Design of an Offset Multi-Faceted Reflectarray Antenna

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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 a significant improvement in band performance compared to its classic single panel version.**

***Index Terms*—reflectarray antenna; multi-faceted configuration; cylindrical parabolic reflector.**

I. Introduction

The interest in reflectarray antennas has grown exponentially in recent years as a solution for many applications. 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 [1].

However, printed reflectarray antennas (RA) usually have narrow bandwidth [2] 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 [1], or more complex elements such as the Phoenix cell [3], among others. For the other limitation, it is possible to improve the performance of the reflectarray, increasing the f/D ratio [1]. 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 that more closely resemble a parabolic surface. These structures also reduce 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 [4] or over the whole parabolic surface [5]. In both cases, it is demonstrated a better performance in-band compared to conventional reflectarray structures.

In this work, we propose the design of a multi-faceted offset reflectarray following a parabolic cylinder in Ka-band, to improve the antenna bandwidth. The designed antenna 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) [6] is used for analyzing the antenna behavior. The design is compared with a flat reflectarray of similar dimensions. A significant improvement in antenna performance is obtained.

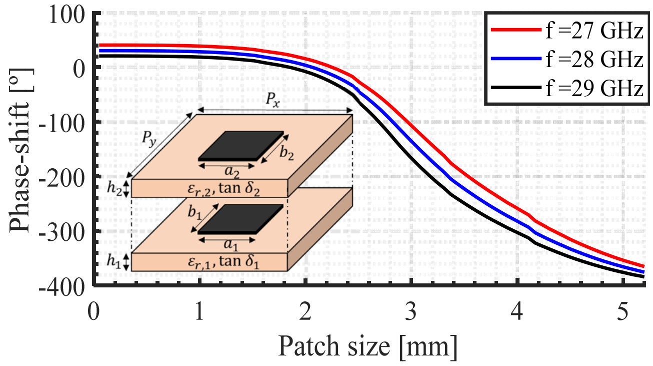


Fig.1. Sketch and phase response of the unit cell as a function of the patch size at different frequencies under normal incidence. The relation between patch sizes $a_2/a_1 = b_2/b_1 = 0.6$.

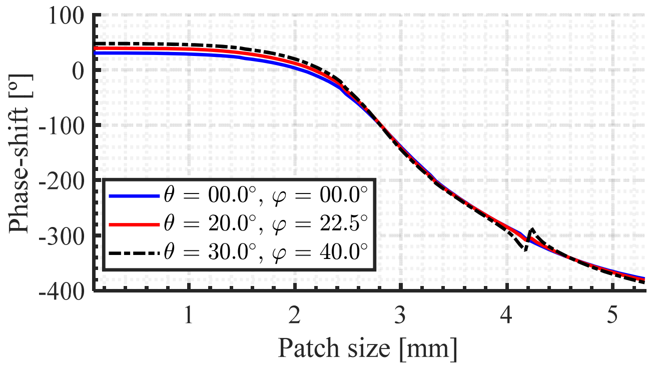
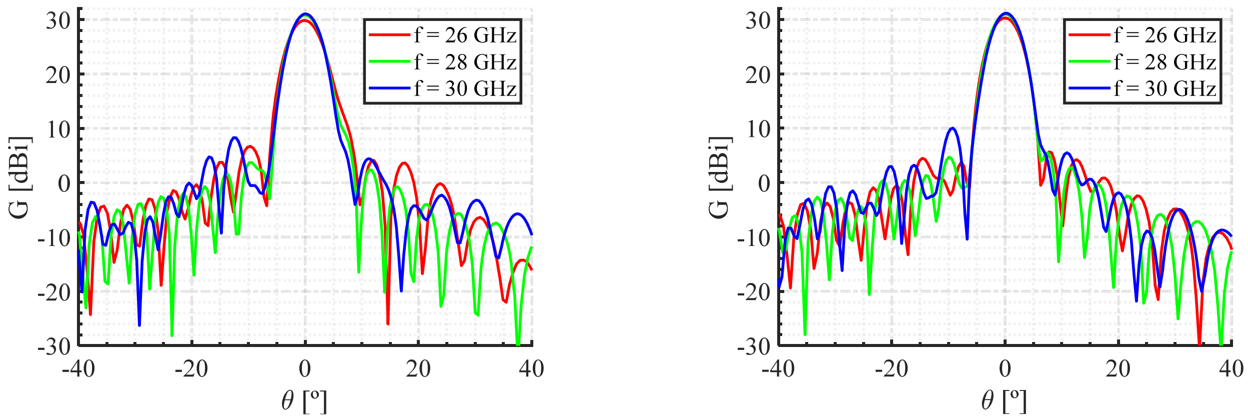


Fig.2. Phase response of the unit cell for different angles of incidence (θ, φ) at 28 GHz.

II. Multi-Faceted Reflectarray Design

A. Unit cell characterization.

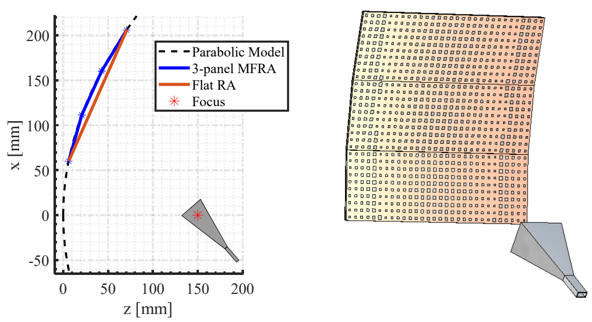
The chosen unit cell consists in two stacked rectangular patches backed by a ground plane, as shown in Fig.1. In both layers, the substrate is DiClad 880 ($\varepsilon_r = 2.26$, $\tan\delta =$



(a) (b)

Fig.3. Gain pattern of reflectarray designs in 4 GHz of bandwidth for polarization Y. Cut ϕ = 0°: (a) Flat reflectarray; (b) Multi-faceted reflectarray.

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. Elements with these angles of incidence corresponds to those near the edge of the reflector. Considering the typical taper in reflectarrays, the distortions in phase response observed will not significantly affect the performance of the antenna.



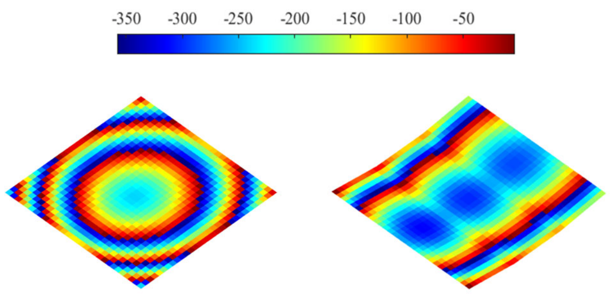
(a) (b)

Fig.4. Geometry of reflectarray designs: (a) XZ plane of multi-faceted and flat reflectarray; (b) 3-D view of multi-faceted reflectarray.

B. Antenna Geometry.

The multi-faceted reflectarray structure is shown in Fig.4. It is formed by 3 identical rectangular panels of 300 elements (10 x 30 in each axes). The vertices of each panel rest on a chordal plane of the equivalent parabolic surface along the XZ plane. The equivalent aperture of the three panels is 159.60 x 160.60 mm ($14.89\lambda_0$/ x $15\lambda_0$). For a meaningful comparison, the equivalent flat reflectarray is formed by 900 elements distributed in a rectangular grid of 30 x 30 with an identical geometry to the multi-faceted configuration.

A Narda 665-20 horn, with a gain of 18.6 dBi, is used as a feed. Its phase center at the 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.4(a). The angle of inclination of the feed is 48.72º respect 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.



(a) (b)

Fig.5. Phase-shift introduced by each cell: (a) Flat reflectarray; (b) Multi-faceted reflectarray.

C. Layout Design Procedure.

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

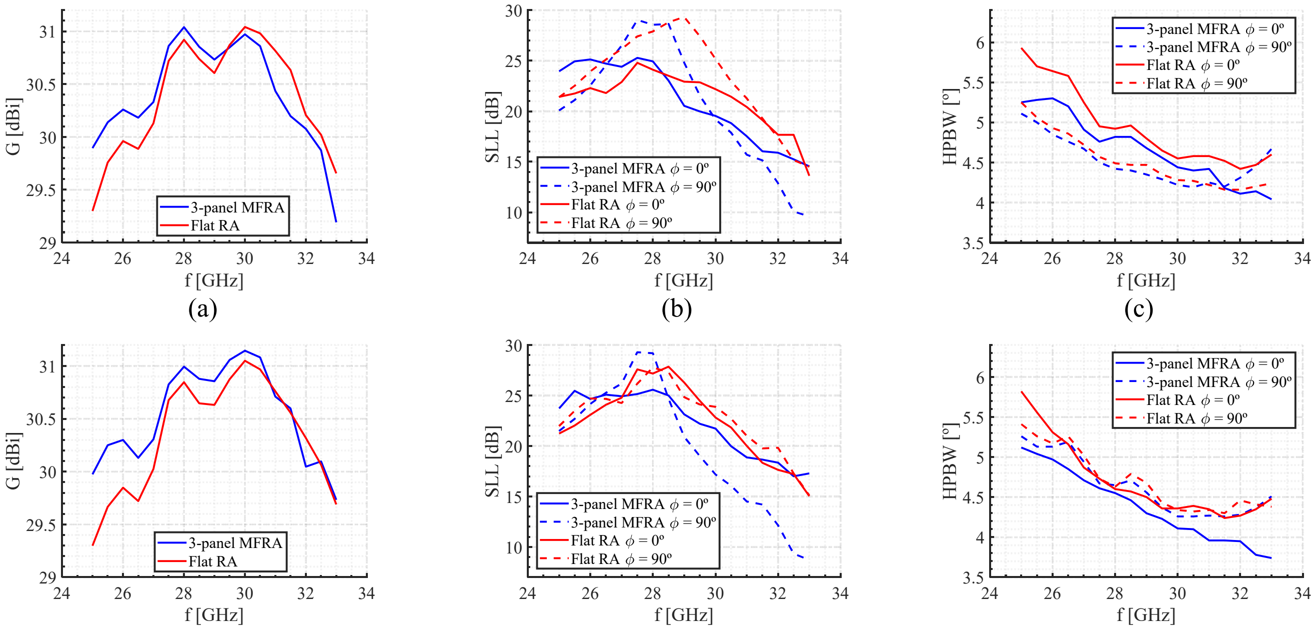


Fig.6. Gain pattern parameters from 25 to 33 GHz for multi-faceted (MFRA) and flat reflectarray designs. Polarization X (top) and Polarization Y (bottom). In columns the main parameter: Gain, Side Lobe Level (SLL) and Half Power Beam Width (HBPW).

$$\phi(x_i, y_i, z_i) = k_0[d_i - (x_i \sin\theta_0 \cos\phi_0 + y_i \sin\theta_0 \sin\phi_0 + z_i \cos\ \theta_0] \quad (1)$$

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.4) as a reference, the phase distribution of both reflectarray designs is calculated to produce a beam in broadside direction ($\theta_0 = \phi_0 = 0$). These phase distributions are translated into patch sizes applying the phase curves obtained in the characterization of the radiant element at 28 GHz, taking into account the real incidence angle in each cell. Using MoM-LP to analyze the layout in each panel and applying PO-methods to obtain the incident field on the reflectarray surface, the reflected field is obtained. From this field the radiation pattern is obtained following [7].

I. RESULTS

Fig.5 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. Being more similar to a parabola, the multi-faceted structure has a smooth phase-shift in the cells along the sectorization axis. However, this is not the case for other axis, where a phase-shift of 360º appears. A sectorization in both axes would allow the use of simpler cell structures without a significant degradation of their performance.

The results of the gain pattern for a bandwidth of 4 GHz are shown in Fig.3. In cut $\phi = 0°$, where sectoring is applied, the multi-faceted design has a more stable behavior in-band compared to the flat reflectarray. In cut $\phi = 90°$, the evolution in-band for both designs are different. Similar behavior occurs for polarization X.

Fig.6 shows the characteristic parameters of the pattern evaluated in a wider frequency range (25 – 33 GHz) for each polarization. As expected, the multi-faceted configuration has a more stable gain than flat design in the frequency range under study, with a less pronounced slope at low frequencies. The multi-faceted reflectarray produces a more directive beam in the sectorization axis, although at frequencies above 28 GHz, it decreases the Side Lobe Level (SLL) faster than the equivalent flat. This is due to the illumination on the reflectarray surface which is affected by one side lobe of the feed that reduces the taper specially in the multi-faceted design. This effect produces greater degradation in X polarization when the side lobe follows the asymmetric cut.

TABLE I. BANDWIDTH COMPARISON

Design	1-dB GAIN BANDWIDTH GHz [%f_0]	
	Pol. X	***Pol. Y***
Multi-faceted RA	6.90 [24.6]	6.70 GHz [23.9]
Flat RA	5.60 [20.0]	5.60 GHz [20.0]

Table-I lists the bandwidth performance of the designs considering the behavior of the gain in-band for both polarizations. Despite the effect of the feed, multi-faceted reflectarray increases the bandwidth by approximately 1 GHz compared to the flat design, which is approximately a 4% of the working frequency.

II. 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 similar 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. However, this improvement 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 work demonstrates the improvement in the antenna performance of multi-faceted offset structures regarding conventional flat reflectarrays.

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