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Design of Octave-bandwidth Phased Array Feed for Large Radio Telescope

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***Abstract*—This paper presents design scenarios of Octave-bandwidth Phase Array Feed (PAF) based on a novel wideband dual polarized tightly-fed Bowtie antenna element. The PAF is optimized for the 4 – 8GHz band aiming to possible later integration in the SKA pathfinder PHAROS2. The proposed design can be a good candidate of PAF for the Five hundred meter Aperture Spherical Telescope (FAST) and Qi Tai Telescope (QTT) as well as other large radio telescopes.**

***Index Terms*—wideband, Phased Array Feed (PAF), Radio Astronomy.**

I. INTRODUCTION

Radio astronomy is primarily an observational science and conducted using large radio antennas referred to as radio telescopes. Detection sensitivity, size of the field-of-view (FoV) and instantaneous frequency band are main performance limiting factors of radio telescopes. High sensitivity can be achieved for radio telescopes with huge aperture area but the field-of-view of large radio telescopes is very limited when equipped with single-pixel feed [1].

Multi-beam feed technology is an effective method to expand the field of view for large radio telescopes [2]. However, the diameter of a horn is typically greater than the half-power diameter of the focal spot, so the beams on the sky are spaced further than two half-power beam-widths, leaving "holes" in the coverage.

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 [3]. Currently, several leading radio astronomy institutions have made significant progress on PAF development, including uncooled broadband PAFs such as APERture Tile in Focus (APERTIF), phased array feed demonstrator (PHAD), the Australian Square Kilometer Array Prototype (ASKAP) Chequerboard PAF as well as Cryogenic PAF in the Arecibo telescope and partially Cryogenic FLAG PAF [4-9].

In the present work, a novel wideband dual polarized tightly-fed Bowtie antenna element is proposed which will be possibly applied into SKA pathfinder PHAROS2 PAF working from 4 GHz to 8 GHz. Design and simulation of 24-element PAF based on the wideband tightly-fed Bowtie antenna element is carried out. With maximum gain (MG) algorithm, radiation pattern is synthesized to evaluate the system performance for future use in large radio telescopes.

II. ARRAY ELEMENT DESIGN

A sketch of the wideband dual polarized tightly-fed Bowtie antenna element is shown in Fig. 1, which is composed of a pair of Bowtie in a cross position, two coaxial lines, two shorted cylinders and a PCB with two orthogonal feeding lines and a common ground plane.

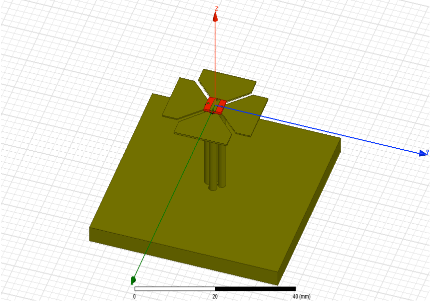


Fig.1. Geometry of the tightly fed Bowtie antenna.

The feeding of the antenna is realized by using two coaxial cables and cross-over copper strips on a PCB. The outer conductor of each 50-Ohm coaxial line for each polarization is connected to one Bowtie arm. The inner conductor is connected to the opposite metallic Bowtie arm through one of the cross-over microstrip lines which are built on a two-layer Rogers 5880 PCB laminates with a relative dielectric constant of 2.2. The other ends of the coaxial cables are connected to SMA connectors which are located underneath the ground plane, opening a possibility to connect the antenna to single-end low-noise amplifiers (LNAs) directly. The ground plane is employed as a reflector for the antenna to produce a unidirectional radiation pattern and the distance between the Bowtie arms and the ground plane is selected as about $\lambda/4$ (where λ is the wavelength at the low end of the frequency band).

Fig. 2 shows the simulated S-parameters of the final design of the tightly fed Bowtie element. The reflection coefficient is below -15 dB and the mutual coupling between the orthogonally polarized Bowtie dipoles below -25 dB over 4.0-8.0 GHz.

Fig. 3 gives the simulated results of radiation patterns in E-, D (diagonal) - and H-planes at 4, 6 and 8 GHz, respectively. As shown, the radiation patterns are nearly symmetrical in the operating bandwidth. The 3-dB beam width is very broad, 90.5 ° ~159.5 ° over the entire bandwidth with cross-polarization level below −25 dB, which indicates this tightly-fed Bowtie antenna element is very appropriate for phased array design.

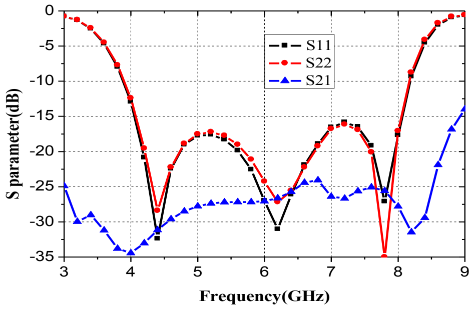
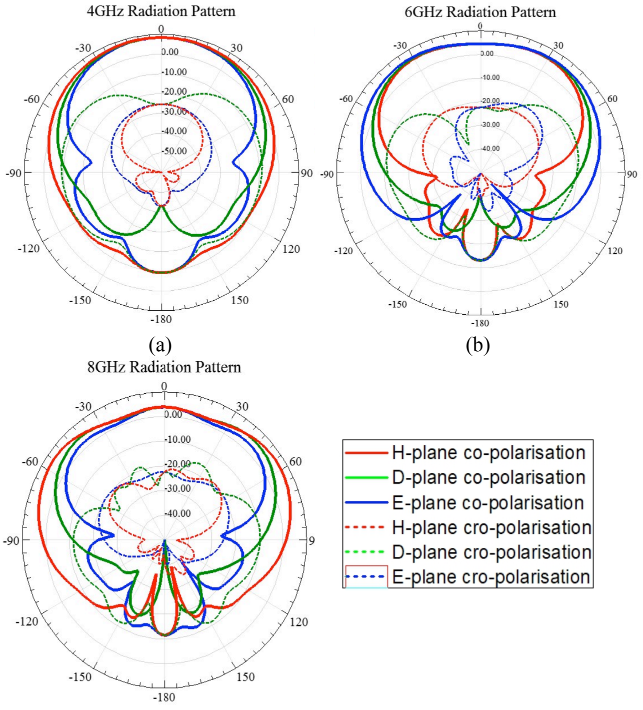


Fig.2. S parameter of the tightly fed Bowtie



(a) (b)

(c)

Fig.3. Radiation pattern of the tightly fed Bowtie (a) at 4 GHz (b) at 6 GHz (c) at 8 GHz

III. ARRAY DESIGN

Grid types and element spacing are main factors that need to be considered in antenna 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 [10]. Selection criterion of element spacing is to avoid grating lobes existing for phased arrays, however in the design of phased array feed, element spacing should be selected to form overlapped secondary radiation pattern fed by adjacent array elements [11].

Considering open scalable modular properties, rectangular grid type is adopted in our array design. Expandable 4-element antenna module is used to construct a 24-element array. To guarantee overlapped secondary radiation pattern, array element spacing should be smaller than 28.2 mm at 6 GHz (when feeding a reflector with f/D of 0.4611) and 25 mm is chosen finally in our design. The simulation model of the C-band phased array feed is shown Fig. 4.

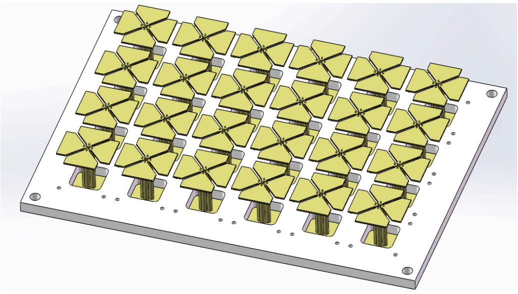


Fig.4. 24-element C-band phased array feed model

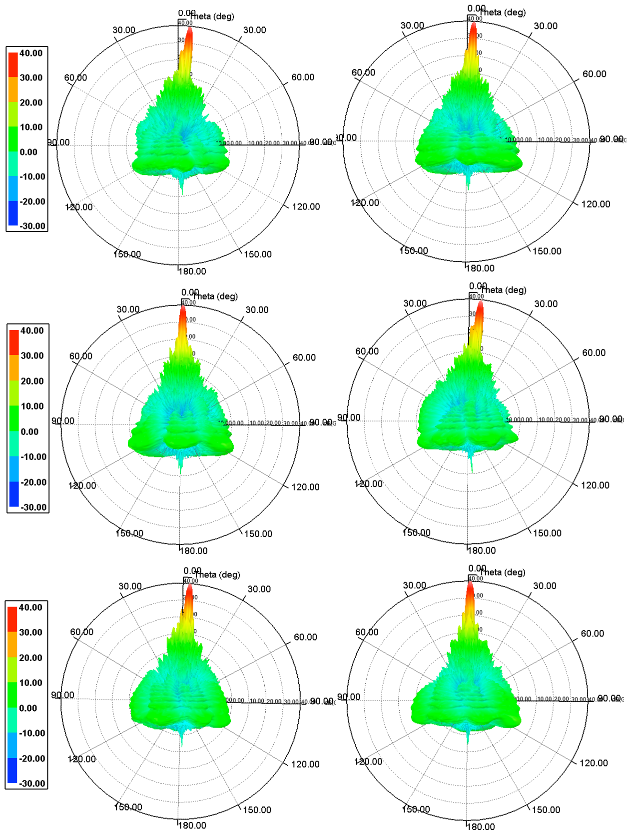


Fig.5. Secondary radiation pattern of a quarter of the array（corresponding to 6 array elements in the first quadrant on the top left of the array）

Secondary radiation patterns of each array element are calculated with 24-element C-band phased array feed feeding a reflector (Aperture diameter of 1.25 m and f/D of 0.4611). As shown in the Fig. 5, secondary radiation pattern for only a quarter of the array elements are given, and the remaining elements pattern can be concluded based on the symmetry of the array structure.

IV. SIMULATED SYSTEM PERFORMANCE

Various algorithms can be used to compute beamformer weight coefficients **w.** The common beamforming algorithms for PAF include conjugate field matching (CFM), maximum gain (MG) and maximum signal-to-noise ratio (MSNR) [12].

The CFM algorithm takes the voltage sampled from the focal plane field as the weight coefficients. Ideally, maximum aperture efficiency can be realized by using CFM algorithm, but mutual coupling between elements is not considered. Interaction and mutual coupling of the array is taken into account in MG algorithm and maximum antenna efficiency can be achieved. The MSNR algorithm, which takes into account not only the gain performance of the antenna, but also the noise of the radio telescope, can maximize the sensitivity of the system.

Weight coefficients of the 24-element phased array feed are calculated by the MG algorithm according to $\mathbf{W}_{D\max} = \mathbf{R}_{iso}^{-1}\mathbf{V}_s$, 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. 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 is increased but the normalized level does not exceed -16.5 dB.

Fig. 7 shows the curves of antenna efficiency varying with scanning angle. As can be seen, the efficiency of the reflector antenna fed by the phased array feed is 70% at the bore sight. In the range of scanning angles of two half-power beamwidths (3.5°) off the reflector axis, the antenna efficiency is still above 65%.

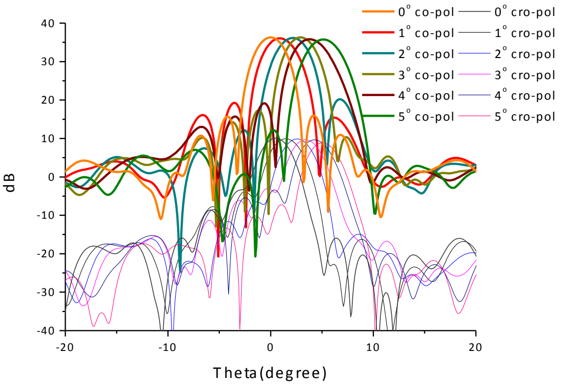


Fig.6. Synthesized secondary radiation pattern

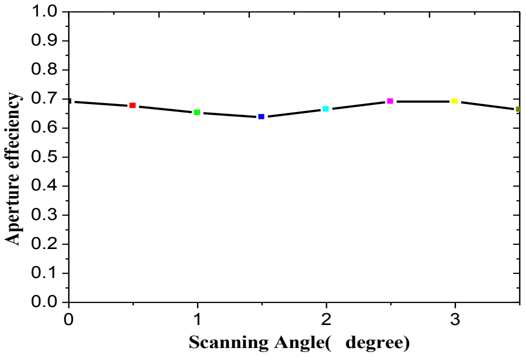


Fig.7. Antenna efficiency of radio telescope fed by the PAF

V. CONCLUSION

An Octave-bandwidth Phased Array Feed (PAF) is proposed based on a novel wideband dual polarized tightly-fed Bowtie antenna element with reflection coefficient below -15 dB and mutual coupling below -25 dB over 4.0-8.0 GHz. A 24-element PAF is designed and the secondary radiation pattern is synthesized with the weight coefficients calculated by the maximum gain algorithm. Simulation shows the antenna efficiency of 70% can be achieved for radio telescope equipped with the PAF. This design will be used for prototype of SKA pioneer PHAROS2 and can also provide reference for FAST and QTT PAF system development.

ACKNOWLEDGMENT

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