Frontend Signal Processing Design for a cryogenic PAF prototype of FAST

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Abstract

For large reflector radio telescopes, cryogenic phased array feed (PAF) has the great potential on enhancing the telescope's performance and thus PAF becomes one of the research frontiers in the field of radio astronomy. The Joint Laboratory for Radio Astronomy Technology (JLRAT) team has been studying on PAF theories and key technologies and developing a cryogenic prototype for the Five hundred meter Aperture Spherical Telescope (FAST). This paper is to present the current progress on the frontend signal processing devices including the signal processing framework design, the system integration and key components development.

1 Introduction

Phased array feed (PAF) is quite a promising receiver technology for reflector antennas and has been developed for over 20 years[1][2]. It can achieve continuous sky coverage in the telescope's field of view by sampling the electromagnetic field across the focal plane of the telescope and using digital beam forming, and make the telescope's gain close to or exceed those of traditional feeds. PAF can realize a variety of observation modes flexibly as well.

As the world's largest single dish radio telescope, the Five hundred meter Aperture Spherical Telescope (FAST) has fully operated in the early 2020. Since the commission phase, the 19-horn receiver has been installed and conducting astronomical observations. However due to the gaps in the sky coverage of the adjacent horns, the FAST telescope needs multiple pointing to form continuous sky coverage, and the sensitivity of the outermost horns drops compared with that of the center feed. By using PAF, it is expected to form continuous sky coverage, increase the sensitivity of each beam which will allow the FAST telescope to survey the sky 4-5 times more quickly. PAF can also achieve point-scanning calibration, compensate the position residuals of the feed cabin, and correct surface shape errors of the large dish, which will greatly improve the overall performance of the FAST telescope.

We are working on an L-band cryogenic PAF prototype for the FAST which aims at acquiring better performance than the 19-horn receiver and replace the 19-horn receiver in future. We have developed a 19-element antenna array consisting of the hexagonal cavity-backed dipole covering the frequency range of 1.05 - 1.45 GHz [3]. And the cryostat was built and tested when the antenna array was installed in it [4] as shown in Figure 1. This paper will describe our work on the frontend signal processing design for the 19-element PAF.

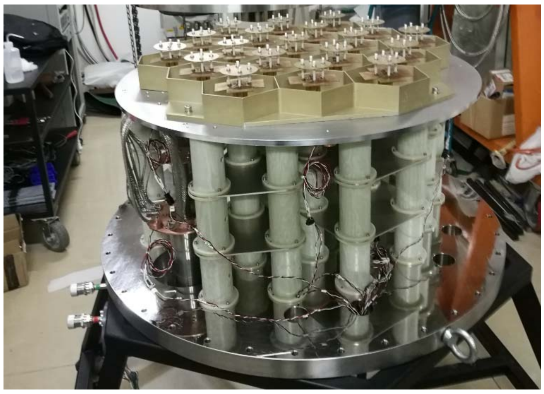


Figure 1. Cryogenic test on the antenna array of the 19-element PAF for FAST. The antenna array was installed in the cryostat supported by G10 pillars.

2 Frontend Signal Processing framework

A PAF usually consists of tens or even hundreds of antenna elements. Each antenna is dual polarized and followed by two signal paths which includes LNAs, radio frequency (RF) amplifiers, RF bandpass filters, mixers, local oscillator, intermediate frequency (IF) amplifiers and low-pass filter, etc. The functions of the signal path are amplification, signal filtering, frequency conversion, power leveling, and finally providing proper signal input for ADCs doing the backend processing.

2.1 Specifications

- Frequency coverage: 1.05 - 1.45 GHz
- Number of element: 19
- Polarization: 2
- RF bandwidth: 400 MHz
- IF bandwidth: 100 MHz
- System noise figure: 0.5 dB
- System gain: about 120 dB, adjustable with attenuators

2.2 System Design

In the current stage, a room-temperature PAF prototype is under development firstly. After function verification completed, we will go to the next step – cryogenic PAF. At room temperature, the noise figure and gain of the LNA are designed as 0.5 dB and 30 dB. For the RF amplifiers, the noise figure should be less than 2.5 dB and the gain should be larger than 30 dB, in which case the noise contribution of the RF amplifiers to the whole system noise temperature can be negligible. The bandpass filter covers the frequency range of 1.05 - 1.45 GHz. The local oscillator should be adjustable and provide 1.05 - 1.35GHz signal. The low-pass filters work at DC-100 MHz to meet the requirement of the current backend system. With the adjustable oscillator, the IF bandwidth can cover the RF bandwidth. The total gain of the system is about 120 dB. If necessary, attenuator can be used to adjust the gain. The frontend system composition and parameter allocation are shown in Figure 2.

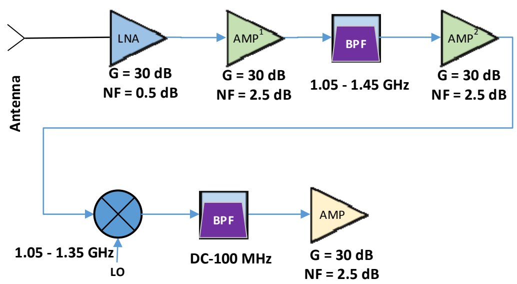


Figure 2. A single frontend signal path framework and the parameter design.

2.3 System integration

As the signal system must be build up for each frontend element and then integrated, therefore they should be easy to produce, maintain, and operate. We start with developing parts of the system according to the special requirements of the PAF, then design and evaluate how to integrate the components effectively.

The frontend signal path is divided into three groups, LNA, RF signal processing, and down conversion and IF signal processing. LNAs are installed as close as to the antenna element, and both the LNAs and antennas are placed in the cryostat and are cooled to 15 – 20 K. Devices related to RF signal processing like band-pass filter, RF amplifiers, are integrated on one PCB and then packaged in one box. Down conversion and IF signal processing parts are assembled together. Considering the supporting structure design, the 19 RF signal processing boxes may be integrated together while down conversion and IF signal processing boxes assembled together. 19-element PAF frontend signal paths framework is shown in Figure 3.

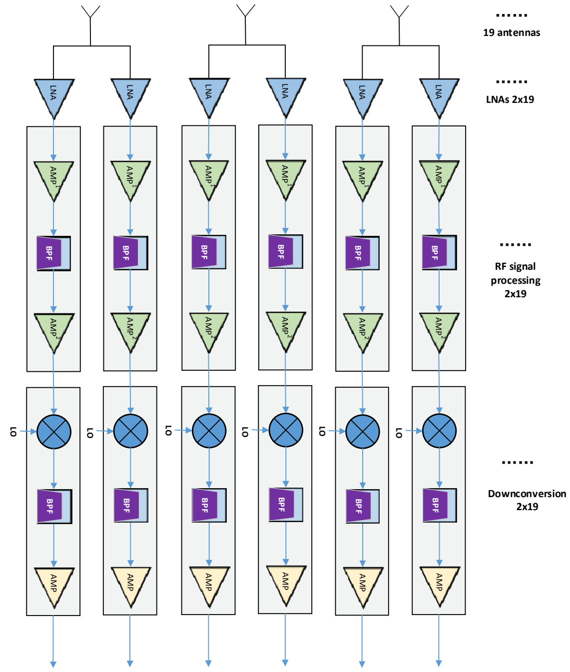


Figure 3. 19-element PAF frontend signal paths framework.

3 Key Components Design and Test

In the current state, we have preliminary design and test results about the LNA, RF amplifier and low-pass filter. Other parts including the bandpass filter, mixer, local oscillator are under development.

3.1 LNA

LNA is the critical part of the frontend signal processing system which has great influence on the system noise temperature. So the LNA should have low noise and enough gain to reduce the impact on the system noise of the subsequence devices. As PAF is comprised of quite a large number of LNAs, costs, sizes, simple biasing, capabilities to be integrated to the antenna and possible filter, mass production, MTBF evaluation, etc., need to be considered.

We selected commercial transistors at the advantage of low noise, high gain, single power supply, simple matching network and biasing network. It makes the design easy to implement and achieve the small size at the same time.

The noise simulation results are shown in Figure 4. The minimum noise figure is 0.25 dB at 1.05 GHz and 0.35 dB at 1.45 GHz. After matching network, biasing circuit and stabilization design, the noise figure is 0.27 dB at 1.05 GHz and 0.36 dB at 1.45 GHz.

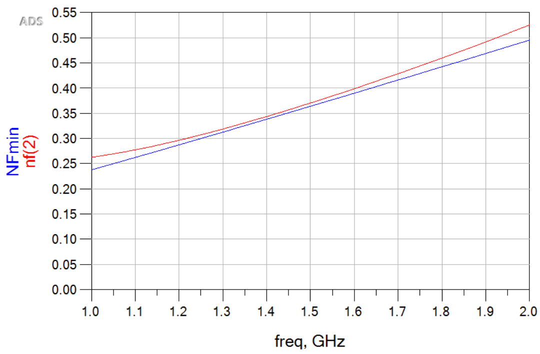
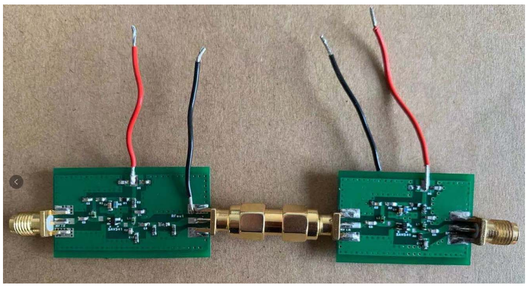
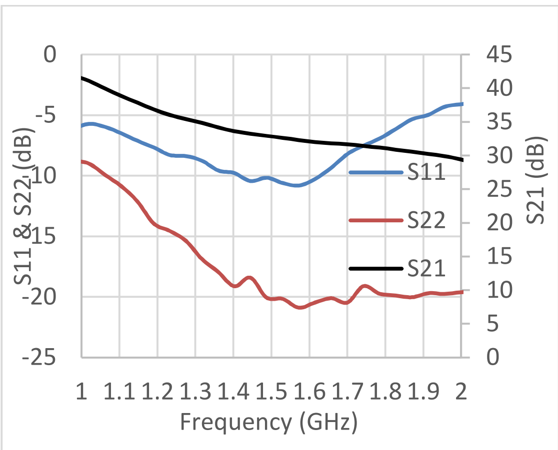


Figure 4. The noise performance simulation of the LNA.

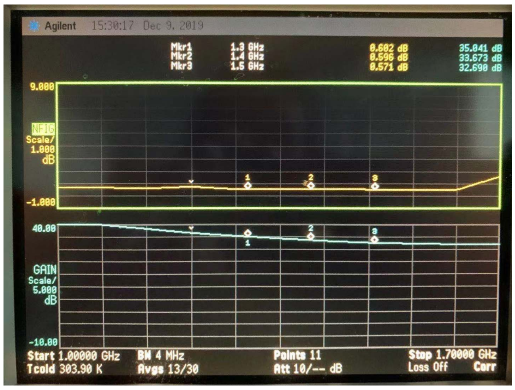
The LNA prototype and measurement results are shown in Figure 5. The prototype consists of two stages. In the experiment board design phase, one transistor is on each board and two boards are connected by SMA connector. The board is about 4 cm × 2 cm. Next step, an integrated board of two stages will be manufactured and the size estimated as 5 cm × 2 cm. The S11 measures better than -6 dB and S22 is better than -10 dB in the operating frequency range. S21 is larger than 33 dB. The noise figure measures 0.6 dB at 1.4 GHz.



(a) The experiment board of LNA



(b) S-parameter measurement results of the LNA

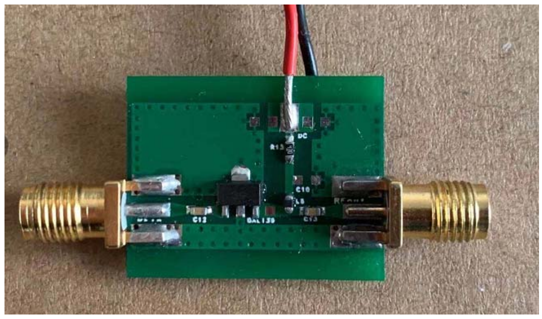


(c) The noise figure measurement of the LNA

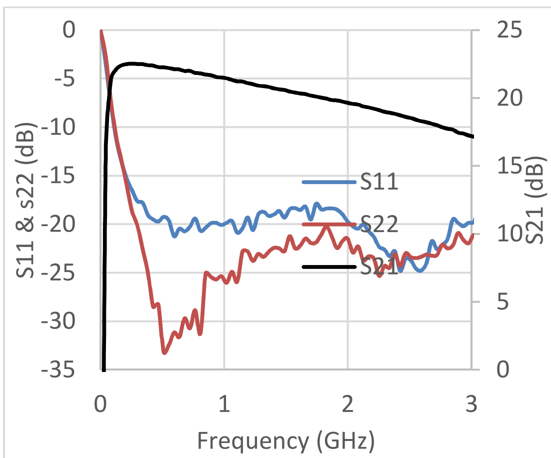
Figure 5. The LNA prototype and measurement results

3.2 RF Amplifier

The RF amplifier experiment board consists of one stage transistor. The S11 measures better than -19 dB and the S22 better than -22 dB at 1.05 - 1.45 GHz. S21 is greater than 20 dB. The noise figure is about 2.5 dB at 1.4 GHz. The results are shown in Figure 6. The size of the board is 2.5 cm × 1.5 cm.



(a) The experiment board of the RF amplifier



(b) S-parameter measurement results of the RF amplifier

Figure 6. The RF amplifier prototype and measurement results

4 Conclusion

The system design for the frontend signal processing of the FAST PAF prototype has been completed. The integration of the multiple signal paths has been preliminarily planed and need further consideration and implementation. Key components such as the LNA, RF amplifier, low-pass filter have been developed and measurement results are given. We will complete other components design and the system integration of the frontend signal path in next step. Then integrate the frontend prototype to the backend and do functional debug in the lab. In the near future this PAF prototype will be assembled on a small telescope to do calibration test and experimental astronomical observations.

5 Acknowlegements

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6 References

1. D. Anish Roshi, W. Shillue1, B. Simon, et al., “Performance of a Highly Sensitive, 19-element, Dual-polarization, Cryogenic L-band Phased-array Feed on the Green Bank Telescope,” the Astronomical Journal, April 2018, doi: 10.3847/1538-3881/aab965

2. German Cortes-Medellin, Stephen Parshley, Donald B. Campbell, Karl F. Warnick, Brian D. Jeffs, and Rajagopalan Ganesh "Concept design of an 80-dual polarization element cryogenic phased array camera for the Arecibo Radio Telescope", Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 99085F (9 August 2016); https://doi.org/10.1117/12.2233899

3. Y. Wu, K. F. Warnick, and C. Jin, “Design Study of an L-Band Phased Array Feed for Wide-Field Surveys and Vibration Compensation on FAST,” *IEEE Transactions on Antennas and Propagation*, 61(6), 2013, pp. 3026–3033. doi:10.1109/tap.2013.2254438

4. M. Guo, X. Chai, D. Wu, C. Jin, and S. Chen, “Fully Cryogenic Phased Array Feed Dewar Design and Heat Transfer Analysis,” *New Technology & New Process*, 2018,05, doi:10.16635/j.cnki.1003-5311.2018.05.005