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Postprint: 1.35–2.0 GHz Low-Noise Amplifier Based on Gallium Arsenide Transistors

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Abstract

Low Noise Amplifier (LNA) is a critical component in receiver systems, whose performance determines the noise temperature of the receiver system and its capability to amplify weak radio-frequency signals. This work employs Avago's Gallium Arsenide (GaAs) process pHEMT ATF-54134 to develop a low-noise amplifier operating within the 1.35–2.0 GHz frequency range. The amplifier utilizes a two-stage topology with single-supply self-biasing configuration. It achieves a typical gain of 28 dB, a typical noise temperature of 35 K, input return loss better than -10 dB, output return loss better than -15 dB, and an input 1 dB compression point of -13 dBm. The amplifier is applicable not only in radio telescope receivers for radio astronomy observations of neutral hydrogen, pulsars, and hydroxyl, but also in radio environment monitoring systems.

Full Text

Preamble

1.35–2.0 GHz Low Noise Amplifier Based on GaAs Transistor

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Abstract

Low-noise amplifiers (LNAs) are critical components in receiver systems, and their performance determines the noise temperature of the entire receiver system and its ability to amplify weak radio signals. This paper presents the development of an LNA operating in the 1.35–2.0 GHz frequency range using Avago's

GaAs pHEMT ATF-54134 transistor. The amplifier employs a two-stage topology with single-supply self-biasing. It achieves a typical gain of 28 dB, a typical noise temperature of 35 K, input return loss better than -10 dB, output return loss better than -15 dB, and an input 1 dB compression point of -13 dBm. In addition to its application in radio telescope receivers for observing neutral hydrogen, pulsars, and hydroxyl groups in radio astronomy, this amplifier can also be used for radio environment monitoring.

Keywords: low-noise amplifier, radio astronomy receiver, GaAs transistor, input 1 dB compression point, two-stage topology circuit

Introduction

Sensitivity is a crucial metric for radio telescopes, inversely proportional to the system noise temperature. Once a radio telescope is designed, the most effective way to reduce system noise temperature is to lower the receiver's noise temperature. The low-noise amplifier (LNA) is one of the core components in radio telescope receivers, responsible for amplifying input signals from the feed source. The noise and gain performance of an LNA collectively determine the receiver's noise temperature [1], while the gain also determines the receiver's signal amplification capability. Since the advent of the high electron mobility transistor (HEMT) in 1980, it has rapidly become a common device for LNA design [2]. HEMT is a modulated-doped heterojunction field-effect transistor with three terminals: gate, source, and drain. Current flows from drain to source, and the channel width for electron movement is controlled by the gate signal voltage, causing variations in drain current and thereby producing gain [3]. HEMT devices exhibit high cutoff frequency, high transconductance, low noise figure, and low parasitic resistance. The pseudomorphic high electron mobility transistor (pHEMT) was developed based on HEMT and offers even higher transconductance and better RF characteristics [4].

This paper selects Avago's GaAs pHEMT ATF-54143 with an 800 m gate width for LNA design. This transistor can achieve a noise temperature below 28 K at 2 GHz operating frequency. The 1.35–2.0 GHz LNA designed in this work achieves a typical gain of 28 dB, a typical noise temperature of 35 K, input return loss better than -10 dB, output return loss better than -15 dB, and an input 1 dB compression point of -13 dBm.

1. Circuit Design

1.1 Minimum Noise Matching and Bias Operating Point

An LNA can be viewed as a multi-stage transistor system, whose noise performance is given by:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

where $F_1, F_2, \ldots, F_n$ are the noise figures of the 1st to nth stage transistors, and $G_1, G_2, \ldots, G_n$ are the gains of the 1st to nth stage transistors. The noise of the first-stage transistor plays a decisive role in the overall receiver noise level, and adequate gain can also suppress noise generated by subsequent stages. In LNA design, the input matching network must be designed for minimum noise figure, while the first-stage transistor must provide sufficient gain. The noise of a single transistor is given by:

$$F = F_{min} + \frac{R_n}{G_s}|Y_s - Y_{opt}|^2$$

where R_n is the equivalent noise resistance of the two-port network, Γ_s is the source reflection coefficient, Γ_{opt} is the optimal source reflection coefficient corresponding to minimum noise, and F_{min} is the minimum noise figure of the amplifier.

Γ_{opt} is determined by the transistor's inherent characteristics and is influenced by the drain current I_{ds}. According to the ATF-54143 transistor datasheet provided by the manufacturer, which includes a plot of noise figure versus drain current [5], the minimum noise figure decreases as drain current I_{ds} decreases, but the gain also decreases accordingly. Considering the impact of I_{ds} on both minimum noise and gain, combined with DC bias point test results from ADS simulation software, this paper selects a bias point with drain current $I_{ds} = 60$ mA, drain voltage $V_{ds} = 2.3$ V, and gate voltage $V_{gs} = 0.58$ V.

Γ_{opt} is the optimal source reflection coefficient for minimum noise, and Γ_s is the source reflection coefficient. When Γ_s equals Γ_{opt}, the two-port network achieves minimum noise figure. To obtain the lowest noise, the input matching network must be designed for minimum noise figure. Generally, the feed source output impedance is 50 Ω, so the impedance corresponding to the optimal source reflection coefficient must be matched to 50 Ω. This paper designs the input matching at 1.5 GHz, where the corresponding optimal source impedance is $(\langle 53.4 + j14.3 \rangle)\Omega$, yielding a minimum noise figure of 0.243 dB.

1.2 Circuit Simulation

To meet the gain requirements, the circuit design employs two ATF-54143 transistors in a two-stage amplifier configuration, as shown in Figure (1). The circuit topology consists of four parts: DC bias network, input/output matching networks, interstage matching network, and gain compression network.

[Figure 1: see original paper]

The DC bias network uses single-supply self-biasing. Compared with dual-supply configurations, self-biasing offers two advantages: (1) it avoids the need for switch sequencing required in dual-supply designs [6]; and (2) any change in drain current automatically adjusts the gate bias voltage to maintain stable drain current. With R1 = R6 = 215 Ω, R3 = R4 = 60 Ω, and R2 = R5 =

2000 Ω, six Murata resistors establish transistor bias conditions of $V_{ds} = 2.3$ V, $V_{gs} = 0.58$ V, and $I_{ds} = 59.5$ mA at a supply voltage $V_{dd} = 6$ V.

C7 = C8 = C9 = C10 are 22 pF decoupling capacitors that bypass high-frequency noise from the DC circuit and can also serve as energy storage capacitors. C11 = 1 F is a bypass capacitor at the power supply that removes high-frequency noise from the source [7].

C1 = 2.3 pF, C2 = 2.2 pF, and L1 = 2.7 nH form the input matching T-network, which conjugately matches the optimal noise source impedance Γ_{opt} to 50 Ω. Compared with L-networks, T-networks offer broader bandwidth and greater impedance transformation, enabling effective control of the response across the entire frequency band. The interstage matching also uses a T-network to conjugately match the first-stage output impedance Z_{out1} to the input impedance corresponding to maximum transistor gain Z_{in2}.

The gain compression network utilizes the principle that resistors affect transistor gain more than capacitors and inductors at low frequencies, while capacitors and inductors have greater impact at high frequencies—resistors exhibit high loss at low frequencies and low loss at high frequencies—to adjust gain flatness. This paper uses R7 = 33.2 Ω, L4 = 6.2 nH, and C6 = 3.2 pF to form the gain compression network, achieving simulated gain flatness better than 1 dB. Additionally, R7, L4, C6, L3 = 3.9 nH, and C5 = 1.2 pF collectively form the output matching network.

Introducing negative feedback at the transistor source can increase input impedance and improve stability [8]. Source resistor feedback increases noise, so four source feedback inductors (L5, L6, L7, L8) are used instead. In practice, small inductances of 0.8–1.5 nH are sufficient; here, 1 nH inductors are used. To minimize parasitic effects from soldering discrete inductors, microstrip lines are used instead of lumped inductors. Calculations show that a 1 nH inductor corresponds to a microstrip line length of 1.7 mm.

PCB material selection significantly impacts LNA noise performance, as loss in the input signal path introduces additional noise that cannot be removed in subsequent optimization stages [9]. This paper uses RO4350B substrate for circuit simulation, which features low high-frequency loss and standard manufacturing process, with a dielectric constant of 3.66, loss tangent of 0.0037, and thickness of 1.524 mm. The component library uses Murata's library, and the PCB electromagnetic model is shown in Figure (2). The co-simulation S-parameters are shown in Figure (3), and noise parameters are shown in Figure (4).

[Figure 2: see original paper]
[Figure 3: see original paper]
[Figure 4: see original paper]

2. LNA Fabrication and Testing

2.1 PCB Process

Electroless Nickel Immersion Gold (ENIG) is a common PCB surface finish process. The process flow primarily involves copper activation, electroless nickel plating, and chemical gold immersion to deposit a gold layer over the nickel layer [9]. ENIG-processed PCB surfaces are flatter, making them suitable for soldering smaller components. Skin effect occurs in the copper layer beneath the nickel layer, which does not affect high-frequency signal transmission. The gold layer thickness should be between 0.005 m and 0.15 m. When the gold layer thickness exceeds 0.15 m, the gold content dissolved into the solder will exceed 3% by weight, making the solder joint brittle and prone to fracture, affecting soldering reliability and causing black pad defects from accelerated nickel corrosion. When the gold layer thickness is below 0.005 m, the gold layer cannot completely cover the nickel surface, resulting in black spots and whitening that affect solderability [10]. The PCB process parameters used in this paper are shown in Table 1 .

2.2 LNA Test Results

Testing was performed using Keysight's PNA-L Network Analyzer N5232B (300 kHz–20 GHz), Agilent Technologies' U3606A voltage source (0–36 V), and N8974A noise figure analyzer (10 MHz–6.7 GHz). The LNA packaged test is shown in Figure (5) with a supply voltage of 6 V. The comparison between measured and simulated S-parameters is shown in Figure (6), and noise parameter comparison is shown in Figure (7).

[Figure 5: see original paper]

From Figure (6), we observe: (1) The measured LNA maximum gain is 28 dB, slightly lower than simulation results, with gain variation trends consistent with simulation; gain flatness across 1.35–2.0 GHz is better than simulated flatness. (2) S22 variation trends are consistent with simulation, remaining better than -15 dB across the entire band, with optimum performance near 1.8 GHz. (3) S11 variation trends are consistent with simulation, but the resonance bandwidth is wider with better high-frequency performance and slightly worse low-frequency performance, remaining better than -10 dB across 1.35–2.0 GHz. From Figure (7), measured noise performance is somewhat higher than simulation results, with variation trends consistent with simulation at high frequencies.

[Figure 6: see original paper]
[Figure 7: see original paper]

Analysis suggests that differences between measured and simulated S-parameters and noise performance may result from: (1) Actual device S-parameters not perfectly matching manufacturer-provided circuit models, with thermal noise higher than ideal devices; (2) The aluminum alloy package acting as a waveguide, altering the LNA's electromagnetic environment; (3)

Measurement errors from the network analyzer, noise source, and calibration process; and (4) Parasitic effects at discrete component solder joints.

This paper tested the LNA's S-parameters and noise temperature at supply voltages of 4.5 V, 5.0 V, 5.5 V, and 6.0 V. As shown in Figure (8), LNA gain increases with supply voltage, with a difference of nearly 1 dB between 6 V and 4.5 V. Figure (9) shows that S11 decreases with increasing voltage, while S22 increases with voltage. Figure (10) demonstrates that noise performance is better at 5.0 V and 5.5 V than at 4.0 V and 6.0 V, with a typical noise figure of 35 K at 1.8 GHz. Considering gain, S-parameters, and noise figure comprehensively, the LNA developed in this paper achieves optimal performance at 5.0 V supply voltage: in-band gain greater than 26 dB, typical noise temperature of 35 K, S11 better than -10 dB, and S22 better than -15 dB.

[Figure 8: see original paper]
[Figure 9: see original paper]
[Figure 10: see original paper]

The 1 dB compression output power (P1dB) is a metric for amplifier dynamic range; larger values indicate greater linear dynamic range [11]. Within the amplifier's dynamic range, output power increases with input power. When input power increases to a certain level, the amplifier enters nonlinear operation, and output power no longer increases with input power, falling below expected values. This paper measured the 1 dB compression point at 1.8 GHz with a 5 V supply voltage, as shown in Figure (11). The measured input 1 dB compression point is -13 dBm.

[Figure 11: see original paper]

3. Conclusion

This paper presents the design of a 1.35–2.0 GHz LNA using GaAs pHEMT ATF-54143. The amplifier employs a two-stage topology with single-supply self-biasing and operates normally at supply voltages of 5–6 V, featuring good input/output matching, high gain, low noise temperature, and large dynamic range. In addition to applications in L-band radio telescope receivers for radio astronomy, the developed LNA can also be used in space satellite communications and radio environment monitoring systems.

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