URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

Design of Ultra-Wideband Phased Array Feed for Radio Telescope

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Abstract

This paper presents an ultra-wideband Phased Array Feed (PAF) based on novel flat bend crossed dipole fed by 50-Ohm coaxial line. The PAF is dual-polarized and made from all-metal to minimize Ohmic losses and simplify cryogenic integration. It is optimized for 1- 2 GHz band and can be good PAF candidate for the Five hundred meter Aperture Spherical Telescope (FAST) and Qi Tai Telescope (QTT) as well as other radio telescopes.

1 Introduction

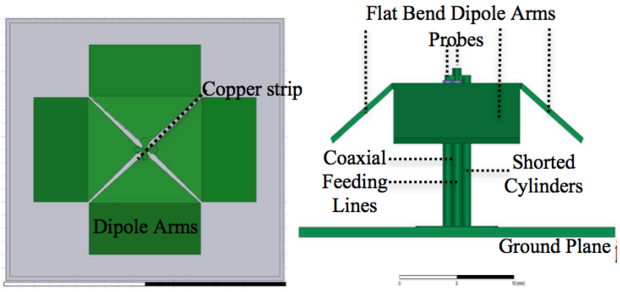
Phased array feed (PAF) is a kind of novel feed for radio telescope consisting of a large number of small antenna elements. Through the beam synthesis network, the signals received by the array elements are weighted and synthesized with controllable amplitude and phase, forming a number of instantaneous beams [1-3], which is an effective method to expand the field of view for large radio telescopes. Currently, several leading radio astronomy institutions have made significant progress on PAF development [4-9].

In the present work, design scenario and simulation of an ultra-wideband PAF based on novel flat bend crossed dipole fed by 50-Ohm coaxial line are carried out with targeted bandwidth from 1 GHz to 2 GHz. The PAF is all-metal to minimize Ohmic losses so as to decrease the noise temperature. Scanning radiation pattern is synthesized to evaluate the PAF system performance for future use in large radio telescope. It will be possibly applied into FAST and QTT L-band cryogenic PAF applications.

2 PAF Element Design

The characteristics of the array element can significantly define the achievable performance of the designed whole array antenna or reflector antenna feed array. Therefore, the selection of array elements plays a crucial role in the phased array feed design.

A sketch of the wideband dual-polarized flat bend crossed dipole is shown in Fig. 1, which is composed of a pair of flat bend dipoles in a cross position, a common ground plane, two shorted cylinders, and two coaxial (air-filled) feeding structures with outer conductors grounded and inner conductors (probes) connected to the opposite metallic arm plate via copper strips at one end, connected to Sub-Miniature A (SMA) connectors underneath the ground plane at the other end [10]. Then, single-end Low Noise Amplifiers (LNAs) can be connected to the dipole directly. The ground plane is employed as a reflector for the antenna to produce a unidirectional radiation pattern. The arm of the dipole bent down at an angle so as to broaden the half-power beam-width and reduce the size of antenna, so large scanning angles can be achieved in phased array applications.



(a) (b)

Fig. 1. Structure of Flat bend crossed dipole (a) Top view (b) Side view

The proposed novel flat bend dipole element has been simulated using the full-wave electromagnetic software Ansys HFSS with periodic boundary. With bent-angle of 40° (angle between horizontal plane and the bend arm), a good in-band properties can be achieved with VSWR below 1.5 from 1 GHz to 2 GHz.

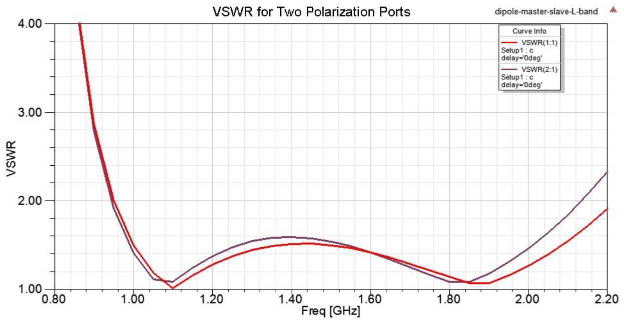


Fig. 2. VSWR for Flat bend crossed dipole element

3 Array Design

Planar array can be located in many types of grids and the most common ones are the rectangular grid and the triangular grid. Considering open scalable modular properties, rectangular grid type is adopted in our phased array feed design. Expandable 6-element antenna module is used to construct a 24-element array.

Element spacing should be selected to form overlapped secondary radiation pattern fed by adjacent array elements [11]. To guarantee overlapped secondary radiation pattern, array element spacing should be smaller than 112.6 mm at 1.5 GHz (when feeding a reflector with f/D of 0.4611) and 112 mm is chosen finally in our design. The simulation model of the L-band phased array feed is as shown in the Fig. 3.

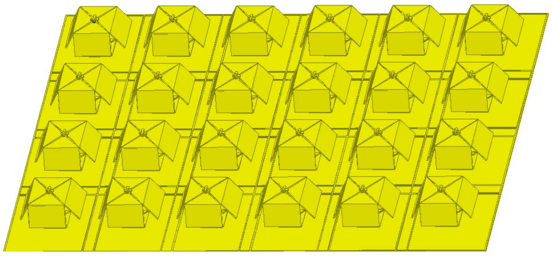


Fig.3. 24-element ultra-wideband phased array feed

4 PAF System Performance

The proposed L-band phased array feed feeding a reflector with aperture diameter of 5 m and f/D of 0.4611 is as shown in the Fig. 4. Secondary radiation patterns of each array element are calculated with 24-element phased array feed feeding a reflector using Physical Optics (PO) and Physical Theory of Diffraction (PTD) as input parameters for beamforming algorithms.

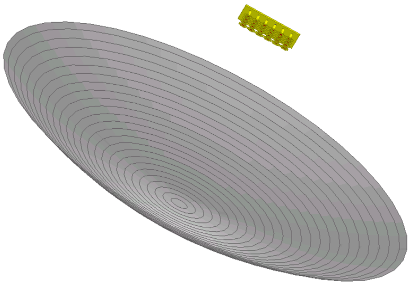


Fig.4. 24-element ultra-wideband phased array feed system model

The beamforming algorithms for PAF mainly include conjugate field matching (CFM), maximum gain (MG) and maximum signal-to-noise ratio (MSNR). Weighting coefficients can be calculated by the MG algorithm according to Equation (1), in which $\mathbf{W}_{D\max}$, $\mathbf{R}_{iso}$ and $\mathbf{V}_s$ are weight coefficients, isotropic noise correlation matrix and signal steering vector respectively [12].

$$\mathbf{W}_{D\max} = \mathbf{R}_{iso}^{-1}\mathbf{V}_s \tag{1}$$

Weight coefficients of the proposed ultra-wideband phased array feed are calculated based on MG algorithm. As can be seen in Fig.5, the amplitude distribution area mainly corresponds to elements in the Airy spot area of incident waves and changes from central four elements to edge of the 24-element PAF when beam scans from bore sight to off bore sight.

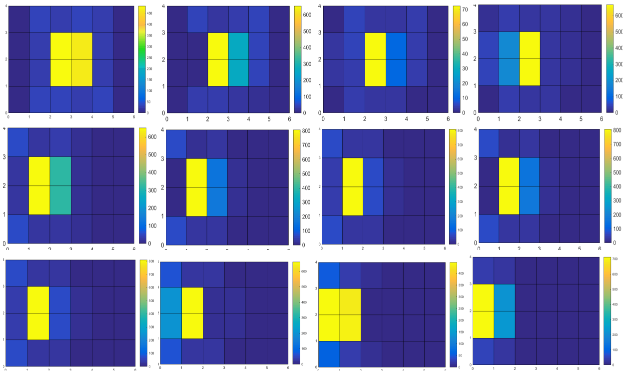


Fig.5. Weighted amplitude distribution for beam scanning of 24-element PAF

The synthesized secondary scanning radiation pattern of the reflector is shown in Fig. 6. It can be seen that the gain of the reflector is well consistent at different scanning angles. With the increase of scanning angle, the first side lobe of the secondary radiation pattern increases but the normalized level does not exceed -16.5 dB and the efficiency of the reflector antenna fed by the phased array feed is 70% at the bore sight.

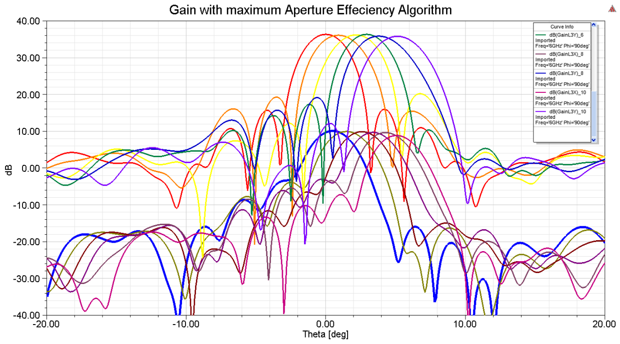


Fig.6. Radiation pattern of radio telescope fed by the PAF

Figure 7 shows the 3-dB beam projection of the 24-element PAF radiation pattern in the two-dimensional plane of the celestial sphere. Compared to the interval of at least two half-power beamwidth of traditional multi-beam feed, continuous 3-dB beam coverage can be achieved for the L-band phased array feed and it verifies the ability of continuous beam scanning of the proposed PAF design.

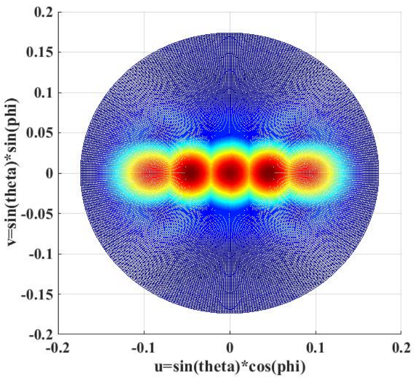


Fig.7. PAF radiation pattern projection in the two-dimensional plane of the celestial sphere

5 Conclusion

An ultra-wideband Phased Array Feed (PAF) is proposed based on a novel flat bend crossed dipole element with VSWR below 1.5 over 1.0-2.0 GHz. A 24-element PAF is designed and the secondary radiation pattern is synthesized with the weighting factor calculated by the maximum gain algorithm. Simulation shows the antenna efficiency of 70% and continuous 3-dB beam coverage can be achieved for radio telescope equipped with the PAF. This design can provide reference for PAF system development of FAST and QTT as well as other radio telescopes.

6 Acknowledgements

This work was supported by Joint Research Fund in Astronomy (U1931129 and U1831117) under cooperative agreement between NSFC and Chinese Academy of Sciences (CAS), NSFC-STINT Grant of 11611130023 (CH2015-6360) and the National Natural Science Foundation of China (NSFC) Grant of 11403054.

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