Circularly Polarized Single-Layer Microstrip Reflectarray Fed With a 2x2 Microstrip Patch Array

Roger L. Farias, Custódio Peixeiro, Marcos V. T. Heckler and Edson R. Schlosser

Abstract— **The design of a single-band singly-layered reflectarray fed by a circularly polarized 2×2 microstrip patch antenna array with corporate feeding to be used in K-band (18.7–19.2 GHz) is proposed in this paper. It is demonstrated by simulations and measurements that the axial ratio bandwidth performance of the reflectarray depends strongly on the circularly polarization purity of the feeder. Simulated and measured results revealed that the complete reflectarray exhibits good performance in terms of input impedance with -10 dB input reflection coefficient bandwidth of 19.0 %, radiation pattern with 3 dB axial ratio bandwidth of 10.55 % and 3 dB gain bandwidth of 2.64 %.**

Index Terms—**Reflectarrays, Circular polarization, Microstrip patch antenna arrays.**

I. INTRODUCTION

The demand for access to high-speed connections has increased in the last years and will gain even more importance in the near future. Although some people use internet connections mostly for entertainment, there are many other services that play an important role in our society. Remote control of equipment for precision agriculture, telemedicine and technical meetings in virtual environment are only some examples where a reliable and high-speed connection plays an important role. This has become explicitly clear during the SARSCoV-2 pandemic, where people could interact with colleagues and even with machines only remotely.

The applications mentioned above may occur everywhere on our planet. Even in remote areas, such as the case of small villages in the Amazon Region, or in mobile platforms, such as in aircraft and ships, access to the internet must be guaranteed. In the former case, optical links are not economically feasible, whereas it is impracticable in the latter situations, since optical communication is still not possible for mobile platforms with worldwide coverage. Therefore, the establishment of internet links by means of satellite communications is still of great interest, and, for this purpose, the use of high-gain antennas

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is necessary, due to the large distances involved between the terminals on the Earth and in-orbit satellites.

Standard parabolic reflector antennas have been used in satellite communications for many decades [1], but, due to their volume and manufacturing costs, reflectarrays have become a good alternative [2]–[7]. Both topologies need a primary source (also called feeder) and a reflecting aperture. In reflectarrays, reflection is achieved by means of scattering elements, which are normally printed on a low-loss microwave laminate; hence it is a much more compact antenna in comparison to its parabolic counterpart. The scattering elements are designed so as to compensate the phase shift introduced by free space propagation of the spherical wave radiated by the feeder until it arrives to the scatterers [8].

Due to the several advantages, research on the design of reflectarrays has increased in the last two decades. In [9], a single-layer unit-cell based on curved variable-length stubs has been presented. The main advantage is the ease of fabrication, since it can be manufactured in a single layer and its physics is very intuitive. In [10], the achievement of multiple polarization capability is discussed and can be accomplished by using stubs in orthogonal orientations. The use of mirroring to design reflectarrays with low cross-polarization has been presented and discussed for linearly polarized (LP) and circularly polarized (CP) reflectarrays in [11] and [12], respectively.

Circularly polarized feeders are normally implemented by the use of horn antennas or open-ended waveguides that support two orthogonal modes along with an external 90° hybrid coupler. Since such antennas are normally bulky, an alternative suitable for satellite communications is a feeder based on microstrip antennas. Circular polarization may be achieved by means of excitation of two orthogonal modes on a single element or by composing an array with sequential rotation and progressive phase shift [13]. Originally, the technique based on the sequential rotation of elements was achieved with linearly polarized antennas, but it has been proven that better CP performance can be obtained by combining this technique with radiators that are already circularly polarized [14]. This technique has been used to design a 2×2 CP microstrip array to serve as the feeder of a reflectarray in [15]. In [16], a 2×2 CP microstrip array suitable to serve as a reflectarray feeder has been developed and issues related to its phase center have been also discussed.

Many authors design reflectarrays by using several idealizations. One typical case is the consideration of an infinite array of unit-cells. This allows the use of a Floquet approach, whereby only one unit-cell needs to be analyzed [17], [18]; hence the scattering phase can be assessed with much lower

computation effort in comparison to the case of simulating the complete reflectarray. Other kind of idealization is present in [12], whereby circular polarization is emulated by using a LP horn, so that the CP operation has been achieved by post-processing.

Aiming at presenting a realistic scenario, this paper describes the design of a single-band singly-layered reflectarray. In the next section, the unit-cell, the feeder and the complete simulation models are described. Full-wave simulations have been carried out and good performance has been obtained. In Section III, fabrication details and the measurement setup are described. The simulation results shown in Section II are compared with measurements. A final discussion is included in Section IV, where the main features of the interaction between the feeder and the reflectarray are described with emphasis on the CP purity of the whole structure.

II. DESIGN OF A SINGLE-BAND SINGLY-LAYERED REFLECTARRAY

A. Unit-cell

The unit-cell configuration, which is based on our previous work [12], is depicted in Fig. 1(a). It consists of a fixed-size circular patch with a pair of attached open-ended orthogonally positioned stubs that work as delay-lines. The stub lengths can be used to change the phase of the scattered electric field and are the key dimensions for beamsteering.

The unit-cell was designed for operation in the band from 18.7 to 19.2 GHz to provide a very low axial ratio (AR). Inspired by the microstrip line feeding technique of microstrip patches, inset feeding is used. Additional axial ratio improvement has been achieved by using a double mirror symmetry arrangement. The spacing between adjacent elements is uniform along the x and y directions and is $L_x = L_y = 7$ mm, which corresponds to $0.45\lambda_0$ at 19.2 GHz (the upper frequency) to avoid grating lobes. The proposed unit-cell is etched on a grounded 0.787 mm thick Rogers RT/Duroid 5880 substrate with relative permittivity 2.2 and loss tangent 0.001.

The phase responses in the center frequency as a function of the stub lengths, under different angles of incidence, are presented in Fig. 1(b), whereby, in this case, $\phi_{sx} = \phi_{sy} = \phi_s$. Detailed information about the design of this unit-cell can be found in [12].

B. Microstrip feeder

The feeder is a 2×2 circularly polarized microstrip array. Circular polarization is achieved by using both the corners-truncated geometry (see Fig. 2(a)) and sequential rotation of elements. The array has been designed to operate at $f_0 = 18.95$ GHz with right-hand circular polarization (RHCP). The radiators have been positioned so as to maximize the gain without exhibiting grating lobes. The power division is based on T-junctions and quarter-wave transformers, and its outputs deliver the same power to each antenna with progressive 90° phase shift. The complete structure has been designed using the same laminate as for the reflectarray itself. The resulting schematic top view is shown in Fig. 2(b). Detailed information about the design of this feeder can be found in [16].
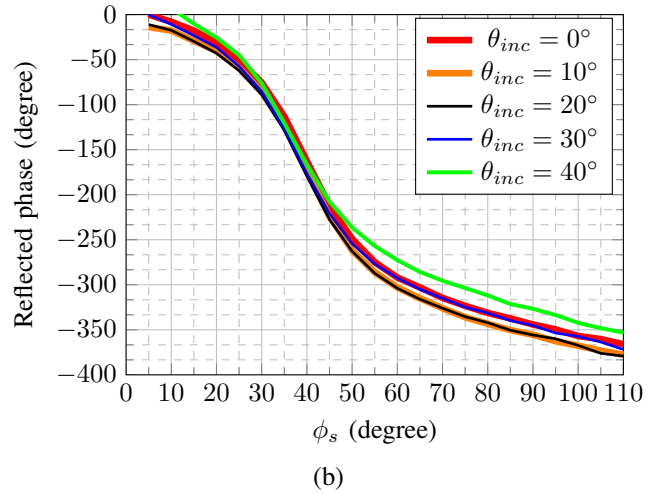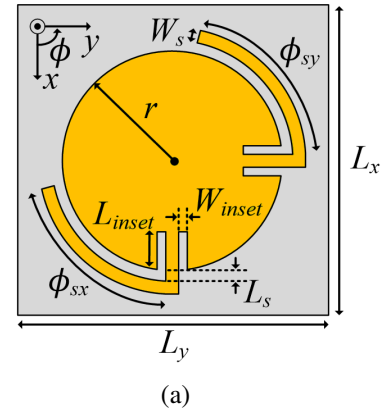

(a)

(b)

Fig. 1. Single-layer unit-cell designed for 18.95 GHz: a) Top view; b) Phase curve at f_0 = 18.95 GHz.

C. Reflectarray with microstrip feeder

The characterization of the proposed reflectarray with an LP feeder has been done in [12]. As mentioned in Section I, CP performance has been assessed mathematically in post-processing. This procedure was important in that stage of development, so as to allow evaluating the inherent performance of the proposed unit-cell without taking into account polarization and bandwidth limitations of the feeder. However, in a realistic scenario, the radiation characteristics of the feeder must be considered for precise practical results. In this sense, the 2x2 microstrip array presented in Section II-B will be used to feed the aperture composed of the unit-cell described in Section II-A.

From the phase center of the feeder, the necessary scattering phases for each unit-cell can be calculated, so as to point the main beam to the desired direction. In this work, the case study of a broadside radiation pattern has been considered with $\theta_b = 0°$ and $\phi_b = 0°$. For this purpose, the stub lengths ϕ_{sx} and ϕ_{sy} can be designed by equating [19]

$$\psi_{r_{i,j}} = k_0(d_{i,j} - (x_{i,j}\cos\phi_b + y_{i,j}\sin\phi_b)\sin\theta_b) - 2n\pi, \quad (1)$$

where

$$d_{i,j} = \sqrt{(x_{i,j} - x_f)^2 + (y_{i,j} - y_f)^2 + (z_{i,j} - z_f)^2} \quad (2)$$

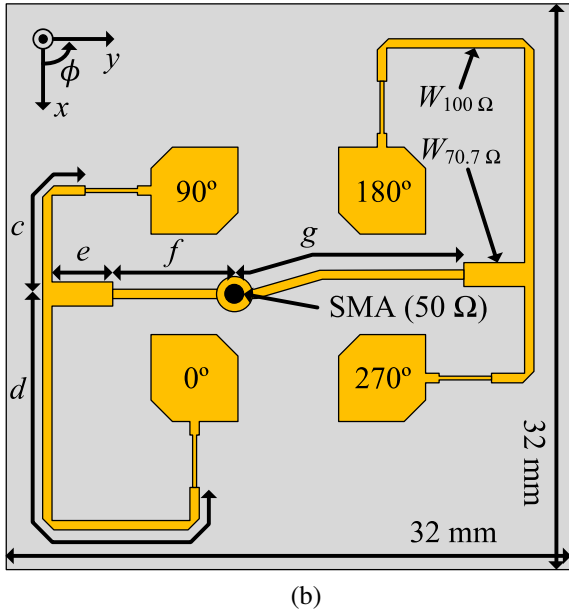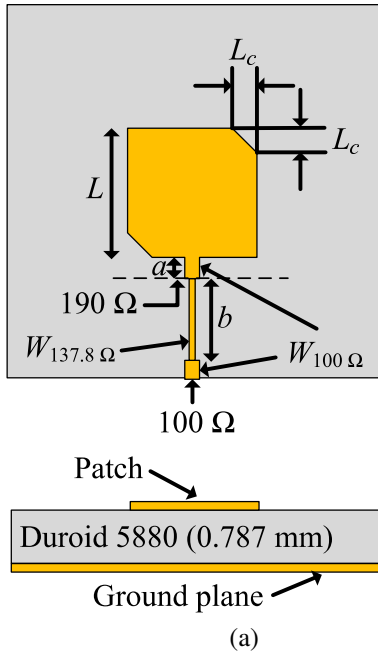Fig. 2.   Designed feeder based on a 2×2 microstrip array: (a) Top view and stack-up of the single element; (b) Top view of the 2×2 array.

Fig. 3.   Combination of proposed microstrip array feed and reflectarray.
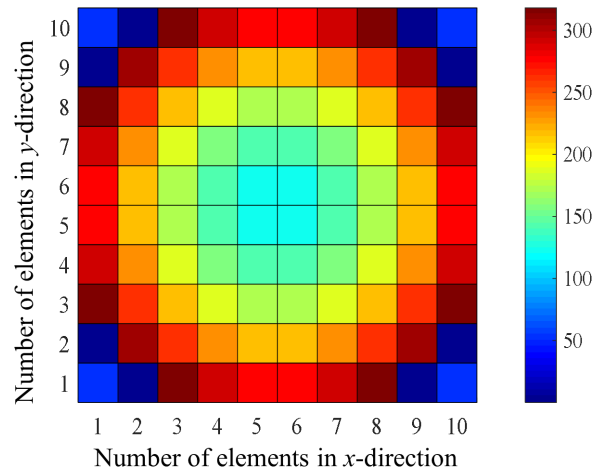
Fig. 4.   Phase distribution on the RA aperture at 18.95 GHz.

is the distance between the feeder phase center and the center of the ij-th unit-cell, k_0 is the propagation constant in free space, $(x_{i,j}, y_{i,j}, z_{i,j})$ are the coordinates of the ij-th unit-cell, (x_f, y_f, z_f) stands for the position of the feeder phase center and n is applied to keep ϕ_s within the variation limits of the phase response presented in Fig. 1(b).

The reflectarray considered in this work is composed of an array of 10×10 elements ($i, j = 1, 2,..., 10$), so that the physical aperture corresponds to a square with $D = 70$ mm edge size. The focal distance F of the reflectarray is also chosen as 70 mm to obtain the focal to aperture ratio $F/D = 1$. This stands for an acceptable trade-off between the tapering and the spillover efficiencies. At the focal point, the microstrip antenna array feeder has been placed centrally over the reflec-
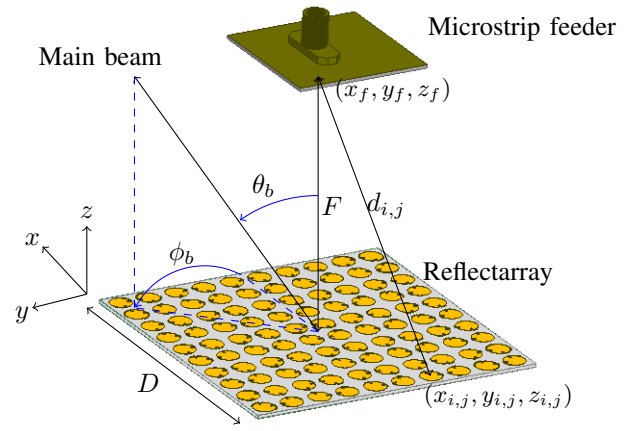
tarry aperture. The electromagnetic model developed in CST Microwave Studio is shown in Fig. 3. The required phase shift for each element is calculated with Eq.(1) at 18.95 GHz. The phase distribution on the reflectarray aperture for the proposed antenna is depicted in Fig. 4.

In Fig. 7, the simulated radiation patterns for $\phi = 0°$ at 18.7, 18.95, and 19.2 GHz are shown. The maximum simulated LHCP gain is 16.51 dBic at 18.95 GHz. The aperture efficiency of the reflectarray antenna is about 18.2 %. The side lobe and the boresight cross-polarization levels are below -11.2 dB and -17.3 dB, respectively. Good results have been obtained also at the lower and higher frequencies of the design band.

Fig. 8 presents the axial ratio behavior in the boresight of the microstrip array feeder and of the complete reflectarray antenna as a function of frequency. The simulated axial ratio of the reflectarray antenna is below 3 dB over the range 17.5-19.5 GHz, which corresponds to a fractional bandwidth of nearly 10.55 %. Aiming to demonstrate the operating range limitation provided by the feeder, the proposed reflectarray is illuminated by two different sources, in which one of them is an LP horn used to emulate CP operation by post-processing and the other is the 2x2 microstrip array presented

in Section II-B. For a fair comparison, the focal to aperture ratio $F/D = 1$ is the same for both feeders. Fig. 8 illustrates the measured AR bandwidth. As it can be seen, the AR bandwidth of the reflectarray using the LP horn (nearly ideal CP) remains below 1 dB for a frequency range larger than 16.7-21.2 GHz (or 23.7 % of fractional bandwidth), whilst, as indicated above, the AR bandwidth obtained by using the 2x2 microstrip array corresponds to the range from 17.5 GHz to 19.5 GHz (10.55 %). It can be therefore concluded that it is necessary to take into account the feeder characteristics since the beginning of the reflectarray design procedure. Otherwise, more than one design iteration is needed.

III. RESULTS

Aiming at validating the reflectarray performance with experimental results, a prototype has been manufactured and measured. Since the electromagnetic model presented in Fig. 3 does not present any supporting structure for the feeder, foam blocks were used to hold the 2×2 microstrip array on top of the reflectarray. It is worth to mention that these foam blocks were not included in the electromagnetic model in CST Microwave Studio, since its dielectric constant is very close to 1. The details of the manufactured foam supports prior to the final assembly, the assembled prototype and the final measurement setup inside the anechoic chamber are illustrated in Fig. 5.

The magnitude of the reflection coefficient, measured at the input of the feeder is shown in Fig. 6. Results for the feeder only, for the feeder with the foam block and for the whole reflectarray are shown. The reflectarray exhibits a large 19 % input impedance bandwidth (for $|S_{11}| < -10$ dB). As expected, the foam has a negligible effect. Moreover, even the reflectarray has not a considerable effect as only a low-level ripple is noticed.

The simulated and measured radiation patterns for both the LHCP and RHCP components at 18.7, 18.95 and 19.2 GHz for the plane $\phi = 0°$ are shown in Fig. 7. The measured LHCP gain of the reflectarray antenna is 16.28 dBic and the aperture efficiency is about 17.26 % at f_0. As previously mentioned in [12] and predicted in the simulations, for a such small aperture, the feeder blockage has significant impact on the overall antenna performance, since roughly 22.9 % of the RA aperture is blocked by the feeder. Thus, the authors believe that the main reason that contributes to the low aperture efficiency is the feeder blockage, since a center-fed configuration has been used [20], [21]. However, the feeder, with its own aperture efficiency of 35 % [12], has also a non-negligible contribution to such low overall aperture efficiency [12]. It is worthwhile to mention that, if this condition was not in question, the off-set configuration would be chosen to avoid the feeder blockage, which is a critical issue in the design of small-aperture reflector antennas. The side lobe and boresight cross-polarization levels are below -10.1 dB and -17.8 dB, respectively. One can see, in Table I, that good agreement is obtained between numerical simulations and experimental results.
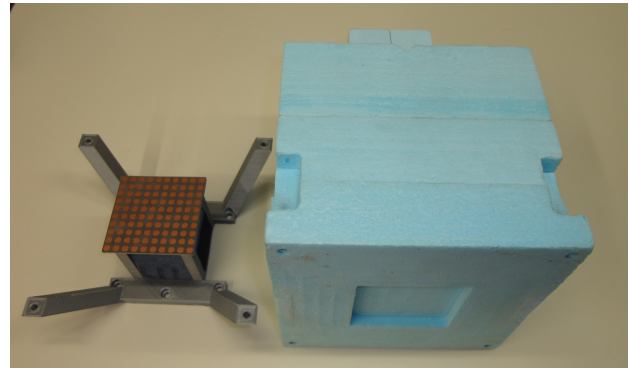
Measured AR results in the boresight as a function of frequency are plotted Fig. 8. Axial ratio levels below 3 dB are
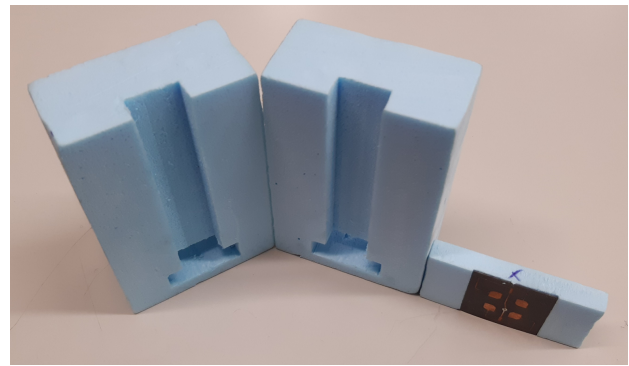
(a)
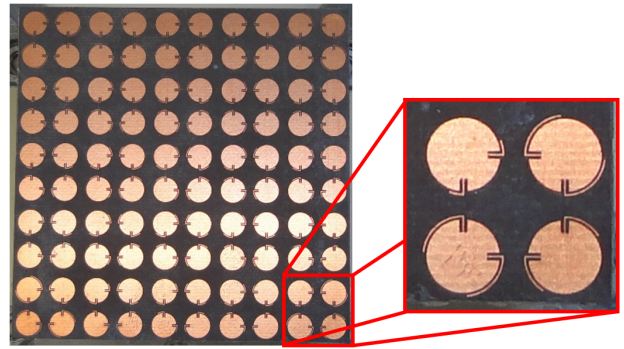
(b)

(c)

Fig. 5. Experimental validation: (a) Foam pieces to hold the 2×2 microstrip feeder; (b) Reflectarray prototype; (c) Reflectarray with plastic and foam holders.

achieved in the frequency range from 17.5 to 19.5 GHz, which corresponds to a fractional bandwidth of 10.55 %. Outside this band, the CP performance degrades significantly and the main reason for that is the CP performance of the microstrip feeder, hence highlighting the already mentioned importance of including a realistic feeder since the beginning of the reflectarray design. The green curve (labelled "RA+Horn feeder – Meas.") corresponds to an ideal CP excitation synthesized from the reflectarray responses to orthogonal LP horn excitations with the same amplitude and 90 degrees phase difference. It proves the excellent CP performance of the reflectarray (AR below 1 dB).Table I summarizes the main figures of merit of the designed reflectarray.
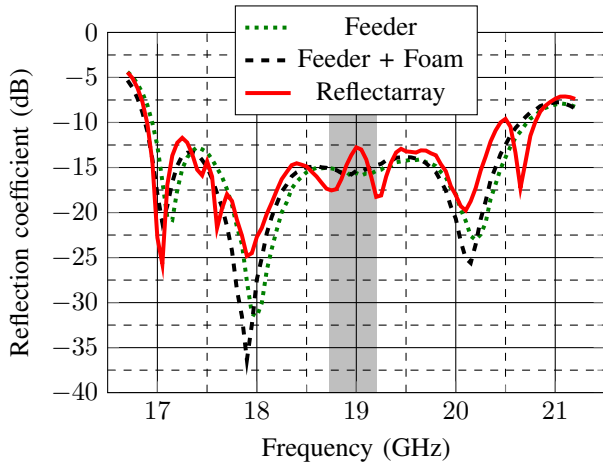
Fig. 6.   Experimental reflection coefficient magnitude at the feeder port.
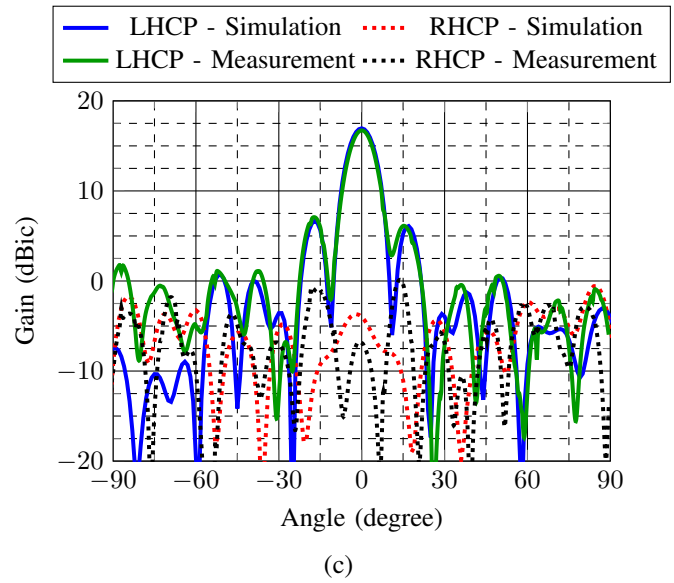

(a)

(b)

(c)

Fig. 7.   Comparison between simulated and measured radiation patterns of the complete reflectarray: (a) 18.7 GHz; (b) 18.95 GHz; (c) 19.2 GHz.
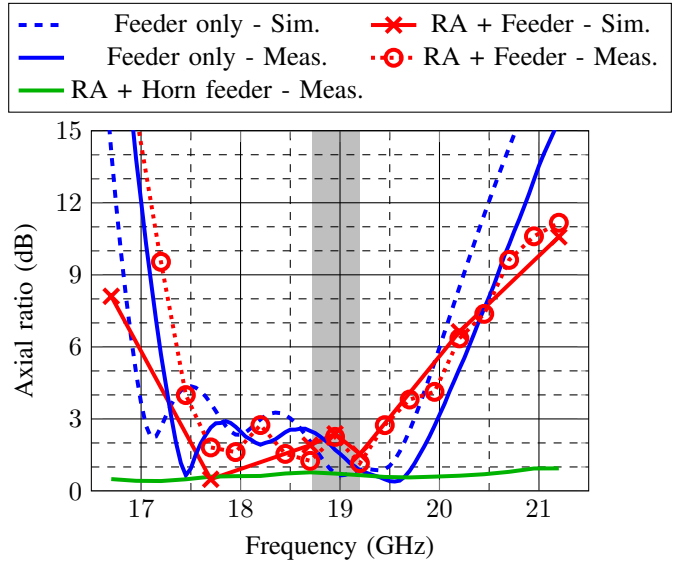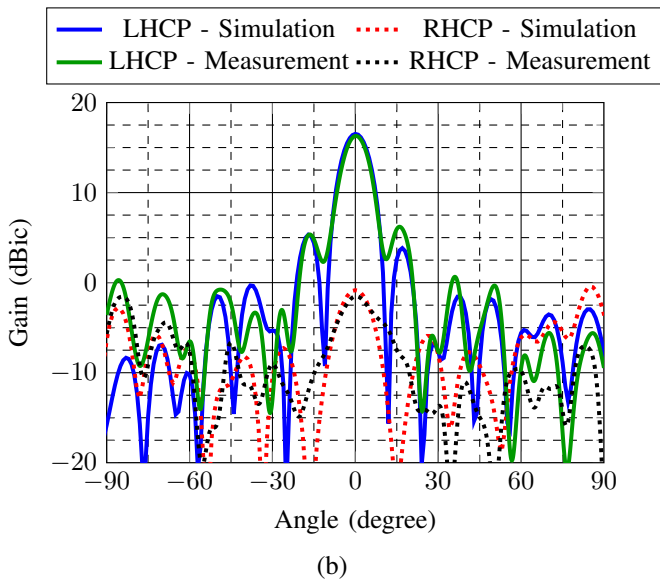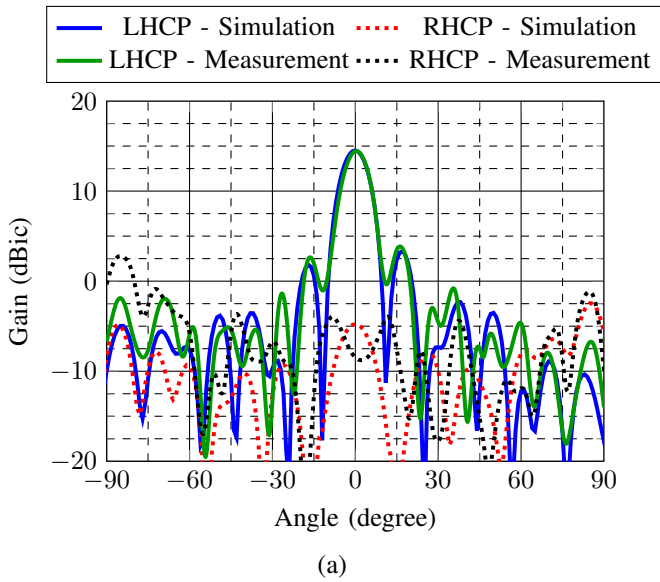

Fig. 8.   Comparison between simulated and measured broadside AR versus frequency.

The gain behavior as function of frequency is shown in Fig. 9. Although the specified fractional bandwidth for the antenna design is 2.64 %, marked in gray in Fig. 9, it must be highlighted that the overall 3-dB gain bandwidth is much larger than this and is equivalent to 13.61 %. This value is closely related to the feeder bandwidth, which corresponds to 14.88 %.

IV. CONCLUSION

Experimental results for a reflectarray fed by a circularly polarized 2×2 microstrip antenna array with sequential rotation of elements and corporate feeding has been presented. An overall good agreement between numerical simulation and experimental results has been obtained. However, the AR and gain performance are slightly degraded above 19.5 GHz.

TABLE I
FIGURES OF MERIT OF THE PROPOSED REFLECTARRAY.

| Parameter	18.7 GHz		18.95 GHz		19.2 GHz	
	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
AR (dB)	1.9	1.25	2.37	2.25	1.55	1.16
Gain (dBic)	14.5	14.43	16.51	16.28	16.95	16.71
Aperture efficiency (%)	11.75	11.57	18.20	17.26	19.61	18.57
SLL (dB)	-11.18	-10.58	-12.68	-10.08	-10.29	-9.63
XPD (dB)	-19.27	-22.91	-17.34	-17.79	-21.00	-23.59
3 dB AR Bandwidth (%)	$\sim$ 10.55 (Simulation) / 10.55 (Experiment)					
3 dB Gain Bandwidth (%)	> 2.64 (Simulation) / > 2.64 (Experiment)					
-10 dB impedance Bandwidth (%)	18.1 (Simulation) / 19.0 (Experiment)					
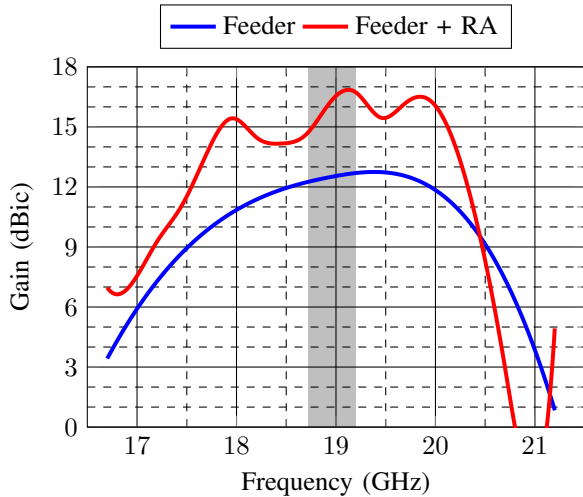
Fig. 9. Gain as a function of the frequency for the reflectarray fed by the microstrip array feeder (in red) and for the feeder itself (in blue).

The reflectarray has a minor effect on the input impedance of the feeder. However, the feeder has strong negative effects on both the aperture efficiency (and consequently on gain) and the AR. The main limitation observed in the analysis is the decrease of the AR bandwidth of the complete reflectarray when compared with the reflectarray and feeder ones. This conclusion is based on the simulation and the experimental results shown in this paper, which highlight the importance of considering realistic models for the feeder since the beginning of the reflectarray design procedure.

Finally, the bandwidth of the complete RA could be increased by the use of a new unit-cell topology, which could be able to compensate for the AR bandwidth limitation of the feeder, as suggested in [6]. However, this was out of the scope of the present research.

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