A Dual-Band Omnidirectional Circular Polarized Antenna Using Composite Right/Left-Handed Transmission Line With Rectangular Slits for Unmanned Aerial Vehicle Applications

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ABSTRACT A dual-band omnidirectional circularly polarized (CP) antenna using composite right/left-handed (CRLH) transmission line (TL) with miniaturized size is presented. The antenna consists of a circular radiation patch and a circular ground connected by three copper shorting vias, on which three rectangular slits are etched. Two sets of opposite branches are arranged in sequence around the radiation patch and ground to widen the impedance bandwidth (BW). The zeroth-order resonance (ZOR) structure by CRLH-TL and meandering technology allow miniaturization of the antenna, and rectangular slits realize wide low axial-ratio (AR) performance in the azimuth plane. The dual-band antenna is fabricated and measured. The overall size of the antenna prototype is only 0.208λL × 0.208λL × 0.026λL, where λL is the free-space wavelength at the center working frequency of the low band. The BW in the lower band has a range of 2.39 GHz to 2.42 GHz, equivalent to 1.25%, and that of the upper band has a range of 5.6 GHz to 6.0 GHz, equivalent to 6.90%. The AR bandwidth (ARBW) has ranges of 1.9 GHz to 2.6 GHz at 2.4 GHz, approximately 29.2%, and 4.6 GHz to 7.3 GHz at 5.8 GHz, equivalent to 46.6%. The overlap BW covers the two frequencies of unmanned aerial vehicle (UAV) image transmission, 2.4 GHz and 5.8 GHz in China.

INDEX TERMS Circularly polarized (CP), omnidirectional antenna, dual-band, ZOR, composite right/left-handed transmission line, rectangular slits.

I. INTRODUCTION

Omnidirectional CP antennas are widely used in systems with high signal requirements, such as spacecraft, television systems and remote sensing systems, because they omnidirectionally radiate CP waves in plane. The general design principle of omnidirectional CP antennas requires two orthogonal omnidirectional linear polarized waves, with horizontal and vertical polarization. These two modes need to be excited with a 90° phase difference to radiate CP waves in addition to a 90° space difference [20]. The dual-band omnidirectional CP antenna, which can work in two frequency bands based on the omnidirectional CP antenna, can effectively increase the practicality of the antenna and serve the image transmission UAV operating at 2.4 GHz and 5.8 GHz. To realize the dual-band antenna, many designs have been proposed, which can be roughly divided into three categories, monolayer multimode dual-band methods [1]–[8], multilayer patch methods [10]–[12] and reactance loading methods [13]–[15]. The monolayer multimode dual-band methods generally use the two lowest orthogonal resonance modes of the rectangular patch, TM01 and TM10 [21], while the multilayer patch method uses patches with different resonance frequencies for superposition [10].

Many dual-band antennas have been realized. In [17], using the special material VO2, the operating frequency of
the antenna can be controlled by adjusting the external temperature. Reference [15] obtained a low-profile dual-band dual polarized antenna with an AMC surface. On the basis of dual band, some omnidirectional CP antennas have realized multi-band, the principle of which is almost identical to that of dual-band. Reference [11] proposed a compact multi-band antenna with asymmetric coplanar strip (ACS) feeding for 2.4 GHz Bluetooth/WLAN, 3.6 GHz LTE and 3.4 GHz WiMAX applications. The omnidirectional CP dielectric resonator antenna with a top-loaded modified Alford loop realized tri-band in [1], and [2] proposed an omnidirectional CP tri-band antenna using the zeroth-order resonance (ZOR) and two first-order resonance (FOR). However, the operating frequency of this kind of antenna is relatively low, which makes it difficult to improve and does not accord with the frequently used image transmission frequencies at 2.4 GHz and 5.8 GHz. In [3], a compact CP patch antenna with a wide AR beam width operating at dual bands compatible for GPS satellite navigation applications is proposed, [18] obtained a dual-band dual-polarized omnidirectional antenna loaded with eight open slots and eight shorted metal pins, and a dual-band antenna using ZOR and FOR mentioned above is realized in [4]. Although these operating frequencies of antennas have more applications, the working BW of the antennas is still narrow, and unable to meet practical demands. The antennas in [5] and [10] both operate at 2.4GHz and 5.8GHz, but each of them is either a directional antenna or a linear polarized antenna. Reference [6] proposed a dual-band omnidirectional CP antenna with the multilayer patch methods, but its size and working frequency are not suitable for the image transmission of UAVs. References [15] and [18] realized the CP antennas using composite metamaterial (MTM) structures and ZOR generated by epsilon negative (ENG) transmission line (TL), respectively, that have wide BW or compact size. However, they are not omnidirectional and dual-band. Table 1 shows a comparison of existing antennas using different methods.

This letter presents an omnidirectional CP antenna with miniaturized size and dual-band operating at the image transmission frequencies of 2.4GHz and 5.8GHz. The antenna uses ZOR by CRLH-TL to generate vertical polarization and two sets of opposite branches to generate horizontal polarization. The ZOR structure not only reduces the antenna profile, but also determines the upper band, while the two sets of branches determine the lower band. Three rectangular slits are respectively etched in the radiation patch and the reference ground to widen ARBW. Finally, the size of antenna is only 0.38λL × 0.38λL × 0.026λL. One of the impedance BWs of the antenna has a range of 5.6 GHz to 6.0 GHz, while the ARBW has a range of 4.6 GHz to 7.3 GHz, and the gain in the azimuth plane is 1.73 dBi at 5.8 GHz. Another impedance BW and ARBW with ranges of 2.39 GHz to 2.42 GHz and 1.9 GHz to 2.6 GHz, respectively, while the gain is 1.75 dBi at 2.4GHz. The Ansoft high-frequency structure simulator (HFSS) is used for a parametric study and antenna optimization.

Table 1. Comparison of existing antennas using different methods.

| Antenna Method | The lower band property | Gain(dBi) | The upper band property | Gain(dBi) |
|----------------|------------------------|----------|------------------------|----------|
| [4] | Monolayer multi-mode | omni-CP | 1.09 | 2.63 | omni-CP | 8.62 | 0.7 |
| [6] | Monolayer multi-mode | omni-CP | 2.64 | 1.4 | omni-CP | 2.85 | 0.96 |
| [7] | Multilayer multi-mode | omni-CP | 8 | 2 | uni-CP | 5.06 | 0.8 |
| [10] | MTM structure | omni-CP | 33.0 | 3.76 | - | - |
| [16] | ENG-TL | uni-CP | 10.8 | 4.17 | - | - |

**II. ANTENNA CONFIGURATION**

Fig. 1 shows the configuration of the proposed dual-band omnidirectional CP antenna. It consists of a circular radiation patch and a circular ground located on the upper and lower surfaces of the dielectric substrate with a height of 3.175 mm respectively, the material of which has a permittivity of 2.2. Two sets of opposite branches are arranged in sequence around the radiation patch and circular ground at angle difference α1 = 60°, also on the upper and lower surfaces of the dielectric substrate. The radiation patch and circular ground are connected by three copper shorting vias arranged at the same distance d = 6mm around the coaxial cable. On the
radiation patch and the circular ground, three rectangular slits are respectively etched by an angle of $\alpha_2 = 57^\circ$. The coaxial cable contacts the radiation patch and feeds directly. The parameters of the antenna are listed as follows: $R_1 = 13\text{mm}$, $R_2 = 8.3\text{mm}$, $R_3 = 8.5\text{mm}$, $W_1 = 2\text{mm}$, $W_2 = 2.25\text{mm}$, $L_1 = 13.5\text{mm}$, and $L_2 = 6.5\text{mm}$.

The ZOR is introduced by connecting the radiation patch and ground above and below the dielectric substrate respectively with shorting vias, which not only produces the vertical polarization but also miniaturizes the antenna size. Additionally, the surrounding branches produce the horizontal polarization, another resonance frequency band. The current on the radiation patch is the radial current, which realizes the function of the electric dipole antenna, while the branches generate the ring current, which realizes the function of the magnetic dipole antenna. The two sets of opposite branches are also coupled with each other to increase the BW and the rectangular slits can improve the match of the antenna and realize wide ARBW.

III. antenna design and discussion

A. DESIGN OF OMNIDIRECTIONAL CP ANTENNA

The generation of CP wave requires two linear polarized components to have orthogonal differences in time and space and the electric field ($\vec{E}$) in the far field generated by the antenna can be expressed as:

$$\vec{E}(\theta, \varphi) = \vec{E}_0(\theta, \varphi) e^{j\phi_1} + \vec{E}_\varphi(\theta, \varphi) e^{j\phi_2}$$ (1)

In this antenna, the vertical polarized component $E_0$ is generated by ZOR, based on which the antenna has the characteristics of small size, light weight and compact structure. In traditional right-handed transmission line (RHTL) resonator, the resonance frequency of the resonator $\omega_m$ with physical length $l$ has the relationship with half-wavelength or electrical length $\theta = \beta l$ as follows:

$$l = \frac{m\lambda}{2}$$ (2)

or

$$\theta_m = \beta_m l = \left(\frac{2\pi}{\lambda}\right) \cdot \left(\frac{m\lambda}{2}\right) = m\pi$$ (3)

where $m = +1, +2, \cdots, +\infty$. From (3), there are countless positive order resonance modes in theory. The antenna usually resonates with the first-order frequency, while the other resonant frequencies are all multiples of the first-order resonant frequency, that is $\omega_m = m\omega_1$. However, the zero-order is composed of left-handed and right-handed transmission line, the composite right left hand, whose electrical length $\theta = \beta l$ can be zero or negative. The order $m$ of the resonator is symmetric with respect to 0:

$$l = |m| \frac{\lambda}{2}$$ (4)

where $m = 0, \pm 1, \pm 2, \cdots, \pm\infty$. In this antenna, the radiation patch, ground and shorting vias connecting them constitute a mushroom type zero-order resonator. The equivalent circuit model of LC network unit cell is shown in Fig. 2, where $L'_R$ and $C'_L$ are the series inductance and capacitance per unit length, $L'_L$ and $C'_R$ are the shunt inductance and capacitance per unit length. To verify circuit model, Fig. 3 is the circuit simulation transmission characteristic curve of the unit cell. Under the condition of balanced structure, LC network unit parameters with the working frequency of 5.8 GHz can be selected as: $C'_L = 9.95pF$, $L'_R = 6.78nH$, $C'_R = 3.72pF$, $L'_L = 2.07nH$. It can be seen from Fig. 3 that according to the circuit simulation results, the center frequency of the resonator is at the equilibrium point, which is also at the zero-order position.

According to the research on CRLH, the periodic boundary conditions are obtained by applying Bloch’s theorem as follows:

$$\beta_n(\omega) = \frac{s(\omega)}{p} \sqrt{\omega^2 L'_R C'_R + \frac{1}{\omega^2 L'_L C'_L} - \frac{L'_R L'_L}{L'_L C'_L} \frac{L'_L}{L'_R C'_R}}$$ (5)

$$s(\omega) = \begin{cases} -1, & \omega < \min(\sqrt{L'_L C'_L}, \frac{1}{L'_R C'_R}), \\ +1, & \omega > \min(\sqrt{L'_L C'_L}, \frac{1}{L'_R C'_R}). \end{cases}$$ (6)

where $\beta_n(\omega)$ is the phase shift constant of the NTH order mode electromagnetic wave, $\omega$ is the angular frequency and $p$ is the unit length. To validate the ZOR mode from CRLH,
Fig. 4 shows the dispersion curve obtained from full wave simulation (Ansoft HFSS) using a unit cell of a rectangular patch. Since the dispersion curve can only be calculated by the infinite periodic structure (IPS) and one third of circular patch cannot be applied to the periodic boundary condition for simulation, a unit cell of one third of circular patch is converted to a unit cell of a rectangular patch shown in Fig. 4, that has the same arc branch and equal area. The IPS is aligned horizontally when calculated as shown in Fig. 4. Thus, the effects of the arc branch are ignored since it is connected to the patch of the periodic boundary and the larger shunt capacitance by the curved branch is also neglected [4]. The ZOR frequency is proportional to \((L'_L C'_R)^{-0.5}\), where \(L'_L\) and \(C'_R\) are shunt inductance (left-handed component) and shunt capacitance (right-handed component), respectively. It can be seen from Fig. 4 that the ZOR frequency of 5.73GHz obtained from the dispersion curve is congruent with the designed frequency (5.8GHz) of the proposed antenna. In addition, the distribution of the equivalent ZOR cavity electric field at 5.8GHz is shown in Fig. 5. It can be seen that the electric field vectors are almost in the same downward direction. Fig. 6 is the S parameter of the equivalent ZOR cavity. From Fig. 6, the antenna only resonates at 5.8 GHz at this time, and the lower band does not exist. The ZOR mode is validated above. When antenna operates in ZOR mode, it radiates omnidirectional electromagnetic waves, similar to a monopole antenna.

Arc branches generate horizontal polarized \(E_{\phi}\). By loading three arc branches around the radiation patch, the antenna can obtain the circular current and realize the omnidirectional CP radiation, as shown in Fig. 7. Its electric field in the far field can be expressed as:

\[
\hat{E}_{\phi} = \frac{[I]}{2\pi} \mu_0 \alpha a J_1(\beta a \sin \theta) \hat{\phi}
\]

where \(J_1\) is the Bessel function of the first order, \([I]\) is the magnitude matrix of current on the loop, \(\mu\) is the free-space permeability, \(\beta\) is the propagation parameter of space and \(r\) is the distance between the antenna and the measuring point. The circular current introduces a resonance mode that is orthogonal to ZOR, thereby obtaining the low-band resonance frequency. The direction of arc branches around the radiation patch is anticlockwise, so the CP mode at 2.4 GHz is left-handed and that at 5.8 GHz is right-handed, the orthogonal mode. The equivalent circuit model is shown in Fig. 8. Similar to the circuit model of ZOR above, Fig. 9 shows the simulation results of transmission characteristic curve of the circuit model. Because the circuit model only uses one unit, there is no series capacitance between the units. The loaded branches lengthen the current path of radiation patch, which is equivalent to increasing the area of radiation patch, and can be regarded as increasing the shunt capacitance and
series inductance. The resonant frequency of the ZOR antenna is:

\[ f_0 = \frac{1}{2\pi \sqrt{L_C R}} \]  

(8)

**FIGURE 9.** Circuit simulation curve of the equivalent circuit model.

Fig. 10 shows the electric field and the surface current distribution of the antenna radiation patch at \( t = 0, T/4, T/2 \) and \( 3T/4 \) to further explain the reason of the CP property. The electric fields (and surface currents) at 5.8 GHz and 2.4 GHz are arranged on the left and right in Fig. 10, respectively. At \( t = 0 \), the entire radiation patch shows a fully charged state, and no surface current flows. Therefore, there are only electric fields at \( t = 0 \). The positive charges are on the surface of the circular patch at 5.8 GHz and the surface of the arc branches are negative charges, as shown in left side of Fig. 10(a). However, the negative charges are on the entire surface of the radiation patch at 2.4 GHz as shown in the right side of Fig. 10(a). It is also found that at 5.8 GHz the electric field is stronger on the circular patch than on the arc branches, therefore, the radiation mainly comes from the circular patch. The opposite is the case at 2.4 GHz, and the radiation mainly comes from the arc branches. In addition, the electric field not only at 5.8 GHz but also at 2.4 GHz mainly contributes vertical waves. Thus, the CP antenna radiates the same vertical electric field as that of the circular patch at both frequencies. At \( t = T/4 \), the negative and positive charges on the curved branches at each mode are fully discharged, resulting in the surface current flow as shown in Fig. 10(b). At this time, there are only surface current. It can be seen that the horizontal current flow on the branches forms the current loop to realize the horizontal polarized wave. Moreover, the direction of the surface current at 5.8 GHz is the reverse of that at 2.4 GHz resulting in the opposite direction of polarization at these frequencies, as shown in Fig. 10(b). At \( t = T/2 \), the circular patch with branches is charged again, and no surface current flows. The antenna radiates the reverse direction wave as the vertical polarized wave in Fig. 10(a). At \( t = 3T/4 \), the positive and negative charges on the branches at each frequency are fully discharged, and the current flows are shown in Fig. 10(d) as opposed to Fig. 10(b). At each resonance frequency, the antenna behaves as a capacitor and is charged and discharged repeatedly in a period of time (T). It also can be seen that there is always a 90° phase difference between the vertical and horizontal wave because of the time difference between the charged and discharged states. Therefore, the 90° phase difference between two orthogonal components at both frequencies inherently exist.

**B. THE REALIZATION OF DUAL-BAND AND WIDE ARBW**

The antenna achieves omnidirectional CP at dual-band of 2.4 GHz and 5.8 GHz, the upper of which is controlled by ZOR and the lower is controlled by the orthogonal mode produced by the arc branches. However, the BW generated by ZOR is generally narrow due to its BW determined by \( L'_L \) and \( C'_R \) not physical size of antenna, thus, such antenna is difficult to works in practice. Therefore, the antenna is loaded with arc branches in the opposite direction around the reference ground and coupled with the branches around the radiation patch to enhance the radiation and widen the bandwidth. Fig. 11 compares the S parameter whether there are branches...
around the reference ground. When the reference ground without arc branches around, it can be seen that the antenna S parameter curve moves up and the impedance bandwidth is relatively narrow. Especially for the upper band, the arc branches around ground broaden impedance bandwidth obviously. It is difficult to broaden the lower band, which may be due to cross polarization.

Opening rectangular slits on the radiation patch and ground improves the CP property of the antenna and realizes a wide ARBW. Fig. 12 shows a comparison of the AR with and without slits on circular patch in dual-band. It can be seen that the slits decrease the AR and widen the ARBW. Fig. 13 shows the E-field distribution of the slits on radiant patch and ground at 2.4 GHz and 5.8 GHz. It can be seen that at the same frequency, the radiation of slits on patch and ground are orthogonal to each other.

C. PARAMETER ANALYSIS AND DISCUSSION

The realization of omnidirectional CP requires the same omnidirectional pattern of vertical polarization $E_\theta$ and horizontal polarization $E_\phi$ orthogonal in space, with 90° phase
time difference. Therefore, the characteristic of CP and the control of dual bands are mainly realized by adjusting arc branches and resonant cavity composed of the radiation patch, ground and shorting vias.

One effect is the radius of radiation patch $R_2$. To change $R_2$ is to adjust the ZOR cavity. Fig. 14 shows the effect of changing $R_2$ on antenna S parameters and AR parameters. It can be seen from Fig. 14(a) that when $R_2$ increases, the resonant frequencies of two bands move close to each other, while Fig. 14(b) shows that the AR curves change irregularly, especially for the upper band. This may occur because increasing $R_2$ results in the reduction of radiation patch area, which reduces the inductance of the coupling or series. Another is the length of arc branches $L_1$. Changing the length $L_1$ changes the vertical polarization $E_\theta$ and coupling between branches. Fig. 15 shows the effect of changing $L_1$ on antenna S parameters and AR parameters. It can be seen from Fig. 15(a) that the resonant frequency of the antenna moves up when $L_1$ decreases, while Fig. 15(b) shows that the AR curve changes in the same way. In addition, the distance $d$ of shorting pins from center, the radius $R_3$ of the ground and the angle $\alpha_1$ between the two sets of branches all affect the performance of dual-band and CP of the antenna.

IV. MEASUREMENT RESULTS

The antenna is fabricated as shown in Fig. 16. The measured overall size of antenna is also $0.208\lambda_d \times 0.208\lambda_d \times 0.026\lambda_d$. Agilent E8363B network analyzer and a far-field system in anechoic chamber are used to measure the parameters of the antenna and it is found to be in good agreement with the simulated results. Fig. 17 shows the simulated and measured values of the S parameter and AR of the antenna. As shown in Fig. 17, the measured BW of antenna in the lower band has a range of 2.37 GHz to 2.41 GHz, equivalent to 1.67%, and the BW of the upper band has a range of 5.5 GHz to 5.9 GHz, equivalent to 6.90%. The ARBW has a range of 2.0 GHz.
to 2.6 GHz at 2.4 GHz, 25%, and has a range of 4.6 GHz to 7.1 GHz at 5.8 GHz, equivalent to 43.1%. In the dual bands, the overlap BW of S parameter and AR covers the two frequencies of UAV image transmission, 2.4 GHz and 5.8 GHz, which indicates good practicability. Fig. 18 shows the simulated and measured radiation patterns of the proposed antenna in the azimuth (xy plane) and elevation (xz plane) planes at 2.4 GHz and 5.8 GHz, respectively. The antenna has good omnidirectivity with a large beamwidth of approximately 110°. The gain of the antenna at 2.4 GHz and 5.8 GHz is 1.75 dBiC and 1.73 dBiC respectively, which may be due to the effect of the large beamwidth.

To show the relative advantages of the antenna proposed in this letter, it is compared with other similar reported antennas, as shown in Table 2. It can be seen that only the antenna in this letter are omnidirectional CP in dual-band and accord with the frequently used image transmission frequencies of 2.4 GHz and 5.8 GHz. Compared with some dual-band antennas, the ARBW of this antenna is wide and the impedance BW at 5.8 GHz is also relatively wider, which indicates that it is more practical. In terms of size, this antenna has compact profile and small radius.

V. CONCLUSION

A dual-band omnidirectional CP antenna is presented in this letter. The dual-band at 2.4 GHz and 5.8 GHz of the antenna are generated by arc branches and ZOR respectively, the ZOR structure by CRLH-TL and meandering technology allow...
miniatrization of the antenna size, which can meet the frequency and size of image transmission requirements of UAVs. The two opposing sets of arc branches are coupled to each other to widen the BW and the slits on the radiation patch and reference ground improve CP characteristics of the antenna to widen the ARBW. The theory of dual-band omnidirectional CP antenna has been described in detail in this letter, and the measured results are in good agreement with the simulation results. Additionally, the ARBW of the antenna in dual bands is wider than the impedance BW, which indicates that the impedance BW of the antenna can be widened to achieve broadband dual-band omnidirectional CP antenna.

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