A Compact Hollow Dual Circularly Polarized Antenna With Folded Coupled Feed Structure for Distance Detection Application

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ABSTRACT

A wideband and dual circular polarization hollow patch antenna fed by a tapered fold coupled structure is presented for distance detection application. The proposed antenna consists of a gear-shaped ring radiation patch etched on a three-layer dielectric substrate, four tapered folded feedlines, a ring ground plane and a feeding network. To achieve right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) characteristics, four hybrids are employed. The proposed hollow antenna can be seamlessly integrated and installed under the cover of sharp shaped aerobat without effect on its flight characteristics. As a proof-of-concept, an antenna working at 1.8 GHz is prototyped and tested. The measured and simulated results show that the proposed antenna exhibits a wide impedance bandwidth of 270 MHz (1.695 - 1.965 GHz) and a wide 3-dB axial ratio (AR) beamwidth of 140 degree.

INDEX TERMS

Patch antenna, hollow antenna, wideband, circular polarization, coupled feeding.

I. INTRODUCTION

Circularly-polarized (CP) antennas have been widely employed in wireless communications for the advantages of reducing the multipath effects and polarization misalignment [1]. It is necessary to use CP antennas under several situations, such as global positioning systems (GPS) and unmanned aerial vehicle (UAV). One typical application is distance detection, in which the distance is calculated based on the concept that the polarization of received CP wave is contrary to transmitted CP wave. During the past decades, various CP patch antennas [2]–[7] have been reported due to the advantages of low cost, easy fabrication, and reliable installation.

As we known, to design a circularly polarized antenna, two orthogonal resonant modes with a 90-degree phase difference must be simultaneously excited [8]. In [9], a single-feed CP antenna was presented based on phase difference between tapped line and parallel coupled line. A CP antenna with folded ground element was designed in [10], in which the antenna was fed by two ports feeding network. To realize specified gain and AR (Axial Ratio) beamwidth, a circular antenna with inner cavity and outer cavity, fed by four ports, was designed for spaceborne applications [11]. However, all the antennas mentioned above have only single circular polarization (LHCP or RHCP), so they are not suitable for the distance detection application.

To obtain a dual CP antenna, there are two typical approaches to control the CP polarization to be LHCP or RHCP. One is to design a multi-feed antenna, in which a feeding network with power divider is needed. In [12], two feeds and a 90-degree directional coupler were employed to excite two different circular polarizations. Because the antenna structure is asymmetric, the radiation patterns with the two polarizations are different. The other is polarization reconfigurable technology [13]–[15]. In [13], the antenna could realize different CP radiation characteristics by injecting water into different holder. In [14], several p-i-n diodes were used to control the polarization switching of the antenna. The same method was employed in [15], in which an L-probe fed square patch antenna with reconfigurable feeding network was reported. However, the polarization reconfigurable CP antennas have complex structures and extra control circuits. In [16], a dual-band antenna with different CP characteristics
was investigated, in which one band is LHCP and the other band is RHCP. However, the antenna [16] is only suitable for communication system with different uplink and downlink bands.

In addition, in a compact transceiver system, the volume for placing antenna is limited. Compared with traditional patch antenna, the ring patch antenna has a smaller size. CP ring patch antenna includes various shapes, e.g., circular, square, or triangular. A ring antenna with two p-i-n diodes was proposed in [17]. The antenna could be operated with linear polarization, LHCP and RHCP. However, it was fed by a probe, meaning that it is not suitable to be manufactured on a thick substrate. In [18], a loaded CP ring antenna for biomedical applications was designed, in which several slots and patches were added to the ring antenna for CP radiation. In [19], a polarization reconfigurable differential-fed CP ring antenna was simulated and measured. In [20], a combination of patch antenna and ring antenna was proposed to realize dual band operation. By controlling the current of the patch and ring antenna, the antenna [20] could operate at TM\(_{11}\) and TM\(_{12}\) modes. However, the feeding network for controlling the polarization is complex. In addition, all the antennas mentioned above are not hollow, so that they are not suitable for the installation in fast aerobat with sharp shape and UAV, as shown in Fig. 1.

Very few works have been reported to focus on the hollow ring dual CP antenna, i.e., with hollow dielectric substrate, hollow ground plane, and side coupled feed. For the fast aerobat with sharp shape and UAV, a hollow antenna is demandable for installing in such a small volume.

In this paper, a compact hollow dual circularly polarized antenna with tapered folded coupled feeding structure is proposed. The antenna is convenient for installing in fast aerobat with sharp shape and UAV. For distance detection application, the LHCP and RHCP characteristics are achieved by setting correct phase and amplitude of feeding ports. Several slots and fixed holes are etched on the patch to improve the antenna performance and easiness of installation. To avoid the introduced inductive of the feeding probe and to improve the impedance bandwidth, four tapered folded coupled feeding structures are arranged around the antenna. An antenna prototype working at 1.8 GHz is manufactured to verify the design concept.

II. ANTENNA DESIGN

A. CONFIGURATION AND TOPOLOGYC

Fig. 2 shows the configuration of the proposed antenna. The antenna is printed on two circular substrates. As shown in Figs. 2(a) and (b), substrate 1 is F4BTME-1/2 with thickness of 4 mm, relative permittivity of 4.4, and dielectric loss angle tangent of 0.003. Substrate 2 consists of two stepped TP-1/2 layers with equal thickness of 6 mm, relative permittivity of 20.5, and dielectric loss angle tangent of 0.0035. On the top of the substrate 1, a gear-sharp ring patch antenna with several symmetrical slots and fixed holes is printed, as shown in Fig. 2(c). Besides, four semi-circles are symmetrically etched around the ring patch to achieve appropriate feeding points. As shown in Fig. 3(a), the ring antenna is fed by four symmetric folded feeding lines, in which the width is tapered to improve the impedance matching. Four feeding lines are...
arranged by 90-degree interval to obtain CP excitation. In order to couple energy to the ring patch radiator, the ends of feeding lines are inserted to the bottom of the substrate 1. The ground plane is located at the bottom layer of substrate 2, with a bigger size than that of the radiator patch. Fig. 3(b) shows the equivalent circuit model of the proposed feeding line and antenna. It consists of a feeding line, a coupling region and an antenna. The coupling region represents the coupling between the feedline and the antenna. The characteristic impedance $Z_f$ and $Z_c$ are associated with the width of the feeding line and the width of inserted area, respectively. The electrical length $\theta_f$ and $\theta_c$ are associated with the length of the feeding line and the length of inserted area, respectively.

All the components of the antenna are hollow, including the patch, the substrates 1 and 2, the ground plane, so does the feeding network. The detail parameters are as follows: $R_1 = 7.2$ mm, $R_2 = 13$ mm, $R_3 = 14.5$ mm, $R_4 = 6.8$ mm, $R_5 = 16.5$ mm, $R_6 = 18.5$ mm, $R_7 = 0.8$ mm, $R_8 = 1.8$ mm, $R_9 = 12.5$ mm, $L_1 = 3.3$ mm, $L_2 = 3$ mm, $W_1 = 0.6$ mm, $W_2 = 2.5$ mm, $W_3 = 2$ mm, $W_4 = 0.85$ mm.

**B. ANTENNA ANALYSIS**

For the installation in the fast aerobat with sharp shape and UAV, the patch antenna should be hollow. Therefore, we adopt a ring antenna. For a traditional ring patch antenna, the TM$_{11}$ mode is the fundamental resonant mode, implying that the mean circumference of a ring equals the wavelength at resonant frequency [21]. The resonant frequency is calculated by

$$f_{11} = \frac{c}{2\pi R \sqrt{\varepsilon_{\text{eff}}}}$$

(1)

where $c$ is the speed of light in free space, $R$ is the mean radius of the ring patch, and $\varepsilon_{\text{eff}}$ is the effective dielectric constant. In (1), $R$ can be approximately calculated by

$$2\pi R \approx \pi (R_1 + R_9)$$

(2)

Based on the detail parameters, the calculated resonance frequency of the ring patch is approximately 1.8 GHz.

Fig. 4 shows three steps for the evolution in the patch antenna design. A circular patch antenna working at TM$_{11}$ mode, named Ant. 1, is simulated at first. Because the current distributes mainly around the edge of the circular patch, which means that the center part of the patch can be removed without influencing the antenna performance. For installing in fast aerobat with sharp shape and then an improved hollow patch, named Ant. 2, is designed. Compared with Ant. 1, the current distribution of Ant. 2 is changed slightly, it is in accordance with theory analysis. Several slots and circular hole are etched at the ring antenna to assemble easily, then a gear-shaped ring antenna (Ant. 3) is derived. The simulated VSWR curves shown in Fig. 5(a) indicate that the impedance characteristics are unchanged almost for Ant.1 to 3. It means that a hollow antenna can be derived from a patch antenna with unchanged antenna performance. Fig. 5(b) shows the simulated axial ratio of Ant. 1 to 3 versus frequency at the maximum direction, the values are much less than 3 dB over whole band, because the radiation patch and the feeding point are completely symmetrical.

To explain work mechanism of the proposed CP antenna clearly, surface current distributions (0°, 90°, 180° and 270°) at 1.8 GHz are shown in Fig. 6. As expected, the current rotates in counterclockwise for RHCP radiation. It can be noticed in Fig. 6 that 0° and 180° phase currents are mainly focused at the upper and lower semi-circles mental patch, especially near the two vertices. The 90° and 270° phase currents are composed by left and right semi-circles, particularly close to the two side vertices.

When the proposed hollow antenna is installed in fast aerobat with sharp shape or UAV, a material is inserted into the hollow of the antenna, then a mutual coupling is occurred between the antenna and the material, and that will affect the performance of the antenna. To verify the variation of antenna performance caused by the inserted material, two types of typical materials are analyzed, one is metal and the other is polyester.
As shown in Fig. 7, the proposed hollow antenna is inserted by metal material, the resonant frequency is changed slightly, which is caused by the coupling between the antenna and the metal material. And the operating frequency of 1.8 GHz is covered in any case.

The simulated VSWR results with and without inserted polyester material are shown in Fig. 8. The comparison results show that the performance of the antenna is stable, which is because the polyester is insulator. And there is no coupling occurred between the polyester and the antenna.

C. MECHANISM OF FEEDING NETWORK

As shown in Fig. 1, the proposed antenna has four feeding ports with 90-degree phase difference one by one. In order to generate the excited signal, a hollow feeding network with four hybrids is designed and manufactured.

Fig. 9 shows the configuration of the feeding network. It is shown in Fig. 9(a) that the feeding network is composed of four planes (three layers), including two ground planes, one plane of RHCP feeding network, and one plane of LHCP feeding network. All the substrates in the three layers are rogers 4350B with 10 mil of thickness. Grounded coplanar waveguide feeding technique is adopted in the proposed feeding network. The width of feedline is 0.5 mm, and the
gaps between feedline and ground plane are 0.36 mm, to get a 50 Ω matched impedance. The two ground planes are connected by irregularly distributed vias, which can improve the electromagnetic compatibility.

As shown in Figs. 9(b) and (c), a total of four quadrature hybrids are employed, to obtain appropriate amplitude and phase for the CP operation. For the RHCP feeding network, as shown in Fig. 9(b), the length difference of feedlines from hybrid 1 to hybrid 2 and from hybrid 1 to hybrid 4 is about λ/2 at central frequency, and then a 180-degree phase difference is obtained between hybrid 2 and 4. The length of the feedlines from hybrid 2 to antenna ports 1 and 2 are equal, which means the two ports get the same amplitude but 90-degree phase difference excitations, and so does from hybrid 4 to antenna ports 3 and 4. Similarly, the LHCP feeding network is designed and shown in Fig. 9(c). The length differences of the feedlines from hybrid 3 to hybrid 2 and from hybrid 3 to hybrid 4 are also about λ/2 at central frequency. Hybrids 2 and 4 are shared by the RHCP and LHCP feeding networks.

III. RESULTS AND DISCUSSION

The proposed hollow circularly polarized antenna has been prototyped and measured. The photograph of the proposed antenna is shown in Fig. 10, and the simulated and measured VSWR and gain are presented in Fig. 11.
TABLE 1. Comparison with other ring CP antennas.

| Antenna | Hollow | Impedance bandwidth | Dual CP | 3-dB beamwidth | Feed method | Antenna profile |
|---------|--------|---------------------|--------|----------------|-------------|----------------|
| [16]    | no     | 19.5-21.5 GHz, 29-31 GHz | yes    | 60 °           | microstrip feed | 0.7\lambda_o |
| [17]    | no     | 3.86-3.98 GHz        | yes    | No given       | probe feed   | 0.73\lambda_o |
| [18]    | no     | 2.34-2.65 GHz        | no     | 75 °           | probe feed   | 0.093\lambda_o |
| [19]    | no     | 1.7-4                | yes    | No given       | probe feed   | 0.97\lambda_o |
| [20]    | no     | 1.565-1.585, 2.32-2.345 | yes    | No given       | probe feed   | \lambda_o |
| This work | yes   | 1.695-1.965 GHz      | yes    | 140 °          | coupled feed | 0.149\lambda_o |

![FIGURE 12. Performance of the proposed antenna at 1.8 GHz: (a) AR (b) Normalized radiation patterns.](image)

The VSWR versus frequency is shown in Fig. 11(a). It is concluded that the antenna operation bandwidth for VSWR < 2 is from 1.695 GHz to 1.965 GHz, and the simulated result match well with the measured one. Fig. 11(b) gives the measured as well as simulated gains. Results shown that the gain is higher than 4 dBi with the max value about 4.5 dBi.

For the axial ratio versus theta and radiation patterns, the simulated and measured results at 1.8 GHz are plotted in Fig. 12. The antenna shows a wide coverage which is about 140° with AR < 3, as shown in Fig. 12(a). It is helpful to a wide range distance detection application. Because the RHCP and LHCP are symmetric, only the results of the measured RHCP characteristics are shown in Fig. 11 and 12(a) for avoiding verbosity. Fig. 12(b) shows that the cross-polarization ratio is more than 20 dB at front radiation direction where RHCP is co-polarization and LHCP is x-polarization.

Table 1 compares the proposed hollow dual-circular-polarization ring antenna with other CP antennas [16]–[20]. The comparison focuses on hollow structure, impedance bandwidth, dual-circular-polarization characteristic, 3-dB beamwidth, feed method, and the antenna profile. This comparison shows that just the proposed antenna has not only a dual CP radiation but a compact hollow structure, and a wide 3-dB beamwidth. The antenna [18] has a compact volume than the proposed antenna, but it does not have dual CP radiation. Therefore, the proposed compact hollow dual CP antenna is more suited to install at compact bodies for distance application than the other antennas.

IV. CONCLUSION

A compact hollow dual circularly polarized antenna with tapered folded coupled feeding structure has been presented in this paper. The proposed hollow antenna is suitable for installing at the front end of bodies, such as unmanned aerial vehicles and sharp end bodies. A hollow feeding network with four hybrids is employed to control the circularly polarization. The compact hollow ring antenna has been fabricated and tested, the measured and simulated results are in a good agreement. Results show the antenna has a wide impedance bandwidth of 270 MHz from 1.695 - 1.965 GHz, 3-dB AR beamwidth of 140 degree, the cross-polarization level ≤−25 dB and dual circularly polarization, and that implies the antenna can be used for distance detection.

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