High Efficiency Octave-Band Feed Horn Antenna for Radio Astronomy Applications

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***Abstract*—A novel multi step quad-ridged horn antenna (QRHA) with corrugations is demonstrated for operation over the 20 GHz to 40 GHz frequency range. The quad-ridged section is responsible for ensuring a wideband operation, whereas the corrugations support hybrid modes to obtain stable radiation patterns that taper to -16 dB at a half-angle beamwidth of 55° over the entire range. The multi-step profile improves efficiency by introducing higher order modes in the horn aperture, and shaping the sidewalls of the ridge horn contributes significantly to the radiation characteristics of the horns. To verify results, the horn is designed and simulated with both CST Microwave Studio and the µWaveWizard. Good agreement between the results of both software packages is observed which confirms the validity of this approach. The input reflection coefficient is mostly better than -20 dB over the entire frequency range, and an aperture efficiency of 75% to 80% is demonstrated.**

***Keywords*— Quad-ridged horn, multistep horn, corrugated horn, octave band feed, aperture efficiency, radio astronomy.**

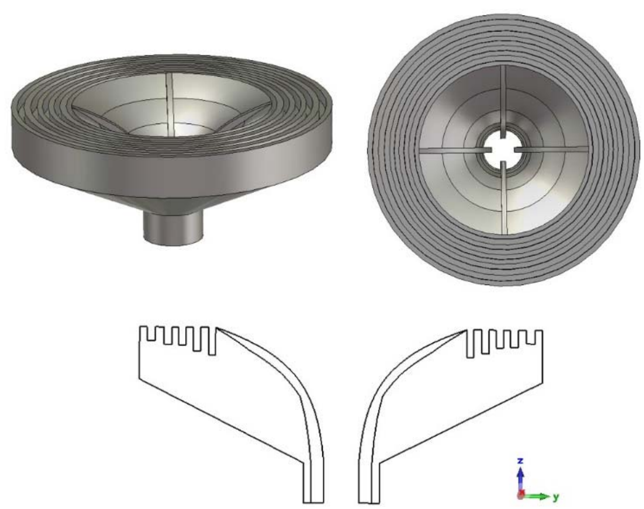

Fig. 1. Prototype of the proposed quad-ridge horn antenna with multi-step flare and corrugations in the aperture.

I. INTRODUCTION

To meet challenges of reducing the number of receivers required for future large radio telescope arrays, such as the Square Kilometer Array (SKA), the Allen Telescope Array (ATA), and the Next Generation Very Large Array (ngVLA), examples of octave band feed horns are introduced. Such designs contribute to reducing manufacturing and operations costs and enable observations that require a wide frequency range [1-7].

Advantages of quad-ridge waveguide technology are a decrease of the cut-off frequency of the fundamental mode for extended bandwidth and the use of dual-linear or, depending on the feed, dual-circular polarization. In a receiver system, after separating the individual polarizations, one single-ended low noise amplifier (LNA) per polarization is required. This is very useful in radio astronomy as more data can be collected. In addition, shaping the profile of the horn and its ridges helps to improve the radiation performance of horns [8]. However, there exist disadvantages for quad-ridged feed horns (QRFHs) such as high cross-polarization levels and asymmetric radiation patterns [9]. Corrugated horn antennas, due to the production of hybrid modes in the aperture with high efficiency, have very low cross polarization, low side lobe levels and consequently good spill-over efficiency when operated with a reflector. These characteristics have made these type of antennas promising candidates for radio astronomy applications [10]. Nevertheless, what restricts their application for satellite communications and radio astronomy is their limitation in achieving wide bandwidth. In recent years, high demand of octave band antennas with sufficient beam symmetry, low cross-polarization and high efficiency has led to the development of different types of ridged corrugated horn antennas [7, 8, 9, and 11].

In this paper, a multistep QRFH with exponential profile and axial corrugations in the aperture is introduced. The proposed feed horn is designed to meet the optics of the Next Generation Very Large Array (ngVLA) radio telescope, which uses an offset Gregorian dish with a primary aperture diameter of 18 m and a secondary aperture diameter of 3.2 m. Based on the specifications of the ngVLA optics, the feed pattern should taper to -16 dB at the opening half-angle of 55° [12] which has been achieved in this design. Contributions of this work include novel exponential profiles for horn and ridges with the aim to achieve a high aperture efficiency of around 80% as well as sensitivity over an octave bandwidth (20 GHz – 40 GHz).

II. ANTENNA DESIGN AND ANALYSIS

A. Quad-Ridged Horn Design

Fig. 1 shows the configuration of the proposed QRFH, which is a six-step horn based on exponential functions for both horn and ridge profile. To have more control over the ridge profile, the exponential function is controlled by two parameters to achieve more ridge depth near the horn aperture. A circular waveguide with a radius of 4.04 mm is used for housing the ridges of 1 mm thickness. The aperture diameter is 53.5 mm and the horn has a length of 17.97 mm.

The beamwidth of a quad-ridged horn is controlled by the flare angle. A multi-step flare decreases the differential phase shift at the throat while also providing a larger aperture size for improving the pattern symmetry of the horn and low back radiation [8]. Moreover, the matching transition between the ridged feed and the corrugated horn section is important. In this study, all parameters are optimized using the built-in capabilities of CST Microwave Studio.

B. *Corrugations*

The effective aperture size of the horn is increased by adding five corrugations in the aperture, as shown in Fig. 1, thus enhancing radiation. The depth of each corrugation is initially chosen to be between λ/4 and λ/2 to obtain equal beam widths, low cross-polarization levels, and low back radiation. Axial corrugations are used due to very compact dimensional requirements and ease of fabrication compared to radial corrugations. [13].

The corrugations improve the beam symmetry and have a notable effect on improving the aperture efficiency. Fig.2 displays the effect of the number of corrugations on aperture efficiency. As the number of corrugations increases, the aperture efficiency improves. More corrugations could be added but since this causes a very large aperture size, nulls in the pattern would appear and reduce the beamwidth required to feed the reflector.

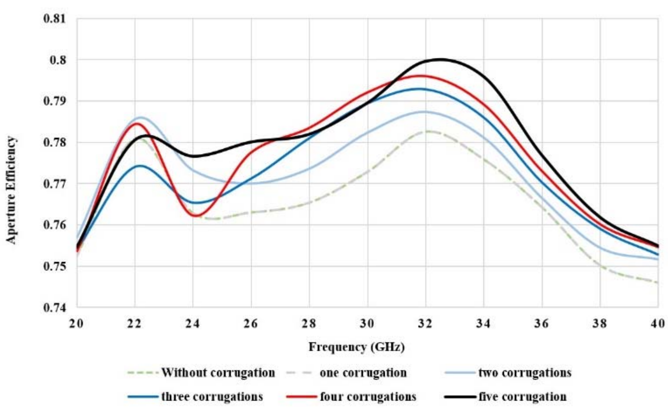

Fig.2. Effect of number of corrugations on aperture efficiency.

The optimization procedure was divided into three stages: The multistep flared parts, the horn with ridges, and the entire design with corrugations. The optimization involved the search for the best performance with a genetic algorithm. The aperture efficiency (ϵ_{ap}), input reflection (S_{11}) and beam symmetry parameters were combined as a single goal function.

III. Results and Discussion

For the purpose of validation, the proposed antenna has been designed and simulated with both µWaveWizard and CST Microwave Studio. Fig.3 shows the simulated S_{11} parameter with both software packages. The results show good agreement in both simulations, which are better than -20 dB for the entire octave-band frequency range.

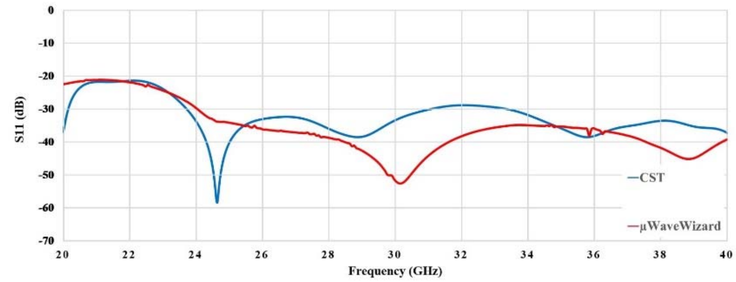

Fig. 3. Input reflection coefficient of the quad-ridged horn.

Fig. 4 plots the variation of the angular beam width over the frequency band with both softwares. It is evident that the beamwidth is around 110° with less than 10° variations in 0, 45, and 90-degree cuts.

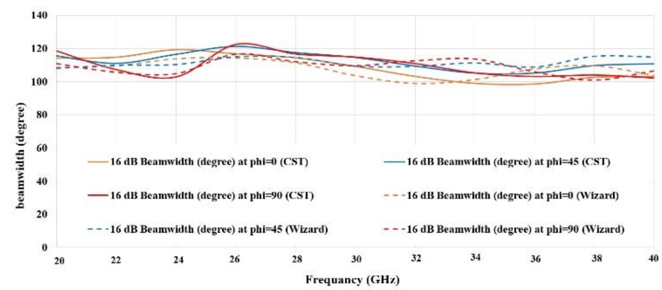

Fig. 4. Angular beamwidth across the bandwidth.

Fig. 5 illustrates the simulated aperture efficiency based on the equivalent paraboloid equations presented in [7] (i.e., the product of phase, amplitude, polarization, and spillover efficiencies) which is between 75% and 80%.

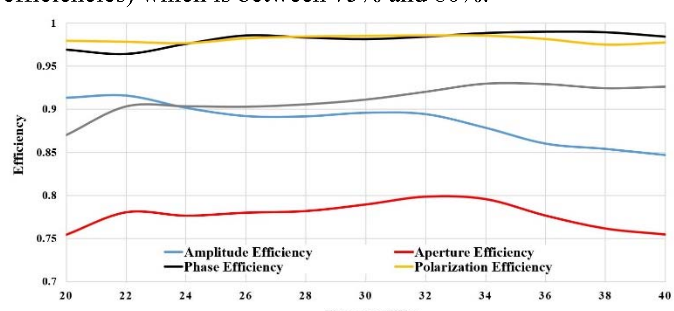

Fig. 5. Simulated aperture efficiency and sub-efficiencies of the optimized horn antenna.

Fig. 6 shows the simulated radiation pattern in the diagonal plane in steps of 2 GHz, and Fig. 7 displays the simulated radiation patterns in the E, H and diagonal planes at 26 GHz and 34 GHz. The agreement between the simulations is good, and the observed differences between the results are mostly below 20 dB.

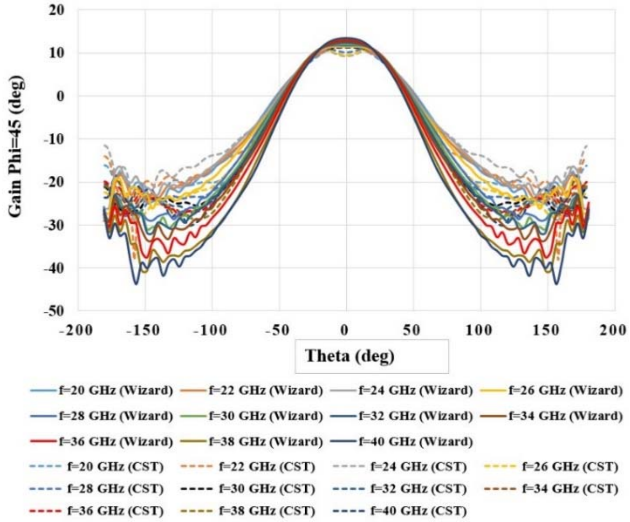

Fig. 6. CST and Wizard simulated radiation patterns of the proposed feed in the diagonal plane.

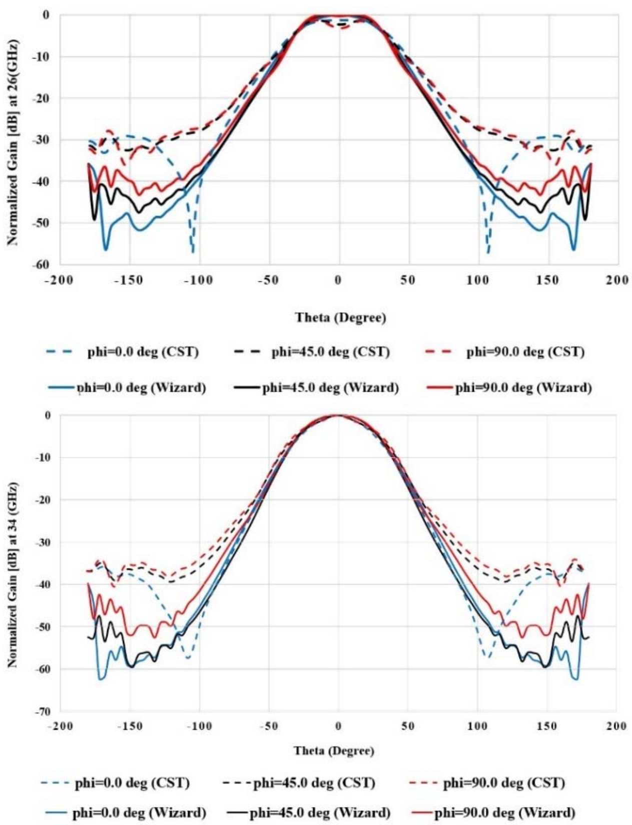

Fig. 7. CST and Wizard simulated radiation patterns of the proposed feed in E, H, and D planes at 26 and 34 GHz.

IV. Conclusion

This paper presents the realization of a quadruple-ridge flared horn with axial corrugations that is designed for an octave bandwidth. The feed exhibits a good impedance match and beam performance over a 2:1 bandwidth. Its sub-efficiencies and radiation patterns show that by adopting horn, ridges and corrugation profiles, more constant beamwidth and more symmetrical radiation patterns are obtained, hence improved efficiencies can be achieved. The proposed feed has a compact structure and can be used for radio astronomy applications. This model is specifically designed to meet ngVLA optics and can be scaled for covering higher and lower frequency bands for any radio telescopes with similar optical requirements. Agreement between simulations with two software packages is an indicator of achieving the desired characteristics for prototyping the presented millimeter-wave horn antenna.

References

[1] B. Dong, J. Yang, J. Dahlström, J. Flygare, M. Pantaleev, and B. Billade, "Optimization and realization of quadruple-ridge flared horn with new spline-defined profiles as a high-efficiency feed for reflectors over 4.6 GHz to 24 GHz," *IEEE Trans. Antennas Propag*., vol. 67, no. 1, pp. 585–590, Jan. 2019.

[2] J. Flygare and M. Pantaleev, "Dielectrically loaded quad-ridge flared horn for beamwidth control over decade bandwidth — Optimization, manufacture, and measurement," *IEEE Trans. Antennas Propag*., vol.68, no. 1, pp. 207 – 216, Jan. 2020.

[3] S. Salem Hesari and L. Knee, "Design and analysis of three Q-band feed horns for radio astronomy applications," in *Proc. IEEE USNC-CNC-URSI North American Radio Science Meet.*, pp. 1-2, July 2020.

[4] A. Dunning, M. Bowen, M. Bourne, D. Hayman, and S.L. Smith, "An ultra-wideband dielectrically loaded quad-ridged feed horn for radio astronomy," in *Proc. IEEE-APS Top. Conf. Antennas Propagat. Wireless Comm*., pp. 787-790, Feb. 2015.

[5] R. Lehmensiek and D.I.L. de Villiers, "First order design of a quadruple-ridged flared horn for the ngVLA Band 1," in *Proc. 16th Eur. Conf. Antennas Propagat*., pp. 1-4, May 2022.

[6] D. Henke, S. Salem Hesari, and L.B.G. Knee, "Axial ring feed horn with logarithmic flare for offset Gregorian optics," in *Proc. URSI GASS General Assembly and Scientific Symp.. Int. Union Radio Science*, pp. 1-4, Aug. Sep. 2021.

[7] D. Henke, F. Jiang, S. Salem Hesari, A. Seyfollahi, B. Veidt, and L. B. G. Knee "Octave bandwidth receiver technology for radio and millimetre-wave telescopes", *Proc. SPIE 12190, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI*, 121901Y, Aug. 2022.

[8] S. Manafi, M. Al-Tarifi, and D.S. Filipovic "45-110 GHz quad-ridge horn with stable gain and symmetric beam," *IEEE Trans. Antennas Propag.,* vol. 65, no. 9, pp. 4858 - 4863, Sep. 2017.

[9] S. Manshari, S. Koziel, and L. Leifsson, "A wideband corrugated ridged horn antenna with enhanced gain and stable phase center for X- and Ku-band applications," *IEEE Antennas Wirel. Propag. Lett*., vol. 18, no. 5, pp. 1031 - 1035, May 2019.

[10] S. Salem Hesari, D. Henke, B. Veidt, V. Reshetov, and L.B.G. Knee, "A compact axial-ring feed horn and vacuum window model for a cryogenic Q-band receiver," in *Proc. IEEE 19th Int.l Symp. Antenna Technol. Appl. Electromagn*., pp. 1-2, Aug. 2021.

[11] Z. Zhao, Z. Wang, J.R. Kelly, and S. Gao, "Balanced feed low cross-polarization quad-ridged horn antenna with center cross fusiform loaded," *IEEE Trans. Antennas Propagat*., vol. 69, no. 9, pp. 6004 - 6009, Sep. 2021.

[12] R. Selina and D. Dunbar, "System Reference Design," Nat. Radio Astron. Obs. NRAO Doc. 020.10.20.00.00- 0001-REP-B-SYSTEM_REFER-ENCE_DESIGN, ngVLA Ref. Des., doi: 020.25.00.00.00-0001-REQ-AANTENNA_PRELIM_TECH_REQS., July 2019.

[13] I. Agnihotri and S.K. Sharma, "Design of a 3D metal printed axial corrugated horn antenna covering full Ka-band*," IEEE Antennas Wirel. Propag. Lett*., vol.19, no. 4, pp. 522 - 526, Apr. 2020.