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A 75-Ω uncooled L-band low-noise amplifier for FAST Core Array

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Abstract: The proposed FAST Core Array, a key future upgrade for the Five-hundred-meter Aperture Spherical radio Telescope, requires highly sensitive but cost-effective uncooled receivers. This paper presents the design, manufacture, and characterization of an uncooled 75-Ω low-noise amplifier for the array's L-band receiver, operating across the band of 1–1.8 GHz. Using an ultra-low-noise indium phosphide pseudomorphic high-electron-mobility transistor and a novel low-loss suspended substrate line for the input matching network, the prototype achieves a gain of approximately 39 dB and a minimum noise temperature of 7.6 K, with input and output reflection coefficients better than –8 dB and –15 dB, respectively. The receiver noise temperature was measured as low as 20 K in the 1.6–1.8 GHz sub-band using the Y-factor method, with the cold sky as the cold load and a room-temperature absorber as the hot load. These results verify the practical viability of the proposed uncooled receiver architecture and demonstrate the feasibility of employing high-performance uncooled low-noise amplifiers to meet the stringent sensitivity and reliability requirements of the next-generation FAST Core Array.

Keywords: FAST Core Array; Uncooled low-noise amplifier; InP pHEMT; Noise temperature; L-band receiver

1. INTRODUCTION

As the world's largest single-dish radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) has extremely high sensitivity and has achieved numerous remarkable scientific results[1]. However, its limited angular resolution restricts its ability to make further discoveries in frontier research areas. Upgrades have been considered for the FAST Phase II project to enhance the high-resolution imaging capability of the telescope[2,3], involving deployment of 64 radio telescopes, each with a 40-m aperture, within a 30-km radius around FAST, forming a large-scale interferometric array dubbed the FAST Core Array. This initiative is expected to significantly improve the FAST's overall observational performance and yield important scientific outcomes across various frontier fields, including cosmology, neutral hydrogen galaxies, pulsars and fast radio bursts, the interstellar medium, active galactic nuclei and black holes, and multi-messenger astronomy.

Each 40-m telescope in the FAST Core Array will be equipped with three receiver sets, covering a frequency range of 0.35–10 GHz, including a low-frequency receiver (0.35–1.05 GHz), an L-band receiver (1–2 GHz), and a high-frequency receiver (2–10 GHz). Both the low-frequency and the L-band receivers will utilize uncooled receiver technology. Unlike traditional cryogenic receivers, which require bulky coolers and compressors, uncooled receivers eliminate the need for such cooling systems. This simplification substantially reduces system complexity and maintenance requirements, offering significant advantages in cost and reliability. Given the distributed nature of the array telescopes, maintenance efforts are considerably challenging. Therefore, the high reliability of uncooled receivers is critical to minimizing the array's long-term maintenance and operational costs.

A key challenge for the FAST Core Array is to reduce the noise of uncooled receivers to improve the telescope's sensitivity. The core component of a receiver is

the Low-Noise Amplifier (LNA), which is positioned at the first stage of the receiver architecture. The LNA contributes significantly to the overall receiver noise, and with sufficient gain, it can also render the noise contributions from subsequent stages negligible. In the past, the noise temperature of uncooled LNAs was typically greater than 30 K[4], and cryogenic cooling was often required to achieve extremely low system noise temperature. For instance, a cooled LNA operating at 15 K can achieve a noise temperature as low as 4–5 K[5].

In recent years, uncooled LNA technology has seen substantial advancements. In 2016, Schleeh et al.[6] developed an uncooled LNA for Square Kilometer Array (SKA) Band 1 (0.35–1.05 GHz), achieving a noise temperature as low as 10 K in part of the band, with input reflection coefficients better than –10 dB across most of the band. In 2021, Weinreb and Shi[7] developed an uncooled LNA with a noise temperature of only 7 K at 1.4 GHz and 25°C, achieving only one-fourth of the noise of the best commercially available LNAs at the time. In 2023, Shi and Weinreb[8] reported an uncooled LNA covering 0.6–2 GHz, with an average noise temperature of 11 K and a maximum noise temperature of about 15 K at 25°C. Separately, Lai et al.[9] developed an uncooled LNA, operating in the 0.3–1.5 GHz range with an ultra-wideband 5:1 coverage ratio. It achieved good performance over a portion of the band, with a noise temperature below 20 K from 0.5 to 1.4 GHz, and input reflection coefficients better than –8 dB from 0.32 to 1.5 GHz.

This article focused on the development of key LNA technologies to enable a high-sensitivity L-band receiver for the FAST Core Array. By utilizing ultra-low-noise indium phosphide pseudomorphic High-Electron-Mobility Transistors (InP pHEMTs), ultra-low-loss Suspended Substrate Lines (SSLINs) for the input matching network, and optimized LNA circuit design, we have developed an uncooled LNA with a 75-Ω input impedance, covering 1–1.8 GHz, and achieving a noise temperature on the order of approximately 10 K (the internal layout of our LNA prototype is shown in Fig. 1). The external dimensions of the LNA, excluding connectors, are 82.2 mm in length, 28 mm in width, and 20 mm in height. In this paper, Section 2 presents the design and simulation results of the LNA, Section 3 describes the prototype measurements and the overall receiver noise temperature test, and Section 4 presents our conclusions.

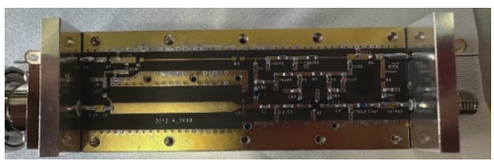

Fig. 1. Photograph showing the internal circuit layout of the 75-Ω LNA prototype.

2. LNA DESIGN

2.1. Ultra-low Noise Transistor Die

The performance of the first-stage transistor in the LNA directly determines the overall noise temperature of the LNA and significantly influences the complexity of broadband circuit design and optimization. In this work, we used commercial ultra-low-noise InP pHEMT dies from Diramics[1]. These transistors have a 100 nm gate length, with gate widths ranging from 10 to 100 μm and gate finger counts of 2, 4, 6, or 8, making them suitable for applications across the L, S, C, Ku, Ka, and Q bands.

Using the small-signal and noise models provided by the manufacturer, we analyzed the noise parameters of transistors with various dimensions and selected the pH-100-4F50 and pH-100-6F66.7 models for the design of the L-band LNA. The noise parameters for these two transistors are summarized in Table 1. The pH-100-4F50 shows a minimum noise temperature (T_{min}) of just 3.9 K at 1 GHz and 5.0 K at 1.8 GHz. The pH-100-6F66.7 demonstrates even lower minimum noise, with T_{min} of 3.1 K at 1 GHz and 4.6 K at 1.8 GHz. However, both transistors present a significant design challenge because of their high optimum source impedance (Z_{opt}) for achieving T_{min}. For example, at 1 GHz, the real part of Z_{opt} (R_{opt}) is 499.7 Ω for the pH-100-4F50 and 276.8 Ω for the pH-100-6F66.7. Transforming from these high R_{opt} down to the standard source impedance of 50 Ω is challenging, particularly while maintaining good impedance matching across the broad bandwidth.

Table 1. Noise parameters for transistors pH-100-4F50 and pH-100-6F66.7

Frequence /GHz	pH-100-4F50				pH-100-6F66.7			
	T_{min}/K	R_{opt}/Ω	X_{opt}/Ω	R_n/Ω	T_{min}/K	R_{opt}/Ω	X_{opt}/Ω	R_n/Ω
0.6	3.5	724.0	411.5	5.79	2.6	435.3	308.2	2.89
1	3.9	499.7	428.7	5.79	3.1	276.8	268.2	2.89
1.4	4.4	360.4	384.7	5.79	3.8	196.7	218.6	2.89
1.8	5.0	275.9	333.6	5.78	4.6	151.5	180.4	2.88
3	7.1	158.4	225.8	5.77	7.1	89.4	114.8	2.87

In this study, we selected the pH-100-6F66.7 transistor as the first transistor in the LNA for the final design, a photograph of which is shown in Fig. 2A, with

1. pH-100 series discrete ultra-low noise InP pHEMTs, available from https://diramics.com/.

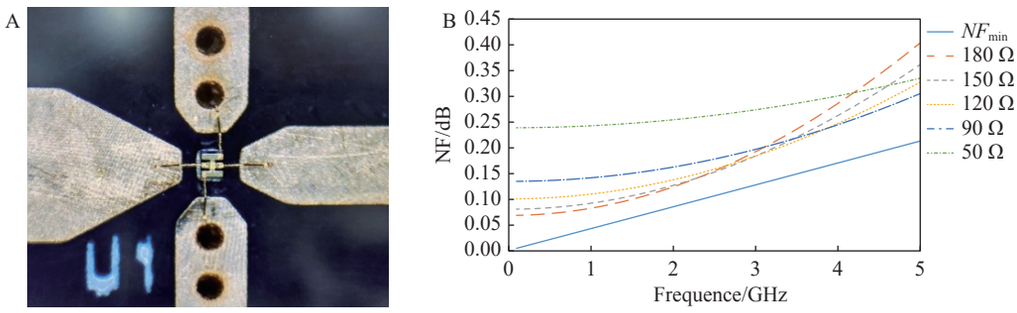

Fig. 2. Diramics transistor die and its noise performance. (A) Photograph of a pH-100-6F66.7 transistor which was electrically bonded to the printed circuit board traces with 25 μm diameter gold wires. (B) Noise figure degradation of pH-100-6F66.7, relative to its minimum achievable noise figure, under different source impedances without an input matching network.

dimensions of 307 × 335 × 100 μm. The bare transistor die was electrically bonded to the printed circuit board traces with 25 μm diameter gold wires. Using unpackaged transistors offers the advantage of minimizing parasitic effects and associated losses from packaging, contributing to lower noise.

In the design for minimum noise matching, the source impedance (typically 50 Ω) is transformed to the optimum noise impedance Z_{opt} through the input matching network, ensuring that the LNA achieves low noise performance. However, because the R_{opt} of the first-stage transistor used in this design is relatively high, the impedance transformation from Z_{opt} to 50 Ω requires a large matching ratio, which makes broadband design particularly challenging. Therefore, we analyze the impact of non-50-Ω source impedance on the noise performance of the LNA to determine a more suitable source impedance value. We analyzed the noise figure degradation of the pH-100-6F66.7, relative to its minimum achievable noise figure (NF_{min}), comparing it with different source impedances without any input matching network (see Fig. 2B).

When the source impedance is 50 Ω, the transistor's noise figure is substantially higher than NF_{min}, significantly hindering simultaneous noise matching and input reflection coefficients optimization across a broadband. As the source impedance increases, the noise figure approaches NF_{min}, and beyond a certain point, further increases in source impedance yield diminishing returns in noise reduction. This means that selecting an appropriate, non-50-Ω source impedance can simplify the input matching network design and facilitate effective broadband noise matching.

For this design, we chose a source impedance of 75 Ω. This value offers a compromise, providing a more favorable starting point for noise matching, compared to 50 Ω, while still being a standard impedance for which calibration kits and adapters are readily available, enabling S-parameter measurements using standard 50-Ω vector network analyzers. Other arbitrary impedance values would cause measurement difficulties.

2.2. Low-loss Input Impedance Matching Network

In conventional uncooled LNAs, even those utilizing transistors with excellent noise performance, the overall noise temperature often exceeds 30 K. This is primarily caused by the significant loss introduced by the input matching network and transistor packaging (typically on the order of 0.3 dB), which can contribute approximately 21 K of noise[7]. Traditional matching components, such as microstrip lines, resistors, and inductors, all introduce additional noise. In cryogenic LNAs, cooling significantly suppresses the noise from passive component loss. For example, a 10-cm-long, 1.1-mm-wide microstrip line (Z_0 ≈ 50 Ω), created on a 0.508-mm-thick Rogers RO4350B substrate, yields approximately 0.21 dB of loss at 2 GHz, equivalent to a noise temperature of approximately 14 K. Using a lower-loss substrate like Rogers RT/duroid 5880 (also 0.508 mm thick), a 10-cm-long, 1.5-mm-wide line (Z_0 ≈ 50 Ω) shows reduced loss of approximately 0.12 dB at 2 GHz, equivalent to 8 K.

As noted previously, R_{opt} of the pH-100-6F66.7 transistor is high (e.g., ≈ 276.8 Ω at 1 GHz). Achieving an effective impedance transformation from this value to 50 Ω necessitates the use of transmission lines with high characteristic impedance. However, achieving such high impedances with standard microstrip technology is challenging, because it requires narrower trace widths, which consequently lead to excessive conductor loss. For instance, on a 0.508-mm-thick RO4350B substrate, a 0.3-mm-wide line (Z_0 ≈ 92 Ω) with a length of 10 cm causes a loss of 0.24 dB at 2 GHz (≈ 16.5 K noise). Pushing to the typical manufacturing limit, with a 0.13 mm width (Z_0 ≈ 120 Ω), results in a loss of 0.34 dB (≈ 23.6 K noise). On the lower-loss RT/duroid 5880 substrate (0.508 mm thick), a 0.3-mm-wide line (Z_0 ≈ 113 Ω) yields 0.15 dB loss (≈ 10.2 K noise), while a 0.13-mm-wide line (Z_0 ≈ 145 Ω) yields 0.24 dB loss (≈ 16.5 K noise).

To overcome this limitation, we use a suspended substrate line structure in which a copper conductor is suspended in air within a hollow outer conductor. This configuration significantly reduces dielectric loss and enables higher characteristic impedance compared with conventional microstrip lines. For example, using an RT/duroid 5880 substrate (0.508 mm thick), a 10-cm-long, 1.9-mm-wide SSLIN achieves a characteristic impedance of approximately 145 Ω while exhibiting a remarkably low loss of only 0.04 dB at 2 GHz, equivalent to a noise temperature of just 2.7 K. Table 2 compares the losses of 10-cm-

Table 2. Loss comparison of 10-cm-long transmission lines with different types and substrate materials at 2 GHz

Substrate	Transmission line	Width/mm	Z_0/Ω	Loss/dB
RO4350B	Microstrip line	0.3	92	0.24
		0.13	120	0.34
RT/duroid 5880	Microstrip line	0.3	113	0.15
		0.13	145	0.24
	SSLIN	1.9	145	0.04

long transmission lines of different types and substrate materials at 2 GHz. The results show that the SSLIN shows better capability of simultaneous high impedance and low loss, compared with microstrip lines.

2.3. LNA Optimization, Design, and Simulation

For the LNA, we used a two-stage hybrid topology (a simplified schematic is shown in Fig. 3A, with the bias circuits omitted for clarity). The first stage incorporates the pH-100-6F66.7 die, and the second stage uses a packaged surface-mount transistor (SAV-581+). An SSLIN section serves as the core of the low-loss, high-impedance input matching network.

The cross-sectional structure of the SSLIN is shown in Fig. 3B. The SSLIN is created on a 0.508-mm-thick RT/duroid 5880 substrate with a 30-mm-long, 2.4-mm-wide copper line suspended in a square outer conductor with a 10 mm × 10 mm cross-section. On the reverse side of the PCB, the copper cladding is removed from a 30 mm × 10 mm area directly beneath the copper line. We solder the PCB to the LNA chassis, and machine a corresponding cavity measuring 30 mm in length, 10 mm in width (W), and 4.492 mm in depth (HL) into the chassis, just beneath the SSLIN. The upper ground plane of the SSLIN outer conductor is formed by the inner surface of the LNA cover, located 5 mm (HU) above the PCB substrate. The lower ground plane is the bottom surface of the cavity in the chassis, located 4.492 mm (HL) below the substrate.

We biased the first-stage transistor at $V_d = 0.5$ V and $I_d = 32$ mA, and the second transistor at $V_d = 2.5$ V and $I_d = 30$ mA. The LNA draws approximately 65 mA from a 3.15 V supply, resulting in a total power consumption of approximately 0.2 W.

We performed optimization at two target bandwidths, 1–2 GHz and 1–1.8 GHz. The primary design challenge was balancing the noise temperature and input reflection coefficient (S_{11}) across the band. For the 1–2 GHz bandwidth, achieving $S_{11} < -10$ dB across the entire band resulted in a slightly elevated noise temperature of 8.5–11.4 K. Relaxing the S_{11} requirement at 2 GHz to –8 dB allowed for a lower noise temperature of 8.5–10.7 K across the band. Furthermore, independent optimization of the feed horn and Orthomode Transducer (OMT) revealed performance degradation in the 1.8–2 GHz range, making full coverage of the 1–2 GHz band challenging for the entire receiver system. Consequently, in this design, we focused on the 1–1.8 GHz band.

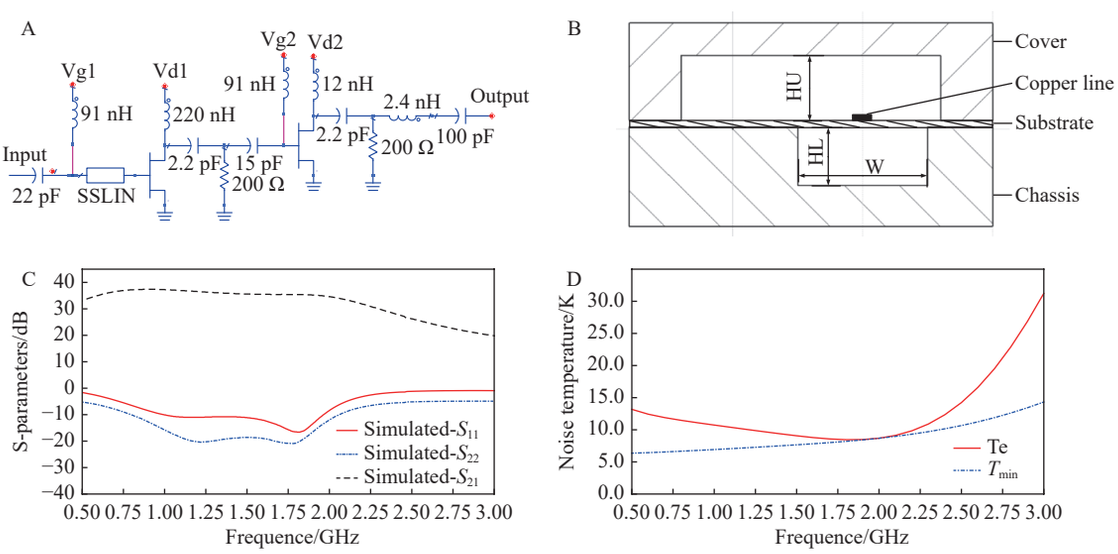

Fig. 3. Schematic and simulation results of the 75-Ω LNA design. (A) Schematic of the two-stage LNA, with the bias circuits omitted for clarity. The input matching network is the SSLIN. (B) Schematic of the SSLIN structure, which is created on a substrate with a copper line suspended in a square outer conductor, formed by the chassis and cover of the LNA. (C) S-parameter simulation results, showing S_{11} better than −10 dB, S_{22} better than −15 dB, and S_{21} of 35.4–37.3 dB. (D) Noise temperature simulation results, showing an equivalent noise temperature of 8.5–10.7 K.

The simulated S-parameters and noise performance for the finalized design are shown in Fig. 3C and Fig. 3D. Across the 1–1.8 GHz frequency range, the simulations predict S_{11} better than −10 dB, S_{22} better than −15 dB, a gain (S_{21}) of 35.4–37.3 dB, and an equivalent noise temperature of 8.5–10.7 K.

3. MEASUREMENT RESULTS

3.1. LNA Prototype Measurement

We measured the S-parameters of the LNA prototype with a Rohde & Schwarz Vector Network Analyzer (9 kHz–8.5 GHz), custom 75-Ω calibration kits, and 75-Ω to 50-Ω impedance transformers. The results are presented in Fig. 4A. Across the 1–1.8 GHz frequency range, the measured S_{11} is better than −8 dB, S_{22} is better than −15 dB, and the gain (S_{21}) ranges from 38.7 dB to 39.1 dB. To measure the noise performance of the LNA prototype, we used an Agilent N8974N noise figure analyzer and an SNS 4000A noise source. Since the noise source has a 50-Ω output port, it cannot be directly connected to the LNA input port for noise measurement. To address this, we connected a 50-Ω-to-75-Ω impedance transformer between the LNA and the noise source. The test setup is shown in Fig. 4B. The measurement thus yields the overall noise of the cascaded impedance transformer and LNA. The noise contribution of the LNA itself can then be extracted using the relation

$$T_{\mathrm{LNA}} = T_{\mathrm{total}} - T_{\mathrm{phy}}(L-1), \tag{1}$$

where T_{total} is the overall equivalent noise temperature of the cascade, measured by the noise analyzer using the Y-factor method, and T_{phy} is the physical temperature of the impedance transformer. L is the intrinsic loss of the transformer, which is derived from its S-parameters measured via the vector network analyzer, defined as

$$L = \frac{|S_{21}|^2}{1-|S_{11}|^2}. \tag{2}$$

The noise measurement results are shown in Fig. 4C, with a noise temperature of approximately 7.6 K to 16.7 K across the frequency range of 1 GHz to 1.8 GHz.

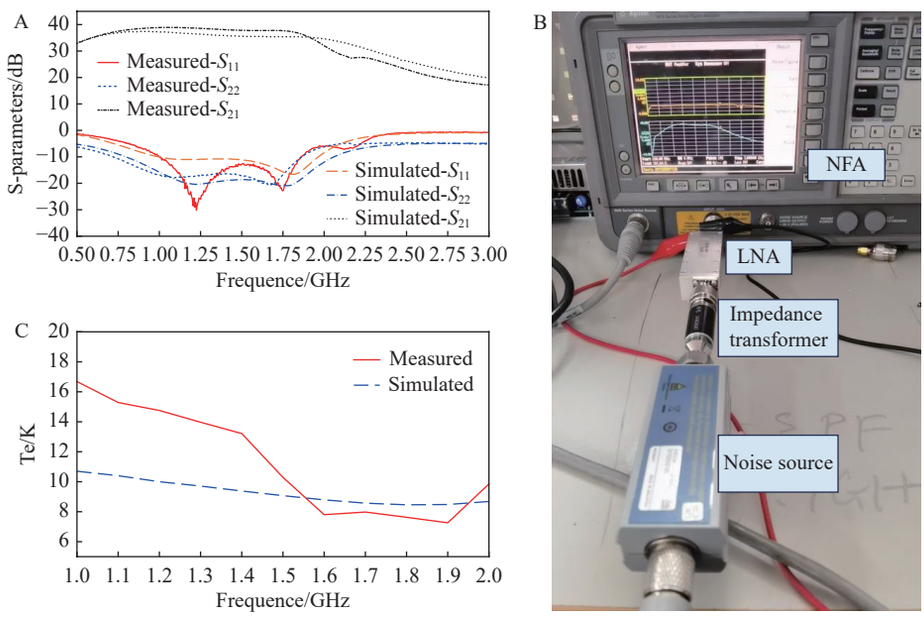

Fig. 4. S-parameters and noise temperature measurement of the 75-Ω LNA. (A) Measured (solid) and simulated (dotted) S-parameters of the LNA, showing good consistency in their variation trends. The measured S_{11} is better than −8 dB, S_{22} is better than −15 dB, and the S_{21} is approximately 38.7–39.1 dB. (B) Test setup for noise measurement, consisting of a noise figure analyzer, a noise source, a 50-Ω-to-75-Ω impedance transformer, and the LNA under test. The transformer enables the 50-Ω-based noise figure analyzer to interface with the 75-Ω LNA. (C) Measured noise temperature of the LNA compared with the simulation results. The measured noise temperature ranges from approximately 7.6 K to 16.7 K over the operating band.

3.2. Receiver Noise Temperature Measurement

Our proposed LNA prototype incorporates a 75-Ω male N-type connector at the input and a 50-Ω SMA connector at the output. The LNA is directly interfaced with the custom-designed feed horn and OMT that incorporates a 75-Ω female N-type connector. This connection design eliminates the need for adapters or cables between the LNA and the OMT, thereby reducing noise caused by insertion loss. The receiver front-end, including the feed, OMT, and LNA, is shown in Fig. 5A.

To measure the overall receiver noise temperature, we established a test setup using the Y-factor method, using the cold sky and a room-temperature absorber as the cold and hot loads, respectively. We manufactured a square scalar horn and placed the receiver front-end inside it (see Fig. 5B). This horn acts as a shielded aperture limiter, ensuring that the receiver alternately views only the defined hot and cold radiative targets. By suppressing stray radiation and stabilizing the electromagnetic boundary conditions, this configuration improves the accuracy and repeatability of the Y-factor measurement. The absorber, which served as the hot load, consisted of four

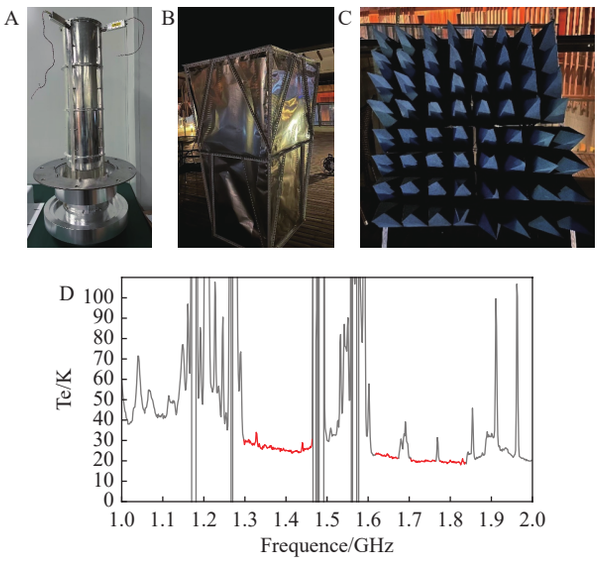

Fig. 5. Y-factor measurement of the receiver noise temperature for the FAST Core Array. (A) The receiver front-end, including the feed, OMT, and LNAs. (B) A square scalar horn, used to test the receiver noise. (C) An absorber at room temperature, used as the hot load in the Y-factor measurement. (D) Measured results of the receiver noise temperature, showing a minimum of approximately 20 K in the 1.6–1.8 GHz sub-band.

separate panels, each measuring 600 × 600 mm, arranged to cover the large aperture of the horn (see Fig. 5C).

The measured receiver noise temperature is shown in Fig. 5D. The lowest receiver noise temperature, approximately 20 K, was achieved in the 1.6–1.8 GHz sub-band. However, this measurement was affected by significant environmental interference and potential gaps in the absorber assembly. In future work, we intend to conduct measurements in an area with lower electromagnetic interference, enhancing the absorber by adding a metal backing plate.

4. CONCLUSION

In this paper, we present the design, fabrication, and measurement of an uncooled 75-Ω LNA, operating from 1 to 1.8 GHz, for the L-band receiver in the FAST Core Array. Table 3 compares the performance of our prototype LNA with previously reported uncooled LNA covering a similar frequency range. Compared with earlier designs, our proposed amplifier introduces several key innovations.

The LNA employs an ultra-low-noise InP pHEMT (pH-100-6F66.7), with excellent intrinsic noise properties (e.g., $T_{min} \approx 4.6$ K at 1.8 GHz), providing a solid foundation for achieving low-noise performance. Additionally, we implemented a suspended substrate line in the input matching network, effectively mitigating the high loss typically encountered when transforming the transistor's high Z_{opt} down to 75 Ω. This mitigates a common bottleneck in conventional uncooled LNA designs.

Our prototype achieved a measured gain of approximately 39 dB and a lowest noise temperature of 7.6 K, with S_{11} better than −8 dB and S_{22} better than −15 dB. While S_{22} is already satisfactory, there remains room for optimization of S_{11} to reach the target of −10 dB.

Table 3. Key performance metrics of the proposed 75-Ω LNA, with uncooled LNAs operating in similar frequency bands

Reference	Frequency/GHz	Source impedance/ Ω	Te/K	Gain/ dB	Power/ mW	IIP1dB/ dBm	Technology	Figure of Merit (FoM)①
[6]	0.45–1.05	50	10–12	50	193	–	InP	9015②
[8]	0.6–2	50	7–15	40	350	−28	InP	1657
[9]	0.3–1.5	50	15–40	34	255	−37	InP	229
ZX60-P162LN+③	0.7–1.6	50	33–54	22	208	−2.6	GaAs	6
WBA1216AS④	1.2–1.6	50	25	35	600	−22	–	24
This work	1–1.8	75	7.6–16.7	39	200	−27	InP	1212

① $FoM = \frac{Gain_{\text{linear}} \times Bandwidth(GHz)}{Power(mW) \times (NF_{\text{linear}} - 1)}$ [10]. The minimum value of Te is used in the calculation of the FoMs.

② It should be noted that the LNA reported by Schleeh et al.[6] shows a FoM significantly higher than those of other LNAs in the table. One of the main reasons is its extremely high gain of 50 dB; however, in receiver design, we do not pursue such a high gain for the LNA. We follow the design principle that the LNA gain should be sufficient to render the noise contribution from subsequent stages negligible, for which a gain greater than 35 dB is typically adequate.

③ ZX60-P162LN+ data sheet. Mini-Circuits, USA.

④ WBA1216AS data sheet. WanTcom Inc, Microsoft Word. https://www.wantcominc.com/DataSheets/WBA/WBA1216A.pdf.

A preliminary measurement of the receiver noise temperature yielded approximately 20 K in the 1.6–1.8 GHz band. This confirms the practical feasibility of using an uncooled LNA for a high-sensitivity L-band receiver in the FAST Core Array. This can enhance system reliability and reduce operational costs. Interference during testing and potential leakage in absorber materials may have contributed to the measured receiver noise, and we will address these aspects in future test setups.

To ensure long-term stability in the FAST Core Array, our LNA will require stabilization using a Thermoelectric Cooler (TEC), either maintaining a constant temperature (e.g., 20°C) or cooling to a fixed value within the range of –20°C to –40°C. This cooling can also contribute

to further noise reduction. Our previous work has explored TEC-based cooling for LNAs[11], and further work will refine the application of TEC cooling.

The LNA developed here demonstrates that modern uncooled technology can achieve noise temperatures previously attainable only with cryogenic systems. This can pave the way for highly reliable and cost-effective receiver systems for the large-scale FAST Core Array.

ACKNOWLEDGMENTS

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AI DISCLOSURE STATEMENT

Deepseek was employed for language and grammar checks within the article. The authors carefully reviewed, edited, and revised the Deepseek-generated texts to their own preferences, assuming ultimate responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Xiaoming Chai conceived the study, designed, tested, and performed the analysis, and wrote the manuscript. Minglei Guo was responsible for LNA assembly and conducted measurements together with Xiaoming Chai. Bin Liu designed the square horn for receiver test, acquired and processed the measurement data, and performed receiver debugging. Hengqian Gan led the system design of the L-band receiver, organized the receiver testing campaign, and coordinated the team effort. Jinglong Yu designed and developed the feed horn and OMT. Yan Zhu was responsible for the backend of the receiver, provided critical guidance on the system design, and advised on technical challenges throughout the development process. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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