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DESIGN, FABRICATION AND CHARACTERIZATION OF A DIELECTRIC RESONATOR ANTENNA REFLECTARRAY IN KA-BAND

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Abstract—A new reflectarray configuration is proposed for low-loss applications at millimeter waves. It is based on the use of dielectric resonator antennas (DRA) as radiating unit-cells. The phase response of the elementary cell is controlled by adjusting the length of a parasitic narrow metal strip printed on the top of each DRA. A 330° phase dynamic range is obtained for DRAs made in rigid thermosetting plastic ($\varepsilon_r = 10$). As the antenna radiating aperture is non flat, an original low-cost fabrication process is also introduced in order to fabricate the parasitic strips on the DRA surface. A 24 × 24-element array radiating at broadside has been designed at 30 GHz and characterized between 29 and 31 GHz. The antenna gain reaches 28.3 dBi at 31 GHz, and the measured −1 dB-gain radiation bandwidth is 5.2%. The 3.2 dB loss observed between the measured gain and theoretical directivity is mainly due to the spillover loss (2.3 dB). The total dielectric and conductor loss is less than 0.9 dB.

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1. INTRODUCTION

A reflectarray antenna combines some of the best features of phased array antennas and reflector antennas [1–3]. It usually consists of a planar array of unit-cells illuminated by a horn-like primary feed. The power captured by each unit-cell is then re-radiated with a given phase. By varying the geometrical or electrical parameters of each cell, the required phase delay can be obtained for tilting or scanning the beam in a given direction. Many advanced prototypes with contoured beam coverage [4], multiple shaped beam radiation patterns [5], broadband operation [6–9], reconfigurable capabilities [10–13], and low profile [14, 15] have been proposed over the last decade [16].

In particular, many different configurations have been investigated so far in single or multilayer microstrip technology since this leads to low-cost and simple manufacturing processes. Nevertheless, at millimeter waves, the conductor loss become serious and the antenna efficiency may be reduced significantly due to ohmic and surface wave loss.

To overcome this potential constraint, dielectric resonator antennas (DRAs) have been proposed due to their interesting features such as low losses, broad bandwidth, small mutual coupling and higher radiation efficiency compared to microstrip antenna [17, 18]. In addition, the beamwidth of DRAs is usually larger than patches, which makes them more suitable for scanning arrays. To our best knowledge, the only prototype of DRA-based reflectarray found in the literature has been implemented in Ka-Band [19]. It has also been used as a benchmark test-case to validate full-wave analysis of DRA reflectarray in [20]. In that design, the required phase delay was achieved by varying the DRA length itself. As a consequence, the corresponding reflectarray was made of DRAs with different sizes, leading to a rather complex fabrication process.

We have proposed recently an alternative solution using a strip-loaded DRA unit-cell [21, 22]. The main idea is to tune the phase of the reflected field by varying the length of the narrow metal strip printed on the top of each dielectric resonator, instead of changing the DRA dimensions. This concept has been validated experimentally using waveguide simulators for unit-cells in C-band [21, 22] and the numerical design of the overall reflectarray has been studied in part in [21–23]. Here, we investigate the capabilities of this new strip-loaded DRA unit-cell with the introduction of a residual substrate layer for the ease of monolithic fabrication. A whole reflectarray is then designed and characterized in Ka-band (Figure 1).

This paper is organized as follows. First, the geometry and

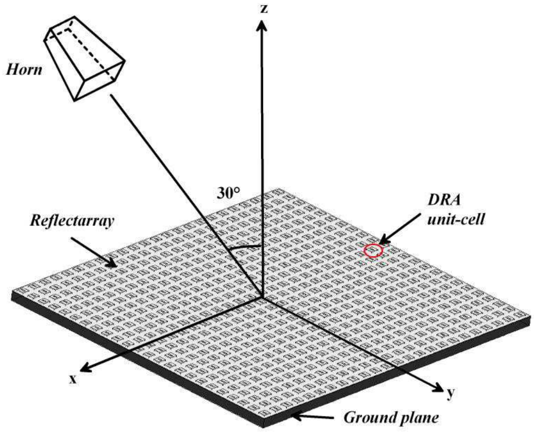


Figure 1. Proposed DRA reflectarray. The reflectarray is illuminated by an offset linearly-polarized pyramidal horn antenna in E plane. The unit-cell is a strip-loaded DRA (Figure 2). The reflectarray has been designed so that it radiates at broadside.

performance of the proposed unit-cell are described in Section 2 at 30 GHz. Then, sensitivity tests are carried out, and an original manufacturing process allowing the fabrication of metal strips on a corrugated surface is introduced in Section 3. The radiation characteristics of the proposed reflectarray are discussed in Section 4. Finally conclusions are drawn in Section 5.

2. DRA UNIT-CELL

The proposed DRA unit-cell is represented in Figure 2. It consists of a square DRA mounted on a metal ground plane. A metal strip ($W_{strip} \times L_{strip}$) made of silver thin film ($t = 1.1\,\mu\text{m}$, $\sigma_{Ag} = 6.3 \times 10^7\,\text{S/m}$) is printed on the DRA top surface: its serves as a tuning element to control the phase of the reflection coefficient S_{11}. As we only consider here linear polarization, the strip is parallel to the incident electric field E^{inc}; its length is adjusted to control the resonant frequency of the fundamental TE_{x111} mode and consequently the reflected phase at the operating frequency. Therefore, all DRA unit-cells have the same dimensions, which simplify substantially the fabrication process. In addition, a thin residual dielectric layer of thickness H_{sub} is kept under the DRA (Figure 3). Consequently all elements are fabricated simultaneously from a single block of dielectric material using a standard milling machine, resulting thereby in a

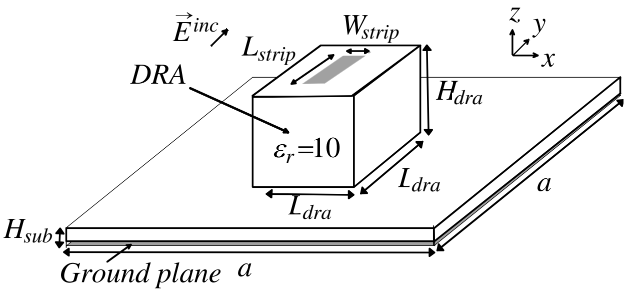


Figure 2. 3-D view of the proposed unit-cell ($a = 5$ mm, $H_{dra} = 0.6$ mm, $L_{dra} = 2.7$ mm, $W_{strip} = 0.3$ mm, $H_{sub} = 0.2$ mm. L_{strip} varies from 0.7 to 2.1 mm).

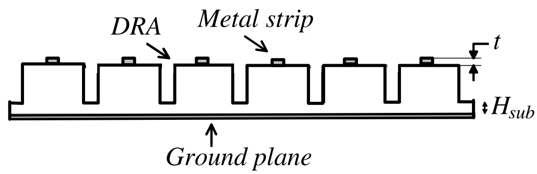


Figure 3. Use of a thin residual layer (of thickness H_{sub}) below the DRA for monolithic fabrication.

monolithic reflectarray. The dielectric material used in this work is a rigid thermosetting plastic from Emerson & Cuming (HiK$^{\text{TM}}$, $\varepsilon_r = 10$, $\tan\delta = 2 \times 10^{-3}$). The thickness of the residual layer has been optimized ($H_{sub} = 0.2$ mm) to guarantee the mechanical robustness of the structure without disturbing the operating mode of the DRA.

The electromagnetic simulations of the unit-cell have been performed using HFSS$^{\text{TM}}$ software, assuming an infinite periodic array with an impinging plane wave under normal incidence. The unit-cell is a square of edge $a = 5$ mm (i.e., half a wavelength in free space at the center frequency 30 GHz). The DRA has a square base ($L_{dra} = 2.7$ mm) and its height equals $H_{dra} = 0.6$ mm. The reflection coefficient in phase and magnitude is represented in Figure 4 versus the strip length L_{strip} (0.7 mm $< L_{strip} <$ 2.1 mm) at three frequencies (29, 30 and 31 GHz). The corresponding phase range reaches 330°, which is suitable for many applications and compatible with standard quantification errors. The total dielectric and conductor loss is less than 0.6 dB at all frequencies.

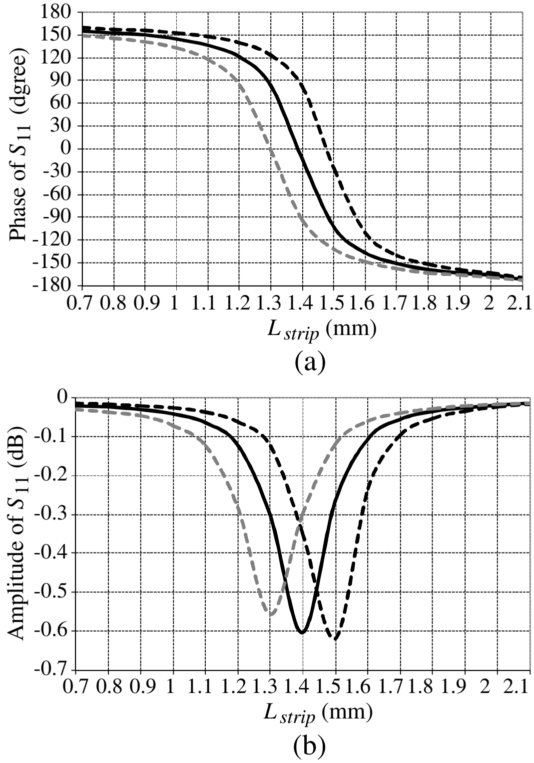


Figure 4. Characteristics of the strip-loaded DRA unit-cell at different frequencies under normal incidence (simulation results). (a) Phase of S_{11}. (b) Amplitude of S_{11}. Black dashed line: $f = 29\,\text{GHz}$. Black solid line: $f = 30\,\text{GHz}$. Grey dashed line: $f = 31\,\text{GHz}$.

3. DRA REFLECTARRAY: DESIGN AND MONOLITHIC FABRICATION

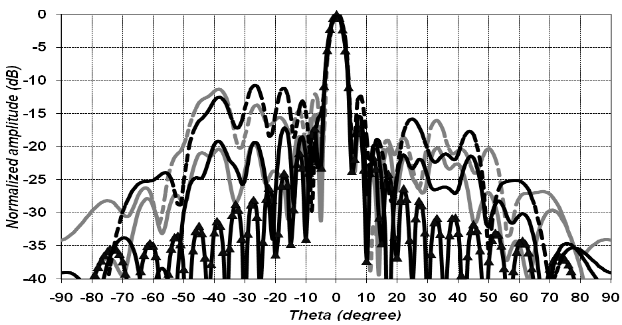
3.1. Proposed Reflectarray

A 24×24 element prototype has been designed at a single frequency (30 GHz) to radiate at broadside (z-axis in Figure 1). It is illuminated by a reduced size light-weight horn antenna fabricated by electrical discharge machining. The horn is located in the E-plane of the reflectarray (yOz plane in Figure 1) with a 30° offset from the normal to the radiating surface; its radiating aperture equals $24 \times 10\,\text{mm}^2$. The F/D ratio is set to 0.8 ($F = 96\,\text{mm}$, $D = 120\,\text{mm}$); this choice provides a satisfactory trade-off between feed blockage, spillover loss and aperture efficiency as explained in [24]. Under these conditions, the edge taper illumination at 30 GHz varies between 6 dB and 5.5 dB in E-plane, and equals 13 dB in H-plane (xOz plane).

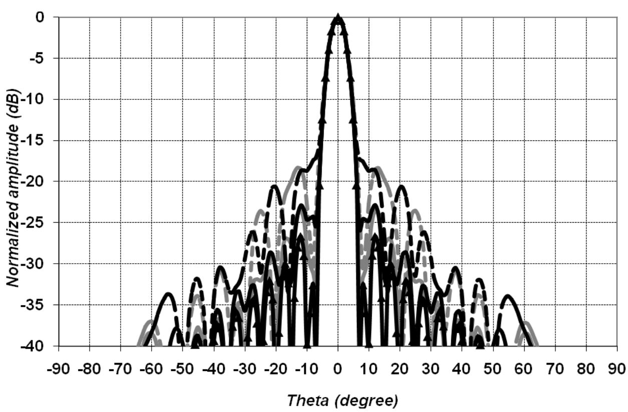
The suitable strip lengths of the unit-cells at 30 GHz are determined according to Figure 4(a) so as to provide a nearly-uniform phase distribution over the radiating aperture plane.

3.2. Sensitivity Study

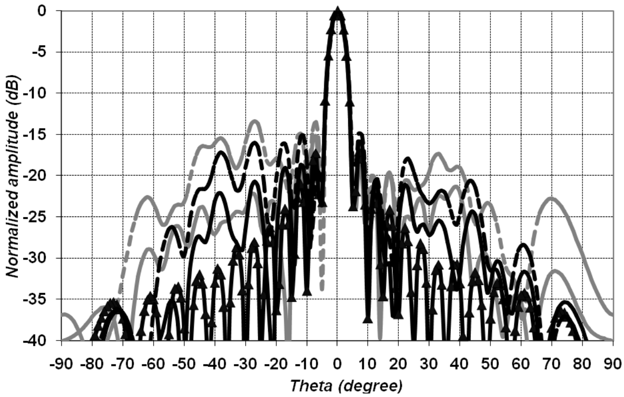
At millimeter waves the manufacturing tolerances are critical. They must be assessed and controlled accurately to minimize possible distortions in the radiation performance. A systematic sensitivity analysis has been carried out for all geometrical parameters defining the unit-cell. It appears that the strip length (L_{strip}) and DRA height (H_{dra}) are among the most critical parameter to be controlled during fabrication. As an illustration, the impact of L_{strip} deviations on the reflectarray co-polarization components is analyzed first in Figure 5(a)



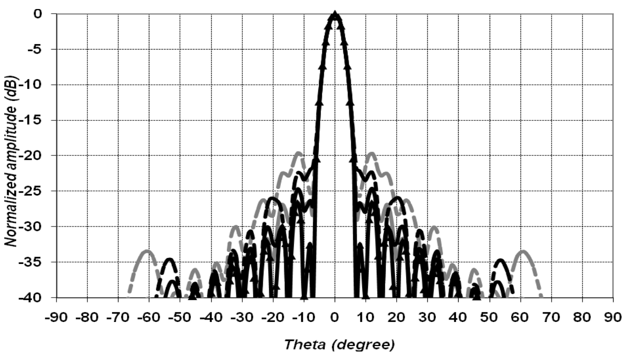
(a (i))



(a (ii))



(b (i))



(b (ii))

Figure 5. Impact of systematic deviations: (a) (ΔL_{strip}) on L_{strip} and (b) (ΔH_{dra}) on H_{dra} values upon the co-polarization components at 30 GHz. Grey dashed line: ΔL_{strip}, $\Delta H_{dra} = -0.2$ mm. Grey line: ΔL_{strip}, $\Delta H_{dra} = -0.1$ mm. Black dashed line: ΔL_{strip}, $\Delta H_{dra} = +0.2$ mm. Black line: ΔL_{strip}, $\Delta H_{dra} = +0.1$ mm. Black line with triangles: nominal value of L_{strip} and H_{dra}. (i) E-plane, (ii) H-plane.

in E- and H-planes. This study is done for an extreme situation where all strip lengths exhibit simultaneously the same error ΔL_{strip}. The radiation patterns are computed using the standard array theory by taking into account the frequency response (Figure 4) of each unit-cell. This figure shows that the side lobe level (SLL) rapidly increases when L_{strip} is different from its nominal value. To keep SLL lower than -15 dB, L_{strip} deviations should be less than ± 0.1 mm; according to Figure 4(a), this corresponds to maximum phase error equal to $\pm 90°$.

Table 1. Sensitivity study.

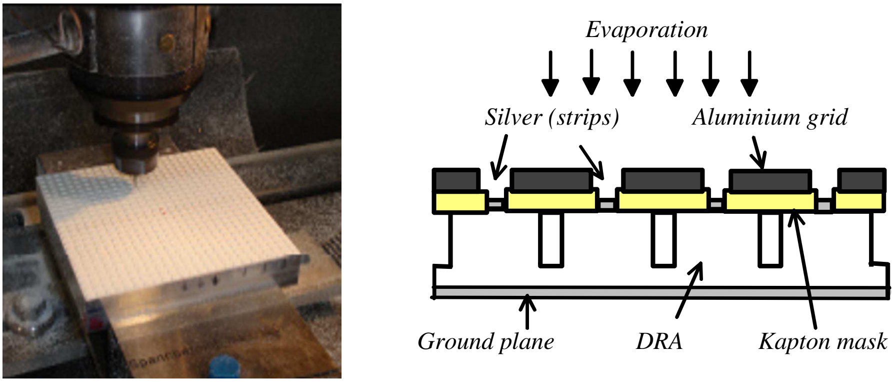
Parameters	Tolerance ranges to keep the SLL lower than −15 dB
L_{strip}	−0.1 to 0.1 mm
H_{sub}	−0.2 to 0.2 mm
W_{strip}	−0.1 to 0.1 mm
L_{dra}	−0.2 to 0.2 mm
H_{dra}	−0.1 to 0.1 mm
$MisX$	−0.2 to 0.2 mm
$MisY$	−0.2 to 0.2 mm

The same procedure is done for the impact of H_{dra} in Figure 5(b). The same conclusions as for L_{strip} deviations are achieved here: H_{dra} has to be less than 0.1 mm in order to keep SLL lower than −15 dB. Additional sensitivity studies have been also carried out to investigate the effects of the strip width (W_{strip}), the residual layer thickness (H_{sub}) and the DRA length (L_{dra}), as well as the impact of strip misalignment along x- and y-axes ($MisX$, $MisY$). In each case, the maximum SLL is limited to −15 dB. The resulting tolerance ranges for all parameters are summarized in Table 1. This table shows that, besides L_{strip} and H_{dra}, extra attention on the fabrication accuracy of W_{strip} should be taken since the tolerance ranges are very critical (±0.1 mm).

3.3. Fabrication Process

The proposed fabrication process consists of two steps: mechanical machining of the dielectric material (Figure 6(a)), and evaporation of the metal strips on the DRA (Figure 6(b)).

Due to limitations in weight and size inside evaporation chamber, the reflectarray panel has been divided in 9 modules, each module consisting of a 8×8 DRA sub-array. These modules are first glued on metal holders and assembled to be milled and polished all together. Once the DRA modules fabricated, each one is metallized individually. To this end, an original metallization process has been implemented to fabricate metal patterns on *non flat* surfaces. The strips are made of 1.1 µm-thick silver film, selected for its high conductivity. They are deposited by evaporation technique through a Kapton shadow mask in direct contact with the DRA top surface. This stencil is made of a polyimide sheet (15 µm-thick) glued on an aluminium grid. Rectangular apertures are etched in the Kapton mask by KrF laser



(a) Monolithic fabrication (b) Silver evaporation process

Figure 6. Fabrication process of the DRA reflectarray.

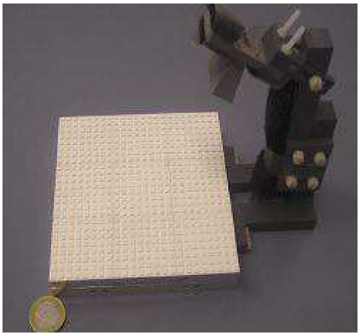


Figure 7. Final prototype after assembly.

(120 shots per aperture; fluence 1.5 J/cm^2). The accuracy of strip dimensions is about ±65 µm, which is within the tolerance ranges of L_{strip} errors discussed in Section 3.2. The final prototype of the DRA reflectarray is shown in Figure 7.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The gain of the reflectarray has been measured by the comparison method using a 20 dBi standard horn. It is represented in Figure 8. It reaches its maximum value (28.3 dBi) at 31 GHz, which suggests a 1 GHz shift of the operating frequency. This frequency shift is due to the cumulative effects of fabrication errors and assumptions in the modelling (especially periodic boundary conditions and normal

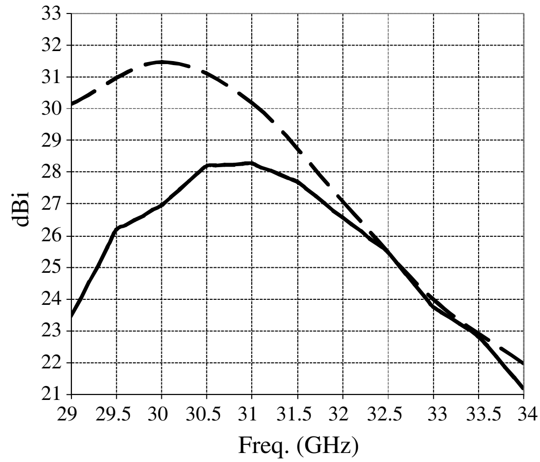


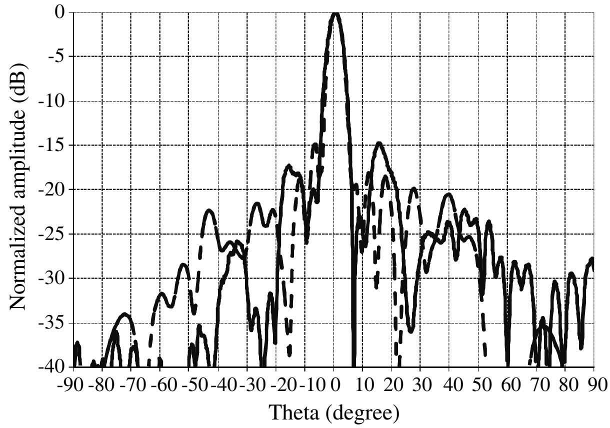
Figure 8. Measured gain (black line) vs. calculated directivity (dashed line).

Table 2. Measured characteristics of the reflectarray.

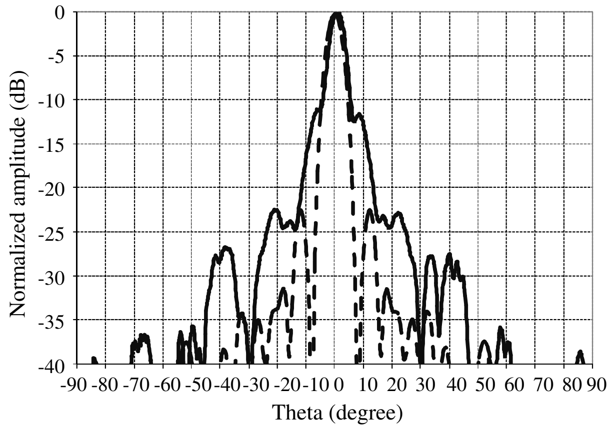
Central frequency	31 GHz
−1 dB gain frequency bandwidth	30.1–31.7 GHz
−1 dB gain fractional bandwidth	5.2%
Beam tilt (E-plane)	0.7°
Measured gain	28.28 dBi
Cross-polarization level	< -30 dB

incidence. Comparison with the antenna peak directivity shows an overall 3.2 dB difference between the measured gain and computed directivity. This mainly comes from spillover loss (about 2.3 dB) due to the small size of the prototype and broad radiation pattern of the feed horn. The remaining 0.9 dB loss corresponds to the dielectric and conductor loss in the DRA (about 0.6 dB from simulations) and phase discrepancy in the fabrication process. The main features of the DRA reflectarray are summarized in Table 2.

The co-polarization components measured at 31 GHz are represented in Figure 9. A satisfactory agreement is observed between simulations and measurements especially in the main beam. The full half-power beamwidths (HPBW) are almost equal in measurements (5.05° and 5.25° in E- and H-planes respectively) and calculations (4.7° and 5.2° in E- and H-planes respectively).



(a) E-plane



(b) H-plane

Figure 9. Co-polarization components at 31 GHz. Comparison between measurements (solid line) and array theory (dashed line).

The 3D amplitude patterns measured in co- and cross polarization are given in Fig. 10 at 29, 30 and 31 GHz for elevation angles varying between $-45°$ and $45°$. A slight beam tilt (less than $0.7°$) is observed in E-plane when frequency increases. Except the significant specular reflection (-11 dB) observed in E-plane at 29 GHz for elevation angles ranging from $20°$ to $45°$ (Figure 10(a)), the SLL remains smaller than -15 dB and -12 dB in E-plane and H-plane, respectively (Figures 10(a) to 10(c)). Finally, the cross-polarization level — computed according to Ludwig's third definition — is kept well below -25 dB for all frequencies.

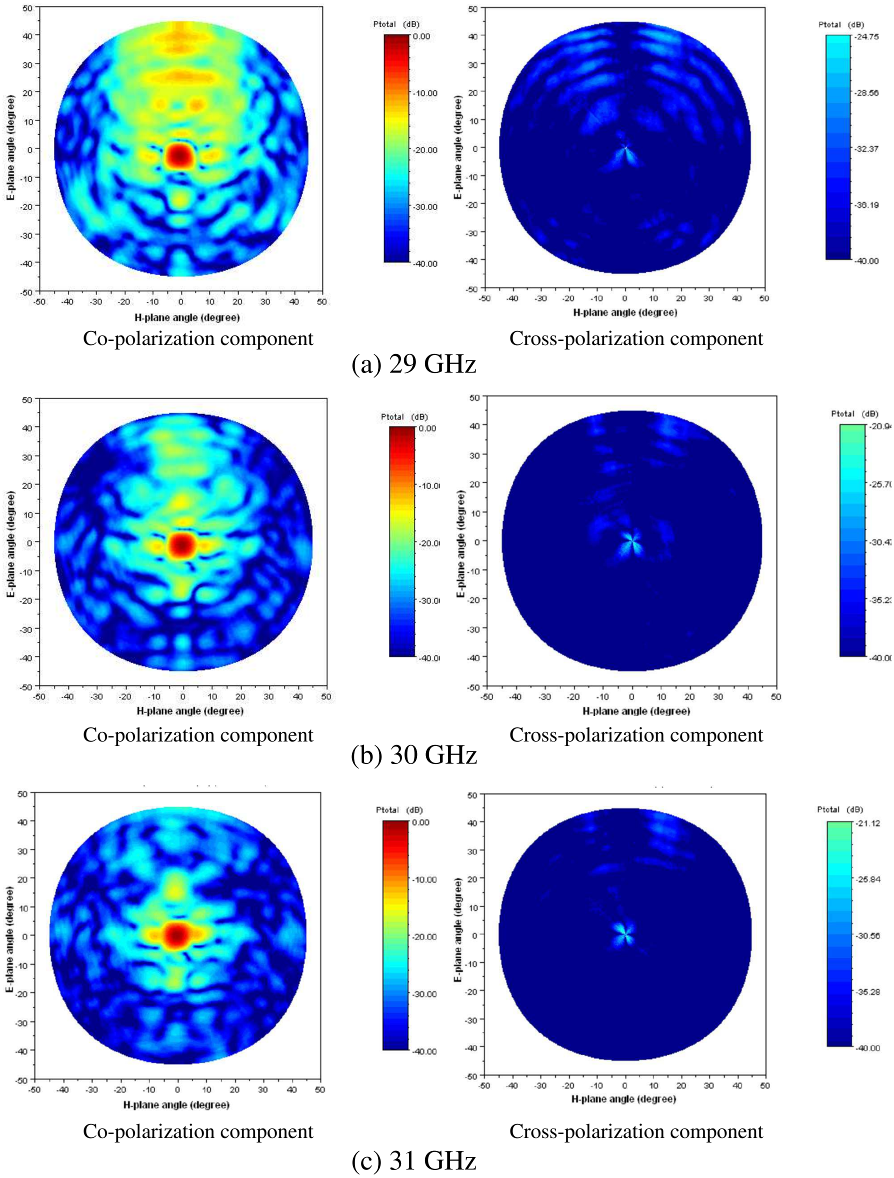


Figure 10. 3D measured radiation patterns at 29 GHz, 30 GHz, and 31 GHz. The cross-polarization component is defined according to Ludwig's third definition.

5. CONCLUSION

A new promising configuration of DRA-based reflectarray has been proposed in *Ka*-band. It relies on the use of strip-loaded DRAs as unit-cells. Such cells produce a phase dynamic range of 330° and exhibit low loss (0.6 dB) at 30 GHz. An original fabrication process using soft shadow masks has been proposed for manufacturing the parasitic silver strips on the DRAs. This process can be used for any conductor deposition on non flat (e.g., corrugated) surfaces.

A 24×24 element reflectarray, with an inter-element spacing of half a wavelength, has been designed to radiate at broadside when illuminated in *E*-plane by an offset small pyramidal horn antenna. The fabricated prototype exhibits a 5.2% -1 dB radiation bandwidth, and its maximum gain reaches 28.3 dBi. The analysis of the power budget shows that the 3.2 dB difference between the measured gain and computed directivity is mainly due to the spillover loss (2.3 dB), confirming thereby that such reflectarray configurations are low loss and could be used as a promising high-gain antenna configuration even at higher frequencies.

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