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Single-Layer Wideband Circularly Polarized Metasurface Antenna with Stepped Stubs Based on Characteristic Mode Analysis

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ABSTRACT: In this work, we present a single-layer, wideband circularly polarized (CP) metasurface antenna fed by a coplanar waveguide (CPW). The proposed antenna employs a rotated CPW feed structure, which achieves circular polarization without adding dielectric layers, significantly simplifying the antenna structure and improving manufacturability, while incorporating two stubs to adjust impedance matching and broaden the bandwidth. Measurement results indicate a -10 dB impedance bandwidth covering 4.23–6.2 GHz (a fractional bandwidth of 37.7%) and a 3-dB axial ratio bandwidth of 5.26–6.32 GHz (a fractional bandwidth of 18.3%), with a peak measured gain of 9 dBi. The antenna targets Sub-6 GHz with strong 5G integration potential.

1. INTRODUCTION

With the rapid development of wireless communication systems, the high demand for reliable communication channels and fast data transmission continuously drives research on high-performance antennas. Polarization is considered one of the most critical performance characteristics for integrating antennas with modern communication systems.

In antenna applications, circularly polarized (CP) antennas receive greater attention than linearly polarized (LP) antennas, as LP antennas are susceptible to interference, lack flexibility, and have limited coverage angles, whereas CP antennas offer advantages such as reduced polarization mismatch, suppression of multipath interference, and mitigation of Faraday rotation effects [1, 2]. Consequently, scholars have conducted extensive research on methods to achieve circular polarization. Current approaches for achieving circular polarization can be categorized into two types: single-feed and dual-feed techniques. However, dual-feed techniques typically employ complex power division networks or hybrid couplers, which not only increase the structural complexity of the antenna but also lead to a significant enlargement of its overall dimensions [3–5].

Numerous methods exist for achieving circular polarization using single-feed techniques, such as employing specific feed slot structures, metasurfaces, and air vias. Ref. [6] proposed a feeding structure utilizing a meandered microstrip line to generate circular polarization, achieving a 12.26% axial ratio bandwidth and a gain of 2.35 dBi. Ref. [7] introduced a method based on a self-complementary metasurface, which leveraged quasi-self-complementary characteristics of the metasurface to achieve circular polarization in the $25.5 \sim 26.5$ GHz frequency band with a gain of 6.03 dBi. Ref. [8] realized a 5.5% axial ratio bandwidth and a gain of 7.1 dBi by creating annular air vias. Although the antennas in the aforementioned literature all achieved circular polarization, these studies share the issue of relatively narrow bandwidth.

In recent years, the use of metasurfaces for designing circularly polarized antennas has become a research hotspot [9–13]. Metasurface antennas have found widespread application in modern wireless communication systems due to their advantages of light weight, compact structure, profile conformity, and low cost. In [9], a polarization-converting metasurface was first applied to antenna design, where slot antennas and patch antennas were used as source antennas to generate linearly polarized signals for conversion. For most previously proposed metasurface-based CP antennas, they require the metasurface to be on a separate dielectric substrate, which is placed above the source antenna. The antenna proposed in [14] employs a two-layer design, achieving circular polarization by loading a polarization-converting metasurface above a slot antenna. Ref. [15] introduced an asymmetric wideband CP metasurface antenna, but it utilized a four-layer substrate in the feeding network, significantly increasing the antenna's size. This complicates the manufacturing process. In our previous work, a method for achieving wideband circular polarization using a double-layer metasurface was proposed [16]. However, the aforementioned results inevitably increase the antenna's profile and cost. Coplanar waveguide (CPW) technology can significantly simplify antenna structures while improving performance. As a critical microwave transmission line configura-

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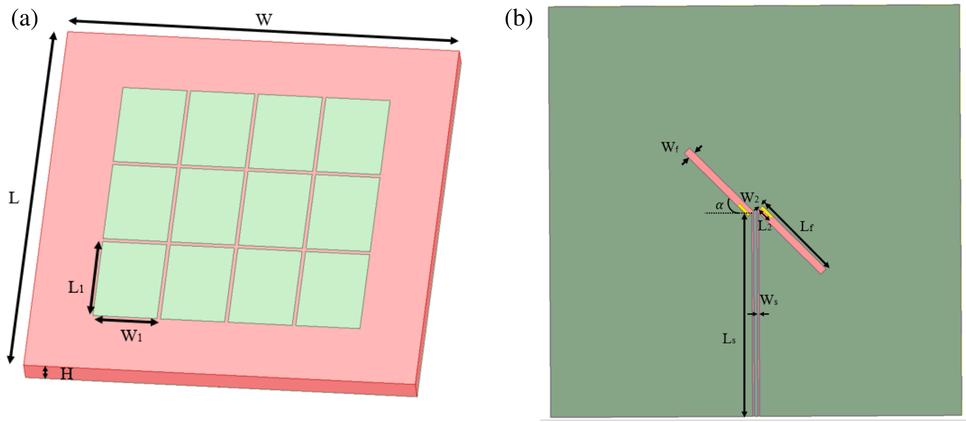

FIGURE 1. Configuration of the proposed antenna. (a) 3D view. (b) Bottom-layer of X-shaped groove.

tion, CPW features a central signal conductor flanked by two adjacent ground conductors, all arranged on the same plane of a dielectric substrate. This structure not only facilitates antenna feeding and integration — further streamlining the design — but also leverages its field confinement properties to effectively suppress surface wave effects, thereby enhancing antenna radiation performance [17, 18].

To address the issues of narrow bandwidth and large size in single-fed metasurface circularly polarized antennas, this paper proposes a single-layer, wideband metasurface antenna fed via aperture coupling from a coplanar waveguide. It achieves a bandwidth of 37% within the 4.23–6.2 GHz range, with a peak gain of 9 dBi. The metasurface (MTS) radiator is formed by nonuniform patch elements on the top side of the substrate (referred to as the nonuniform metasurface in the following sections) and is fed by a stepped aperture from the bottom CPW feedline. The specialized stepped aperture enables adjustment of the antenna's input impedance, thereby imparting wideband characteristics. The primary features of this antenna design are its wide impedance bandwidth, single-layer structure, and ease of fabrication.

The structure of this paper is organized as follows. Section 1 serves as the introduction. Section 2 presents the antenna design and analysis, detailing both the evolutionary process of antenna design and theoretical fundamentals. Section 3 reports the simulated and experimental results, while Section 4 concludes the study.

2. ANTENNA DESIGN AND ANALYSIS

2.1. Antenna Structure

The proposed single-layer metasurface antenna is illustrated in Figure 1. It consists of a metasurface patch on the top and a coplanar waveguide at the bottom. As shown in Figure 1(a), the top metasurface structure is placed on a Rogers 5880 substrate with a thickness of H, length L, width W, a dielectric constant of 2.2, and a loss tangent of 0.0009. The metasurface is composed of a 3×4 array of metasurface unit cells, with each individual unit cell having a length L_1 and width W_1. As depicted in Figure 1(b), the bottom of the dielectric substrate contains a CPW feedline with a rotation angle α and geometric dimensions L_f, W_f, L_s, W_s. Incorporated into the coplanar waveguide are two stepped branches, each with a length L_2 and width W_2. The specific dimensions of this antenna are provided in Table 1.

TABLE 1. Antenna geometry.

Parameters	L	W	H	L_1	W_1	L_f	W_f
Value/mm	55	55	3.2	12.2	9	12	1
Parameters	L_2	W_2	L_s	W_s			
Value/mm	2	0.4	27.5	0.2			

2.2. Antenna Design Process

Figure 2 clearly illustrates the design evolution of the proposed antenna. Figure 2(a) shows Antenna Model 1, which employs a conventional CPW feed on the bottom layer. Figure 2(b) presents Antenna Model 2, where circular polarization is achieved by rotating the CPW feedline of Antenna 1. Figure 2(c) displays the final proposed antenna in this work, which introduces two stepped stubs based on the CPW of Antenna Model 2. The introduction of these two stepped stubs adjusts the antenna's impedance matching and broadens its bandwidth. It is worth noting that Antenna Model 1, Model 2, and the proposed antenna all utilize the identical metasurface structure.

The performance comparison between the proposed antenna, Antenna 1, and Antenna 2 is shown in Figure 3. It can be observed that by rotating the CPW feed line, Antenna 2 achieves circular polarization performance, but still suffers from a narrow bandwidth. The introduction of two stepped stubs effectively improves the antenna's impedance matching and expands its bandwidth.

2.3. Working Principle of the Proposed Antenna

In recent years, characteristic mode analysis has been employed to investigate the operating mechanisms of metasurface antennas [19]. First, we performed Characteristic Mode Analysis (CMA) on a 3×4 feedless MS operating in the 4–8 GHz fre-

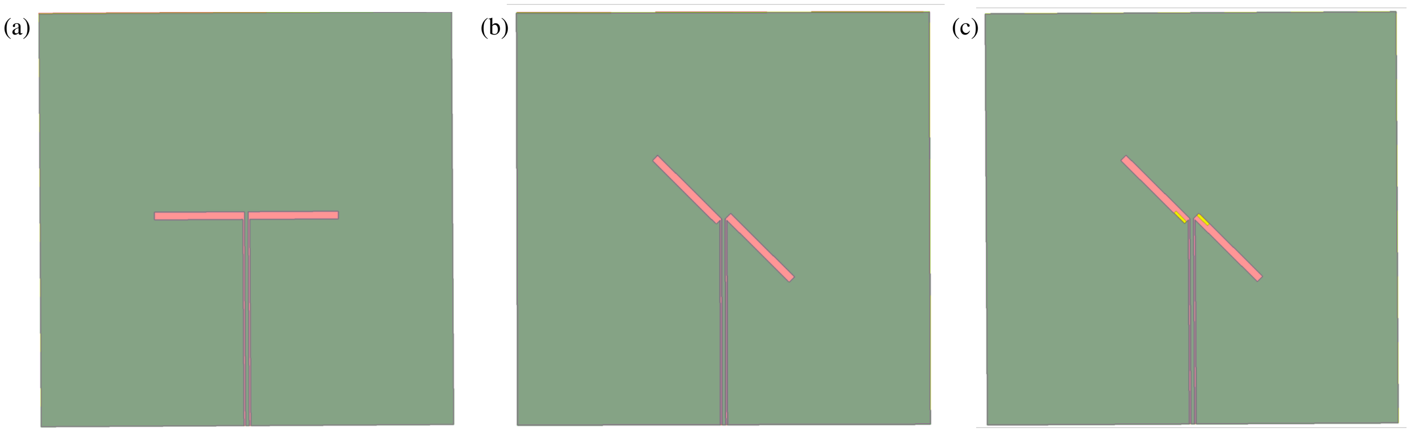

FIGURE 2. The proposed antenna and two reference antennas. (a) Antenna 1. (b) Antenna 2. (c) The proposed antenna.

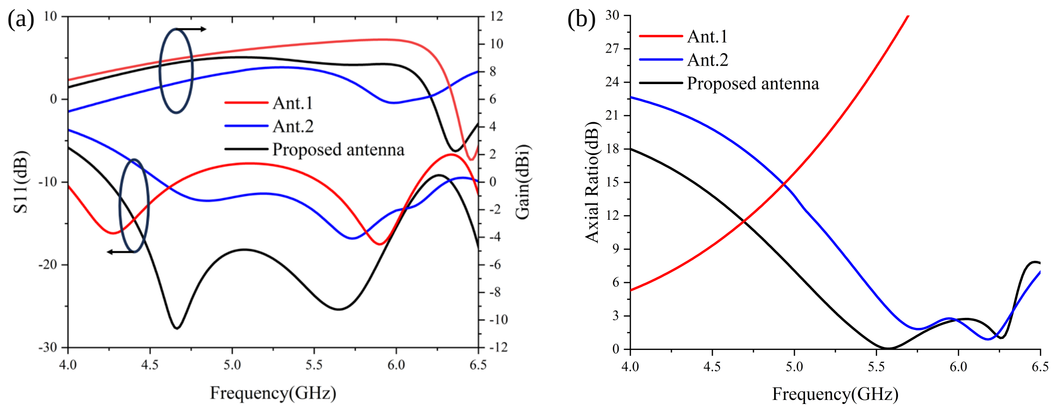

FIGURE 3. Reflection coefficient, axial ratio and gain of the proposed antenna compared with two reference antennas. (a) Reflection coefficient and gain curves. (b) Axial ratio curve.

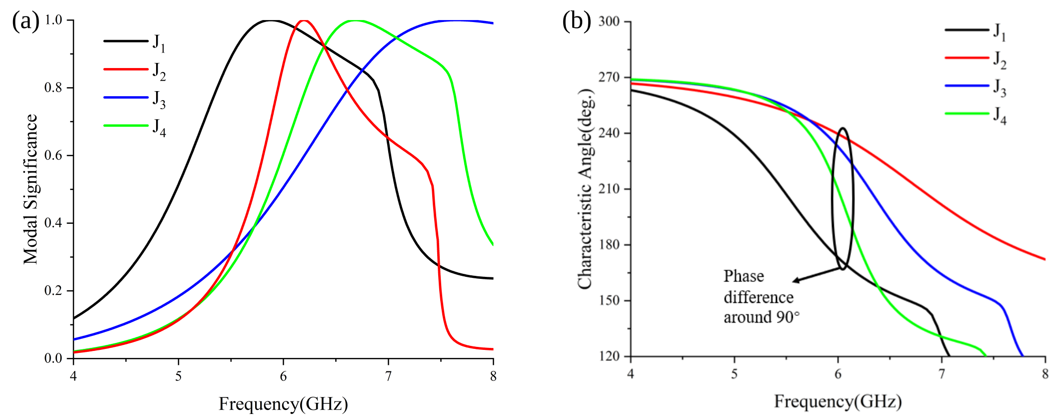

FIGURE 4. Characteristic mode significance and characteristic angle. (a) Modal significance. (b) Characteristic angle.

quency band using Computer Simulation Technology (CST) Microwave Studio. It should be noted that in the simulation of dielectric and characteristic modes, the ground plane is considered infinite in the xy-plane. CMA provides two important parameters useful for designing circularly polarized antennas: Modal Significance (MS) and Characteristic Angle. In the characteristic mode technique, MS refers to the inherent radiation properties of the structure. $MS = |1/(1 + j\lambda n)|$ where λn is the eigenvalue obtained by solving the generalized eigenvalue equation. When $MS = 1$, the mode is at resonance, whereas when $MS = 0$, the mode is non-resonant. To generate circular polarization performance, it is necessary to simultaneously excite two orthogonal modes with equal MS (or comparable) and a 90° difference in characteristic angle.

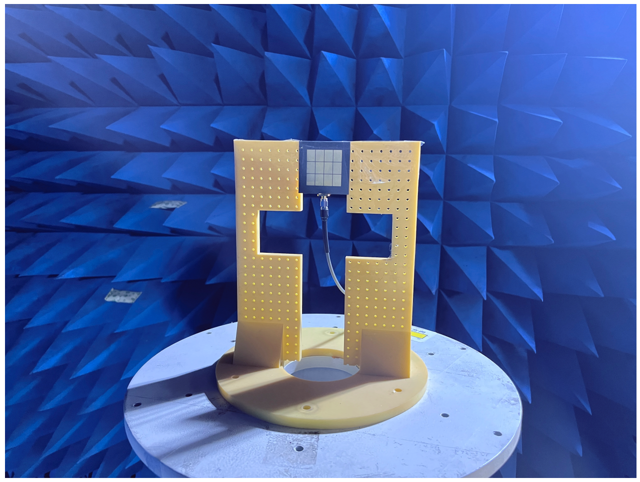

FIGURE 5. Antenna prototype.

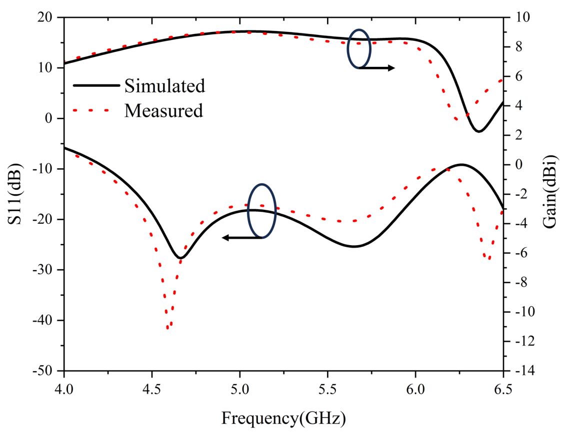

FIGURE 6. The reflection coefficient and gain curves of the proposed antenna.

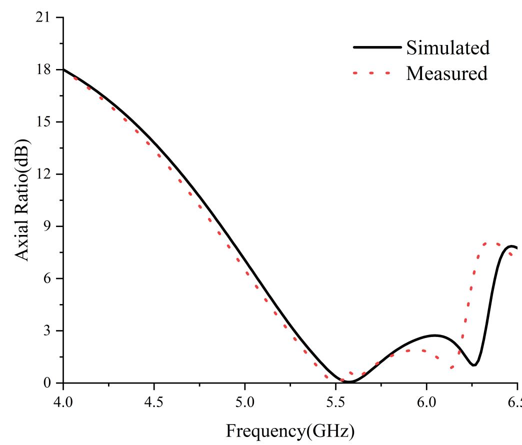

FIGURE 7. Axial ratio curve of the proposed antenna.

The Modal Significance (MS) of the first four modes is shown in Figure 4. Mode 1 and Mode 2 are excited at 6.1 GHz and exhibit a 90° phase difference. This indicates that at 6.1 GHz, the antenna generates two orthogonal modes with equal MS and a 90° characteristic angle difference, satisfying the conditions for circularly polarized radiation between J1 and J2.

3. RESULT AND DISCUSSION

The feed substrate was fabricated using printed circuit board (PCB) technology, and after assembly, measurements were conducted in an anechoic chamber to validate the antenna performance. Figure 5 shows the measurement setup of the antenna prototype in the anechoic chamber.

Figure 6 shows the impedance bandwidth and gain curve of the antenna. The antenna's -10 dB impedance bandwidth covers 4.23–6.2 GHz (a fractional bandwidth of 37.7%), with a stable high gain across this impedance bandwidth and a maximum gain of 9.04 dBi.

Figure 7 shows the axial ratio curve of the proposed antenna. It can be observed from Figure 7 that the antenna achieves an axial ratio bandwidth of 18.3% (5.26–6.32 GHz). This axial ratio bandwidth is fully functional because it completely falls within the impedance bandwidth.

Figure 8 shows the radiation pattern at the frequency of minimum axial ratio (5.65 GHz). As expected, broadside radiation patterns are obtained in both the $\phi = 0°$ and $\phi = 90°$ planes. In both planes, the field strength in the left-hand circular polarization direction is more than 20 dB greater than that in the right-hand circular polarization direction, indicating that the antenna operates with left-hand circular polarization.

Table 2 presents a comparison between the antenna proposed in this work and previously reported circularly polarized metasurface antennas. While multilayer metasurface structures such as those in references [14–16] achieve relatively wide axial ratio bandwidths, our proposed antenna, with its simple single-layer structure, not only attains a comparable axial ratio bandwidth but also demonstrates a broader impedance bandwidth. Compared with the single-layer antenna in [7], both

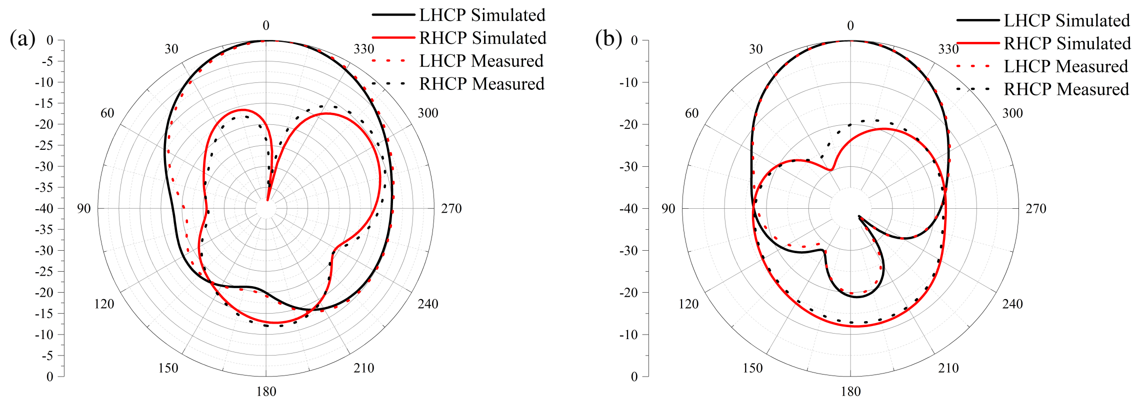

FIGURE 8. Radiation pattern of the antenna at 5.65 GHz. (a) $\phi = 0^\circ$. (b) $\phi = 90^\circ$.

TABLE 2. Comparison with previously reported work in literature.

REF	Impedance BW (%)	Overlapping BW (%)	Gain max (dBi)	Number of Layers	Size ($\lambda_0 \times \lambda_0 \times \lambda_0$)
[14]	25	14.7	8.6	2	$1.3 \times 1.3 \times 0.14$
[15]	16.7	17.4	6.6	4	$0.85 \times 0.85 \times 0.07$
[16]	24.2	20.01	9.89	2	$1 \times 1 \times 0.06$
[7]	5.1	1.5	6.03	1	$6.28 \times 4.13 \times 0.757$
Proposed work	37.7	18.3	9	1	$0.834 \times 0.834 \times 0.04$

the impedance bandwidth and axial ratio bandwidth are significantly improved.

In summary, the proposed antenna achieves a good balance between electrical performance and structural complexity, realizing wideband circular polarization with relatively high gain using a simple structure, and shows promising application potential in the Sub-6 GHz band.

4. CONCLUSION

This paper presents the design of a single-layer metasurface antenna fed by a rotated coplanar waveguide. By employing the rotated coplanar waveguide feeding method, circular polarization is achieved without the need for additional dielectric layers. Additionally, impedance matching is enhanced through the use of two stub. This antenna boasts the advantages of a simple structure and excellent performance, showing promising application prospects in the Sub-6 GHz frequency band. Moreover, due to its single-layer characteristic, it can be combined with other high-performance antennas to achieve even better performance.

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