Design and experimental validation of Convex Conformal Reflectarray Antennas

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In this work the design, the numerical analysis and the experimental characterization of a Convex conformal Reflectarray (CRA) has been carried out, with the aim of investigating the feasibility of reflectarrays bent on convex curved surfaces. A medium-size offset CRA in Ka-band has been designed, and a demonstrator has been manufactured and measured. The results prove the correctness of the design procedure and the feasibility of this type of antenna, pointing out the differences, also in terms of radiation performances, with respect to a planar reflectarray.

Introduction: Since their introduction in early '90s [1], printed Reflectarrays (RAs) have been investigated by many research groups around the world. In view of their good electrical and mechanical characteristics, RAs seem in fact good candidates for a wide range of applications, where not only high radiation performances are required, but also reduced weight and low profile. The possibility to be easily folded and deployed is also a key aspect [2], [3].

RAs with re-radiating elements printed on multi-facet panels or on non-planar concave structures have already been considered [4], [5] with the main aim of increasing the bandwidth, one of the most critical features of this type of antennas. More recently, RAs printed on multi-facet composite panels or on a doubly curved (parabolic) surface have been proposed as a possible low-cost, low-weight solution for contoured beam antennas for space applications, in alternative to shaped reflectors [6]-[9].

In both cases (multi-facet or parabolic-shape panels) the RA's surface is concave and this contributes to improve its radiating features because not far from the standard parabolic surface. However, there are other applications, as the case of the antennas mounted on the fuselage of an aircraft, where the use of a convex RA (CRA in the following) represents a good alternative to other configurations, since it allows an easy placement of both feed and reflecting surface, a good integration and camouflage on the structure where they are located, including the possibility of beam scanning.

In view of its potential applications, in recent years the effects of the curvature on the design procedure and on the performances of convex reflectarrays have been examined, considering several offset configurations, with the reflector bent to fit cylinders with different radii of curvature [10]-[13]. As a proof of the concepts introduced in [11], [12], in this letter the results relative to the design, numerical analysis and experimental characterization of a medium-sized offset CRA are presented.

CRA design: A single-curvature printed CRA consists in a reflectarray where the re-radiating elements (in the case at hand, square patches) are printed on a substrate bent to a cylinder with a given radius of curvature. With reference to Fig. 1 if the feed is offset, its axis can be located in a plane perpendicular to the cylinder axis, and therefore the direction of maximum re-radiation is in the same plane (although, with an appropriate choice fo the phase distribution, the maximum direction could be anywhere). This configuration, having the plane of incidence in the same direction of the maximum curvature of the surface, is more complex since the effects of the curvature are stronger than in other previously considered solutions [10].

As already pointed out in [11], [12], the effect of the curvature has to be taken into account both in the analysis of the CRA unit cell and in the design of the entire antenna. For what concerns the first aspect, the computation of the phase variation of the field re-radiated by the unit cell with given geometrical parameters (here only the square patch side) cannot be carried out through the full-wave analysis of a periodic structure, but it is instead necessary to consider a proper finite-size array.

As regards the design and the performances of the whole CRA, the following three differences with respect to the planar case have to be taken into consideration: the reflector is no longer a (quasi) 2D structure, and therefore, referring to the coordinate system introduced in Fig. 1, the phase of the field re-radiated by each element depends also on z, i.e.

$$\phi_R(P_i) = k_0(d_i - x_i\cos\varphi_{max}\sin\theta_{max} - y_i\sin\varphi_{max}\sin\theta_{max} - z_i\cos\theta_{max}) \quad (1)$$

where $P_i \equiv (x_i, y_i, z_i)$ are the coordinates of the i^{th} element, d_i is its distance from the phase center of the feed and $(\theta_{max}, \phi_{max})$, is the beam maximum direction of the entire CRA; the direction of maximum radiation of the patches vary from one to another; the path difference between the feed and the elements located in the perimeter of the reflector increases with respect to the planar case.

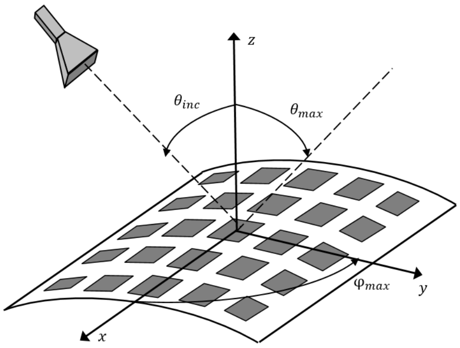

Fig. 1 *Sketch of an off-set convex reflectarray, with square re-radiating elements.*

With these considerations in mind, an offset convex reflectarray has been designed, simulated and then manufactured. The CRA has been printed on a single layer 0.8 mm thick of Diclad 527, characterized by $\epsilon_r = 2.55$ and $\tan\delta = 0.0022$, and it has a size of 193.5×193.5 mm, i.e. it is slightly larger than $19\lambda\times19\lambda$ at the working frequency $f_0 = 30$ GHz. At this frequency, the unit cell is slightly smaller than $\lambda/2$, since its size is 4.5 mm, and the radius of curvature of the cylinder where the CRA is mounted is $R = 20\lambda$. The offset feed is a standard rectangular horn with a maximum gain of 15.6 dBi, an HPBW of 24°; the distance between the horn phase center and the central point of the CRA is again 193.5 mm; the feed polarization is linear TM: the E-field is in the yz plane, which is therefore the E-plane for the entire antenna. In that plane, the direction of maximum radiation of the horn forms an angle $\theta_{inc} = 25°$ with respect to the normal to the CRA in the central point (see Fig. 1).

The dependence of the re-radiated field phase on the square patch side w is computed varying w in the range [0.5,4] mm: the obtained phase curves show a linear variation of the phase in a range of about 280°, which is generally sufficient, although with some error, to compensate the phase delay introduced by the different distances of the re-radiating elements from the feed. The phase distribution on the CRA surface necessary to have a direction of maximum radiation specular to that of incidence (i.e. $\theta_{max} = \theta_{inc}$ in Fig. 1), is shown in Fig. 2. In Fig.3 a photograph of the demonstrator is shown.

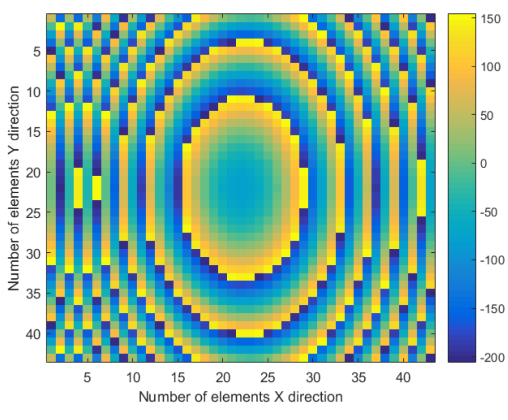

Fig. 2 *Color map of the required phase distribution of the offset Conformal Reflectarray.*

Numerical and experimental Results: A numerical analysis of the whole reflectarray has also been carried out, using CST Microwave Studio. The measured and computed radiation patterns of the CRA in the E- and H-plane at the frequency f_0 are plotted in Fig. 4.

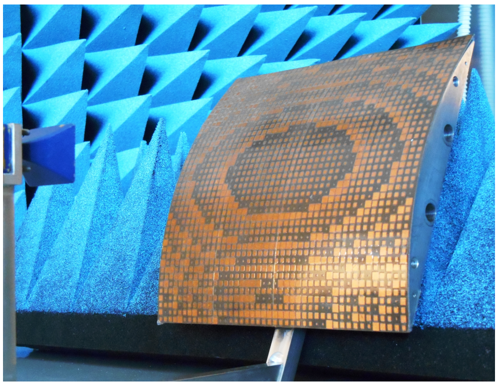

Fig. 3 *Photograph of the manufactured offset Conformal Reflectarray demonstrator.*

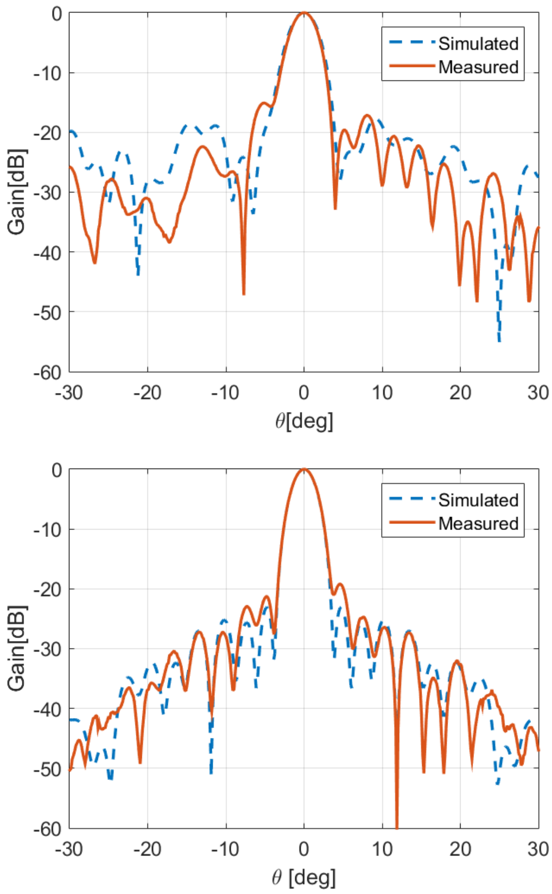

Fig. 4 *Computed and measured radiation patterns in the E-plane (top) and H-plane (bottom) at* 30 *GHz.*

As it can be seen, there is a good agreement between the numerical and experimental results, especially in the H-plane. The slightl misalignment in the E-plane is due to the fact that in the simulations some parts of the structure, as the feed boom, are not taken into account. The side lobe levels are quite low: in the vertical plane they are a little bit higher because of the effect of the curvature, sharpened by the offset position of the feed.

In Table 1, the measured values in the two principal planes of the main parameters characterizing the CRA radiation are reported for three different frequencies. The gain at the central frequency is 29.7 dB, while at the other two frequencies it has nonsymmetric lower values, that continue to decrease for frequencies out of the considered interval, resulting in a 1-dB bandwidth of approximately 7 %, that is lower than the bandwidth of a planar RA with the same size. We must however observe that, in addition to the curvature effects already mentioned in the previous section, the equivalent aperture of the RA, and therefore its gain are also reduced. Note that the relatively low gain is also due to the non optimized horn high spillover. In both planes the HPBW does not change significantly with the frequency, as well as the side lobe level (SLL) in the H-plane. Vice versa, in the E-plane, where the effect of curvature adds to that of the offset feed position, moving from 30 to 29.2 GHz causes a remarkable increase of the SLL, that passes from -15.1 to -9.6 dB.

Table 1: Measured performances of the CRA in the E and H-planes for different frequencies

f [GHz]	Gain [dB]	HPBW [°] E-Plane	HPBW [°] H-Plane	SLL [dB] E-Plane	SLL [dB] H-Plane
29.2	29	3.63	3.15	-9.6	-17.4
30	29.7	3.34	3.06	-15.1	-19.19
30.8	29.2	3.36	2.98	-14.9	-19.6

Conclusions and further developments: In this letter the design, numerical analysis and experimental characterization of a new type of Convex Reflectarray are proposed. While the obtained results prove the feasibility of such a type of antenna, they also highlight how the effect of the curvature downgrades somewhat its performances with respect to the planar case. A possible solution for their enhancement would be that of using more complex reradiating elements, as for instance those introduced in [14], characterized by more degrees of freedom, that could be adopted to improve the CRA radiation characteristics.

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