AN INPUT MATCHED X-BAND BALANCED LOW NOISE AMPLIFIER DESIGN AND IMPLEMENTATION USING DISCRETE TRANSISTORS

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By

Çağdaş Ballı

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

AN INPUT MATCHED X-BAND BALANCED LOW NOISE AMPLIFIER DESIGN AND IMPLEMENTATION USING DISCRETE TRANSISTORS

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M.S. in Electrical and Electronics Engineering

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X-Band, which is defined as the frequency range from 8 GHz to 12 GHz by IEEE, is used for the applications such as satellite communications, radar and space communications. These applications require an input matched, high gain and low noise amplifier as a front-end component in their receiver chains. In this work, an input matched X-Band balanced low noise amplifier is designed and implemented by using GaAs HJ-FET transistor. Measurements of the fabricated amplifier show a maximum noise figure of 1.74 dB, a minimum gain of 12.1 dB and a minimum input return loss of 11.4 dB from 8.2 GHz to 8.4 GHz.

Keywords: low noise amplifier, balanced amplifier, noise figure.

ÖZET

AYRIK TRANSİSTÖRLER KULLANILARAK X-BANTTA GİRİŞ EMPEDANS UYUMLU, DENGELİ VE DÜŞÜK GÜRÜLTÜLÜ YÜKSELTEÇ TASARIMI VE GERÇEKLENMESİ

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IEEE tarafından 8 GHz ile 12 GHz arasında tanımlanmış frekans aralığı olan X-Bant, uydu haberleşme, radar ve uzay haberleşme gibi uygulamalar tarafından kullanılan bir banttır. Bu uygulamalar, almaç zincirinde uç eleman olarak, giriş empedans uyumlu, yüksek kazançlı ve düşük gürültülü yükseltece gerek duymaktadır. Bu çalışmada, X-Bantta giriş empedans uyumlu, dengeli, düşük gürültülü yükselteç tasarlanmış ve gerçeklenmiştir. Üretilen yükselteç, 8.2 - 8.4 GHz bandında en fazla 1.74 dB gürültü figürü gösterir iken, en az 12.1 dB kazanç ve en az 11.4 dB giriş geri dönüş kaybı göstermektedir.

Anahtar sözcükler: düşük dürültülü yükselteç, dengeli yükselteç, gürültü figürü.

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Chapter 1

Introduction

X-Band is defined as the frequency range from 8 GHz to 12 GHz by IEEE. Well-known applications in X-Band frequencies are satellite communications, radar and space communications. In these applications, low noise amplifiers (LNA) have a crucial role among the RF blocks in a receiver chain. They are expected to amplify received signals such that the effect of the noise of subsequent stages are minimized while maximizing Signal-to-Noise Ratio (SNR) by contributing minimum amount of noise. In addition, they should be stable for the large range of load and source impedances and have high input return loss over the frequency range of operation.

GaAs FET devices are commonly used in the design of low noise amplifiers because of its low noise and reasonably high gain at high frequencies. Another advantage of using GaAs is to have better radiation hardness which is significant for aerospace and military applications [1].

Satellite and space applications bring the need for low noise amplifiers which have low noise figure, high gain and low input VSWR. Usually there is a trade-off between the minimum noise figure and low input VSWR. Depending on the application, an optimization for noise figure and gain can be considered. However, simultaneously satisfying both of the requirements without going into optimization would be a better solution.

In this thesis, an input matched X-Band balanced low noise amplifier is designed and implemented on RO4003 substrate with $\epsilon_r = 3.38$ and thickness of 20 mil. The design covers the frequency range from 8.2 GHz to 8.4 GHz. X to Ku-Band super low noise HJ-FET on GaAs substrate manufactured by NEC Electronics is used in the design. In addition to the balanced LNA, noise matched single-ended LNA is designed and fabricated in order to observe the implemented noise figure performance before the implementation of the balanced LNA. In the balanced LNA, design is separated into two parts which are active bias circuit and RF part. Lumped elements are used for the design of active bias circuit and both lumped and distributed elements are used for the design of RF part. Then, two parts are integrated in a silver coated aluminum housing which is specifically designed for this work. After having tested both the single-ended and balanced configurations, the results are evaluated and conclusions were drawn on which configuration would be better to use in demanding satellite applications.

In Chapter 2, low noise amplifier concepts are explained in detail such as equivalent noise temperature, noise figure, stability, linearity and input/output matchings. In addition, the working principle of the balanced topology is described. Since measurement accuracy plays a key role in determining the performance of LNA truly, noise figure measurement techniques are explained in detail as well.

In Chapter 3, firstly, the design and simulation of the single-ended LNA is explained. After then, the design and simulation of balanced LNA based on the single-ended LNA and Wilkinson power divider with 90 degree offset are explained. Moreover, EM-simulations are done to obtain more accurate results.

In Chapter 4, measurement setups are explained. After then, measurement and simulation results are compared. Measurement of single-ended LNA with an isolator is also included for the complete comparison.

Lastly, Chapter 5 concludes the thesis with a complete comparison of single-ended, balanced and single-ended with an isolator low noise amplifiers in terms of measured and simulated RF performances and cost.

Chapter 2

Background

2.1 Definition

Low noise amplifiers (LNAs) play a key role in receiver systems. Their main function is to provide enough gain to minimize the noise of subsequent stages while contributing a minimum amount of noise, thus preserving the required Signal-to-Noise Ratio (SNR) of the system to extremely low power levels. In addition, an LNA should be linear enough to handle large signals with minimal introduction of distortion to eliminate in and out of channel interference. Lastly, LNA must present a specific impedance, typically 50 Ω, to the input source especially when a filter, duplexer, etc. precedes the LNA. Thus, the key parameters for an LNA can be summarized as noise figure, gain, linearity and input matching.

2.2 Low Noise Amplifier Concepts

2.2.1 Equivalent Noise Temperature and Noise Figure

Amplifier noise power is the power measured at the output of an amplifier when there is no input signal applied to it. Total output noise power consists of amplified input noise power and noise power generated internally by the amplifier. It is possible to represent the added noise power by the amplifier as a noisy resistor at the input and make the amplifier noiseless. In other words, a noisy resistor can be used in modeling of noise power. This noise is known as thermal noise which is caused by random motion of electrons in the resistor due to thermal agitation [5, 6]. Available noise power of a resistor is given by

$$P_N = kTB$$

where k is a Boltzman's constant ($1.38 \times 10^{-23} J/K$), T is temperature in kelvins and B is the noise bandwidth in cycles/sec which is generally the bandwidth of device to be measured.

Equivalent noise temperature of a two-port device is defined as the increase in the temperature of the source resistance required to account for all of the noise contribution of the two-port device [8]. In other words, if a given noise source produces an available power of P_S watts in a bandwidth of B Hz, it can be modeled as an equivalent thermal noise source characterized by an equivalent noise temperature which is given by

$$T_e = \frac{P_S}{kB}$$

By using this definition, if the source resistor is at a physical temperature of $T_S = 0°K$, a noisy two-port, an amplifier for instance, can be modeled by a noiseless amplifier with an input resistor at an equivalent noise temperature which is given by

$$T_e = \frac{P_n}{G_A kB}$$

where P_n is the noise power generated only by the amplifier itself.

Total output noise power is obtained by adding amplified input available noise power to the noise power generated internally by the amplifier if they are uncorrelated. It can be expressed as follows:

$$P_{No,total} = G_A P_{Ni} + P_n = G_A k B (T_S + T_e)$$

where P_{Ni} is the input available noise power at a physical temperature of T_S.

In addition to equivalent noise temperature, a noisy two-port can be characterized through the concept of noise figure whose definition is the ratio of the total available noise power at the output to the output available noise power caused by thermal noise coming only from the resistor at the standard room temperature ($T_o = 290°K$). Thus, noise figure can be written as

$$F = \frac{P_{No,total}}{G_A P_{Ni}} = \frac{G_A P_{Ni} + P_n}{G_A P_{Ni}} = 1 + \frac{P_n}{G_A P_{Ni}} = 1 + \frac{T_e}{T_o}$$

or

$$T_e = (F - 1) T_o$$

Alternate definition of noise figure is a measure of the degradation between available signal-to-noise power ratio at the input and available signal-to-noise power ratio at the output, which is only valid when the input noise power, P_{Ni}, is equal to kT_oB and it can be written as

$$F = \frac{SNR_{in}}{SNR_{out}} = \left. \frac{P_{Si}/P_{Ni}}{P_{So}/P_{No}} \right|_{P_{Ni}=kT_oB}$$

It can be questioned that why there is a reference temperature value for the input noise source. The reason is simply found by assuming that there is no noise at the input of a two-port network which means $T_o = 0°K$, then input signal-to-noise ratio is equal to infinity and output signal-to-noise ratio is a finite number which means that noise figure definition does not give any reasonable result. Therefore, there must be a reference temperature value for the input noise source. In addition, it is interesting to note that the reason why $290°K$ is the reference temperature is simply that $kT = 4.00 \times 10^{-21} J$, which is suggested by Harald Friis[2].

In a typical microwave system, several stages are connected in cascade where each stage degrades signal-to-noise ratio by adding noise. Cascaded noise figure can be determined if the noise figure of each particular stage is known. For a cascade of n stages, overall noise figure can be written as [1]:

$$F_{cascade} = F_1 + \frac{F_2 - 1}{G_{A1}} + \frac{F_3 - 1}{G_{A1} G_{A2}} + \cdots + \frac{F_{n-1}}{G_{A1} G_{A2} \cdots G_{An-1}}$$

By using the definition given above, overall equivalent noise temperature for a cascade of n stages can be written as

$$T_{e,cascade} = T_{e,1} + \frac{T_{e,2}}{G_{A1}} + \frac{T_{e,3}}{G_{A1} G_{A2}} + \cdots + \frac{T_{e,n}}{G_{A1} G_{A2} \cdots G_{An-1}}$$

2.2.2 Stability

Stability is defined as the ability of an amplifier to maintain effectiveness in its nominal operating characteristics under different conditions [1]. If a negative resistance condition occurs at the input or output, reflection coefficients becomes

$$|\Gamma_{IN}| > 1$$

or

$$|\Gamma_{OUT}| > 1$$

Having reflection coefficients greater than unity means that reflected power is greater than the incident, therefore, instability, in other words, oscillation occurs. In addition, stability is frequency-dependent means that an amplifier can act as an oscillator for the out-of-band frequencies while maintaining its nominal characteristics for the intended frequency band. Therefore, it can be concluded that stability should be studied in detail.

Stability of an amplifier can be investigated either graphically using stability circles on Smith Chart or analytically using a set of mathematical conditions. In this work, to determine the degree of stability relative to other devices in addition to unconditional stability, stability is investigated using single parameter test criterion (μ-Parameter) with [1]:

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

and

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

For unconditional stability, the following criteria must be satisfied:

$$\mu > 1$$

To make an amplifier unconditionally stable, loss should be introduced. Since the loss at the input significantly increases the noise figure of an amplifier, parallel or series resistors should be placed at the output of an amplifier.

2.2.3 Linearity

1-dB compression point, P_{1dB}, and third-order intercept point, $IP3$, are commonly used as linearity measures of an amplifier. 1-dB compression point is defined as the power level where the gain drops by 1 dB. This point is usually used to determine the linear output power level and it is more important for power amplifier characterization rather than low noise amplifier characterization [3]. In addition, 1-dB compression point is referred to either output or input.

Operating an amplifier under large-signal conditions causes distortion in the output signal and this distortion causes new frequencies to appear at the output signal. These new frequencies are called as harmonics for a single sinusoidal signal. When input signal consists of two or more sinusoids, these new frequencies are called as intermodulation products which are present along with harmonics. It can be easily seen that all additional frequencies can be filtered out in narrow-band amplifiers except the intermodulation products $2f_1 - f_2$ and $2f_2 - f_1$ due to the fact that they are very close to the fundamental frequencies and hence fall within the amplifier bandwidth. This effect is called third-order intermodulation distortion. It is important to note that third-order intermodulation products are significant for amplifiers because they set the upper limit on the dynamic range [1].

The third-order intercept point which is used to calculate the levels of the third order intermodulation products is defined as a hypothetical intercept point where the first-order and third-order powers are equal [4]. This intercept point is specified for either output or input.

2.2.4 Input and Output Matching

Since the first aim of LNA design is to obtain minimum noise figure, input matching should be done accordingly. For an amplifier, there is an optimum source impedance, Γ_{opt}, which leads to minimum noise figure. In order to obtain minimum noise figure, input impedance of an amplifier should be matched to this optimum source impedance value. It is important to note that, however, optimum source impedance that gives minimum noise figure is not necessarily the optimum impedance for the maximum power transfer [2]. Therefore, one must sacrifice the power gain, and therefore return loss, to obtain minimum noise figure, and vice versa in order to optimize output signal-to-noise ratio unless those impedances are same by coincidence.

In addition to obtain minimum noise figure, one of the other challenges in LNA design is to obtain the maximum available gain. Therefore, conjugate matching should be done at the output of the amplifier in order to get the best S/N at the output of the system.

2.3 Balanced Amplifier

One of the commonly used techniques for obtaining large bandwidth and good input and output VSWR is the balanced amplifier topology [7, 12]. It also provides better stability and higher linearity compared to single-ended amplifiers. It consists of two identical amplifiers and two 90° hybrid couplers as shown in Figure 2.1. Firstly, the input power is split into two with a phase difference of 90°. After amplifier stage, amplified signals are recombined in phase by the output hybrid coupler. For the reflected signals from the amplifiers, they are cancelled out at the isolating resistor due to 180° phase difference between the branches caused by the 90° offset line. Thus, input is matched to 50 ohm without any matching network. This means that input matching network can be designed regardless of the input return loss since it is already matched.

In this work, a 3 dB Wilkinson power divider with 90° offset line is used for hybrid coupler but it should be known that it can be also realized by a 3 dB Lange coupler or a 3 dB branch-line coupler.

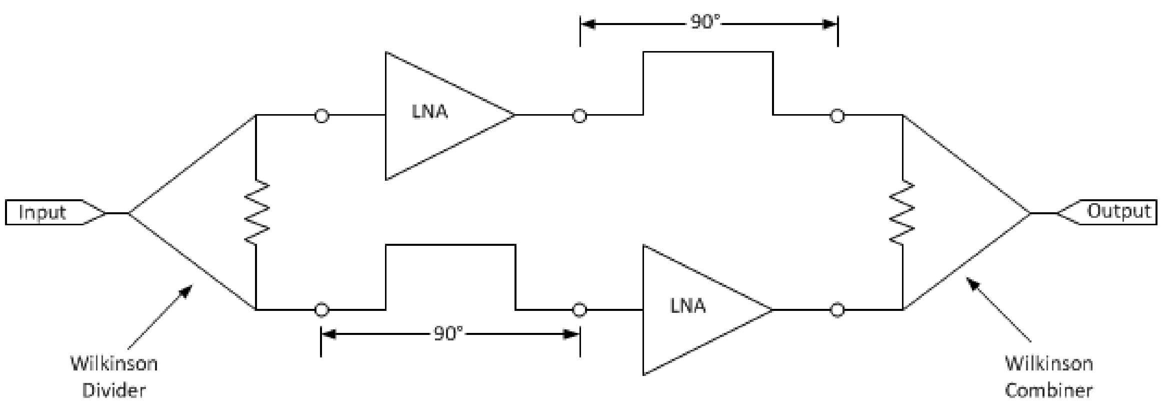


Figure 2.1: Balanced amplifier configuration

In a single-ended amplifier, it is notably hard to achieve minimum noise figure and minimum VSWR simultaneously as indicated in Section 2.2.4. Nonetheless, minimum noise figure can be obtained without sacrificing VSWR by implementing inductive source degeneration or balanced amplifier topology [15]. Inductive source degeneration technique is more useful at low frequencies because it becomes difficult to control the source inductance as frequency increases. Uncontrolled source inductance can make the circuit unstable and lead oscillations [19]. However, it is possible to use this technique in MMIC applications at high frequencies [16]. Thus, it is more reasonable to implement balanced amplifier topology when discrete components are used. In the balanced topology, since reflected signals from the amplifiers on each branch are cancelled at the termination port of the coupler or the isolation resistor of the Wilkinson divider, the input matching of the balanced amplifier depends only the input matching of the coupler [12]. Thus, it provides the possible designing of the amplifier simultaneously for minimum noise figure and minimum VSWR without compromise. If the couplers and amplifiers have similar characteristics and the loss of the couplers are ignored, noise figure of the balanced amplifier is the same with the single-ended amplifier while showing the matched load to the input [11]. Furthermore, it is also important to note that balanced amplifiers are more stable compared to the single-ended amplifiers because reflections are absorbed by the terminations of the couplers.

In addition, gain of the balanced amplifier is the same with the single-ended amplifier except for the additional path losses if the gain of the each amplifier is assumed to be the same. Moreover, it will still operate with 6 dB less gain despite the fact that one of amplifiers fails. Another key thing to remember is the fact that it becomes advantageous to use balanced amplifiers instead of the single-ended amplifiers in terms of intermodulation and gain compression since the signal power is shared equally between two branches and then recombined by the output hybrid coupler in balanced amplifier topology therefore having 3 dB higher OIP_3 and P_{1dB} values compared to the single-ended amplifiers [12].

All things considered, it seems reasonable to implement balanced amplifier topology for the design of low noise amplifier if input reflection distortion and redundancy are required parameters.

2.4 Simulation Techniques Used

In order to succeed in a complete LNA design with minimum iterations, advance simulation techniques must be used. In this work, all simulations are made by using Advance Design System (ADS) by Agilent.

Scattering parameters are used to characterize high frequency microwave components. In other words, S-Parameters provide a complete description of the network consisting of N-ports. All of the components, resistors, capacitors, transistors, etc., used in this work have S-Parameters which are provided by their manufacturers in *.s2p file format. S-Parameter file of the transistor also includes the noise parameters which enable the noise calculations.

2.5 Noise Figure Measurement Techniques

2.5.1 Y-Factor Method

Y-factor method is commonly used in the measurement of noise figure. In this method, there are two matched loads at significantly different temperatures. The input of the Device under test (DUT) is connected to these matched loads respectively and then output power is measured for each termination. Then, unknown equivalent noise temperature (T_e) of DUT can be obtained through Y-factor which is defined by [1]:

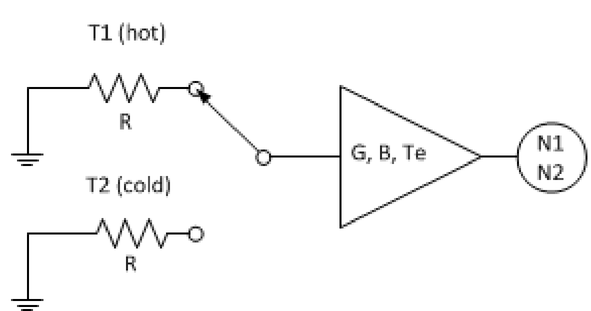


Figure 2.2: Y-factor method

$$Y = \frac{P_{No,1}}{P_{No,2}}$$

where

$$P_{No,1} = G_A kB(T_1 + T_e)$$

$$P_{No,2} = G_A kB(T_2 + T_e)$$

Thus,

$$Y = \frac{T_1 + T_e}{T_2 + T_e}$$

$$T_e = \frac{T_1 - YT_2}{Y - 1}$$

It is important to note that two matched terminations must be at significantly different temperatures; otherwise, inaccurate results will be obtained. These different temperature are usually obtained from active noise source which provides specific noise power in a particular frequency range and they are characterized by their excess noise ratio (ENR) values versus frequency. ENR is defined as:

$$ENR = 10log_{10}\left(\frac{T_N - T_o}{T_o}\right)$$

where T_N is the equivalent noise temperature of the noise source in hot state and T_o is the equivalent noise temperature of a passive source at room temperature ($290°K$) in cold state.

Note that the definition of ENR assumes that the equivalent noise temperature of a noise source in cold state is always $290°K$. However, equivalent noise temperature in cold state may be hotter or colder than $290°K$ and in that case ENR value will not be correct and this leads to en error in noise figure because ENR values are always referenced to $290°K$. The physical temperature of the cold noise source should then be measured and the equivalent noise temperature of a noise source in cold state should be corrected. Temperature correction is mostly done by noise figure instruments [9].

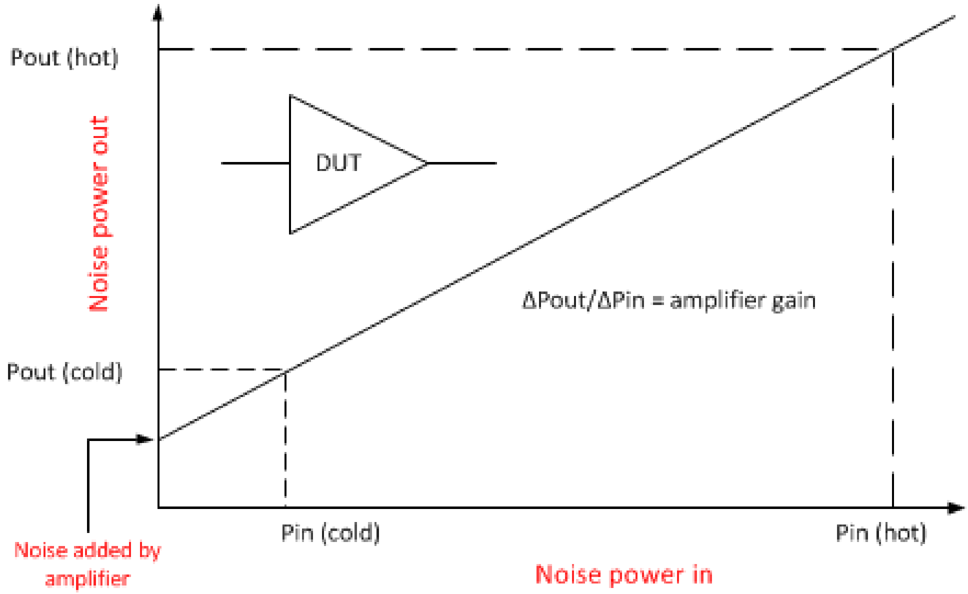


Figure 2.3: Graphical representation of Y-factor method

As it can be seen from Figure 2.3, two output noise power values must be known for the calculation of the noise figure.

Another key thing to remember is that there are several assumptions and uncertainties about the measurement equipment. Unfortunately, the accuracy of Y-factor method relies on these assumptions [10]. The first assumption is that noise source has a perfect 50 ohm match. In most cases, it can be considered as reasonable when the noise source is directly connected to the DUT. Yet it causes significant amount of error if there is coaxial or adapter between DUT and noise source. Second assumption, which is partially related to the first one, is that the output match of the noise source is insensitive to the state (hot/cold) changes. In other words, output impedance of the noise source does not change with diode on/off states because it is assumed that the output impedances of the biased and unbiased diode are the same which is not practical in reality. The last parameter which contributes the overall uncertainty is the ENR values. The uncertainty of the ENR values which is usually supplied by the manufacturer attributes to the error budget. Furthermore, it is crucial to use a low ENR noise source when the expected noise figure is low in order not to increase the noise power levels inside the noise figure instrument [9].

2.5.2 Cold Source Method

Instead of using two matched loads at significantly different temperatures, a single matched load at room temperature, which is the reason why the method is called as cold source, is used for the output noise power measurement. This output noise consists of the amplified input noise and the noise generated internally by the amplifier. If the gain of the DUT is accurately known, then the noise generated by the amplifier can be easily calculated. Vector network analyzer (VNA) is used for making the gain measurement with a high degree of precision.

As it can be seen from the Figure 2.4, a single output power measurement is enough for the calculation of noise figure thanks to known DUT gain in contrast to the Figure 2.3.

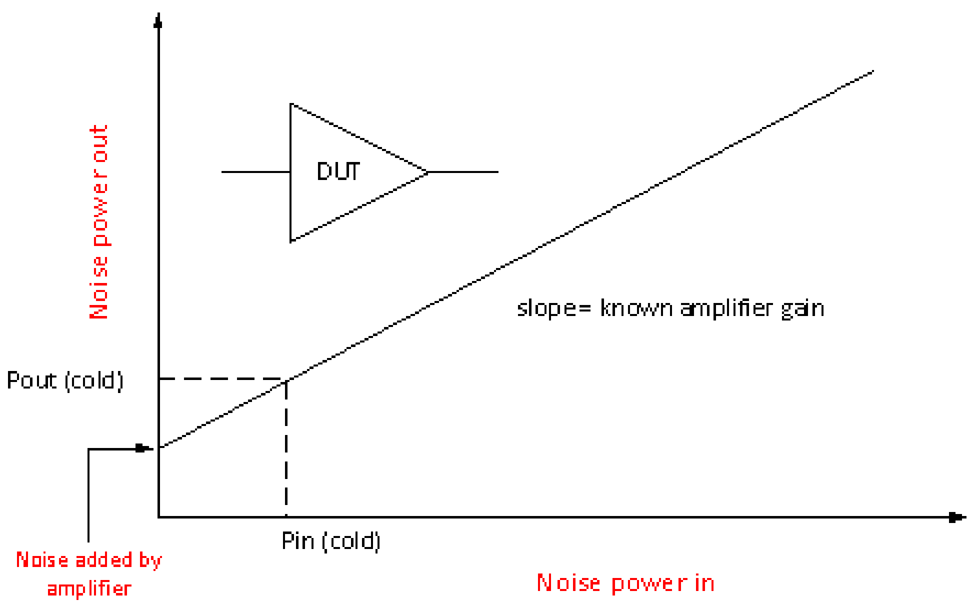


Figure 2.4: Graphical representation of cold-source method

Cold-source method presents a more accurate measurement compared to the Y-factor since it does not have the uncertainties that Y-factor method has but still it has some uncertainties such as the S-parameter uncertainty and the 50-ohm termination at the input of the DUT on which the error magnitude greatly depends. Although cold-source method has its own uncertainties, it has lower measurement uncertainty (0.2 dB) than the Y-factor method (0.5 dB) [10].

Chapter 3

Design and Simulation

3.1 Transistor Selection

Since noise parameters of a transistor plays a key role in the noise figure of a complete amplifier, transistor selection is an important step in laying the foundation of the design of low noise amplifier. In this work, N-channel HJ-FET NE3511S02 manufactured by NEC Electronics is used. It has a minimum noise figure of 0.26 dB and associated gain of 13 dB at 8.3 GHz when the drain voltage is 2 V and drain current is 10 mA.

In this work, a single-ended low noise amplifier is designed and simulated in ADS. As a second step, a balanced topology is implemented using the designed single-ended amplifier.

3.2 Single-Ended Low Noise Amplifier Design

3.2.1 Active Bias Circuit

Bias conditions for minimum noise figure and reasonable gain at X to Ku-Band are suggested by the manufacturer. In this work, these conditions are provided by using an active bias circuit. Although the active bias circuit occupies more space, has higher cost and complexity, using active bias is still reasonable since it is insensitive to transistor parameter variations which can easily affect the noise figure [13]. For instance, change in I_D of the transistor directly affects the noise figure. When I_D increases, active bias circuit reduces the V_{GS} and therefore reduces I_D.

A general purpose PNP transistor, MMBT2907A is used for the design of active bias circuit. In order to simulate the active bias circuit, spice models of both NE3511S02 and MMBT2907A provided by their manufacturers are used. Active bias circuit which provides the drain voltage of 2 V and drain current of 10 mA is shown in Figure 3.1.

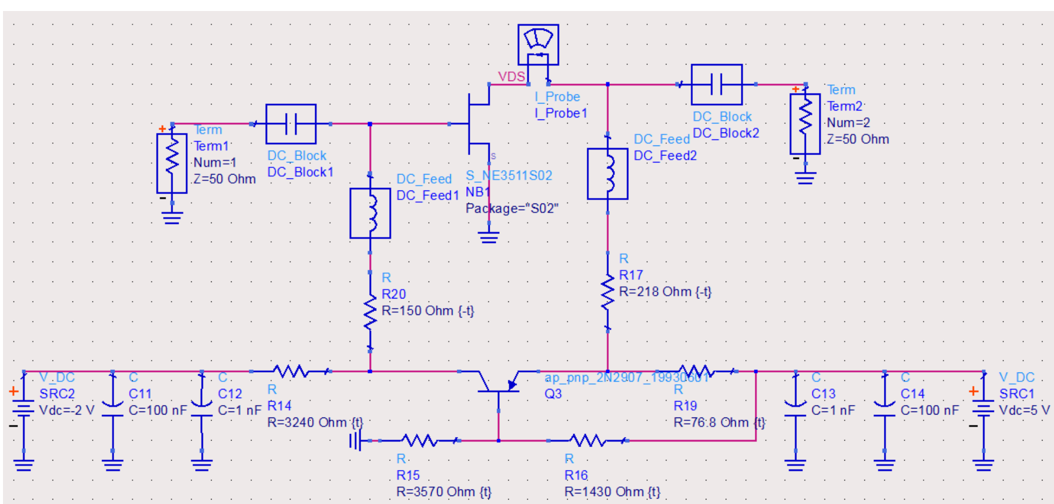


Figure 3.1: Active bias circuit

Active bias circuit is connected to the RF part of the amplifier through a bias tee which should be properly designed to isolate RF and bias. Inductors are commonly used as RF-choke. Their self-resonance frequency should be higher than the frequency of operation. Otherwise, they may act like a capacitor rather than an inductor. For this reason, high impedance $\lambda/4$ length transmission lines are generally used as RF-chokes at high frequencies rather than lumped elements. A shorted $\lambda/4$ length transmission line acts as an open circuit at the frequency of operation. Another benefit of using shorted $\lambda/4$ length tranmission line is that they also short out the second harmonic. Furthermore, radial stubs are also used to improve isolation.

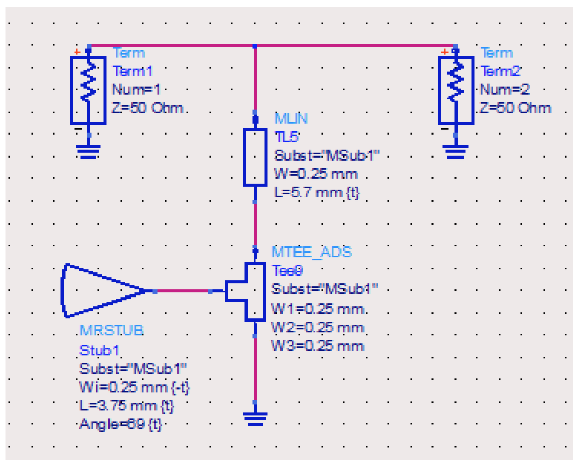


Figure 3.2: Bias tee

3.2.2 Stability

In order to stabilize the circuit unconditionally, μ-parameter method is used in a wide frequency range. From this point on, all simulations except active bias are done with the S-parameters of the transistor because using measured data is more reliable. The simulated μ-parameter for the circuit given in Figure 3.1 is shown in Figure 3.3. As it can be shown from the figure, circuit is conditionally stable before stabilization.

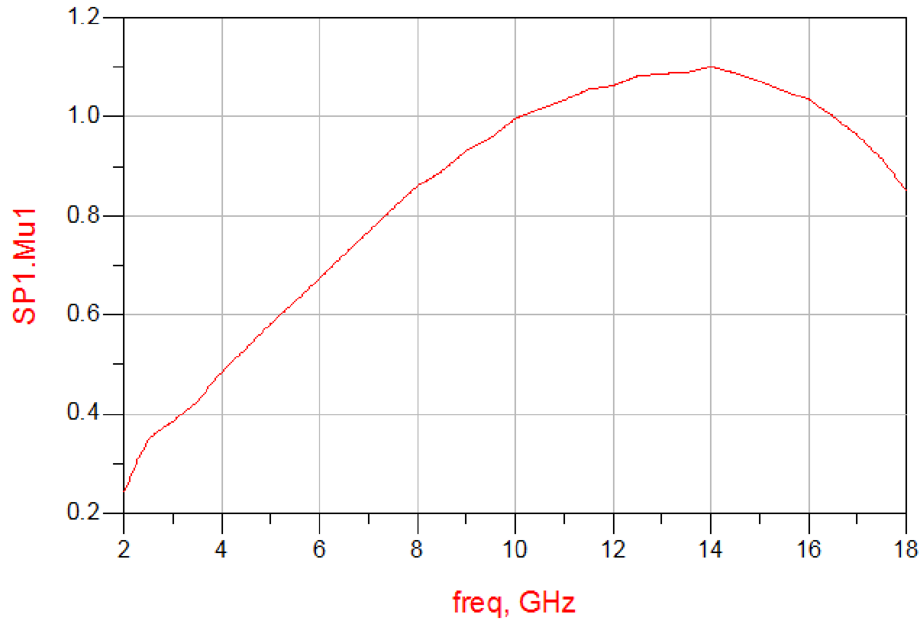


Figure 3.3: μ-parameter before stabilization

Usually a series resistor is used for stabilization. It is important to note that, however, resistor causes the loss in the circuit which significantly degrades the noise figure. Therefore, it must be placed after the transistor and a capacitor must be placed in parallel with it so that the capacitor shorts out the resistor at the frequency of operation. In addition, S-parameters of these components are used in the simulation for more reliable results. Schematics of the circuit after stabilization is given in Figure 3.4. The simulated μ-parameter for this circuit is shown in Figure 3.5. It can be concluded that the circuit is unconditionally stable.

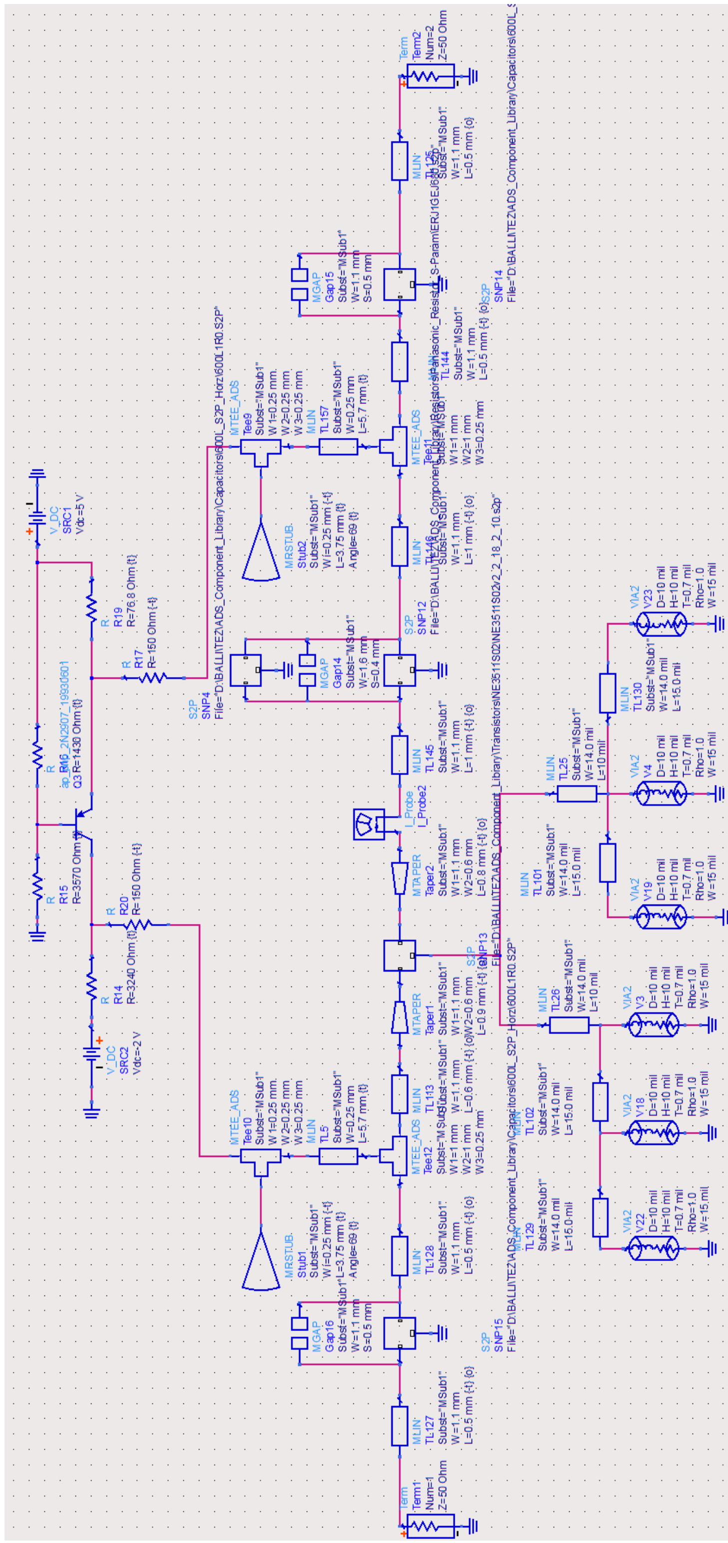


Figure 3.4: Schematics of the circuit after stabilization

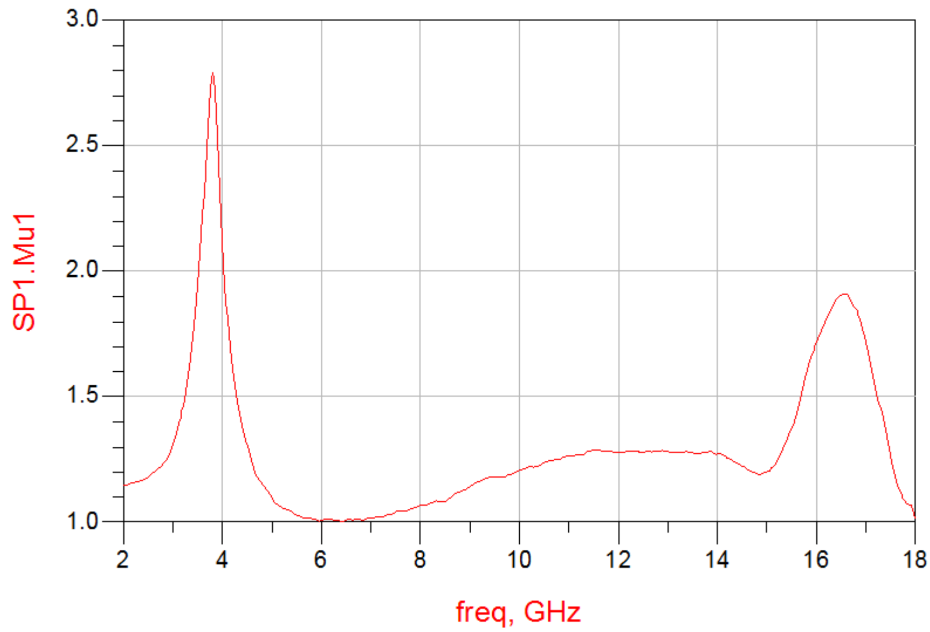


Figure 3.5: μ-parameter after stabilization

3.2.3 Input Matching Network

Input matching determines the noise figure, gain and input return loss of the amplifier. Since our goal is to achieve minimum noise figure which can be obtained from the transistor, the input impedance of the transistor should be matched to the optimum source impedance for the minimum noise figure which is provided by the manufacturer. As a result of noise matching that is regardless of input return loss, gain will be reduced.

S-parameter simulations are done for the design of input matching. The simulation results of unmatched circuit is shown in Figure 3.6. Red circles are the noise circles with 0.1 dB step and blue circles are the gain circles with 1 dB step. As it can be seen from the figure, the optimum source impedance for minimum noise figure and the impedance for maximum power transfer (conjugate matching) is far away from each other. Note that the impedance for maximum power transfer is obtained by using available gain circles.

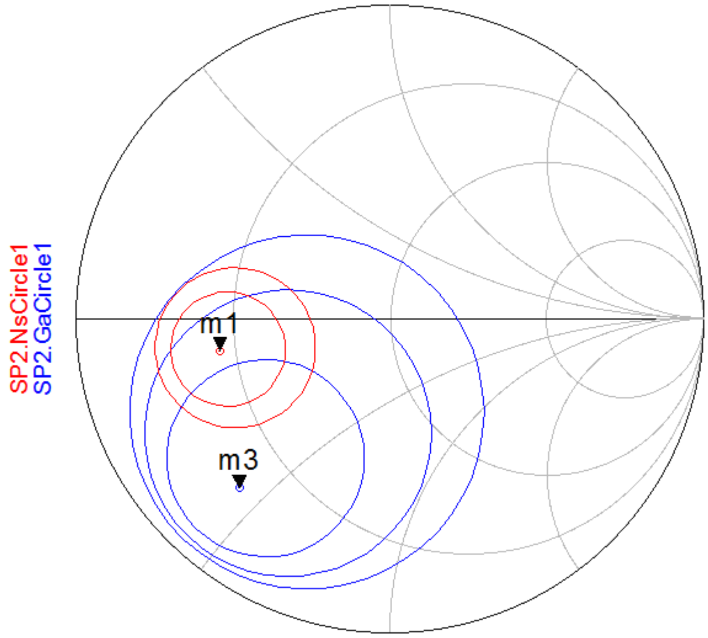


Figure 3.6: Noise and gain circles before input matching

Distributed elements are used for matching networks because lumped elements may degrade the RF performance at high frequencies. Moreover, using distributed elements simplifies the circuit implementation since they do not require soldering. Hence, input matching is realized by a series transmission line followed by an open stub shown in Figure 3.7. After the realization of the input matching, the source impedance is shown in Figure 3.8. As it can be seen from the figure, source impedance is matched to the optimum impedance for the minimum noise figure.

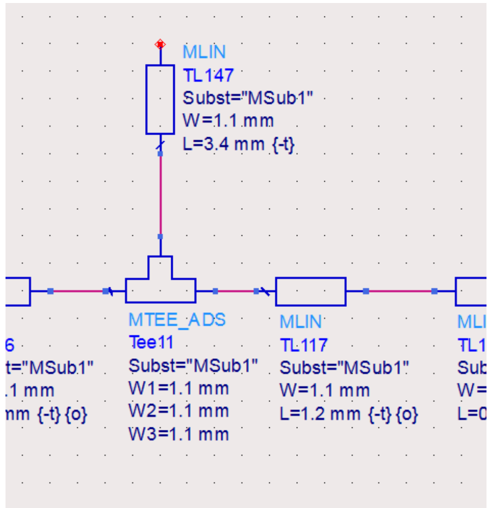


Figure 3.7: Input matching network

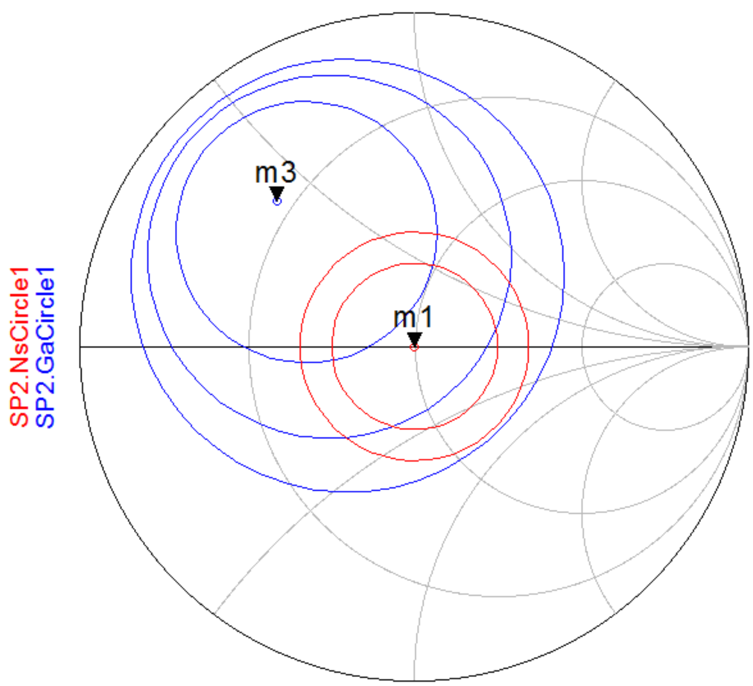


Figure 3.8: Noise and gain circles after input matching

3.2.4 Output Matching Network

Conjugate matching is implemented for maximum power transfer at the output side. The output matching network is realized by series transmission line followed by an open stub as it can be seen from Figure 3.9. Optimum source impedances for minimum noise figure and output impedances are shown in Figure 3.10 and Figure 3.11, before and after the realization of output matching network, respectively. As it can be seen from the results, output of the transistor is conjugately matched from 8.2 GHz to 8.4 GHz.

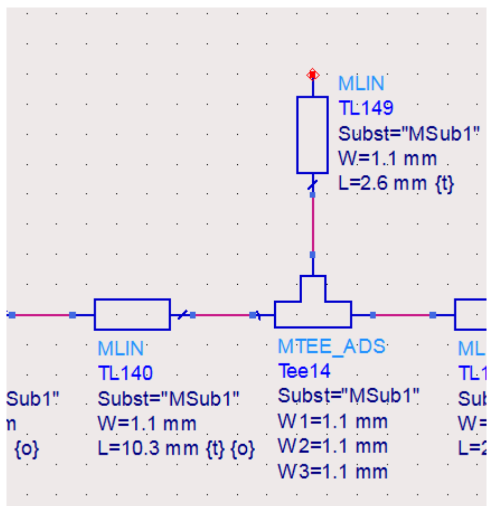


Figure 3.9: Output matching network

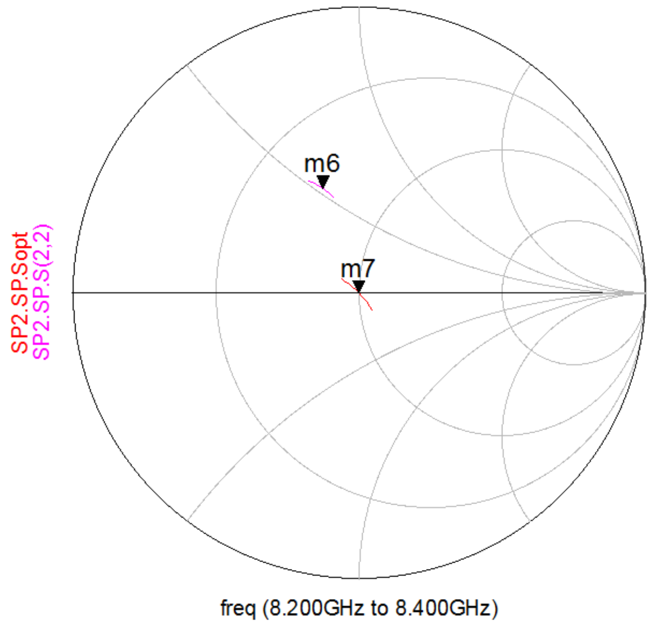


Figure 3.10: Output impedance before output matching

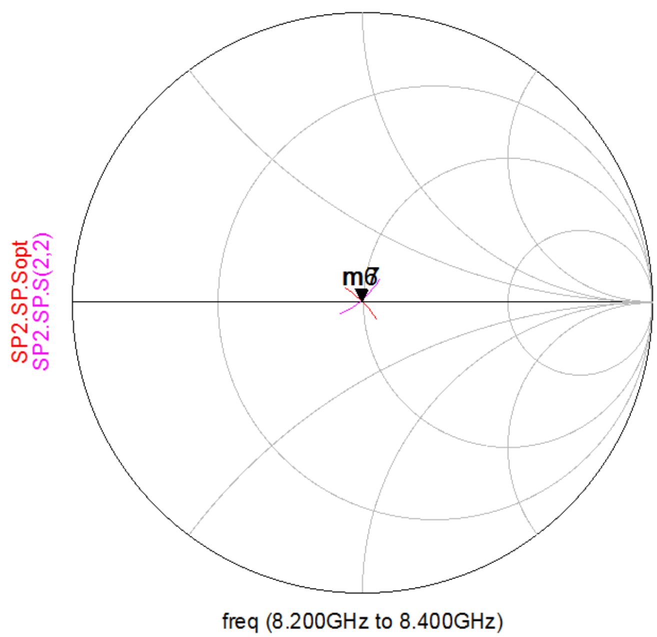


Figure 3.11: Output impedance after output matching

3.2.5 Final Design and Layout

Single-ended low noise amplifier is designed with linear simulations in ADS. In order to improve design performance and increase confidence, Momentum, which is a 3D planar electromagnetic (EM) simulator of ADS, is used for passive circuit modelling and analysis in the design. It uses frequency-domain Method of Moments (MoM) technology to accurately simulate complex EM effects including couplings and parasitics. Thus, the more accurate results can be obtained.

After some tuning and optimization in Momentum, design is completed and the final schematics including Momentum EM-model is shown in Figure 3.12. Stability, S-parameter and noise figure simulation results of this circuit are shown in Figure 3.13, 3.14 and 3.15, respectively. As it can be seen from the results, complete circuit is unconditionally stable while having a maximum noise figure of 0.54 dB, a minimum gain of 13.8 and a minimum input return loss of 5.7 dB.

PCB is also designed in Momentum. Rogers 4003 with 20 mil thickness is used. Final layout of the design is shown in figure 3.16. Note that thin lines with small gaps are added to the each open stub for tuning during real-time measurements.

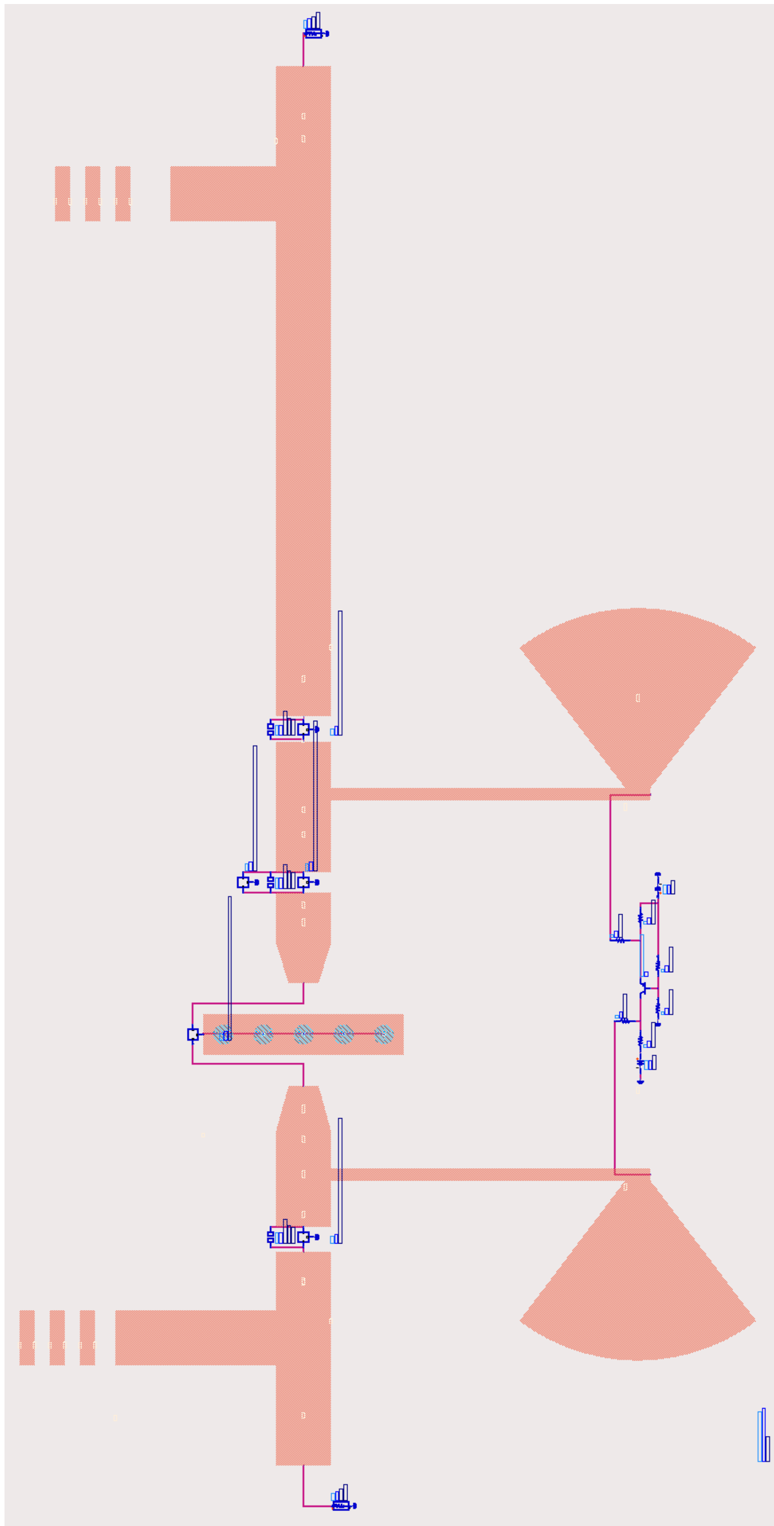


Figure 3.12: Complete schematics of the circuit including Momentum layout

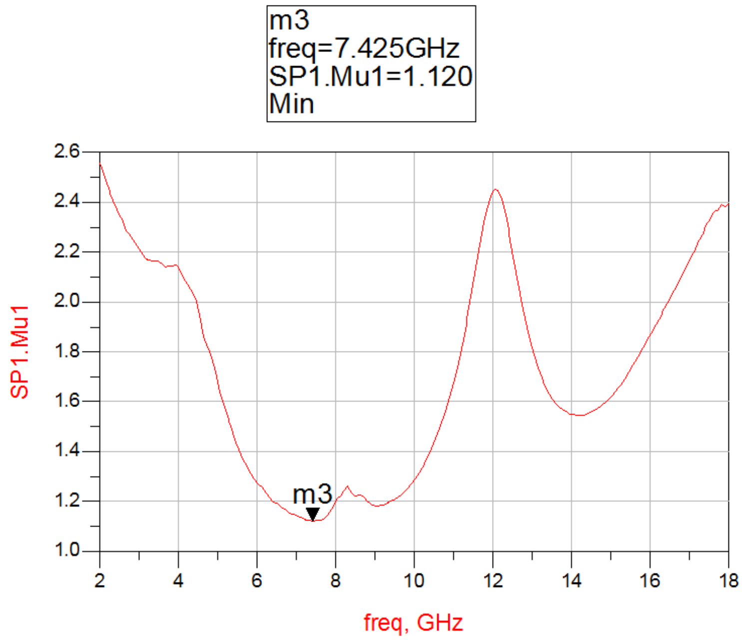


Figure 3.13: Simulated μ-parameter of the designed amplifier in Momentum

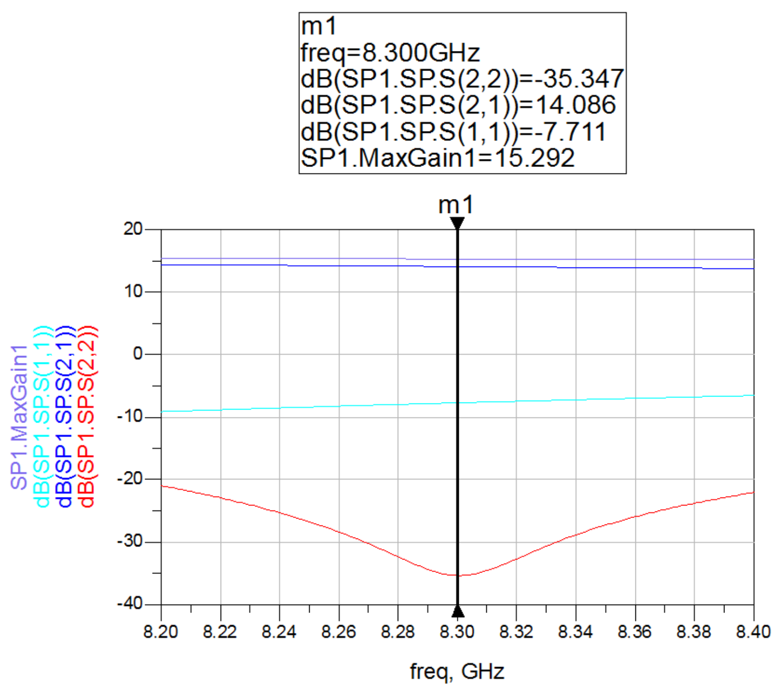


Figure 3.14: Simulated S-paramters of the designed amplifier in Momentum

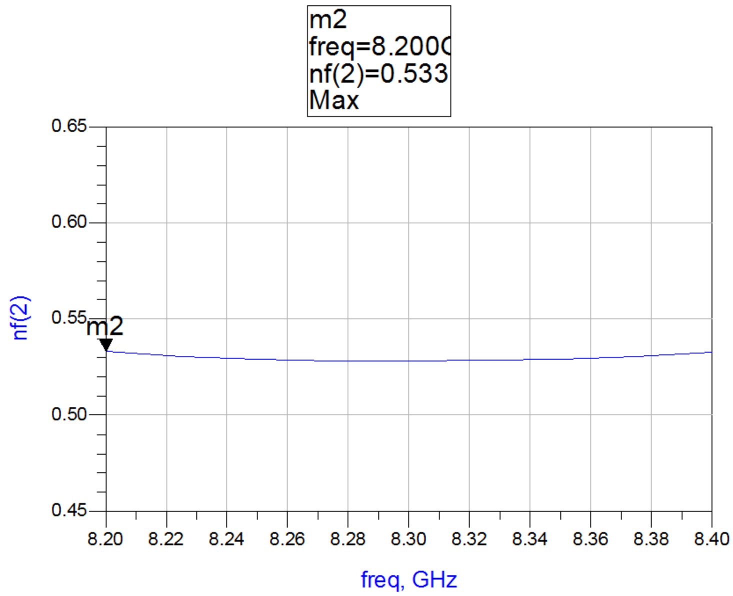


Figure 3.15: Simulated noise figure of the designed amplifier in Momentum

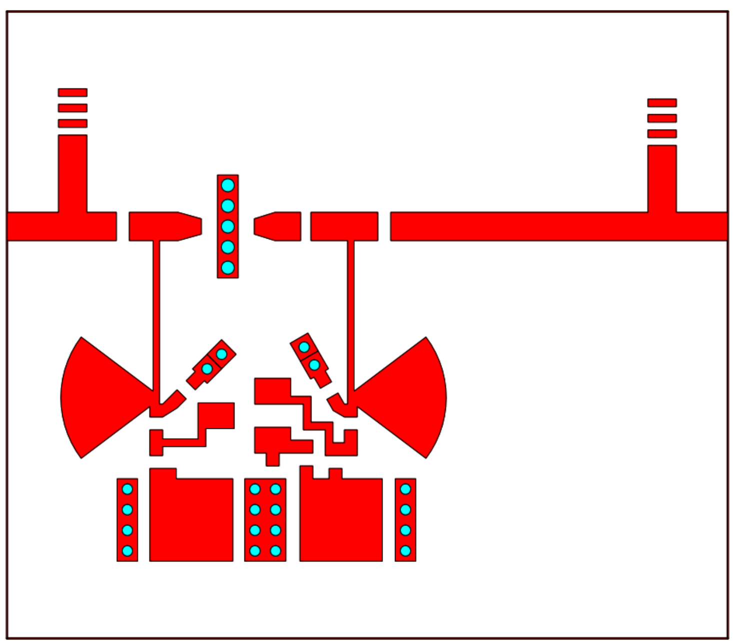


Figure 3.16: Final layout of the single-ended low noise amplifier

3.3 Balanced Low Noise Amplifier Design

3.3.1 Active Bias Circuit

Active bias circuit and bias tee designed for the single-ended design are used in the balanced amplifier because bias conditions of the transistors are same.

3.3.2 Stability

Since the designed single-ended circuit is already stable, there is no need to add more resistors for stabilizing the circuits in the balanced design. Thus, same stability resistors and capacitor are used for the balanced design.

3.3.3 Input Matching Network

In order to achieve minimum noise figure which can be obtained from the transistor, input impedance of the transistor should be matched to the optimum source impedance which is provided by the manufacturer. Since this matching is done for the single-ended design, there is no need to re-design it. Same matching network is used for the transistors on each branch.

3.3.4 Output Matching Network

Output matching network for the single-ended design is used in the balanced design as well because conjugate matching should be done for maximum power transfer.

3.3.5 Wilkinson Power Divider/Combiner

Wilkinson power divider with 90° offset is designed for the purpose of hybrid coupler. It can be also realized with branch-line or Lange coupler. There are many parameters which should be considered in the design of Wilkinson power divider but the most significant one is the phase unbalance. It is crucial to achieve minimum phase unbalance. Otherwise, reflections from the inputs of the amplifiers may not be terminated and cancelled out at the frequency of operation. In addition to phase unbalance, loss is also a significant parameter as the loss in front of the transistor is directly added to the noise figure. In order to accurately determine the phase unbalance and the loss, Wilkinson divider is designed and simulated by using Momentum. As it can be seen from the Figure 3.18, phase unbalance is approximately 3° peak-to-peak and maximum loss is 0.11 dB across the frequency band.

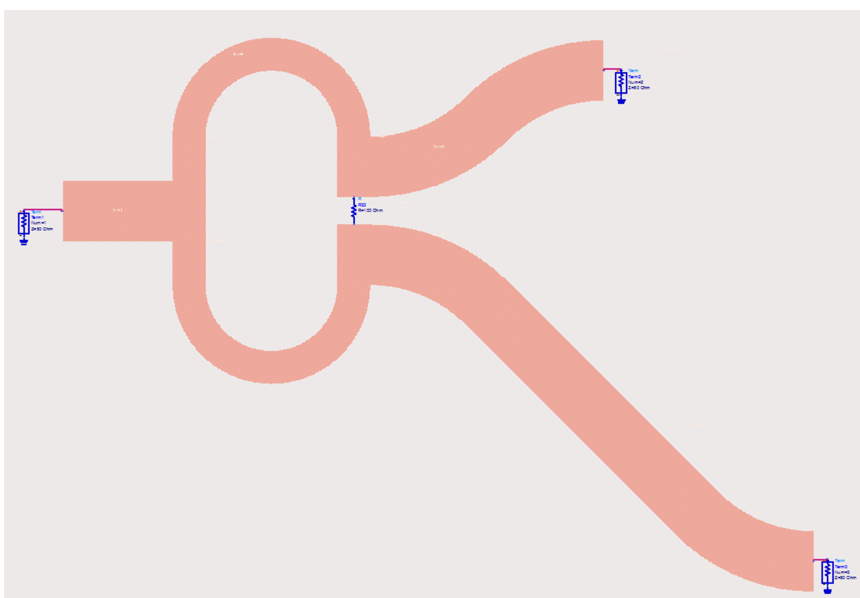
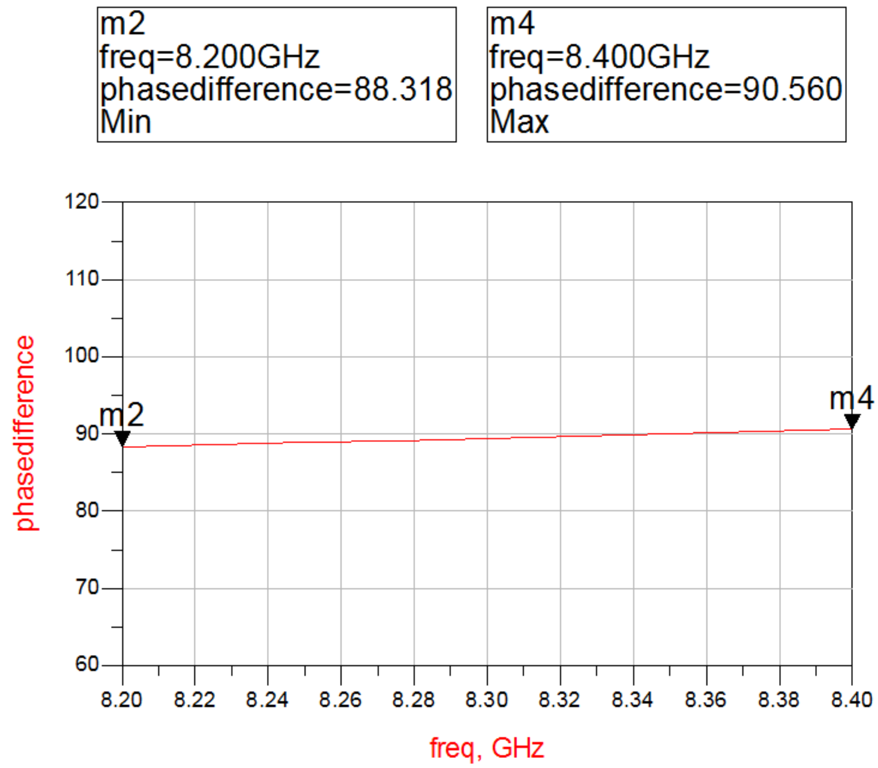
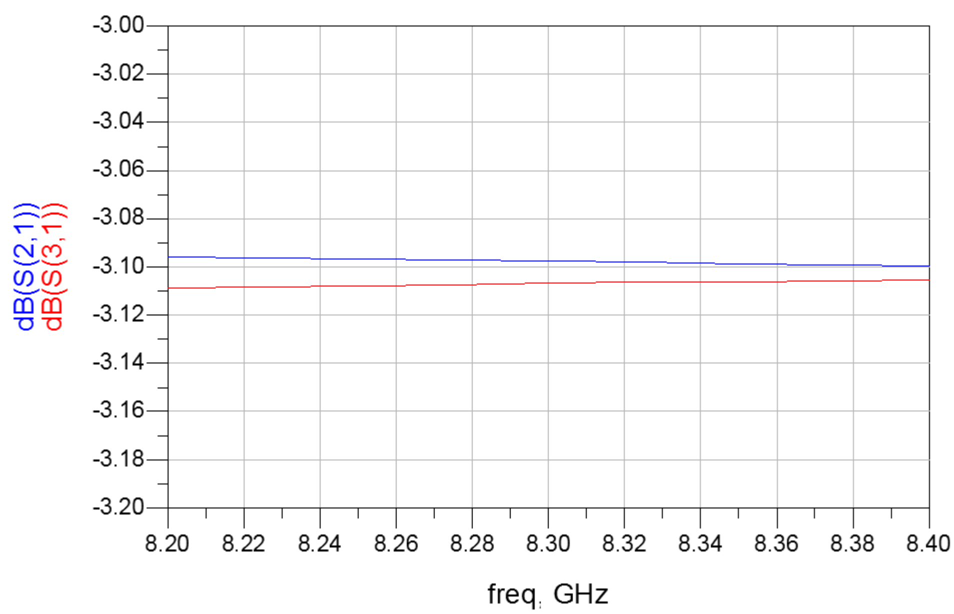


Figure 3.17: Schematics of the Wilkinson power divider



(a) Phase difference of the two arms



(b) Loss of the two arms

Figure 3.18: Simulation results of Wilkinson power divider

3.3.6 Final Design and Layout

After some tuning and optimization in Momentum, the design is completed and the final schematics of the balanced low noise amplifier including Momentum EM-model is shown in Figure 3.19. Input and output impedances and optimum impedance value for minimum noise figure of this circuit are shown on the Smith chart given in Figure 3.20. All of them are located at the center of the Smith chart. In addition, stability, S-parameter and noise figure simulation results of this circuit is shown in Figure 3.21, 3.22 and 3.23, respectively.

As it can be seen from the results, complete circuit is unconditionally stable while having a maximum noise figure of 0.63 dB, a minimum gain of 13.8 dB and a minimum input return loss of 31.2 dB. Note that gain is approximately the same with single-ended design. However, noise figure is increased by 0.1 dB due to the contribution of path loss caused by Wilkinson power divider. This small increment can be considered as the cost of obtaining low VSWR values in the design of low noise amplifiers with balanced topology.

PCB design is done by using Momentum. Rogers 4003 with 20 mil thickness is used as in the single-ended design. Final layout of the design is shown in figure 3.24. Note that thin lines with small gaps are added to the each open stub for tuning during real-time measurements as in the single-ended design. As it can be seen from Figure 3.24, active bias circuit is not included as in single-ended LNA. In balanced LNA, RF and bias circuits are separated for easy debugging. Final layout of active bias circuit is given in Figure 3.25.

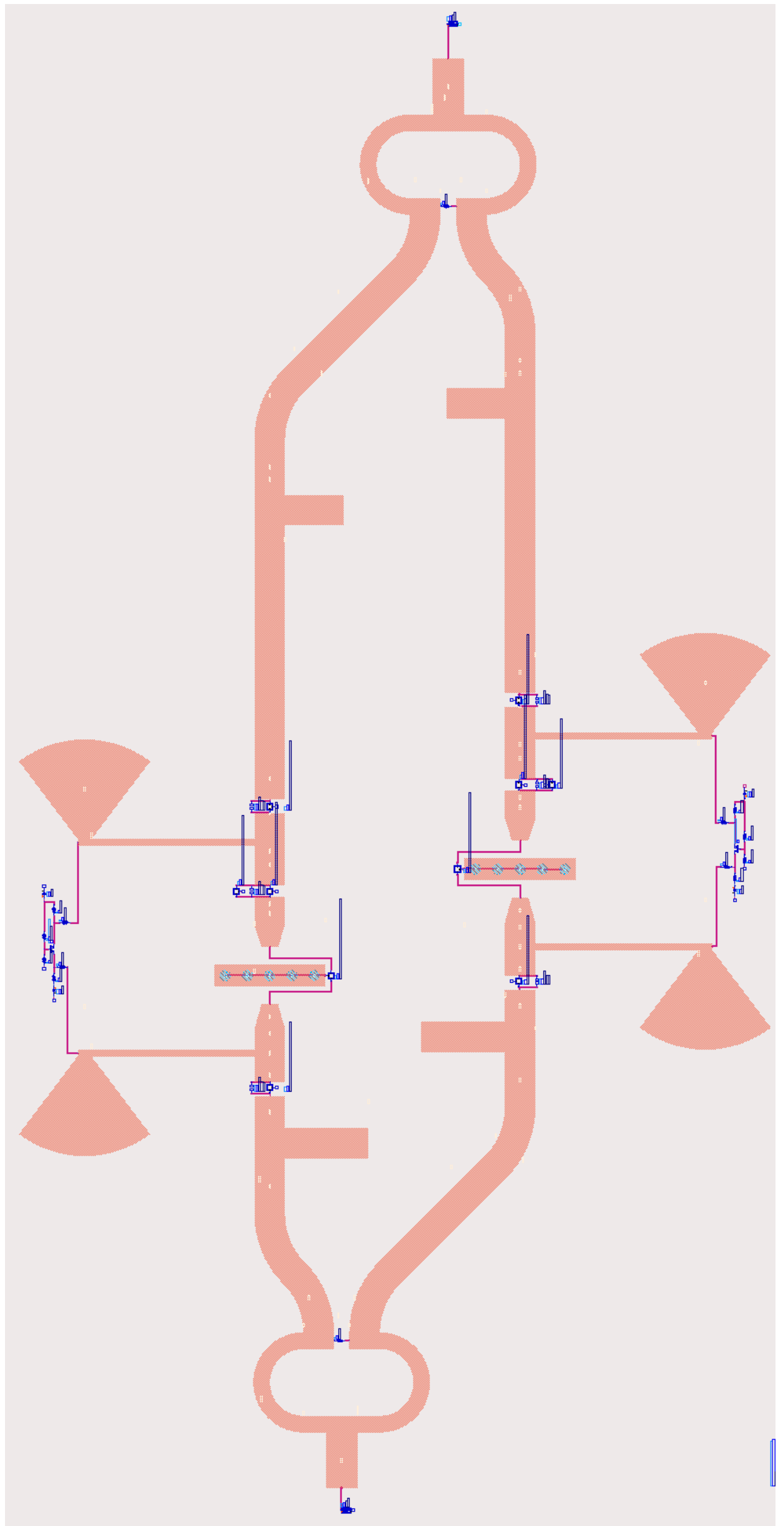


Figure 3.19: Schematics of the final design of the balanced low noise amplifier

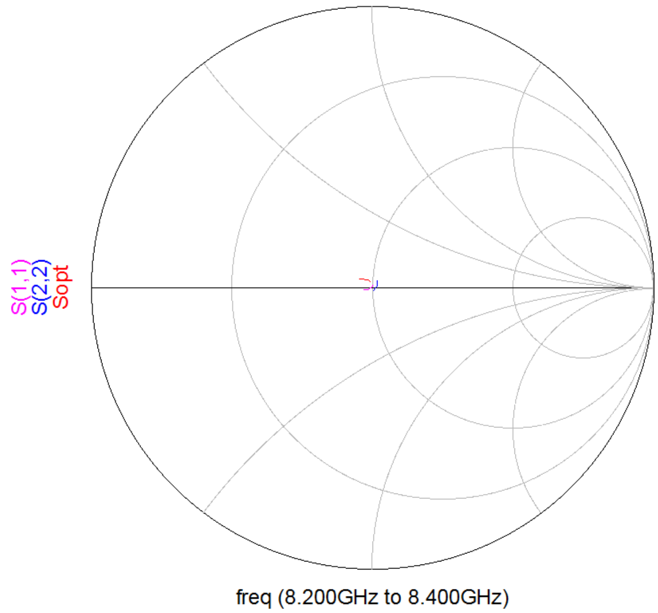


Figure 3.20: Input and output impedances of the balanced low noise amplifier

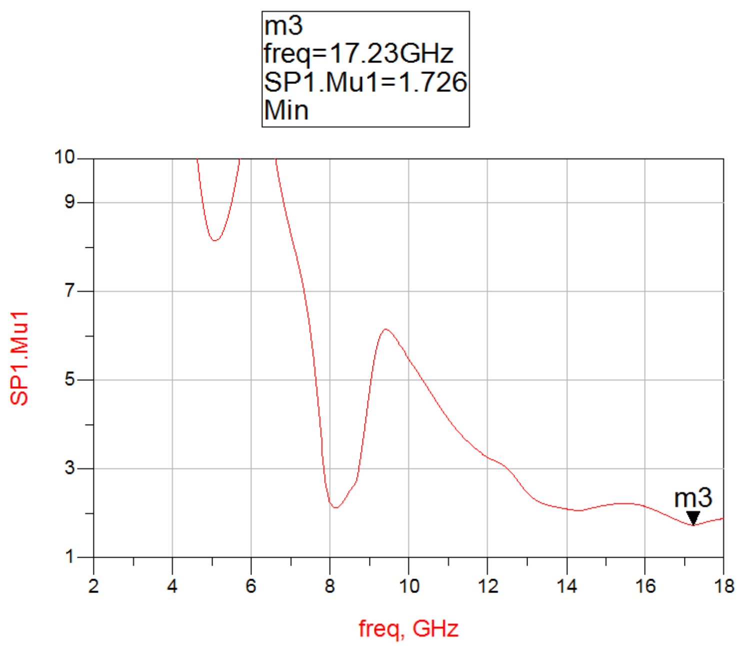


Figure 3.21: Simulated μ-parameter of the balanced low noise amplifier designed in Momentum

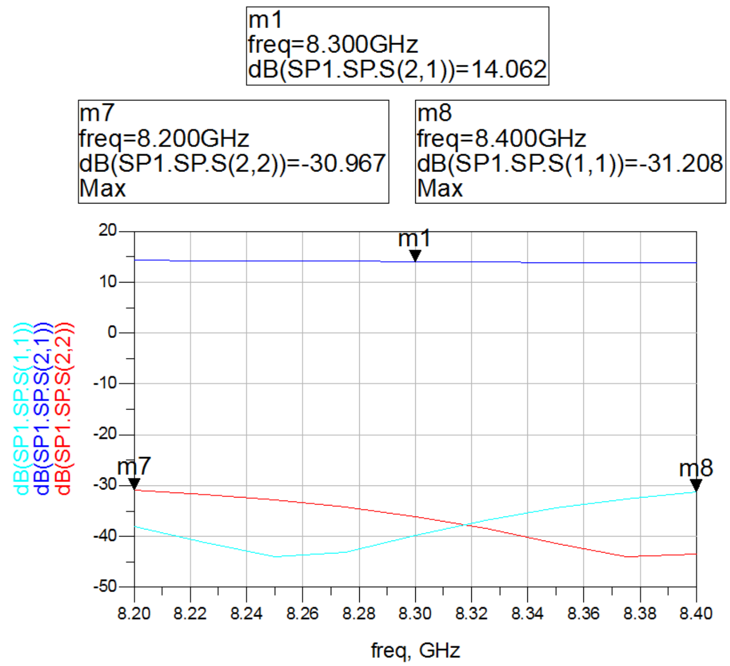


Figure 3.22: Simulated S-parameters of the balanced low noise amplifier designed in Momentum

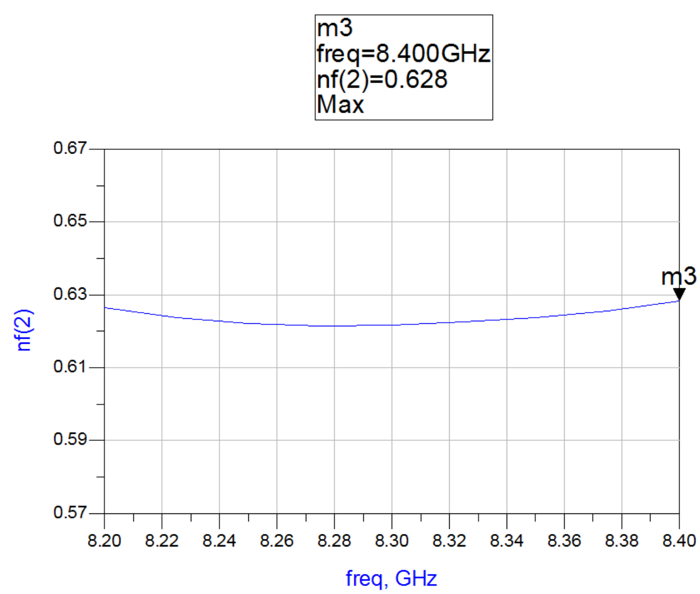


Figure 3.23: Simulated noise figure of the balanced low noise amplifier designed in Momentum

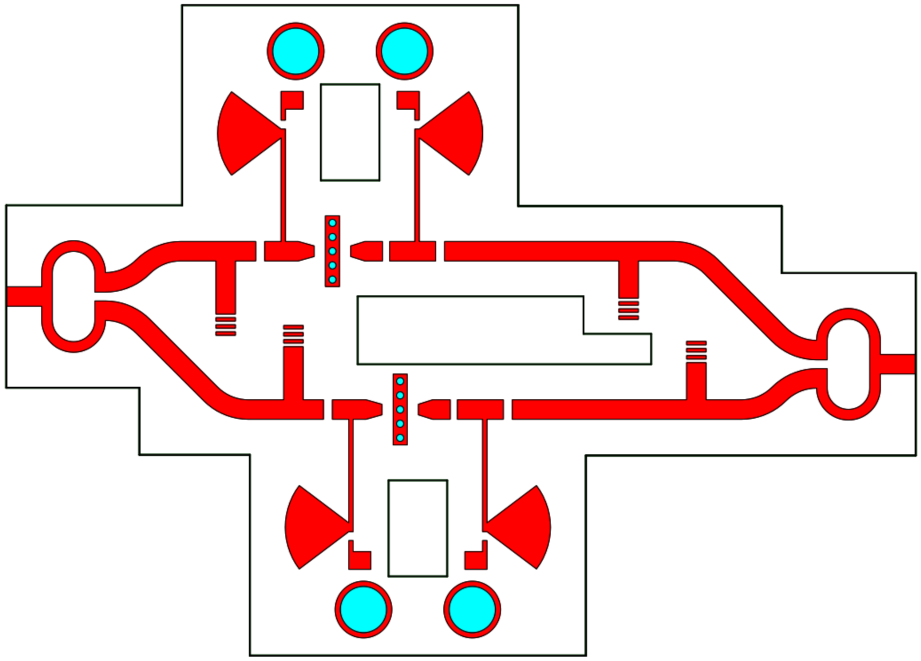


Figure 3.24: Final layout of the balanced low noise amplifier

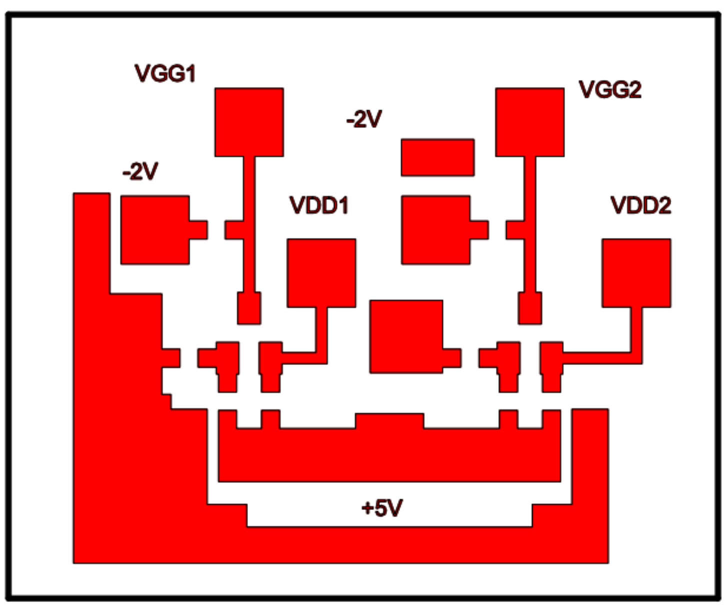


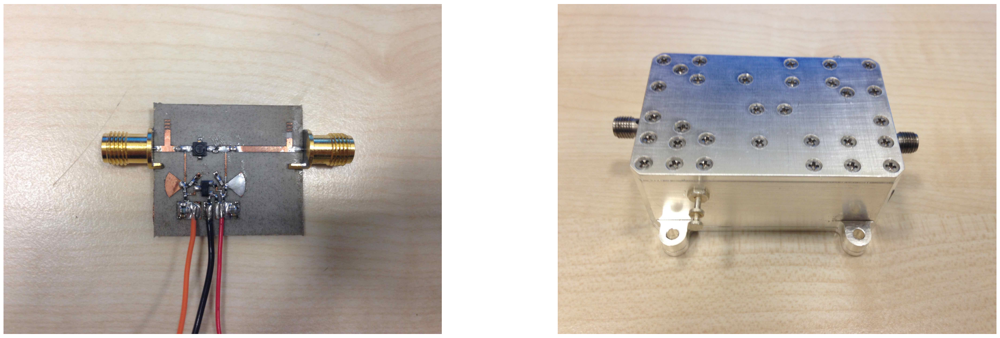
Figure 3.25: Final layout of the active bias circuit

Chapter 4

Measurements

4.1 Measurement Preparations and Setups

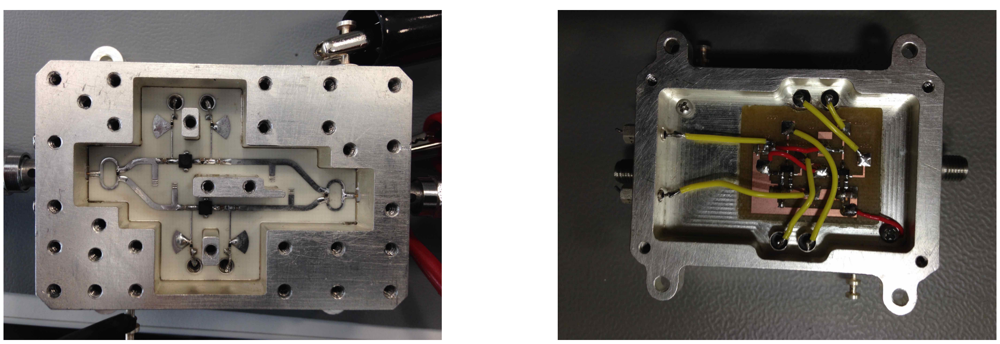
Firstly, single-ended LNA is mounted on the PCB and tested. After then, the balanced LNA is mounted on the PCB and then assembled as shown in Figure 4.1. In order to complete the design and implementation of an amplifier, metal housing must be provided to prevent possible interference and oscillations and avoid bending of thin PCB. Unusual shape of the PCB of balanced amplifier, which can be seen from Figure 3.24, is caused by the internal walls of the metal housing. These walls are placed intentionally and the cavity dimensions are minimized to avoid box resonances as much as possible.



(a) Single-Ended (b) Balanced

Figure 4.1: Fabricated and assembled PCBs

PCB of balanced amplifier is placed at the top side of the housing and the PCB of the active bias is placed at the bottom side of the housing. Silver epoxy is used for bonding the PCB to the housing. Top and bottom sides of the metal housing without covers are shown in Figure 4.2.



(a) Top side of the housing (b) Bottom side of the housing

Figure 4.2: Metal housing

4.1.1 S-Parameter Measurement Setup

S-Parameter measurements are done with Agilent PNA-X Network Analyzer as shown in Figure 4.3. Stimulus power is adjusted to -30 dBm so that the amplifier stays in linear region.

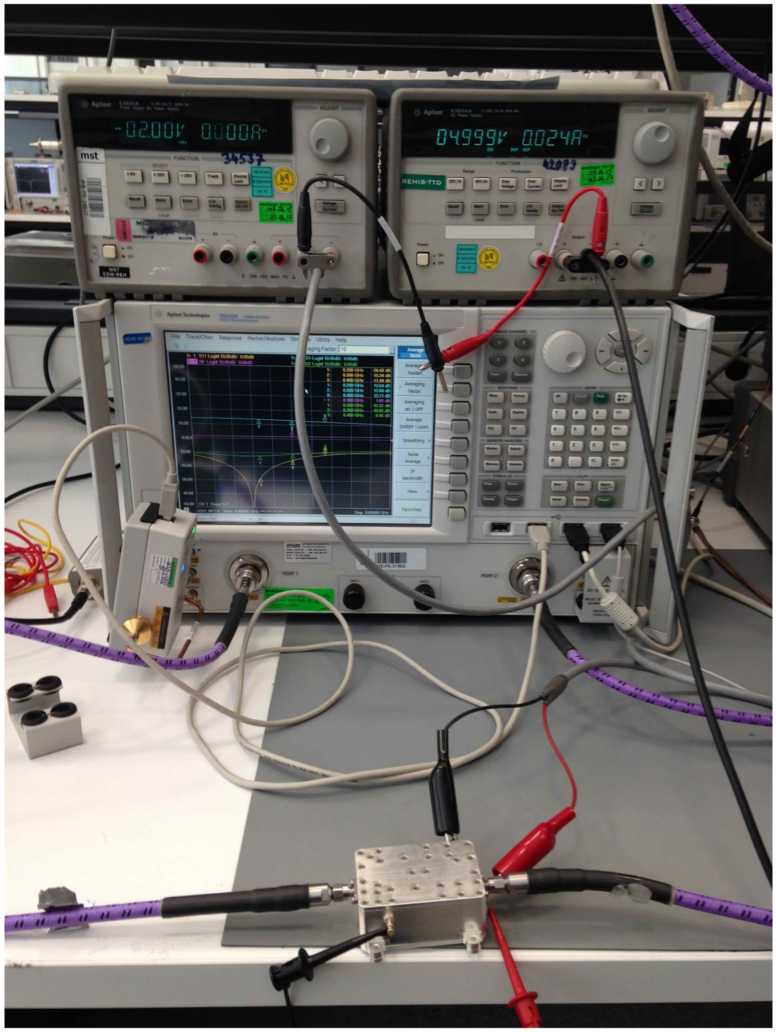


Figure 4.3: S-Parameters measurement setup

4.1.2 Noise Figure Measurement Setup

Noise figure measurements are done with Agilent E4440A Spectrum Analyzer for Y-factor method as shown in Figure 4.4 and Agilent PNA-X Network Analyzer for cold source method. PNA-X has specific noise receivers for the noise figure measurements in addition to the standard receivers for S-Parameters measurements. Therefore, the setup shown in Figure 4.3 is also used for the noise figure measurement. It is important to note that during calibration the same noise source is used for the better measurement accuracy in both setups.

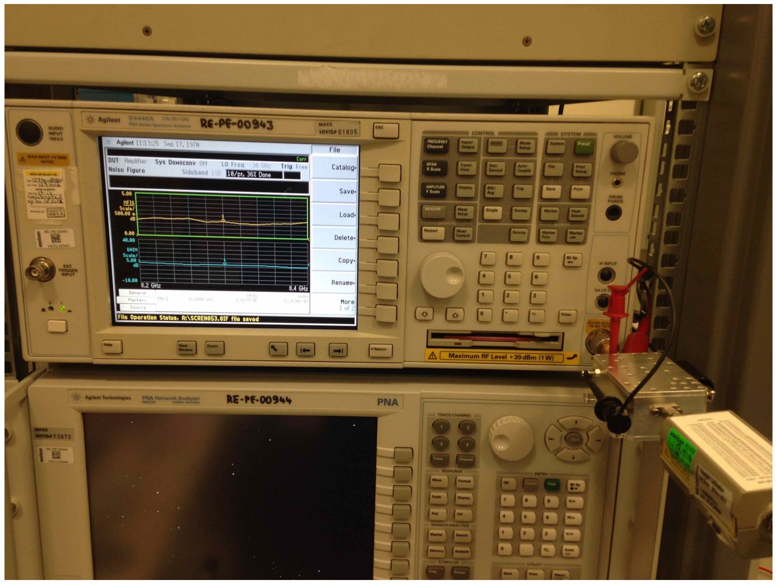


Figure 4.4: Y-factor noise measurement setup

4.1.3 P_{1dB} Measurement Setup

P_{1dB} measurement is done with Agilent PNA-X Network Analyzer which is the same network analyzer used for the S-Parameters and noise figure measurements. It has an option called Gain Compression Application (GCA) which computes the compression points from the transfer curves of the amplifier at a given number of points in the given frequency band [14].

4.1.4 IP_3 Measurement Setup

Two tone intermodulation measurement is done with two Agilent 8257D Signal Generator and Agilent E4440A Spectrum Analyzer to measure OIP_3. Two tones, which are combined with a power combiner, separated by 1 MHz are applied to the input as shown in Figure 4.5. Furthermore, 16 dB attenuators are added to the inputs of the combiner to increase isolation and eliminate mixing products.

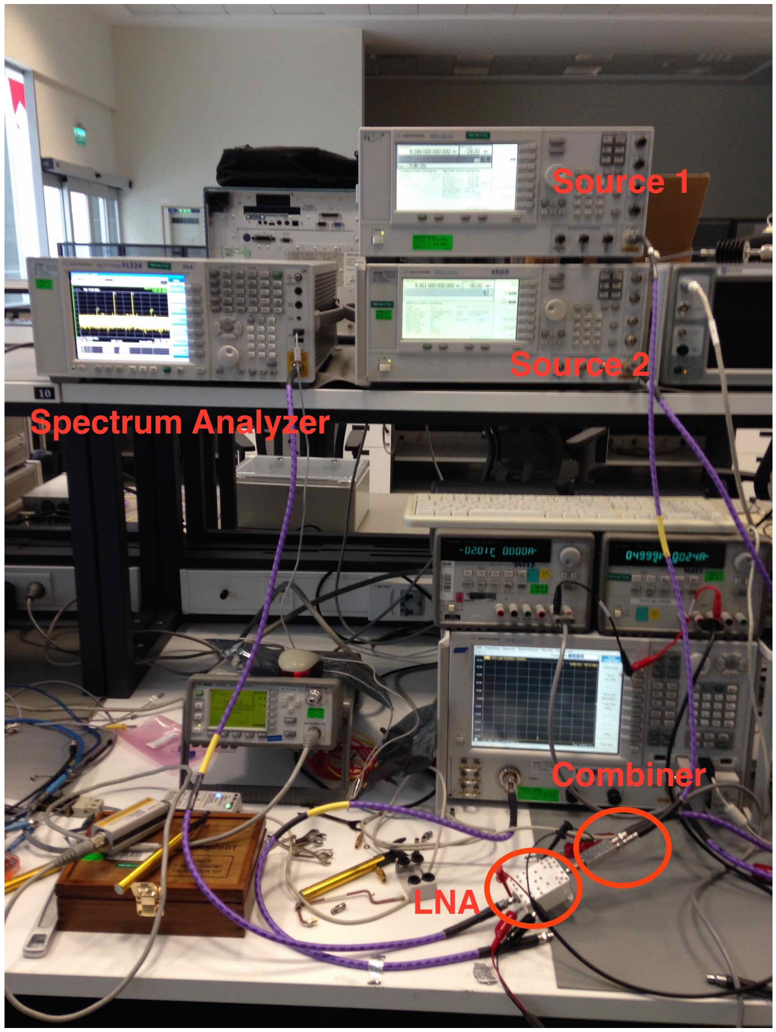


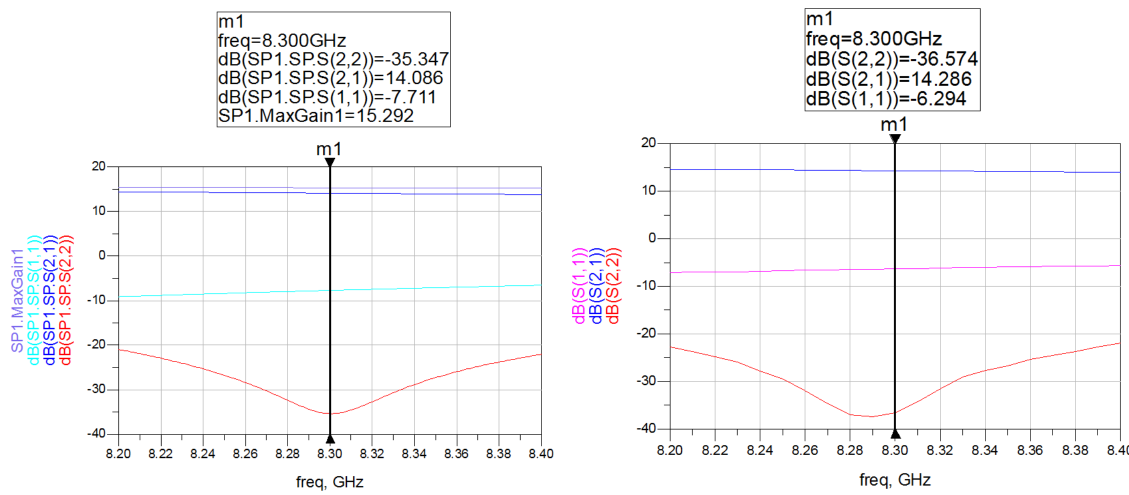
Figure 4.5: IP_3 measurement setup

4.2 Measurement Results and Comparison

4.2.1 S-Parameter Measurements

4.2.1.1 Single-Ended LNA

S-Parameter measurements were taken using the setup given in Figure 4.3. Minimum small-signal gain of the amplifier is 13.9 dB while having a minimum input return loss of 5.7 dB and a minimum output return loss of 22 dB. Simulated S-Parameters and measured S-Parameters are compared in Figure 4.6. As it can be seen, they are very close to each other.

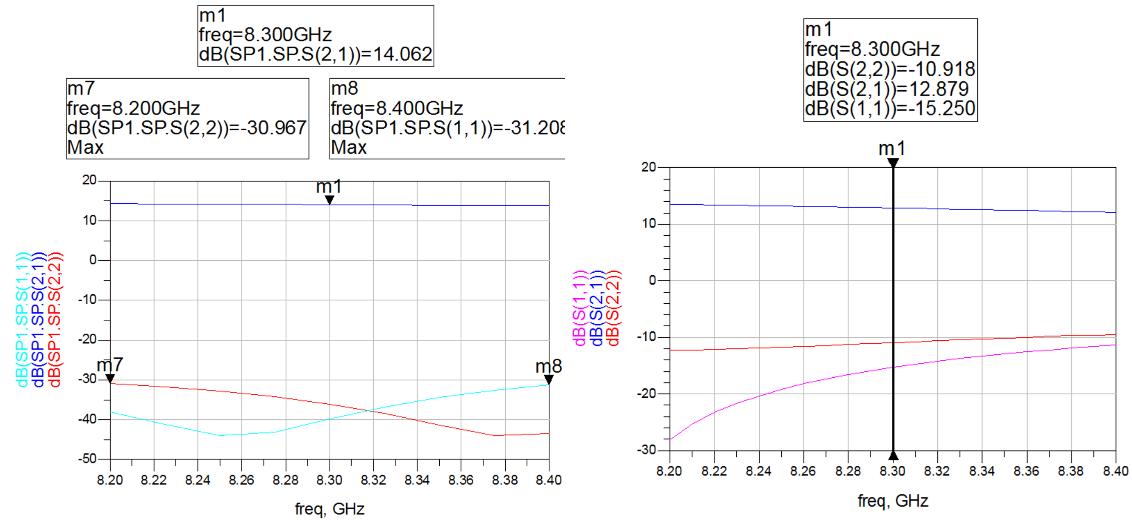


(a) Simulation (b) Measurement

Figure 4.6: S-Parameter measurements of Single-Ended LNA

4.2.1.2 Balanced LNA

S-Parameter measurements of Balanced LNA were also taken using the setup given in Figure 4.3. Minimum small-signal gain of the amplifier is 12.1 dB while having a minimum input return loss of 11.4 dB and a minimum output return loss of 9.5 dB. Simulated S-Parameters and measured S-Parameters are compared in Figure 4.7. As it can be seen, they are slightly different from each other. It is probably because of the frequency shift of Wilkinson power divider.



(a) Simulation

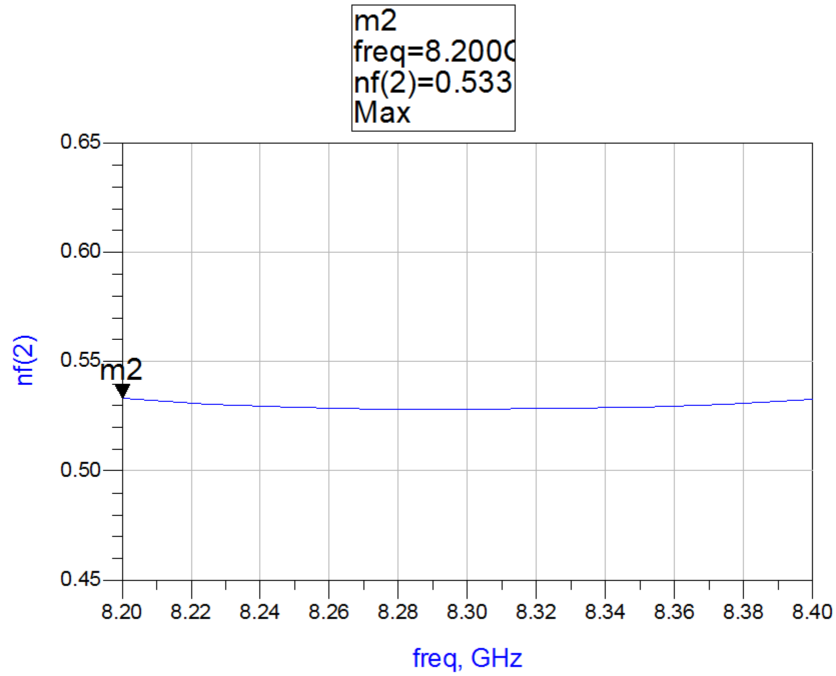
(b) Measurement

Figure 4.7: S-Parameter measurements of Balanced LNA

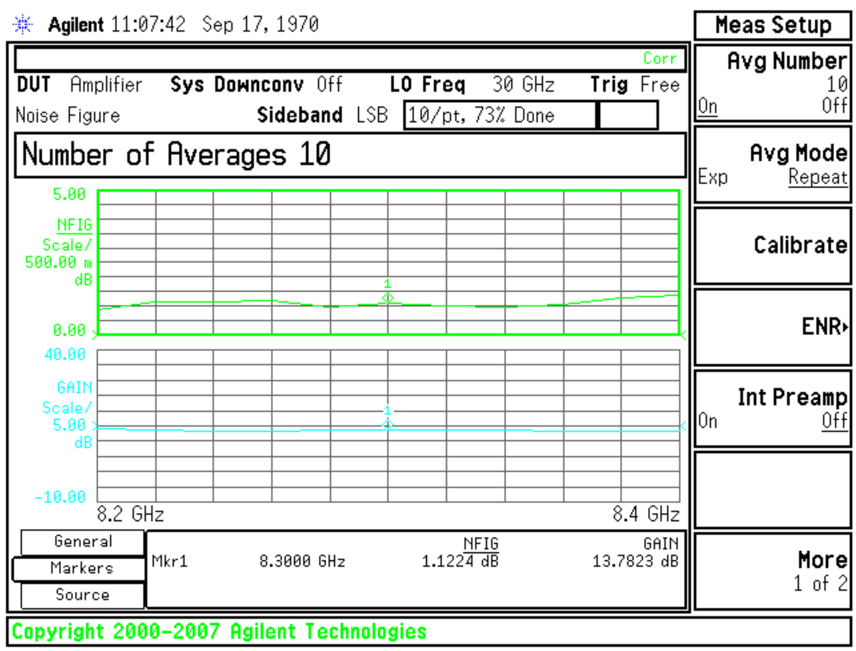
4.2.2 Y-Factor Noise Figure Measurements

4.2.2.1 Single-Ended LNA

Measurement was taken using the setup given in Figure 4.4. Simulated and measured values are compared in Figure 4.8. Maximum measured noise figure is 1.4 dB which is different than simulated value. One of the reasons behind this difference is the input connector because its loss is directly added to the total noise figure.



(a) Simulation

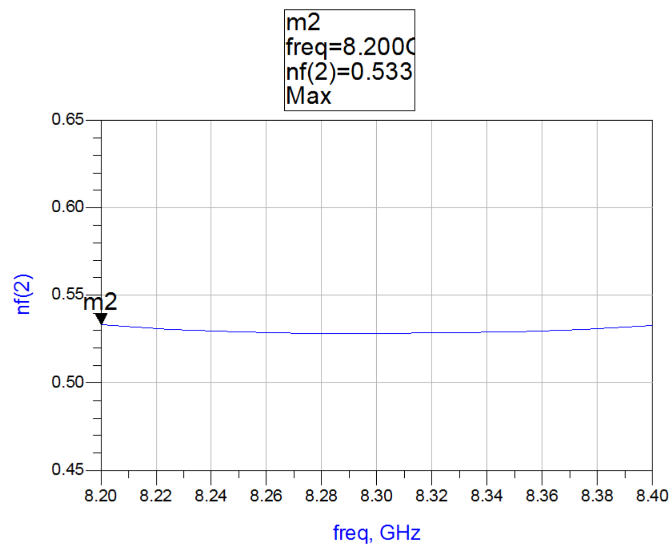


(b) Measurement

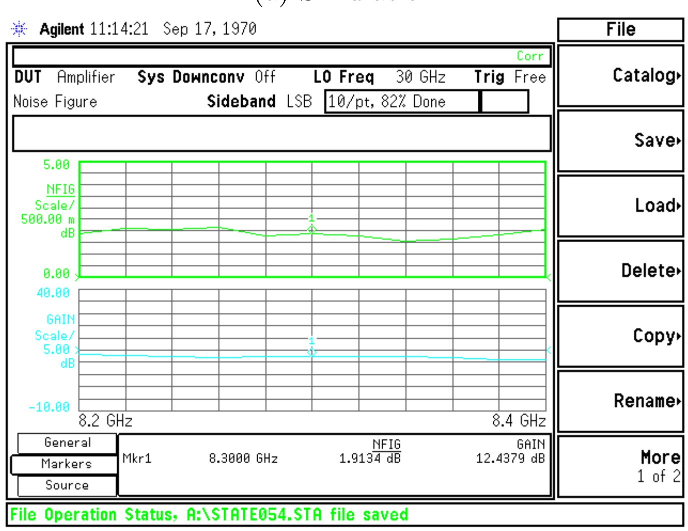
Figure 4.8: Y-factor noise figure measurement of Single-Ended LNA

4.2.2.2 Balanced LNA

Measurement was taken using the setup given in Figure 4.4. Simulated and measured values are compared in Figure 4.9. Maximum measured noise figure is 2.1 dB which is different than simulated value. Another reason for this difference can be that the noise source may not be perfectly matched to 50 ohms.



(a) Simulation



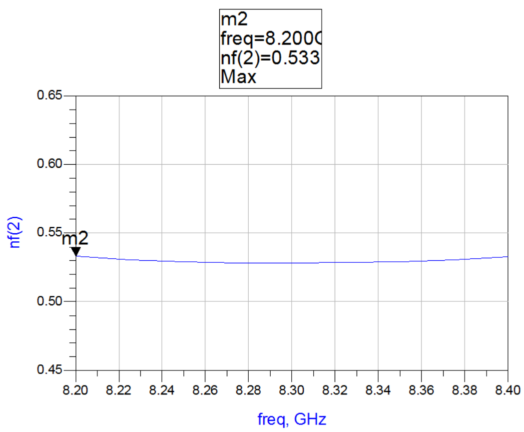
(b) Measurement

Figure 4.9: Y-factor noise figure measurement of Balanced LNA

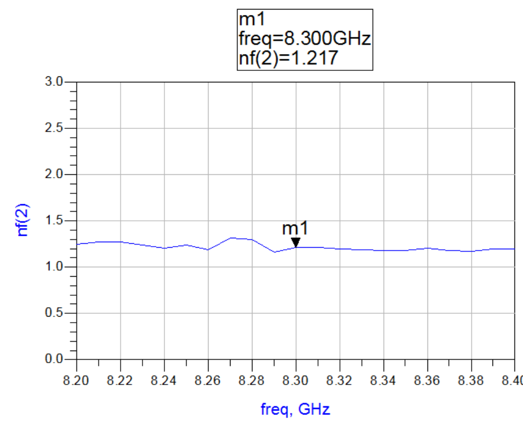
4.2.3 Cold Source Noise Figure Measurements

4.2.3.1 Single-Ended LNA

Measurement was taken using the setup given in Figure 4.3. Simulated and measured values are compared in Figure 4.10. Maximum measured noise figure is 1.32 dB which is slightly different than the value taken in Y-factor measurement due to vector correction capability of PNA-X.



(a) Simulation

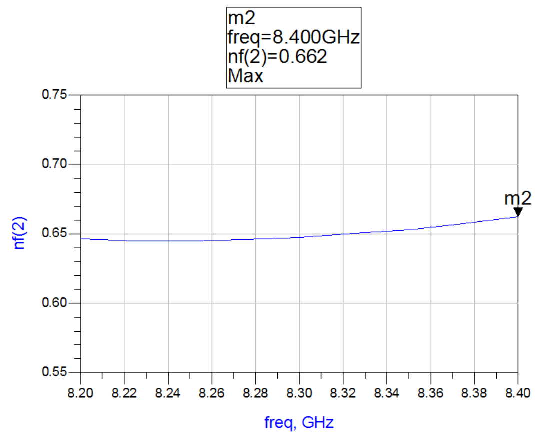


(b) Measurement

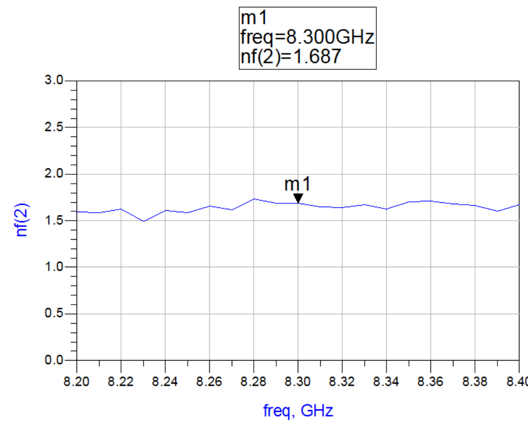
Figure 4.10: Cold source noise figure measurement of Single-Ended LNA

4.2.3.2 Balanced LNA

Measurement was taken using the setup given in Figure 4.3. Simulated and measured values are compared in Figure 4.11. Maximum measured noise figure is 1.74 dB which is slightly different than the value taken in Y-factor measurement. It can be considered that vector correction in cold source method is an important factor to achieve accurate noise figure measurement in low noise amplifier measurements.



(a) Simulation



(b) Measurement

Figure 4.11: Cold source noise figure measurement of Balanced LNA

4.2.4 P_{1dB} Measurement

4.2.4.1 Single-Ended LNA

Measurement was taken using an option of PNA-X network analyzer which is called as Gain Compression Application (GCA) which derives the compression point from transfer curve. Since the high-frequency model of the transistor is not provided by the manufacturer (except S-parameters), non-linear simulation for OP_{1dB} could not be done. Measurement result is given in Figure 4.12.

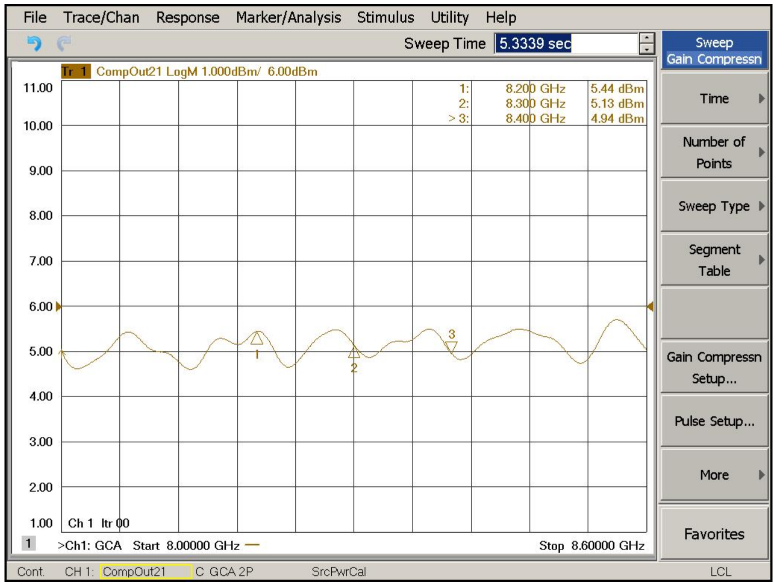


Figure 4.12: OP_{1dB} of Single-Ended LNA

4.2.4.2 Balanced LNA

As for the single-ended LNA, measurement of balanced LNA was also taken using the option of PNA-X network analyzer which is called as Gain Compression Application (GCA) which derives the compression point from transfer curve. Measurement result is given in Figure 4.13. As it can be observed from the result, balanced LNA has 3 dB higher OP_{1dB} than single-ended LNA as expected.

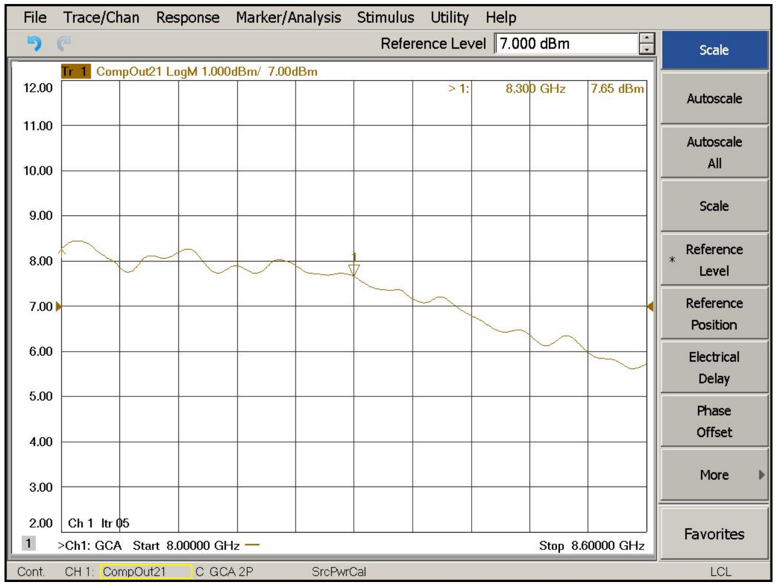


Figure 4.13: OP_{1dB} of Balanced LNA

4.2.5 IP_3 Measurement

4.2.5.1 Single-Ended LNA

Measurement was taken using the setup shown in Figure 4.5 and the result is shown in Figure 4.14. Calculated OIP_3 is 18.7 dBm which is approximately 10-15 dB higher than the measured P_{1dB} of single-ended LNA as expected.

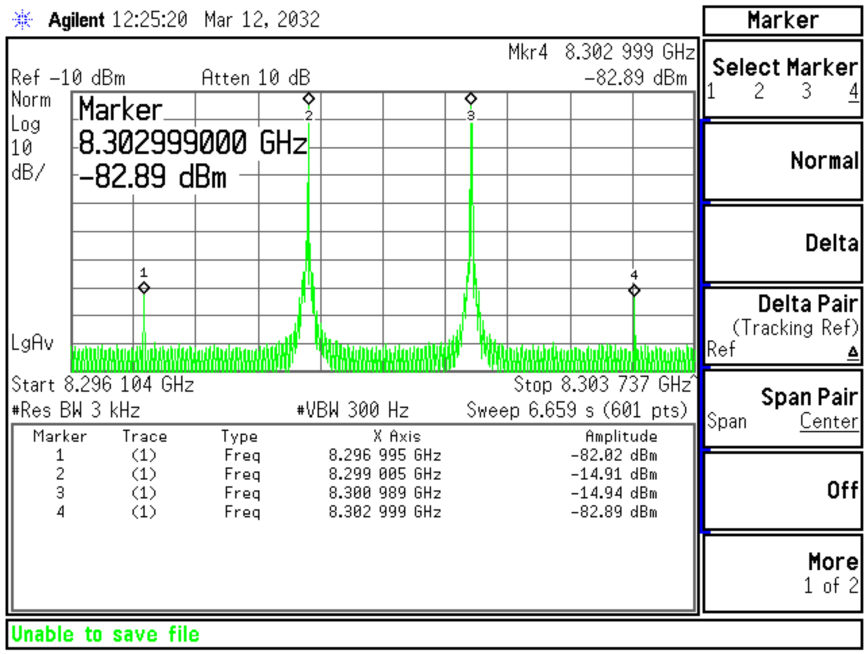


Figure 4.14: Two tone intermodulation test of Single-Ended LNA

4.2.5.2 Balanced LNA

Measurement was taken using the setup shown in Figure 4.5 and the result is shown in Figure 4.15. Calculated OIP_3 is 21.5 dBm which is approximately 10-15 dB higher than the measured P_{1dB} of single-ended LNA as expected. As it can be observed from the results, balanced LNA has approximately 3 dB higher OIP_3 than single-ended LNA as expected.

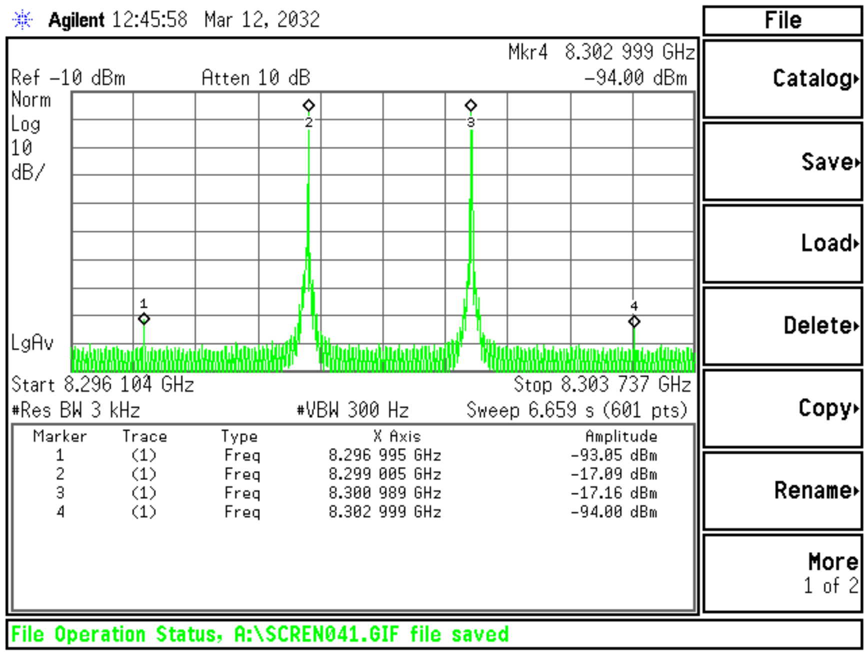


Figure 4.15: Two tone intermodulation test of Balanced LNA

4.2.6 Measurement with an Isolator

Since the alternative way of achieving simultaneous noise and power matching is to place an isolator in front of the noise matched amplifier, it is necessary to measure the noise figure of the single-ended LNA with an isolator to compare the cases on equal basis. Therefore, an X-band isolator was connected to the single-ended LNA as shown in Figure 4.16. Measurement was taken using the cold source noise figure measurement setup and the result is given in Figure 4.17. LNA with isolator has a maximum noise figure of 1.67 dB, a minimum gain of 13.9 dB and a minimum input return loss of 18.9 dB across the frequency band.

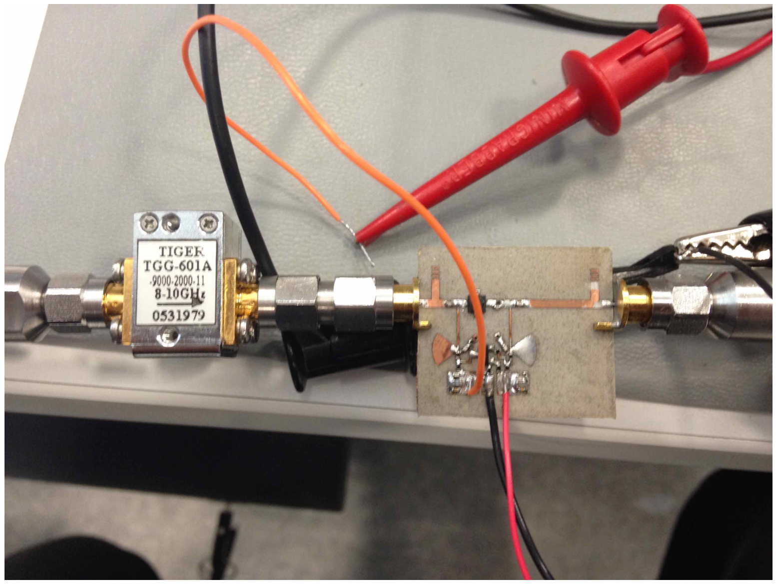
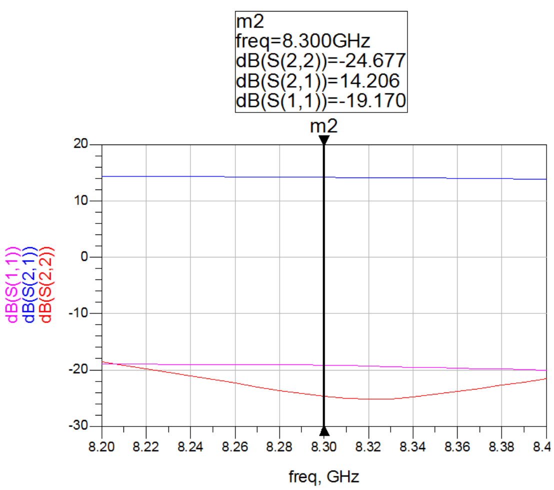
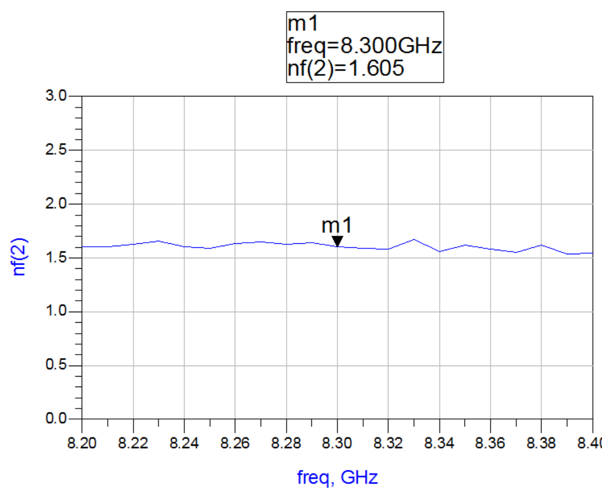


Figure 4.16: Single-Ended LNA with an X-band isolator



(a) S-Parameter measurement results



(b) Cold source noise figure measurement result

Figure 4.17: Measurement results of Single-Ended LNA with isolator

4.2.7 Summary

Table 1, Table 2 and Table 3 shows the summary of single-ended LNA, balanced LNA and single-ended LNA with isolator, respectively. The best and worst values are given along the frequency band.

Specification	**Simulated Value**	**Measured Value**
Frequency Band	8200 MHz - 8400 MHz	8200 MHz - 8400 MHz
Noise Figure	0.53 dB - 0.54 dB	1.16 dB - 1.32 dB
Gain	14.3 dB - 13.8 dB	14.6 dB - 13.9 dB
Input Return Loss	9.1 dB - 5.7 dB	7.2 dB - 5.7 dB
Output Return Loss	35.4 dB - 29 dB	37.5 dB - 22 dB

Table 4.1: Summary of the Single-Ended LNA

Specification	**Simulated Value**	**Measured Value**
Frequency Band	8200 MHz - 8400 MHz	8200 MHz - 8400 MHz
Noise Figure	0.62 dB - 0.63 dB	1.5 dB - 1.74 dB
Gain	14.3 dB - 13.8 dB	13.5 dB - 12.1 dB
Input Return Loss	44 dB - 31.2 dB	28.1 dB - 11.4 dB
Output Return Loss	44 dB - 31 dB	12.3 dB - 9.5 dB

Table 4.2: Summary of the Balanced LNA

Specification	**Measured Value**
Frequency Band	8200 MHz - 8400 MHz
Noise Figure	1.54 dB - 1.67 dB
Gain	14.4 dB - 13.9 dB
Input Return Loss	20 dB - 18.9 dB
Output Return Loss	25.2 dB - 18.6 dB

Table 4.3: Summary of the Single-Ended LNA with isolator

Chapter 5

Conclusion

In this work, design and implementation of an input matched X-band low noise amplifier was studied, constructed and measured. Input matching is an important parameter if a filter precedes the LNA. Poor matching results in excessive loss in the filter, which degrades the overall system performance. These input filters are usually designed so that the output termination impedance of the filter is 50 ohms and they are very sensitive to the changes in the output termination impedances, which makes the input matching critical [17]. However, input matching becomes insignificant if there is no input filter in the receiver architecture. Another key work in the design of LNA is to optimize Signal-to-Noise Ratio (SNR). Since the transmitter power cannot be increased indefinitely, the only way to increase SNR is to provide sufficient gain to minimize the noise of subsequent stages while contributing a minimum amount of noise by the input stage. Therefore, there should be a lower limit for the gain, for instance 10 dB, to avoid the excessive noise contribution from the subsequent stages.

To accomplish the goals mentioned above, several techniques from the literature were investigated and balanced amplifier topology was chosen to work on. Balanced topology provides matched input and output impedances due to the fact that reflected signals from the output of the coupler are cancelled at the termination port of the coupler. Thereby, it is possible to design matching networks regardless of the input/output return losses. Thus, the input of the LNA is directly matched to the optimum source impedance for minimum noise figure while maintaining matched load to the input source. For the output of the LNA, maximum power transfer matching is done. In addition to the balanced LNA, noise matched single-ended LNA is designed and fabricated in order to observe the implemented noise figure performance before the implementation of the balanced LNA.

The designed single-ended amplifier produced a maximum noise figure of 0.54 dB and a minimum input return loss of 5.7 dB during the simulations. The fabricated single-ended amplifier has a maximum noise figure of 1.32 dB and a minimum input return loss of 5.7 dB. Input connector, fabrication tolerances, lot-to-lot variations and in the lot variations of the transistor in terms of noise properties can be considered as the possible reasons for the difference between the simulation and measurement results.

After successfully implementing the single-ended LNA, the balanced LNA was designed and fabricated. Moreover, aluminum housing for the balanced LNA was designed and fabricated to prevent possible interferences and avoid bending of the thing PCB. The main goal in the design of the housing is to prevent box resonance without absorber by minimizing the internal dimensions of the housing. Furthermore, RF and active bias circuits are separated so that they are placed back-to-back on the central plate of the housing. The designed amplifier produced a minimum noise figure of 0.65 dB and a minimum input return loss of 26.5 dB during the simulations. The assembled balanced amplifier has a maximum noise figure of 1.74 dB and a minimum input return loss of 11.4 dB. Measured noise figure value is slightly higher than the simulated one. One of the reasons for this difference can be attributed to the possible gain difference between the branches which results in an increased noise figure [18]. In addition, mismatch in the coupler can be considered as one of the reasons for an increased noise figure because phase difference at the center frequency is no longer 90 degrees. During measurements, it is observed that box resonance occurs when the cover of the housing is screwed tightly. Therefore, absorber is attached to the cover to avoid the box resonance. It can be easily observed that frequency shift is occurred in the fabricated balanced LNA in spite of the fact that single-ended LNA does not have a such frequency shift. This fact indicates that the Wilkinson power divider might be causing the frequency shift.

Lastly, noise figure and gain measurements of the single-ended LNA were repeated with an X-band isolator for a comparison on equal basis. The measured maximum noise figure is 1.67 dB and minimum input return loss is 18.9 dB. The results are quite similar with the results of balanced LNA when it is assumed that the frequency shift is corrected. Thus, cost should be considered as a parameter for the choice of which one will be used since the RF performances are similar. In that case, the balanced amplifier would be better to use because isolator costs much higher than a couple of transistors, resistors and capacitors.

For the future work, noise figure of the balanced amplifier can be reduced by minimizing the loss between the input connector and the gate of the transistor. Moreover, frequency shift which is a result of the mismatch in the coupler can be corrected.

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