An Electrically Large Metallic Cavity Antenna With Circular Polarization for Satellite Applications

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***Abstract*—An electrically large metallic cavity antenna with circular polarization (CP) is proposed in this letter. The aim is to increase the size of satellite antennas working in the Ku-band and other higher-frequency bands through low cost and easy fabrication. A brass C-band antenna prototype is designed, fabricated, and measured for concept verification. The overall dimensions of the antenna are $0.67\lambda_0 \times 0.67\lambda_0 \times 0.83\lambda_0$ at the working frequency. The resonant mode of the proposed cavity antenna is excited by a coaxial feeding probe, and circular polarization is realized by an inserted perturbation screw. The measured impedance bandwidth for $|S_{11}| \leq -10$ dB and 3-dB axial-ratio bandwidth are 1.02 GHz (6.07–7.09 GHz) and 320 MHz (6.59–6.91 GHz), respectively. The measured gain is 8.5 dBic across the whole 3-dB axial-ratio bandwidth. The measured 3-dB axial-ratio beamwidths at the central frequency are 150° and 148° in the xoz- and the yoz-planes, respectively, which is wide enough to cover the $>$0-dBi gain beamwidths of 120° for practical engineering applications. The measured and the simulated results show good agreement.**

***Index Terms*—Circular polarization (CP), electrically large, metallic cavity antenna (MCA), satellite applications.**

I. INTRODUCTION

SATELLITE communications are being developed from low-frequency bands like the L-band and the S-band to high-frequency bands such as the Ku-band and the Ka-band to obtain broader bandwidths, higher data rates, and higher gains with the same radiating aperture. Therefore, the need for high-frequency-band satellite antenna designs is becoming increasingly more urgent. Meanwhile, circularly polarized antennas, which are immune to the orientation and the motion of the transceivers, are usually required for satellite systems to enhance link stability and reliability. Microstrip patch antennas (MPAs) adopting slots and slits as geometric perturbations have been proposed in [1] and [2] to implement circular polarization (CP), and many other studies have been done to broaden the antennas' axial-ratio beamwidth [3]–[5]. A circularly polarized MPA mounted on a pyramidal ground plane and partially enclosed by a flat conducting wall was designed in [3], and a 3-dB axial-ratio beamwidth of more than 130° was realized. A dual-frequency dual circularly polarized patch antenna with 3-dB axial-ratio beamwidths of more than 165° and 175° for the high- and the low-frequency bands, respectively, was presented in [4] by extending the substrate beyond the ground plane. In spite of the advantages such as low profile, light weight, and easy fabrication for low-frequency satellite systems, these MPAs' performance will deteriorate severely due to manufacturing deviation when scaled to high-frequency bands like the Ku-band where the wavelengths are only a few millimeters with a certain substrate attached. In addition, their power-handling capability is limited.

Cavity-backed circularly polarized antennas have been proposed to realize broadband and high-gain performances, where air-filled metallic cavities [6]–[11] or substrate-integrated cavities [12]–[14] are adopted to achieve unidirectional radiation patterns. A sequentially rotated four-element slot antenna fed by a microstrip network to achieve CP and backed by a rectangular metallic cavity was designed in [6], realizing a 3-dB axial-ratio bandwidth of 15% and 8.7-dBic gain centered at 6.0 GHz. In [8], a combination of a cavity-backed slot and strip loop radiating circularly polarized waves at two adjacent frequencies was proposed to achieve bandwidth enhancement. A circularly polarized stacked patch antenna excited by a novel single feed was developed in [10] to increase the axial-ratio bandwidths, and a short horn was mounted to get high gain. A substrate-integrated cavity-backed circularly polarized patch antenna was investigated in [14], and techniques for feeding transitions and bandwidth enhancement were designed and experimentally proved.

However, separate circularly polarized radiators need to be developed for cavity-backed circularly polarized antennas, and the cavities only serve as reflectors. This letter presents a cylindrical metallic cavity antenna (MCA), and circularly polarized waves are realized by structural perturbations to decompose the cavity resonant mode into two orthogonal components with the same amplitude but 90° phase difference, hence saving the trouble of designing an additional circular polarizer compared to cavity-backed antennas. The dimensions of the presented cylindrical MCAs are generally larger than half a wavelength in the center operating frequency, which is easy to fabricate and low-cost for high-frequency satellite applications. A metallic C-band prototype is designed and fabricated to prove our concept, and good agreement is obtained between the simulated and the measured results.

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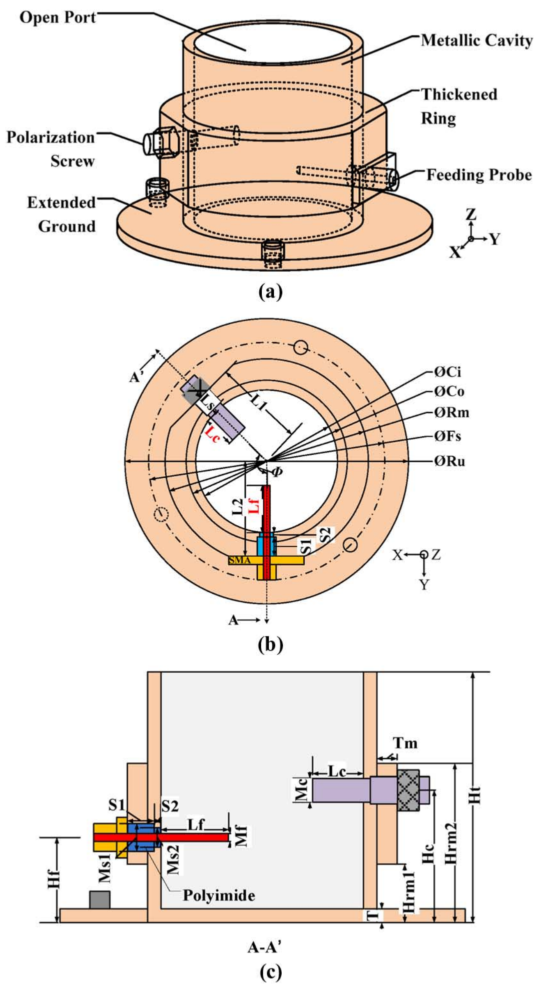


Fig. 1. Geometry of the proposed circularly polarized MCA: (a) 3-D view; (b) top view; (c) sectional view.

TABLE I
DIMENSIONS OF THE DESIGNED C-BAND MCA

Parameter	$ØC_i$	$ØC_o$	$ØR_m$	$ØF_s$	$ØR_e$	L_1
Value(mm)	30.0	34.0	43.0	50.0	60.0	20.0
Parameter	L_2	L_c	L_f	H_f	M_f	S_1
Value(mm)	20.0	7.6	10.0	12.0	1.27	4.0
Parameter	S_2	M_{s1}	M_{s2}	M_c	T_m	T
Value(mm)	1.0	4.1	3.0	3.0	3.0	2.0
Parameter	H_{rm1}	H_c	H_{rm2}	H_t	Φ	
Value(mm)	8.0	19.5	23.5	37.0	135°	

II. ANTENNA DESIGN

A. Antenna Structure

The geometric structure of the proposed MCA is shown in Fig. 1. A C-band prototype made of brass with right-hand circular polarization was designed, and details of the dimensions are shown in Table I.

The size of the radiating aperture is 30.0 $(0.67\lambda_0) \times$ 30 mm^2 $(0.67\lambda_0)$ in the horizontal plane, and the overall height is 37 mm $(0.83\lambda_0)$, where λ_0 is the wavelength at the center frequency 6.74 GHz. The proposed antenna consists of an air-filled cylindrical cavity, a feed probe, a polarization screw, a thickened ring surrounding the outer wall of the cavity, and an extended ground plane, as shown in Fig. 1(a). Fig. 1(b) and (c) gives the top view and a sectional view, respectively. The feed probe is used to excite the basic operating mode of the cavity, and its inserted length L_{f} together with its vertical height H_{f} determines the impedance matching of the designed antenna. The upper port of the cylindrical cavity is open, while the lower port is kept short so as to radiate energy unidirectionally. Meanwhile, circularly polarized waves are realized by the polarization screw inserted in the middle of the cavity height to decompose the exciting fields into two orthogonal components. The circularly polarized frequency and purity are mostly influenced by the diameter M_{c} and the inserted length L_{c} of the screw. The rotating direction of the circularly polarized waves is determined by the angle Φ between the feeding probe and the polarization screw, as indicated in Fig. 1(b). Right-hand circular polarized waves are realized when Φ is 135°, and left-hand circular polarized waves are obtained when the angle Φ is further extended to 225°.

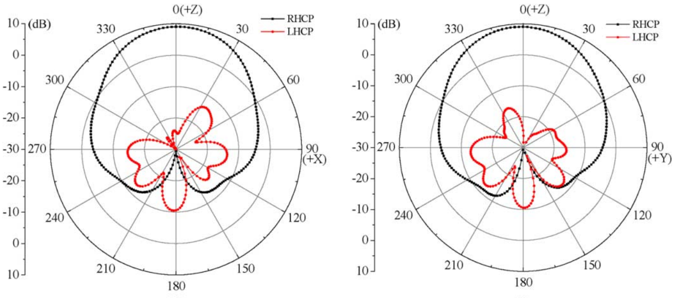
The thickened ring is used to fix the SMA connector and the polarization screw, and the shield of the feed coaxial cable is connected to the outer wall of the cavity. This fixing structure has been carefully designed for convenience of installation and minimization of cross polarization. The only dielectric employed in the antenna is a small piece of polyimide with a relative permittivity ε_{r} of 3.8, which is chosen to isolate the feeding probe from the cavity wall and also to prevent damage by cosmic rays, as shown in Fig. 1(c). The lower port of the cavity is short and can work as a reflecting ground plane. An extended ground plane with a size of 60.0 $(1.34\lambda_0) \times 60$ mm^2 $(1.34\lambda_0)$ is added outside the lower port to mount the antenna onto the surface of satellites by screw fasteners.

B. Antenna Characteristics

Considering the capacitance effect caused by the edge fields between the radiators and the ground, the resonant lengths of the commonly used antenna units such as dipoles, microstrip patch antennas, and slot antennas are usually smaller than half a wavelength [15], and they will become much smaller when the radiators are attached to substrates with a certain dielectric constant. Therefore, they require a high degree of fabrication accuracy to maintain good performances when applied to high-frequency bands like the Ku-band and the Ka-band. However, the dimensions of air-filled metallic cavity antennas are larger than half a wavelength, as indicated by the dispersion (1), where k is the total propagating wave number, k_{t} is the wavenumber in the transverse section, and k_{z} is the wave number in the longitudinal section

$$k^2 = k_{\mathrm{t}}^2 + k_{\mathrm{z}}^2. \tag{1}$$

Due to the inversely proportional relation between wavenumber and wavelength, the resonant lengths in both the transverse and the longitudinal sections must be larger than half a wavelength. As a result, the proposed metallic cavity antennas are electrically larger than traditional antennas, which can reduce the demand for processing precision, make the fabrication much easier, and also lower the manufacturing cost for high-frequency-band satellite applications.



(a) (b)

Fig. 2. Simulated radiation patterns of realized gain at 6.74 GHz for the designed C-band MCA: (a) xoz-plane; (b) yoz-plane.

Combining the theory of an electrically large antenna design and circularly polarized techniques, we finally propose a metallic cavity antenna as shown in Fig. 1. A C-band example is designed, and its performance is simulated and analyzed by Ansoft HFSS based on the finite element method (FEM). The simulated impedance matching characteristics and the axial-ratio bandwidth are shown in Figs. 5 and 6, respectively. Good impedance matching can be achieved by adjusting the probe length and its vertical position, whereas the axial ratio can be tuned to a minimum by changing the size and the length of the inserted screw. The axial-ratio bandwidth is also influenced by the vertical height of the polarization screw. The simulated -10-dB impedance bandwidth is 1.05 GHz (6.05–7.10 GHz), and the simulated 3-dB axial-ratio bandwidth is 300 MHz (6.58–6.88 GHz).

Fig. 2 demonstrates the radiation patterns of realized gain for the designed metallic cavity antenna centered at 6.74 GHz where a minimum axial ratio of 0.12 is realized. The patterns are symmetrical in both the xoz- and yoz-planes. The maximum realized gain in the two planes is 9.0 dBi at the boresight. The simulated gain is about 9.0 dBi across the whole axial-ratio bandwidth with a fluctuation of 0.25 dBi, as shown in Fig. 6. In practice, $>$0-dBi gain beamwidth is frequently used as the specification for low earth orbit (LEO) satellite applications. The simulated $>$0-dBi gain beamwidths are 118° and 120° in the xoz- and yoz-planes, respectively. The simulated axial-ratio beamwidths in the two principal planes are shown in Fig. 3, where we can see that the simulated 3-dB axial-ratio beamwidths at the central frequency are 156° and 154° in the xoy- and the yoz-planes, respectively. Therefore, the designed electrically large C-band metallic cavity antenna with circular polarization has a relatively high gain, and the 3-dB axial-ratio beamwidth is wide enough to cover the $>$0-dBi gain beamwidth for practical engineering applications.

III. MEASUREMENTS

An antenna prototype for C-band satellite communication systems is fabricated and measured to verify experimentally our design, and the detailed parameter values are listed in Table I. Fig. 4 shows a photograph of the mechanically processed cavity antenna sample. The performance of the manufactured antenna is measured and compared to the simulated results.

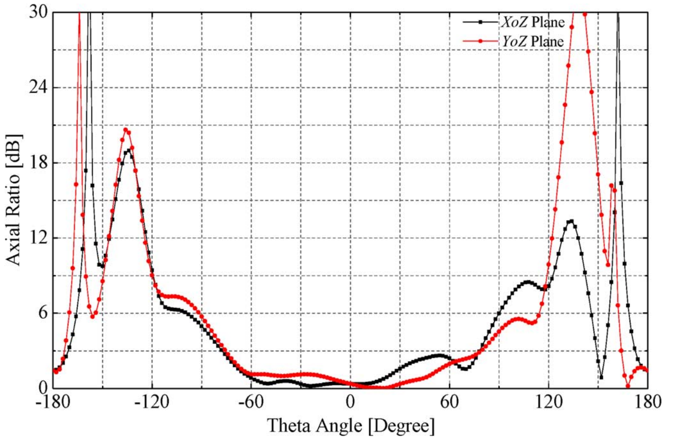


Fig. 3. Simulated axial ratio of the designed C-band MCA at 6.74 GHz in the two principal planes.

Fig. 4. Photograph of the fabricated antenna prototype.

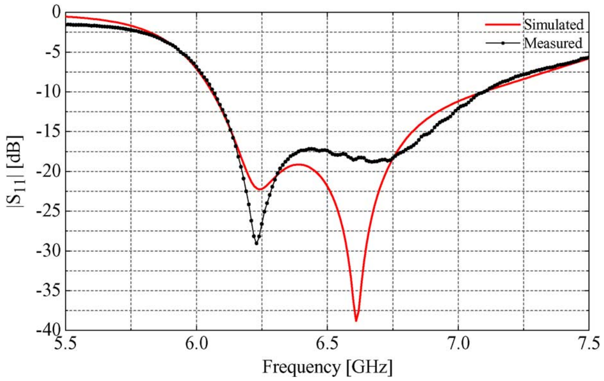


Fig. 5. Measured and simulated $|S_{11}|$ of the designed metallic cavity antenna.

The measured and the simulated reflection coefficients of the antenna prototype are compared in Fig. 5, and the measured and the simulated impedance bandwidths for $|S_{11}| \leq -10$ dB are 1.02 GHz (6.07–7.09 GHz) and 1.05 GHz (6.05–7.10 GHz), respectively, which shows good agreement. The measured and the simulated axial ratios at the boresight are shown in Fig. 6, and the measured and the simulated 3-dB axial-ratio bandwidths are 320 MHz (6.59–6.91 GHz) and 300 MHz (6.58–6.88 GHz), respectively. The measured and the simulated boresight gains are also compared in Fig. 6. The measured gain varies from 8.2 to 8.9 dBic across the 3-dB axial-ratio bandwidth. The measured

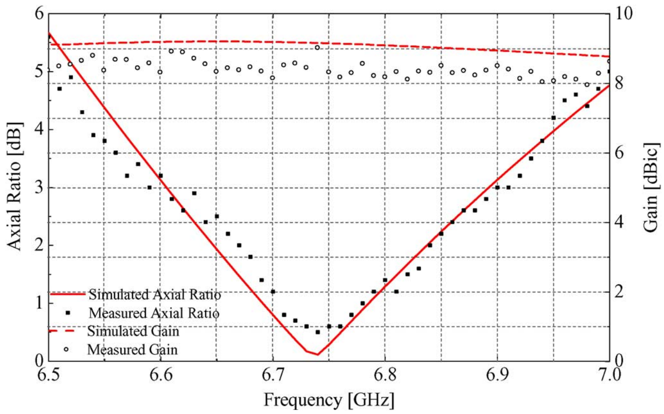
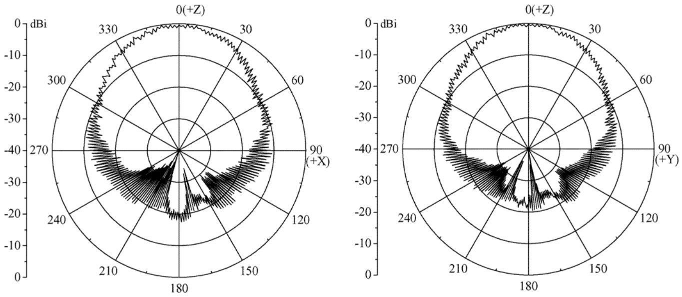


Fig. 6. Measured and simulated axial ratio and gain at the boresight.



(a) (b)

Fig. 7. Measured normalized circularly polarized radiation patterns at 6.74 GHz: (a) xoz-plane; (b) yoz-plane.

and the simulated results differ slightly, mainly because of the mechanical tolerances, the uncertainty of the dielectric constant, and the measurement system setup, but overall they agree well with each other.

The measured circularly polarized radiation patterns of the antenna prototype at 6.74 GHz in both the xoz- and yoz-planes are plotted in Fig. 7, where we can see that the radiation patterns in the two principal planes show similar symmetrical characteristics. The measured $>$0-dBic gain beamwidths are 120° and 122° in the xoz- and yoz-planes, respectively, and the measured 3-dB axial-ratio beamwidths in the two planes are 150° and 148°, respectively. The measured radiation patterns agree well with the simulated ones, and the measured axial ratio is below 3 dB across the whole $>$0-dBic gain beamwidth.

IV. CONCLUSION

This letter proposes an electrically large metallic cavity antenna that is circularly polarized. The dispersion equation of the resonant cavity is applied to explain the antenna's electrically large characteristics. Circular polarization is realized by an inserted screw positioned in the diagonal line of the feeding probe. A C-band prototype has been experimentally studied to validate the simulation. The measured impedance bandwidth and 3-dB axial-ratio bandwidth of the designed antenna are 15.1% and 4.7%, respectively. The antenna's 3-dB axial-ratio beamwidth well covers the $>$0-dBic gain beamwidth. In addition, the designed antenna has symmetrical radiation patterns in both principal planes and low back radiations. The proposed antenna has the merits of low cost, low loss, and high power-handling capability. It can also reduce the stringent requirement for machining precision and alleviate the severe performance degradation caused by processing deviation, which makes the antenna a suitable candidate for the Ku-band and other higher-band satellite communication systems.

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