

# A low insertion loss L-band feed front-end for the FAST Core Array

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Received: September 18, 2025; Accepted: December 1, 2025; Published Online: December 2, 2025; <https://doi.org/10.3724/ati2025070>; <https://cstr.cn/32083.14.ati2025070>

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Citation: Yu, J. L., Gan, H. Q., Cao, Y., et al. 2026. A low insertion loss L-band feed front-end for the FAST Core Array. *Astronomical Techniques and Instruments*, 3(5): 412–418. <https://doi.org/10.3724/ati2025070>.

**Abstract:** We designed a low insertion loss L-band feed front-end system to operate over a 1.15–1.75 GHz frequency range for the Five-hundred-meter Aperture Spherical radio Telescope (FAST) Core Array. The L-band feed front-end system comprises quadruple-ridge ortho-mode transducers and a choke horn. The coaxial output of the transducers extracts two mutually orthogonal polarization signals by coupling the input of a circular waveguide. Two non-cryogenic low temperature low-noise amplifiers with average noise of only 10 K at room temperature connected to coaxial outputs respectively. Because it operates at room temperature, the new developed ortho-mode transducer requires lower insertion loss than in designs intended to operate in extremely cold environments. This paper focuses on the 1.15–1.75 GHz L-Band ortho-mode transducer and choke horn design, with a measured L-band return loss of more than –20 dB, and an insertion loss of more than 0.09 dB. Considering the large quantity of front-end systems required for array applications, our design of ortho-mode transducers balances performance, adjustability, and ease of manufacture, and our choke horn design has high aperture efficiency across the L-band.

**Keywords:** Ortho-mode transducers; Feed; Reflector antenna; Quad-ridged; Choke horn

## 1. INTRODUCTION

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) Core Array has an ideal electromagnetic environment for the construction of a hybrid aperture interference array with ultra-high sensitivity and high angular resolution. This array is expected to enhance existing spatial resolution and imaging capabilities, provide world-class sensitivity, and make important contributions to various frontier scientific issues in the field of radio astronomy<sup>[1]</sup>. The project involves the construction of 64 40-m-aperture radio telescopes, which has been planned to be carried out in three phases. The goal of the first phase is to build 24 40-m aperture antennas within 5 km around FAST by 2027, to form a synthetic aperture array. After the completion of the array, primary observations will be carried out for specific scientific objectives.

Each 40-m antenna is a primary feed reflector with a focal diameter ratio of 0.375, comprising an antenna reflector and a feed cabin, with a 22-m diameter aluminum alloy solid panel in the center of the main reflector. The

surface panel is constructed from an external stainless steel wire mesh, supported by aluminum ribs. The total weight of each radio telescope antenna is approximately 400 t.

To optimize sensitivity in different frequency ranges, each antenna is equipped with three customizable feeds. The half angle of the feed illumination is approximately 67.5°, and a low-noise amplifier (LNA) for the low frequency band receiver, which operates at room temperature. This P&L receiver covers the P- and L-bands, which span the range of 350–1.05 MHz and the range of 1.05–1.75 GHz, respectively. During the initial debugging and validation phase, each antenna will be equipped with a room temperature L-band receiver to verify the performance of the antenna.

The room temperature L-band receiver consists of a low insertion loss feed, ortho-mode transducers (OMTs), and an ultra-low-noise amplifier. Compared with the traditional helium-cooled receivers, room temperature receivers are much cheaper in cost, making them an attractive prospect for arrays that require tens or even hundreds of

radio telescope antennas. With the development of ultra-low-noise amplifiers below 10 K at room temperature environment, it is possible for room temperature receivers to replace cryocooler receivers, yielding comparable performance in some frequency bands.

Here, we present a detailed description of the design of the front-end feed source and orthogonal mode coupler for the L-band receiver, and briefly assess the performance of the L-band ultra-low-noise amplifier.

## 2. DESIGN AND PERFORMANCE

### 2.1. Design and Dimension of the Feed

Radio telescope and satellite communication antennas commonly use primary feed reflectors to receive or transmit signals, the most common of which is usually a

choke horn at microwave frequencies, comprising a waveguide opening surrounded by several choke coils or ripples. The function of a choke coil is to balance the radiation modes in the E-plane and H-plane, to improve symmetry, while reducing cross polarization and side-lobes<sup>[2]</sup>. For small F/D primary-fed reflector antennas, F/D is the ratio of focal length to aperture diameter for the reflector antenna, flange choke groove horns are typically used<sup>[3]</sup>. Considering the F/D of the 40-m radio telescope antenna is 0.375, we used this design as a basis for the work presented in this paper. This design includes a choke groove that gradually transitions into a flange, with a stepped structure. We call it a tapered choke groove horn. This structure results in a radio telescope antenna that is suitable for small F/D after optimization. The cross-sectional structure and dimensions of the feed completed design are given in Fig. 1.

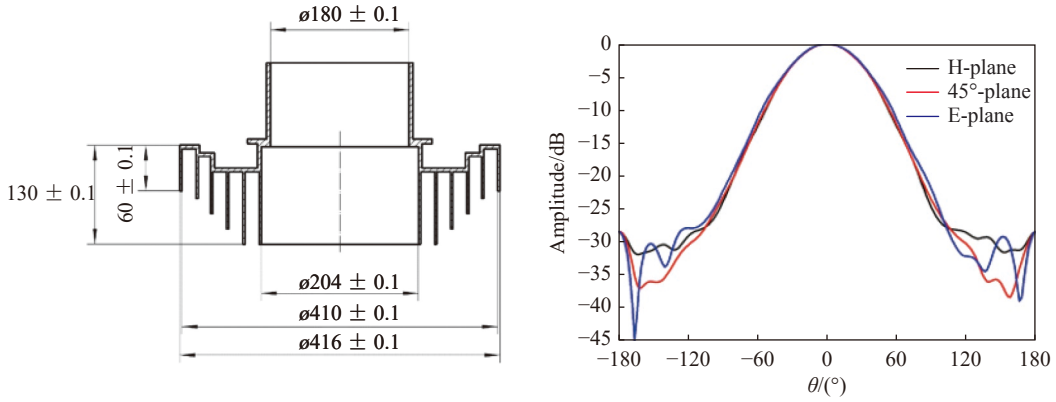


Fig. 1. The cross-section of the tapered choke groove horn, with simulation results of the E-plane, 45°-plane, and H-plane at 1.42 GHz.

The horn consists of a TE<sub>11</sub> mode circular stepped waveguide, connected to a corrugated section with five simple choke grooves, as shown in Fig. 1. Here, TE<sub>11</sub> is the primary operating mode of circular waveguides. Coaxial choke grooves are used to reduce the diffraction from the outer edge of the horn<sup>[4]</sup>. This makes the horn easier to machine and numerically optimize, compared with other shapes. To create this design, we used the Ansys Electromagnetic High Frequency Structure Simulation (AnsysEM HFSS) software package, optimizing the depth and width of the choke groove. The E-plane, 45°-plane and H-plane of the horn at 1.42 GHz are shown in Fig. 1. For optimum performance, the feed needs to include an edge taper of −13 dB and a symmetrical far-field pattern.

### 2.2. OMT

According to previously published reports in the literature<sup>[5–10]</sup>, compared with OMT designs based on square and circular waveguide structures, a four-ridge OMT design has the advantage of a wider single-mode bandwidth. Based on the need to suppress high-order modes, we have designed the quadruple-ridge OMT to be relatively long, which results in a large insertion loss, generally between 0.15–0.2 dB<sup>[11–14]</sup>. This is quite significant,

considering that the room temperature receiver system will be used for a 40-m antenna; therefore, an important objective is to further reduce this insertion loss.

The FAST Core Array L-Band OMT provides excellent performance in the frequency range of 1.15–1.75 GHz, with a return loss of 20 dB or higher and an insertion loss of 0.09 dB or better. This insertion loss and return loss are easily modeled, with simulations providing accurate results. Consequently, the L-Band OMT has a low insertion loss when adding the noise coupler together with the feed. The outer wall of our quadruple-ridge OMT incorporates a straight cylindrical circular waveguide with a triangular reflection cavity. The transition curve from the spine waveguide to the circular waveguide adopts a sine square curve, given by

$$y = w/2 + (R - w/2) \times \sin^2(\pi/2 \times z/L), \quad (1)$$

where  $w$  is the distance between the two ridges,  $R$  is the inner radius of the OMT waveguide, and  $L$  is the length of the waveguide section without the reflection cavity, with a ridge thickness of 15 mm. The reflection cavity angle, as well as the position and structure of the probe, have all been optimized, resulting in the structure shown in Fig. 2.

We have verified our OMT design, with quadruple ridge and triangular reflector cavity, in simulations, using the AnsysEM HFSS software package. Simulation results for the main electrical performance parameters, return loss, isolation and insertion loss are shown in Fig. 3. We achieve a return loss greater than 20 dB, isolation greater than 35 dB, and insertion loss less than 0.1 dB, meeting the design requirements.

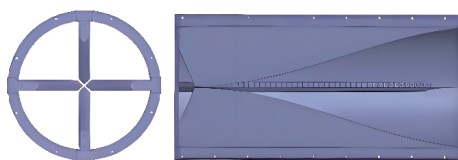


Fig. 2. Diagram showing a cross-section of our OMT design.

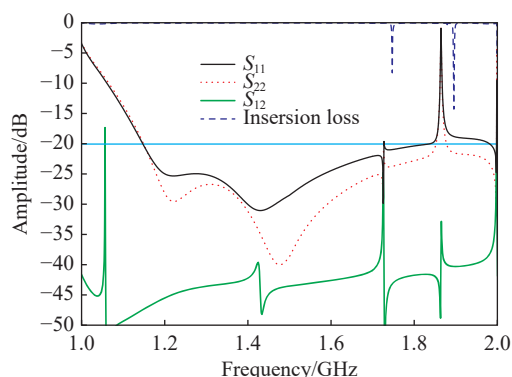


Fig. 3. The return loss ( $S_{11}$  and  $S_{22}$ ), isolation ( $S_{12}$ ), and insertion loss simulation results for the OMT.

### 2.3. LNA

Generally, radio astronomy receivers need to be cryogenically cooled for L-band observations, but considering factors such as quantity, cost, maintenance difficulty, and reliability, the FAST Core Array receiver will operate at room temperature. In addition, with the development of room temperature amplifier technology, the noise level of the recorded data is gradually approaching that of cooled amplifiers.

Since the successful development of room temperature low-noise indium phosphide (InP) transistors, significant progress has been made in the development of room temperature L-band LNA. In 2021, Weinreb et al.<sup>[15]</sup> developed a room temperature amplifier with a minimum noise temperature of only 7 K in the L-band at room temperature.

At present, this technology can achieve low noise output at room temperature in the range of 0.6–2 GHz, with an average noise temperature of 11 K<sup>[16]</sup>. Consequently, room temperature low-noise receivers, with their simplified structure, high reliability, and good performance, have become an ideal choice for radio telescopes, to expand observation frequency bands and achieve observation capabilities comparable to those attainable with cooled receivers. This can also significantly reduce receiver manufacturing and maintenance costs.

## 3. MANUFACTURE AND MEASUREMENT

### 3.1. Feed

To design and optimize our feed, we used the Ansys-EM HFSS software package. Our selected construction material for both the feed and OMT is aluminum alloy, processed using an anodizing treatment after machining. The finished product after anodic oxidation is shown in Fig. 4.

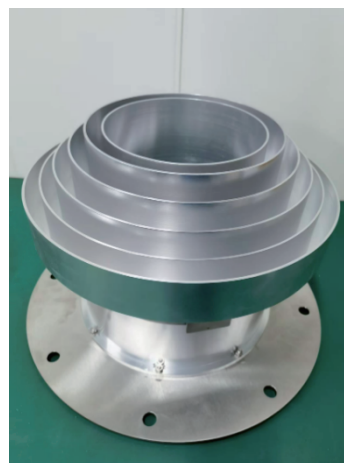


Fig. 4. The Photograph of the finished feed prototype.

### 3.2. OMT

Our OMT design has a split structure, with four ridges dividing the waveguide wall into four parts of equal size, except for differences at the probe connection points. The OMT has a length of 426 mm, which is much smaller than the L-Band OMT design currently in use by other observatories. The ridges have a segmented structure, with the waveguide wall and ridges being held in electrical contact by clamping and fastening.

In addition to reflection loss and isolation, insertion loss is a key design indicator to be considered. This OMT design is used for the front-end of the room temperature receiver. The output of the OMT is directly connected to the room temperature LNA, so the insertion loss must be as small as possible to ensure that the noise temperature of the receiver system is kept relatively low.

After manufacturing, an OMT is typically given an anodizing surface treatment but this does little to improve insertion loss. Previous studies have reported that the insertion loss of an OMT in the L-band is approximately in the range of 0.12–0.2 dB. To further reduce the insertion loss, we have given our OMT the additional surface treatments of polishing and silver plating. To evaluate the effects, we measured the insertion loss results separately after polishing and after polishing with silver plating. The level of smoothness can reach 0.8 after surface finish. The insertion loss after polishing is around 0.1 dB, and the insertion loss after polishing with silver plating is approximately 0.07–0.08 dB. The results of some frequency

point is around 0.05 dB. The improvement in insertion loss should be at least 30%. A comparison is shown in Fig. 5.

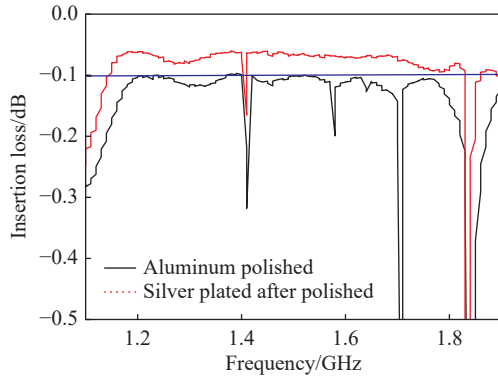


**Fig. 5. Comparison of measured insertion loss after two surface treatments.**

### 3.3. Combination Feed and OMT

To evaluate the combination of our OMT with the segmented structure and choke feed, we ran simulations using AnsysEM HFSS. All simulation results were set with excitation ports and radiation boundaries, resulting in a final mesh size of approximately 60237 tetrahedral and convergence results. Mesh generation is a fundamental step in HFSS simulation, which transforms a continuous simulation area into a finite number of discrete, small cells (tetrahedral meshes) to facilitate the numerical solution of Maxwell's equations. For the optimization of key parameters, we performed fast frequency scanning and used interpolated frequency scanning to control the final results (the return loss and isolation simulation results are shown in Fig. 6).

The combination of the OMT, with its segmented structure, and the feed is shown in Fig. 7, in the microwave anechoic chamber at the FAST project site. The measured return loss, isolation, and noise temperature of the receiver and LNA are shown in Fig. 8. The noise temperature of completed LNA is approximately 5.5–13 K. The processed and assembled feed and OMT meet the design



**Fig. 7. The combined OMT and feed, and the E-plane far-field directional pattern of the feed in the 1.42 GHz, in the microwave anechoic chamber at the FAST project site.**

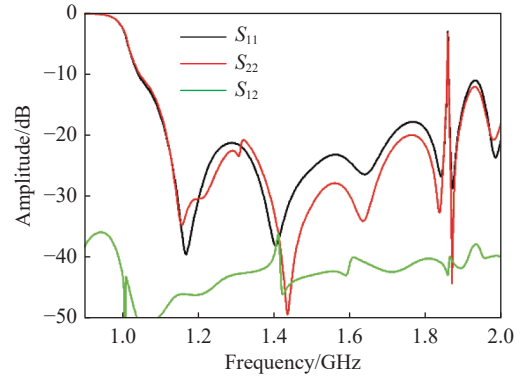


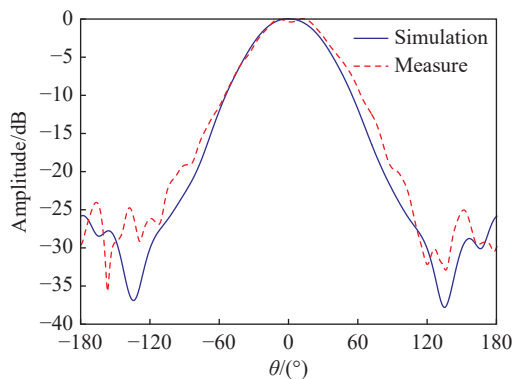
**Fig. 6. Simulated return loss and isolation for the combined feed and OMT.**

requirements, with a return loss of more than 20 dB from 1.15 GHz to 1.75 GHz, and the isolation is more than 30 dB over the full bandwidth. The noise temperature of the receiver is more than 30 K from 1.3 GHz to 1.8 GHz, as shown in Fig. 8. Owing to radio frequency interference, the test results for some frequency points require further correction.

We also performed preliminary tests on the E-plane far-field directional pattern of the feed at 1.42 GHz, using the microwave anechoic chamber at the FAST project site. A comparison between the measured and simulated results of the E-plane far-field directional pattern of the feed is shown in Fig. 7, and are in good agreement at the frequencies of interest.

### 3.4. Installation and Observation

The room temperature receiver system was installed in the feed cabin of a single 40 m radio telescope antenna, for further evaluation. The measured antenna efficiency was greater than 54.3%, and the sensitivity of 40 m radio telescope was approximately 18–20 m<sup>2</sup> K<sup>-1</sup>. After installation, joint measurements were conducted with FAST and separate pulsar observations were carried out. The obtained fringes detection results between the antenna FAST Core Array 01 (FCA01) and FAST are shown in Fig. 9, and the pulsar observation result is shown in Fig. 10.



The data were correlated in the Distributed FX (DiFX) correlator, and analyzed with the software of Haystack Observatory Post Processing System (HOPS).

The big Signal Noise Ratio (SNR) value, as well as the small single band delay (SBD) and multiband delay (MBD), indicate the success of these fringe observations.

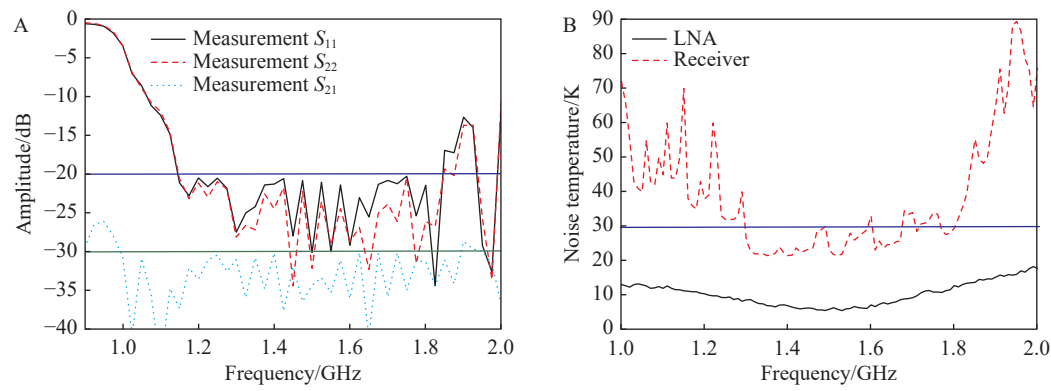


**Fig. 8. (A) The return loss and isolation measurement results of the combined feed and OMT. (B) Noise temperature of the receiver and LNA.**

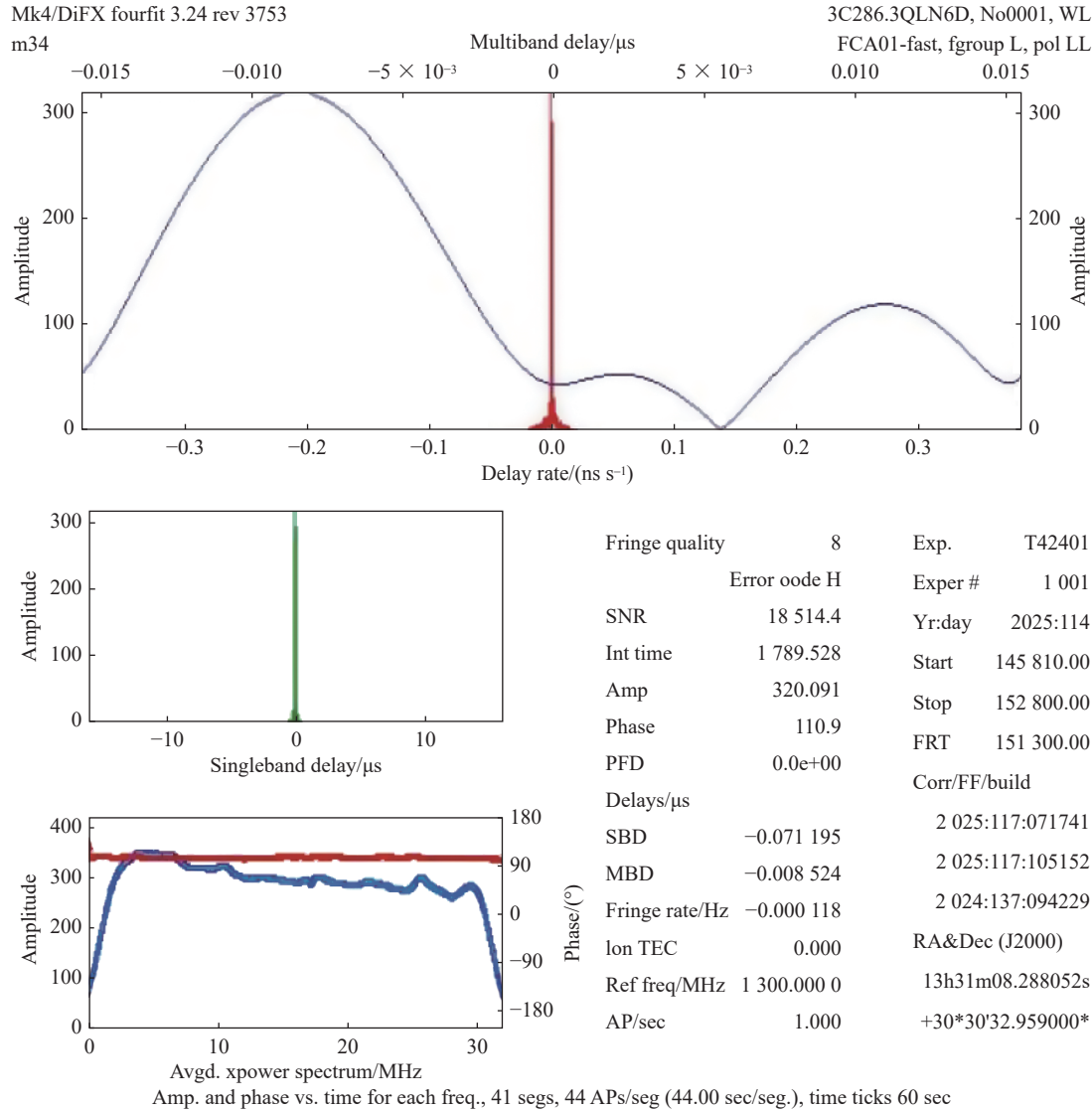


**Fig. 9. Fringes detection results for 3C286 between antenna FCA01 and FAST. The total integration time was 1789.5 s, covering the frequency range from 1300 to 1428 MHz. Top: Multiband delay and delay rate. Bottom left: Single band delay. Bottom right: Averaged power spectrum over a 32 MHz bandwidth.**

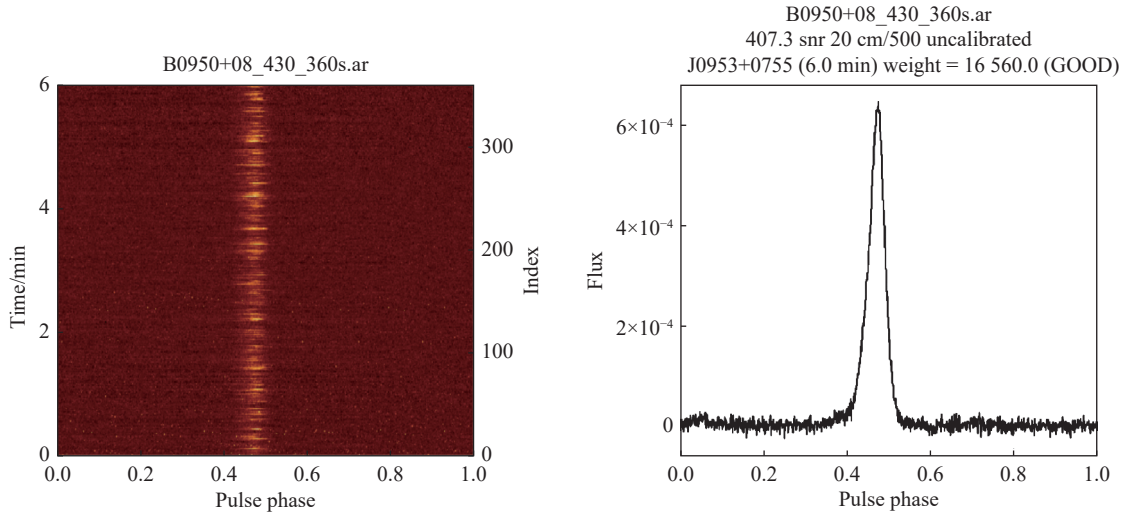


**Fig. 10.** Observations of pulsar B0950+08, recorded using a 40 m antenna. The flow rate is  $S_{1400} = 0.1$  Jy, the period = 253 ms, and the pulse ratio is  $W = 21$  ms.

#### 4. DISCUSSION

Our OMT and feed are designed to reduce insertion loss for a low noise receiver operating at room temperature. The optimization included length and surface treatment. The reduced length makes this design less effective at suppressing high-order modes, resulting in a decrease in bandwidth and inability to achieve the coverage of the octave band. If the length is increased to meet the octave band requirements, the corresponding insertion loss will also increase, which is detrimental to the receiver operating at room temperature.

#### 5. CONCLUSIONS

We designed new low insertion loss L-band feed front-end system for the FAST Core Array L-Band room temperature receiver, and manufactured and tested a prototype. In our tests, it exceeded the design specifications in terms of return loss performance and low insertion loss. The equipment met the expected technical specifications and the observation results were quite satisfactory after installation. Our OMT design places emphasis on manufacturability and ease of assembly, with the individually processed parts able to be simply bolted together. Based on these characteristics, the proposed low insertion loss L-band feed front-end is suitable for array antenna projects on a much larger scale.

#### ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China (2022YFA1602904), the National Natural Science Foundation of China (12273072), Qiannan Prefecture Science and Technology Projects (QNKHSZ [2024]10), the science and technology innovation program of Hunan Province (2024JC0001), and the Guizhou Provincial Science and Technology Projects (QKHFQ[2023]

003, QKHFQ[2024]001, QKHPTRC-ZDSYS[2023]003, QKHPTRC-GCC[2022]003-1, QKHPTRC[2021]Postdoctoral-Research-Station-001).

#### AI DISCLOSURE STATEMENT

AI-assisted technology is not used in the preparation of this work.

#### AUTHOR CONTRIBUTIONS

Jinglong Yu provided the ideas and used software for simulations. Hengqian Gan and Yang Cao provided mechanical processing and design. Xiaoming Chai provided LNA design and testing. Bin Liu provided receiver debugging and antenna performance testing. Rurong Chen provided astronomical observation results. All authors read and approved the final manuscript.

#### DECLARATION OF INTERESTS

The authors declare no competing interests.

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