Analysis of a Multi-Faceted Reflectarray in Offset Configuration

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Abstract- **This paper describes the analysis and design of an offset multi-faceted reflectarray structure composed of three identical panels distributed following a parabolic cylinder. Working in Ka-band, the antenna is designed to generate a pencil beam in the broadside direction of the structure. Its performance is compared with a flat reflectarray of similar aperture size. The multi-faceted reflectarray design achieves an improvement in band performance compared to its classic single panel version.**

I. INTRODUCTION

The interest in reflectarray antennas has grown exponentially in recent years as a solution for many applications as space communications [1]. Reflectarrays are an interesting alternative to parabolic reflectors for their better mechanical characteristics. Also, they are a good candidate in comparison with phased array antennas, thanks to their lower losses [2].

Printed reflectarray antennas (RA) usually have narrow bandwidth [3] due mainly to two factors: the bandwidth of resonant elements and the differential spatial phase delay. Several strategies on the radiant element have been proposed to overcome the first limitation, such as using stacked structures of simple shapes [2], or more complex elements such as the Phoenix cell [4], among others. For the other limitation, it is possible to improve the performance of the reflectarray, increasing the f/D ratio [2]. However, this solution produces larger reflectarray designs and a possible increment in spillover.

Another option to reduce the phase delay difference is the use of curved or multi-faceted reflectarrays. Their closets resemblance with a parabolic surface reduces the phase-shift variation that the radiating element must introduce. Some works have been proposed in this sense, sectoring one dimension as a parabolic cylinder [6] or over the whole parabolic surface [7]. In both cases, it is demonstrated a bandwidth improvement compared to conventional reflectarray structures.

In this paper, it is proposed the design and analysis of a multi-faceted offset reflectarray following a parabolic cylinder in Ka-band. The designed reflectarray radiates a pencil-beam pattern in the broadside direction of its parabolic equivalent model working in dual-linear polarization (X and Y polarization). A Method of Moments based on Local Periodicity (MoM-LP) [8] is used for analyzing the antenna behavior. The design is compared with a flat reflectarray of similar dimensions. An improvement in antenna performance is obtained.

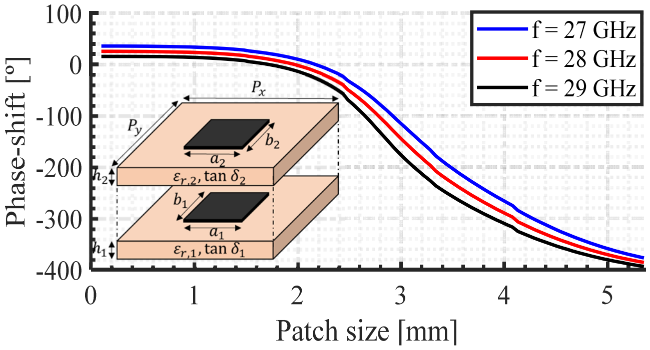


Fig. 1. Sketch and phase response of the unit cell as a function of the patch size at different frequencies under normal incidence. The relation between patch sizes $a_2/a_1 = b_2/b_1 = 0.6$.

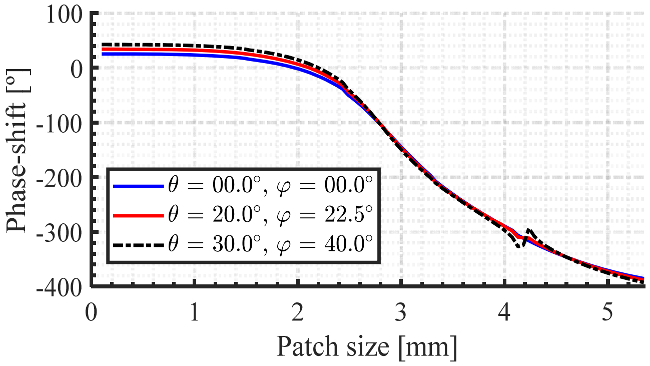
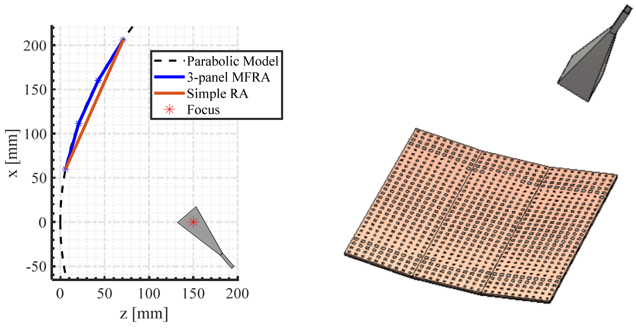


Fig. 2. Phase response of the unit cell for different angles of incidence (θ, φ) at 28 GHz.

II. MULTI-FACETED REFLECTARRAY DESIGN

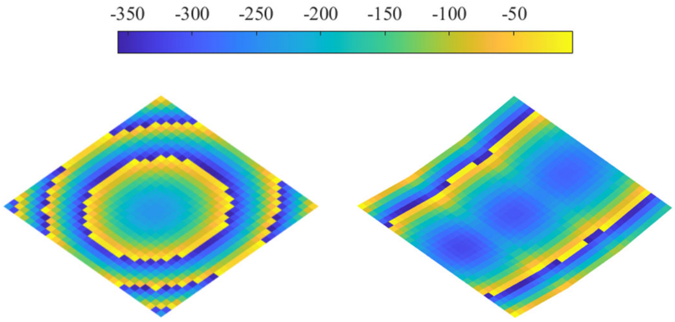
A. *Unit cell characterization.*

The chosen unit cell consists in two stacked rectangular patches backed by a ground plane, as shown in Fig. 1. In both layers, the substrate is DiClad 880 ($\varepsilon_r = 2.26$, $\tan\delta = 0.0025$) with a thickness of $h_1 = 0.762$ mm and $h_2 = 1.524$ mm. The periodicity is 5.35 mm ($\lambda_0/2$, considering a working frequency of 28 GHz). This topology provides the phase curves shown in Fig. 1 considering normal incidence. The unit cell is able to provide a phase-shift greater than 360º for different frequencies. According to Fig. 2, the behavior under conditions of oblique incidence is similar. For high angles of incidence, some distortions in the curve happens for patch sizes near to the periodicity. However, only the elements near the edges of the reflector are in similar conditions, which will not significantly affect the performance of the antenna.



(a) (b)

Fig.3. Geometry of reflectarray designs: (a) XZ plane of multi-faceted and flat reflectarray; (b) 3-D view of multi-faceted reflectarray.



(a) (b)

Fig.4. Phase-shift introduced by each cell: (a) Flat reflectarray; (b) multi-faceted reflectarray.

B. Antenna Geometry.

The multi-faceted reflectarray structure is shown in Fig.3. It is formed by 3 identical rectangular panels of 300 elements (10 x 30 in each axis). Each panel rest on a chordal plane of the equivalent parabolic surface along the XZ plane. The equivalent aperture of the entire structure is 159.60 x 160.60 mm ($14.89\lambda_0$/ x $15\lambda_0$). In order to evaluate the improvements of this antenna, it is designed an equivalent flat reflectarray, formed by 900 elements distributed in a rectangular grid of 30 x 30.

A Narda 665-20 horn, with a gain of 18.6 dBi, is used as a feed. Its phase center at working frequency is placed at the focus coordinates of the equivalent parabola, at 150 mm from the center of the parabolic system, as shown in Fig.3(a). The angle of inclination of the feed is 48.72º with regard to the system of the structure. To avoid the blockage, a single-offset configuration, with a clearance of 60 mm, is considered. In both designs the f/D relation is approximately 0.934.

C. Layout Design Procedure.

The phase-shift that each reflectarray element must introduce on the incident field to produce a pencil-beam in a generic direction (θ_0, φ_0) is given by,

$$\phi(x_i, y_i, z_i) = k_0[d_i - (x_i \sin\theta_0 \cos\varphi_0 + y_i \sin\theta_0 \sin\varphi_0 + z_i \cos\ \theta_0] \tag{1}$$

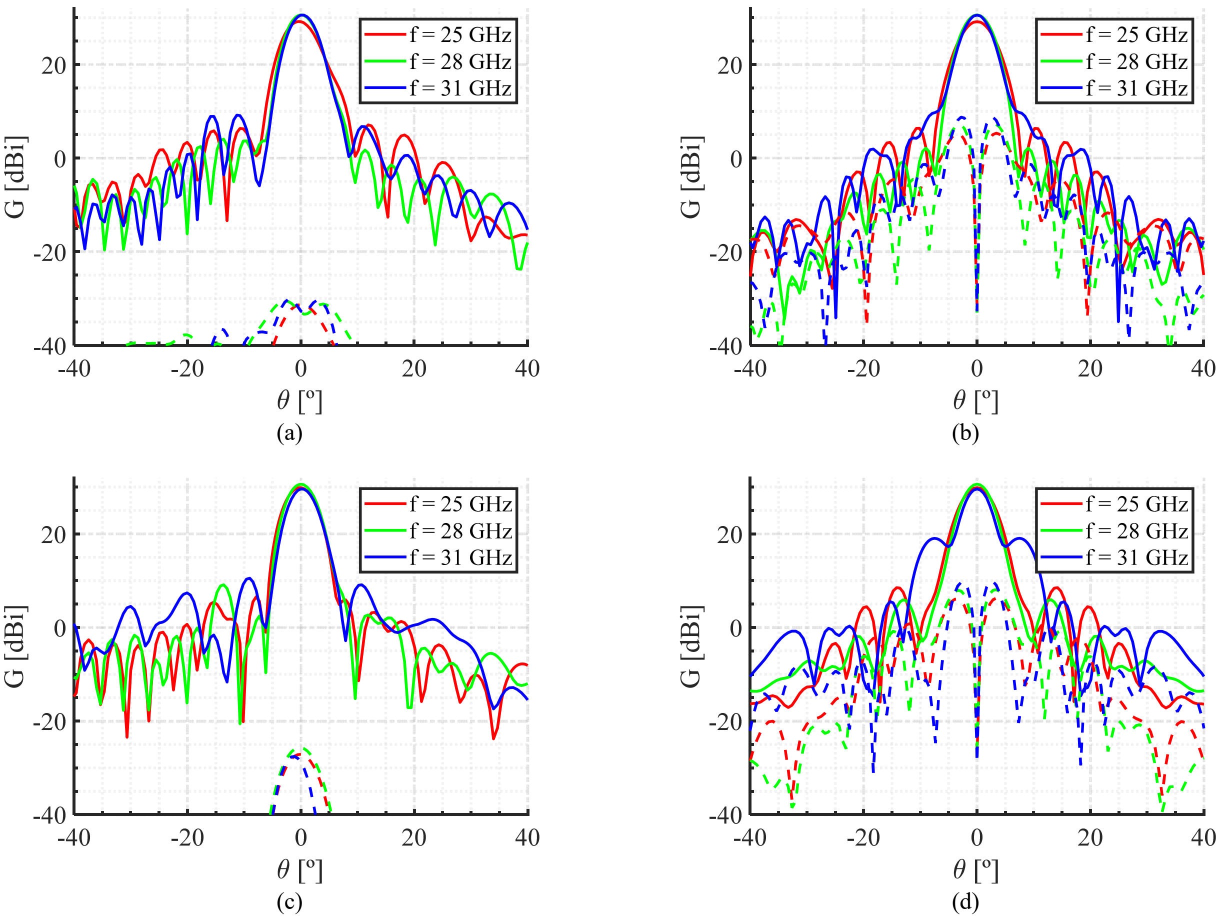
where (x_i, y_i, z_i) are the coordinates of the i-th reflectarray element, k_0 is the propagation constant in vacuum and d_i is the distance between the element and the phase center of the feed. Considering the coordinate system of the equivalent parabolic model (see Fig.3) as a reference, the phase distribution of both designs is calculated to produce a beam in broadside direction ($\theta_0 = \varphi_0 = 0$). These phase distributions are translated into patch sizes applying the phase curves shown in Fig. 1 at 28 GHz taking into account the real incidence angle in each cell. The reflected field is obtained using MoM-LP [8] to evaluate the layout and applying PO-methods to obtain the incident field on the surface of each panel. From this field the radiation pattern is calculated following the methodology explained in [9].

III. RESULTS.

Fig.4 shows the phase distribution of both reflectarrays designs using (1). It is observed that the variation of phases in the axes of sectorization is significantly lower in the multi-faceted reflectarray than in the flat design. The multi-faceted structure has a smooth phase-shift in the cells along the sectorization axis because its close similarity to a parabola. The panels of the reflectarray in the other axis do not follows the curvature of the parabola. This implies that the required phase-shift was 360º. A sectorization in both axes reduce the phase-shift range which the radiant element must introduce. This would allow the use of more simpler cell topologies, which translates into the reduction of the cost of the antenna.

The results of the gain pattern for a bandwidth of 6 GHz are shown in Fig.5. The copolar gain results show a better performance of the multi-panel structured in comparison with its flat equivalent. In cut $\varphi = 0°$ (Fig.5(a)), where sectoring is applied, the main beam in the flat reflectarray has a significant deformation while in the multi-faceted structure it remains stable. In the non-sectorized cut ($\varphi = 90°$) appears a significant degradation in band for both designs. In terms of crosspolar, both designs have low levels in the main cuts, which means a good crosspolar discrimination. Similar behaviour occurs for polarization X.

Fig.6 shows the maximum gain levels of the patterns evaluated in a wider frequency range (24 – 34 GHz) for each polarization. As expected, the multi-faceted configuration has a more stable copolar gain than flat design. In both polarizations, the multi-faceted structure has a higher gain at frequencies below 28 GHz in comparison with the flat design. Above the working frequency, the level of the side lobes increases faster in the multi-faceted structure, in particular in the cut $\varphi = 90°$ as can be seen in Fig.5(d). The higher level of side lobes, the lower copolar gain achieved. The main cause of this pattern degradation is due to the illumination on the reflectarray surface which is affected by the side lobes of the feed that reduces the taper specially in the multi-faceted design. It is produced a greater distortion in Y polarization when the side lobes affect the non-sectorized cut. A sectorization in this axis would generate a more robust pattern as seen in the cut X and therefore an improvement in the gain achieved in-band. Regarding the crosspolar level, the multi-faceted reflectarray has a slightly high level in the whole band, although at higher frequencies both designs are equalized.



(a) (b) (c) (d)

Fig.5. Gain pattern of reflectarray designs in 6 GHz of bandwidth. Polarization Y. Cut $\varphi = 0$ ° (a) and $\varphi = 90$ ° (b) for flat design. Cut $\varphi = 0$ ° (c) and $\varphi = 90$ ° (d) for multi-faceted design. Solid and dotted lines correspond with copolar and crosspolar fields, respectively.

Table-I lists the bandwidth performance of the designs considering the behavior of the copolar gain in-band for both polarizations. Despite the effect of the feed, multi-faceted reflectarray increases the bandwidth by approximately 1.5 GHz compared to the flat design, which is about a 5% of the working frequency.

TABLE I. BANDWIDTH COMPARISON

Design	**1-dB GAIN BANDWIDTH GHz [%f_0]**	
	Pol. X	***Pol. Y***
Multi-faceted RA	5.7 [20.4]	6.5 [23.2]
Flat RA	4.0 [14.3]	5.0 [17.9]

IV. CONCLUSIONS.

A multi-faceted reflectarray of three panels in single-offset configuration has been designed at 28 GHz to generate a pencil beam in the broadside direction of the structure. The design follows the geometry of a cylindrical parabolic reflector in order to reduce the differential spatial phase delay effect. The multi-faceted reflectarray is compared with a flat version of reflectarray with identical physical size.

With the phases to be introduced for each element calculated analytically and knowing the behavior of the cell, the layout of each of the panels is obtained. Using MoM-LP with PO-methods, the performance of the two proposed designs is evaluated.

In the sectoring axis, the phase-shift range to be introduced by multi-faceted design elements is reduced. This would allow the use of simple cell topologies with phase ranges below 360º, if sectoring is applied in both axes. Regarding the antenna performance, the multi-faceted structure has a better behavior in-band in the sectoring cut compared to the flat version, which allows an appreciable improvement in-band performance, with a slightly increase in the crosspolar. The improvement in performance is reduced due to the sectorization in one axis, the offset-configuration, and the behavior of the incident field in the range frequencies under study.

This contribution demonstrates the improvement in the antenna performance of multi-faceted offset structures regarding conventional flat reflectarrays. Future works will focus on the analysis of multi-faceted structures with sectorization on both axes in order to increase the bandwidth improvement.

ACKNOWLEDGEMENTS

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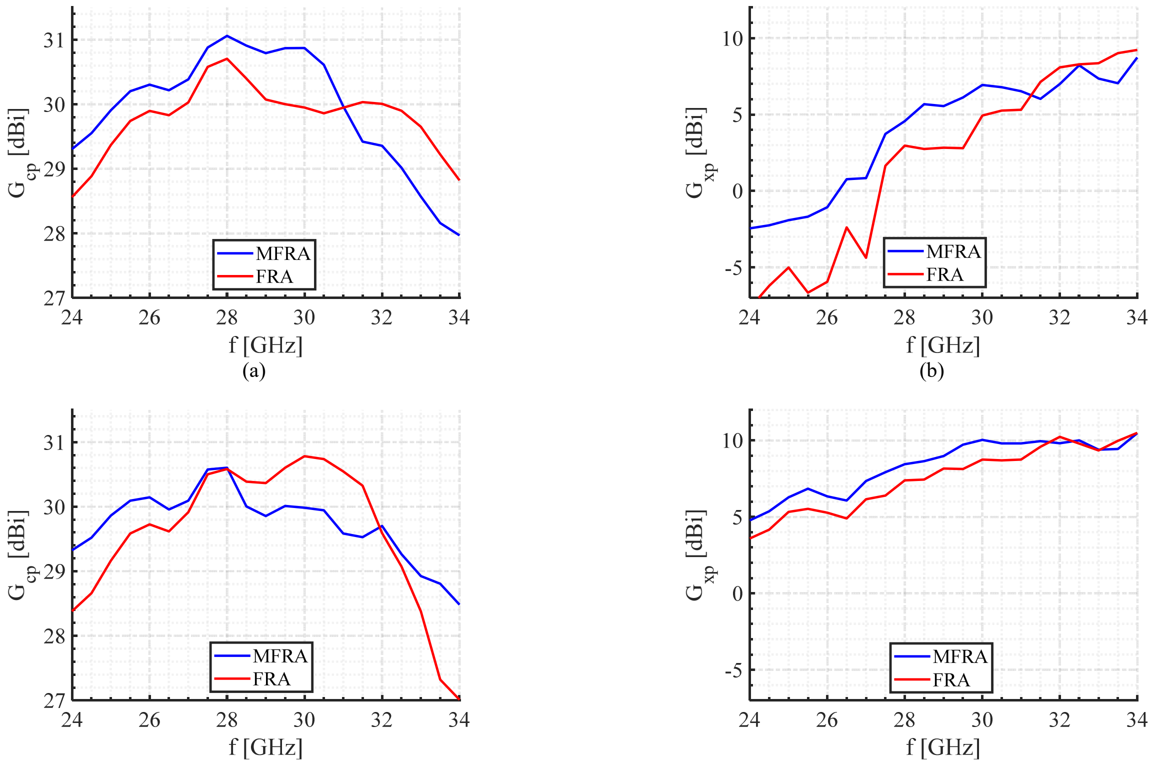

(a) (b) (c) (d)

Fig.6. Levels of maximum copolar and crosspolar gain from 24 to 34 GHz for multi-faceted (MFRA) and flat reflectarray (FRA) designs. Polarization X (top) and Polarization Y (bottom). In columns the maximum copolar and crosspolar gain level.

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