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Strategy and Overview for Development of Beyond-Decade-Bandwidth Quad-ridge Flared Horns for Radio Astronomy

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***Abstract*—This paper considers the potential of the dielectrically loaded Quad-ridge Flared Horn (QRFH) feed to provide continuous beyond-decade bandwidth in reflector telescopes for radio astronomy. An overview of the beam pattern evolution over frequency in a recent ultra-wideband feed designed for 1.5–15.5 GHz is presented.**

***Index Terms*—ultra-wideband, reflector feed, quad-ridge flared horn, dielectric load, radio astronomy**

I. Introduction

The strive towards ultra-wideband (UWB) receivers in the super high frequency (SHF) region of radio astronomy and space geodesy has produced a multitude of reflector feed options over the last two decades: Eleven feed [1], Dyson quad-spiral array (DYQSA), [2], Quad-ridge flared horn (QRFH) [3], log periodic Antonio feed [4], and Quasi self-complementary (QSC) feed [5]. This together with the development of new low-noise amplifier (LNA) technology (e.g. [6], [7]) has given scientists access to continuous bandwidth over multi-octave frequency ranges. The QRFH is a common choice for typical bandwidth of 6:1 in reflector geometries with low f/D. The preference towards QRFH feeds other than its good radiation and impedance properties over wide frequency bands, is a low-loss design, intrinsic linear dual-polarized configuration for two single-ended 50 Ω outputs, as well as a compact and robust structure. Typically, the beamwidth of QRFHs gets narrower over the bandwidth as frequency increases and more drastically so in the H-plane ($\phi = 90°$); the principal plane of the beam pattern orthogonal to the polarization. To reduce this effect, spline-defined rather than analytical profiles of both the horn and ridges have been introduced with more degrees of freedom to manipulate the mode-propagation in the feed [8]. In order to suppress higher-order modes from being excited at the feeding point, a quadraxial solution has been shown as an effective tool over multi-octave bandwidths [9], [10]. It was shown in [11] that multilayer dielectric loading of a QRFH together with a corrugated skirt can improve beam symmetry simultaneously for the high and low frequencies in a 6:1 feed. The BRoad-bAND (BRAND) is a research project to develop an UWB radio astronomical receiver over 1.5–15.5 GHz, with the first prototype designed for the 100 m Effelsberg primary focus ($f/D = 0.3$) reflector [12]. To achieve beamwidth stability over this 10:1 frequency range, a dielectric load in Polytetrafluoroethylene (PTFE) was designed together with the traditional QRFH metal structure [13]. The small dimensions of the homogeneous dielectric, see Fig. 1, allows the QRFH to maintain a compact footprint and robust metal structure for integration in cryogenic dewars with a vacuum window.

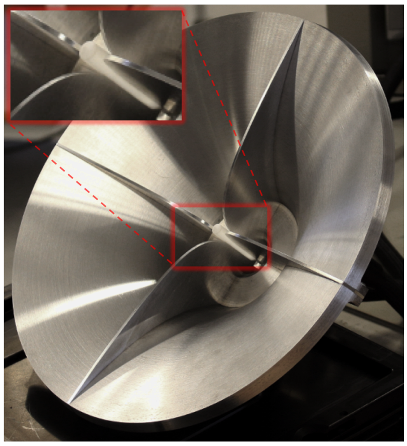

Fig. 1. Dielectric load at QRFH center allow for better control of the H-plane beamwidth over decade bandwidth and beyond.

With the introduction of dielectric loading to the QRFH-concept, new UWB feed solutions are possible with improved illumination performance. The degrees of freedom for such a feed design are manifold - which puts emphasis on the beam pattern evolution over frequency as multiple combinations of the design parameters influence the radiation performance. For consistent radiation performance of such a feed, further design strategy and analysis is needed. In this contribution we discuss this topic with a brief overview, exemplifying with beam pattern analysis of the feed in [13] simulated beyond the design frequency range.

II. Reflector Feed Sub-efficiencies

The reflector feed aperture efficiency, η_a, can be divided into a product of five sub-efficiencies (no surface losses), which helps to analyze the beam pattern evolution over wide

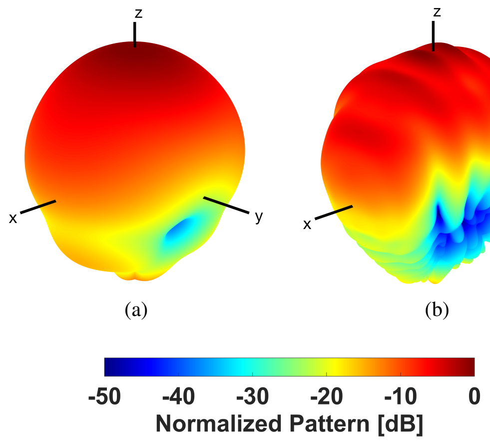

Fig. 2. Normalized beam pattern for dielectrically loaded QRFH in [13]: (a) 1.5 GHz (b) 8 GHz.

frequency ranges [14]. The product of the illumination and spillover efficiency, $\eta_{\text{ill}}\eta_{\text{sp}}$, is the most relevant combination for a symmetric near-Gaussian feed, typically octave band, as the polarization (η_{pol}) and azimuth-mode or BOR_1 (η_{BOR1}) efficiencies are close to unity in most cases [15]. With a symmetric beam pattern, the product $\eta_{\text{ill}}\eta_{\text{sp}}$ would typically be near-constant across the octave. The phase efficiency, η_{ph}, is location dependent relative to the reflector focal point and therefore the stability of the feed's phase center over frequency is crucial - and therefore a challenge for UWB design. Because of the numerical design approach to mode-propagation in the QRFH with multiple degrees of freedom, a near-constant η_a can be the product of sub-efficiencies varying as the beam pattern evolves over frequency. This can be seen in, e.g., Fig. 3 of [8], and Fig. 12 of [3] where in the latter also the dominance of the fundamental mode TE_{11} over the lower part of the frequency bandwidth is illustrated in the same figure - which corresponds to a more symmetric and "smooth" beam. In these examples, the product of $\eta_{\text{ill}}\eta_{\text{sp}}$ changes over the frequency range while the total, η_a, stays near-constant for large sections.

III. Dielectrically Loaded QRFH

The QRFH designed for 1.5–15.5 GHz ([13]) has been simulated and measured up to 18 GHz, with some of those results presented here. The radiation performance of the first octave is dominated by the horn and ridge profiles - with a negligible effect from the dielectric load (Fig. 10 in [13]). At the cut-off frequency of 1.5 GHz the fundamental mode, TE_{11}, is dominant and the beam has only small variation in azimuth, see Fig. 2a. The pattern's azimuth "smoothness" is the reason for the high η_{BOR1} efficiency, see Table I. As the pattern evolves over frequency, higher order modes are created resulting in more power loss to azimuth mode variations, here exemplified at 8 GHz in Fig. 2b, and therefore a lower η_{BOR1}. Despite this, the total aperture efficiency with the dielectric load is nearly constant at 56 % and 53 % for 1.5 GHz and 8 GHz respectively, see Table I. The illumination efficiency is also nearly constant for the two frequencies, as the dielectric broadens the H-plane pattern at 8 GHz but has no effect at 1.5 GHz. Furthermore, η_{sp} is considerably lower for 1.5 GHz resulting in an increased spillover temperature, which will affect sensitivity response and is discussed further below. The polarization efficiency η_{pol} is increasing slowly with frequency as an improved symmetrical effect on the beam pattern principal planes with dielectric loading: a slowly narrowing E-plane ($\phi = 0°$) pattern and a more stable H-plane ($\phi = 90°$) pattern over frequency. In Fig. 3 the polar contour plots of beam patterns for 1.5 GHz and 18 GHz (outside design interval) are displayed without dielectric load (top-row) and with dielectric load (bottom-row). The outer edge represents the reflector rim in a $f/D = 0.3$ primary focus. The broadening effect on the beam pattern due to the dielectric is clearly seen at 18 GHz, which again increases illumination efficiency as well as reduces power loss due to azimuth mode variations, see Table I. This result suggests that further design development can extend the bandwidth beyond current frequency range.

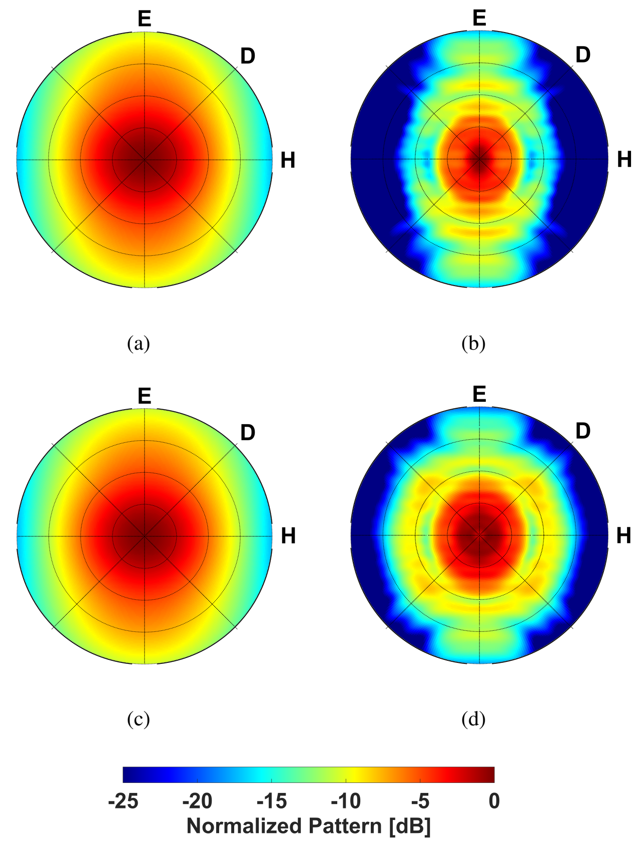

Fig. 3. Polar top view θ=[0°, 80°], ϕ=[0°, 360°]: (a) without dielectric load, 1.5 GHz; (b) without dielectric load, 18 GHz; (c) with dielectric load, 1.5 GHz; (d) with dielectric load, 18 GHz. Radial markers are in 20° steps, the outer most edge represents $\theta = 80°$, (half-subtended angle for $f/D = 0.3$). The plane-cuts are marked as E ($\phi = 0°$), D ($\phi = 45°$), and H ($\phi = 90°$).

TABLE I
EFFICIENCIES FOR QRFH IN [13], WITHOUT AND WITH DIELECTRIC LOAD AT 1.5 GHZ, 8 GHZ, 18 GHZ IN PRIME-FOCUS $f/D = 0.3$ REFLECTOR.

	η_{ill}	η_{sp}	η_{BOR1}	η_{pol}	η_{ph}	η_{a}
without Diel. Load, 1.5 GHz	74	89	99	90	96	56
with Diel. Load, 1.5 GHz	74	89	99	90	96	56
without Diel. Load, 8 GHz	66	96	86	88	97	47
with Diel. Load, 8 GHz	72	96	86	91	98	53
without Diel. Load, 18 GHz	46	99	86	88	89	31
with Diel. Load, 18 GHz	52	99	93	92	91	40

IV. DESIGN GOAL CONSIDERATIONS

The design target for an ideal UWB feed for astronomy application is high sensitivity over frequency - where both spillover temperature and aperture efficiency contributes. Because of the beam pattern evolution over frequency illustrated above, the sensitivity should be the main figure-of-merit in UWB optimization. To exemplify this, we estimate illumination sensitivity as T_a/η_a (lower value is better), assuming 0 K receiver noise, with $T_a = T_{sp} + T_{sky}$ and the simplification that all the spillover-power in a primary-focus reflector is ground-noise pickup, $T_{sp} = 290(1\text{-}\eta_{sp})$ K. For these frequencies the sky brightness temperature contribution in zenith can be estimated as $T_{sky} = 5\eta_{sp}$ K resulting in $T_a/\eta_a = 65$ K for 1.5 GHz, and $T_a/\eta_a = 31$ K for 8 GHz. Despite the similar aperture efficiency and sky brightness, the difference in sensitivity is close to a factor of two because of the reduced spillover noise temperature at 8 GHz. Furthermore, a varying sky brightness temperature or receiver noise temperature over frequency, as is likely for UWB design, can change the condition for optimal sensitivity further. This puts emphasis on the approach to optimize UWB feeds, for the intended reflector, with maximum sensitivity as the main goal. Another important property is the polarimetric performance of the feed on dish, which is not directly addressed in the approach to maximize sensitivity. Poor beam symmetry between the principal planes results in a lower η_{pol} and reduced polarization purity or intrinsic cross-polarization ratio (IXR, [16]), which is of great importance in polarimetric science. Because of the beam pattern evolution with frequency, this puts further emphasis on pattern analysis during optimization.

V. CONCLUSION

The introduction of a dielectric load to the quad-ridge flared horn (QRFH), has the potential to extend frequency bandwidths beyond decade performance while retaining a compact footprint. Initial simulation suggests that the presented concept for dielectric loading can extend the performance, but that consideration for the beam pattern evolution must be taken into account. The metal structure (horn-funnel and ridges) dictates the lower frequency part (first octave in [13]) performance of the QRFH, while the dielectric load is of strong importance as the frequency increases. For improved performance in sensitivity and polarimetric response over the full bandwidth, further combinations of previously known design features of the QRFH must be explored. To include these degrees of freedom in the QRFH parameter search space, the beam pattern evolution with frequency should be addressed during the analysis to achieve optimal high performance across the full bandwidth. While manufacturing techniques and material was not discussed here, important considerations are dielectric losses, shape deformation due to thermal shrinkage (for cryogenic systems), and receiver integration.

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REFERENCES

[1] J. Yang *et al.*, "Cryogenic 2-13 GHz eleven feed for reflector antennas in future wideband radio telescopes," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 1918–1934, Jun. 2011.

[2] K. A. Abdalmalak *et al.*, "Ultrawideband Conical Log-Spiral Circularly Polarized Feed for Radio Astronomy," *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1995–2007, Mar. 2020.

[3] A. Akgiray, S. Weinreb, W. A. Imbriale, and C. Beaudoin, "Circular quadruple-ridged flared horn achieving near-constant beamwidth over multioctave bandwidth: Design and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1099–1108, Mar. 2013.

[4] W. J. Welch *et al.*, "New cooled feeds for the allen telescope array," *Publ. Astro. Soc. Pacific*, vol. 129, no. 974, Mar. 2017.

[5] G. Cortes-Medellin, "Non-planar quasi-self-complementary ultra-wideband feed antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 1935–1944, Jun. 2011.

[6] S. Weinreb, J. C. Bardin, and H. Mani, "Design of cryogenic SiGe low-noise amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 11, pp. 2306–2312, Nov. 2007.

[7] J. Schleeh *et al.*, "Cryogenic 0.5-13 GHz low noise amplifier with 3 K mid-band noise temperature," in *IEEE MTT-S Int. Microw. Symp. Dig. (IMS 2012)*, Montreal, QC, Canada, 2012.

[8] B. Dong *et al.*, "Optimization and Realization of Quadruple-ridge Flared Horn with New Spline-defined Profiles as a High-efficiency Feed over 4.6-24 GHz," *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 585–590, Jan. 2019.

[9] T. S. Beukman, P. Meyer, M. V. Ivashina, and R. Maaskant, "Modal-based design of a wideband quadruple-ridged flared horn antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 1615–1626, 2016.

[10] K. Kotze and P. Meyer, "Improving Modal Purity in Quadraxially Fed Quadruple-Ridged Flared Horn Antennas," in *Proc. 14th Euro. Conf. Antennas Propag. (EuCAP 2020)*, Mar. 2020.

[11] 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 Conf. Antennas Propag. Wireless Communic. (APWC 2015)*, Turin, Italy, Sep. 2015, pp. 787–790.

[12] G. Tuccari *et al.*, "BRAND: A very wide-band receiver for the EVN," in *Proc. 23rd Working Meeting of the Euro. Very Long Baseline Interferometry Group for Geodesy and Astrometry (EVGA 2017)*, Gothenburg, Sweden, May 2017, pp. 81–83.

[13] 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.

[14] P.-S. Kildal, "Factorization of the feed Efficiency of Paraboloids and Cassegrain Antennas," *IEEE Trans. Antennas Propag.*, vol. 33, no. 8, pp. 903–908, Aug. 1985.

[15] P.-S. Kildal, J. Yang, and M. Ivashina, "New BOR1 and Decoupling Efficiencies for Characterizing Ultra-Wideband Reflectors and Feeds for Future Radio Telescopes," in *Proc. 5th Euro. Conf. Antennas Propag. (EuCAP 2011)*, Rome, Italy, Apr. 2011, pp. 3712–3714.

[16] T. D. Carozzi and G. Woan, "A fundamental figure of merit for radio polarimeters," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 2058–2065, Jun. 2011.