A Novel Omnidirectional Circularly Polarized Pagoda Antenna with Four Shorting Pins for UAV Applications

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***Abstract* -** A novel omnidirectional circularly polarized (CP) pagoda antenna with four shorting pins is presented. In this structure, four curved branches are utilized to generate horizontal polarization, while coaxial cable and four shorting pins produce vertical polarization. Omnidirectional CP radiation is achieved by combining the radiation from the branches and the shorting pins. The curved branches loaded with shorting pins reduce the size of the antenna and the antenna is loaded with the lower substrate with two coupling patches to improve the bandwidth. The novel pagoda antenna is fabricated and measured. Its final dimensions are $0.42\lambda_0$*$0.42\lambda_0$*$0.33\lambda_0$ (λ_0 is the free-space wavelength at operating frequency). The impedance bandwidth ($S_{11}\leq$-10dB) is 0.53GHz and the axial ratio (AR) bandwidth (AR$\leq$3dB) is 0.95GHz, which can be used for unmanned aerial vehicles' diagram transmission in China.

***Index Terms* -** Circularly polarized (CP), coupling patch, curved branch, omnidirectional antenna, shorting pin.

I. INTRODUCTION

Omnidirectional circularly polarized (CP) antennas have attracted more and more attention from experts and scholars due to they widely used in wireless communication, remote sensing and telemetry and satellite communication systems. Omnidirectional antenna can radiate electromagnetic wave in any direction in a plane, which is suitable for multipoint simultaneous communication and communication in uncertain position during movement. The CP antennas can accept arbitrary polarized wave, reduce multipath interference, and have high polarization isolation. Having both advantages of omnidirectional antenna and CP antenna, omnidirectional CP antenna can meet the requirements of accurate signal transmission of unmanned aerial vehicle (UAV) systems and be used as its image transmission antenna, which can effectively reduce the signal blind area and polarization interference.

In recent years, many methods of realizing omnidirectional CP antennas have been proposed, which can be roughly classified into three categories. The first method is circular polarized method of omnidirectional antenna that a circular polarizer is loaded outside the omnidirectional antenna. In [1], the omnidirectional CP antenna is realized by using the parallelepiped medium element with high dielectric constant to embrace around the coaxial probe. In [2], the inner conductor is fed, while the spiral groove is opened on the outer cylinder conductor. The second method is element combination [3-6], which uses the combination of CP antenna elements to achieve omnidirectivity. In [3], circular open rings loaded with parasitic rings are used as CP antenna elements, and they are combined around cylinder to attain omnidirectivity. In [4], a rectangular ring is used as a CP antenna element.

However, omnidirectional CP antennas realized by these two methods are generally large in size and have high profile, which is difficult to install on small and lightweight UAVs. In order to reduce the size and profile, a third method is proposed, which combines the antenna that generates the vertical polarized wave with the antenna that generates the horizontal polarized wave [7-15]. In [7], a broadband omnidirectional CP antenna was proposed, in which two sets of dipoles were used to generate omnidirectional CP waves. In [8], capacitive feeding is used to widen the bandwidth of the antenna. The antenna's profile is greatly reduced, but the radius is still large. In [9], planar sector-shaped endfire elements are used to realize omnidirectional circular polarization of the antenna, which further reduces the antenna profile. V-shaped slot on the same principle was used in omnidirectional CP antenna [10], which also makes the size of the antenna even smaller. The profile and radius of this kind of antenna are small, but the bandwidth is too narrow to meet the actual needs.

Based on the comparison with the antenna mentioned above, this paper proposes an omnidirectional CP antenna suitable for UAV image transmission system. The antenna's size is relatively small and has an adequate bandwidth to ensure the transmission of information. Coaxial cable and four shorting pins

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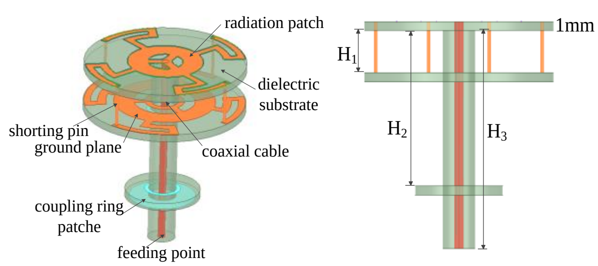
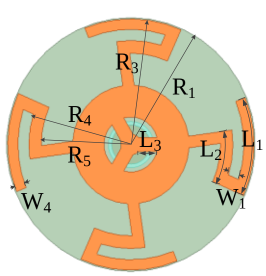
are used to generate vertical polarized waves, while four curved branches are used to generate horizontal polarized waves. The structure of curved branches loaded with shorting pins are used to reduce the size of the antenna, and the dielectric substrates at the bottom with two ring patches are coupled to extend the bandwidth. Finally, the antenna's size is $0.42\lambda_0 * 0.42\lambda_0 * 0.33\lambda_0$. The impedance bandwidth of the antenna ($S_{11} \leq$-10dB) ranges from 5.56GHz to 6.09GHz, and the axial ratio (AR) bandwidth (AR≤3dB) is from 5.07GHz to 6.02GHz, effectively covering UAVs' diagram transmission frequency in China at 5.8GHz. The configuration, principles, simulation used by Ansoft high-frequency structure simulator (HFSS) and results of the antenna are described detailedly in the following sections.

II. ANTENNA CONFIGURATION

Figure 1 shows the configuration of omnidirectional CP pagoda antenna. It consists of three dielectric substrates with a thickness of 1mm, a radiant patch, a reference ground, four shorting pins and four ring patches. The radiation patch and ground plane are located on the upper surface of the upper substrates and the middle substrates respectively, the material of which is FR-4 with the permittivity of 4.4 and the loss tangent of 0.002. The radiation patch and ground plane each contains four curved branches in opposite direction connected by shorting pins at the end, which are commonly used to reduce the size of antenna. The coaxial cable is in direct contact with the radiation patch for feeding. The inner conductor of coaxial cable and shorting pins are both made of copper.



(a) (b)



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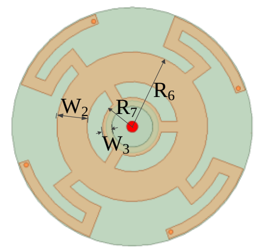

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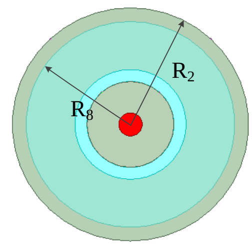


(e)

Fig. 1. Geometrical configuration of the proposed antenna. (a) Perspective view. (b) Side view. (c) Top view of the upper substrates. (d) Top view of the middle substrates. (e) Top view of the lower substrates.

The curved branches loaded with shorting pin reduce the size of the antenna, but the bandwidth is relatively narrow. In order to improve the bandwidth for better practicability, the antenna is loaded with the lower substrate with two ring patches on the upper surface and the lower surface respectively. The lower substrate with two ring patches acts as a choking coil, similar to a metal sleeve. Because it can be coupled with the radiation patch to enhance the radiation intensity, the lower substrate broadens both impedance bandwidth and AR bandwidth. The parameters of the antenna are listed as follows: R_1=11mm, R_2=5.1mm, R_3=10.9mm, R_4=9mm, R_5=8mm, R_6=6.9mm, R_7=2.7mm, R_8=4.5mm, W_1=1mm, W_2=2.75mm, W_3=0.82mm, W_4=0.9mm, L_1=8.74mm, L_2=5mm, L_3=3mm, H_1=4.65mm, H_2=17.09mm, H_3=24mm.

III. PRINCIPLE AND METHODOLOGY

For omnidirectional CP pagoda antenna is understand clearly, working principle and parameters analysis of the proposed antenna are discussed in this section.

A. Omnidirectional CP property

CP waves are composed of two orthogonal linearly polarized waves with a phase difference of 90°. According to the duality principle, the electric field ($\vec{E}$) in the far field generated by the magnetic currents on the pagoda antenna can be expressed as:

$$\vec{E} = \hat{\theta}E_\theta + \hat{\phi}E_\phi. \quad (1)$$

It is found that when there are more branches, omnidirectivity of the antenna is better, as shown in Fig. 2. And the operating frequency is reduced as the increase in the number of branches, which has the function of miniaturization, as shown in Fig. 3. However, considering the size of the antenna, four branches are finally chosen. The four branch elements are arranged in sequence and fed by coaxial cables, forming a clockwise current loop. The end of each branch element is connected to the ground plane by a shorting pin, that form a current path. According to the boundary condition, the clockwise current loop generates a vertical down magnetic pole ($\vec{J} = \vec{n} \times \vec{H}$), which forms a horizontal polarization component, the E_φ field. The radius of the current loop is R_1. The far field of the current loop E_φ can be expressed as [16]:

$$E_\varphi = \frac{[I]R_1\omega\mu_0}{2r} J_1(\beta R_1 \sin\theta)\hat{\varphi}. \quad (2)$$

Where $[I]$ represents the magnitude of current on the loop, ω is the operating frequency, μ_0 is the free-space permeability, J_1 is Bessel's first order function, β is the propagation parameter of space and r is the distance between the antenna and the measuring point.

Vertical polarized waves are generated by coaxial cable and four shorting pins, which act as electrodes. What is more, the vertical polarized waves produced by the electrodes are omnidirectional. The height of the shorting pin can be seen as H_1. Its far field E_θ can be expressed as [16]:

$$E_\theta = j\frac{[I]H\omega\mu_0}{4\pi r} \sin\theta\ \hat{\theta}. \quad (3)$$

Based on (2) and (3), it is noted that as long as the current $[I]$ through coaxial cable, curved branch and shorting pin is uniform, there will be a 90° phase difference between the vertical polarized component and the horizontal polarized component. The CP radiation pattern will be generated when the magnitude of E_θ and E_ϕ are adjusted to be equal. As shown in the Fig. 4, it can be found that the current passing through does not change its direction in one time. Therefore, two polarization components exist 90° phase difference to each other in the far field. Due to the compact structure of the antenna, two polarization components have the same amplitude and orthogonal to each other in space at the same time. Finally, the omnidirectional CP pagoda antenna is realized in theory.

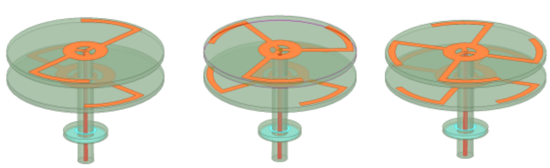


Fig. 2. Three improved prototypes of the proposed antenna.

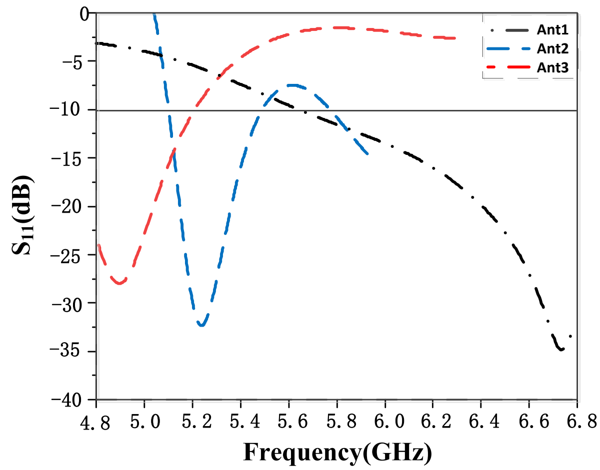


Fig. 3. Simulated $|S_{11}|$ of Ant 1, Ant 2 and Ant 3.

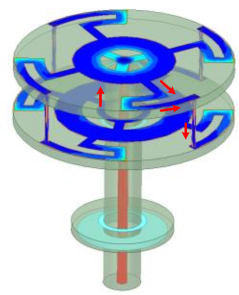


Fig. 4. Current distribution of the proposed antenna at 5.8GHz.

B. Parametric study and analysis

Curved branch can change the path of current, effectively reducing the size of the antenna. The length of the branches is approximately determined by:

$$\frac{R_6\pi}{4} + L_2 + \frac{W_4}{2} + R_5 = \lambda. \quad (4)$$

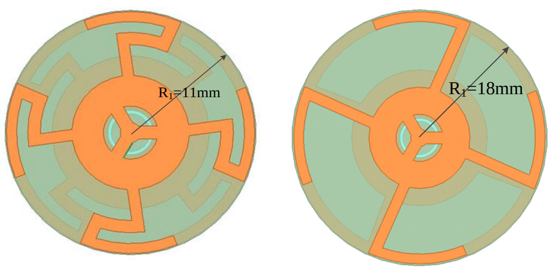
Where λ is the operating wavelength. As shown in Fig. 5, the radius of the curved branch is much smaller than that of the straight branch by adjusting the width of the branches when the current passes through the same length.

The shorting pin at the end of the branch not only supports the upper and middle dielectric substrates, but also miniaturizes the antenna. The two ends of the radiation patch are open, and there must be zero potential points in the standing wave. Loading shorting pin at zero potential points, the original state of standing wave will be made from open circuit to short circuit state, equivalent to make $\lambda/2$ to $\lambda/4$ harmonic resonance. The antenna size (R) can be approximately calculated by [17]:

$$R = \frac{\lambda}{4} = \frac{c}{4\times\sqrt{\varepsilon_{eq}}\times f}, \quad (5)$$

$$\varepsilon_{eq} = \frac{H_1+H_2}{\frac{H_1}{\varepsilon r}+\frac{H_2}{\varepsilon_{air}}}. \quad (6)$$

Where c is the speed of light in vacuum, and ε_{eq} is the equivalent dielectric constant of multilayered substrate. Figure 6 compares the *S* parameters of antenna with shorting pin and without shorting pin. As can be seen from Fig. 6, the impedance characteristic of the antenna with shorting pin is obviously better than that without shorting pin, and the resonant frequency of antenna reduces, thus achieving the miniaturization. Therefore, the antenna size is reduced due to the curved branch loaded with shorting pin.



(a) (b)

Fig. 5. Radius of (a) curved branch and (b) straight branch.

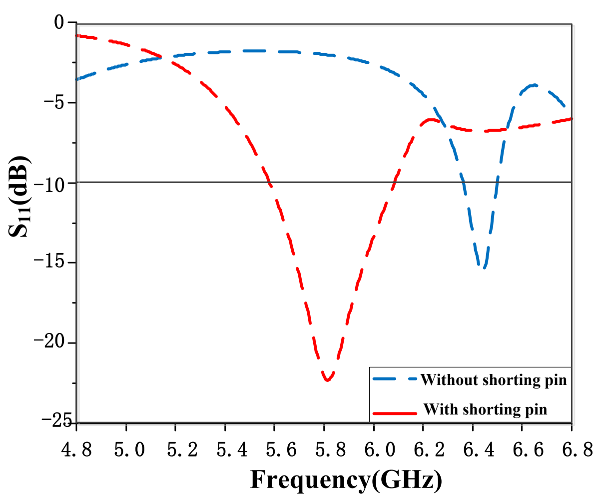


Fig. 6. Simulated $|S_{11}|$ of the proposed antenna with and without shorting pins.

The lower substrate with two coupling patches can adjust the resonance point and enlarge the bandwidth of the antenna. Figure 7 shows the comparison of *S* parameters and AR bandwidth of antennas with and without the coupling patches. It can be seen that the impedance bandwidth and AR bandwidth of the antenna both increase after the coupling patches loaded.

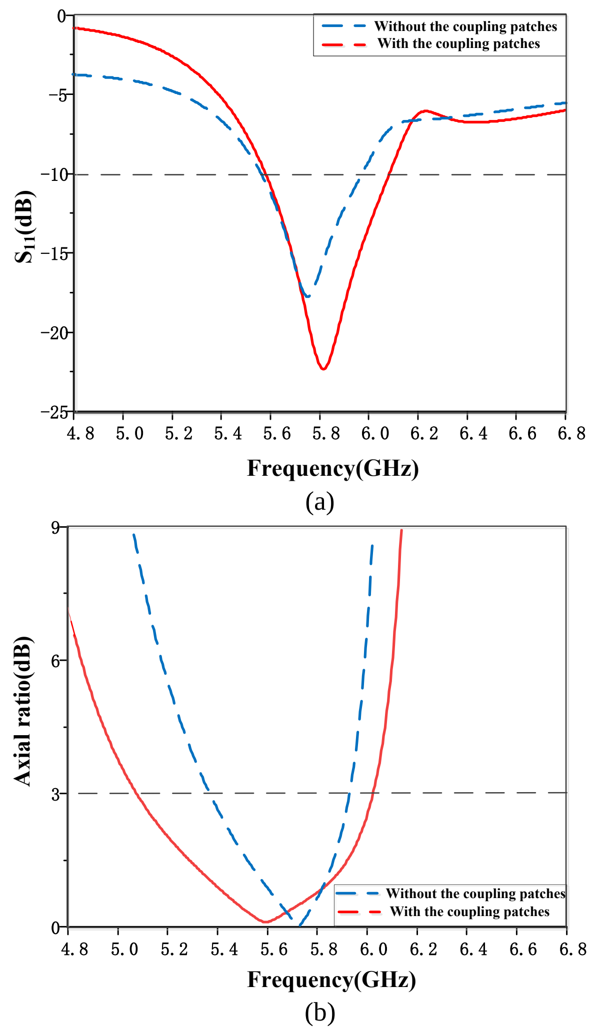
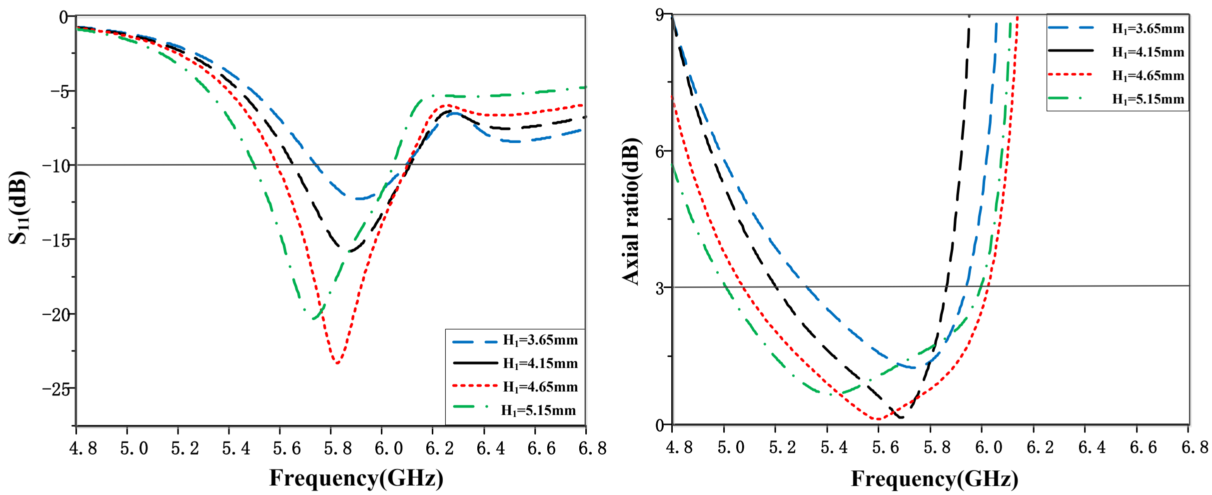


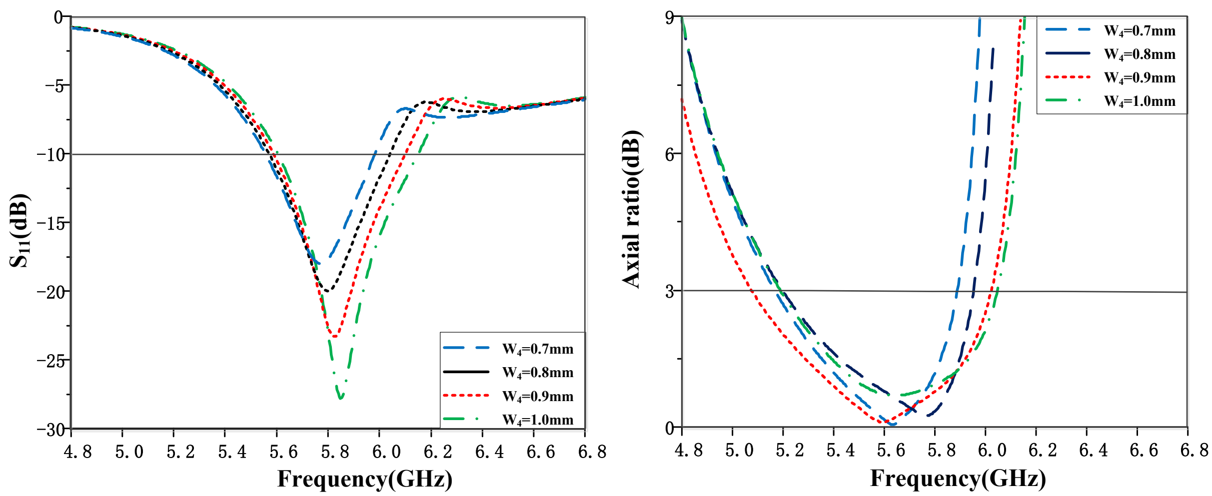
Fig. 7. Simulated (a) $|S_{11}|$ and (b) AR of the proposed antenna with and without coupling patches.

The coupling strength is affected by two factors [18], one is the distance between the upper substrate and the middle substrate H_1, the other is curved branch arc width of the radiation patch W_4. Figure 8 shows the influence of the distance H_1 on the operating frequency of the antenna. It can be seen from Fig. 8(a) that when the distance H_1 decreases, the resonant frequency of the antenna increases, while Fig. 8 (b) shows that AR points shift towards higher frequency. Figure 9 shows the effect of the width W_4. Figure 9 (a) shows that when W_4 decreases, the S-parameter curves of the antenna decrease while Fig. 9 (b) shows that the AR values have no obvious changes.



(a) (b)

Fig. 8. Simulated (a) $|S_{11}|$ and (b) AR of the proposed antenna with different H_1.



(a) (b)

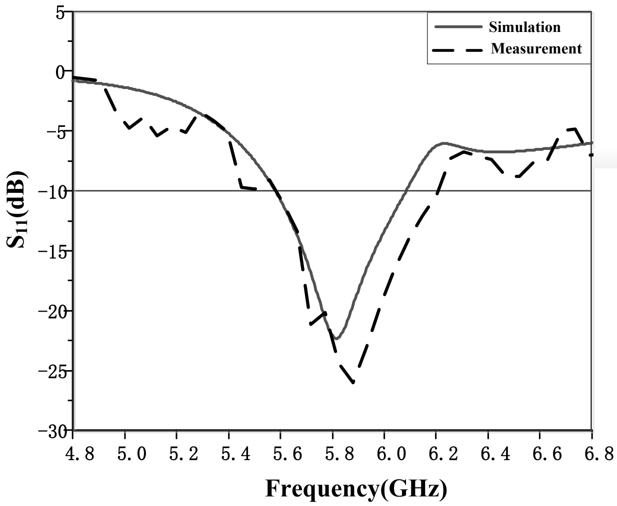
Fig. 9. Simulated (a) $|S_{11}|$ and (b) AR of the proposed antenna with different W_4.

IV. EXPERIMENTAL RESULTS

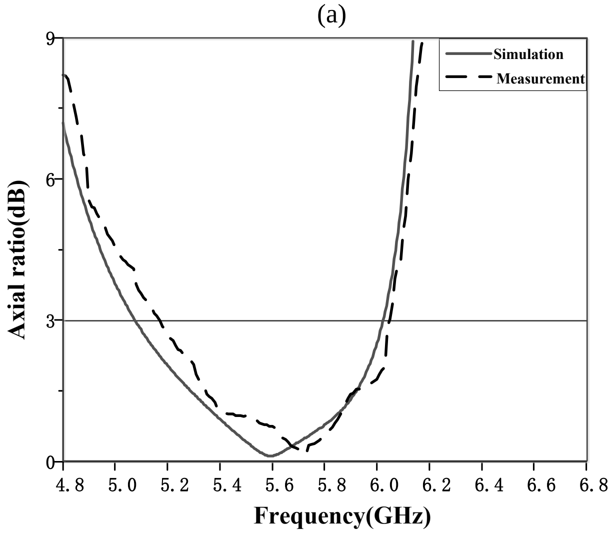
In order to validate the proposed method, the antenna is fabricated, as shown in the Fig. 10. The antenna weighs only 4 grams, which makes it more suitable for UAVs diagram transmission because it's light enough. The measurements were implemented by an Agilent E8363B network analyzer and a far-field system in anechoic chamber.

Simulated and measured S parameters of antenna are shown in Fig. 11 (a). It can be seen that the measured S parameters agree with the simulated values well. The measured bandwidth of the antenna ($S_{11}\leq$-10dB) is 0.64GHz, from 5.56GHz to 6.21GHz, equivalent to 11% at 5.8GHz. Figure 11 (b) shows simulated and measured AR bandwidth of antenna. The AR bandwidth (AR≤3dB) is 0.9GHz, from 5.10GHz to 6.00GHz, equivalent to 15.5%. It can be found that the overlapped bandwidth of Impedance and AR from 5.56GHz to 6.00GHz covers the UAVs diagram transmission frequency of 5.8GHz in China.

Fig. 10. Photograph of the fabricated antenna.



(a)



(b)

Fig. 11. Simulated and measured (a) $|S_{11}|$ and (b) AR of the fabricated prototype.

Figure 12 shows simulated and measured AR of the antenna in the azimuth plane (θ =90◦) at 5.8GHz. It can be seen that there are some small differences between the simulated and measured values due to fabrication errors. From the figure, when it is simulated, the ARs fluctuate within 1dB. The measured ARs are slightly higher than the calculated results in all directions, but they are all less than 3dB in the plane, the ripple of which is 0.7dB. Both the simulated and measured values meet the requirement of circular polarization, which indicates that the antenna has good CP characteristics at 5.8GHz.

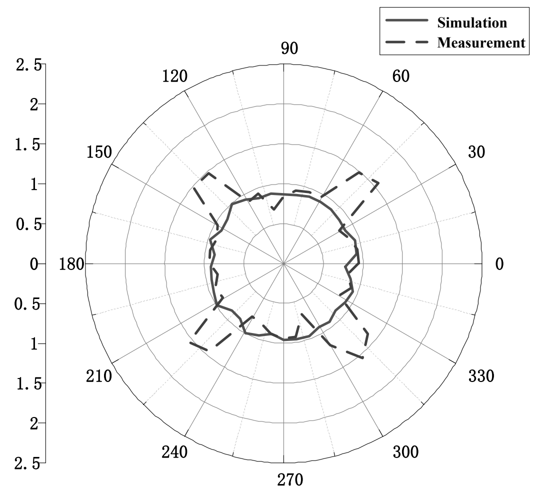


Fig. 12. Simulated and measured AR of the CP antenna in the azimuth plane (θ =90◦).

The simulated LHCP gain at 5.8 GHz is 1.12 dBic. Figure 13 shows the measured and calculated radiation patterns of the proposed antenna at 5.8 GHz in the azimuth (xy plane) and elevation (xz plane) planes, respectively. In xy plane, both the simulated and measured values of left-hand circularly polarized (LHCP) fluctuate around 1dB, while the simulated and measured values of right-hand circularly polarized (RHCP) are less than -15dB. In xz plane, it also can be seen that the results of the simulated and measured agree well with each other, and the level differences between the RHCP and LHCP are more than 15dB, that indicates the antenna is LHCP and has good omnidirectivity.

In order to show the advantage of the antenna, Table 1 compares the omnidirectional CP pagoda antenna with existing antennas in bandwidth and dimensions, from which the overall advantage of the novel pagoda antenna can be seen. Compared with the existing antenna, the overall size of novel pagoda antenna proposed is more advantageous. For the same size, the bandwidth is wider than that of the compared antenna.

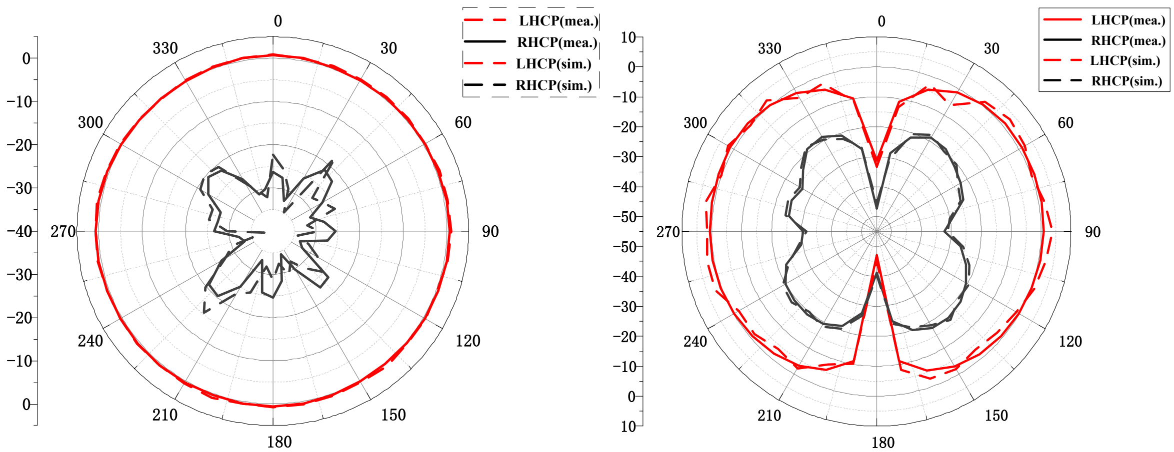


Fig. 13. Simulated and measured radiation patterns in (a) azimuth (xy plane) and (b) elevation (xz plane) planes at 5.8GHz.

Table 1: Performance comparison of reported omnidirectional CP antennas with existing antenna

Ref.	Dimensions (λ_0)	Imp. Bandwidth (%)	3dB AR Bandwidth (%)	Usable Bandwidth (%)
[7]	$1.63\lambda_0 \times 1.63\lambda_0 \times 0.28\lambda_0$	21.60	25.3	21.60
[9]	$0.62\lambda_0 \times 0.62\lambda_0 \times 0.029\lambda_0$	3.97	-	3.97
[10]	$0.52\lambda_0 \times 0.52\lambda_0 \times 0.026\lambda_0$	3.50	-	3.50
[15]	$0.24\lambda_0 \times 0.24\lambda_0 \times 0.12\lambda_0$	3.90	7.5	3.90
This work	$0.42\lambda_0 \times 0.42\lambda_0 \times 0.33\lambda_0$	9.00	16.4	9.00

V. CONCLUSION

A novel omnidirectional RHCP antenna is presented in this letter. The novel pagoda antenna loaded with the shorting pin and the lower substrate with two coupling patches achieves miniaturization in size with adequate bandwidth. The principle and experiment of the antenna are discussed in detail above. Finally, the impedance bandwidth of novel pagoda antenna is 0.53GHz, AR bandwidth is 0.95GHz and usable bandwidth is 0.53GHz, which can cover the UAVs diagram transmission frequency of 5.8GHz in China. With the final dimensions of $0.42\lambda_0 * 0.42\lambda_0 * 0.33\lambda_0$, the antenna has advantages compared with the existing antennas. At the same time, it can be found that the AR bandwidth of the antenna is wider than the impedance bandwidth, which provides a potential for the following research. Impedance bandwidth can be further broadened to achieve miniaturized broadband omnidirectional CP pagoda antenna.

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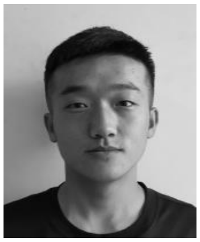

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