A Compact Low-profile 5G Millimeter-wave Circularly Polarized Antenna Based on LTCC

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Abstract **–** In this paper, a circularly polarized millimeter-wave L-shaped dipole antenna based on low temperature cofired ceramic (LTCC) technology is proposed, which realizes compact size and low-profile performance. The designed antenna consists of radiation patches and the grounded coplanar waveguide-substrate integrated waveguide (GCPW-SIW) feeding structure, which connects each other by two via holes. The radiation patches include a pair of L-shaped patches and four parasitic patches. The simulated results show that the proposed antenna operates from 26.5 to 29.5 GHz for $|S_{11}| < -10$ dB and AR $<$ 3 dB with a peak gain of 6.7 dBic. The antenna element size is only $0.58\lambda_0 \times 0.58\lambda_0 \times 0.056\lambda_0$, where λ_0 is free-space wavelength at the center frequency of 28 GHz. A sample of the antenna is fabricated and measured to verify the proposed design, which has a good agreement with the simulated ones, indicating that the antenna has potential applications for the fifth generation (5G) mm-Wave n257 (26.5 - 29.5 GHz) frequency band communications and satellite communication systems.

Index Terms **–** 5G millimeter wave (mm-Wave), circularly polarized (CP), low-profile, low temperature cofired ceramic (LTCC), substrate integrated waveguide (SIW).

I. INTRODUCTION

To meet the demands of users for high-capacity and high data transmission rate of the fifth generation (5G) mobile communication, the 5G millimeter-wave (mm-Wave) band is being extensively studied and applied [1–2]. As one of the 5G commercial millimeter-wave bands, n257 (26.5-29.5 GHz) frequency band is of great practical significance in the research of the antenna.

The traditional processes of manufacturing circular polarization antennas mainly include printed circuit board (PCB) technology and low temperature cofired ceramic (LTCC) technology. With the rapid development of fabrication technology, miniaturization and integration have become a research hotspot. Especially, LTCC technology has become a good candidate for designing miniaturization and integration of electronic components [3].

Recently, different kinds of LTCC and PCB mm-Wave antennas have been reported for various circularly polarized applications [4–21]. For example, an s-dipole based on PCB is employed to constitute an 8×8 broadband circularly polarized (CP) antenna array, which has an impedance bandwidth of 27.6% and axial ratio bandwidth up to 32.7% [4]. Nevertheless, the antenna size is $0.71\lambda_0 \times 0.71\lambda_0 \times 0.46\lambda_0$, which needs to be further reduced. Similarly, a 4×4 magnetoelectric dipole array is devised in [5], which uses sequential rotary feed network to obtain the wide bandwidth. However, it needs to be further miniaturized. Because the LTCC has unique multilayer technology and high dielectric constant performance compared to the PCB process, it can be used to design miniaturization and integration antennas. Accordingly, a 4×4 60 GHz LTCC helical antenna array is proposed, which achieves a bandwidth of 20% with a small plane size [6]. However, its profile and the antenna structure need to be further reduced and simplified. Meanwhile, an antenna-in-package array with relatively simple structure based on LTCC technology with low-profile has been proposed in [7]. Unfortunately, the antenna sacrifices bandwidth to obtain low-profile characteristics. Accordingly, a LTCC low-profile and wide bandwidth helical antenna is shown in [8]. Moreover, a

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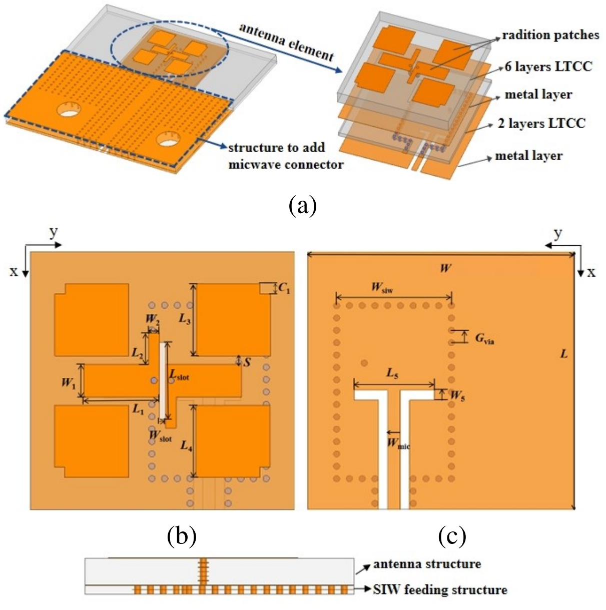
SIW cavity and L-shaped planar probe were combined to form circularly polarized radiation, which realizes high gain performance [9]. However, the axial ratio bandwidth still needs to be enhanced. Therefore, designing a compact, low-profile, and easy to manufacture circularly polarized antenna is a challenging task.

In this paper, a circularly polarized L-shaped dipole antenna with four parasitic patches based on LTCC technology is proposed, which realizes compact size and low-profile performance. The antenna operates at 26.5-29.5 GHz with $|S_{11}|$ < -10 dB and AR < 3 dB. The peak gain value within the operating frequency band is 6.7 dBic. A prototype is fabricated and measured to verify the simulated results, which are basically consistent with the simulated ones.

II. DESIGN OF CP ANTENNA

A. Antenna Geometry

Figure 1 (a) presents the geometry of the proposed antenna, which mainly includes two parts: one is radiation patches with six layers LTCC and the other is the GCPW-SIW feeding structure with two layers LTCC. The L-shaped dipole patches at the top layer are connected with the SIW-based rectangular slot through two via holes. Moreover, four patches with square chamfer are placed around the L-shaped patch as parasitic elements to improve the AR bandwidth. It should be noted that an extra via hole is inserted into SIW to improve the impedance matching. Furthermore, an extra structure is added at the end of the antenna to install the microwave connector.



(a)

(b) (c)

(d)

Fig. 1. (a) 3D view, (b) top view, (c) bottom view of the bottom layer, and (d) side view of the antenna.

Table 1: Dimensions of the antenna (unit: mm)

L	***W***	***Wsiw***	***L1***	***W1***
6.25	6.25	2.7	1.61	0.7
W_2	L_3	L_4	C_1	L_{slot}
0.25	1.65	1.61	0.2	1.9
S	L_5	W_5	W_{mic}	G_{via}
0.2	2.02	0.45	0.29	0.3

B. Design Theory of the Proposed Antenna

Figure 2 gives the improvement process of the proposed antenna structure. Type 1 is the initial structure with a thickness of h = 1.2 mm, and two centrosymmetric L-shaped patches are employed to form orthogonal line current for the sake of producing CP radiation. However, the AR bandwidth cannot meet the requirement of 26.5-29.5 GHz, and the profile needs to be further reduced. Hence, our proposed LTCC employs eight layers to attain a lower profile, as shown in the type 2 structure. Concurrently, the performance of the antenna deteriorates, especially the axial ratio performance. Therefore, four parasitic patches with square chamfer are introduced to compensate the degradation results, as shown in type 3 structure.

Figure 3 displays the simulated results of $|S_{11}|$ and axial ratio of types 1 - 3 antennas. The type 1 has excellent impedance bandwidth according to Fig. 3 (a). However, the axial ratio bandwidth of type 1 does not satisfy the desired bandwidth, and the antenna profile is high as displayed in Fig. 3 (b). Therefore, the type 2 antenna

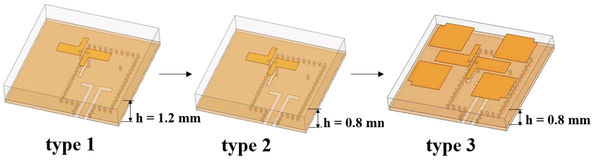
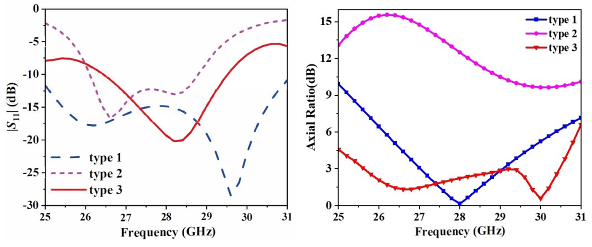
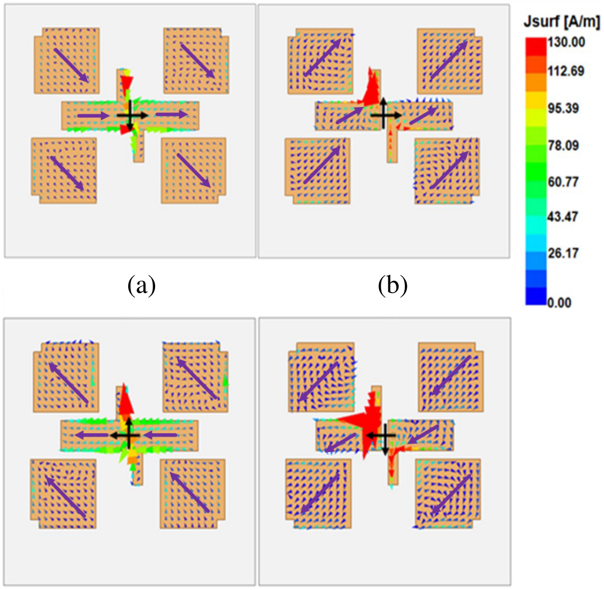


Fig. 2. The process of the antenna design.



(a) (b)

Fig. 3. (a) Simulated $|S_{11}|$ of types 1-3 structure and (b) simulated axial ratio of types 1-3 structure.



(a) (b)

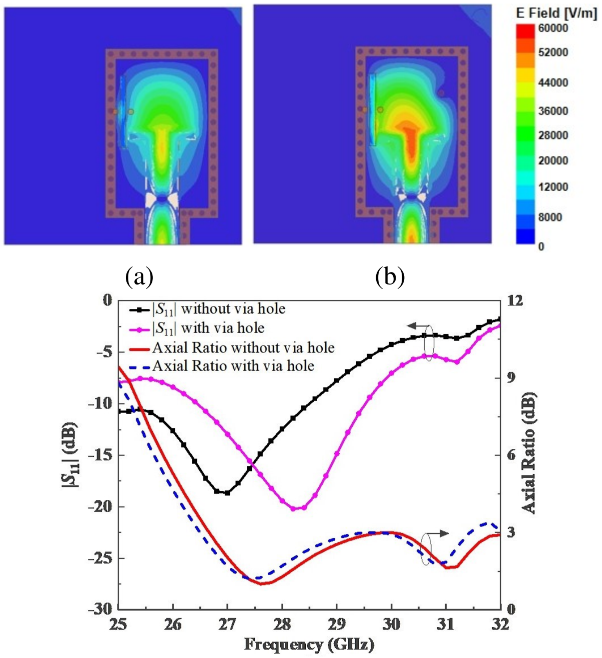
(c) (d)

Fig. 4. Current distributions of the proposed CP antenna at 28 GHz: (a) t = 0(T), (b) t = T/4, (c) t = T/2, and (d) t = 3T/4.

is designed to decrease the profile compared to type 1. Nevertheless, the bandwidth of type 2 still cannot meet the requirements of the n257 frequency band, as the reduction of profile affects the performance of the antenna. Hence, to obtain the desired bandwidth, type 3 is proposed, based on type 2, which commendably covers the 26.5-29.5 GHz frequency band whether impedance or axial ratio bandwidth.

In order to explain the operating principle of the proposed antenna, Fig. 4 shows the simulated surface current distribution of the radiation elements at 28 GHz. According to the change of the surface current on the L-shaped dipole, the orientation of the surface current rotates 360° within one period, which reveals that right-handed circular polarization is formed. Moreover, the orientation of the surface current of the additional chamfered parasitic patches changes counter-clockwise in one period, which will form another circular polarization resonance. As a result, the axial bandwidth is expanded to cover the 26.5-29.5 GHz frequency band.

Figures 5 (a) and (b) show the field distributions of the SIW cavity without and with via hole, respectively, which indicates that the via hole disrupts the field distribution in the SIW cavity. Moreover, the via hole is placed at the site of the weak electric field, which is equivalent to that the cavity wall moves inward. Therefore, the operating AR bandwidth frequency shifts to the high frequency and realizes the required n257 frequency band, as shown in Fig. 5 (c).



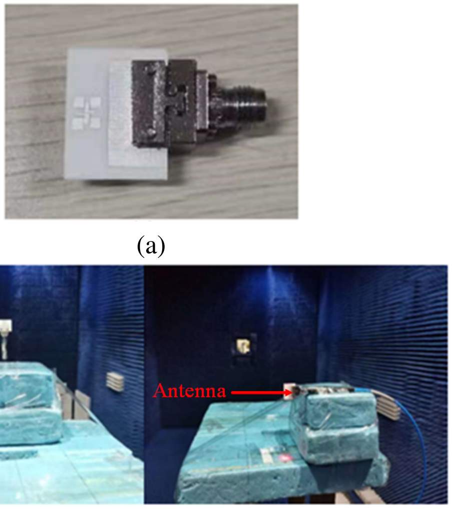
(a) (b)

(c)

Fig. 5. (a) Electric field distribution without via hole, (b) electric field distribution with via hole, and (c) simulated $|S_{11}|$ and axial ratio in both (a) and (b) cases.

III. SIMULATION RESULTS AND EXPERIMENTAL VERIFICATION

In order to verify the validity of simulated results, a physical model is manufactured and measured. Figures 6 (a) and (b) show the photographs of the



(a)

(b)

Fig. 6. Fabricated prototype of the CP antenna: (a) Prototype with connectors installed and (b) antenna under test in the anechoic chamber.

fabricated sample based on the LTCC process and the arrangements of the far-field measurement, respectively. It should be noted that an additional structure is added at the end of antenna feeding structure, as shown in Fig. 6 (a), which is convenient for the installation of the microwave connector.

Figure 7 presents the simulated and measured results of $|S_{11}|$ and RHCP gain. It indicates that the simulation and measured impedances bandwidth of the antenna are 25.9-29.5 GHz and 26.3-29.5 GHz for $|S_{11}| <$ -10 dB, which illustrates that the simulation and measured $|S_{11}|$ results have good consistency. In addition, compared to the simulated RHCP gain of the proposed antenna, the measured result has a slight deviation owing to the slight variation in dielectric constant of LTCC. The measured peak gain of the proposed CP antenna is 6.7 dBic within the operating frequency band.

The comparison of axial ratio between measured and simulated results are shown in Fig. 8, which reveals that the simulated axial ratio is less than 3 dB within 26.5-29.5 GHz. However, the measured axial ratio is deteriorated to about 6 dB within 26.5-29.5 GHz, which is caused by the test environment. During the test process of axial ratio, the linear polarization test scheme is adopted due to the lack of a circularly polarized horn antenna. Using the measured horizontal and vertical polarization results, the axial ratio of a circularly polarized antenna can be calculated. Moreover, it should be noted that the measured results of pitch angle deviation may be about 5 degrees residual. Considering the measurement tolerance error, the deviation between the simulation and the test results is within a reasonable range (AR $<$ 4 dB). Furthermore, Fig. 9 shows the simulated and measured co-polarized and cross-polarized radiation patterns of the antenna at 27 GHz, 28 GHz, and 29 GHz. It can be observed that measured results of the primary and cross polarization patterns are basically consistent with the simulated results.

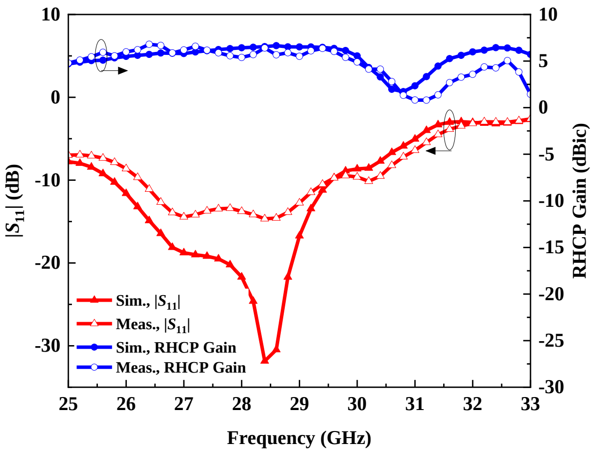


Fig. 7. Simulated and measured $|S_{11}|$ and RHCP gain of the fabrication model.

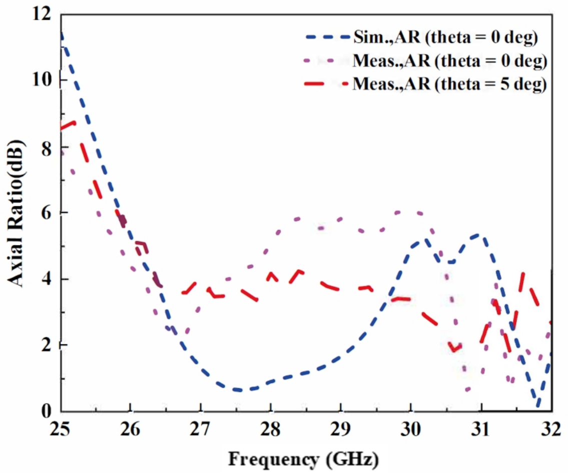


Fig. 8. Simulated and measured axial ratio of the fabrication model.

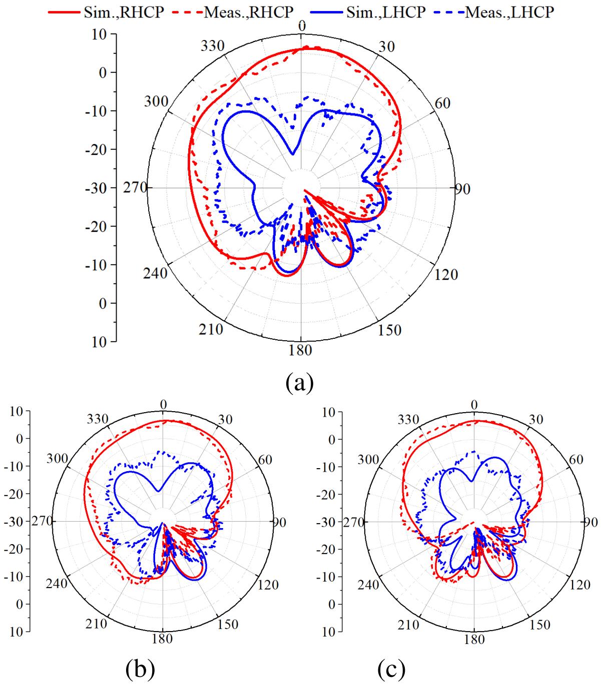


Fig. 9. Simulated and measured radiation patterns: (a) 27 GHz, (b) 28 GHz, and (c) 29 GHz.

To further illustrate the features of the proposed antenna, the performance comparison of the proposed CP antenna with the existing CP antennas are given in Table 2. References [19], [22], [23], and [24] present polarized antennas based on PCB technology, which can achieve wide bandwidth. However, their superiority in miniaturization is not outstanding comparing to the other circularly polarized antennas based on LTCC

Table 2: Comparison of existing CP mm-Wave antennas

Ref.	Process Technology	f_0 (GHz)	Antenna Element Size (mm)	Thickness* λs $(\lambda s = \lambda 0/\sqrt{\varepsilon r})$	Impedance Bandwidth	Axial Ratio Bandwidth
[19]	PCB	28.63	$8+8$ $(0.84 \cdot 0.84\lambda_0)$	0.25	21.83%	5.9%
[22]	PCB	60	$5.6+5.6$ $(1.12 * 1.12\lambda_0)$	0.22	23.8%	23.4%
[23]	PCB	30.5	$9.5+9.5$ $(0.99 \cdot 0.99\lambda_0)$	0.3	27.7%	28.5%
[24]	PCB	28.35	$12+12$ $(1.13 \cdot 1.13\lambda_0)$	0.31	$>14\%$	14%
[17]	LTCC	35	$3.83+3.83$ $(0.45 * 0.45\lambda_0)$	0.24	29.6%	$>26\%$
[18]	LTCC	60	$3.5 * 4$ $(0.7 * 0.8\lambda_0)$	0.19	16.5%	11.5%
Thiswork	LTCC	28	$6.25+6.25$ $(0.58+0.58\lambda_0)$	0.18	$>10\%$	$>10\%$

technology proposed in [17] and [18]. Moreover, the profile of the proposed antenna in this paper is lower than the other antenna structures (see Table 2) with the bandwidth exactly covering the required n257 operating frequency band.

IV. CONCLUSION

In this paper, a compact low-profile circularly polarized mm-Wave L-shaped dipole antenna with four parasitic patches is proposed. Four parasitic patches with square chamfer are placed around the centrosymmetric L-shaped patches to improve the axial ratio bandwidth. The designed antenna bandwidth is more than 10%, which can meet the required n257 operation frequency band. Additionally, it has the feature of smaller size and lower profile. The measured results have good agreement with the simulated ones. Hence, the proposed antenna can be an appropriate candidate for the applications of 5G millimeter-wave n257 (26.5 - 29.5 GHz) frequency band communications and satellite communications systems.

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