Analysis of Multi-faceted Reflectarrays based-on Cassegrain Optics

Borja Imaz-Lueje[1], David González-Ovejero[2], Marcos R. Pino[1], Manuel Arrebola[1], Ronan Sauleau[2]
[1] Group of Signal Theory and Communications, University of Oviedo, Spain, {bimaz, mpino, arrebola}@uniovi.es
[2] Univ. Rennes, CNRS, IETR, (Institut d'Electronique et des Technologies du numérique) - UMR 6164, Rennes, F-35000, France, {david.gonzalez-ovejero, ronan.sauleau}@univ-rennes1.fr

***Abstract*- This contribution presents a compact multi-faceted reflectarray in a Cassegrain configuration. The reflectarray surface is comprised of five identical panels arranged edge to edge following a cylindrical parabolic profile. The antenna provides dual-linear polarization (LP) and it operates in Ka-band, generating a broadside beam pattern. The performance of this antenna is assessed and compared with two alternative approaches: a single-facet reflectarray and a multi-faceted structure with three identical panels. The proposed multi-faceted structure achieves the best in-band performance, with a 60% enhancement in the gain–bandwidth product compared to the single-facet case and a 10% improvement compared to the multi-faceted approach based on three panels.**

I. Introduction

Printed reflectarrays [1] have emerged as a feasible antenna solution in several applications, including cellular systems, radar, or satellite communications [2] – [4]. Compared to other architectures, such as parabolic reflectors or antenna arrays, reflectarrays exhibit various advantages. Namely, they provide a high degree of flexibility in shaping the radiated field while maintaining a lower profile and cost compared to parabolic reflectors. Moreover, reflectarrays may achieve higher aperture efficiencies than arrays.

The typical configuration of a reflectarray antenna is in front-feed or single-offset [1]. However, they can be designed in dual-reflector configurations, such as Cassegrain [5] – [9]. These configurations feature folded optics that decrease the antenna profile and allow one to better accommodate the feed. In addition, they exhibit more degrees of freedom, resulting in enhanced control of the antenna performance during the design process [10]. In these antenna configurations, reflectarrays can perform the roles of the sub-reflector [5], main reflector [6] - [8], or both [9]. Using reflectarrays as the main reflector provides a compact and lightweight approach, which is particularly advantageous in certain applications such as monopulse radar systems [7].

Nevertheless, these reflectarray-based configurations exhibit an inherent narrow bandwidth due to the in-band behavior of the reflectarray surface. The bandwidth of a printed reflectarray is mainly limited by two factors [11]: the bandwidth of the radiating element and the differential spatial phase delay. The former can be alleviated by using multi-resonant cell topologies [12]-[14] while the latter can be reduced using true-time delay cells [15] or by optimizing the geometry of the unit-cell [13]. Other broadband strategies focus on reducing the differential spatial phase delay at the antenna optics level. One option is the use of a high f/D ratio [1] but this results in a lack of antenna compactness. Alternatively, parabolic [4] or multi-faceted reflectarrays [16] – [18] reduce the differential spatial phase delay due to their assembly following a parabolic profile. Multi-faceted structures can enlarge the bandwidth of conventional reflectarrays while maintaining their low-profile and compactness advantages [17], [18].

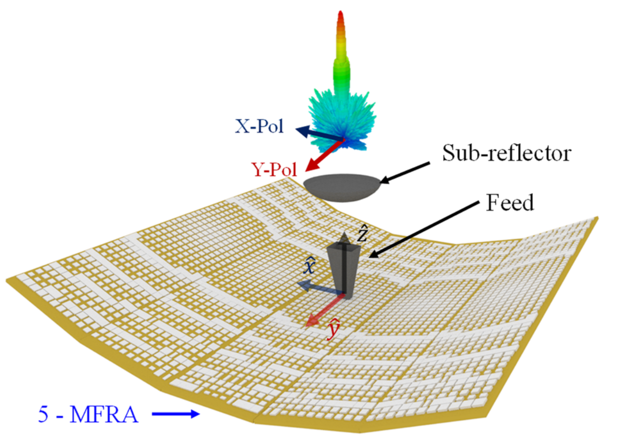

Fig. 1. Perspective view of the proposed multi-faceted reflectarray antenna.

This paper presents the analysis and design of a five-panel multi-faceted reflectarray (5-MFRA) disposed of in a compact Cassegrain configuration. The antenna generates a pencil-beam pattern in dual-linear polarization (X and Y polarization) at 31 GHz. The panel arrangement follows a parabolic profile to enlarge the bandwidth of the compact configuration. The analysis and design of the proposed antenna are carried out through an equivalent front-feed model which considers the effects of the different elements of the dual-reflector approach. The performance of the five-panel structure is compared to a single-facet equivalent (SFRA), and the design reported in [18] consists of a multi-faceted reflectarray comprised of three panels (3-MFRA).

II. Multi-Faceted Cassegrain Reflectarray Design

A. Antenna Optics.

Fig. 1 depicts the proposed multi-faceted approach, whereas Fig. 2 shows the cross-section of both the 5-MFRA and the equivalent SFRA. This antenna optics is based on the configuration reported in [18] for the 3-MFRA. The Cassegrain structure consists of three parts: a main reflector, a polarized-feed, and a sub-reflector.

The main reflector is a multi-faceted reflectarray (solid blue line in Fig. 2 composed of five panels identical in

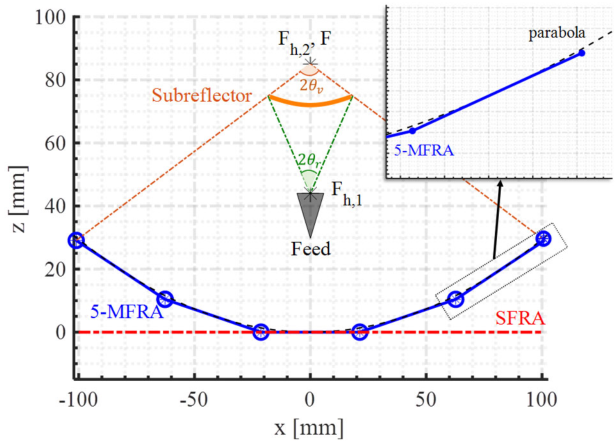

Fig. 2. Cross-section of the proposed multi-faceted reflectaray. XZ plane: 5 panel multi-faceted approach (5-MFRA), blue solid line and single-facet (SFRA) red dashed line.

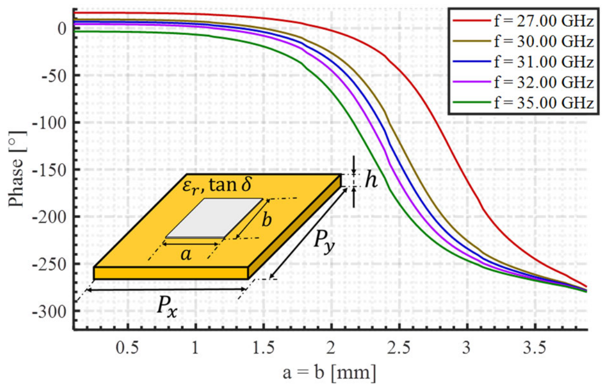

Fig. 3. Unit-cell geometry and phase response of the unit-cell as a function of the patch size for different frequencies under normal incidence.

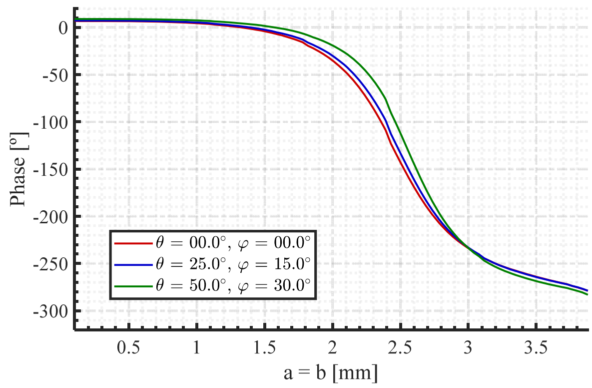

Fig. 4. Phase response of the unit-cell as a function of the patch size for different angles of incidence at design frequency (31 GHz).

dimensions; the lateral panels present mirror symmetry along the YZ plane and follow a parabolic profile (dashed black line in Fig. 2) regarding the XZ plane. The focus of this parabola is F= 85 mm. Each panel is made of 572 elements distributed in a rectangular grid of 11 x 52 elements. Thus, the equivalent aperture of the reflectarray is 202.0 mm x 201.8 mm. Following the same antenna optics, the equivalent single-facet reflector (dashed red line in Fig. 2) consists of 2704 elements, distributed in a rectangular grid of 52 x 52 elements and with an aperture of 201.8 mm x 201.8 mm.

The feed is characterized using an ideal $\cos^q \theta$ with the same q factor for both the E- and the H-planes. This factor is equal to 7.9 at design frequency (31 GHz) and varies linearly in frequency. The feed is a single linearly polarized source, so it is rotated regarding the z axis of Fig. 1 to provide the dual-linear polarization. The aperture of this source is located 44 mm above the reflector. The sub-reflector consists of a metallic hyperbola of diameter 35.10 mm, which corresponds a 17% of the total aperture of the reflectarray. The focal points of the hyperbola are located at $F_{h,1} = 44$ mm and $F_{h,2} = 85$ mm; and its vertex is at 72 mm above the main reflector.

According to this antenna optics, the subtended angle between the sub and the main reflector (θ_v) is 59.6º and the angle between the feed and the hyperbola (θ_r) is 29.8º. Both reflectarrays have an f/D ratio of 0.43 and compactness (calculated as the ratio of the height of the sub-reflector and the reflectarray aperture) of 0.36.

B. Unit cell.

Fig. 3 the geometry of the unit-cell used in the reflectarray designs. It comprises a rectangular patch of variable-size, printed on duroid5880 substrate ($\varepsilon_r = 2.30$, $\tan\delta = 0.003$) with thickness $h = 0.762$ mm. The periodicity of the cell ($P_x = P_y$) is 3.88 mm, which is $0.4\lambda_0$ at the design frequency. Fig. 3 and Fig. 4 depict the unit-cell response in-band and under different angles of incidence when the dimensions of the patch (a, b) vary. This topology provides a response in S-shape curve, which is typical for this unit-cell topologies [1], with a phase range limited to 280º at the design frequency. The phase curve exhibits angular and in-band stability at frequencies close to 31 GHz. At frequencies further away, such as 27 and 35 GHz, the excursion of the curve becomes significant.

C. Layout design

The reflectarray proposed in this work is designed to collimate the beam in a certain direction of the space $\vec{r}_0(\theta_0, \varphi_0)$. To do this, each radiating element must provide a phase shift in the impinging wave calculated as [1]:

$$\phi(\vec{r}_n) = k_0[d_n - \vec{r}_n \cdot \vec{r}_0]\,, \qquad (1)$$

where $\vec{r}_n$ is the position vector of the n-th reflectarray element, k_0 is the propagation constant in vacuum and d_n is the distance between the element and the focus of the parabolic profile (F in Fig. 2). The goal phase distribution required in each panel of the designs is calculated to generate a broadside beam $(\theta_0, \varphi_0) = (0.0°, 0.0°)$, considering the coordinate system of Fig. 1. The design process of each reflectarray panel is carried out element by element, adjusting properly the dimensions a and b of the patch to provide the required phase on each polarization. The analysis of the radiating element is performed using the Method of Moments in Spectral Domain (MoM-SD) reported in [20], accounting for the actual incident angle on each cell. The resulting layouts of the 5-MFRA are depicted in Fig. 1. In the sectorization plane XZ, the layouts exhibit a smooth variation of the patch sizes. This is a distinctive feature of multi-faceted reflectarrays, resulting from the phase distribution $\phi(\vec{r}_n)$ required in each panel [17]. The smoother variation of the patch sizes leads to a reduction of the phase wraps (i.e., abrupt variations in the size of consecutive patches due to the use of unit-cells with phase range less than a full cycle). The phase wraps have a negative impact in the in-band performance of the antenna, as stated in [3].

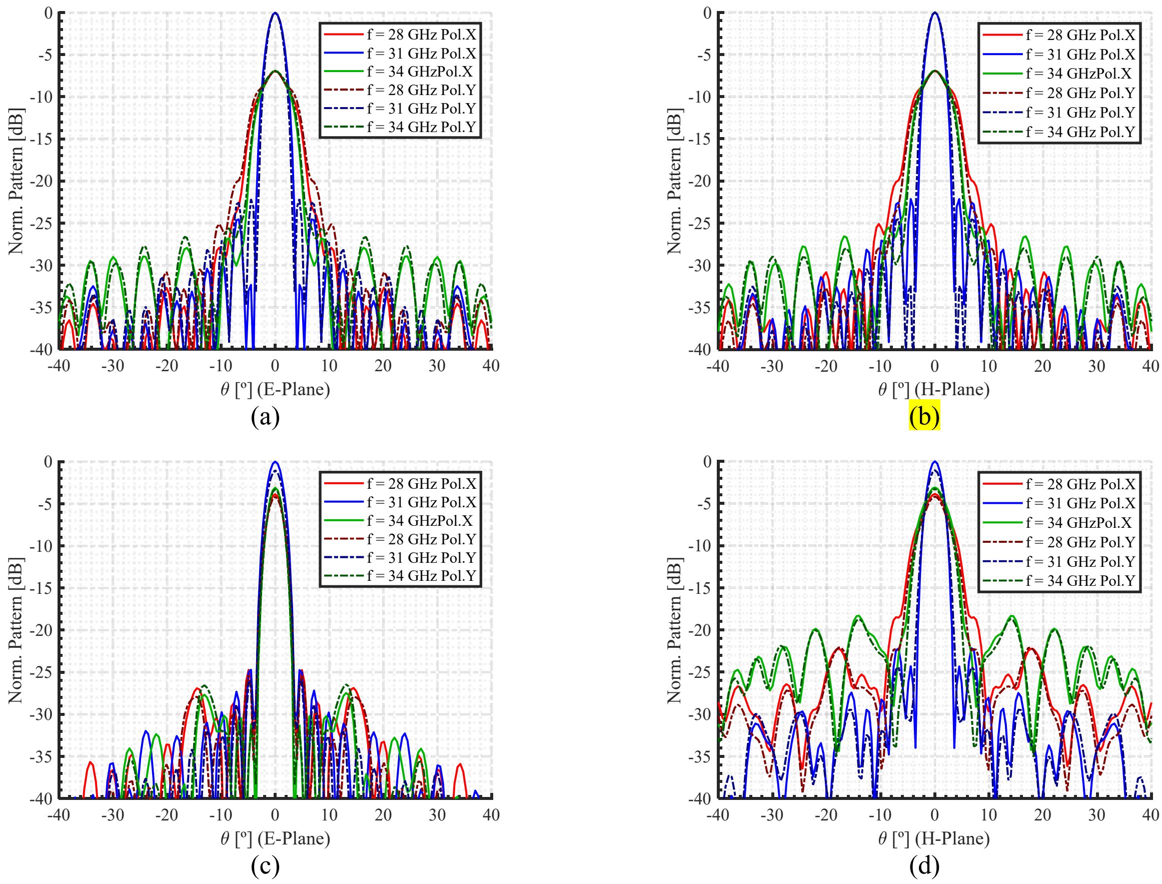

Fig. 5. Main cuts of the radiation pattern over 6 GHz of bandwidth. E-Plane (left) and H-plane (right) cuts of the pattern. Field normalized to the gain at design frequency (31. GHz) in X polarization.: (a), (b) SFRA; (c), (d) 5-MFRA.

III. Antenna Performance

The Cassegrain designs have been evaluated through an equivalent model to the antenna configuration shown in Fig. 2. The primary feed and sub-reflector are substituted by a single feed, located at the focus of the parabola. To consider the effect of the sub-reflector on the incident field in the reflectarray panels, the equivalent feed has a broader beamwidth than the original feed. The beamwidth ratio between the original and the equivalent feed is equal to the ratio between the subtend angles $\theta_v/\theta_r = 2$. Based on this equivalent antenna optics, the reflectarrays have been assessed using the MoM-SD [20] to analyze the behavior of the panels and the methodology outlined in [17] to compute the total radiated farfield of each structure.

Fig. 5 shows the radiation pattern of the 5-MFRA and the SFRA between 28 and 34 GHz, normalized to the maximum gain at 31.0 GHz in polarization X. At the design frequency, both Cassegrain antennas exhibit a broadside beam with an SLL of about -22 dB and an HPBW of 3º. However, the antennas exhibit a different in-band response. In the E-Plane (corresponding with the XZ plane in Fig. 2), the 5-MFRA shows a more stable beam in-band in comparison to the SFRA, with little variations of the HPBW and a slight increase in SLLs. In the H-Plane, both antennas experience a significant defocusing of the beam and higher SLLs.

In terms of gain, Fig. 6 and Table I provide the gain of the reflectarrays assessed at design frequency (G_{max}) and in a wide range of frequencies (27 – 35 GHz). This study also includes the performance of an equivalent multi-faceted reflectarray (3-MFRA), whose features were described in [18].

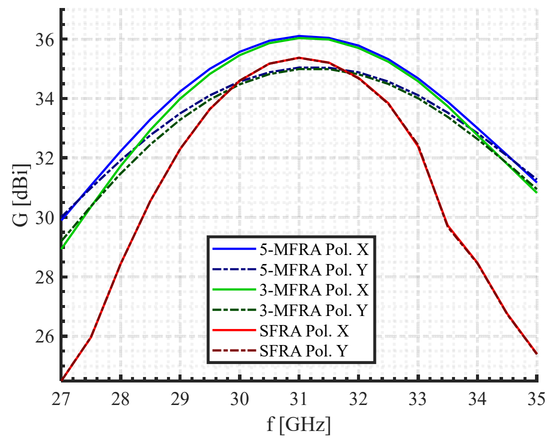

Fig. 6. Copolar gain from 27 to 35 GHz for the 5 panel (5-MFRA) and 3 panel (3-MFRA) multi-faceted designs and single-facet reflectarray (SFRA).

Compared to the SFRA, both multi-faceted approaches exhibit a lower in-band gain loss, shown in Fig. 5 and Fig. 6. The response of the SFRA is nearly identical in both polarizations. Conversely, both 5-MFRA and 3-MFRA have some differences between the response at X- and Y-polarization. This is due to the different illumination of the multi-faceted reflectarrays for each polarization. The 5-MFRA achieves slightly higher levels of gain in-band compared to the 3-MFRA.

Table I lists the 1- and 3-dB gain bandwidth of the three reflectarray designs. In addition, it is included the Gain-Bandwidth Product (GBP) parameter, calculated as described in [18]. For both polarization and gain thresholds, the 5-panel

TABLE I. ANTENNA GAIN BANDWIDTH

	SFRA		3-MFRA		5-MFRA	
	Pol. X	Pol.Y	Pol. X	Pol.Y	Pol. X	Pol.Y
G_{max} [dBi]	35.4	35.4	36.0	35.0	36.0	35.0
BW_{1dB} ($\%f_0$) [GHz]	2.2 (7.1)	2.2 (7.1)	2.9 (9.4)	3.6 (11.6)	3.3 (10.65)	3.8 (12.26)
GBP (1 dB)	24618	24618	37303	36714	42398	38770
BW_{3dB} ($\%f_0$) [GHz]	4.0 (12.1)	4.0 (12.1)	5.3 (17.1)	5.7 (18.4)	5.7 (18.39)	6.4 (20.65)
GBP (3 dB)	44729	44729	68076	58186	73212	65301

approach exhibits the best gain–bandwidth response of the three antennas. Regarding the SFRA, it features an enhancement of roughly 50% and 60% in the bandwidth and the GBP respectively. The 5-MFRA achieves 10% more bandwidth and GBP than the 3-MFRA.

IV. CONCLUSIONS.

This contribution presents a compact five-panel multi-faceted reflectarray that employs a Cassegrain feeding system. The panels are assembled edge to edge following a parabolic profile along one axis to reduce the differential spatial phase delay effect, so the antenna bandwidth is enhanced compared to a conventional reflectarray under the same optics. The antenna has been designed at 31 GHz in dual-linear polarization to provide a single pencil beam. Their electrical performance is assessed and compared with two equivalent Cassegrain structures: a single-facet approach and a multi-faceted structure comprised of three panels.

The proposed multi-faceted approach requires a smooth phase distribution along the sectorization plane, thanks to the panel arrangement following a parabolic profile. Consequently, the variability of the size patches in this plane is reduced, which mitigates the existence of phase wraps and their negative effects on the antenna in-band response.

The radiation pattern provided by the five-panel structure achieves a better in-band behavior than a conventional single-facet approach. In the sectorization plane, it enhances the stability of the main beam and side radiation, which results in an improvement in the antenna bandwidth and the gain-bandwidth product. The enhancement is notable regarding a conventional reflectarray, but it is not as significant when compared to the three-panel approach.

This work corroborates the capabilities of multi-faceted reflectarrays in Cassegrain configurations. They improve the gain bandwidth ratio regarding conventional reflectarrays while maintaining the compactness of the structure.

ACKNOWLEDGEMENTS

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