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***Abstract*—In this paper, some numerical results on the possibility to design a 3D-printable dielectric ReflectArray (RA) antenna that can be conformed to a cylindrical surface are presented. The reflectarray is designed to be manufactured using a dielectric material characterized by a high relative dielectric constant: this choice drastically decreases the RA thickness, favouring its flexibility and therefore its possibility to be bent to a curved surface. Results on the numerical analysis of medium-size RAs conformal to cylinder with different radius show that the decrease of the antennas performance is kept down over a wide range of variation for the curvature radius, confirming their feasibility and their potentialities.**

***Index Terms*—reflectarray antennas; conformal antennas; 3D-printed antennas; additive manufacturing.**

I. Introduction

In the recent years, ReflectArrays (RAs) [1], [2] have increased their popularity, since they represent an efficient alternative to other configurations, as reflectors and arrays, for the realization of high gain antennas. In view of this, a lot of effort has been put into the improving of their characteristics, to make RAs suitable for many different applications requiring wide bandwidth, good efficiency, multi-beams or beam-scanning capabilities, and many solutions have been proposed for the design and realization of reflectarrays with enhanced features. Examples of this are the introduction of printed re-radiating elements with more degrees of freedom, printed on different layers, as in [3], [4] or on the same dielectric substrate [5]- [9] to enlarge the bandwidth, or the introduction of active elements as varactors [10], pin diodes [11], MEMS switches [12] or either the use of liquid crystals for the unit-cell realization [13] in order to achieve beam scanning, multi-beams or reconfigurability capabilities [14].

Also pushed by the spreading of the use of Additive Manufacturing (AM) techniques for the realization of objects with non conventional shape, recently new, dielectric-only RA configurations have been investigated. The reflectarrays in [15]- [17] have been designed using dielectric parallelepiped resonators as unit-cells: in [15], [16] the phase of the re-radiated field is controlled through the height of the resonators, while in [17] the dielectric parallelepipeds have a variable transverse section; in all the cases, reduced size RAs have been manufactured using 3D printing techniques. In [18] a C-shaped dielectric unit-cell with height approximately equal to 1.5λ at the design frequency of 28 GHz is adopted for the design of a center fed RA with diameter of 10λ, that can radiate a linear or a circular polarization, while in [19] a unit-cell consisting in a parallelepiped with a central square hole, whose size is used to control the amplitude and phase of the reflection coefficient, is used to design a medium size RA. Finally, in [20], [21] cross shape elements are introduced to realize dual or circular polarization whose performance have been tested through the manufacturing of small size prototypes.

Even if in many applications the flatness of the reflecting surface is an advantage with respect to the bulkier structure of a conventional reflector, in some other cases it would be preferable if the reflectarray could be conformed to the surface on which it has to be mounted, to reduce its visual impact or to increase its integration on the supporting framework. For this reason, the feasibility and the performance of conformal reflectarrays have been recently investigated. In [22], [23] the radiation features of reflectarrays bent to convex or concave cylindrical surfaces with different radius of curvature R_c are compared: as expected, for some values of R_c concave RAs outperform planar configurations, while in the convex case the performance always decreases with the increasing of the curvature, i.e. with the decreasing of R_c. Since this second type of configuration seems to be the most interesting from an application point of view, the researchers' activity is mainly focused on convex RAs, even if in [24] results on a prototype conformal to a parabolic cylinder are summarized. In [25], [26] results on the numerical and experimental analysis of a medium-large reflectarray, realized with square patches printed on a single layer dielectric substrate and conformal to a cylinder with radius $R_c = 20\lambda$ are presented. The use of PCB techniques for the manufacturing of a conformal reflectarray could be not the optimal choice, since its bending to the curved supporting surface can be not very simple. For this reason, other solutions have been recently considered, as the employment of direct-write process for directly printing the re-radiating elements or for creating metasurfaces on flexible layers that can be easily adapted to the surpporting structure, as proposed in [27], or the use of a flexible reflecting element that can be reconfigured thanks to the encapsulation of liquid metal in polydimethylsiloxane (PDMS) [28].

Here, a different solution is presented, in which the reflectarray is completely dielectric, apart from the back plane. Using a dielectric material with a sufficiently high relative dielectric constant it is possible to strongly reduce the thickness of the unit-cell [29] and this results in a RA sufficiently flexible to be adapted easily to curved surfaces. Moreover, the features of the proposed unit-cell guarantee good reflectarray performance, and its reduced degradation with the increasing of the RA curvature.

II. Dielectric Unit-Cell

The unit-cell was already introduced in [29], but for sake of clarity its description is summarized in the following. As shown in Fig. 1, it consists in a dielectric cylindrical resonator, located on a thin square slab, that can be placed on a metallic ground plane. The phase and amplitude of the reflection coefficient S_{11} are controlled varying the diameter d of the cylinder, while its height H_c is kept constant; as discussed in the following, the size L of the unit-cell H_c and the thickness H_b of the basis are selected to optimize the range of variation for the phase of S_{11}.

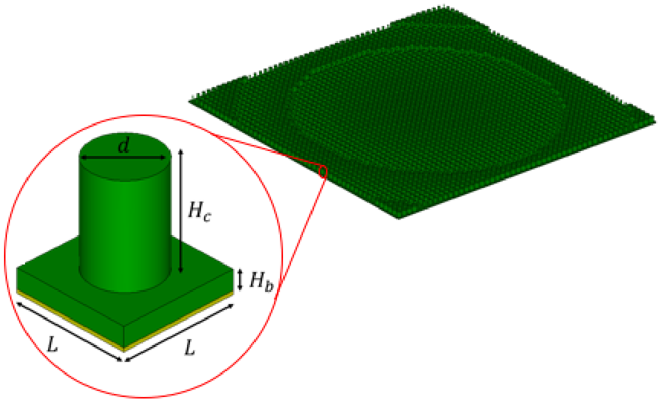

Fig. 1: Sketch of the dielectric RA structure and blow out of the unit-cell.

To make the unit-cell printable with an AM technique, and in particular with the Fused Deposition Modeling (FDM) process a suitable dielectric material must be used and its geometrical parameters must be optimized to maximize its performance but also to satisfy the constraints dictated by the tolerances of the manufacturing procedure, as discussed in [30]. Moreover, to reduce the unit-cell thickness, with the aim to increase the reflectarray flexibility, it is convenient to use a material with a high relative dielectric constant. Among those available for FDM-based 3D printers the PREPERM® ABS1000 has been chosen, since it is characterized by a nominal relative dielectric constant of $\varepsilon_r = 10$ and $\tan\delta = 0.004$. The unit-cell has been designed in Ka-band at the operating frequency $f_0 = 30\,\text{GHz}$ and its optimization, carried on a frequency interval around f_0, is aimed to find the best values of its geometric parameters that maximize the RA performance still taking into account the tolerances of the 3D printing process. In view of this, first the size of the unit-cell is fixed to a value $L = 0.3\lambda_0 = 3\,\text{mm}$, then the interval of variation for d is selected. While in [29] it was taken equal to $[0.4 - 2.8]\,\text{mm}$ to obtain a phase range of approximately $360°$, the constraints imposed by the manufacturing process force to chose cylinders with a larger diameter to avoid that they become too thin and breakable and therefore the lower bound is moved to $d_{min} = 1\,\text{mm}$, accepting to slightly reduce the phase range. To partially compensate the effects of the reduction of the interval of variation for d, the total thickness of the unit-cell is taken equal to $H_T = H_c + H_b = 0.31\lambda_0$.

III. Convex Conformal Reflectarrays

The unit-cell adopted above is adopted for the design of squared reflectarrays with side $D = 15.3\lambda_0$, discretized with 2601 re-radiating elements and bent to cylindrical surfaces with different radius of curvature. In all the considered cases, the feed is the horn introduced in [26], located at a distance from the RA equal to $1.1D$ and in offset position, so that the field impinges on the reflective surface with an angle $\theta_f = -20°$ (see Fig. 3). The phase distribution for the reflectarrays conformal to cylinders with radius of curvature equal to $R_C = 15\lambda_0$ and $R_C = 40\lambda_0$ are shown respectively on the top and the bottom of Fig. 2, while in Fig. 3 a 3D view of the configuration with $R_C = 20\lambda_0$ is displayed.

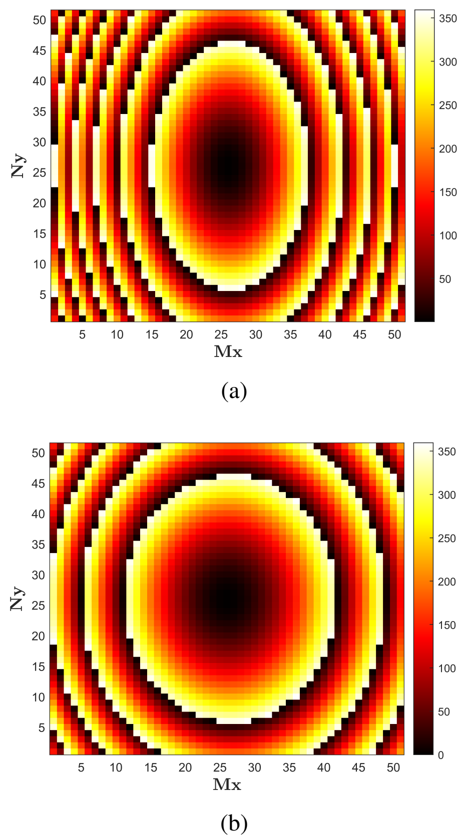

Fig. 2: Phase distribution on the RA surface for the cases in which it is bent to a cylinder with radius of curvature (a) $R_C = 15\lambda_0$ and (b) $R_C = 40\lambda_0$.

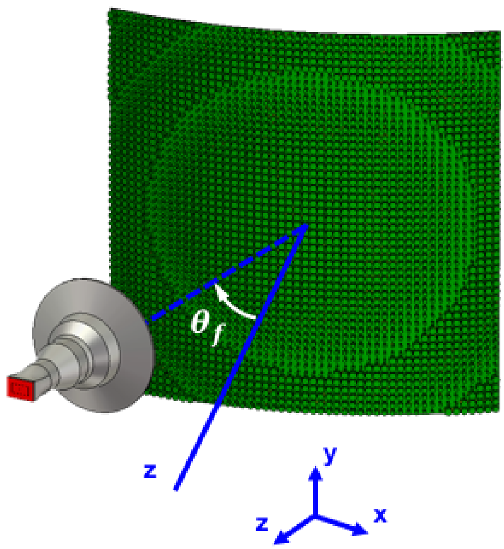

Fig. 3: 3D view of the RA conformal to a cylinder with radius of curvature $R_C = 20\lambda_0$.

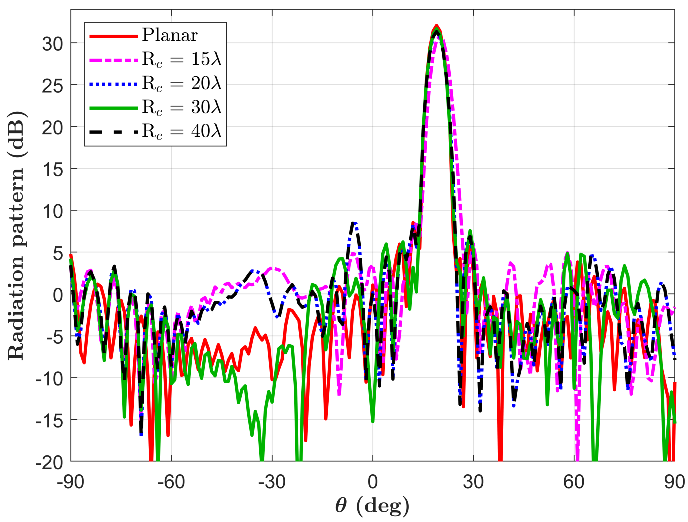

Fig. 4: Radiation patterns of the designed reflectarray for different values of the cylinder radius of curvature R_C in the E-plane.

The reflectarray has been numerically analyzed with CST MW Studio: the resulting radiation patterns at 30 GHz in the E- end H- planes are shown respectively in Figs.4, 5 for different values of R_C. As it appears from these plots, in both the planes the radiation patterns are slightly affected by the curvature over the considered range of variation for R_C; when R_C is equal to $20\lambda_0$, $30\lambda_0$ and $40\lambda_0$ they almost overlapped those obtained in the planar case, also plotted. When $R_C = 15\lambda_0$ the maximum gain slightly decreases, as also proved by the plot in Fig. 6, showing the variation of the maximum directivity as a function of R_C and by the results summarized in the first row of Table I: from the values of the gain reported in the Table, it appears that its reduction is lower than 1 dB when the radius of curvature changes from $15\lambda_0$ to $40\lambda_0$ while the discrepancy with the planar case is just a little bit larger. From Fig. 4 it also emerges that in the E-plane, which is the most affected by the curvature, there is also a misalignment of approximately 1° of the main beam pointing direction.

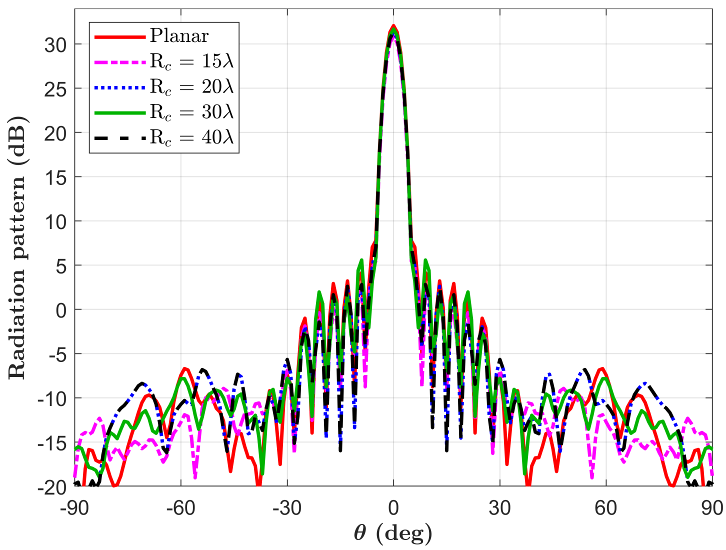

Fig. 5: Radiation patterns of the designed reflectarray for different values of the cylinder radius of curvature R_C in the H-plane.

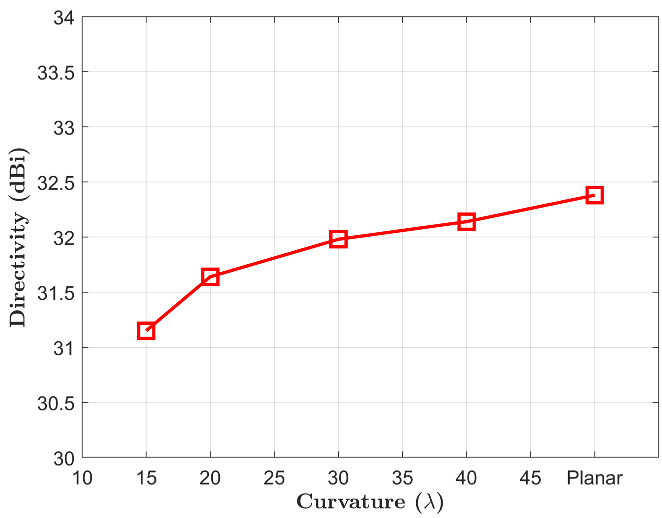

Fig. 6: Variation of the directivity evaluated at 30 GHz with the radius of curvature R_C.

A summary of the radiation performance of the reflectarrays designed considered different values of the radius of curvature is finally reported in Table I. The results in rows 1, 4-7 are directly related to the radiation patterns in Figs. 4, 5 and confirm the comments already done for those plots.The aperture efficiency evaluated at f_0 is listed in the second row of the Table: even if the increasing of the curvature actually decreases the effective area illuminated by the field radiated by the feed, the aperture efficiency keeps in all the considered cases a high value, since it is always larger than 40%. Another interesting result is that summarized in the following row, relative to the 1-dB bandwidth: in fact, as demonstrated in [31] the bandwidth of a reflectarry is affected by the curvature of the surface to which it is conformed, but the wide band behaviour of the adopted unit-cell allows to obtain a limited reduction also for $R_C = 15\lambda_0$.

TABLE I: Performance of RAs conformal to cylindrical surfaces with different radii of curvature.

R_C	$15\lambda_0$	$20\lambda_0$	$30\lambda_0$	$40\lambda_0$
max gain	30.9 dBi	31.3 dBi	31.7 dBi	31.8 dBi
aperture efficiency	41.3%	46.2 %	50%	51.8 %
1-dB bandwidth	9.6 %	10.6 %	11.5 %	11.7%
$HPBW_E$	4.5°	4.3°	4.2°	4.2°
$HPBW_H$	4°	4°	4°	4°
SLL (E-plane)	-22.4 dB	-22.9 dB	-24.1 dB	-24.2 dB
SLL (H-plane)	-26.1 dB	-28.5 dB	-26.1 dB	-26 dB

IV. Conclusions

In this paper, a dielectric unit-cell is used to design reflectarrays bent to cylindrical surfaces. The use of a 3D printable material with a high value relative dielectric constant and the optimization of the unit-cell geometrical parameters result in a thin and flexible structure, suitable for the manufacturing of conformal RAs. Moreover, its broadband attitude guarantees that the radiation performance of the RA stays stable over a wide range of variation for the radius of curvature.

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