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Optimizing Microstrip Length for Enhanced S-Parameters in 2.4GHz Low Noise Amplifier

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Abstract
An essential component of every RF system's reception chain is the Low-Noise Amplifier(LNA). The sensitivity and performance of subsequent stages in the receiver chain are significantly influenced by the LNA, which is the initial step. Creating an LNA requires carefully balancing trade-offs in order to have the best possible performance in terms of gain and noise characteristics. Achieving optimal functioning and efficiency in the radio frequency system requires finding the correct balance. This article presents the design of an LNA circuit at the lowest cost without adding components such as inductors, active components, or several stages, which increase the complexity of the circuit, consume power, and add additional noise, by controlling the lengths of the microstrip line, LNA circuit was created by ADS software, and add a matching circuit. At the operating frequency of 2.4 GHz, the suggested design achieved good results with a gain of 17.48dB, NF of 0.7dB, stability factor of 1.5dB, and S11-S22 (-41dB, -25dB) in that order.

Keywords
LNA, ASIC, RFIC, Power Gain, Noise Figure, Stability, Topology, Impedance Matching.

I. Introduction

Since the inception of the internet and mobile technologies, there has been an insatiable human desire for continuous improvement. With each passing day, the demand for higher speeds, greater bandwidth, and lower latency in communication networks grows exponentially.

To meet these escalating requirements, the introduction of 5G networks has become imperative. As the latest generation of mobile technology, 5G surpasses its predecessor, 4G LTE, with the ambitious goal of connecting everything and everyone, ranging from machines and network devices to various smart objects. The core objective of 5G wireless technology is to achieve peak data rates in the tens of Gbps (Gigabits per second) range, while simultaneously ensuring higher network reliability to reduce latency. By accomplishing these feats, 5G networks aim to revolutionize the way we communicate, allowing for seamless connections and enhanced user experiences. The potential of 5G is vast, promising a future where the exchange of data and information occurs at unprecedented speeds, unlocking opportunities for innovation and connectivity on an unprecedented scale [1]. Some countries choose to allocate the operating band for 5G operations around the already existing 2.4GHz. band. This frequency band is attractive due to its widespread use and compatibility with various devices. However, one of the challenges in this frequency range is managing interference and ensuring efficient utilization of available resources. The LNA plays a critical role in the receiver chain, serving as the initial stage. Its significance lies in its ability to amplify weak signals while introducing minimal additional noise. This feature directly impacts the receiver's sensitivity, which is crucial for detecting and processing weak signals effectively. It is important to mention some earlier research in this area. Previous research looked at methods of increasing bandwidth using base-mounted shunt and series peaking inductors; the findings revealed an average power usage of 17.6 mA, a noise figure of 3.1 dB, and a frequency range of 24-48 GHz [2]. In [3], an LNA with 90 nm SOI (Silicon on Insulator) CMOS technology that is capable

of functioning from 26 to 42 GHz was created. It offered a noise figure of 3.6 dB, a gain of 11.9 dB, and a power draw of 17 mA. A 20–44 GHz LNA was introduced in a 22 nm FDSOI (Fully Depleted Silicon on Insulator) technology [4]. It displayed a minimal noise figure of 3.1 dB, a gain of 17 dB, and a 20.5 mW total power usage. The authors of [5] developed a 24-44 GHz LNA with a low noise figure of 4.2 dB and a gain of 20 dB using 45 nm CMOS technology. The LNA consumed 58 mW of power. within A 20–44 GHz LNA was built using a 22 nm GF FDSOI technique [6]. By adjusting the lengths of the microstrip line, the LNA circuit was created by ADS software, and a matching circuit was added. This article presents the design of an LNA circuit at the lowest cost without adding components like inductors, active components, or several stages, which increase the complexity of the circuit, consume power, and add additional noise. Considering the importance of the LNA's performance, its design becomes a focal point in achieving high receiver sensitivity and overall system efficiency. Careful consideration of tradeoffs is necessary to strike a balance between noise figure, gain, power consumption, and linearity to achieve optimal receiver performance in 5G and other communication systems [7].

II. Design Concept

Since LNAs are an essential part of RF and microwave systems, their primary function is to amplify weak input signals while adding as little additional noise as possible. This is necessary to maintain a high signal-to-noise ratio (SNR) and to ensure the successful processing of weak signals in the presence of noise [8]. Before starting the design process, it is necessary to mention the most important factors that affect and are considered a measure of the efficiency of the circuit.

1. **Noise Figure (NF)**
   The noise figure is a critical parameter that quantifies how much additional noise the LNA contributes to the input signal. Given as:

$$NF = SNR_i\,dB - SNR_o\,dB \tag{1}$$

   It is expressed in decibels (dB) and represents the degradation in SNR caused by the amplifier. Lower noise figures indicate better performance since less noise is introduced during amplification [9].

2. **Gain**
   Gain refers to the amplification factor of the LNA, representing the ratio of output signal amplitude to input signal amplitude. A high gain is desirable to boost weak signals, but it should be balanced with the noise figure to avoid excessive noise amplification [5] The gain of the LNA must be large enough to minimize the noise contribution of subsequent stages, specifically, the down-conversion mixer(s).

3. **Bandwidth**
   The bandwidth of an LNA defines the range of frequencies over which it can operate effectively. For communication systems like 5G, the LNA should cover the desired frequency range and have sufficient bandwidth to process various signals efficiently.

4. **Linearity**
   Linearity A measurement of an electronic device's linearity known as IP3 (Third-Order Intercept Point) is frequently employed concerning amplifiers and mixers. It is a crucial metric for RF (Radio Frequency) applications and communication systems since it measures how well a device can handle many input signals without significantly increasing nonlinear distortion as in Fig.1. When two sinusoidal input signals are applied to a linear system, the output should only include the original input frequencies and not any additional distortion. However, nonlinearities in real-world electrical systems might result in the output having unwanted intermodulation products [10].

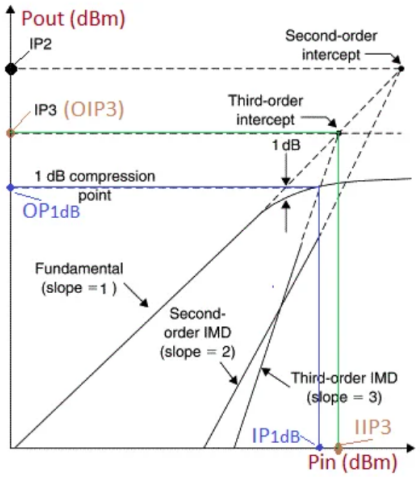


Fig. 1. Outline Illustrates IIP3 for Non-Linear Device [1].

5. **Biasing**

   The process of applying DC voltages to a transistor's various terminals to determine the appropriate operating

point or quiescent point is known as biasing in transistors. The transistor will function in its linear area for amplification applications or in the saturation and cutoff regions for switching applications if the biasing is done properly. For transistor circuits to function properly and remain stable, biasing is essential. Proper biasing of the LNA's active components (transistors) is necessary to achieve stable and reliable operation. Transistor biasing primarily comes in two types Fixed Biasing and self-biasing. The specific application, transistor type, and required performance all influence the biasing method selection. The transistor must be biased correctly to function reliably and effectively. It aids in avoiding distortion, ensuring linearity, and managing power loss. Furthermore, biasing is essential to maintain the transistor's DC operating point within a desirable range. Distortion, thermal instability, or even transistor failure can result from improper biasing [11].

6. **Technology**
LNAs can be implemented using various technologies, such as Bipolar Junction Transistors (BJTs), Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), Gallium Arsenide Field-Effect Transistors (GaAsFETs), and others. Each technology has its advantages and disadvantages concerning noise, gain, and other performance characteristics [11]. LNA technology includes:

   (a) **SiGe (Silicon Germanium) bipolar transistors:** are excellent at high frequencies and have low noise figures, making them suitable for RF and microwave applications.

   (b) **Complementary Metal Oxide Semiconductors (CMOS):**
   Due to their low cost and compatibility with other digital and analogue circuitry, CMOS LNAs are frequently utilized in integrated circuits. They are constructed using normal CMOS methods.

   (c) **Gallium arsenide (GaAs):**
   GaAs-based LNAs are ideal for use in microwave circuits, wireless systems, and satellite communication because of their exceptional high-frequency performance, low noise figures, and high gain. GaAs LNAs are frequently employed in high-frequency systems where cost is subordinate to performance.

   (d) **InP and GaN (Gallium Nitride):**
   technologies are employed for LNAs in very high-frequency applications, such as millimeter-wave and terahertz systems. These technologies are excellent for high-frequency and high-power applications because they have great power-handling capacities.

7. **Power Consumption**

Mobile and battery-powered devices, power efficiency is essential. Designers often optimize the LNA to consume minimal power while maintaining adequate performance. in the design must take power consumption into account, especially for portable electronics, battery-powered systems, and energy-saving applications. To extend battery life, reduce heat dissipation, and improve overall system efficiency, it is imperative to minimize power consumption while still achieving the appropriate performance parameters. Trade-offs between power usage, size, and performance are frequent. To achieve the appropriate balance between power efficiency and performance, designers must carefully evaluate the requirements of the application and optimize the amplifier circuit in accordance [12].

8. **Matching Networks**
External matching networks may be used to optimize the LNA's performance and impedance matching with the surrounding circuitry. by transmission RF energy with the lowest possible losses. LNAs are typically designed to provide a 50-ohm input resistance and negligible input reactance. This requirement limits the choice of LNA topologies. In other words, we cannot begin with an arbitrary configuration, design it for a certain noise figure and gain, and then decide how to create input matching, and proper input (conjugate) matching of LNAs requires certain circuit techniques that yield a real part of 50 ohms in the input impedance without the noise of a 50-ohm resistor [13, 14].

9. **Stability**

The Stern stability factor is frequently employed in LNA design as a metric to assess the stability of the circuit under consideration. According to the definition

from [15], it is expressed as follows:

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

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

For the above equation, we have stability for the condition $K > 1$ and $\Delta < 1$. Understanding RF fundamentals, microwave circuit theory, and the behaviours of active devices is essential for designing a stable LNA. Before the LNA is used in a finished product or system, stability tests, such as stability circles, and lab measurements are crucial. In the long run, time, money, and possible reliability difficulties can be avoided by ensuring stability early in the design phase.

10. **Topology**
Numerous alternative topologies are available for LNA design. Some of the prominent ones include; Common-Source this topology can incorporate either a resistive feedback network or an inductor as the circuit's load. Common-Gate Another option is the common gate topology, which has a low input impedance of the common-gate (CG) stage making it attractive for LNA design. The trade-off between the robustness of the input match and the lower constraint on the noise figure determines which of the CG and CS LNA topologies should be used. While the latter has a lower noise figure, the former offers an accurate input resistance that is mostly independent of package parasitic. So, if the desired LNA noise figure can be about 4 dB, we choose the CG stage; for lower values, we choose the CS stage. CS counterpart can use either an inductive load or a feedback network [16, 17].

III. Design Circuit Step

As previously indicated, by increasing the intensity of the received signal before further processing, LNAs play a crucial role in enhancing the sensitivity and overall performance of RF receivers. High gain, low noise ratio, great linearity, as well as low power consumption and stability, are the main objectives of LNA design. To fulfil the unique needs of an application, the design process combines RF circuit theory, transistor device physics, and optimization methods [18]. In the first step, we define the requirements for the design of this department as in Table I.

TABLE I

Frequency	2.35-2.45, GHz.	used in WiFi, communications.
Gain	$> 14.$	Transistor capacity, according to data sheet.
S_{11}, S_{22}.	$< -15.$	the minimum, acceptable limits, for S_{11} and S_{22}, is -10, to ensure good, impedance matching, and minimize, power reflections.
NF	$< 1.4.$	Transistor capacity, according to, data sheet.
Stability factor	$> 1.$	definition from [15], The farther away, from 1, the more stable, it is Features.
Transistor	ATF-, 21170	• Low Noise Figure:, 0.9 dB Typical, at 4 GHz, • High Associated Gain:, 13.0 dB Typical , at 4 GHz, • High Output Power: , 23.0 dBm Typical , P1 dB at 4 GHz, • Hermetic Gold-Ceramic, Microstrip Package [19].

The second step is choosing software like Keysight Technologies to create the robust electrical design automation (EDA) software environment known as ADS (Advanced Design System). The design and modelling of RF (Radio Frequency) and high-frequency circuits and systems make extensive use of it. Engineers and researchers can create complicated electronic circuits including amplifiers, mixers, filters, oscillators, and more by using the extensive toolkit offered by ADS. As seen in Fig. 2 LNA designed the R_1, and R_2 values to (420Ohm-15Ohm) respectively, Its values were determined by a tuning process such that it provides a current of 20 mA (based on a datasheet) on the transistor drain so that it is a working point in the load line in the middle to ensure that no interruption occurs in the amplified signal. to represent stable components, R_1 have the lowest possible value so that it does not consume power, R_2 have the largest value so that no drawback the gained, and the optimization process can be

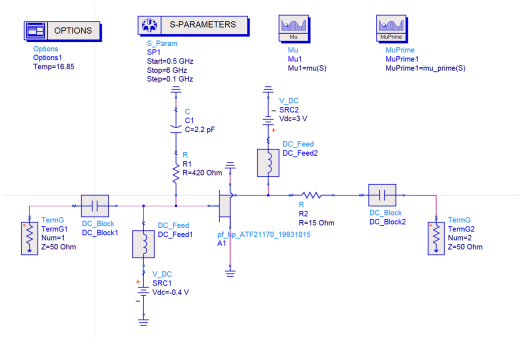


Fig. 2. LNA Circuit Stable Component R1, R2 and Coupling Capacitor, Bias Circuit.

used to find values. $DC_Feed_{1,2}$ represent the $Bais_T$ circuit in Fig.3 Its objective is to choose the appropriate operating point or quiet point of the transistors. If the bias is done correctly, the transistor will operate in its linear region for amplification applications or in its saturation and cutoff regions for switching applications. The optimization process can be used to find microstrip line lengths. TL_14 is a large value to prevent RF transmission to a DC source. DC Block, C_3, and C_1 represent coupling capacitors so we chose values that prevent IDC transmission to output and same time commercially available.

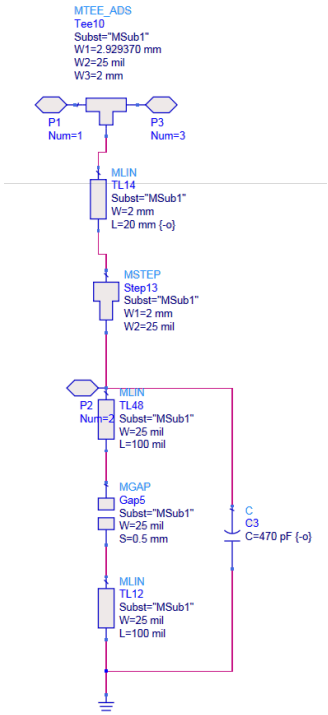


Fig. 3. Bias Tee circuit.

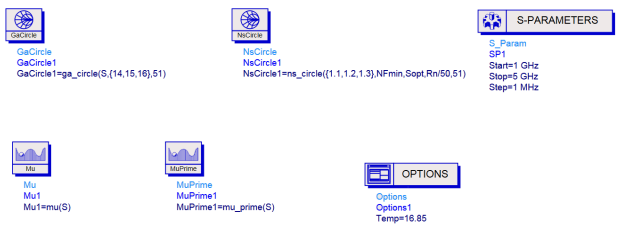


Fig. 4. Matching tool in ADS.

A. Matching Circuit To implement the matching circuit, used the Smith Chart tool, Gain circle, and Noise circle as in Fig. 4.

In GaCircle, the NaCircle tool selects three desired values. Then choose the meeting point(m10) of the circle that represents the largest gain(m5) with the circle that represents the smallest Noise Figure(m8) to find the matching impedance.

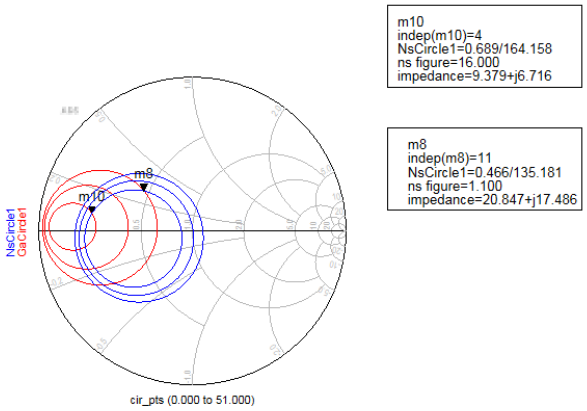
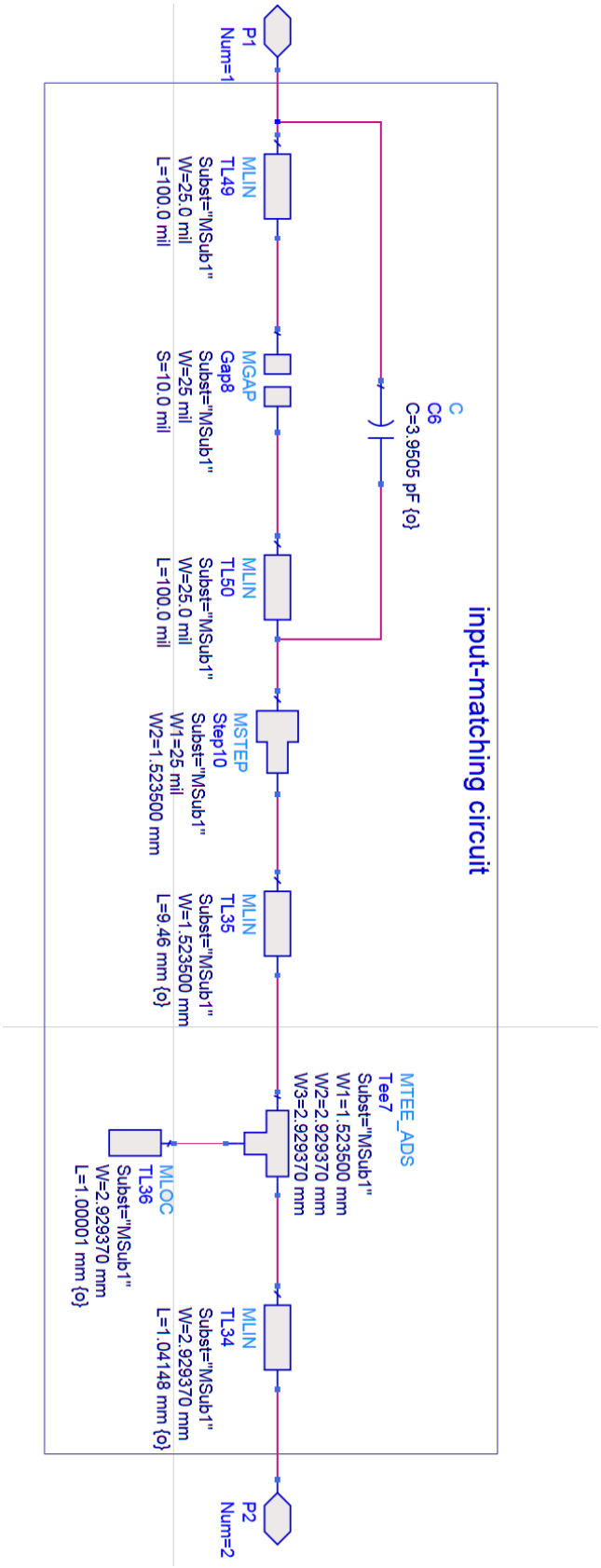
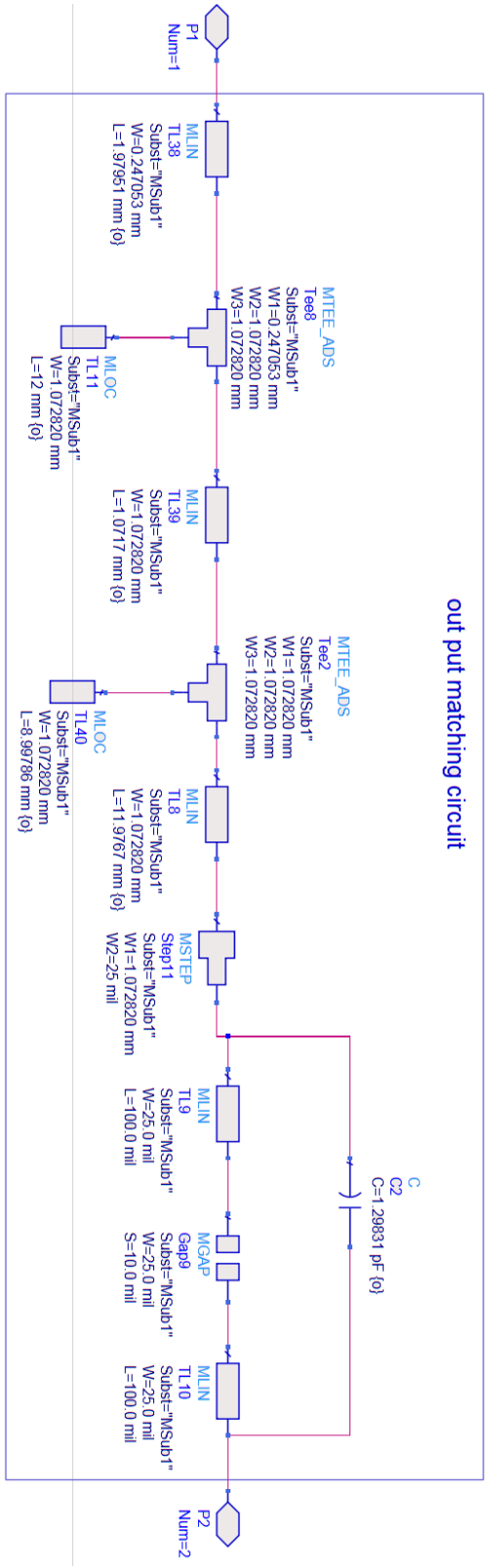


Fig. 5. Smith diagram showing a circuit of Ga and NF with the impedance value at the point of intersection.

To get the best signal transmission with the least reflection, low noise, and large gain, the impedance in point m10 (9.739+j6.716) must match 50ohm. using the Smith chart tool. Choose the appropriate transmission line. Then it is converted to a microstrip line by using the Line Cala tool.



(a) A diagram showing the matching circuit of the input after the optimization process.



(b) A diagram showing the matching circuit of the output with the values after the optimization process.

Fig. 6. Matching circuits after the optimization process: (a) input matching circuit, (b) output matching circuit.

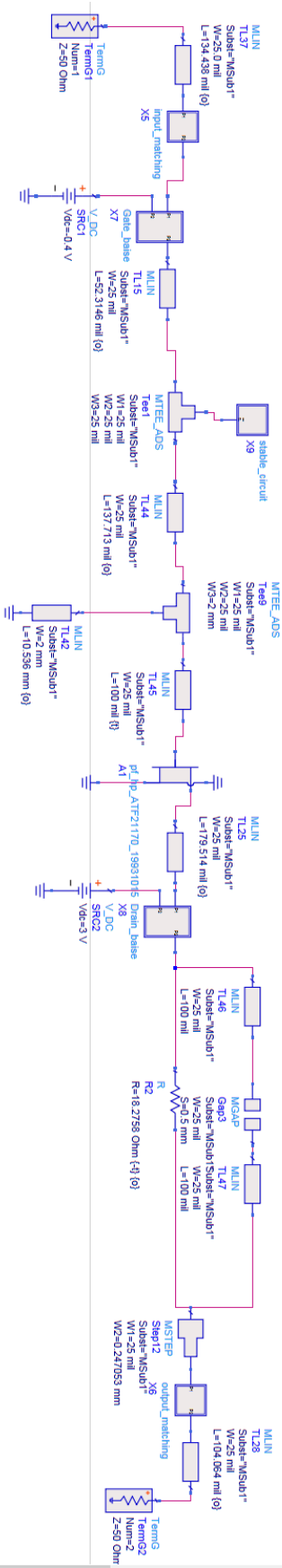


Fig. 7. Final LNA Circuit

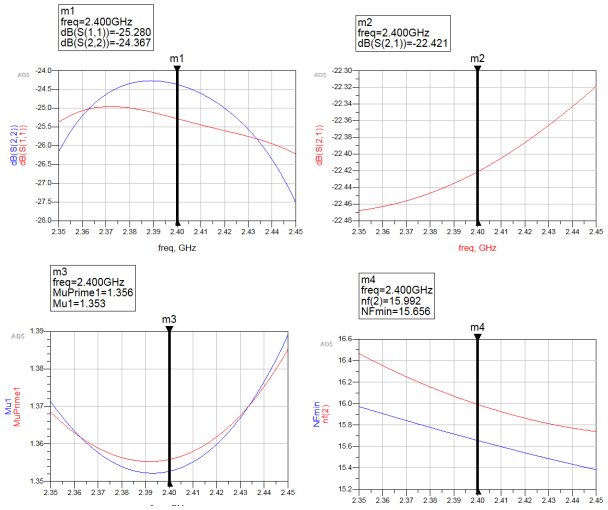


Fig. 8. Results Appears S-parameter, NF, and Stability Factor Mu Before Optimization

In Fig. 8 see S-parameter and noise figure need to be improved by using the optimization tools.

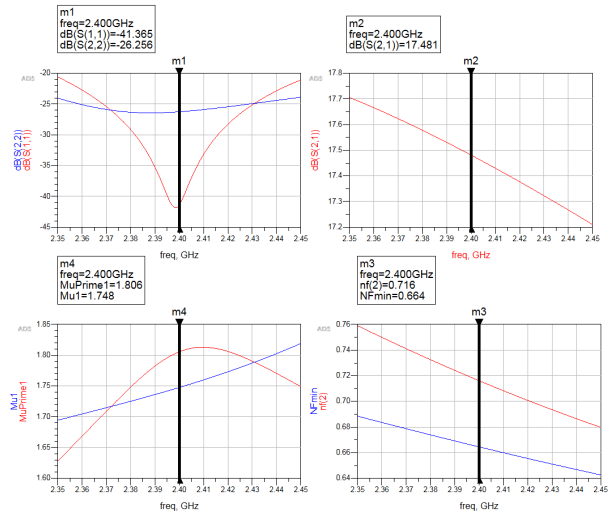


Fig. 9. Results Appears S-parameter, NF and Stability Factor (Mu)After Optimization

The purpose of these processors is to improve the signal transmission power with the least possible loss, by reducing the values of S_11, and S_22. Because they represent the amount of loss in the signal. Reduce the Noise figure (NF)value. A lower noise figure in an LNA is preferred because it shows that the amplifier adds less noise and better maintains the quality of the weak input signal, to reduce the deterioration of signal quality in communication systems and other sensitive

TABLE II.
COMPARISON BETWEEN THIS STUDY AND EARLIER WORKS.

Parameter	[20]	[21]	[22]	[23]	[24]	[25]	This work.
Power Supply (V).	1	1.8	1	1	1.8	1.5	3
Bandwidth (GHz).	8.5 -20.	1 -5	7.7 -29.	3.1 -10.6	0.4 -10	3.1 -10.6	2.35 2.45
Gain (dB).	11.13	21 -25	10.7	17 -25	11.2	9.7	17.4
NF(dB)	2.1 -3.2	2.6 -3	4.5 -5.6	4.1 -9.4	4.4 -6.5	5.2 -7	0.7
S_{11} (dB)	< -9.4	< -7	<	< -12	< -10	< -13.5	< -41
Mu(dB)	-	-	-	-	-	-	1.8

applications, LNAs are often designed to have a low noise figure. Increase the gain(S_21) To amplify the weak signal received. Power gain, or the LNA amplifying the signal at the output compared to the input, is indicated by a positive value for S_21. And loss, which would be undesirable in an LNA, is indicated by a negative value for S_21. preferred$Mu > 1$, which this measurement gives the distance from the centre of the Smith chart to the nearest output (load) stability circle. if Mu is greater than 1, the LNA is unconditionally stable. If K is less than 1, it indicates potential instability, and the designer needs to take measures to ensure stability, such as adding stabilizing components.

IV. RESULT

Referring to Fig(9), note that the values of S21, NF and stability factor (Mu) do not meet the requirements mentioned in Table 1, but the values of S_{11} and S_{22} are good. To improve it, we need to either add additional stages or components, which increases the complexity and cost of the circuit. Or we rely on the method of controlling the lengths of the microstrip, which is the least expensive method that we followed in this research. This can be done by relying on the optimization tools found in ADS. Fig(10) shows the amount of improvement in parameters after performing the optimization process. Table 3 shows the difference in results and the amount of improvement in Gain (S_{21}), Noise Figure (nf_2), Stability Factor(Mu) and Reflection Coefficient(S_{11}, S_{22}).

V. CONCLUSION

This paper demonstrates the design of an LNA using a GaAs FET transistor (ATF-21170). A Baise circuit was used to feed the transistor and make its working point on the load line in the middle to ensure that no part of the signal was lost when amplifying. Adding a stabilization circuit to ensure output stability. Adding a matching circuit from the source side and the output side to get the least loss when receiving the signal, we got the results in Fig. 8, which were not suitable for the requirements of Table 1. To improve them we changed the lengths of the microstrip line. Fig. 9 shows the improvement in values at 2.4 GHz as follows (17.4 dB gain), (0.7 dB NF), (1.8 dB stable factor (Mu)), (-41 dB S_{11}), (-26 dB S_{22}). In future work, the design could be made on several layers of microstrip lines.

TABLE III.
S PARAMETERS BEFORE AND AFTER OPTIMIZATION

Parameters(dB)	Before Optm	After Optm
S_{11}	-25	-41
S_{22}	-24	-26
S_{21}	-22	-17.4
Mu	1.353	1.806
Nf_2	16.038	0.716

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CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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