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Design and optimization of cross bow-tie dipole feed with cavity for FAST

Jing-Long Yu, You-Ling Yue and Jian-Bin Li

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; *yjl@bao.ac.cn*
CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

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Abstract A cross bow-tie dipole feed with cavity and symmetrical E and H plane pattern is presented for the Five hundred-meter Aperture Spherical radio Telescope (FAST). In this paper we describe the design, optimization and simulation results of a wide-band cross dipole feed with cavity covering the frequency range from 300 MHz to 600 MHz for FAST. The main goals of our design are to ensure that, (1) we cover the octave bandwidth, (2) the feed has symmetrical E and H plane pattern, and (3) the physical dimension is suitable for mounting it in the reserved position of the FAST feed cabin. The initial results indicate that we have met most of our design goals. This kind of feed had been equipped with the multi-beam receiver to carry out observation on the platform of FAST cabin.

Key words: telescope — feed — bow-tie — dipole — cavity — FAST

1 INTRODUCTION

The Five hundred-meter Aperture Spherical radio Telescope (FAST) is national facility available for carrying out astronomical and astrophysical studies. It is the largest single-aperture radio telescope in the world and it has an aperture of 500 m diameter. Multi-beam and multi-band receivers will be installed covering frequency range of 70 MHz − 3 GHz (Jiang et al. 2019). The present paper deals with the development of octave bandwidth feed system to be used for FAST below 1 GHz.

Most common feeds of the reflector antenna are resonant half wave dipoles and small open-ended waveguides or horn antennas. The half wave dipole can get nearly symmetrical E- and H-plane radiation patterns by using two parallel dipoles with half wavelength spacing (Christiansen & Hogbom 1969), or by locating a metal ring of about one wavelength diameter above the dipole (Kidal & Skyttemyr 1982; Kildal et al. 1997). However, it is very difficult to realize octave bandwidth because of the limitations of different dipole structures. The feed described in the present paper is a kind of two parallel dipole feed that uses a new structure with octave bandwidth.

The horn feed became very popular during 1980's. In particular, corrugated horns are popular as feeds for dual reflector antennas, and they can have octave bandwidth (Thomas et al. 1986, 1995). The feed used in primary-fed reflectors is often a choke horn. This kind of feed can achieve small variation of the beam-width and the phase center location over a bandwidth of 1.8:1 (Ying et al. 1995). However, these two kinds of horns will need to be very large if they used in low frequency bandwidth, such as below about 1 GHz.

The main objective of the present work is to research and develop an octave bandwidth feed for the big reflector antennas such as FAST below 1 GHz and to use the feed system to scale in other low frequency range.

2 CHARACTERIZATION OF FEED

The main goals of the feed system design were to obtain a reasonable aperture efficiency, symmetrical E and H-plane patterns and, a suitable physical dimension for mounting it in the reserved position of the FAST feed cabin. For low frequency, two kinds of feed system have been used in radio telescope. One is the Fat Dipole of Netherlands Institute for Radio Astronomy (ASTRON) with 1.56:1 bandwidth (Woestenburg 2004). The other one is V-folded Dipole of Giant Metrewave Radio Telescope (GMRT) with Voltage Standing Wave Ratio (VSWR) less than 2 over the frequency range of 55 to 80 MHz (Uoiudaya Shankar et al. 2009; Shahram 2010). However, it is difficult for both of the above mentioned feed to cover octave bandwidth with VSWR less than 2. So the desired frequency range of operation ($300 - 600$ MHz) for FAST should be researched and kept development.

Some conventional wide-band dipole antennas include: the planar wide-band dipole (blade, bow-tie, diamond, elliptical, etc.), Log Periodic Dipole Antenna (LPDA), the sleeve volumetric dipole, the droopy-blade dipole and the folded dipole of different variations etc. A modified fat dipole antenna used in ground penetrating radar (GPR) system with a broad bandwidth, between 100 MHz and 350 MHz is developed by Korea Electro technology Research Institute (KERI & Microline Co., Ltd. 2003).

A kind of volumetric ribcage dipole configuration used in wide-band Ultra High Frequency (UHF) for Digital television (TV) system is researched by F. Scappuzzo (Scappuzzo et al. 2009).

In primary design, We choose the X-LPDA for the candidate feed to cover the octave bandwidth in low frequency range. In this kind of feed system. the radiation pattern is very different in E- and H-planes. The phase center varies strongly with frequency. This caused low efficiency, high spillover and cross polarization.

Therefore, we should take into account both octave bandwidth and performance in the next design work. In addition, the installation location and size should be carefully selected to avoid a feed that is too large. After comprehensive consideration, we choose the cross bow-tie dipole feed with cavity antenna as our design and optimization scheme.

In this paper, High Frequency Structure Simulator (HFSS) is used to model cross bow-tie dipole feed with cavity antenna design with some improvements for this kind of dipole, as follows: (a) A concentric aluminum tube is used for feed line instead of a coaxial line. (b) The shape of the dipoles is modified to achieve the match and required bandwidth.

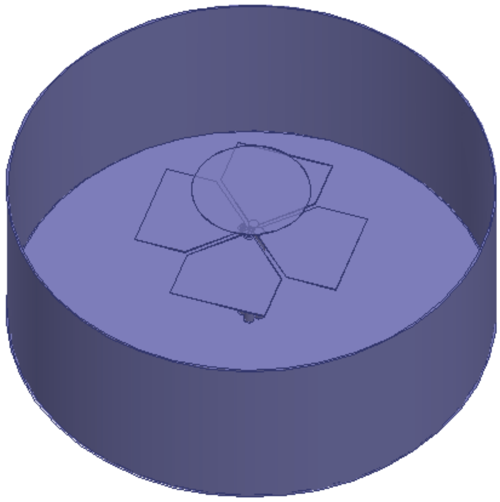

Fig. 1 The model of cross bow-tie dipole with back cavity in HFSS.

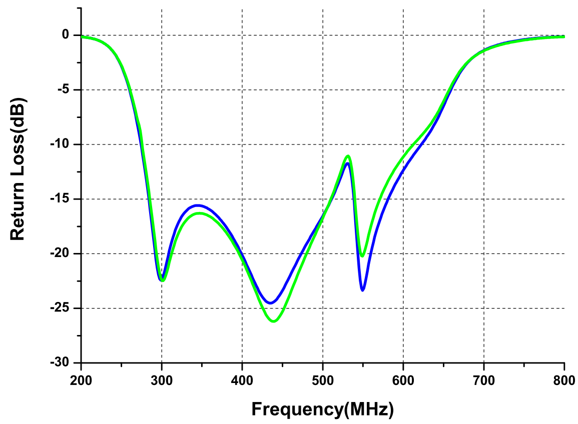

Fig. 2 The simulation results of return loss for preliminary model.

3 FEED DESIGN

The main goals of the feed system design were to obtain a reasonable aperture efficiency, symmetrical E and H-plane patterns and a suitable physical dimension for co-locating it with the existing multi-beam feed on the FAST feed cabin platform, with minimum interference to its operation. The desired frequency range of operation ($300 - 600$ MHz) was chosen to facilitate pulsar survey in the band protected for radio astronomy ($322 - 328$ MHz and $406 - 410$ MHz) and to minimize the radio frequency interference (RFI) due to the TV radio band below 223 MHz and starting beyond 470 MHz.

The LPDA is not suitable to use for the feed of paraboloid antenna because the phase center varies strongly with frequency and also because of its unsymmetrical far field pattern. Similar shortcomings also exist in the Quad Ridged Flaring Horn (QRFH). Meanwhile, the QRFH cannot be equipped with the Multi-beam receiver on the platform of FAST because of very large dimension in this frequency band. The large size for low frequency is a similar problem such as the Eleven feed. Furthermore, the extra insertion loss of micro strip feed structure of the Eleven feed will increase the system noise temperature of the receiver.

A kind of feed system consisting of cross bow-tie dipoles with a back cavity configuration was developed because it provides more symmetric E and H-plane patterns than a single dipole feed. The bow-tie antenna is a dipole with flaring, triangular shaped arms. The shape gives it a much wider bandwidth than an ordinary dipole, which is widely used in UHF TV antennas. Moreover, it can provide symmetric E and H-plane patterns in octave bandwidth benefit from the back cavity. After extensive simulations and field trials, it was decided to co-locate the new

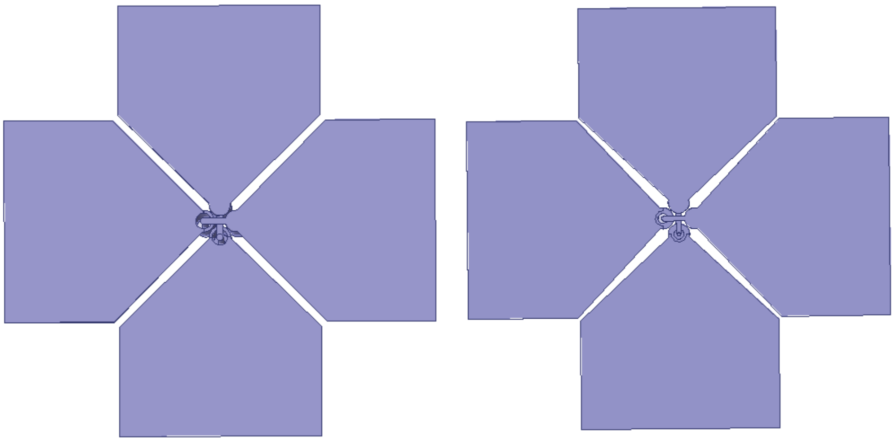

Fig. 3 The flare angle change of the cross bow-tie dipole: 90 degree for preliminary design (*left*) and 94 degree for optimization design (*right*).

feed with the existing multi-beam feed because of its compact construction.

A concentric aluminum tube is used in this kind of feed for feed line instead of the traditional coaxial line considering the need for further optimization. This structure is not only beneficial to support the dipole, but also to adjust the impedance number according to the matching. In the optimization process, impedance can be adjusted by adjusting the ratio of inner to outer diameter of concentric cylinder. Because the dipole impedance is usually bigger than 50 ohm, it is impossible to adjust using coaxial feed line.

The geometry structure and simulation model in HFSS of cross bow-tie dipoles with a back cavity is shown in Figure 1. The 90 degree flare angle of the bow-tie dipole is chosen in the preliminary design work. At the same time, the impedance of the concentric aluminum tube feed line is 50 ohm.

All simulations are performed in HFSS, with the radiation boundary, with final meshes of about 36 290 tetrahedral, and with a good convergence history. For parametric optimization, the fast frequency sweep is used; all final results have been controlled using discrete frequency sweep. Figure 2 presents the simulated results of return loss for the preliminary design model.

In this study we focus on the octave bandwidth from 300 MHz to 600 MHz. Clearly, the cross bow-tie dipole with back cavity demonstrates a broadband behavior with good performance.

4 OPTIMIZATION DESIGN

The shape of the dipoles is the key factor to achieve good performance with wide bandwidth, which is the crux of the matter for the impedance match. So the improvement to the shape of the dipole is necessary. The optimization

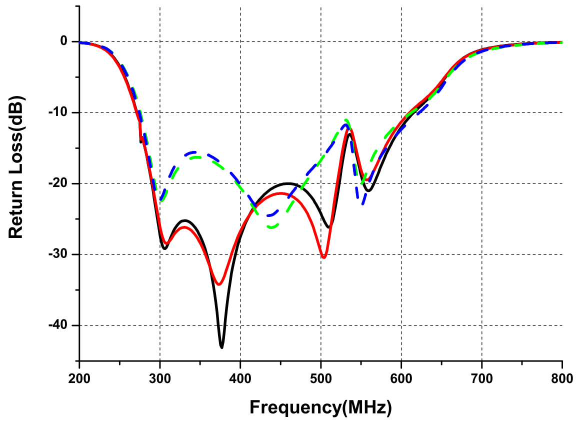

Fig. 4 A comparison of return loss simulation results for preliminary design (*blue and green dotted line*) and optimization design (*black and red solid line*).

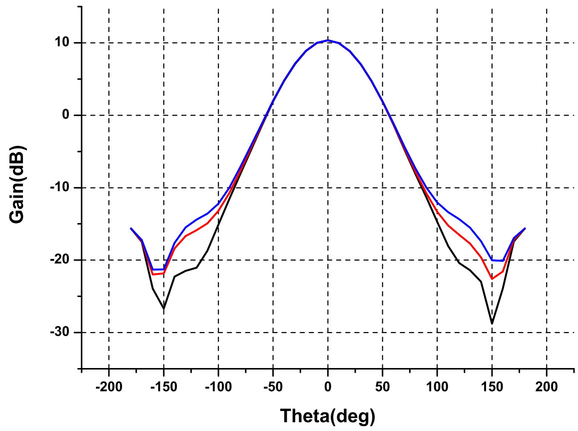

Fig. 5 The radiation pattern for cross bow-tie dipole with back cavity.

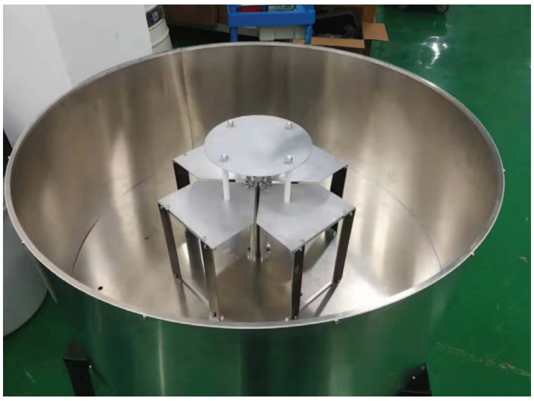

Fig. 6 The prototype of cross bow-tie dipole with back cavity.

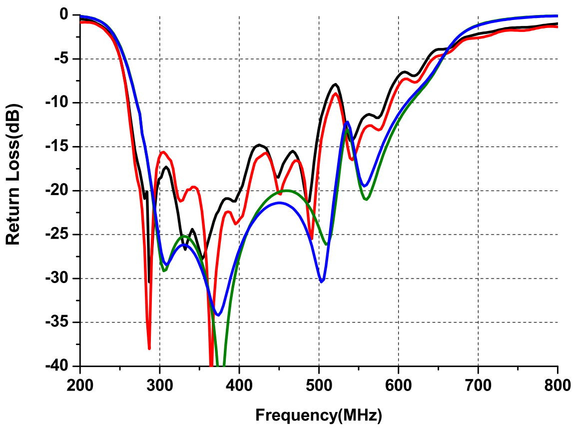

Fig. 7 Simulated (*blue and green line*) and measured results (*black and red line*) for the prototype of cross bow-tie dipole with back cavity.

increases the flare angle of the bow-tie dipole, which will benefit the impedance match.

Figure 3 presents the flare angle change of the cross bow-tie dipole. This figure is a top view for this kind of cross dipole. The flare angle of preliminary design is 90 degrees for this kind of structure, and the flare angle after optimization design is about 94 degrees. The simulation setup is the same as that mentioned in Section 3.

Increasing the flare angle of the bow tie dipole is beneficial to improve the impedance match between the dipole and concentric aluminum tube feed line. At the same time, the impedance of concentric aluminum tube feed line is also adjusted in the optimization process.

The ratio of inner to outer diameter of concentric aluminum tube is 2.3 in preliminary design. The impedance is about 50 ohm, but the dipole's impedance is about 65 ohm. The matching degree between of them is not very good. Consequently, we adjust the ratio of inner to outer diameter of concentric aluminum tube to 2.885 after optimization. So the impedance of concentric aluminum tube feed line is about 63.57 ohm, which is very close to the impedance value of the bow-tie dipole antenna and improvement matching degree between feed line and dipole.

A comparison of return loss simulation results before and after optimization for two polarization is shown in Figure 4. It is obvious that the performance of return loss for this kind of feed has improved significantly compared to before optimization. The return loss is better than -20 dB from 292 MHz to 520 MHz.

Furthermore, we are also interested in the far field radiation pattern for this kind of feed system. Because of back cavity, the feed has a symmetrical far-field pattern in the working bandwidth. Given that it provides symmetric E and H-plane patterns, the illumination of telescope will be stable in the available bandwidth. The far-field radiation patter simulation results of the center frequency 450 MHz for this kind of feed are shown in Figure 5 and the symmetry of far-field pattern is very good.

5 PROTOTYPE AND MEASUREMENT

The prototype of this kind of feed is fabricated as shown in Figure 6. The S parameters were measured using an Agilent E5071C network analyzer. The simulated and measured results are plotted in Figure 7, showing that a good agreement is obtained between them. This kind of feed had been installed on the platform of feed cabin together with 19-beam receiver in April 2019.

6 CONCLUSIONS

The present paper has introduced and discussed the use and optimization design work of the wide-band cross bow-tie dipole as a feed for FAST with symmetrical E and H plane radiation pattern. The simulation results illustrate that the performance of return loss for this kind of feed has improved significantly compared to before optimization. Measurement results of this kind of feed show that it is in good agreement with the optimization results. This kind of feed is a candidate of radiation element for an octave bandwidth feed system.

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