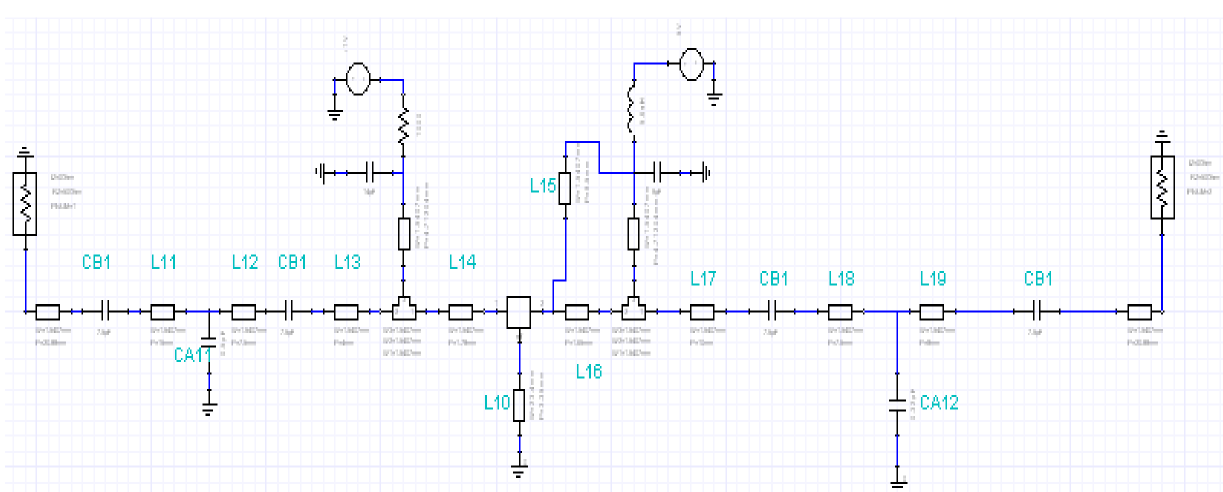

Fig. 5: Complete schematic single stage LNA amplifier

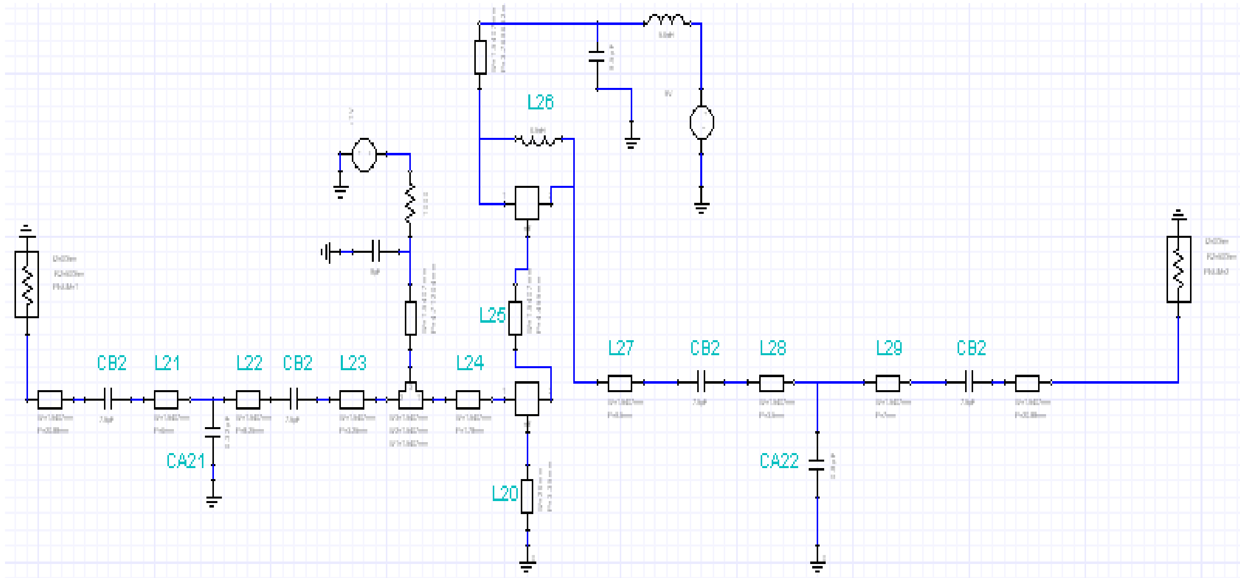

Fig. 6: Complete cascoded LNA amplifier circuit designed using inductive feedback to drain LNA

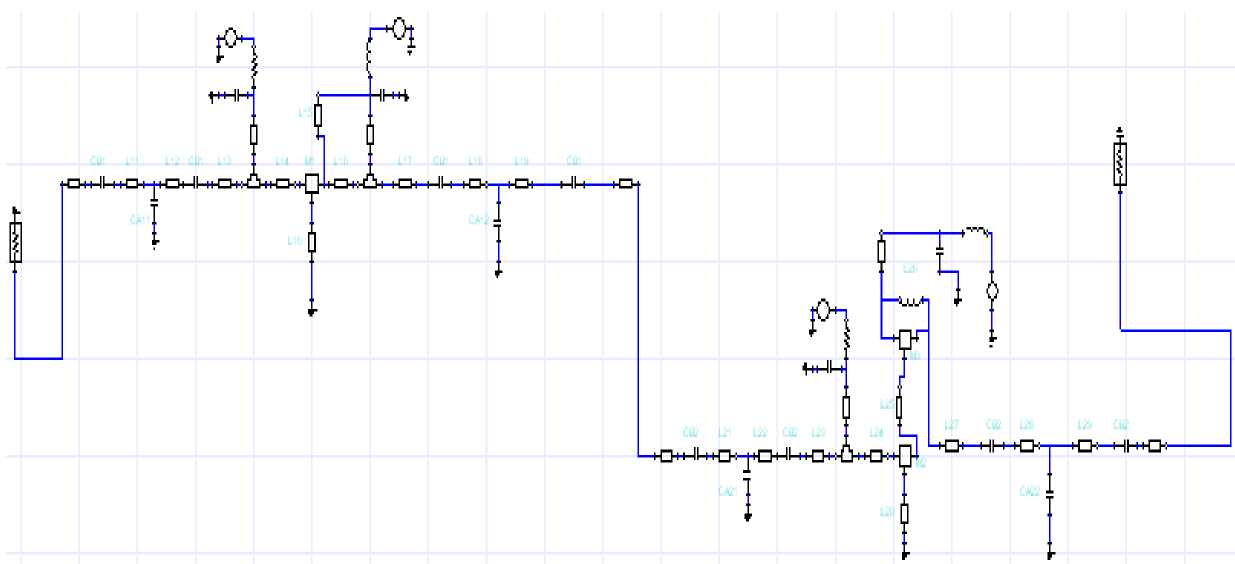

Fig. 7: Complete single LNA cascaded with cascoded LNA using inductive feedback

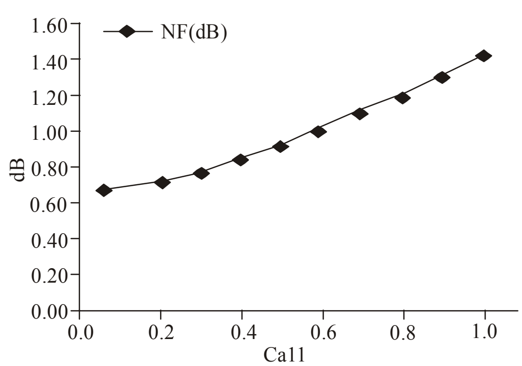

Fig. 8: Affect changes value the CA_{11} to the overall noise figure

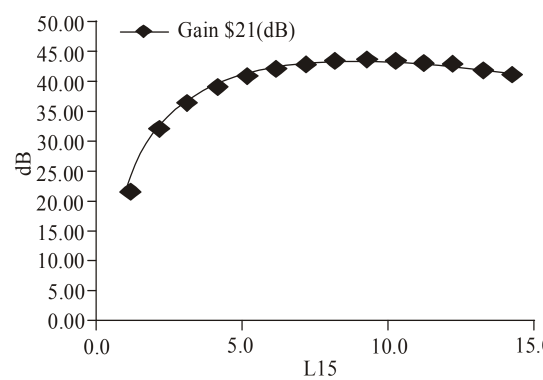

Fig. 9: Affect changes value the L_{15} to the overall gain

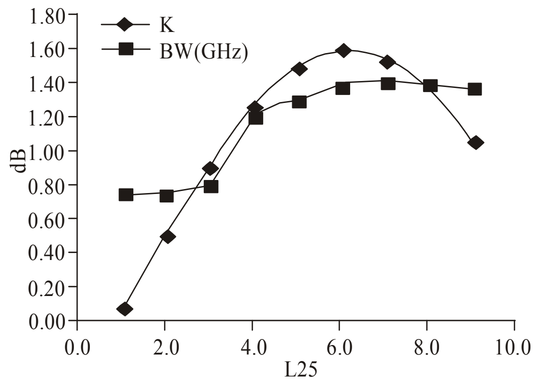

Fig. 10: Affect changes value the L_{25} to the overall gain and stability

$$G_T = \frac{P_L}{P_{in}} = \frac{|S_{21}|^2 (1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-(S_{12}S_{21}\Gamma_S\Gamma_L)|^2} \quad (8)$$

Available Power Gain, G_A is the ratio of P_{avs}, power available from the source, to P_{avn}, power available from 2-port network, that is:

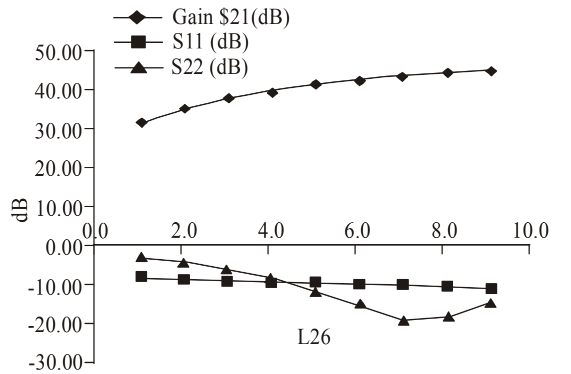

Fig. 11: Affect changes value the L_{26} to the overall gain and output matching

$$G_A = \frac{P_{avn}}{P_{avs}}$$

The power gain is P_{avn} when $\Gamma_{in} = \Gamma_s^*$.

Therefore Available Power Gain is given by Eq. (9), (Ibrahim *et al*., 2011):

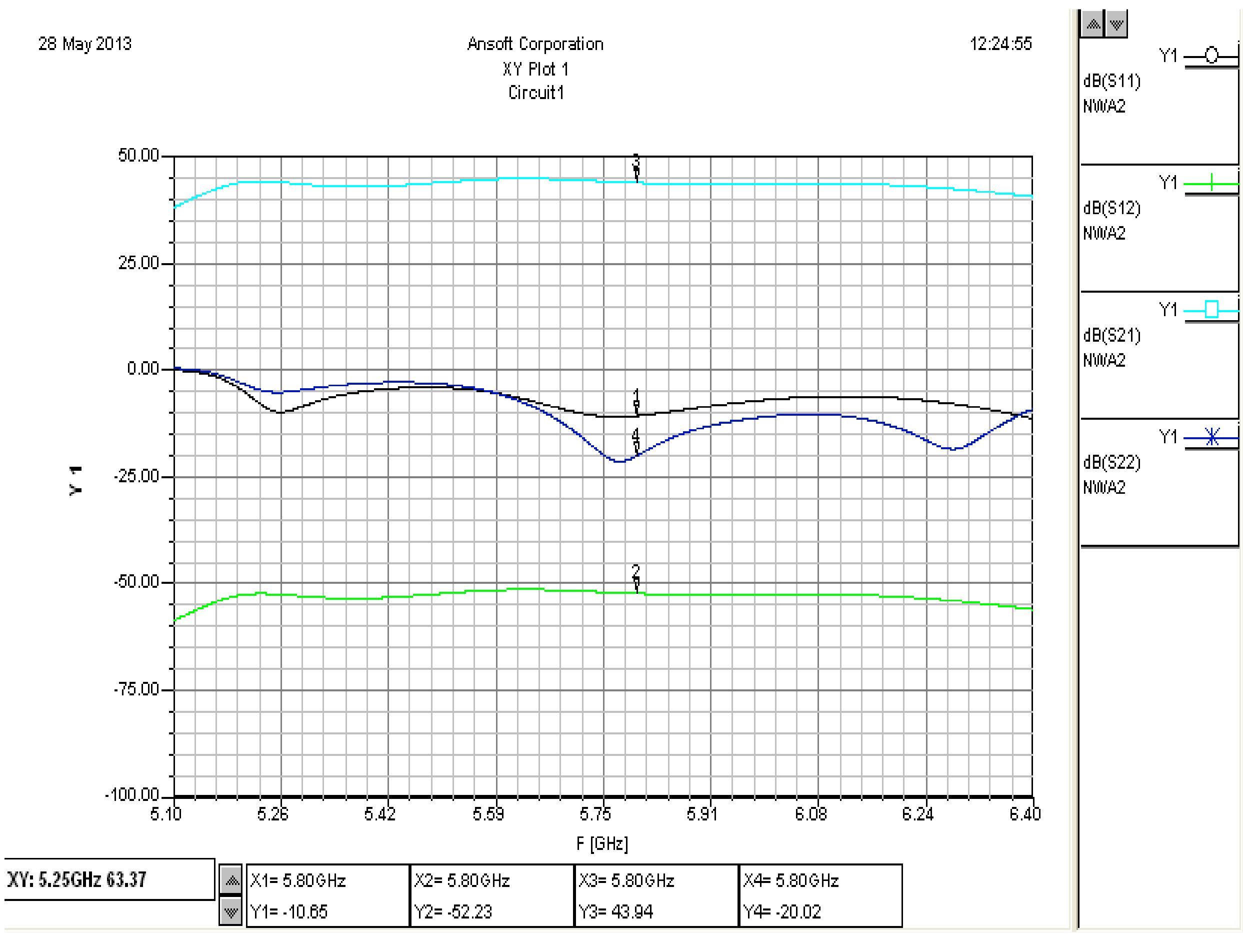

Fig. 12: S-parameter for single LNA cascaded with cascoded LNA

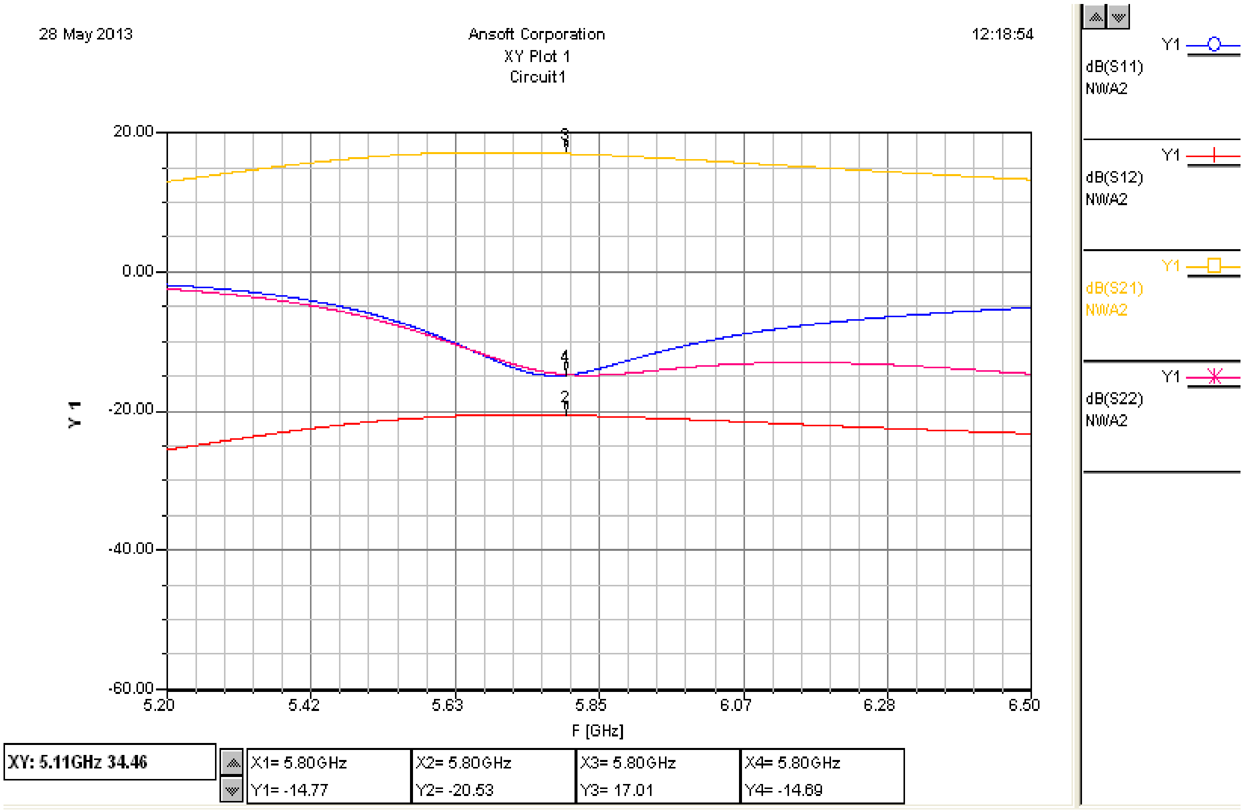

Fig. 13: S-parameter for single LNA

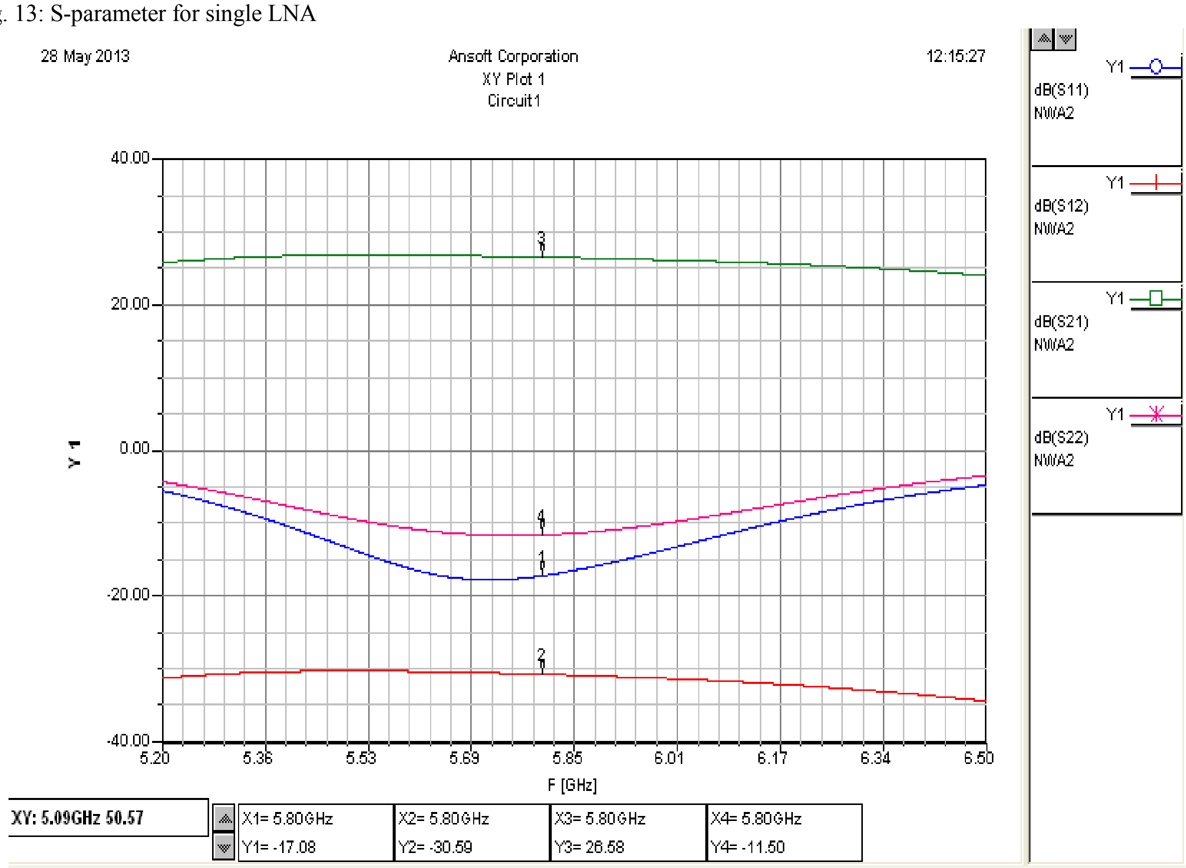

Fig. 14: S-parameter for cascoded LNA

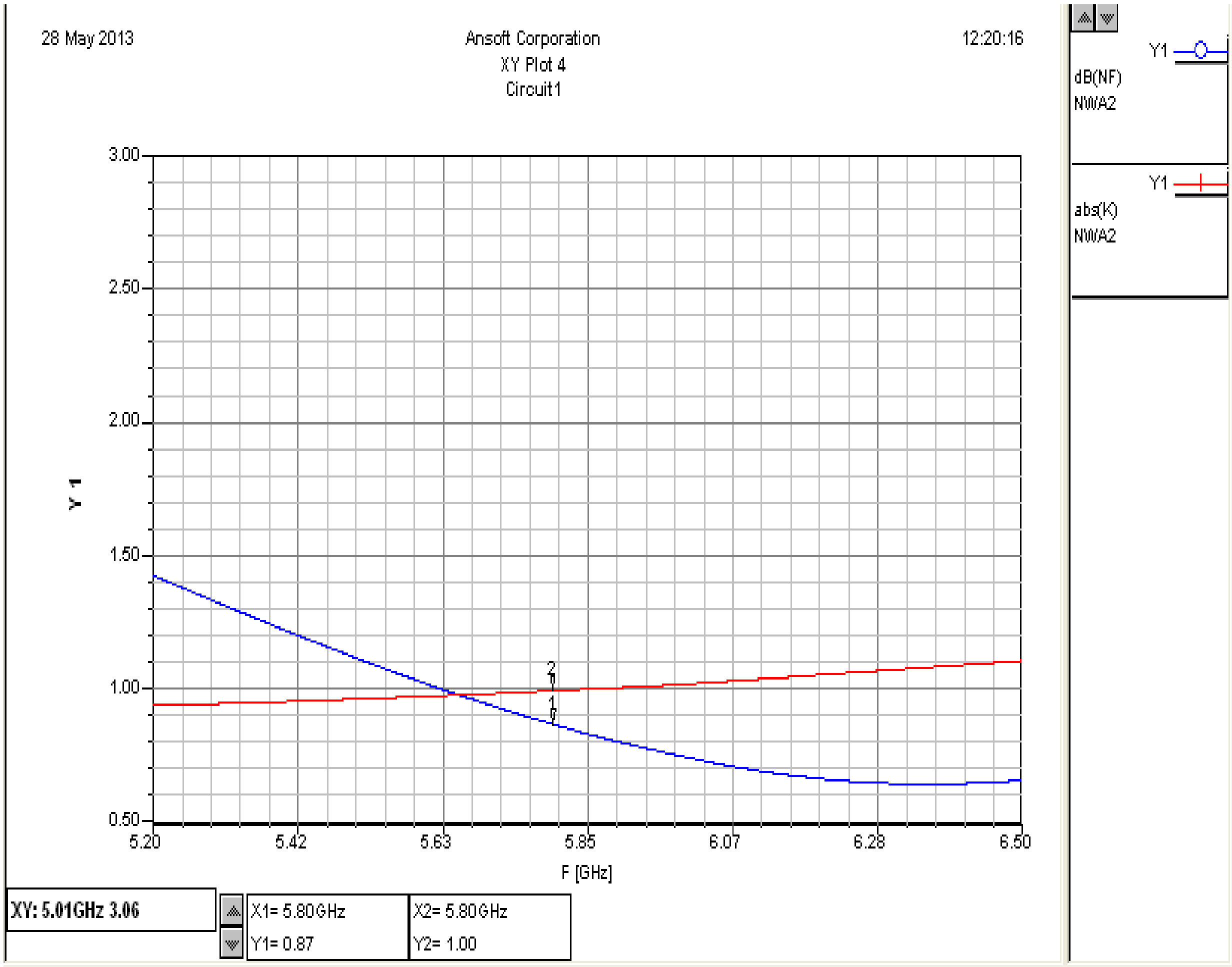

Fig. 15: Noise figure and stability for single LNA

$$G_A = \frac{P_{avn}}{P_{avs}} = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2}|S_{21}|^2\frac{1}{|1-S_{22}\Gamma_L|^2} \quad (9)$$

Design of single LNA cascaded with cascoded LNA: The proposed configuration diagram single LNA cascaded with cascoded LNA is shown in Fig. 4.

Single LNA cascaded with cascoded LNA design is based on the specifications stipulated in Table 3 PHEMT Transistor FHX76LP was used to design a single LNA cascaded with cascoded LNA. S-parameters for PHEMT is shown in Table 3, where the parameters were obtained at V_{DD} = 2V and I_{DS} = 10 mA of bias set at PHEMT.

Overall performance of low noise amplifier can be determined by calculating or simulating on the transducer gain using Eq. (8), noise figure using Eq. (2) and also on the input and output standing wave ratios, $VSWR_{IN}$ and $VSWR_{out}$. The optimum, Γ_{opt} and Γ_L were obtained as Γ_{opt} = 21 + j48.02 and Γ_L = 79.90-j7.299 for cascoded LNA. While, Γ_{opt} = 18.41 + j50.12 and Γ_L = 79.913-j7.304 for a single LNA.

Figure 5 shows the complete schematic single stage LNA amplifier. The design of single LNA topology as given in the schematic used T-matching network placed at the input and output impedance. Passive elements contained in the input matching network at the LNA circuit is built as follows L_{11}, L_{12}, L_{23} and CA_{11}. While there are passive elements in the output matching network, they are L_{17}, L_{18}, L_{19} and CA_{12}, which characteristics of the T- network element used lump reactive element and micro-strip line impedance. There are additional features in the single LNA designed placing inductive source generation L_{10} at source M_1 and L_5 inductor peaking structure at the drain of M_1

The design of the cascoded LNA has a new technique and topology, where we introduced an inductive feedback L6 is connected to the drain of the M1, inductive source generation L10, which is connected to the source M3 while inductive L5 is placed between the source and drain of M2 and M3 (Fig. 6). The design of single cascoded LNA topology as given in the schematic also used T-matching network placed at the input and output impedance. Passive elements

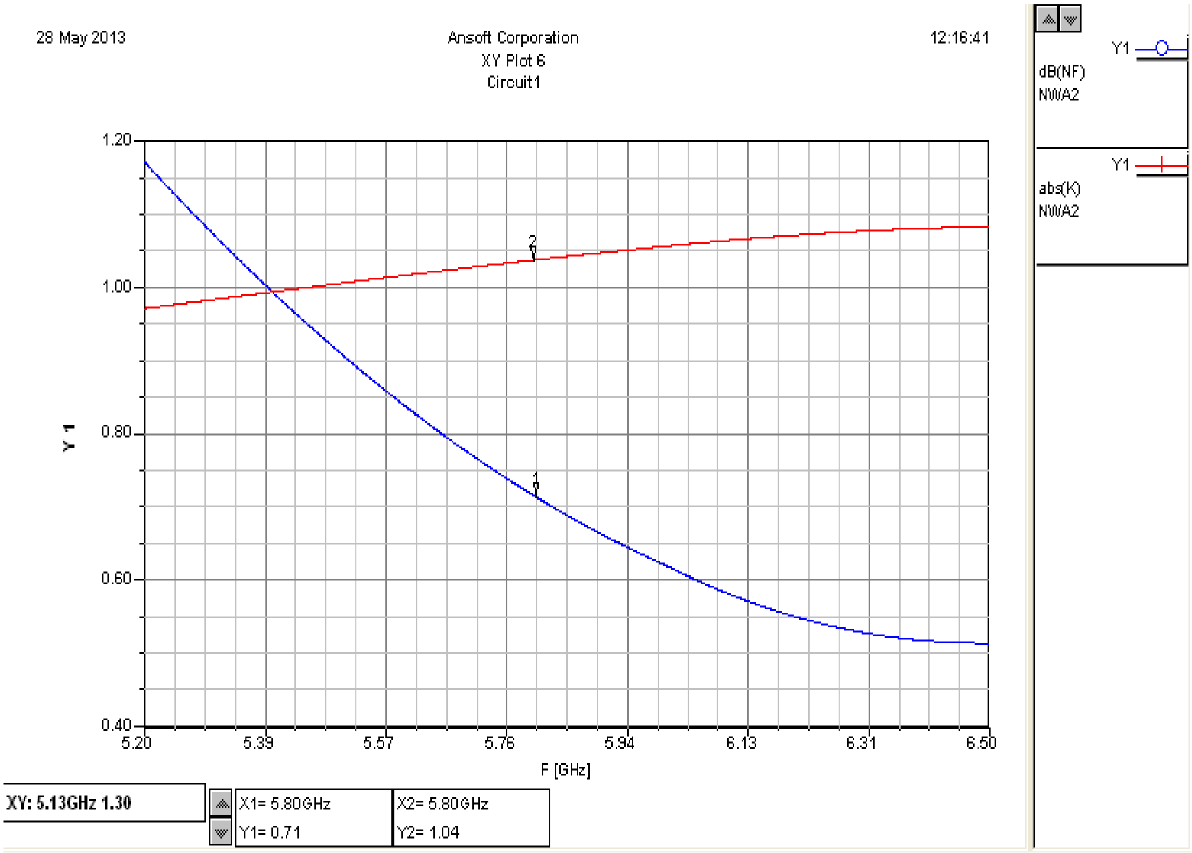

Fig. 16: Noise figure and stability for cascoded LNA

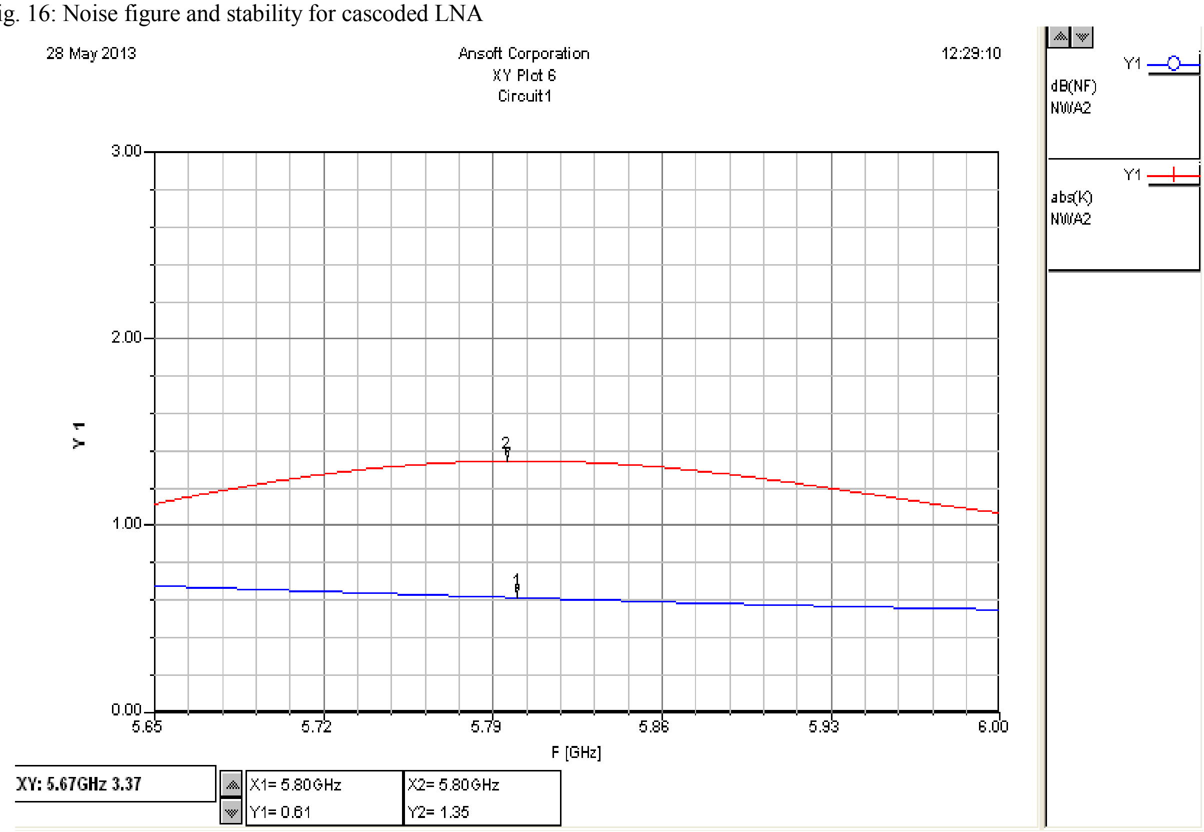

Fig. 17: Noise figure and stability for single LNA cascaded with cascoded LNA

Table 4: Double-stage cascoded LNA amplifier parameters

Single LNA cascaded with cascoded LNA			
Single LNA		Cascoded LNA	
Components	Value	Components	Value
L11	0.084 nH	L21	1.129 nH
L12	1.302 nH	L22	1.238 nH
L13	0.756 nH	L23	0.707 nH
L14	0.401 nH	L24	0.401 nH
L15	1.331 nH	L25	0.927 nH
L16	0.373 nH	L26	7.840 nH
L17	1.365 nH	L27	1.333 nH
L18	1.302 nH	L28	0.848 nH
L19	0.926 nH	L29	1.371 nH
L10	0.081 nH	L20	0.073 nH
CA11	0.100 pF	CA11	0.700 pF
CA12	0.320 pF	CA22	0.800 pF
CB1	7.500 pF	CB2	9.000 pF

contained in the input matching network at the LNA circuit are L21, L22, L23 and CA21. There are also passive elements in the output matching network, they are L27, L28, L29 and CA22.

To achieve the targeted overall gain of more than 35 dB, it was decided to design a single LNA cascaded with cascoded LNA using inductive feedback to double the LNA gain. The cascaded and cascoded amplifier was redrawn again using Ansoft Designer SV and the related frequency response is shown in Fig. 7. By using Ansoft Designer SV, Smith Chart matching technique, the components for the amplifier are as shown in Table 4.

From the observation of the single LNA cascaded with cascoded LNA amplifiers, there are some passive component that should be optimized to achieve a targeted specification as required for WiMAX. This passive component values determine the high gain, low noise, good stability and maintain the value of the required bandwidth despite the increasing stage of LNA amplifiers. For example, CA_{11} capacitance passive component was influencing the overall system noise figure. This can be shown in Fig. 8.

From Fig. 8, the changes in value of CA_{11} from 0.1 to 1 pF caused noise figure of the amplifier to change from 0.61 to 1.6 dB. This change also resulted in decreased bandwidth amplifier from 1.24 to 1.05 GHz. Meanwhile, changes in the value of a single LNA inductive L_{15} resulted in changes in the overall system gain when the length of the micro-strip L_{15} was changed from 1 to 14 mm as shown in Fig. 9.

In addition, changing the value of inductive L15 also affects the noise figure from 5.9 to 0.69 dB but bandwidth increase from 0.59 to 1.24 GHz. L10 is used as an inductive generation for the single LNA amplifier to allow more flexibility in matching to terminal 50 ohm at the input stage.

In the second stage, a cascoded LNA amplifier, the inductive L25 is placed between M1 and M2. The variable value of the inductance L25 will give the cascoded LNA real input impedance and helps in getting the input and output of the optimal matching. When this condition occurs, it enhances the grain and stability as shown in Fig. 10.

The cascoded transistor M_2 suppresses the Miller capacitance of M_1 thereby increases the reverse isolation. The suppression of the parasitic capacitances of the input transistor also improves the high frequency operation of the amplifier (Lorenzo and De Leon, 2010). When inductive components for the L_{26} values raised from the set value, will cause an increase in the gain change dramatically. Additionally inductive L_{26} allows output matching at 50 Ohm impedance terminals, it will show at Fig. 11.

At the input, the matching network consists of passive elements such as L11, L12, L13 and CA11. While the passive elements in the output matching network are L27, L28, L29 and CA22. Good selection of passive component in the input and output matching cause LNA amplifiers to be on high gain at the desired frequency. Capacitor CB1 and CB2 are acting as DC block to the single LNA cascaded with cascoded LNA circuit, in which they proposed is worth 10 times the original value of the CB1 or CB2 because it acts as a bypass capacitor (Roger, 2004).

RESULTS

Table 5 shows the s-parameters output for comparison of topology LNA. It is simulated using Ansoft Designer SV. The recorded result for the single LNA cascaded with cascoded LNA gain S_{21} is 43.94 dB. The input reflection S_{11} is -10.65 dB while the output reflection loss S_{22} is -20.02 dB, overall Noise Figure (NF) is 0.61 dB and the return loss S_{12} is -52.23 dB. These values are within the design specification as stated in Table 2. The stability factor and noise figure obtained after matching load is 1.35 at 5.8 GHz frequency. The value of stability obtained is greater than 1, the LNA amplifiers are currently in a state ofunconditionally stable and, provides no isolation. From Figure 11 c, it is observed that, the 3dB bandwidth of around 1.24 GHz was obtained and this complies with the targeted result of more than 1 GHz. The output S-parameter for different LNA topology are shown in Figure 11 a to c. While noise figure and stability are shown in Fig. 11 d to f, respectively. Table 6 shows the comparison of recently reported LNA.

CONCLUSION

The single LNA cascaded with cascoded LNA amplifier using inductive drain feedback was successfully designed, and developed compliant with

Table 5: The S-parameters output for comparison of topology LNA

S-parameter	Single LNA	Cascoded LNA	Single LNA cascaded with cascoded LNA
Input reflection S_{11} dB	-14.77	-17.08	-10.65
Output reflection S_{22} dB	-14.69	-11.50	-20.02
Forward transfer S_{21} dB	17.01	26.58	43.94
Return loss S_{12} dB	-20.53	-30.59	-52.23
NF dB	0.87	0.71	0.61
BW MHz	1.08	1.60	1.24
Stability (K)	1.00	1.04	1.35

Table 6: Comparison of recently LNAs

S-parameter	This work	Kim *et al*. (2007)	Othman *et al*. (2012)
Topology	Single LNA cascaded with cascoded LNA	2 stages cascoded	Cascaded LNA
Input reflection S_{11} dB	-10.65	<-7	-22.540
Output reflection S_{22} dB	-20.02	<-7	-36.700
Forward transfer S_{21} dB	43.94	20.4	36.100
Return loss S_{12} dB	-52.23	-	-40.400
NF dB	0.61	3.3-6.4	1.171
BW GHz	1.24	3.4-8.2	-
Stability (K)	1.35	-	1.492

the IEEE standard 802.16 WiMAX. Observations made from the results of S-parameters in the single LNA cascaded with cascoded LNA amplifier is better than the predetermined specifications listed in Table 2. The double-stage cascoded LNA amplifier designed achieved the lowest noise figure and high gain due to the noise optimization in the implementation of input matching using passive element CA 11, inductive L 15 peaking structure and inductive drain feedback L26. Recorded result for single LNA cascaded with cascoded LNA amplifier observed provide the gain S21 43.94 dB at frequency of 5.8 GHz. While the input reflection loss S11 -10.65 dB and, the output reflection loss S22 was -20.02 dB. The S12 return loss was -52.23 dB. The stability (K) and Noise Figure (NF) were 1.35 and 0.61 dB, respectively. In conclusion, it has been shown that by using a single LNA cascaded with cascoded LNA amplifier, a minimum noise figure, higher gain, and wider the bandwidth can be obtained and which are better than the recent research (Kim *et al*., 2007) and (Othman *et al*., 2012).

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