ABSTRACT In this study, a hybrid embedded metasurface (MTS) structure is proposed and applied to realize a miniaturized MTS antenna. In contrast to the conventional periodic rectangular MTS, the proposed MTS structure is formed by hybrid embedded patches composed of several X and rectangle metal patches. The gap between the hybrid patches introduces additional capacitances, which can reduce the resonance frequency of the MTS antenna and achieve significant miniaturization. Characteristic mode analysis (CMA) is then utilized to analyze the MTS operating mechanism and guide the best possible feeding positions for wideband circularly polarized (CP) radiation. Subsequently, a cross-slot and microstrip line are used to excite a pair of degenerate modes to obtain CP radiation and broadband impedance matching. Finally, for demonstration, the proposed MTS antenna was fabricated and measured with an overall aperture of 0.46 λ₀ × 0.46 λ₀ × 0.07 λ₀ at 5 GHz. The measured 3 dB axial ratio bandwidth (ARBW) is 21.40%. Thus, it can be demonstrated that the proposed antenna can radiate effectively with significant miniaturization and the desired wideband CP radiation patterns, revealing promising prospects for wireless communication systems.

INDEX TERMS Characteristic mode analysis (CMA), circularly polarized (CP), metasurface (MTS) antenna, miniaturized, wideband.

I. INTRODUCTION

Circularly polarized (CP) antennas are commonly used in a variety of applications, including sensors, radio frequency identification (RFID), satellite communication, and radar systems because of their significant contribution to mitigating multipath effects and polarization mismatch losses [1], [2]. So far, researchers have investigated a variety of CP antennas, such as dual-band shared-aperture antenna [3], low-profile broadband antennas [4], [5], [6], high-efficiency compact antenna [7], high-gain antenna [8], wide-beam microstrip antennas [9], [10], and silicon solar cells integration antenna [11]. However, in circumstances such as small satellites and user terminals, wideband CP antennas with compact size, lightweight, and high gain are desired simultaneously because the space is small. Accordingly, achieving miniaturization of the CP antenna while maintaining high gain and broad bandwidth is a great challenge.

In recent years, metasurface (MTS) antennas have attracted considerable attention owing to their advantages such as low profile, low loss, high gain, and wide bandwidth. Some studies on miniaturized MTS antennas have been reported in [12], [13], [14], and [15]. According to [12], a compact MTS antenna is achieved by loading capacitors across layers on the MTS structure; however, it is not applicable for satellite communication because of its linear polarization radiation. In [13], a miniaturized antenna was proposed by loading parasitic loops stacked around a cross-dipole MTS structure. However, both two methods introduce cross-layer capacitance by increasing the number of antenna layers, which results in a higher profile. In [14], a miniaturized antenna was designed based on an analysis of the dispersion characteristics of an MTS structure. The traditional rectangular MTS has limited miniaturization of the antenna. Paper [15] proposed a structure for loading microstrip lines on a corner-truncated patch to introduce capacitance and achieve miniaturization. But its feed structure is simple and the 3dB axial ratio bandwidth (ARBW) is only 8.5%. Although these reported works provide promising approaches for realizing...
Miniaturized MTS antennas, problems such as high profile, narrow-band, and poor CP radiation performance still exist. Thus, the theory of characteristic mode analysis (CMA) can be used for antenna design because of its advantages in predicting the current modal behaviors [16], [17] and revealing physical insights [18], [19], thus guiding the miniaturization and wideband CP design of MTS antennas.

In this study, a novel hybrid embedded X/rectangle-shaped MTS structure with a miniaturized aperture, broadband, and good CP performance is proposed. First, a significant size reduction is achieved by introducing interdigital-like capacitance through the gap between the X/rectangular hybrid structures. Subsequently, based on CMA theory, the best possible feeding positions for wideband CP radiation are obtained. A combined cross-slot and microstrip line feeding structure are employed to excite two orthogonal modes, providing a 90° phase difference. Finally, an MTS antenna prototype is fabricated, measured, and achieved a large 3 dB ARBW of 21.40% with a small radiation aperture of $0.46 \lambda_0 \times 0.46 \lambda_0 \times 0.07 \lambda_0$. The results validate the attractive features of the proposed antenna, including its miniaturized size, low cost, wide bandwidth, and good CP performance, which appear to be good candidates for various communication systems, such as C-band satellites.

Section II focuses on the antenna geometry and principle of miniaturization. Section III presents the simulation and measurement results. Finally, Section IV concludes the paper.

**II. DESIGN OF MTS ANTENNA**

**A. ANTENNA CONFIGURATION**

Fig. 1(a) shows the configuration of the proposed hybrid embedded MTS antenna. It is a multilayer structure consisting of an MTS layer, substrate I, GND with orthogonal slots, substrate II, and microstrip feed lines from top to bottom. The dielectric substrates are FR4 ($\varepsilon_r = 4.4$, $\tan \delta = 0.02$) with thicknesses of $h_1$ and $h_2$, respectively. Fig. 1(b) shows the metallic MTS layer, which consists of a $2 \times 2$ hybrid embedded array with a spacing of $d/2$. Each hybrid embedded array contains an X-shaped patch in the center and eight small square patches evenly arranged. Fig. 1(c) shows the feed structure, combined with a cross-slot and microstrip feed line to couple microwave energy to the MTS antenna. Here, the feed structure has the same configuration as that in [2], but excites different MTS layers. Furthermore, the MTS antenna proposed in this study exhibits a more compact profile by improving traditional rectangular patches. The design process is as follows:

**B. MINIATURIZATION OF THE MTS**

Fig. 2. Shows the evolution of the proposed MTS structure. At first, the $4 \times 4$ traditional MTS [20] composed of subwavelength square patches is presented, as shown in Fig. 2(a). Where $w_0$ is the width and $g$ is the gap of square patches. The surface impedance of the conventional MTS structure is generally regarded as an $LC$ resonance circuit [12], [15], where $L$ represents the grounded dielectric slab inductance and $C$ is edge capacitance introduced by the gaps between opposite and adjacent square metal patches. It can be seen from [21] that the patch width $W_0$ and the gap width $g$ determine the size of the equivalent capacitance $C$, while the substrate thickness $h$ mainly affects the equivalent inductance $L$. According to the frequency resonance condition $f_0 = \sqrt{LC}$, when $C$ increases, $f_0$ will be decreased, thereby realizing miniaturization [22], [23].

![FIGURE 1. Configuration of the proposed antenna: a) 3-D view, b) top views of the MTS layer, and c) feeding scheme of the microstrip line.](image1)

![FIGURE 2. The evolution of the proposed MTS structure.](image2)

To introduce additional capacitance, the MTS is modified, as shown in Fig. 2(b). Each square patch is split into an X-shaped patch at the center and eight small square patches. The distance between the four square patches opposite the center is $g_1$, and the distance between the four square patches embedded with the cross patches is $g_2$. Therefore,
the structure introduces two capacitors of different values, that are arranged periodically, thereby introducing more interdigital-like capacitors.

Fig. 2 shows the equivalent circuits of the proposed MTS structure. The resonance frequency $f_0$ of the parallel resonant LC circuit can be expressed by [12], [22]:

$$f_0 = \frac{1}{2\pi \sqrt{(L_g + L)(C_1 + C_2)}}$$

where $C_1$, $C_2$, $L_d$, and $L_g$ can be approximately calculated by:

$$C_1 = \frac{w_1 \varepsilon_0 (1 + \varepsilon_t)}{\pi} \cosh^{-1} \left( \frac{a}{g_1} \right) = \frac{w_1 \varepsilon_0 (1 + \varepsilon_t)}{\pi} \cosh^{-1} \left( \frac{d}{4g_1} \right)$$

$$C_2 = \frac{w_1 \varepsilon_0 (1 + \varepsilon_t)}{\pi} \cosh^{-1} \left( \frac{b}{g_2} \right) = \frac{w_1 \varepsilon_0 (1 + \varepsilon_t)}{\pi} \cosh^{-1} \left( \frac{d\sqrt{2}}{8g_2} \right)$$

$$L = \mu h$$

$$L_g = \frac{2Z_0 \omega \tan \left( \frac{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r} \sqrt{1 + 2\varepsilon_r}}{2}(w_1 - 2p) \right)}{\omega}$$

Obviously, it is easily found that the length of the X-shaped patch ($W_1$, $W_2$), square patch $p$, and period spacing $d/2$ determines the gap $g_1$ and $g_2$ of the MS, further affect the capacitance $C_{total}$. As the $C_{total}$ increase leads to a decrease $f_0$, and then miniaturization can be realized. For convenience, we analyze only the local equivalent circuit of the hybrid patches in the x-direction, as shown in Fig. 2. When the MTS structure is under an incident electric field $E$ in the x-direction, a large number of electrons are excited on the surface and move along the x-direction, forming surface current $i$. Therefore, fringing capacitances $C_1$ and $C_2$ can be introduced through the gaps between the X-shaped and rectangular metal patches. In addition, the radiating metal layer provides strip inductance $L_g$ and $L$ is the inductance introduced by the ground plate. Thus, MTS can be regarded as a parallel resonant LC circuit, as shown in Fig. 2. As an increase in $C_{total}$ leads to a decrease in $f_0$, miniaturization can be realized.

C. CHARACTERISTIC MODE ANALYSIS OF THE MTS

The CMA method is used to guide the simulation of the MTS antenna to effectively excite the proposed MTS structure and to design a reasonable feeding structure. According to CMA theory [16], [17], [18], [19], the total current distributed across a perfect electric conductor (PEC) can be described as a linear superposition of the characteristic current

$$\bar{J} = \sum_n \alpha_n \bar{J}_n$$

where $\alpha_n$ is the modal weighting coefficient, employed to characterize the proportion of the characteristic current $\bar{J}_n$ in the total current $\bar{J}$. When excitation is considered, $\alpha_n$ is expressed as

$$\alpha_n = (\bar{J}_n, \bar{E})/|1 + j\lambda_n|$$

where $\lambda_n$ is the eigenvalue of characteristic current $\bar{J}_n$, $\bar{E}$ is the incident electric field. The denominator of $\alpha_n$ is defined as the modal significance (MS) and can be expressed as

$$MS = 1/|1 + j\lambda_n|$$

where $MS$ represents the inherent properties of each mode and is related only to the antenna structure. The value range of $MS$ is $[0, 1]$. The closer the MS value to 1, the easier the mode resonance and the more effective the antenna radiation. Therefore, strongly exciting the modes at the desired resonant frequency, avoiding the excitation of undesired modes, and then placing a suitable feed structure at the selected position can obtain the desired antenna characteristics.

Therefore, the proposed MST geometry without the feeding structure was simulated using the commercial simulation software, CST. Fig. 3(a) shows the boundary setup for the CMA, where the ground plane and MST layers were set as the PEC. The substrate and ground plane were infinitely extended.

FIGURE 3. Boundary setup and modal significance of the MTSs: a) boundary setup for the CMA, b) modal significance, and c) comparison of the proposed and conventional MTS structures in MSs.

FIGURE 4. Modal currents and far-field patterns of the conventional MTS at 6 GHz: a) $j_{01}$, b) $j_{02}$, c) $j_{03}$, d) $j_{04}$, where $w_0 = 5$mm, $g = 0.5$mm.
As shown in Fig. 3(b), the electrical currents of the proposed MTS patches are solved, and the MSs of the first four modes from 5 to 8 GHz are calculated, where $J_n$ represents the mode current. As shown, $J_1/J_2$ resonances at about 5.7-8 GHz (MS $> 0.707$), $J_3/J_4$ resonances at approximately 6.75-7.3 GHz (MS $> 0.707$). Fig. 3(c) compared the MSs of the two MTS structures and $J_{0n}$ and $J_n$ are used to represent the mode current of the conventional and embedded MTS structure, respectively. The MSs of the first 4 modes from 5 to 8 GHz are calculated. For $2 \times 2$ conventional structure, $J_{01}$ and $J_{02}$ are a pair of degenerate modes, and the other two modes are ideal modes for omnidirectional radiation. The modes $J_{01}/J_{02}$ resonate at 7.25 GHz (MS = 1), and $J_{03}$ and $J_{04}$ resonate at high frequency. For the proposed hybrid structure, $J_1/J_2$ resonances at about 6.25 GHz and the four modes of the proposed hybrid MTS all move to low frequency. In other words, for the MTS structure of the same size, the new hybrid structure proposed in our work has a lower resonance frequency, demonstrating that the proposed MTS structure can effectively achieve miniaturization. This is consistent with the previous results of equivalent circuit analysis.

Meanwhile, Fig. 4 and Fig. 5 demonstrate that the proposed and the conventional MTS structures have similar current distribution and far-field radiation characteristics. For our work, the strongest currents of all four modes are concentrated on the four X-shaped patches in the center, where $J_1/J_2$ is distributed at low frequencies, about 1 GHz lower than $J_3/J_4$. To access the applicable CP radiation characteristic, we should choose these two orthogonal modes ($J_1/J_2$) to synchronously excite with a 90° phase difference. Thus, it can be concluded that to effectively excite $J_1/J_2$ and avoid exciting $J_3$ and $J_4$, we should design a CP radiation feed structure resonating in the bandwidth range of 5.7-6.75 GHz.

Based on the above analyses, a hybrid embedded CP MTS antenna with feeding work was designed in the HFSS, as shown in Fig. 1(a). According to the current distribution and characteristics analyzed above, the feed structure should be placed under the X-patches of the MTS so that $J_1/J_2$ can be adequately excited. Therefore, we combined a cross-slot and microstrip feed line as the feeding scheme to excite MTS antenna, as shown in Fig. 1(c). The circular microstrip lines on the cross-slot differ in length by $\lambda_{g}/4$ (wavelength in medium), so that the energy can be coupled to the MTS patch through the slot in GND, and then CP radiation can be generated [24], [25]. The final optimized dimensions with impedance matching are as $d = 26$ mm, $w_1 = 9$ mm, $w_2 = 3$ mm, $p = 2.2$ mm, $ws = 0.7$ mm, $ls = 13$ mm, $w_0 = 1.6$ mm, $los = 12$ mm, $h_1 = 4$ mm, $h_2 = 1$ mm, and $w = 27.64$ mm.

Owing to the effects of the feed network and multilayer board loss, the operating frequency of the antenna is shifted to lower frequencies. Fig. 6 shows the current distributions of the proposed MTS antenna with different phases of the excitation signal at 5 GHz. Obviously, because $J_1/J_2$ is excited effectively and there is a 90° phase difference, the current vector (marked with a black arrow) on the antenna appears to rotate clockwise with the phase. So that, the right-handed circular polarization (RHCP) characteristics can be clearly observed.

### FIGURE 6. Current distributions of the proposed CP MTS antenna from different phases of the excitation signal at 5 GHz.

### III. FABRICATION AND MEASUREMENT

The proposed MTS antenna prototype was fabricated and measured, as shown in Fig. 7. The S-parameter of the proposed miniaturized MTS antenna was measured using an Agilent E8361A vector network analyzer (VNA) and the realized gain was measured in an anechoic chamber.

Fig. 8 demonstrated that the measured results of the proposed MTS antenna, including S-parameters, gains, radiation efficiency and AR, all agree well with the simulations. As shown in Fig. 8(a), the measured 10 dB impedance bandwidth is 29.7% (4.3-5.8 GHz), and the measured gain values vary from 4 to 5.6 dBiC within the whole CP operating band. Fig. 8(b) presents the simulated and measured results in 3 dB ARBW and radiation efficiency, which reveals that
the measured bandwidth is 21.4% from 4.46 to 5.53 GHz. The measurement radiation efficiencies are higher than 75% in the 3 dB ARBW and consistent with the simulation results well.

Fig. 9 shows that the MTS antenna has good radiation patterns performance stability in both xoz-plane and yoz-plane at 4.5, 5, and 5.5GHz. It is shown that the main polarization is right-hand CP (RHCP), and left-hand CP (LHCP) is the cross-polarization. The cross-polarization level is better than -15 dB, implying that the feed system excites the idea mode currents ($J_1/J_2$). Additionally, the radiation patterns simulated and measured are in good agreement.

Table 1 presents a comparison of the proposed antenna with other recently published CP patch antennas. Compared
to other antennas, our antenna has a smaller size while maintaining excellent performance on −10 dB impedance bandwidth. Meanwhile, the proposed antenna achieves wider bandwidth on 3 dB ARBW compared to [2], [15], [26], [27], [28], and [29]. In addition, owing to effective miniaturization, the radiation aperture decreases correspondingly, leading to a decrease in gain to a certain extent, which is common and reasonable in antenna design. In general, our design offers a smaller dimension and wider CP operating band while maintaining effective radiation gain and efficiency, which demonstrates great potential for MTS antenna miniaturization and wideband CP radiation.

IV. CONCLUSION

In this study, we present a novel hybrid embedded X/rectangle-shaped CP MTS antenna. On the one hand, the gaps between the hybrid structures can form interdigital-like capacitors, which introduce large capacitances and realize significant miniaturization of the antenna. On the other hand, based on CMA theory, a slot coupling feed system is employed to excite a pair of orthogonal current modes and achieve wideband CP radiation. The simulated and measured results show that the proposed antenna can obtain a large ARBW of 21.40% with a small radiation aperture of 0.46 λ×0.46 λ×0.07 λo. It offers attractive features, including miniaturized size, wide CP bandwidth and low cost, and provides a feasible solution for realizing miniaturized broadband CP antennas for wireless communication systems.

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