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Design and Simulation of a 12 GHz Two-Stage LNA for Ku-Band Telecommunication Applications

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ABSTRACT

The Low Noise Amplifier (LNA) is typically the initial step in any microwave receiver circuit and is crucial to the receiver's quality. The design, analysis, and modeling of single-stage and multi-stage low-noise amplifiers combined with an optimal matching network at wideband frequencies between 11 - 13 GHz are presented in this study. The amplifier circuit's heart, the embedded GaAs FET transistor MGF2407A in Advance Design System tool, operates in class AB mode with a drain source voltage of 4 V and a gate source voltage of -0.2 V. The matching circuit was constructed and optimized at the transistor's input and output after the source and load impedances were extracted using the source and load-pull technique. The stability factor of simulated amplifier was greater than 4 in the 11–13 GHz frequency range. The noise figure (NF) and power gain at 12 GHz were 34 dB and 0.391, respectively. The input and output sides have exceptionally low reflection coefficients, with values below -15 dB. According to simulation results, the LNA has a broad bandwidth of 2 GHz and an acceptable NF between 0.5 and 0.3 within the bandwidth range of the Ku-Band applications. This amplifier circuit model can be used to create and build various LNA circuits for a variety of uses.

1. Introduction

The revolution of telecommunication technologies is increasing in our life day by day. There has been a huge upgrade in the generations of communications and systems [1]. Wideband circuits exhibiting high noise sensitivity are utilized in widely applicable applications such as transceivers with high data rates, instrumentation systems, satellite communication, and image processing systems. A wideband LNA is a crucial part of these systems' receivers. It can be difficult to design a broadband LNA because it must meet several strict requirements over a large bandwidth, such as high gain, low noise figure (NF), low power consumption, and good linearity. The LNA represent one of the main challenges of any RF circuit in modern communication systems and a key block in the receiver section [2-4]. The first stage in most communication receiver systems is LNA, it is designed to amplify very low signals while maintaining the highest possible signal-to-noise ratio (SNR) and minimizing noise [5-7]. Noise figure and gain are the essential indicators of the LNA which enhance the sensitivity of the receiving system and improve the quality of service [1, 8, 9, 10]. As seen in Figure 1, the LNA is consists of three primary stages: the matching circuit for input side, the active component like transistor and the matching circuit for output side [11].

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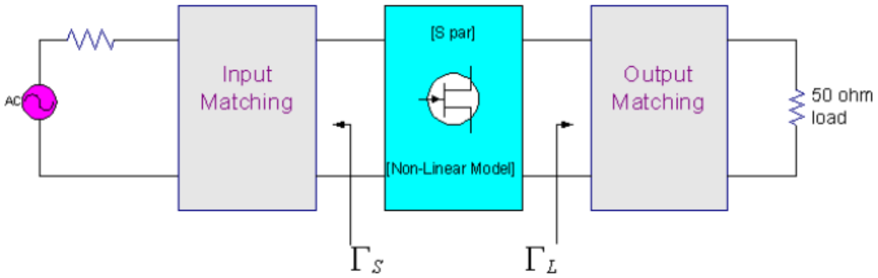


Figure 1. Single stage LNA [11, 12]

The LNA design has been widely used in CMOS, HBT, and MESFET. In particular, CMOS provides low power consumption without NF or gain. Moderate gain and greater NF are provided by HBT and MESFET, respectively. The goal of the LNA is to achieve high gain and minimal NF. GaAs FET technology is selected because it satisfies the design's goals. To get more gain and low NF, the Ku band LNA design is more difficult. To overcome these obstacles and get better results, we use a class AB amplifier to reduce noise and improve linearity in the first stage of LNA and choose optimal values for input and output impedance. At the same time, we use a second stage amplifier to work as a signal amplifier and achieve high gain.

In [13], a two-stage Ku band LNA based on hetero-junction field effect transistor (HJFET) was designed and simulated to operate in the frequency band of 12 GHz for satellite applications. HJFET transistor was used as an active device to achieved low NF. Input and output matching of the transistor maximized power gain, achieving up to 25.81 dB. However, the amplifier has a wide bandwidth and small k-factor of 1 GHz and 1.058 respectively. At the operation frequency of 12 GHz, the LNA produces a return loss equal to -10.61 dB and a NF of 0.40 dB.

The work in [14] presented a LNA with GaAs-MESFET at Ku Band for satellite receiver. A transistor of type GaAs MESFET was used as the main component to build the LNA circuit. The LNA exhibited an acceptable power gain of 9 dB and 2.2 dB NF at 12 GHz center frequency. However, the amplifier has a bandwidth and small K-factor of 500 MHz and 1.826 respectively.

The LNA based on a hetero-junction FET transistor for satellite communication applications was designed and simulated in [15]. In order to reduce out-of-band interference, a LPF is integrate to the heterojunction transistor's output side based on a judicious matching structure selection. At 12 GHz, The LNA obtains a power gain of over 24dB and an NF of less than 1.6dB.

Designing process of LNA is usually started by defining the application that implies a specific figure of merits. Table 1 lists the main requirements of LNA design of Ku-band telecommunication applications. The design process of the amplifier was carefully done to make sure the requirements are met.

Table 1: Design goals

Frequency	**12 GHz**
Bandwidth	Wide band
NF	< 1 dB
Gain	>20 dB
S11	< -15 dB
S22	< -15 dB

The structure of this work is as follows: The LNA design procedures are given in Section 2. In the third section, an ADS software-based single- and double-stage LNA circuit design is presented. Section four presents the simulation results and comments.

2. LNA Design

Class AB configuration was chosen for this work because of its capacity to provide low noise figure and excellent linearity. Actually, the most important stage in designing a LNA by choosing the type of transistor. At the lowest possible current consumption [16], the transistor is expected to operate with the highest third intercept point (IP3), low NF and acceptable gain. while maintaining reasonably easy matching at the operating frequency [17, 18]. Using lumped elements based on input and output T-matching circuits, the FET transistor is utilized to magnify the input signal at 12 GHz. Through a meticulous design process, the element values were determined with the goal of lowering reflection at the input and output terminals. The transistor is biased to function at the selected class (AB) using gate source voltage (Vgs) of -0.2V and drain source voltage (Vds) of 4V. Figure 2 shows the design steps for designing the LNA. The single stage LNA topology design process is illustrated in this section. Such as, input and output matching network analysis, tuning-optimization characterization, S-parameter simulation, DC bias and stability simulation.

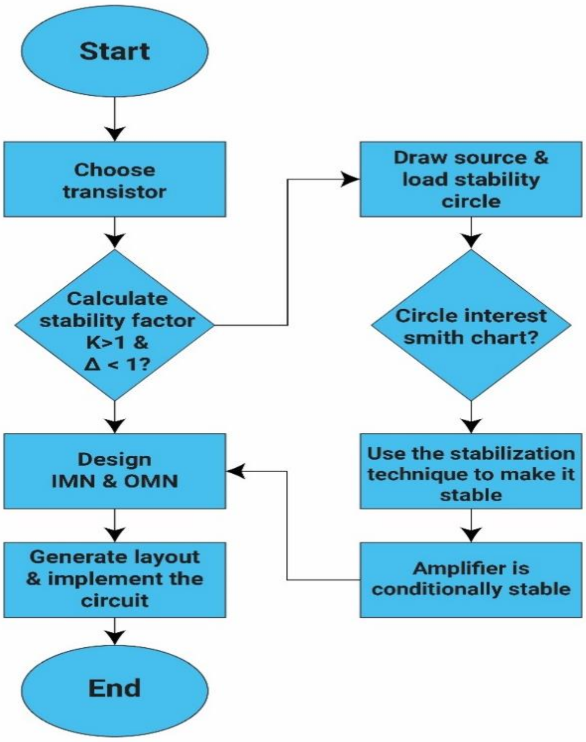


Figure 2. Design steps of LNA

2.1 DC Biasing and Stability of LNA

Modeling the transistor's I-V characteristics at various Vgs values (0 to -1V) and Vds values (0 to 5V) was the initial step in the design process, as illustrated in Figure 3. The transistor must be biased at a point between the cut-off region and the class A Q-point in order to performed as a class AB amplifier. This study selected an ideal point between the Q-point and cut-off zone, as indicated in Figure 3 (marker-mBiasPt), which produced Vgs and Vds values of -0.2V and 4V, respectively. With an output current of 31.7 mA, this configuration is an effective choice for achieving high output power and low noise figure (NF).

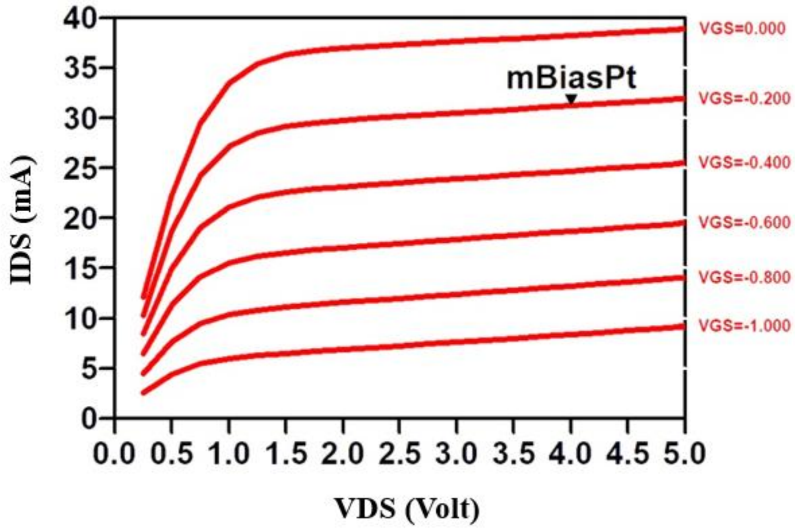


Figure 3. The results of biasing circuit

In this work, an optimum point as shown in Figure 4 (marker-mBiasPt) was chosen above the Q-point that has resulted in Vgs and Vds values of -0. 2V and 4V respectively. This gives an output current of 31.7 mA which makes it a good candidate to deliver high gain with low noise figure.

The LNA's operation point was modified to ensure that the transistor operates in a region of unconditional stability. Equations 1 and 2 mathematically shows how this factor mostly depends on the reflection coefficients. [19- 23]

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

$$\Delta = S_{11}.S_{22} - S_{12}.S_{21} \quad (2)$$

where Δ: Rollett's stability factor, $k: stability\ factor$, S: scattering parameter coefficient.

Figure 4 illustrates the selection of k>1 and Δ<1 at the operational frequency of 12 GHz in our work.

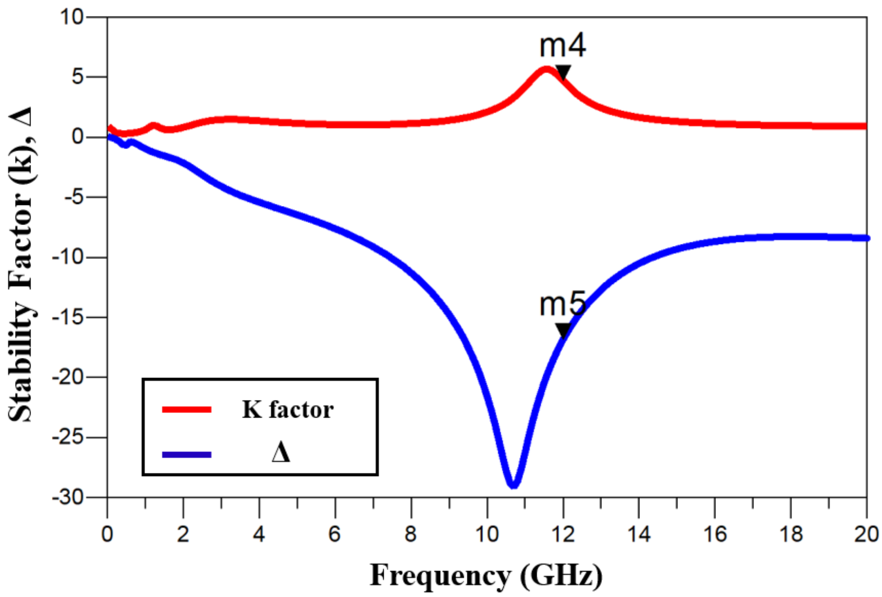


Figure 4. Stability of transistor

In this work, the selected transistor is unconditionally stable, where k=4.697 > 1 and Δ < 1 at the operational frequency of 12 GHz, as shown in Figure 4. In typical radio frequency systems, the LNA design's NF is especially important when the signal's amplitude is low. Equations 3 and 4 provide the two-stage amplifier's NF and available gain [24-26].

$$NF = F_{min} + \frac{4 * R_n * \left|\Gamma_s - \Gamma_{opt}\right|^2}{Z_O * \left(\left|1 + \Gamma_{opt}\right|^2\right) * (1 - \Gamma_S^2)} \quad (3)$$

$$G_A = \frac{1 - |\Gamma_S|^2}{|1 - S_{11} * \Gamma_S|^2} * |S_{21}|^2 * \frac{1}{1 + |\Gamma_{OUT}|^2} \quad (4)$$

where
F_{min}: minimum noise figure
R_n: *impedance of a source noise*
Γ_s: source reflection coefficient
Γ_{opt}: *optimum* reflection coefficient
Γ_{out}: output reflection coefficient

The source impedance, Fmin, Rn, and Γopt all affect the NF. As shown in Figure 5, a set of maximum available gain (MAG) circles, comprising the NF circles, were constructed on the Smith chart in order to extract the value of the NF. The desired LNA at 12 GHz achieved NF of 0.4 dB with a MAG of 15.2 dB.

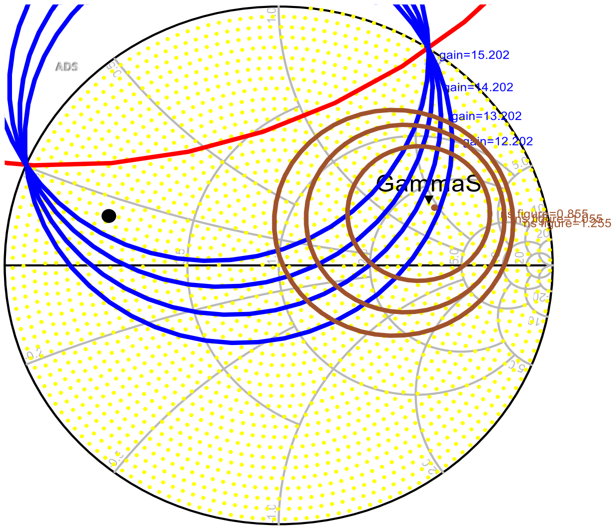


Figure 5. Maximum available gain and minimum NF

2.2 Matching network design

The matching network (MN) design is a very important step in designing LNA because it is aimed to achieving highest output deliver power and high gain [27-29]. The design of matching circuit is challenging and requires careful process to select the impedances of the transistor for input and output sides at operating frequency. It is well known that the impedance of the transistor varies with the applied DC voltages (Vds and Vgs). The values of Vds and Vgs were fixed at 4V and -0.2V, giving a source impedance and load impedance of the transistor as shown in Figure 6. According to Fig.6, the extracted transistor's load and source impedances are (10.9+j7.18) Ω and (121.45+j91.1) Ω, respectively. These values were selected for the transistor's input and output impedance since they give as maximum as output power and lowest noise figure by load and source pull tool in ADS software and shown in Figure 6.

The input and output MN were implemented using T-match simple element matching network. In this work, the quality factor for the matching network was set to 10. To implement matching network, Smith chart was used to utilize method is providing by ADS software, as shown in Figure 7.

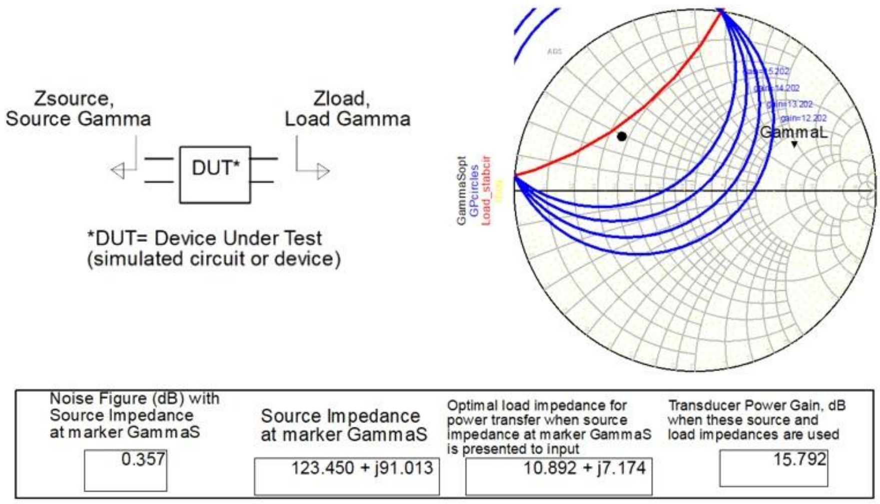
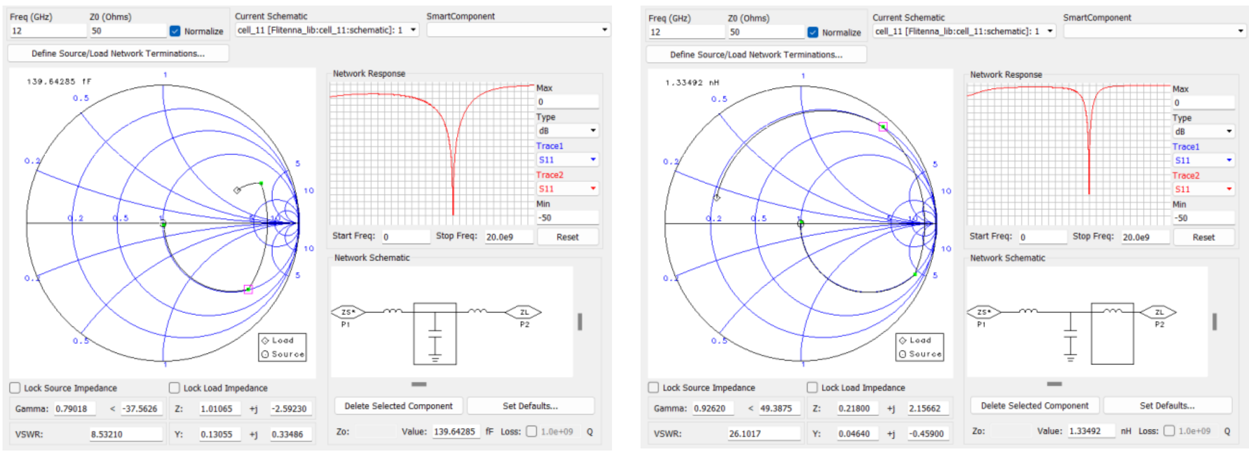


Figure 6. Input and output impedance by load and source pull tool



a) b)

Figure 7. Matching network design, a) IMN, b) OMN

3. LNA Circuit and Simulation

3.1 Single stage amplifier design

Figure 8 illustrates the single stage LNA with the T-style matching network, which includes R1 and R2 as stabilizing elements. In this work, the length of the open stub and microstrips line for the MN is determined using the FR4 substrate, which has a permittivity of 4.3 and a loss tangent of 0.025 at an operating frequency of 12 GHz. For the transmission lines, copper with a 0.035mm thickness was utilized.

To validate and verify the proposed design, the schematic design of the circuit was transformed into the Momentum platform of the ADS software to create the layout designs, as shown in Figure 9.

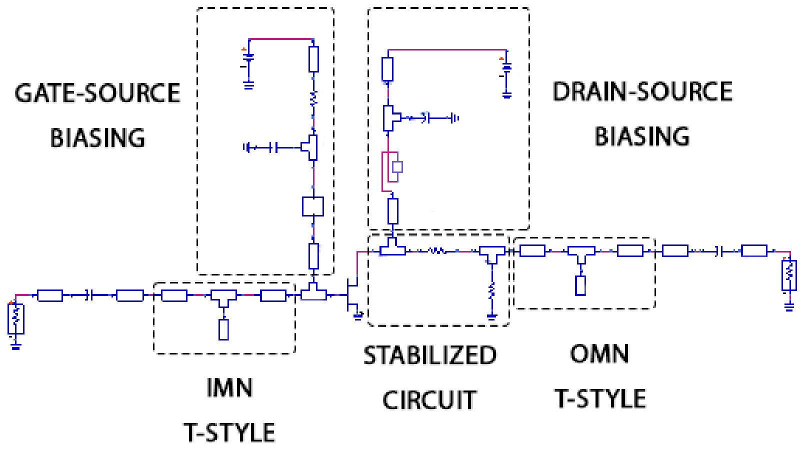


Figure 8. The proposed LNA as microstrips

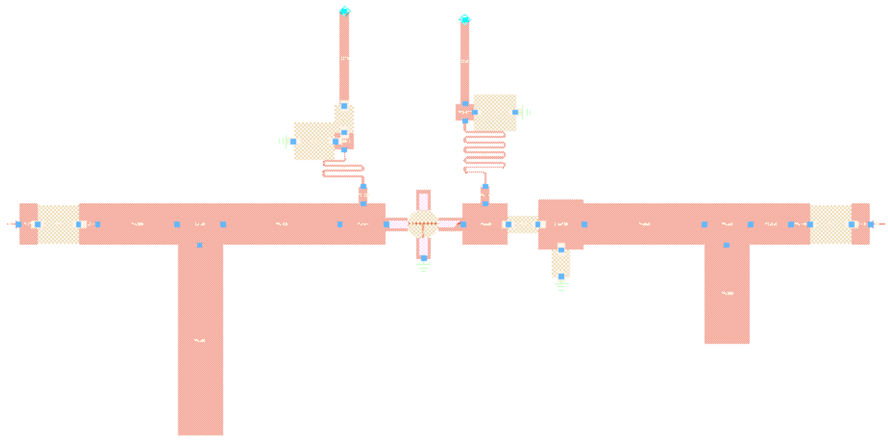


Figure 9. The Layout of the LNA with input and output MN

3.2 Multistage amplifier design

In this work, a two-stage LNA using T type matching networks was designed and simulated for Ku-band telecommunication applications to achieve high gain and good performance. Transistor of type GaAs FET MRF2407A is used as the active device in the first and second stages of the design process. The substrate selected for the matching circuit structure was glass epoxy FR-4. ADS software was employed during the design phase to determine the scattering characteristics, insertion, and reflection losses of each port. Figure 10 shows the final circuit design of a LNA multi-stage integrated with a suitable matching network.

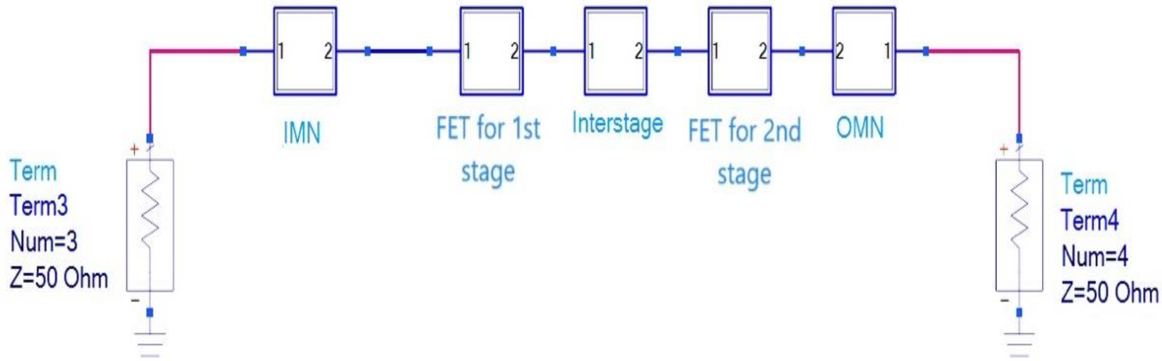


Figure 10. Circuit Diagram of a Multi-Stage LNA

Figure 11 obtained the simulation results of two-stage LNA. At 12 GHz, the desired LNA has achieved a 34 dB gain and a 0.391 dB NF, which could be suitable for different applications such as satellite telecommunication applications.

The S-Parameter result of multi-stage and single stage LNA shown in Figure 12. The results show the simulated values of S11 for the single-stage LNA (red-colored dotted line) and two-stage LNA (straight line) designs, the proposed amplifier achieving a bandwidth of 2 GHz with S11 and S22 values at 12 GHz, with approximately -15 dB and -68 dB, respectively.

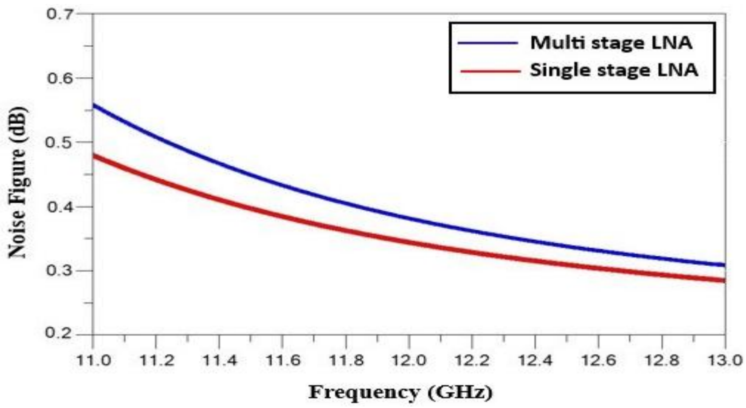
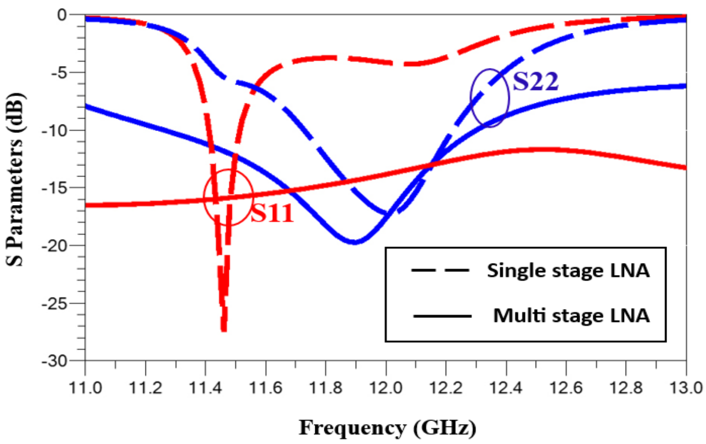
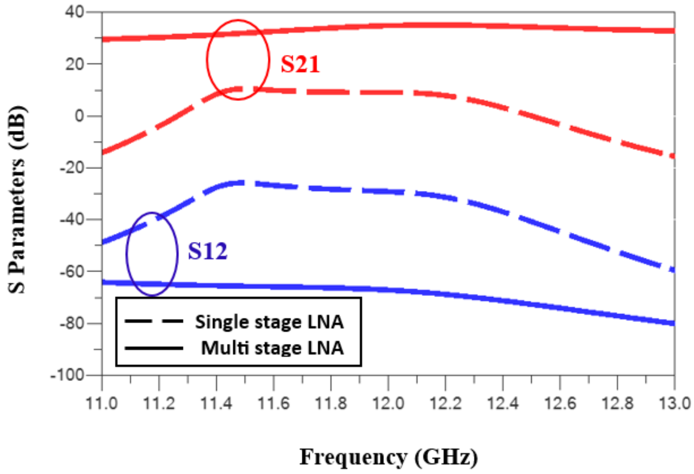


Figure 11. Noise Figure



a)



b)

Figure 12. S-Parameter Result of Multi-Stage and Single Stage LNA a) Output and Input Return Losses, b) Gain and Isolation Losses

Cascading two amplifiers will boost the LNA's gain. However, cascading two amplifiers together could raise the system's total (NF). The difference between the two amplifier stages can be minimized through careful design of the interstate matching network. Two identical amplifier stages are cascaded in this design to produce a high gain and a straightforward circuit construction.

The S-Parameter analysis of the proposed Single Stage LNA in comparison with multi-stage LNA design is shown in Fig.١٢. The obtained results had been compared with results obtained from references [9, 13, 14, 15, 30-34] as shown in Table 2.

Table 2: Compares the performances of the proposed LNA with other reported simulation and experimental works

Reference	Topology	Frequency (GHz)	Noise figure (dB)	Stability factor	Gain (dB)	S11 (dB)	S22 (dB)	S12 (dB)
Ref. [9]	InGaAs HEMT	12-18	1.008	15	29.7	-13.05	-11.97	-66.58
Ref. [13]	HJFET	12	0.4	1.058	25.81	-10.61	-33.4	-
Ref. [14]	GaAs-MESFET	12	2.188	1.826	8.90	-22.62	-22.63	-
Ref. [15]	HJFET	12-13	1.55	-	24	-	-	-
Ref. [30]	GaAs HEMT	10.3-10.5	1.43	1.02	21.654	-39	-39	-16.16
Ref. [31]	CMOS	12-18	4.958	2.344	10.123	-11.31	-4.851	-24.76
Ref. [32]	GaAs pHEMT	11-19	1.4	-	20	>-20	-	-
Ref. [33]	GaAs HEMT	13-17	1.6 – 2	-	23.2 – 25.5	-11	-35	-
Ref. [34]	GaAs FET	10.5-12.5	0.56	3-3.5	20	-14	-25	-
This work	GaAs FET	11.5-12.5	0.391	4.697	34	-15.26	-18.21	-67.92

When compared to other studies conducted at 12 GHz, Table 2 demonstrates that the gain per stage and the NF for this investigation are superior. Compared to previous efforts, an LNA with a high gain of 34 at 12 GHz was created in this work.

Table 2 compares the performances of the proposed LNA with other reported simulation and experimental works [13, 14, 30-34] including gain, NF, stability factor, and S-parameters. The comparison indicates that proposed design has successfully achieved competitive figures of merit, making it a promising candidate for satellite telecommunication systems.

The desired LNA in this work is more stable (with k-factor more than 4) compared to the LNA in [13, 14, 30, 31] (with K-factor less than 2.5), and this is due to the use of series and parallel resistors and band pass filter, where highest stability factor was achieved in [9] with a value of 15, compared to 4.27 obtained in this work. Moreover, the proposed design has better characteristics in terms of higher gain, wider bandwidth and NF is 0.391 dB. Furthermore, the proposed design recorded a better S11, S12, S21, and S22 values compared to LNA in [9, 13, 30-34]. This can be attributed to the careful consideration of multiple factors during the design process, including optimized matching network designs and the selection of transistor load and source impedances, both of which are crucial for maximizing the amplifier's output power and minimizing NF. Furthermore, in comparison to other research in [14, 15, 30, 31], the suggested amplifier shows a wide B.W. of more than 2 GHz, which is directly related to the use of microstrip transmission lines in matching network design

4. Conclusions

A Ku-band LNA operating at 11–13 GHz has been designed for satellite applications, focusing on achieving a minimum noise figure (NF), maximum gain, and low power consumption. The MRF2407A GaAs FET transistor was used in the construction of the dual stage LNA. This work demonstrates that both NF and gain can be improved by selecting optimal source and load impedances for the transistor and utilizing a T-type matching network. The Agilent Design System (ADS) software is used in this work in order to implement the proposed LNA circuit. The proposed LNA achieved a 0.391 dB NF and a 34 dB gain at 11–13 GHz. The output (S22) and input (S11) return losses, according to the simulated results, are less than -15 dB. The designed LNA is unconditionally stable with a k-factor greater than 4, ensuring stability across the 11–13 GHz range. The LNA's isolation is optimized with an S12 value of less than -65 dB These results confirm that the proposed Ku-band LNA is well-suited for satellite applications, showing a better matching between the design objectives and the simulated performance.

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