Design of C-band Low-noise Amplifier (LNA) Using E-pHEMT Device for Satellite Communication System

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Abstract. A low-noise amplifier (LNA) plays an indispensable role in a communication system for amplification purposes at the transceiver. LNA design in radio frequency (RF) circuits involve various key attributes, namely noise figure (NF), gain, and power consumption. This paper focuses on the design of a C-band LNA for satellite communication system with a centre frequency of 6 GHz using ATF-55143 enhancement-mode pseudomorphic high-electron-mobility transistor (E-pHEMT) technology. The LNA performance is augmented by adding inductors to the drain and gate of the ATF-55143 transistor. Smith chart impedance matching technique is implemented to foster a more precise matching for input and output of the LNA. In this work, the C-band LNA is biased at V_DS of 2.7 V and I_DS of 10 mA. Electromagnetic (EM) software is used to design and simulate the performance of the LNA circuit layout. Simulation results indicate NF of 2.66 dB and power gain (S₂₁) of 12.29 dB. The LNA consumes 27 mW from a 3 V DC supply.

1. Introduction

Low-noise amplifier (LNA) is commonly the most crucial element in a radio frequency (RF) transceiver system. At the receiver section, LNA is used to amplify weak RF signals at microwave frequency with minimal distortion prior to passing them to the later stages of the system [1-2]. Critical parameters which determine the LNA performance are input and output impedance matching, noise figure (NF), gain, and linearity [3-5]. The LNA performance, in turn, has a dominant influence on the gain, NF, signal bandwidth, and power consumption of the overall reception chain [6-8].

The standard configuration of an LNA includes an input matching network, a transistor amplifier, and an output matching network [9]. Numerous LNA designs have been stated to apply high-electron-mobility transistors (HEMTs) or pseudomorphic high-electron-mobility transistors (pHEMTs) process due to their low-noise intrinsic traits [10-11]. However, pHEMT technology is favoured in LNA transceiver systems as it offers low noise, high gain, high reliability, high linearity, and high transconductance [12-13]. The C-band LNAs are also widely implemented for wireless local area networks (WLANs) and satellite communications since they offer low-noise performance, high data rate, and high speed with less power dissipation [14].

RF devices are built to function at the diverse frequency spectrum of the RF bands. The proposed LNA is initiated to operate at 6 GHz which is in the C-band frequency range. This particular band is appropriate for both wireless and satellite communications, and radiolocation applications [15].
Communication satellites operating in the C-band employ uplink/downlink frequencies of 6/4 GHz. The C-band is the first portion of the radio spectrum to be applied for satellite communications and is still widely used due to its usability in heavy rain and high accessibility of components.

Iyer and Shanmuganantham designed an LNA for C band applications with a power gain \( S_{21} \) of 13 dB and NF of 2.2 dB at 6 GHz [7]. In 2017, the design of LNA for satellite uplink proposed by Iyer and Shanmuganantham obtained an \( S_{21} \) of 8.96 dB and NF of 2.56 dB at 6 GHz [16]. A wideband p-HEMT LNA designed by Kumar and Pathak revealed an \( S_{21} \) of 9 dB and NF of 1.5 dB over the frequency range of 5-6 GHz [17]. Parkavi and Ravi has introduced an RF low noise and high gain amplifier for wireless communication in 2016 with \( S_{21} \) of 13.2 dB and NF of 0.8 dB at 6 GHz [18].

In this paper, an effort to design a C-band LNA operating at 6 GHz for satellite communication system using enhancement-mode pseudomorphic high-electron-mobility transistor (E-pHEMT) technology is initiated. Single stub matching network on both sides (input and output) of the transistor amplifier are designed and included in the LNA circuit to attain an accurately matched impedances for better S-parameter performance. Additionally, they also provide better bandwidth while ensuring maximum output power and maximum possible gain supply by the transistor. DC biasing is performed across the LNA system which permits DC power flow while simultaneously impedes the coupling of microwave signals to the DC supply. The LNA is designed by using electromagnetic (EM) simulator. Simulated results of the proposed C-band LNA are presented.

2. C-band LNA circuit design

The LNA design procedure is as listed below:

- Selecting a proper active device i.e. transistor.
- Inspecting the stability of the device using S-parameters.
- Employing appropriate techniques to stabilise the device if it is found unstable at the chosen operating frequency.
- Exerting proper biasing based on the operating goal desired and design purpose.
- Optimising the input and output matching circuit design.

The general LNA structure consists of an active device represented by its S-parameters [19]. When designing for an LNA, it is essential for the active device to have the least intrinsic noise. E-pHEMT is a semiconductor technology optimised for wireless applications, operating from a single positive voltage source. E-pHEMT devices are non-conductive and only sink current when both the drain and gate are biased, irrespective of the sequence. Therefore, negative voltage supply, drain switch, and sequencing circuitry are not necessary. This technology solves system-integration problems and allows pHEMT circuits to be easily applied for assorted applications [20].

Stability is determined based on the selected S-parameters using Rollet’s stability factor given by (1) and (2). The transistor amplifier is unconditionally stable if \( K \) is greater than unity (\( K > 1 \)) whereas it is conditionally stable if the \( K \) is less than unity (\( K < 1 \)). Plotting stability circle on the Smith chart is crucial to establish knowledge in which area the LNA is not stable to avoid it from oscillating. Rollet’s stability factor defined in [21] is given by:

\[
\Delta = \frac{1 - |\Delta_{11}|^2 - |\Delta_{21}|^2 + |\Delta|^2}{2|\Delta_{12}||\Delta_{21}|} \geq 1
\]

\[
|\Delta| = |\Delta_{11}\Delta_{22} - \Delta_{12}\Delta_{21}|
\]

In this work, the stability factor, \( K \) is 1.04. Thus, the device is unconditionally stable for any arrangement of source and load impedances.
Figure 1 shows the simulated K-factor of the E-pHEMT device (ATF-55143).

![Figure 1](image1.png)

**Figure 1.** Simulated K-factor of ATF-55143.

If the transistor amplifier is conditionally stable ($K < 1$), its gain becomes maximum stable gain (MSG) which is given by

$$K_{\text{MSG}} = \frac{|K_{21}|}{|K_{12}|}$$

(3)

However, if the device is unconditionally stable ($K > 1$), the gain is denoted as

$$K_{\text{MSG}} = \frac{|K_{21}|}{|K_{12}|} (\pm \sqrt{K^2 - 1})$$

(4)

Figure 2 shows the simulated maximum allowable gain (MAG) of ATF-55143.

![Figure 2](image2.png)

**Figure 2.** Simulated MAG of ATF-55143.
The E-pHEMT process is selected for the design as it reaches the requirements of the proposed C-band LNA. With reference to the stability analysis, biasing conditions for the LNA are determined. Operating bias points of ATF-55143 are designed by adhering to the datasheet with $V_{DS} = 2.7$ V and $I_{DS} = 10$ mA. The bias circuit includes resistors between the drain and gate of the transistor amplifier, and DC power supply, which represent a voltage divider network. The resistors are coupled with a series capacitor ($K = l \square$) in a feedback loop to inhibit feedback effect on the DC bias. The structure of the DC bias circuit is constructed by an EM simulator. Resistor values are calculated as $K_1 = 4460 \Omega$, $K_2 = 28.6 \Omega$, $K_3 = 10 \Omega$, and $K_4 = 940 \Omega$ to obtain the bias points mentioned. The bias circuit, powered with a 3 V DC supply, is shown in figure 3.

![Figure 3. DC bias circuit with $V_{DS} = 2.7$ V and $I_{DS} = 10$ mA.](image)

From the ATF-55143 datasheet, the S-parameter $S_{12}$ (reverse-transmission coefficient) is 0.094 at 6 GHz which is considered insignificant ($S_{12} = 0$). Therefore, unilateral amplifier design is assumed while designing the impedance matching circuits of the LNA. This suggests that the transistor network is guaranteed to have almost zero internal feedback. According to the unilateral amplifier design rule, when $S_{12} = 0$, input reflection coefficient, $\Gamma_{in} = \square_{11}$ and output reflection coefficient, $\Gamma_{out} = \square_{22}$ [21]. 50 $\Omega$ load terminations are utilised to calculate S-parameters of the network. The Smith chart matching impedances are drawn and calculated to obtain the length and width of the transmission lines and stubs for both input and output matching impedances.

From the plotted Smith chart, the transmission line and stub lengths at the input matching network are $l_1 = 7.9$ mm and $l_2 = 8.1$ mm. For the output matching network, the transmission line and stub lengths are $l_3 = 11.6$ mm, $l_4 = 17.6$ mm, $l_5 = 11.4$ mm, and $l_6 = 9.0$ mm respectively. All transmission line and stub widths are the same ($w = 3.0$ mm) since they are designed at 50 $\Omega$ terminations.
The LNA circuit is designed on FR-4 with specifications of $\varepsilon_r = 4.6$, $H = 1.6$ mm, $T = 0.035$ mm, and $\tan \delta = 0.01$ according to [22]. A complete schematic diagram of the proposed C-band LNA is shown in figure 4.

![Schematic diagram of the proposed C-band LNA design.](image)

Figure 4. Schematic diagram of the proposed C-band LNA design.

3. Results and discussion

The C-band LNA circuit is designed and simulated by using an EM simulator. The DC power supply, $V_{DD}$ is set at 3 V with bias points $V_{DS} = 2.7$ V and $I_{DS} = 10$ mA. Inductors ($\quad 1 = \quad 2 = 1 \mu H$) are incorporated into the DC bias network to boost the LNA gain. When a high-frequency signal is fed into port 1 of the LNA, the impedances of $L_1$ and $L_2$ escalated up to $37.7$ kΩ at 6 GHz. This provides large input impedance for the DC bias circuit.

At 6 GHz signal frequency, impedances of $L_1$ and $L_2$ are increased and the DC bias network i.e. $R_1$, $R_2$, $R_3$, and $R_4$ are totally separated from the matching impedance network (transmission lines and stubs). This provides a purely matched input and output for the source and load of the LNA. In other words, as the 6 GHz signal enters the transistor amplifier, both $L_1$ and $L_2$ act as chokes where they block the AC signal from entering the DC power supply, $V_{DD}$. 
The LNA circuit incorporated with inductors to improve the gain response is shown in figure 5.

![Circuit Diagram]

**Figure 5.** Addition of inductors to the LNA circuit.

Assimilating inductors to the C-band LNA system offers high-frequency isolation which upgrades the LNA performance and increases the power gain delivered at the output of the LNA up to 12.29 dB.
Figure 6 shows the simulated S-parameter results of the C-band LNA. The input and output reflection coefficients ($S_{11}$ and $S_{22}$) shown in figure 6(a) are -25.21 dB and -20.12 dB respectively at 6 GHz.

![Figure 6(a)](image1)

Meanwhile, the LNA power gain ($S_{21}$) shown in figure 6(b) has a peak value of 12.29 dB at the designated frequency operation.

![Figure 6(b)](image2)

**Figure 6.** (a) Input and output reflection coefficient ($S_{11}$ and $S_{22}$). (b) Power gain ($S_{21}$).
Figure 7 shows the simulated NF. At 6 GHz, the NF obtained is 2.66 dB.

![Figure 7. Simulated NF.](image)

Table 1 refers to figure 6 and figure 7 which illustrate the simulation results of the proposed LNA circuit design.

**Table 1.** Simulated results of the proposed LNA.

| Parameters                        | Simulated results (dB) |
|-----------------------------------|------------------------|
| Input reflection coefficient ($S_{11}$) | -25.12     |
| Output reflection coefficient ($S_{22}$) | -20.12     |
| Power gain ($S_{21}$)             | 12.29       |
| Noise figure (NF)                 | 2.66        |

4. **LNA performance comparison**

Table 2 represents the performance comparison of the designed LNA with other similar, published studies operating at close frequency ranges (6 GHz). The reviewed characteristics of the LNAs include input reflection coefficient ($S_{11}$), output reflection coefficient ($S_{22}$), power gain ($S_{21}$), NF, and power consumption.

**Table 2.** Comparative simulated results.

| Parameters                        | Proposed design | [7]  | [16]  | [17]  | [18]  |
|-----------------------------------|-----------------|------|------|------|------|
| Input reflection coefficient ($S_{11}$) | -25.12 dB     | -48.00 dB | -49.32 dB | -12.50 dB | -12.91 dB |
| Output reflection coefficient ($S_{22}$) | -20.12 dB     | -40.00 dB | -44.94 dB | N.A.  | -14.61 dB |
5. Conclusion

A C-band LNA for satellite communication system application operating at 6 GHz has been presented in this paper. Both input and output matching networks are designed by employing a single open-circuited stub. Smith charts are used to obtain the matched input and output impedance networks. The LNA DC bias is set as such $V_{DS} = 2.7$ V and $I_{DS} = 10$ mA. Inductors are added to the DC bias circuit to isolate it from the matching impedance layout circuit which instigated a better LNA power gain. EM software is utilised to design and simulate the proposed LNA circuit layout. The simulated input and output reflection coefficients ($S_{11}$ and $S_{22}$) are -25.21 dB and -20.12 dB respectively at 6 GHz. A power gain ($S_{21}$) of 12.29 dB is attained from the LNA simulation, with the NF of 2.66 dB. The LNA consumes 27 mW of power from a 3 V DC supply.

References

[1] Kalamani C 2019 Design of differential LNA and double balanced mixer using 180 nm CMOS technology *Microproc. Microsys.* **71** 102850
[2] Haji Konang S 2015 Design of low noise amplifier for radar application (Melaka: Universiti Teknikal Malaysia Melaka)
[3] Chen K, Lu J, Chen B et al. 2007 An ultra-wide-band 0.4-10-GHz LNA in 0.18-μm CMOS *IEEE Trans. Cirs. Syst. II: Express Briefs* **54** 217–221
[4] Wang R, Chen S, Huang C et al. 2008 2-6GHz current-reused LNA with transformer-type inductors *Asia-Pacific Microwave Conf.* (Macau: IEEE)
[5] Kushwah A and Katare S 2017 An ultra low voltage, wideband low noise amplifier design technique *Int. Res. J. Eng. Technol. (IRJET)* **4** 805–8
[6] Diaz-Chinea D, Garcia-Vazquez H, Montesdeoca M, Khemchandani S and Pino J del 2015 A wide-band noise-cancelling CMOS LNA based on current conveyors *Conf. on Design of Circuits and Integrated Systems (DCIS)* (Estoril: IEEE)
[7] Iyer M and Shanmuganantham T 2017 Design of LNA for C band applications *Int. Conf. on Circuits and Systems (ICCS)* 211–214
[8] Kumar M and Deolia V 2019 Performance analysis of low power LNA using particle swarm optimization for wide band application *Int. J. Electron. Commun.* **111** 152897
[9] Pozar D 2008 *Microwave Engineering* ed Kulek P and Aiello G (New Jersey: Wiley) chapter 11 540-541
[10] Wu C, Pao C, Yau W et al. 1995 Pseudomorphic HEMT manufacturing technology for multifunctional Ka-band MMIC applications *IEEE Trans. Microw. Theory Tech.* **3** 257–266
[11] Mimura T 2002 The early history of the high electron mobility transistor (HEMT) *IEEE Trans. Microw. Theory Tech.* **50** 780–2
[12] Sharma S and Sharma S 2014 Design and simulation of three stages pHEMT LNA at C-band *Int. J. Res. Appl. Sci. Eng. Technol.* **2** 358–361
[13] Khan M, Zhang H, He P, Shahzad S and Ullah R 2015 A pHEMT based wideband LNA for wireless applications *China Commun.* **12** 109
[14] Larson L 1996 *RF and Microwave Circuit Design for Wireless Communications* ed Larson L E (Norwood: Artech House Inc.)
[15] U.S. Department of Commerce National Telecommunications and Information Administration, United States Frequency Allocations [Online] Available: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf
[16] Iyer M and Shanmuganantham T 2017 Design of LNA for satellite uplink *Int. Conf. on Intelligent Computing Systems (ICICS)* 255–264
[17] Kumar A and Pathak N 2014 Design and characterization of a wideband p-HEMT low noise amplifier Int. Conf. on Advances in Computing, Communications and Informatics (ICACCI) 785-788

[18] Parkavi N and Ravi T 2016 Design and analysis of RF low noise and high gain amplifier for wireless communication ARPN J. Eng. App. Scis. 11 11584-8

[19] Lahsaini M, Zenkouar L and Bri S 2013 Design of broadband low noise amplifier based on HEMT transistors in the X-band Int. J. Eng. Technol. 5 468–476

[20] Kong S, Lee H, Kim C and Park B 2017 A 21.9-dB Gain 18.9–35.9-GHz low noise amplifier using InGaAs E-mode 0.15-μm pHEMT technology IEEE Asia Pacific Microwave Conf. (APMC) 1203–1206

[21] Yip P 1990 High-Frequency Circuit Design and Measurements (London: Chapman & Hall) chapter 6 101-102

[22] Turkish Electric Power FR-4 data sheet [Online] Available: \nhttp://www.turkishelectricpower.com/wp-content/uploads/2015/11/FR4-_used-for-PCB_-_Technical-Specifications.pdf