Circularly-Polarized Discrete Lens Antennas in the 60-GHz Band

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Abstract. *This paper presents the design and demonstration of two circularly-polarized transmit-arrays operating in the 60-GHz band and generating a broadside beam and a 30°-tilted beam respectively. These arrays have a fairly simple structure with only three metal layers and are fabricated with a standard printed-circuit board technology. The simulated results show the performances of the unit-cells as well as the whole arrays, and detail their power budget. The experimental results in V-band are in very good agreement with the simulations and demonstrate very satisfactory characteristics. Power efficiencies up to 53.7% are reached with a 1-dB gain-bandwidth up to 9.1%, and low cross-polarization level.*

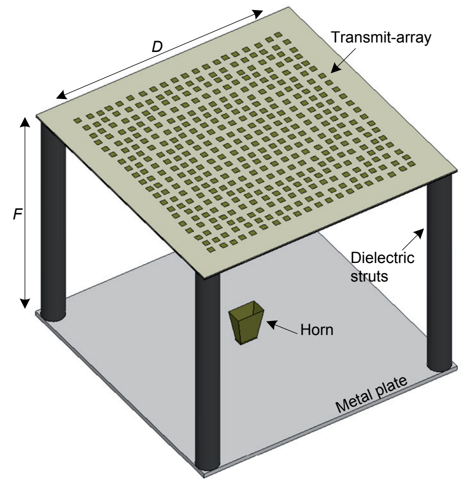
Keywords

Discrete lens, transmit-array, unit-cell, millimeter-wave antennas, 60-GHz band.

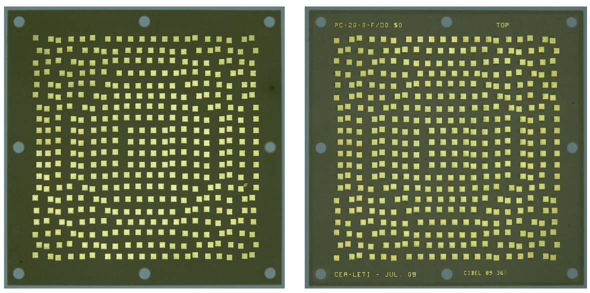
1. Introduction

Discrete lenses (also called transmit-arrays) [1]-[3] are high-directivity planar multilayer antennas currently investigated for many applications in the microwave and millimeter-wave bands, such as point-to-point communications, satellite communications, or civil and military radars. Compared to other antenna solutions (horn antennas, dielectric lenses, reflectors, and reflect-arrays), promising characteristics have been already demonstrated at frequencies below *X*-band in terms of efficiency, polarization purity, light weight and low cost. Recently, several research groups have also studied these structures in *Ku*- and *Ka*-bands for various wireless applications (e.g. [3]-[6]). We believe that several important applications lie in the *V*-band (57-66 GHz) such as wireless high-definition video transmission, personal or local area networks, radio-over-fiber networking solutions, or in the *E*-band (70-80 GHz) for metropolitan area networks [7],[8].

To our best knowledge, the work presented here is the first one investigating the radiation performance of circularly-polarized (CP) transmit-arrays operating in *V*-band [9], [10]. The corresponding unit-cell relies on similar concepts as those recently introduced in *X*-band to generate either linear or circular polarization with a very simple fabrication process and low insertion loss [11], [12].



(a)



(b) (c)

Fig. 1. Perspective view of the transmit-array antenna (a), top view (b) and bottom view (c) photographs of the broadside-beam transmit-array.

The paper is organized as follows. The geometry and characteristics of the proposed unit-cells are presented in Section 2.1. The design and expected performance of circularly-polarized transmit-arrays are discussed in Section 2.2, and experimental results are given in Section 3. Finally, conclusions are drawn in Section 4.

2. Antenna Design and Numerical Results

2.1 Description of the Unit-Cell

The proposed unit-cell is represented in Fig. 2. Its size is 2.5×2.5 mm^2 ($\lambda_0/2\times\lambda_0/2$ at 60 GHz), and it consists of two identical square patch antennas (1.55×1.55 mm^2) connected by a vertical via. The bottom patches (focal source side) have the same orientation for every cells, while the top patches (free space side) are rotated by an angle α (α = 0°, 90°, 180°, and 270°) for the four different unit-cells, generating a circularly-polarized (CP) wave through sequential rotation (Fig. 2b).

The geometry and performances of these unit-cells were described in detail in [10]. They were designed using the Ansys-HFSS electromagnetic simulation software using Floquet ports and periodic boundary conditions. Their simulated *S*-parameters under normal incidence show a reflection coefficient lower than -10 dB at 59.5-61.9 GHz, an insertion loss of 0.35 dB at 60.4 GHz, and a 1-dB transmission bandwidth of 3.9 GHz (6.5%). Their theoretical radiation patterns at 60 GHz show a maximum gain of 4.85 dBi and a 3-dB beamwidth of 88° and 131° in E- and H-planes, respectively.

Fig. 3 shows the variation of the *S*-parameters of the 0° unit-cell for several incidence angles from 0° to 45° in the E-plane. The resonant frequency of the patches is slightly decreasing for increasing incidence angles. For a 45° incidence, the central frequency is shifted to 59.3 GHz, the insertion loss is slightly increased to 0.44 dB, and the 1-dB bandwidth is reduced to 2.45 GHz (4.1%). Above 67 GHz, a higher-order resonance mode appears for a 45° incidence, but this mode does not have any visible effect on the full transmit-array. In H-plane, a similar but weaker effect is observed with a frequency shifted to 59.6 GHz for 45° incidence. Similar results are obtained for the three other unit-cells as well.

As explained in the next section, the *F*/*D* ratio of transmit-arrays designed here equals 0.5, which means that the highest incidence angle reached for the unit-cells located at the center of the array edges will be 45°. Fig. 3 confirms that good performances are preserved. Although their contribution are of minor importance, the unit-cells located in the four corners of the array will see a highest incidence angle of 54.7° in their diagonal plane, but simulations have shown that the *S*-parameters deviations were negligible as well.

2.2 Antenna Configuration and Design of Transmit-Arrays

The focal source is a 10-dBi linearly-polarized pyramidal horn. A fixture composed of a metal plate and four dielectric struts (Delrin, Ø = 6 mm) is used to hold and align the array and the focal source. The size of the transmit-array was chosen as 20×20 unit-cells (50×50 mm^2, $10\lambda_0\times10\lambda_0$ at 60 GHz), which corresponds to a maximum theoretical directivity of 31 dBi for a uniform aperture distribution.

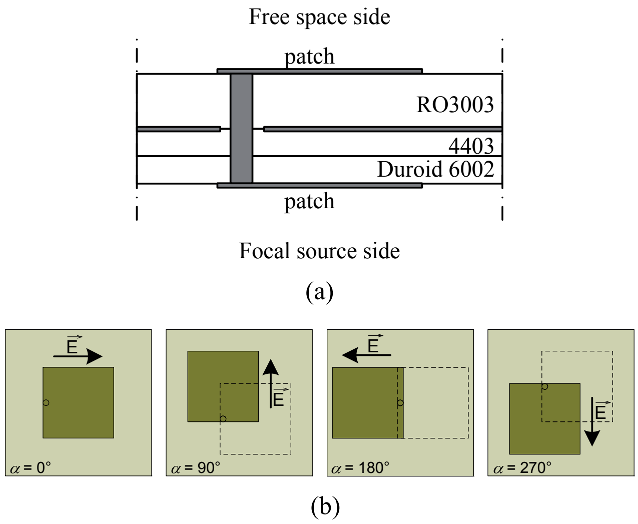


Fig. 2. Geometry of the unit-cell. (a) Cross-section view of the 0° unit-cell. (b) Top view of the four unit-cells; the bottom patches in dotted lines are horizontally polarized, the top patches in continuous lines are rotated by 90° between each cell.

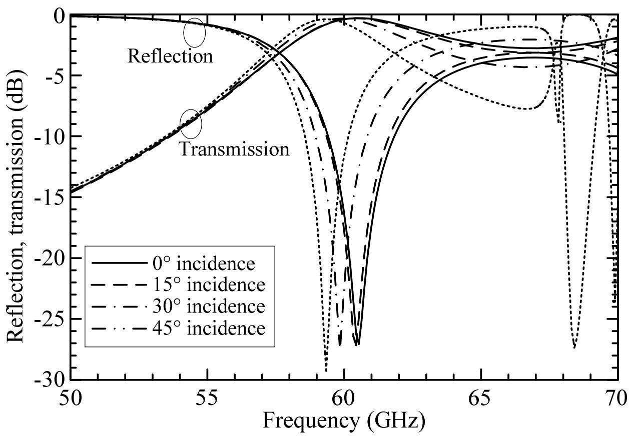


Fig. 3. Computed reflection and transmission coefficients of the 0° unit-cell under several incidence angles (0°, 15°, 30°, 45°) in E-plane.

The design and simulation procedure of such antennas is similar to those applied for reflect-arrays. The electromagnetic simulation of the focal source and the unit-cells is performed using Ansys-HFSS; their radiation patterns and *S*-parameters are transferred to a numerical home-made software where the analytical model of the transmit-array is implemented. This procedure has been described in detail in previous papers [10], [11] and has proven to be very efficient in terms of simulation time and computer resources.

Several circularly-polarized transmit-arrays have been designed and fabricated based on the four unit-cells presented in Section 2.1. Fig. 4a shows the directivity, gain, and axial ratio that can be achieved as a function of the ratio F/D for a broadside beam and a 30° beam-shift. F/D is defined as the ratio of the distance F between the array and the focal source to the side dimension D of the array (as mentioned above, $D = 50$ mm or $10\lambda_0$ at 60 GHz). The directivity increases as a function of the focal distance and converges toward a maximum value for large focal distances corresponding to a uniform aperture illumination of the array. The maximum directivity for the broadside beam is 27 dBi, because of a 4-dB quantification loss due to the 90° phase resolution. The gain is maximum for $F/D = 0.5$, this value corresponds to the best trade-off between the taper loss for low F/D values, and the spill-over loss for high F/D values. The axial ratio oscillates between 0.6 and 2.3 dB as a function of F/D, as a result of the array finite unit-cell number and phase quantification. For a 30° beam-shift, the directivity and gain are reduced by about 1.6 dB as a result of the finite beamwidth of the unit-cells. The axial ratio in this case is nearly independent of F/D (~1.1-1.4 dB).

Based on this study, two transmit-arrays were designed with $F/D = 0.5$ ($F = 25$ mm) and with a broadside beam or 30°-tilted beam. The unit-cell distributions of these two designs are represented in Fig. 4b. Their theoretical power budget is detailed in Tab. 1. In both cases, the taper loss, spill-over-loss and insertion loss equal 0.9 dB, 2.24 dB, and 0.46 dB respectively. The quantization loss equals 4.7 dB for the broadside-beam design, and 5.4 dB for the 30° beam-shifted design. The radiation efficiency, defined as the ratio of the gain to the directivity is 53.6-53.7%. The experimental gain values are in good agreement with the theory, confirming thereby this power budget analysis. It is important to note that quantization losses can theoretically be reduced down to zero using circularly-polarized elements on the free-space side and appropriate rotation angle α for each cell, which would significantly improve the gain and directivity of the antenna.

3. Experimental Results

Fig. 5 shows the reflection coefficient measured at the input port of the feed horn with ($F = 25$ mm) and without the discrete lens. In both cases, a very good matching is preserved across the V-band (50-75 GHz).

The radiation performances of the prototypes have been characterized in an anechoic chamber in far-field configuration. The antenna-under-test is illuminated with a 20 dBi linearly-polarized horn, and circular-polarization components are calculated from measured vertical and horizontal linear components. A radiation gain calibration was performed with a reference 20 dBi horn.

The two prototypes have been characterized between 50 and 70 GHz in the main beam direction (Fig. 7). For the broadside-beam prototype (Fig. 6a), a good agreement with the simulation is obtained across the whole measurement frequency band. The gain-frequency response shows a band-pass characteristic with a simulated 1-dB bandwidth of 57.5-68.5 GHz. The experimental 1-dB bandwidth starts at 58.3 GHz but its higher cut-off frequency was rejected beyond 70 GHz and could not be measured. The axial ratio response is also in good accordance with the simulations with an axial ratio lower than 3 dB across the whole measurement band and lower than 1 dB from 57 to 66 GHz. This good polarization quality is obtained across the whole bandwidth of the array thanks to the sequential rotation configuration.

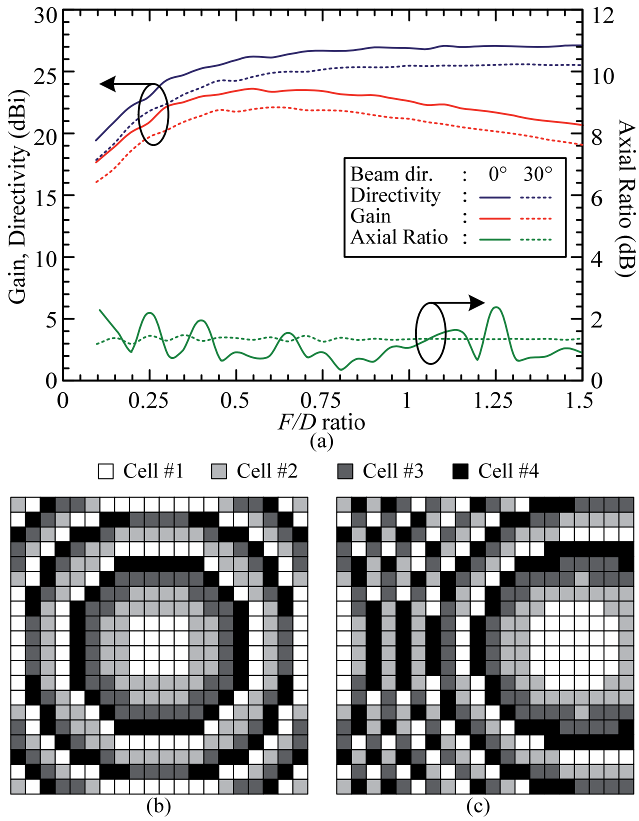


Fig. 4. Theoretical directivity, gain and axial ratio of the transmit-arrays as a function of F/D (a); unit-cell distribution of the proposed transmit-arrays with a broadside beam (b) and 30°-shifted beam (c).

For the tilted-beam prototype (Fig. 6b), the gain-frequency response in the main beam direction shows a good agreement with the simulation for the lower half of the frequency band, but the band-pass shape is not well defined in the upper half. The measured 1-dB bandwidth equals 58.5-64.1 GHz (5.6 GHz, 9.1%), and is significantly larger than the simulated one (57.3-61.4 GHz, 6.9%). A possible cause for this discrepancy is the fabrication dispersions across the array, which may be more critical in a tilted-beam case. The most challenging dimensions are the via diameter (∅ = 0.1 mm) and the ground plane aperture diameter (∅ = 0.3 mm) around each via, which are critically small for this fabrication technology. The prototypes fabrication was subcontracted and realized with standard printed-board industrial techniques. The experimental axial ratio response at $\theta = 30°$ exhibits strong similarities with the simulations with a minimum close to 0.5 dB and a steep increase for frequencies above 65 GHz, the measured 3-dB axial ratio bandwidth is 57.8-63.1 GHz (5.3 GHz, 8.8%). This small bandwidth (compared to the broadside-beam transmit-array) observed when measuring at $\theta = 30°$ is due to the variation of the main beam direction as a function of frequency. Hence, the simulated main beam direction varies from 36.5° down to 25° across the 50-70 GHz band (Fig. 7). On the other hand, the simulated axial ratio in the main beam remains below 2 dB across the whole band (Fig. 6b).

Beam angle	0°	30°
Max. theoretical directivity (dBi)	31	30.4
Quantization loss (dB)	4.6	5.4
Taper Loss (dB)	0.9	0.9
Antenna directivity D_{ant} (dBi)	25.5	24.1
Spill-over loss (dB)	2.24	2.24
Insertion loss (dB)	0.46	0.46
Theoretical gain (dBi)	22.8	21.4
Radiation efficiency (%)	53.6	53.7
Axial ratio (dB)	0.76	0.88
Measured gain (dBi)	23	21.9

Tab. 1. Power budget and gain of the two prototypes at 60 GHz ($F/D = 0.5$).

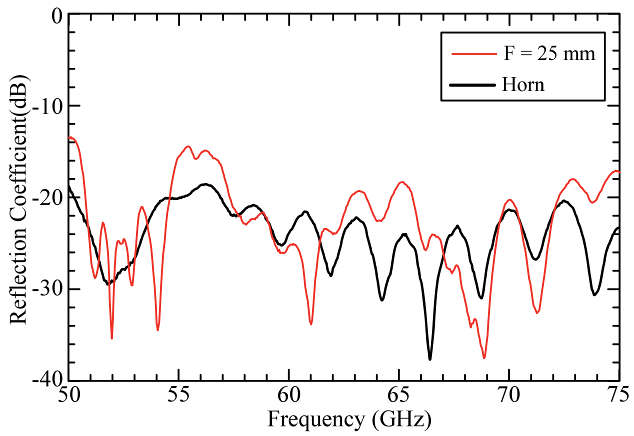
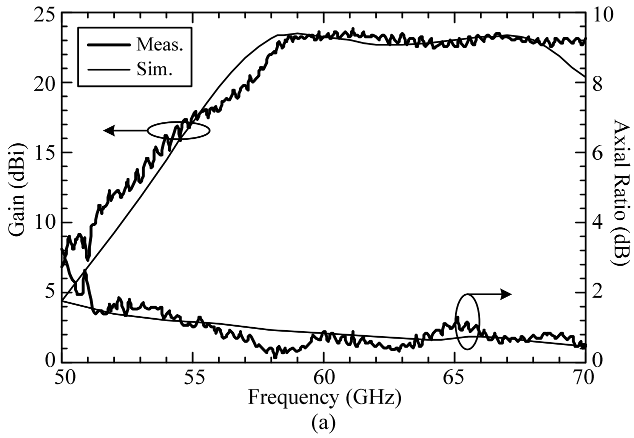


Fig. 5. Measured reflection coefficient at the input of the horn focal source alone and with a discrete lens at a distance $F = 25$ mm ($F/D = 0.5$).

The simulated and measured radiation patterns of the broadside-beam arrays are plotted in Fig. 8. This figure confirms the very good agreement between simulations and experiments: the computed and measured gain, beamwidth and side lobes equal 22.8/23 dBi (sim./meas.), 6.1°×6.6°/6.6°×7.2° (sim./meas.), and -19.6/-16.1 dB (sim./meas.), respectively. The cross-polarization level in the main beam is lower than -25 dB in simulation and close to -20 dB experimentally.

The tilted-beam prototype exhibits experimentally a main beam at $\theta = 26.5 \pm 1°$, slightly shifted from the design value (30°). This shift is attributed to (i) the relative position of the focal source and the array, and (ii) a slightly bowed shape of the array which is thin and flexible. The simulated and measured radiation patterns are again in good agreement (Fig. 9).



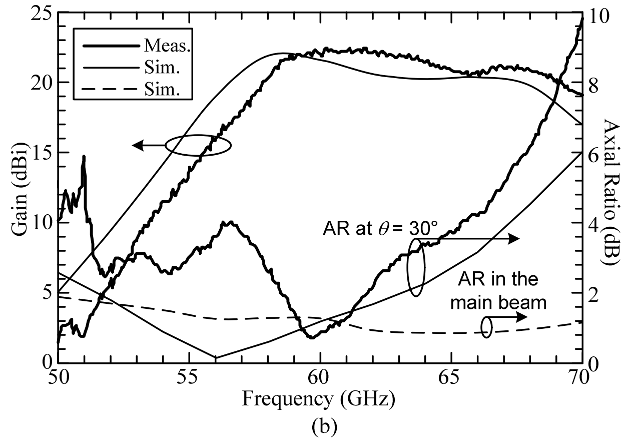


Fig. 6. Computed and measured gain and axial ratio for the broadside (a) and beam-shifted (b) transmit-arrays.

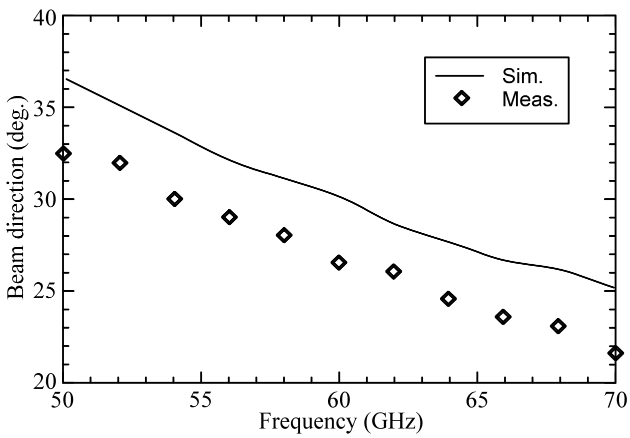


Fig. 7. Computed and measured beam direction of beam-shifted transmit-arrays as a function of frequency.

4. Conclusion

Low-cost directive antennas are strongly needed for emerging wireless applications in the millimeter-wave domain. In this article, *V*-band circularly-polarized discrete-lenses based on a simple three-metal layer unit-cell are studied. Their numerical characterizations lead to very promising features: low insertion loss, good efficiency, broad radiation pattern, and broadband phase response with a 2-bit quantization in circular polarization.

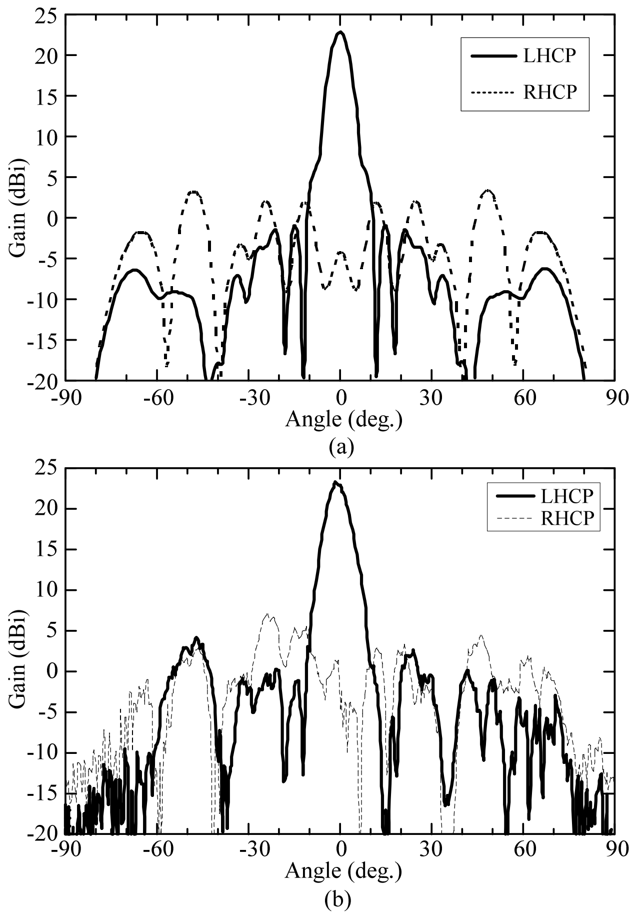


Fig. 8. Computed (a) and measured (b) radiation patterns of the broadside-beam transmit-array at 60 GHz in the vertical plane.

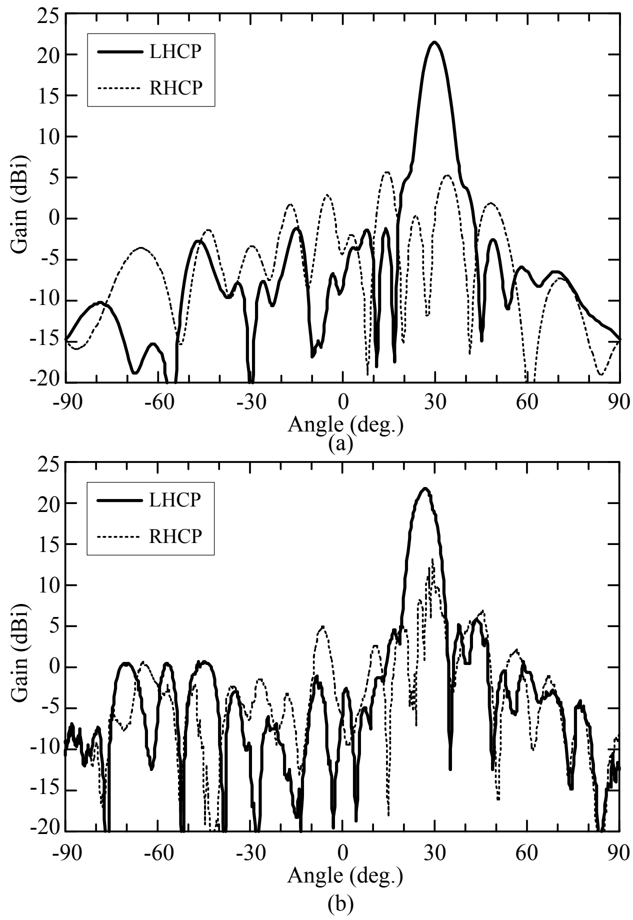


Fig. 9. Computed (a) and measured (b) radiation patterns of the 30°-beam-shifted transmit-array at 60 GHz.

Two discrete lenses have been designed and fabricated for a broadside beam or a beam tilted at 30°. Its measured radiation characteristics are in very good agreement with the simulations in terms of gain frequency response, axial ratio, and radiation pattern.

Acknowledgements

The authors would like to thank the European Science Foundation for its contribution to the work (project RNP NEWFOCUS). They also would like to thank CEA and CNES for their financial support.

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