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High-performance Room-temperature LNA Development for Radio Astronomy

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Abstract

This paper focuses on the development of high-performance room-temperature low-noise amplifiers (LNAs) for radio astronomy aiming to compete with traditional cryogenic LNAs. The LNA, a core component of the radio telescope receiver, is essential for minimizing the system noise temperature and achieving high sensitivity. This paper details the design and measurement results of two LNAs: LNA1 (1 – 1.8 GHz) for the FAST core array and LNA2 (0.9 – 1.3 GHz) for the BINGO telescope. The results demonstrate that these room-temperature LNAs can match the performance of cryogenic LNAs to some extent, with significantly reduced noise temperatures, particularly when thermoelectric cooling is applied. These advancements provide a more reliable and cost-effective solution for receivers of telescope arrays and multi-beam receivers in radio astronomy.

1. Introduction

The low noise amplifier (LNA), a core component of the radio telescope receiver, is crucial for minimizing the system noise temperature of radio telescopes to achieve high sensitivity. Historically, room-temperature LNAs often had noise temperatures exceeding 30 K. In contrast, cryogenic receivers, which operate at extremely low physical temperatures like 20 K, offer superior noise performance. For instance, the 19-beam receiver currently in use at FAST has a system noise temperature of just 20 K. The LNAs in this receiver have a noise temperature of 5 K. However, cryogenic receivers are complex, requiring components such as vacuum Dewars, refrigerators, and compressors that demand regular maintenance. Additionally, the costs associated with cryogenic receivers are high. For telescope arrays, which require numerous receivers and have a wide distribution, high-performance room-temperature receivers are a more practical choice from the perspectives of reliability, operation, and maintenance costs. The key technological challenge is to develop an LNA that can achieve the same noise level as cryogenic LNAs while operating at room temperature.

In recent years, room-temperature low-noise amplifiers have witnessed remarkable progress. In 2021, a room-temperature LNA developed using InP HEMT transistors exhibited a noise temperature of merely 7 K at 25 °C and 1.4 GHz [1], which is 4.2 times lower comparing to the best commercially available room-temperature LNAs. As mentioned in the relevant paper, a large decrease in noise of InP HEMT will occur when cooling to -40 °C, bringing the noise level of the room-temperature LNA down to that of a cryogenic LNA. However, the specific method for implementing thermoelectric coolers (TECs) for the LNA cooling to -40 °C was not detailed in the article. In 2023, a room-temperature LNA with a frequency range of 0.6 – 2 GHz was developed [2]. At 25 °C, it had an average noise temperature of 11 K.

The Five-hundred-meter Aperture Spherical Radio Telescope (FAST) Core Array [3], currently under construction, will comprise 24 or more 40-m parabolic antennas extending within a 5-km radius of the FAST site. This setup aims to merge FAST's unparalleled sensitivity with high angular resolution (4.3" at 1.4 GHz) to achieve breakthrough scientific outcomes. Each antenna will be equipped with three receivers, operational across the frequency range of 350 MHz to 10 GHz. Among them, two receivers are intended to operate at room temperature. This decision is primarily due to the weight and space constraints of the feed cabin, as well as considerations related to construction cost and maintenance difficulties. Therefore, the development of high-performance room-temperature LNAs is both urgent and highly significant.

High-performance room-temperature LNAs are also beneficial for multi-beam receivers in radio astronomy. For example, the BINGO telescope being constructed in Brazil has a 28-beam receiver [4]. Each feed is too large to cool. The initially planned LNA was a commercial one with a typical noise temperature of 25K. The room-temperature LNA we developed for BINGO has an average noise of only 11K, which significantly improves the telescope's sensitivity.

In this article, two LNAs are detailed in Section 2: LNA1(1-1.8 GHz) is designed for the FAST core array, while LNA2 (0.9-1.3 GHz) is intended for the BINGO telescope. The measurement results are presented in Section 3. Section 4 describes the thermoelectric cooling test for LNA2.

2. LNA Description

In order to compete with cryogenic LNAs, a high-performance InP HEMT transistor [5] with extremely low noise is employed in the design. A significant portion of the noise in room-temperature LNAs originates from the input matching circuit. Consequently, in this design, a suspended-substrate microstrip line is utilized for input matching, which has extremely low loss. The circuit topologies of both LNAs are identical, but the component values are optimized. The circuit schematic is presented in Figure 1. The physical appearance of the LNA modules is illustrated in Figure 2.

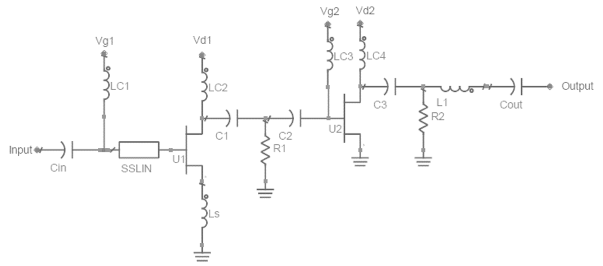

Figure 1. LNA circuit schematic (excluding biasing).

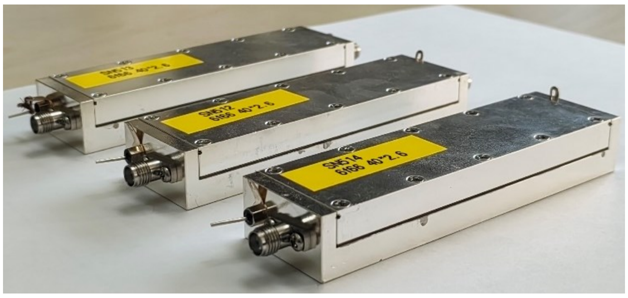

Figure 2. LNA chassis: 82×28×15 mm for LNA1 and 98×28×15 mm for LNA2 (excluding connectors).

3. Measurement Results

The S-parameters of both LNAs were measured using the Rohde & Schwarz ZNB Vector Network Analyzer. The measured results for LNA1 are presented in Figure 3 and compared with the simulated results. The gain, represented by S21, is approximately 38 dB. S11 is better than -10 dB across most of the band (1 – 1.8 GHz), except for a point at 1.8 GHz where it is -8.6 dB. S22 is better than -10 dB.

The noise temperatures were measured using the Agilent N8974A Noise Figure Analyzer, along with the N4000A noise source (ENR of 6 dB), and the results are displayed in Figure 4. The lowest noise temperature in the band is 5.3 K at 1.8 GHz, with an average noise temperature of 10 K.

Using the same test equipment, the S-parameters and noise temperatures of LNA2 (0.9 – 1.3 GHz) were measured, and the results can be seen in Figures 5 and 6. The gain, or S21, of LNA2 is around 41 dB. Both S11 and S22 are better than -10 dB. The noise temperatures range from 9 – 13 K, with an average of 11 K.

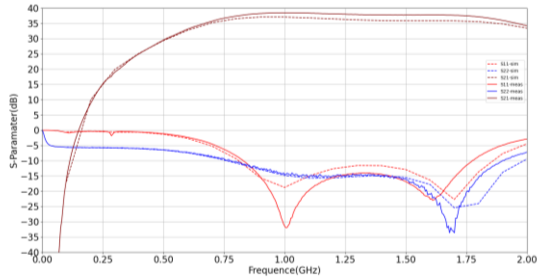

Figure 3. Measured (solid lines) and simulated (dotted lines) S-parameters of LNA1 at 25 °C. Bias: stage 1, Vg = 0 V, Vd = 0.5V, Id = 32 mA, stage 2, Vd = 2.5V, Id = 30 mA.

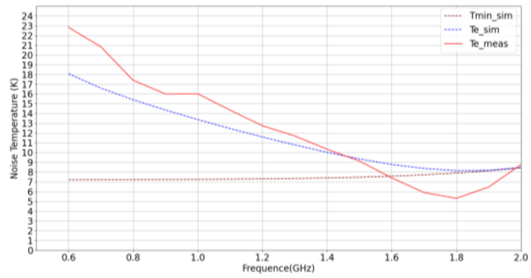

Figure 4. Measured (solid line) and modeled (dotted lines) noise temperatures of LNA1 at 25 °C. Bias: stage 1, Vg = 0 V, Vd = 0.5V, Id = 32 mA, stage 2, Vd = 2.5V, Id = 30 mA.

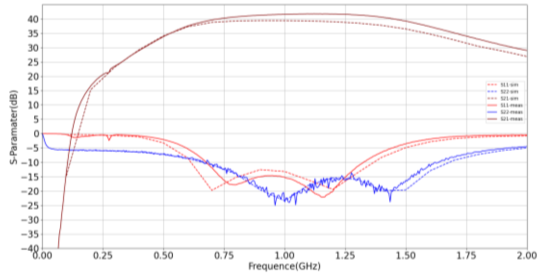

Figure 5. Measured (solid lines) and simulated (dotted lines) S-parameters of LNA2 at 25 °C. Bias: stage 1, Vg = 0 V, Vd = 0.5V, Id = 32 mA, stage 2, Vd = 2.5V, Id = 30 mA.

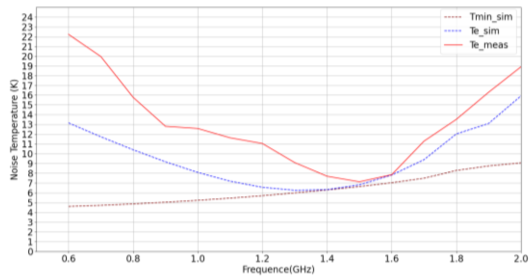

Figure 6. Measured (solid line) and modeled (dotted lines) noise temperature of LNA2 at 25 °C. Bias: stage 1, Vg = 0 V, Vd = 0.5V, Id = 32 mA, stage 2, Vd = 2.5V, Id = 30 mA.

4. Thermoelectric cooling test

Although we achieved a low noise temperature at room temperature, the noise temperature of the LNAs at the lower band edge was not satisfactory. Therefore, we conducted a thermoelectric cooling test to further reduce the noise.

Two 30×30×6.5 mm TECs were used to cool the entire LNA module. Each TEC has two stages and a nominal maximum cooling temperature difference of up to 85°C. The test fixture is shown in Figure 7. The LNA was placed in foam for temporary insulation. The hot surface of the TEC dissipates heat through heat sinks, heat pipes, and fans. The LNA temperature was cooled from 27°C to -22°C, and the temperature remained stable with a change of only 0.01°C.

The noise temperatures of the LNA2 module were measured at 27 ℃ and -22 ℃, with the results presented in Table 1. At 27 ℃, the noise temperature ranges from 6.9 K to 13 K. When cooled to -22 ℃, it decreases to between 5.7 K and 8.9 K. Specifically, at the low-frequency end of the band (0.9-1.3 GHz), the noise temperature has been reduced by 4.1 K.

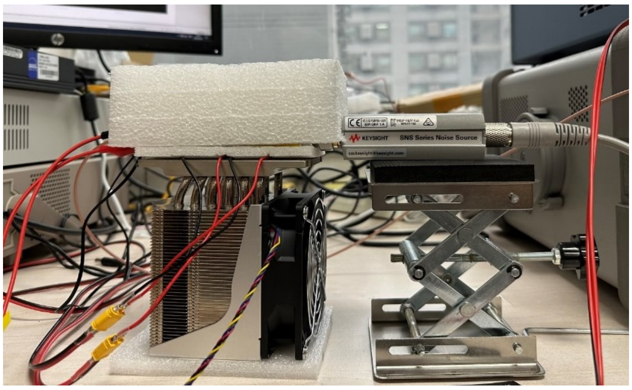

Figure 7. LNA thermoelectric cooling test.

Table 1. Noise temperature of LNA2 measures at 27 ℃ and -22 ℃

Freq(GHz)	Te(K) at 27℃	Te(K) at -22℃	Δ(K)
0.9	13.0	8.9	4.1
1.0	11.7	8.4	3.3
1.1	11.6	8	3.6
1.2	8.8	7	1.8
1.3	6.9	5.7	1.5

In this experiment, the power consumption is 119 W. The current heat management methods are insufficient for effective heat dissipation, thus hindering further reduction in the LNA module's temperature. Simultaneously, the module's input, output, and power supply ports must be connected to the noise source, signal line, etc., and cannot be completely isolated from the air, leading to noticeable frost and condensation at the ports.

In the subsequent experiment, a small-sized TEC (9×6.4×3.9 mm) was embedded within the LNA chassis, and cooling was applied solely to the first-stage transistor. The TEC, featuring a tri-layer structure, possesses a cooling capacity that can achieve a temperature differential of up to 110 ℃. Cooling was conducted from 22 ℃ down to -38 ℃, with an actual temperature difference of approximately 60 degrees. The voltage and current of the TEC were measured at 8.6 V and 0.86 A, respectively, and the power dissipation was a mere 7.4 W. Moving forward, we intend to continue refining the experimental setup to achieve a substantial temperature difference of 80 degrees, thereby fulfilling the cooling demands once the LNA is installed on telescopes.

5. Conclusions

This paper presents the development and application of high-performance room-temperature LNAs in radio astronomy. By employing high-performance InP HEMT transistors and low-loss input matching circuits, the designed LNA1 and LNA2 achieved extremely low noise temperatures at room temperature. LNA1, operating in the 1 – 1.8 GHz band, had an average noise temperature of 10 K, while LNA2, operating in the 0.9 – 1.3 GHz band, had an average noise temperature of 11 K. Thermoelectric cooling tests further reduced the noise temperature of LNA2 at the low-frequency end, demonstrating the effectiveness of thermoelectric cooling in enhancing the performance of room-temperature LNAs. These achievements offer a high-performance, reliable, and cost-effective solution for multi-beam receivers and telescope arrays in radio astronomy. Future work will focus on optimizing the heat management system and further reducing the temperature of the LNA module to meet the requirements for telescope installation.

6. Acknowledgements

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