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Low Profile Dual-Band (K-/Ka-band), Wideband and Dual-Circularly Polarized Tile-Based Antenna for Low Earth Orbit Satellites

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Abstract

This paper proposes a novel multi-mode cavity-backed slot and tile-based antenna with functions of low profile, dual-band (K-/Ka-band), wide bandwidth, and dual-circularly polarized. For a low profile dual band and dual polarization antenna, the main technical challenges are to simultaneously achieve the functions of dual-band, wide bandwidth and reduction of multi-mode interference. This work proposes an innovative cavity-backed slot antenna generating multi-modes to fulfill both dual-band and wide bandwidth requirements. The proposed slot antenna has novel stepped-cavity walls to excite not only a magnetic dipole mode for low-frequency (K-band) coverage but also to excite an antiphase TM_{20} higher-order mode for high frequency (Ka-band) coverage. It is because that size optimization of the stepped-cavity walls generates many proper resonant paths to create targeting frequencies. Also, to meet the bandwidth requirements of low Earth orbit (LEO) dual-band satellites, this study proposes two matching structures: (1) Disconnected parasitic slots added below the open end of the main slot excite an additional magnetic dipole mode to enhance the bandwidth of the low frequency band, and (2) Multiple branch slots are introduced above the main slot and generate a TE_{20} higher-order mode to enlarge the bandwidth of the high frequency band. According to the measured results and comparison with other related research results, our proposed antenna has superior performances in impedance bandwidth (21.05% in K-band; 12.1% in Ka-band) and AR bandwidth (11.5% in K-band; 8.7% in Ka-band), which meets the requirements of dual-band LEO satellites.

1. Introduction

With the deployment of 6G mobile communications, low Earth orbit (LEO) satellites have become an important topic. The demand for millimeter-wave antennas in LEO satellites includes characteristics such as low profile, dual-band operation, wide bandwidth, dual circular polarization, and array adaptability. Dual-band antennas commonly utilize stacked elements or multi-mode antennas to achieve dual-band performance. In [1], by using two stacked-curl radiators, the proposed antenna attains both K- and Ka-bands with broad axial ratio (AR) bandwidths. In [2], the proposed antenna generates a higher-order mode to achieve dual-band operation. However, in order to maintain bandwidth and prevent mode interference in these two methods, it is difficult to keep a low profile and minimize the area in [1] and [2]. In [3], meandered vias help compensate for the phase difference caused by the use of a thin substrate. Here, an Antenna-in-Package (AiP) structure is applied to integrate the antenna array and RFICs easily [4].

In this paper, a novel multi-mode cavity-backed slot and tile-based antenna for LEO satellite communications is proposed to address the above mentioned technical challenges related to the requirements of low profile, dual-band operation, wide bandwidth and dual polarization. The antenna configuration, its working principle and measurement results are illustrated in Section 2. The summary is drawn in Sections 3.

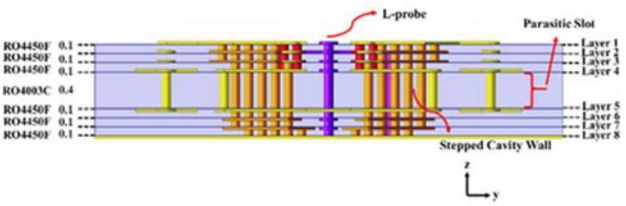
2. Antenna Configuration

As shown in Fig. 1(a), the proposed antenna consists of eight metal layers and seven dielectric layers (layers 1 to 8). Layer 4 is made of Rogers RO4003C substrate ($\varepsilon_r = 3.55, tan\delta = 0.0027$) and the rest of the layers are made of Rogers RO4450F substrate ($\varepsilon_r = 3.52, tan\delta = 0.004$). The thicknesses of the core and prepreg dielectric layers are 0.4 mm and 0.1 mm, respectively. The total thickness of the proposed antenna is about 1 mm. The bottom metal layer is the ground plane of the antenna.

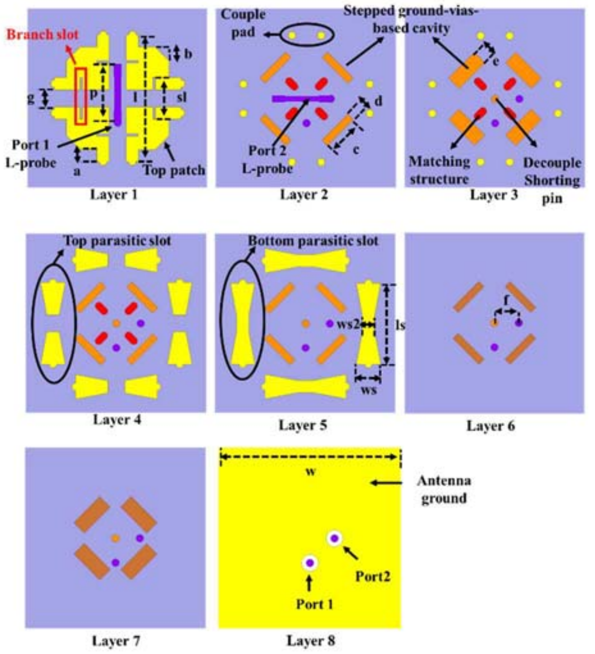
2.1 Antenna Working Principles

1) Cavity-Backed Slot Antenna Exciting K-band Frequency: The layout of the K-band slot antenna radiator and its substrate are shown in Fig. 1(b) on layer 1. Here, a cross-shaped $\lambda/2$ slot operates at 17.7 GHz.

2) Cavity-Backed Stepped-Cavity Walls Generating Ka-band Frequency Compared with the Straight Cavity Wall: The stepped-cavity walls are shown in Fig. 2. This structure applies multilayer via holes to form three stepped-cavity walls with different distances (r1, r2 and r3) from the center axis. By optimizing the distances, the three stepped-cavity walls generate proper resonant paths for the target frequencies. As shown in Fig. 3, the antiphase TM_{20} higher-order mode is excited and covers 27.5 GHz to 29 GHz.



(a)



(b)

Fig. 1. The geometry of the proposed antenna: (a) ide view and (b) top view of antenna layout in each layer, from layer 1 to layer 8 are shown. And each layer includes metallic and substrate parts except layer 8, where l = 5.2, w = 7.5, sl = 1.7, p = 2.4, a = 0.5, b = 0.56, c= 1.5, d = 0.3, e = 0.6, f = 1, g = 0.7, ls = 3.34, ws = 1, ws2 = 0.45, all in millimeters.

3) Disconnected Parasitic slots Enhancing K-band Bandwidth:

As shown in Fig. 1(b), the disconnected parasitic slots located in layer 4 and layer 5 are added beneath the cavity-backed slot to generate a new resonant slot mode at 19.5 GHz. According to the simulated current flow direction shown in Fig. 4(a) and the simulated electric field directions shown in Fig. 4(b) at 19.5 GHz, the result demonstrate a fundamental slot mode.

4) Branch Slots Enhancing Ka-band Bandwidth:

Although the novel stepped-cavity structure radiates in Ka-band, it cannot meet the frequency bandwidth requirement of 2.5 GHz for LEO satellites. To resolve this problem, a branch slot is introduced in [5] and generates a new resonant higher-order mode at 30 GHz but also induces coupling between the two L-probes. Therefore, a shorting pin is placed below the two L-probes to cut off the coupling current path between these two ports.

5) Dual polarization for K- and Ka-bands:

In order to achieve dual circular polarization for the K- and Ka-bands, two orthogonal L-probes with ±90 degree phase difference are proposed on layer 1 and layer 2.

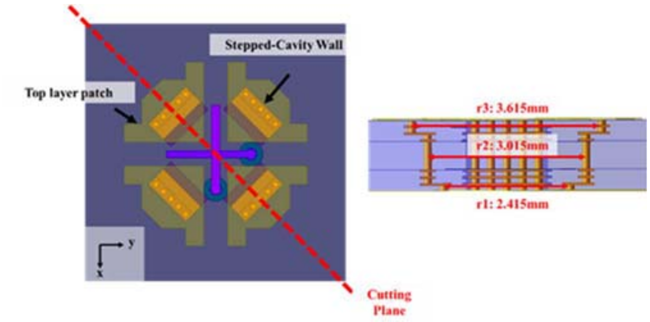
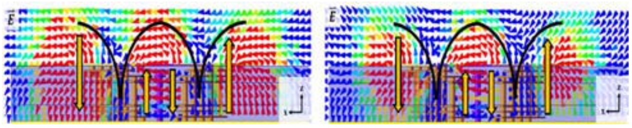
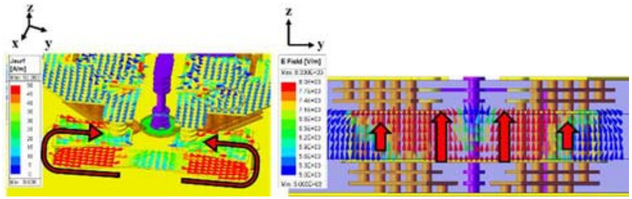


Fig. 2. The top view and side view of the stepped cavity wall.



(a) 27.5 GHz (b) 29 GHz

Fig. 3. The electric fields of antiphase-TM20 mode: (a) 27.5 GHz and (b) 29 GHz. The electric field directions are also shown as arrow directions.



(a) (b)

Fig. 4. (a) The current flow direction and (b) the electric field direction at 19.5 GHz.

2.2 Comparison between Simulation and Measurement Results

As shown in Fig. 5, the proposed antenna has been validated by comparing the simulated and measured S11, S22 and S21, which are matched. The figure shows that the antenna has good impedance matching in the K-band (17-21 GHz) and the Ka-band (27-30.5 GHz). Also, the isolation between the two L-probes in the dual bands is below -20 dB. In Fig. 6, the simulated and measured axial ratio (AR) in the broadside direction of the proposed antenna is less than 3 dB for both 18-20.2 GHz (11.5%) and 27.5-30 GHz (8.7%), which indicates that the proposed antenna has good circular polarization performance in the dual bands. Fig. 7 shows the simulated and measured gains versus frequency of the proposed antenna, where the peak gains are about 6 dBi and 7 dBi for the K-band and the Ka-band, respectively. The simulated and measured radiation patterns are shown in Fig. 8, which include both RHCP (Co-pol) and LHCP (X-pol) for the dual bands at 18 GHz and 28 GHz. The simulation results are close to the measured ones.

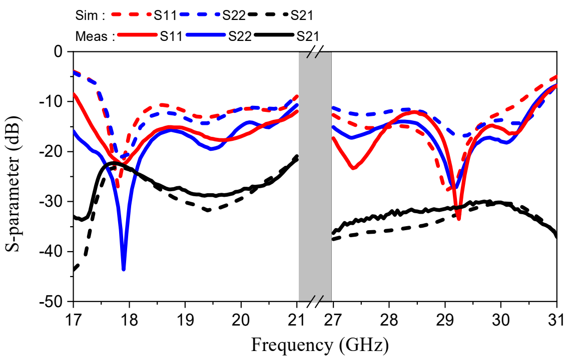


Fig. 5. The measured and simulated S parameters of the proposed antenna.

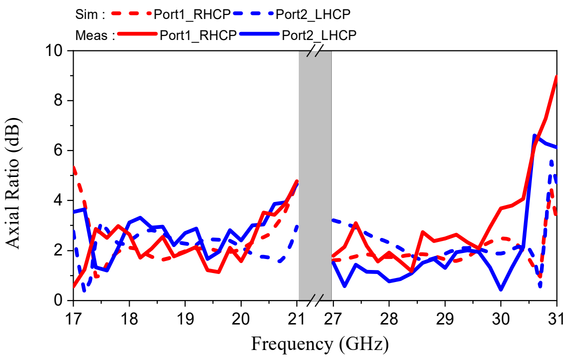


Fig. 6. The measured and simulated AR of the proposed antenna.

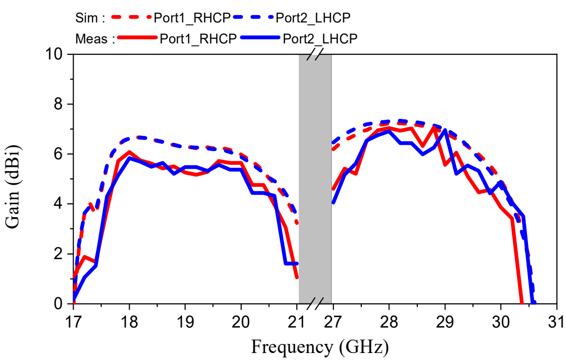
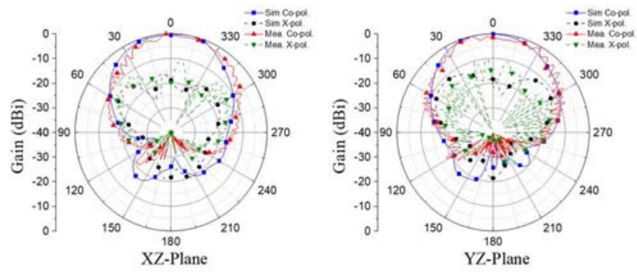
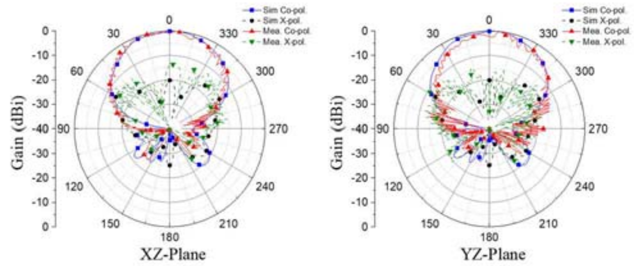


Fig. 7. The measured and simulated gain of the proposed antenna.



(a) 18 GHz



(b) 28GHz

Fig. 8. The dual band radiation patterns (normalized) of the proposed antenna: (a) 18GHz (b) 28 GHz. Co-pol and X-pol cases are both shown.

3. Summary

Table I compares our results with other related research results. It is found that our proposed antenna has superior performances in impedance bandwidth (17-21 GHz, 21.05% and 27-30.5 GHz, 13.79%) and AR bandwidth (18-20.2 GHz, 11.05% and 27.5-30 GHz, 8.7%), which fulfills the requirements of LEO satellites.

Table I Comparison of the proposed dual-band antenna array with other recently reported antenna arrays.

Ref	Impedance Bandwidth	Polarization	HPBW	AR bandwidth (<3dB)	Type	Thickness (λ_0)	Peak gain (peak)
[4]	21.28-24.46 GHz 13.9 %	LP	40°	-	Cavity backed slot	1.95 mm 0.143 λ_0 @ 22 GHz	6.81 dBi
	26.23-31.44 GHz 18.06 %	LP	30°	-			5.15 dBi
[6]	26.3-32.3 GHz 20.5 %	LP	50°	-	SIW Cavity backed slot	1.285 mm 0.12 λ_0 @ 28 GHz	4.8 dBi
	37.4-38.4 GHz 18.06 %	LP	40°	-			9 dBi
[7]	27.7-39.8 GHz 2.6%	RHCP	50°	27.9-28.7 GHz 2.8%	SIW Cavity backed slot	0.889mm 0.08 λ_0 @ 28GHz	8 dBi
	36.1-38.9 GHz 7.5%	LHCP	40°	37.8-38.8 GHz 2.6%			7.9 dBi
This work	17-21 GHz 21.05%	Dual LP/ Dual CP	≈ 90°	18-20.2 GHz 11.5%	Cavity backed slot	1mm 0.06 λ_0 @ 18GHz	6 dBi
	27-30.5 GHz 12.1 %		≈ 55°	27.5-30 GHz 8.7 %			7 dBi

This paper presents an innovative cavity-backed slot antenna with feature of low profile, dual band, and dual circular polarization. The impedance bandwidth and the AR bandwidth of the proposed antenna in the dual bands fulfills the requirements of LEO satellites.

4. Acknowledgements

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