32nd URSI GASS, Montreal, 19-26 August 2017

Quad-Ridge Flared Horn feed design and analysis for WBSPF in Radio Telescope

Y. Ma*(1), (2) , B. Billade(3) and Z.Z. Abidin(4)

(1)National Astronomical Observatories, Chinese Academy of Sciences
(2)Key Laboratory of Radio Astronomy, Chinese Academy of Sciences,
Beijing 100012, China
yuema@nao.cas.cn
(3)Chalmers University of Technology, Onsala Space Observatory and bhushan.billade@chalmers.se
(4)Research Center of Applied Electromagnetic, University Tun Hussein Onn Malaysia,
Parit Raja, Batu Pahat, Johor, Malaysia and zuhairia@uthm.edu.my

Abstract

A dual polarized Quad-Ridge Flared Horn (QRFH) feed for receiver systems is proposed and presented. The cryogenic 1.6-5.2 GHz feed system design is considered with emphasis on its application in future wideband radio telescope systems. A great deal of simulated and measured results are presented throughout this paper. Hence, the results showed that the proposed design achieved a low reflection coefficient, a main lobe with near-constant symmetrical beam width and an aperture efficiency higher than 64% across the bandwidth. Further developments needed to completely fulfill the requirements for these future wideband radio telescopes are also discussed. It is expected the present design could be a possible feed candidate that is suited for SKA radio telescopes, especially in SKA wideband single pixel feed (WBSPF) - advanced instrumentation programs (AIP) within the pre-construction phase.
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1. Introduction

The Square Kilometre Array (SKA) is a revolutionary telescope program that will address a broad range of key science areas in galaxy evolution and cosmology, fundamental physics, and astrobiology. It will provide about a million square metres of collecting area. This huge increase in scale compared to existing telescopes demands a revolutionary break from traditional radio telescope design. The key science goals of the SKA are in place and a well-structured with the detailed design and preparation on a global technology development program is ongoing [1]. The wideband single pixel feed (WBSPF) is one of the SKA's two advanced instrumentation programs (AIP) within the pre-construction phase of the SKA project. The WBSPF – AIP aims to greatly extend the bandwidths of the radio astronomy receivers, beyond conventional broadband octave receivers while maintaining the same sensitivity criteria; design and prototyping a wideband feed system covering the frequencies from 1.6 GHz to 24 GHz (Band A : 1.6-5.2 GHz, Band B 4.6-24 GHz) using two feed packages integrated inside a single cryostat. The idea of the WBSPF design is to decrease the cost of large arrays, by reducing the number of expensive cryogenic receiver required on thousands of antennas [2]. Hence, a dual polarized Quad-Ridge Flared Horn (QRFH) feed for receiver system is required. Due to increasing interest in wide bandwidth radio astronomy, there has been much emphasis in feed antennas achieving such large bandwidths in the last years. As a result, number of ultra-wideband feed antennas with dual linear polarization have been developed. Some feeds are under consideration for the SKA WBSPF Band A project such as Eleven feed, Sinuous feed and QRFH feed [2]. The advantages of the QRFH are easier feeding. The insertion loss of the QRFH is lower. However, because it is an aperture antenna, the phase centre and the beam-width are not very constant with frequency. Compared with the QRFH, the phase centre and pattern of the Eleven Feed are less sensitive to the frequency, Both the Eleven Feed and Sinuous feed, the feeding is much more difficult.

Ridged waveguides with constant cross-section in the direction of propagation have previously been analyzed, demonstrating of wideband propagation depending on waveguide geometries. By comparison, some analysis of ridged horns with cross-sections that flare in the direction of propagation is notably missing from the literature [3]. Quad-ridged waveguides have been analyzed using the finite-element method and magnetic field integral equations and also by using mode fields of the first few modes as a function of ridge-to-ridge gap and ridge thickness. The results showed that while the dominant mode cutoff frequency in quad-ridged structures is decreased by key factors, the single mode bandwidth of such waveguides is not as large as their dual-ridged counterparts [4]. Hence, the Quad-ridged structures are widely used in many microwave applications compared to others.

In this paper, a Quad-Ridge Flared Horn feed for WBSPF AIP at Band A 1.6-5.2 GHz was investigated for Radio telescope Feed system. A new broadband QRFH with dual polarizations and novel waveguide transition structure are presented. A circular geometry is used in ridged waveguide to enhance the return loss performance of the horn. The proposed design exhibits good return loss, isolation and gain performance in the operating frequency range of 1.6 to 5.2 GHz. Further, the aperture efficiency has been calculated in 15 m offset dual-reflector antennas in Gregorian geometries (SKA-P dish) with GRASP software.

2. Design Method

In order to achieve the required performance from these wideband feed systems, it is inadequate to optimize the feeds for a specific opening angle of the sub-reflector. Therefore, an optimization of the trade-off between the aperture efficiency and spill over noise contribution for a specific dish geometry have to take into account in order to provide better feed solution. Considering this, we adopted an optimization process as shown in Figure 1. The feed is simulated either in CST Microwave Studio or HFSS, and then the result of the far field pattern of the feed is imported in GRAPS for analysis in the SKA reflector geometry. [2]

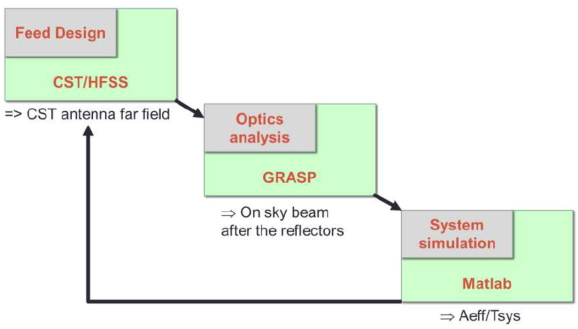
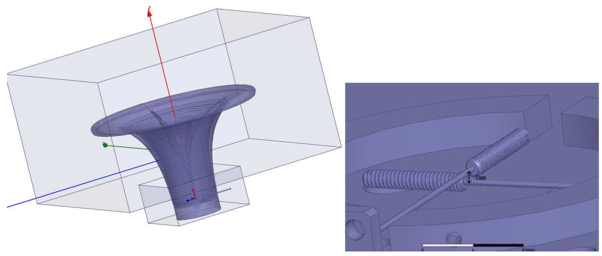


Figure 1. Flow chart for design QRFH feed in this study.

3. Horn Antenna Design

Figure 2(a) depicts the structure of QRFH feed which are divided into two parts: a waveguide transition and a flare section of the horn with tapered quadruple ridges. As stated in [4], the waveguide transition of the horn antenna can be divided into two parts: a quadruple-ridged waveguide and a shorting plate located at the back of the waveguide.

Therefore, the proposed QRFH design will consists of quadruple-ridged waveguide, the side wall taper, ridge waveguide, the back short panel, two feed probes and two SMA connectors. The quadruple-ridged waveguide is a circular one loaded with a same size of the four ridges for symmetrically exciting of the dual linear polarizations as shown in Figure 2(b). The length and width of the ridge are determined for single-mode operation. The ridge's height and width must be such that the associated impedance taper is a smooth transition from the waveguide impedance 50 Ω to the free space impedance, 377 Ω [4]. The overall length of the designed horn is 260 mm with 200 mm diameter and modeled by using Ansoft's High Frequency Structure Simulator (HFSS).



(a) (b)

Figure2. Antenna Horn (a) QRFH Structure, and (b) Feed Probes

As seen in Figure 2 (b), the horn antenna model must include both orthogonal feeds where the feed pins need to cross the gaps between the ridges to prevent the transition happens at the same point. Further, the return loss performance of the horn antenna is critically depending on the transition between coaxial probes to the quadruple-ridged waveguide. Therefore, to obtain a good transitional performance, a circular shorting plate is needed in the horn structure [4-7].

In addition, for a good impedance-matching between the quadruple-ridged waveguide and the free space, four ridges with exponential shapes are needed. Two ridges are added in the cavity region and another two are added n the horizontal direction. On the cavity region, the ridges is placed in the direction where the front coaxial port is excited to shorten the distance between the backing metallic plate and the front coaxial port. While, the other ridges are added in the horizontal direction because the horizontal coaxial probe is placed farther away from the shorting plate [8-10]. Both of these direction is expected could improve the return loss performance.

4. Simulated Results and Discussion

A QRFH antenna prototype was shown in the Figure 3. Figure 4 depicts the results of the simulated and measured return loss, S_{11} for two ports. It is observed that both have a good matching, with the S_{11} is less than -10 dB between 1.6 to 5.2 GHz.

Figure 3. The prototype for QRFH feed

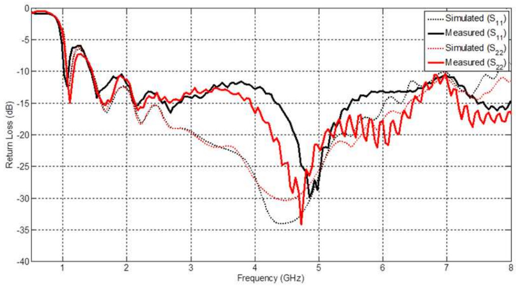


Figure 4. Return Loss for the QRFH antenna

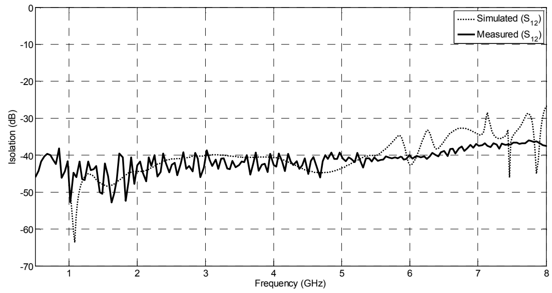


Figure 5. Isolation for the QRFH antenna

Figure 5 depicts the comparison between the simulated and measured results of the isolation between two ports. It is a good agreement between both results with the isolation is less than -35 dB within the operating frequency band.

The radiation patterns were studied for QRFH antenna from the E-plane, 45 degree plane and H-plane at band A. It can be found that a good beamwidth constancy in 10 dB beamwidth for the three planes with the illumination angle can be achieved 90 degree at low and high frequency band (see Figure 6 - 8).

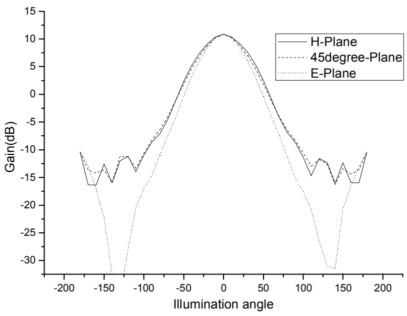


Figure 6. The radiation pattern for QRFH at 1.6 GHz

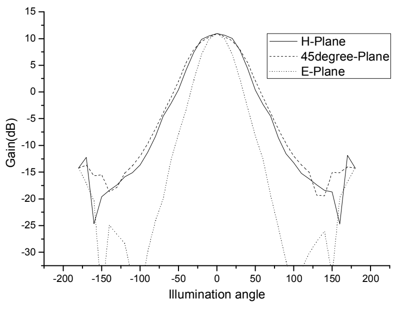


Figure 7. The radiation pattern for QRFH at 3. 5 GHz

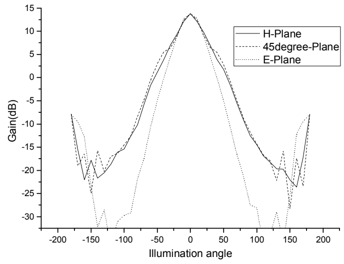


Figure 8. The radiation pattern for QRFH at 5. 2 GHz

The aperture efficiency was calculated based on the 10 dB beamwidth of the E plane, 45 degree and H plane radiation pattern results. The results were extracted and simulated by using GRASP software with 15 m SKA-P dish antenna as depicted in Figure 9. It can be seen that the simulated aperture efficiency with the half-angle subtended by reflector at feed 58 degree on SKA Dish is above 64% and show that the value meets the typically range of the aperture efficiency which is within the range of 50 to 80 %.

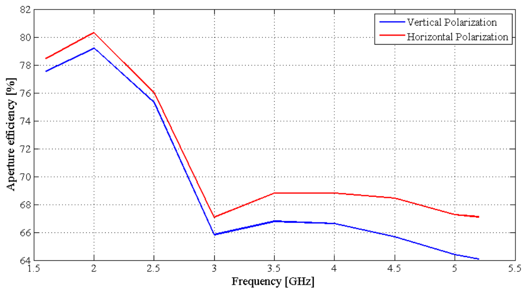


Figure 9. Simulated Aperture efficiency on SKA Dish

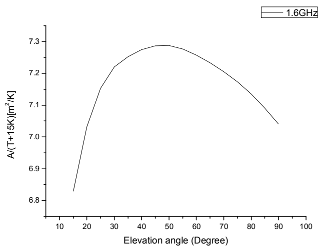


Figure 10. System sensitivity at 1.6GHz

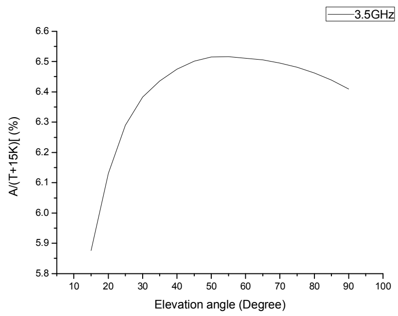


Figure 11. System sensitivity at 3.5GHz

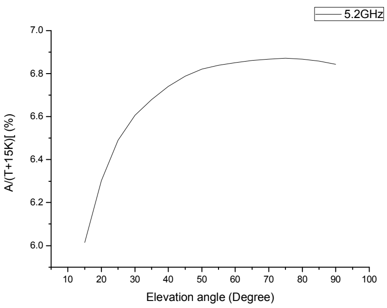


Figure 12. System sensitivity at 5.2GHz

From the Figure 10 - 12 it can be seen that the system sensitivity are achieved at 6.8, 5.8, 6 at 1.6 GHz, 3.5 GHz and 5.2 GHz respectively.

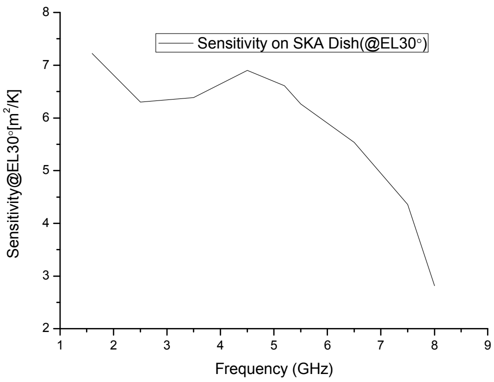


Figure 13. System sensitivity at elevation angle 30°

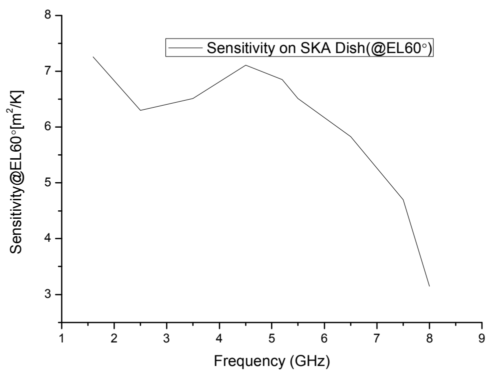


Figure 14. System sensitivity at elevation angle 60°

Meanwhile, from Figure 13 – 14 it can be observed that the system sensitivity are achieved at 6.5, 6.2 at elevation angle 30°, 60°, respectively.

5. Conclusion

As summary, the performance of the new quad-ridge horn antenna design has been presented. A good agreement between measured and simulated results were obtained for the design. The antenna was well matched over a relative bandwidth larger than 3:1 for over 1.6 GHz to 5.2 GHz. Good radiation patterns that were reasonably constant and rotationally symmetrical were obtained. Analysis of the QRFH with a SKA-P dish antenna, using both pattern integration with 3D simulated patterns and Physical Optics (PO) indicated that the antenna would be capable of achieving high aperture efficiencies (larger than 64 %) over at least a 3:1 bandwidth.

6. Acknowledgements

This work was supported by the National Science Foundation of China under grant No. 11503049. Special thanks to Prof. Raed A. Abd-Alhameed and Dr. Chan Hwang See from University of Bradford in UK, who gave me assistance in the antenna designing ideas.

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