X-band monolithic three-stage LNA with GaAs E-mode PHEMT

Zhengxing Zuo¹, Shufeng Sun²

¹Xi’an Branch, China Academy of Space Technology, Xi’an, 710000
²Xi’an Branch, China Academy of Space Technology, Xi’an, 710000

Corresponding author e-mail: lotlance86@gmail.com

Abstract. An LNA for 8~12 GHz is proposed in this paper. The amplifier uses a GaAs process with cost-effective, E-mode HEMTs with gate widths of 0.25 µm and 0.45 µm. The three stages of the LNA are powered by dual power supplies, with a drain operating voltage of +3V and a gate operating voltage of +0.7V. The simulation results of the schematic diagram show that the noise factor of the low-noise amplifier is less than 2.5dB in the frequency range of 8-12GHz, the in-band gain is greater than 30dB, the gain flatness is ±1.5dB, the 1dB compression point is 7dbm, the VSWRs are less than -10dB, and the LNA is absolutely stable in the X-band.

1. Introduction
The main role of an LNA is to amplify the signal received by the antenna, which is the first active device in the front end of the radar receiver, and the performance and cost of the LNA largely determine the performance and cost of the whole radar. Therefore, it is very important to design an LNA with reasonable gain, low noise, reliable and stable in the receiver front-end design. The LNA designed in this paper covers the X-band of the geomagnetic spectrum. The MMIC is designed using 0.25 µm and 0.45 µm low-noise E-HEMT processes and can be used as a unit circuit in a transceiver multifunction chip[1].

2. Design Theory
Microwave network theory has become a powerful tool for microwave technology, and its parameters can be obtained by simple calculations or experimental measurements. The transistor amplifier is a typical two-port network[2]. The block diagram is shown in Figure 1, where Γ_S represents the source reflection coefficient, Γ_in represents the transistor input reflection coefficient, Γ_out represents the transistor output reflection coefficient, and Γ_L represents the end-load reflection coefficient. Different Γ_S and Γ_L will directly determine the stability, noise figure, gain, VSWRs and other performance parameters of the transistor circuit[3].

Figure 1 Transistor amplifier circuit schematic
2.1. Stability
For RF systems, since the LNA must be connected to 'external', the LNA is connected to a source impedance that is very difficult to control. Therefore, for any source impedance and any frequency, the LNA should remain absolutely stable. Some people will feel that the low-noise amplifier simply needs to maintain stable operation in its operating frequency range, and does not need to maintain stability in other frequency ranges, but assuming that the low-noise amplifier will generate oscillation at a certain frequency, then the low-noise amplifier will become highly nonlinear, and its gain will be severely attenuated[2].

The Stern stability factor is used to characterize circuit stability and is defined as in Equation 1.

\[ K = 1 + \frac{\Delta}{2|S_{11}|S_{12}} \]

In the above equation \( \Delta = S_{11}S_{22} - S_{21}S_{12} \). If \( K > 1 \) and \( \Delta < 1 \), then the circuit is unconditionally stable, the low-noise amplifier will not oscillate under any combination of source and load impedances[2].

In modern RF transceiver designs, the load impedance part of the low-noise amplifier is relatively easy to control, so \( K \) is a conservative measure of stability. Therefore, another single parameter is also proposed to determine the stability of the two-port, which can compare the mutual stability of two or more devices, as defined in Equation 2. When \( \mu > 1 \), the device is unconditionally stable, and the larger the value, the higher the stability[3].

\[ \mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}| + |S_{21}|S_{12}} > 1 \]

2.2. Noise characteristics
The noise factor \( F \) of a low-noise amplifier can be expressed by the following equation 3.

\[ F = F_{\text{min}} + 4 \frac{R_n \left| \Gamma_s - \Gamma_{\text{opt}} \right|^2}{Z_o \left( 1 - \left| \Gamma_s \right|^2 \right)^2 \left( 1 + \left| \Gamma_{\text{opt}} \right|^2 \right)^2} \]

In the above equation, \( F_{\text{min}} \) is the minimum noise coefficient that can be obtained from the device; \( R_n \) is the equivalent noise resistance of the device, and \( \Gamma_{\text{opt}} \) is the optimal reflection coefficient to obtain the minimum noise coefficient. Therefore, when \( \Gamma_s = \Gamma_{\text{opt}} \), noise coefficient reaches the best. However, the optimal noise point is often different from the optimal power matching point, and the power matching determines the VSWR of the circuit, so the ideal input VSWR is often not obtained when using minimum noise matching[2].

2.3. Gain
The gain of the low-noise amplifier must be large enough so as to reduce the effect of post-stage circuit noise on the overall RF link noise, but increasing the gain will make the nonlinearity of the post-stage more severe. Therefore, the design of the low-noise amplifier requires a compromise between gain, noise factor and linearity of the receiver[2].

3. LNA structure design and schematic simulation results

3.1 Device selection and DC bias circuit design.
To design a low-noise amplifier, the first step is the selection of amplifier transistors. From the consideration of operating band and datasheet, the process of Xiamen Sanan is selected for this design. Before designing the DC bias circuit, the DC parameters are scanned and the transistors exhibit different operating states at different static operating points[4].
Considering the compromise between noise factor and gain, a transistor with a gate width of 0.25 µm is selected for the first stage, and a transistor with a gate width of 0.45 µm is selected for the last two stages. The first stage transistor is selected to work between the \text{\textit{I}} and \text{\textit{IV}} regions.

3.2. Stability design
The LNA design should ensure that it remains absolutely stable over the full frequency band to prevent self-excitation. Therefore, after determining the DC bias circuit, the stability simulation of the transistor using ADS yields K less than 1, which is potentially unstable. To improve the stability of the LNA, a form of negative feedback is used in series with the source stage, which means that a section of grounded microstrip line is connected in series with the source stage[5].

3.3. LNA design and schematic simulation results
In this design, considering the design complexity, the first stage uses microstrip lines with decoupling capacitors to achieve DC bias, and multi-order LC matching is used to obtain wide VSWRs[6]. Figure 2 and Figure 3 show the topology and layout of the first stage amplifier.

Figure 2 Pre-stage LNA structure
Figure 3 Layout of Pre-stage LNA

Figure 4 is the first stage amplifier schematic simulation results, you can see the pre-stage low noise in the X-band full frequency band to meet \(\text{NF} < 2.25\text{dB}\), \(S_{11}\) and \(S_{22}\) are less than -10dB, and leave a certain amount of protection bandwidth. It can be seen that in the range of 8GHz-12GHz, the gain decreases with the increase of frequency, so when designing the post-amplifier circuit, it is necessary to suppress the low frequency gain and raise the high frequency gain to improve the gain flatness of the amplifier.

![S-parameters](image)

Figure 4. Simulation results of the first stage circuit schematic.

The second stage and the third stage use the same negative feedback design structure to reduce the design difficulty and circuit complexity and improve the high frequency gain. The main purpose of this design is to improve the gain flatness of the low noise amplifier. Secondly, the third stage LNA should also ensure the excellent performance of the output VSWR. The figure 5 and figure 6 show the topology and layout structure of the second and third stage amplifiers.
The second and third stage circuit is mainly to improve the gain flatness and output standing wave, so it can be set when sacrificing some noise factor. It can be seen that the NF < 3db, and the gain increases with the increase of frequency.

Since each amplifier stage is matched to 50 ohms, the three stages can be directly cascaded. The final tuned and optimized three-stage amplifier has a noise factor of NF<2.6dB, S12<-60dB, VSWRs<-10dB and gain >30dB with gain flatness of ±1.5dB. The simulation results of the three-stage low-noise amplifier schematic are shown in Figure 8.

4. Conclusion
A low noise amplifier in X-band is proposed in this paper, using 0.25 µm and 0.45 µm GaAs PHEMT technology, the schematic performance index is simulated by ADS, according to the simulation results, the low noise amplifier can provide 30 dB-31 dB gain in X-band, while having a noise factor less than
2.5 dB, VSWRs less than -10 dB, The output power of 1dB compression point is 9.6 dBm, which verifies that the post-amplifier uses feedback technology to improve the gain flatness. However, in order to obtain good VSWRs characteristics, the matching circuit uses a large number of inductors, resulting in noise deterioration and excessive layout area, and the subsequent design should reduce the use of inductors.

References
[1] Darabi, H. (2015) Radio Frequency Integrated Circuits and Systems. Cambridge University Press.
[2] Razavi, B. (2012) RF Microelectronics, Second Edition. Pearson Education, Inc.
[3] David M. Pozar. (2005) Microwave Engineering, Third Edition. John Wiley & Sons, Inc.
[4] Lessi, C., Karagianni, E.,(2014) An X-Band Low Noise Amplifier Design for Marine Navigation Radars. In: Int'l J. of Communications, Network and System Sciences, pp.7-9.
[5] Caddemi, A., Cardillo, E. (2019). Systematic experimental analysis of an optical sensing microwave low-noise amplifier. In: IET Microwaves, Antennas & Propagation (15).
[6] Balla, L., Gollakota, V.K.S. (2019). Single Stage 38 GHz LNA using 0.1 μm GaAs HEMT.In: International Journal of Innovative Technology and Exploring Engineering (IJITEE).