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Single-Layer Sequential Rotation Network in Gap Waveguide for a Wideband Low-Profile Circularly Polarized Array Antenna

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ABSTRACT A low-profile circularly-polarized sequential rotation fed 4 × 4 array antenna working in the Ka-band from 27.5 GHz to 31 GHz is presented. The particularity of the antenna lies in its single-layer sequential rotation feed network implemented in a bed of nails using a combination of groove and ridge gap waveguides. The basic radiating element is one slot loaded by a simple coffee-bean-shaped parasitic element on top. Experimental results show an antenna matching below −10 dB in a 13.6% bandwidth and a measured axial ratio below 1.3 dB in the desired band.

INDEX TERMS Array, circular polarization, gap waveguide, Ka-band, SATCOM, sequential rotation.

I. INTRODUCTION

Circular polarization (CP) purity in planar antennas is a challenge often pursued because of its multiple applications [1], [2]. In the particular context of the Ka-band, it is especially desirable to have an antenna with good polarization purity apart from other features, such as low weight, low profile, and low cost. Specifically, for satellite communications (SATCOM) on-the-move applications in this band, the critical requirement is working with an axial ratio (AR) below 1.25 dB in a frequency range from 27.5 GHz to 31 GHz. Even more restrictive specifications go as far as imposing 1 dB as a maximum threshold. At any rate, the ideal antenna design would be one providing an AR reaching these levels and satisfying the other requirements mentioned above, while being scalable to potentially attain high gains. As can be guessed, this is not an effortless challenge, and in the past, numerous interesting approaches to achieve circularly polarized antennas have been proposed in the literature.

For example, metallic waveguides using crossed [3], [4], inclined [5], [6], Y-shaped [7], T-shaped [8], [9], ring-shaped [10] or L-shaped slots [11], [12] are some of the options commonly used to achieve the 90° phase shift between the two orthogonal polarizations. These solutions are useful and widely used, but they tend to have low radiation efficiency in printed antennas or narrow band in series-fed metallic slotted-waveguides arrays.

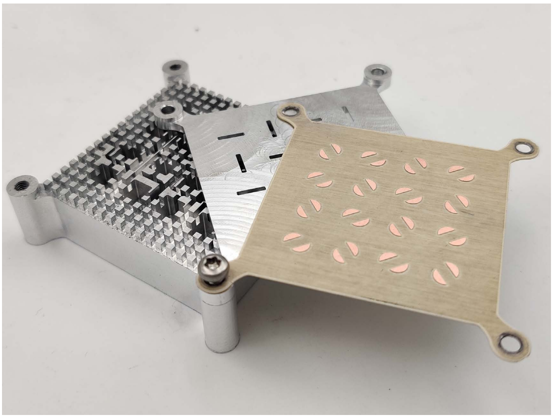

FIGURE 1. Fabricated low-profile circularly-polarized sequential rotation fed 4 × 4 array antenna.

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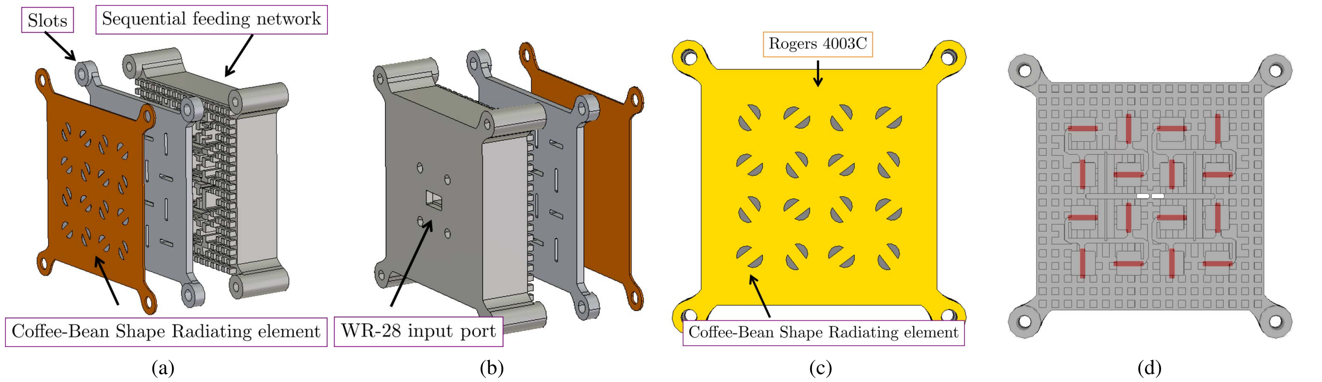


FIGURE 2. Different schematic views of the antenna: (a) Front perspective view with the parts exploded for better visualization; (b) exploded view from below; (c) assembled antenna top view, (d) top view of the antenna with the cover hidden and highlighting the position of the slots.

An alternative that avoids this type of problem is using all-metal polarizers on a slot [13], [14] since full-metal corporate-fed components are commonly preferred for SATCOM. Still, of course, they are also usually bulky and heavy. While it is true that a certain lightness and low cost can be achieved with the new plastic plating techniques, the bulkiness is hardly avoidable [15].

Moving one step further, and with all these assets available, sequential rotation feeding networks have also often been studied to improve the AR bandwidth of circularly-polarized array antennas. Many approaches to implement sequential rotation feed networks have been proposed [16]–[20]. Interestingly, and to some extent logically as stated in [20], there are scarcely all-metal sequential rotation feeding networks due to the complexity of the sequential rotation feeding mechanism, especially when employing hollow waveguides. Here, a gap waveguide (GW) network is used to achieve a wideband design with competitive characteristics.

The choice to use GW technology in this case is not trifling due to several considerations. First of all, it must be taken into account that the size of antennas in the millimeter-wave band can complicate manufacturing and, above all, assembly. Bed of nails, specific to GW, has proven to be an effective alternative to conventional waveguides for confining the field within the waveguides even in the presence of air gaps between metal parts that ideally should be in contact.

This has been widely reported and demonstrated in the past on multiple antennas [21]–[23].

Thus, this antenna presents a coffee-bean-shaped radiating element fed by a novel single-layer sequential rotation network in a 2×2 unit cell using a horizontally polarized groove gap waveguide (Figs. 1 and 2).

The technical details of this work are presented now as follows. Section II provides all the design aspects that make this antenna particular, from the sequential rotation feeding network to the radiating element. Section III is devoted exclusively to the experimental work and appropriately compared and discussed against the simulations. Section IV ends with the conclusions.

II. ANTENNA DESIGN

This section describes the most specific features of this antenna in detail. The aperture is 50×50 mm^2 and 18 mm thick. While this is a prototype of small dimensions, the corporate-feed network is perfectly scalable to achieve arrays of higher gain. Here, the experimental breadboard is presented as a proof of concept. The ultimate goal is to use an element with good, but not excellent, polarization purity and then, thanks to a sequentially rotated feeding network, improve the AR bandwidth in a low-profile antenna as much as possible. Therefore, the critical elements in this antenna are the circularly-polarized element and the novel single-layer rotation feed network, which are detailed below.

A. COFFEE-BEAN RADIATING ELEMENT

The high purity of flat panel antennas has hardly been approached in the past, as also recently pointed out by other authors [1]. There are different methods to address the problem, as seen in the introductory part. Our proposal is an element as simple as possible, both in terms of design and fabrication. Such element resembles a coffee bean from a top view and is capable to transform the linear polarization radiated by a slot into circular polarization in a simple and intuitive way.

In [24], the basic idea of this simple structure was presented for the first time. By combining the radiation of a conventional rectangular slot and this coffee-bean-shaped parasitic element, a circularly polarized wave is generated, reaching an AR below 3 dB from 27.5 GHz to 31 GHz. This particular band was specifically chosen because it is the one regulated for transmission in SATCOM on-the-move applications in Ka-band. However, that work did not delve into an experimental validation of the element. While this was a good starting point, sometimes a 3 dB threshold is insufficient for specific applications, and even better circular polarization purity, with an AR below 1.5 dB, must be achieved. This challenge will be faced in the next section, where thanks to sequential rotation techniques, further improvement in AR is reached.

TABLE 1. Featured dimensions of the prototype.

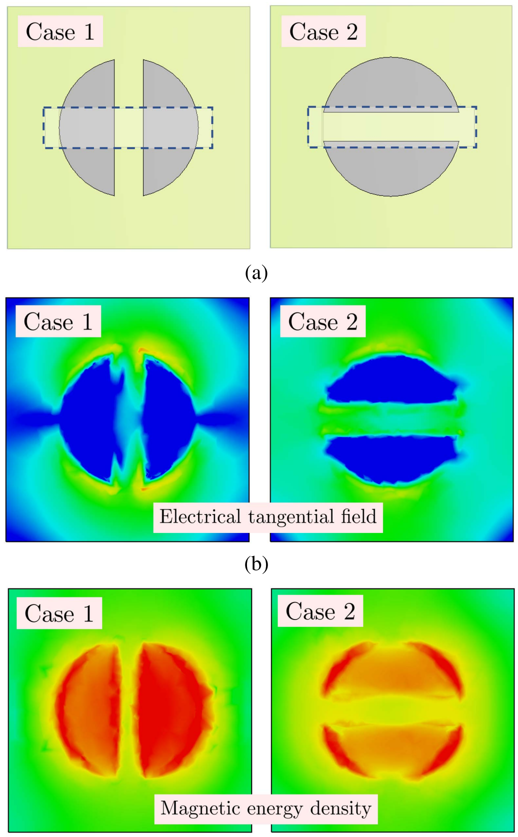
-	l_{in1}	l_{in2}	w_{in1}	w_{in2}	w_{RGWa}	w_{RGWb}	w_p	p_p	h_{RGW}	h_p	w_{GGW}	h_c	h_s	h_{RO}	h_a
Dim. (in mm)	5.5	6.85	2.2	3.556	3.22	0.35	1.4	2.5	2.15	2	1	0.035	2	0.51	1.06

TABLE 2. Comparison with other sequential feed antennas.

	Freq. Band	Number of Elements	1.5 dB Axial Ratio BW(%)	Total layers	Max Rad. Eff.	Antenna Physical Size (λ^2)	Peak Gain (dBi)	Tech.
[20]	Ka	8×8	≈ 13%	3	80%	$41\lambda^2$	23.5	GW
[25]	V	4×4	≈ 11%	7	n/a	$38\lambda^2$	20.5	PCB
[26]	Ka	16×16	≈ 5%	2	n/a	$152\ \lambda^2$	25.5	SIW
This work	Ka	4×4	≈ 14 %	3	85%	$16\lambda^2$	19.24	GW

The principle of operation of the polarizing element is to use a combination of slot and dipoles. The basic geometry, shown in Fig. 3a, consists of a metallic circle from which a central strip is removed. A vertically and a horizontally removed strips are shown for illustrative purposes. Note that in the final design, the eliminated central strip is rotated 45° with respect to the lower horizontal slot. Then, if the element is illuminated with the strip vertically, it behaves like an array of two parallel dipoles. When the strip is horizontal, it acts as a slot. The behavior of the tangential electric field and magnetic energy density are shown in each case in Figs. 3b and 3c, respectively. By varying the inclination angle, a hybrid slot and dipole performance can been achieved, and it is well known that an orthogonal dipole and slot can produce good circular polarization purity.

The simplicity of this element relies on a few tuning details. In the end, the concept consists of two semicircles placed just above the slot. Core parameters for good purity are the radius of the semicircles, their angle of rotation, and the distance between them, all indicated in Fig. 4.



(c)

FIGURE 3. Description of the behavior of the fields at two positions of the coffee-bean-shaped radiating element. (a) Basic cell with the central strip of the circle perpendicular to the slot (Case 1) and parallel to it (Case 2); (b) and (c) show the tangential electric field and magnetic energy density, respectively.

B. SEQUENTIAL ROTATION FEEDING NETWORK

Our starting point is the coffee-bean element in [24], which exhibited a simulated 3-dB axial ratio from 27.5 GHz to 31 GHz. However, this is not enough for SATCOM applications, where AR values as low as 1.5 dB are often required. As it is well-known, the sequential rotation technique significantly improves AR in those antennas where it is implemented. Here we describe the sequential rotation arrangement on the coffee-bean element.

Ultimately, the manufactured and measured antenna has 4 × 4 radiating elements, but we choose to describe the unit cell composed of 2 × 2 elements for a more precise explanation. A descriptive scheme of this 2 × 2 cell is presented in Fig. 5a. Notice that the network is embedded in a bed of nails, but this subplot has been made transparent for a clearer view of the network. The input port of the sub-array is excited by a ridge gap waveguide (RGW) then connected to a horizontally polarized groove gap waveguide (GGW). This type of combination was first presented in [23] and later employed as a functional alternative solution for compact single-layer antenna arrays [27], [28]. Then, the rest of the network is exclusively composed of GGWs feeding each square cavity conveniently. The side dimension of these square cross-section cavities is 4.8 mm, which is approximately λ/2 at the upper frequency of the working band (31 GHz). Note that the four cavities that make up the 2 × 2 subarray are fed from different sides and with the appropriate phase to achieve the desired sequential rotation feeding. In this regard, all the parameters involving the input port (Fig. 5b), the groove gap waveguide, and the ridge gap waveguide are embedded in the bed of nails (Fig.5c) are indicated in Table 2.

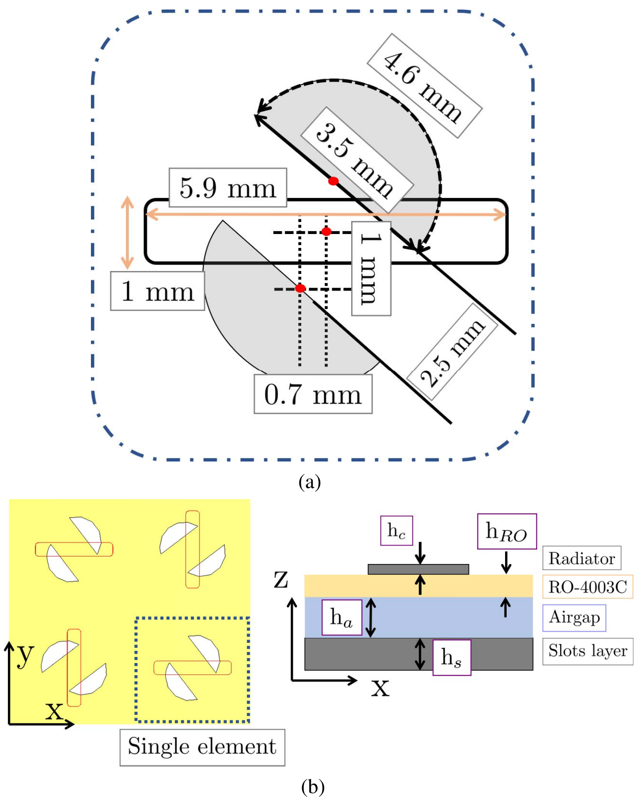


FIGURE 4. (a) Coffe-bean-shaped radiating element dimensions. (b) Top view of the 2 × 2 subarray and side view schematic of the lid, including the slots and the radiators.

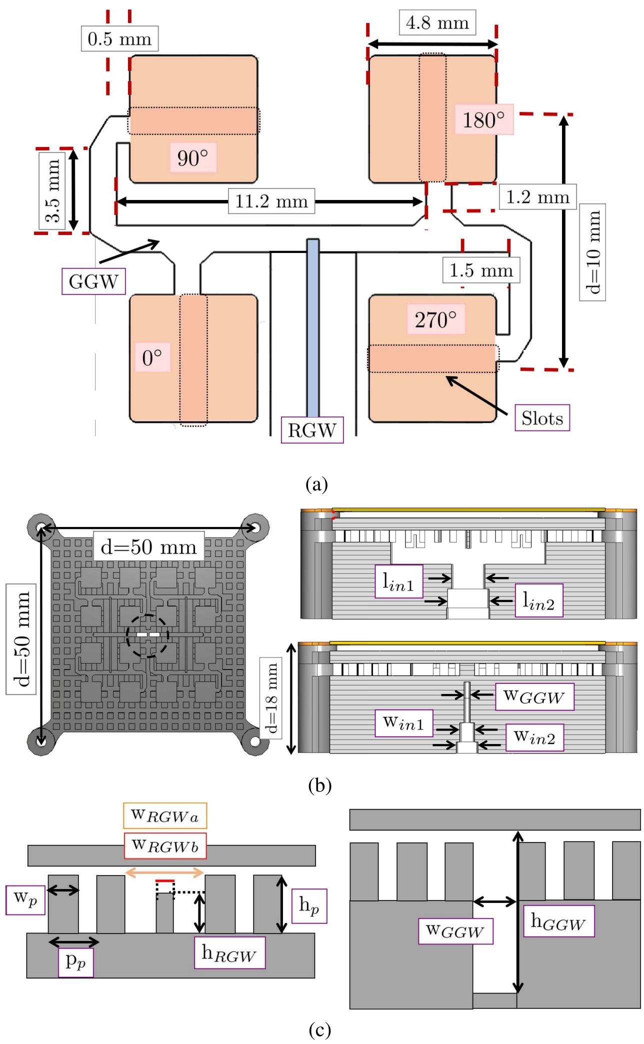


FIGURE 5. Antenna schematics. (a) Top view of the sequential rotation network embedded in the bed of nails. (b) Top and side views of the prototype. Main dimensions of the input port are indicated.
(c) Dimensions of the groove gap waveguide and ridge gap waveguide used in the feeding network.

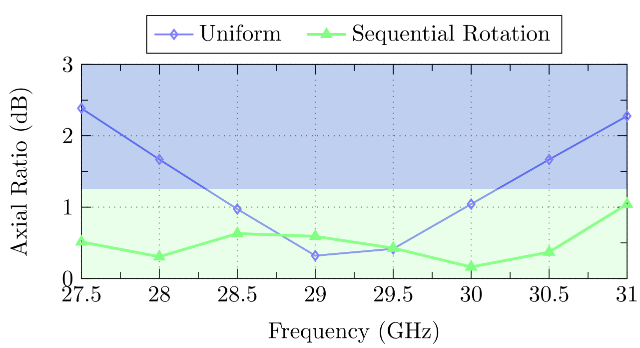


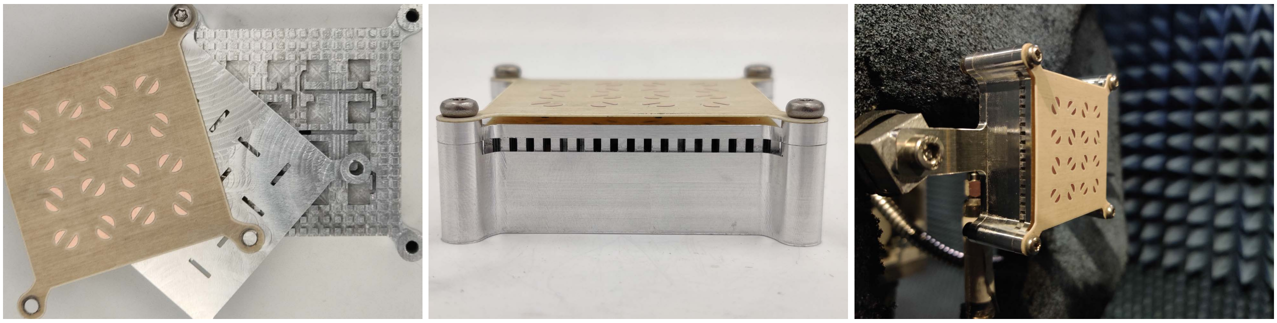
FIGURE 6. Simulated AR comparing a 2 × 2 CP array antenna either uniformly or sequentially rotation fed. The area below 1.25 dB is indicated with green shading and the area between 1.25 dB and 3 dB is marked with blue shading.

It may seem a priori that it becomes a complex and unwieldy network, but this is not entirely so. This approach has been used countless times in planar technology [29], [30]. The difficulty in transferring the idea from the planar world to hollow waveguide structures has been in achieving such a compact design to have the elements close enough (i.e., within one wavelength). The key point is to use the narrow-face waveguide to make the network much more compact. The cost of using E-plane power dividers is that the height of the lower structure is higher than if they were H-plane waveguides. However, it is a price worth paying to have all the elements close together in a single layer. Also, note that the total height of the antenna, including the coffee-bean parasitic element, is 1.8 cm only.

Lastly, the improvement provided by using this feeding network is demonstrated in Fig. 6. This graph shows the AR obtained by a 2 × 2 array with all elements in phase with a blue line. The network is then replaced by the one proposed in this work. Note that the radiating element must also be rotated 90° sequentially according to the network as shown above in Figs. 2c and 4b. Thus, while the uniformly fed array provides an AR of less than 3 dB in a 4 GHz bandwidth, thanks to sequential rotation, the AR flattens to below 1 dB for the same frequency range.

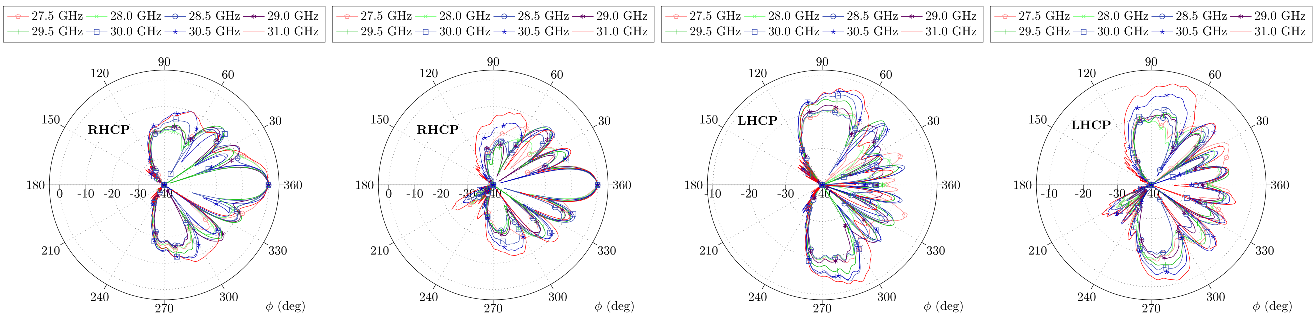
III. EXPERIMENTAL RESULTS

An experimental measurement campaign carried out on the manufactured prototype (Fig. 7) is now presented. Fig. 8 shows the radiation patterns over the entire bandwidth of interest, i.e., from 27.5 GHz to 31 GHz, in 500 MHz steps, in total eight different frequencies. For better clarity of the plots, they are separated into four subfloats showing the two



(a) (b) (c)

FIGURE 7. Different views of the fabricated antenna. (a) Top view with the pieces slipped for better visualization, (b) side view of the assembled prototype, and (c) antenna under measurement in the anechoic chamber.



(a) (b) (c) (d)

FIGURE 8. Normalized copolar measured radiation patterns for several frequencies: (a) XZ-plane and (b) YZ-plane; and crosspolar: (c) XZ-plane and (d) YZ-plane.

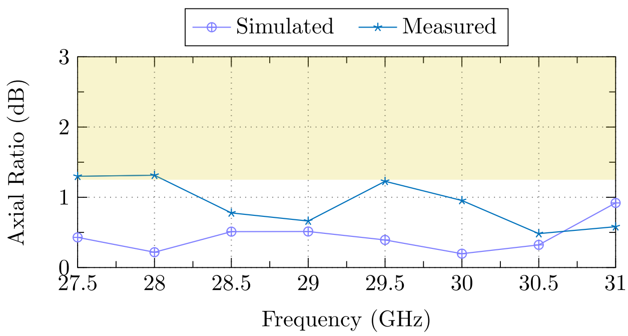


FIGURE 9. Measured and simulated axial ratio of the proposed antenna. Threshold of 1.25 dB is highlighted in yellow.

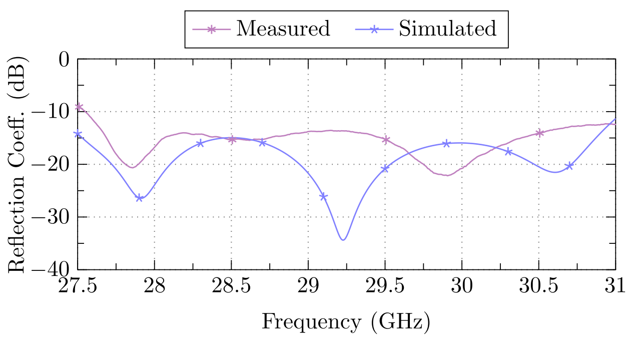


FIGURE 10. Measured and simulated reflection coefficient of the proposed antenna.

co-polar (RHCP) and cross-polar (LHCP) patterns in the two principal antenna cuts (XZ and YZ planes). Good stability

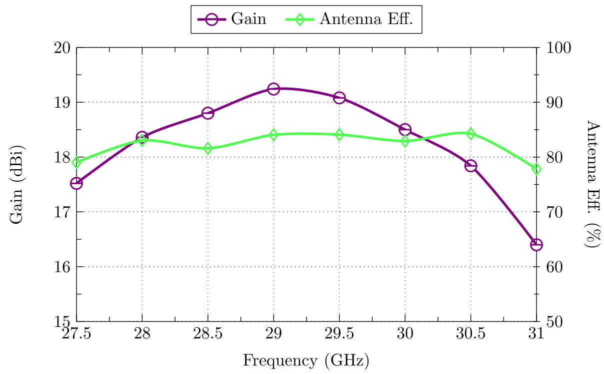


FIGURE 11. Measured antenna gain and antenna efficiency.

of all the patterns is clearly appreciated, even though they seem to be more stable in the center of the band. Only slight deterioration appears in the lower part of the band of the XZ plane. Regardless, it can be seen that the ratio between the co-polar and the cross-polar components in the broadside direction is always higher than 20 dB, which indicates a good CP purity. Fig. 9 shows the comparison between the measured and the simulated AR. While the simulated axial ratio did not exceed 1 dB, the measurement does not exceed 1.3 dB, thus validating the excellent performance of combining the coffee bean-shaped radiating element and the sequential rotation feed. As for the rest of the essential features of the antenna, the reflection coefficient obtained is also shown and compared with the simulated one in Fig. 10.

An average measured gain of 18 dBi has been obtained with a good average antenna efficiency of 80%, relatively constant throughout the band. Fig. 11 shows the measured values in equispaced frequencies along the band of interest. A maximum peak gain of 19.24 dBi is observed at 29 GHz. For the sake of framing these results, a comparative table including recent works on sequentially fed antennas is finally provided in Table 2. It is worth highlighting the good AR bandwidth below 1.5 dB for the proposed low profile and practically all-metal antenna.

Finally, it is appropriate to discuss why the reflection coefficient and AR do not fully agree between simulation and measurement. While a firm assertion is difficult, some plausible conjectures can be guessed. For example, the usual possible manufacturing deviations and a slightly visible warping of the dielectric sheet could be highlighted. The RO4003C sheet on which the copper coffee-bean parasitic elements are located is 0.5 mm thick, suspended 1 mm above the radiating slots and only supported by the four corner poles. A better approach for larger antennas might be to stick this dielectric layer on a near-air permittivity foam to avoid this slight warping of the layer. At any rate, it has been proven that this fact has not been an obstacle to obtain an excellent polarization purity and S_{11} below -10 dB along the whole 3.5 GHz bandwidth.

IV. CONCLUSION

An antenna with a measured axial ratio below 1.3 dB from 27.5 GHz to 31 GHz, typically a critical requirement in SATCOM on-the-move, is presented. This Ka-band 4×4 circularly polarized antenna array consists of three pieces. The thickest piece contains a sequential rotation distribution network to excite the cavities, all embedded in a bed of nails. This piece is coupled to an array of slots. Finally, the CP performance is improved by using a coffee-bean-shaped element. While this element already provides CP by itself, using the rotational feed significantly improves the CP purity. Taking advantage of this feature, it is possible to extend the AR bandwidth with respect to the 1.25 dB upper bound typically required in highly-demanding applications in the Ka-band.

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