Design of a 5-panel Multi-Faceted Reflectarray in Offset Configuration

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***Abstract*—In this paper, a multi-faceted reflectarray structure is proposed to improve the in-band performance of a conventional reflectarray. The proposed antenna consists in 5 panels distributed on an offset cylindrical parabolic structure. To evaluate the improvements of this structure, a 5-panel reflectarray antenna is designed to generates a pencil beam in the broadside direction in Ka-band and it is compared to a single facet reflectarray of equivalent aperture as well as other multi-faceted structure. The multi-faceted reflectarray reduces significantly the requirements imposed on the radiating elements what would allow the use of low-cost, low-profile cells without a degradation in antenna performance. Besides, the multi-faceted reflectarray achieves a better in-band performance compared to a conventional reflectarray. Indeed, the bandwidth of the proposed multi-faceted antenna is broader than other multi-faceted structures composed by a smaller number of panels, although the enhancement is smaller compared to the single facet case.**

Keywords—reflector antennas; reflectarrays; multi-faceted structures.

I. INTRODUCTION.

The development of new telecommunication services has stimulated the need for high-performance wireless systems. Antennas, a fundamental part of these systems, must be also adapted to strict specifications in terms of efficiency, size, scalability, etc. In this sense, reflectarray antennas [1] have been positioned as an interesting solution. They are flat structures composed of an array of radiating elements that conform to the power from a feed in a given direction or coverage. Printed reflectarrays are proposed as a good candidate in several applications, as far-field [2] and near-field [3] coverages in 5G, or measurement systems [4]. The space sector is the main supporter of these antennas, where can be found communication systems using reflectarrays, such as NASA's MarCO [5] and SWOT [6] missions.

The interest in using printed reflectarrays comes from their advantages compared to other conventional antennas. Reflectarrays can achieve higher aperture efficiencies than phased arrays. Also, they are compact, low profile, and allow beamforming, which position them as an alternative to parabolic reflectors [1]. Nevertheless, printed reflectarrays usually have narrow bandwidth [7] mainly due to two causes: the bandwidth of the radiant element and the spatial phase delay effect, which is particularly critical in electrically large reflectarrays.

In the literature, there are several broadband strategies focused on mitigating these issues. At the element level, the use of multi-resonant [8],[9] is proposed as well as true-time delay cells [10], among others. To overcome the spatial phase delay, it is possible to increase the distance between feed and reflector. However, this solution produces larger reflectarray designs and a possible increment in spillover [1]. Alternatively, parabolic [11],[12], and multi-faceted reflectarrays [13]-[17] have demonstrated a bandwidth improvement in comparison with conventional reflectarrays. Their closets resemblance with a parabolic surface reduces the different paths between the feed and the phase front. Regarding multi-faceted structures, there are some examples of them, sectoring one dimension [14]-[15] or considering facets over the whole parabolic surface [16],[17].

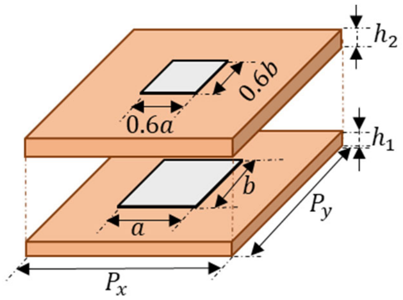


Fig.1. Sketch of the unit cell. The relation between patch sizes is 0.6.

In this contribution, a 5-panel offset reflectarray following a parabolic cylinder in Ka-band at 28 GHz is designed and assessed to mitigate the spatial phase delay and therefore improve the bandwidth of a conventional reflectarray. The antenna radiates a pencil-beam pattern in the broadside direction working in dual-linear polarization (X and Y polarization). Then, the multi-faceted structure is compared to a single facet equivalent and the design proposed in [15]. A Method of Moments based on Local Periodicity (MoM-LP) [18] is used to analyzing and design both antennas.

II. MULTI-FACETED REFLECTARRAY DESIGN.

A. *Unit cell characterization.*

The radiant element is shown in Fig.1. It consists of two stacked rectangular patches backed by a ground plane. In both layers, DiClad 880 ($\varepsilon_r = 2.26, \tan\delta = 0.0025$) is used. The thicknesses are $h_1 = 30\,mils$ and $h_2 = 60\,mils$ respectively. The distance between elements is 5.35 mm in both dimensions, which corresponds to $\lambda_0/2$. This topology provides the reflection coefficient shown in Fig.3. The unit cell can provide a phase-shift range larger than 360º with low losses around 28 GHz. The performance of the cell is similar under conditions of oblique incidence, showing good angular stability.

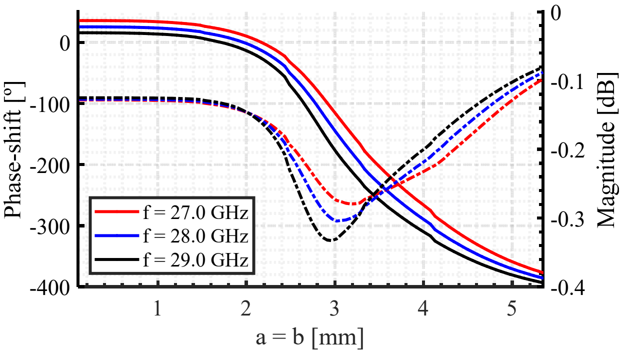
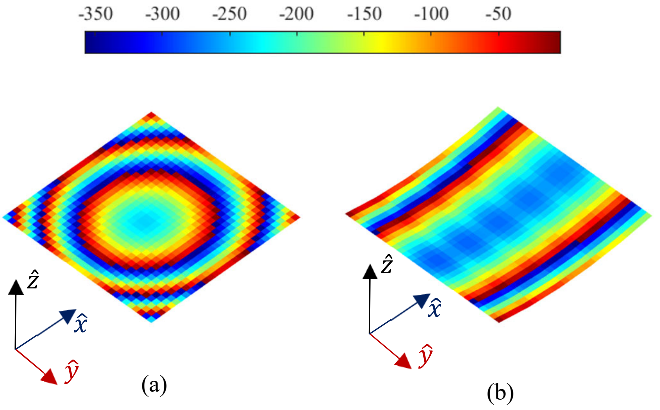
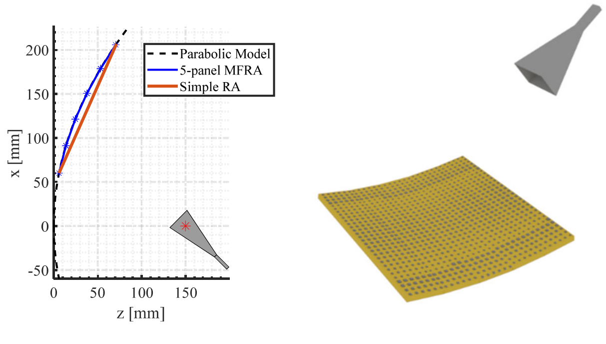


Fig.3. Phase and Magnitude response of the unit cell as a function of the patch size at different frequencies under normal incidence.



(a) (b)

Fig. 4. Phase-shift introduced by each cell for both polarizations: (a) Flat reflectarray; (b) Multi-faceted reflectarray.



(a) (b)

Fig. 5. Geometry of reflectarray designs: (a) XZ plane of multi-faceted and flat reflectarray; (b) 3-D view of multi-faceted reflectarray.

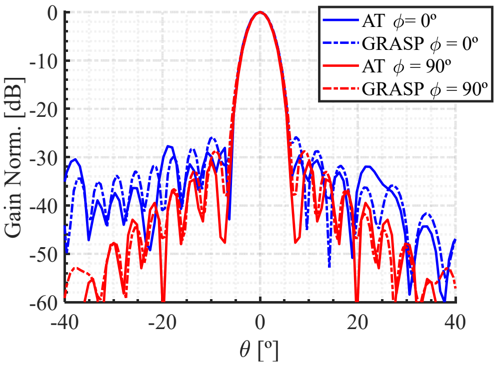


Fig. 2. Main cuts of the normalized radiation pattern at 28 GHz of the 5 panel multi-faceted reflectarray. Comparison between the simulation based on the analysis technique proposed in this paper (AT) and using GRASP.

B. *Antenna optics.*

Fig. 5 shows the geometry of the multi-faceted structure. It is formed by 5 rectangular panels of 180 cells each one, distributed in a rectangular grid of 6 x 30 elements. The panels are placed on chordal planes of an equivalent parabolic surface along the XZ plane, with a focal distance of 150 mm. The equivalent aperture of the whole structure is 159.4 x 160.5 mm. In parallel, it is designed a flat reflectarray of identical dimensions, composed of 900 elements distributed in a grid of 30 x 30.

As feeding, it is used the Narda 665-20 horn which provides a gain of 18.6 dBi at the working frequency. Its phase center is located at the focus of the equivalent parabola as shown in Fig. 5(a). To avoid the blockage, a single-offset configuration is considered, with a clearance of 60 mm and a feed inclination of 48.7º with regard to the Z-axis. In terms of the parabolic equivalent, the f/D ratio is close to 1 in both designs.

C. *Layout Design & Analysis.*

The phase of the reflexion coefficient of each cell $\phi(x_i, y_i, z_i)$ can be obtained analytically, according to the equation,

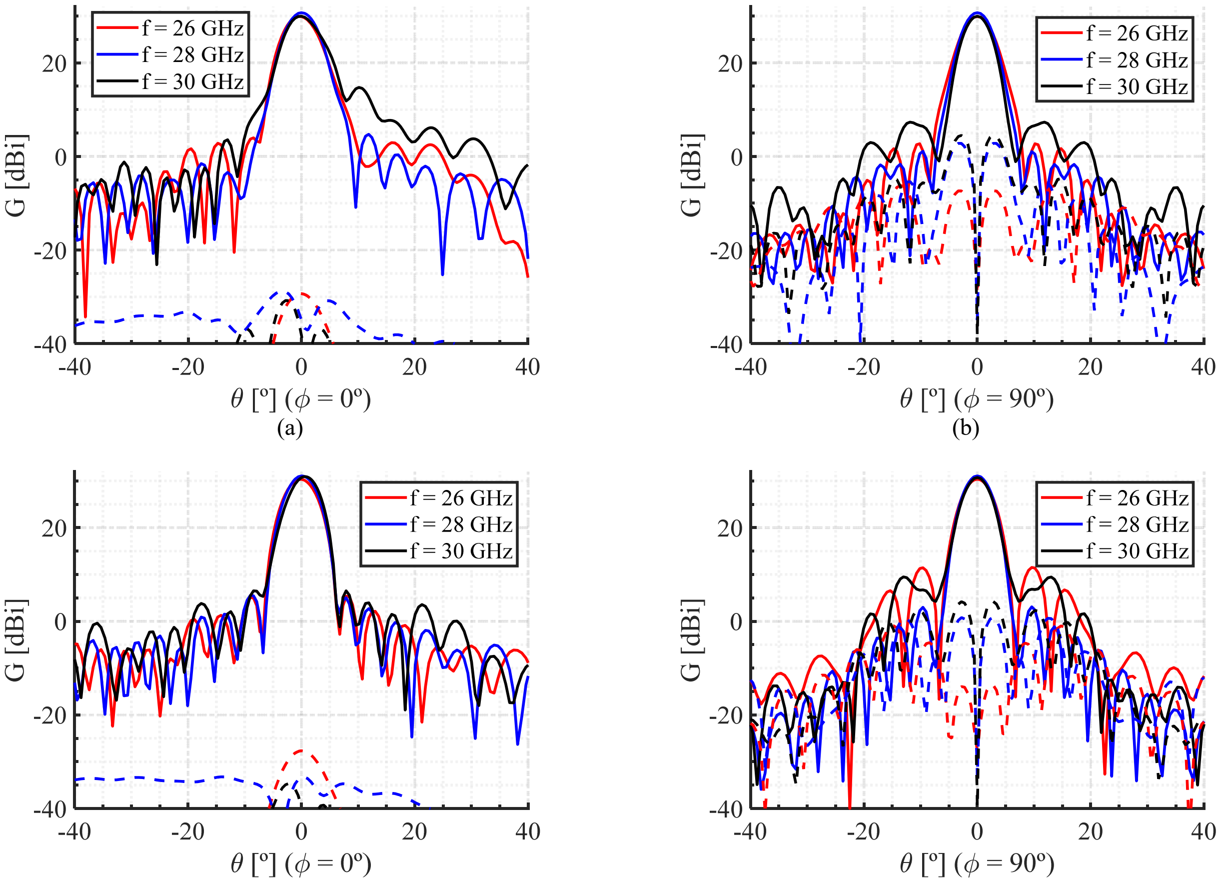
$$\phi(x_i, y_i, z_i) = k_0[d_i - (x_i \sin\theta_0 \cos\varphi_0 + y_i \sin\theta_0 \sin\varphi_0 + z_i \cos\ \theta_0] \tag{1}$$

where (x_i, y_i, z_i) are the coordinates of the i-th radiant element, k_0 is the propagation constant in vacuum, d_i is the distance between the element and the feed and (θ_0, φ_0) the beam pointing direction. Taking the parabolic model system as reference, the phase distribution is calculated for both designs to generate a beam in the broadside direction ($\theta_0 = \varphi_0 = 0°$). Based on the cell analysis at working frequency (see Fig. 5), the phase distributions are translated into patch sizes considering the real incidence angle, using a MoM-LP method to calculate the cell behavior. The performance of both designs is evaluated using a technique based on the MoM-LP mentioned, and the methodology described in [19].

III. RESULTS.

The phase distribution of both reflectarray designs is shown in Fig. 4. In the sectorization axis X, the multi-faceted reflectarray has a smooth phase as contrasted with the flat design case. The multi-faceted structure is closer to a parabola, so the required phase range is far less than a full cycle (360º). In fact, the phase required along x-axis is approximately 100º, more than 3 times less. In this sense, single layer [20],[21] can perfectly provide the required phase range. These cells have lower profile and losses compared to the cell topology presented in this work. On the other axis, both multi-faceted and single facet reflectarrays require a phase range of 360º because they do not follow the parabola surface and therefore it is necessary to use a cell that can provide the full cycle.

Fig. 2 shows the diagram pattern of the multi-faceted structure for Y-polarization at 28 GHz analyzed with the analysis technique as well as a simulation using GRASP [22]



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

Fig. 6. Gain pattern of reflectarray designs in 4 GHz of bandwidth. Polarization X. 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.

in order to validate the technique used. A good agreement between both methods is achieved for both cuts, especially in the area around the main beam.

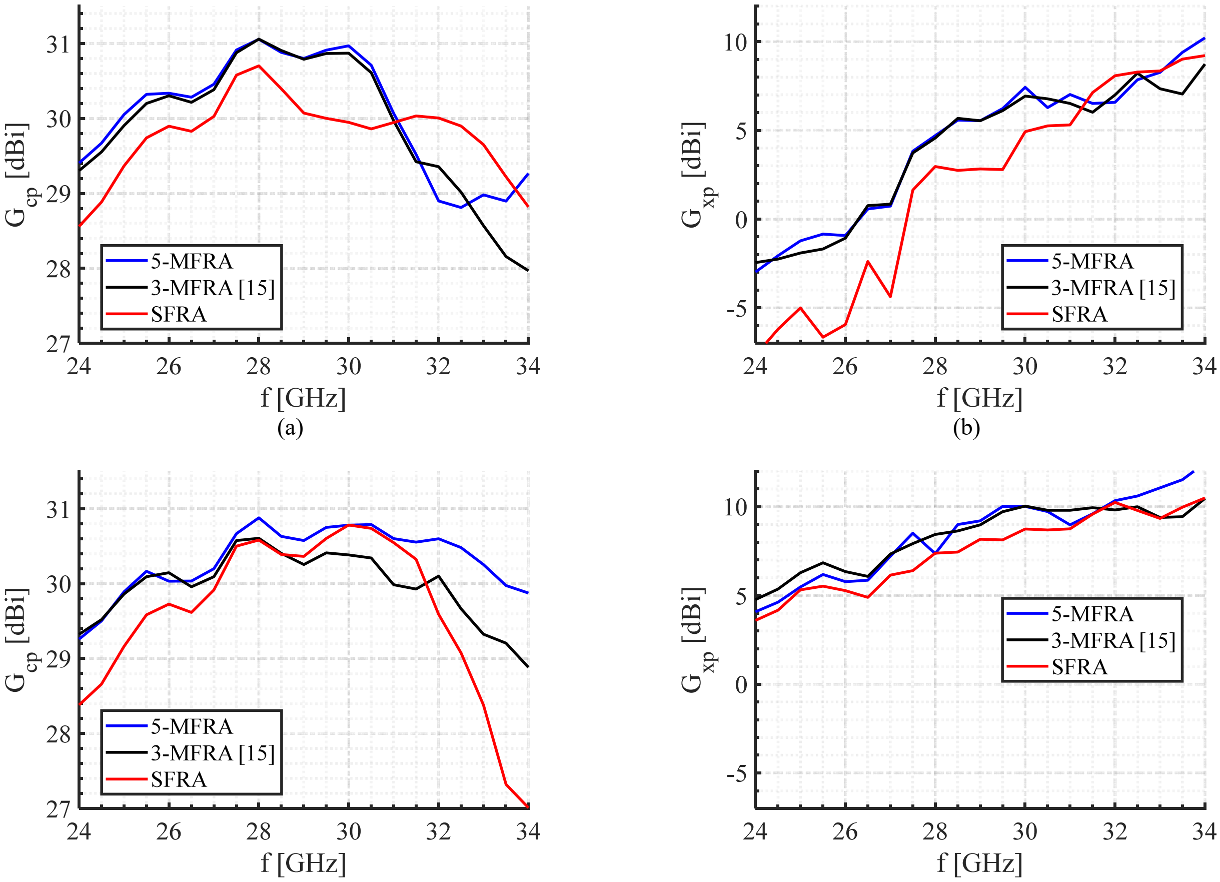
Fig. 6 shows the gain achieved in both designs considering 4 GHz bandwidth. At 28 GHz, the reflectarray designs generate similar beams with a gain of 31 dB, and side lobe levels 25 dB less than the main beam. Regarding the behavior of the pattern in-band, the beam in the multi-faceted structure remains stable when the sectoring is applied ($\varphi = 0°$), while in the single-faceted reflectarray significant deformations appear. Both designs suffer significant degradations in-band for the non-sectorized cut ($\varphi = 90°$). The main causes of this degradation are due to the behavior of the incident field in the reflectarray and the performance of the in-band radiating element. In terms of crosspolar, it is observed a slight increase in the level of the multi-faceted reflectarray. However, it maintains a good crosspolar discrimination. It is achieved similar results for polarization Y.

Another interesting study is the in-band antenna gain performance. Fig. 7 shows the gain levels of the pattern evaluated in a wider frequency range (24-34 GHz) for each polarization and design. In this case, the results achieved in [15], where a multi-faceted structure consisting of 3 panels is evaluated, are also included. This design has the same cell type, optics, and dimensions as the antennas analyzed in this paper. At frequencies below 28 GHz, multi-faceted configurations have a higher and more stable gain in compared to the single facet design. The same behaviour can be seen for Y-polarization at frequencies above the frequency designed. The 5-panel reflectarray has higher values above 28 GHz than the 3-panel version. The gain values in the multi-faceted structures are rapidly reduced if the frequency increase for X-polarization. This is because of the degradation in the non-sectorized cut (see Fig. 6(c), (d)) and the behaviour of incident field at high frequencies. In terms of crosspolar, the multi-faceted reflectarrays show a higher level in the whole band compared to the flat version but tend to equalize with the flat equivalent as the frequency increases.

TABLE I. BANDWIDTH COMPARISON

Design	**1-dB GAIN BANDWIDTH GHz [%f_0]**	
	Pol. X	***Pol. Y***
5- MFRA	6.0 [21.4]	8.0 [29.0]
3-MFRA	5.7 [20.4]	7.5 [26.8]
Flat RA	4.0 [14.3]	5.0 [17.9]

Table-I lists the antenna bandwidth based on the 1 dB drop of the copolar gain for both polarizations. The 5-panel configuration has better performance in-band in comparison to the single facet reflectarray, with a bandwidth enhancement of 6 and 9 for X- and Y-polarization respectively. This multi-faceted configuration also achieves better bandwidth than the 3 panel reflectarray, although the enhancement in this case is between 1 and 2 percent.



(a) (b)

(c) (d)

Fig. 7. Levels of maximum copolar and crosspolar gain from 24 to 34 GHz for 5 panel (5-MFRA) and 3 panel [15] (3-MFRA) multi-faceted designs and single-facet reflectarray (SFRA). Polarization X (top) and Polarization Y (bottom). In columns the maximum copolar and crosspolar level.

IV. CONCLUSIONS.

A multi-faceted structure composed of 5 panels has been designed in Ka-band. The antenna follows a cylindrical parabolic reflector in offset configuration to overcome part of the spatial phase delay effect and therefore improve the in-band performance of a conventional reflectarray. The multi-faceted design is compared to its flat equivalent and a 3-panel version of identical dimensions and optics. For this purpose, a analysis technique is carried out, which use of a MoM-LP to evaluate the behavior of the radiant element, and PO-optics to estimate the field incident on the surface. The technique is compared to a simulation based on a commercial software obtaining good agreement between both results.

Considering phases required in the multi-faceted reflectarray, the range of phases to be introduced by the element is drastically reduced. A sectorization in both axes means relaxation in the requirements imposed on the cells and, therefore, the possible use of simpler cell topologies. According to the diagram pattern achieved in the sectoring axis, the multi-faceted structure has a better stability in-band than the single facet version, at the cost of slightly increasing the level of crosspolar. The improvement in the performance of the pattern is also translated into the gain achieved, which is restricted to the sectorization in one axis, the offset configuration, and the cell behavior. Comparing both multi-faceted structures, they have similar values of gain for X-polarization. Nevertheless, for the other polarization, the 5 panel reflectarray achieves higher values of gain compared to the 3-panel version at higher frequencies. Therefore, the 5-panel multi-faceted reflectarray has higher bandwidth than the 3-panel version. Though, this bandwidth enhancement is lower than those achieved regarding the single facet version.

This work corroborates the enhanced performance of multi-faceted reflectarrays as well as serving as a preliminary step to the study of more complex structures that significantly improve the in-band performance of conventional printed reflectarrays.

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