A dual-band circularly polarized antenna with wide HPBWs for CNSS applications

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Abstract: A dual-band circularly polarized (CP) antenna with wide half power beamwidths (HPBWs) for compass navigation satellite system (CNSS) applications is proposed in this paper. The CP radiation is realized by feeding four sequentially rotated U-shape patches shorted to the ground at both ends of them with a 90° phase difference feeding network. Loading four parasitic arc-shape patches with one end shorted to the ground provides the dual-band CP operation. Experimental results show that the proposed antenna exhibits two overlapped impedance and axial ratio relative bandwidth of 2.8% and 3.3%. Wide HPBWs of over 122° at center frequencies (1.268 and 1.561 GHz) of the CNSS-2 B3 and B1 bands are obtained. With these good performances, the antenna can be a good candidate for CNSS applications.

Keywords: dual-band, circularly polarized, wide HPBWs

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

1 Introduction

With the rapid development of the compass navigation satellite system (CNSS), it has been widely used in civilian and military areas. In most applications of CNSS-2, the antennas are required to operate at B3 (1.268 GHz ± 10 MHz) and B1 (1.561 GHz ± 2 MHz) bands with right hand circularly polarization (RHCP) radiation patterns, simultaneously. Many studies have been done to realize the dual-band RHCP, such as the stacked microstrip patch antenna in [1], the concentric annular or rectangular rings antenna in [2, 3], the crossed dipole antenna with asymmetrically barbed arrowheads in [4] or complementary split-ring resonators in [5] and so on. However, most of the dual-band antennas are narrow in beamwidths. The half power beamwidths (HPBWs) is valuable for the CNSS applications in order to stabilize the receiving signals and improve the covering area. To get wide HPBWs of the antenna, many techniques have been used such as adopting the quadrifilar helix antenna in [6], extending the substrate beyond the ground plane in [7], loading with monopoles around microstrip antenna in [8], loading with curved microstrip resonant structures in [9], utilizing the curved dipoles and ground planes in [10], employing various kinds of conducting walls or ground structure in [11, 12], loading with artificial magnetic conductor in [13] and so on. Nevertheless, the antennas mentioned above have relatively large structures and most of them focus on single-band work. Hence, it’s necessary to get a dual-band CP antenna with wide HPBWs.

In this paper, a dual-band CP antenna with wide HPBWs is proposed. Four U-shape patches shorting to the ground are sequentially rotated around the center patch and fed by a compact sequential phase feeding network (SP) to get the CP radiation. Four parasitic arc shaped patches are added to achieve the dual-band
operation. The overall dimension of the proposed antenna is \(80 \times 80 \times 21.5\) mm\(^3\). The impedance band (\(|S_{11}| < -10\) dB) is from 1.228 GHz to 1.660 GHz, while the corresponding axial ratio (AR) bands (AR < 3 dB) are 36 MHz (1.252–1.288 GHz) and 52 MHz (1.528–1.580 GHz), covering the CNSS-2 B3 and B1 bands respectively. Meanwhile, the HPBWs at 1.268 GHz and 1.561 GHz are both greater than 120°. Details of the proposed antenna design are presented in Section 2.

2 Antenna geometry and design process

2.1 Antenna geometry

Fig. 1 shows the geometry of the proposed antenna. The antenna mainly consists of three parts: the upper printed circuit board (PCB), the lower PCBs (including two substrates) together with the middle connecting structures (including feeding pins, metal shorting posts and nonmetal supporting poles).

The upper PCB is 1 mm-thick FR4 substrate with a relative permittivity of 4.4. Four U-shape patches that sequentially rotated around the center circle patch are etched on the top layer of the upper substrate as shown in Fig. 1(a). Each U-shape patch is connected to the feeding network by a feeding pin (with radius of 0.8 mm) and is shorted to the ground plane with a pair of metal shorting posts (with radius of 1.5 mm) at both ends of them. Four parasitic arc patches with one end shorted to the ground plane are added inside each of the U-shape patches respectively. Four
nonmetal poles are employed as the structural support between the upper and lower PCBs.

The lower PCBs consists of two substrates, and both are 0.5 mm-thick PTFE substrates with a relative permittivity of 2.65. The SP feeding network is composed of three layers on the two substrates. Fig. 1(d) shows the layout of the feeding lines of the SP feeding network. A 50Ω coaxial line is used as the input feeding structure and the middle layer is used as the ground plane. Based on the out-of-phase property between the inner and outer conductors of the coaxial line, the outer conductor of the coaxial line is connected to the bottom layer, whereas the inner conductor is connected to the top layer and a stable 180° phase difference between the top and bottom layers is achieved. A circular aperture at the center point is removed from the ground plane on the middle layer. Two concentric vacant-quarter rings are etched on the top and bottom layers and are used as 90° phase delay lines to achieve 90° phase offsets between the four output ports, respectively. To achieve impedance matching, the characteristic impedance of the microstrip transmission line with width of $W_{f1}$ is chosen as 25Ω, while the lines with width of $W_{f2}$ and $W_{f3}$ are chosen as 50Ω.

The simulated S-parameters and transmission phases of the SP feeding network are shown in Fig. 2. The transmission coefficients (from $|S_{21}|$ to $|S_{51}|$) are $-6.1 \pm 0.3$ dB, while the reflection coefficient at Port 1 ($|S_{11}|$) is below $-26$ dB across the frequency range of 1.2–1.6 GHz as shown in Fig. 2(a). A phase difference of approximately $90^\circ \pm 8^\circ$ is achieved between the adjacent output ports in the frequency range of 1.2–1.6 GHz as shown in Fig. 2(b).

The optimized antenna design parameters are as follows: $L = W = 80$ mm, $L_1 = 24.4$ mm, $W_1 = 4$ mm, $W_2 = 5.8$ mm, $W_3 = 4$ mm, $S_1 = 7.6$ mm, $S_2 = 2$ mm, $S_3 = 2.2$ mm, $R_1 = 9$ mm, $R_2 = 11$ mm, $R_f = 8.8$ mm, $W_{f1} = 3.6$ mm, $W_{f2} = 1.3$ mm, $W_{f3} = 1.3$ mm, $H = 20$ mm, $H_1 = 1$ mm, $H_2 = 0.5$ mm.

### 2.2 Design process

Fig. 3 shows the design process of the proposed antenna without the feeding network. In the initial design (Design 1), there are only four U-shape patches arranged symmetrically to the center patch. In order to get wide HPBW, the
vertical currents are necessary to enhance the electric field at low elevation angles so that four pairs of shorting posts are added at both ends of the U-shape patches from Design 1 to Design 2. The Design 2 can be regarded as four inverted-L antennas rotated sequentially around the center point. Finally, four shorted arc shape patches are loaded inside the U-shaped patches in Design 3, respectively. All of the three designs use the same substrates with the same dimension of 80 × 80 × 21.5 mm³.

Fig. 3. The design process of the proposed antenna (without the feeding network).

The simulated $|S_{11}|$ of the designs without the feeding network are shown in Fig. 4. As can be seen in Fig. 4, the resonant frequency shifts downwards from Design 1 to Design 2. This phenomenon occurs because the electric length increases due to adding the shorting posts. Meanwhile, the dual-band operation is achieved from Design 2 to Design 3 with a little change of the resonant frequency at high band. The main reason is that at the low band the effective electric lengths increase due to the horizontal arc shape patches and the vertical shorting posts.

The simulated normalized radiation patterns at resonant frequencies of the three designs (Design 1 at 1.87 GHz, Design 2 at 1.57 GHz, Design 3 at 1.268 GHz and
1.561 GHz) in the XOZ plane are plotted in Fig. 5. As shown in Fig. 5, the HPBWs of the proposed antenna get enlarged from 69° to 121° from Design 1 to Design 3 at the corresponding resonant frequency. By adding the shorting posts, the vertical currents of the proposed antenna are generated so that wide HPBWs can be obtained.

Fig. 6 shows the simulated current distributions of the proposed antenna when the Port 1 and 3 are excited with the same amplitude and in phase of 0° and 180° without the feeding network, respectively. It is obvious that at 1.561 GHz the horizontal surface currents mainly focus on the U-shape patches and the corresponding shorting posts, whereas there is little current distributed on the inner arc shape patches as shown in Fig. 6(b). Nevertheless, at 1.268 GHz the horizontal currents focus on not only the U-shape patches but also the inner arc-shape patches in Fig. 6(a). Due to the extension of the current path at the low band, the second resonant frequency is achieved.

As can be seen in Fig. 6(a), the vertical currents mainly focus on the shorting posts of the inner arc shape patches at 1.268 GHz. The vertical currents along the opposite shorting posts flow in the opposite direction. In the XOZ plane, the radiated electric fields by the shorting posts cancel each other at low-elevation angles, while in the XOZ plane the radiated electric fields are added together due to the distance between them of about 0.23 \( \lambda_0 \), where \( \lambda_0 \) represents corresponding free-space wavelength at 1.268 GHz. Hence, the gains at low elevation angles are
enhanced. At 1.561 GHz, the vertical currents mainly focus on the shorting posts
are in the same direction as shown in Fig. 6(b) so that the radiated electric fields are
enhanced at low elevation angles. When the proposed antenna is fed by a sequential
90° phase feeding network, wide CP HPBWs are generated due to the radiation
from the vertical currents along the shorting posts.

3 Simulated and measured results
The ANSYS High Frequency Structure Simulator (HFSS) is used to investigate
and optimize the antenna configuration. A prototype of the proposed antenna is
fabricated and measured as shown in Fig. 7. The $|S_{11}|$ is measured with the Wiltron
37269A vector network analyzer and the radiation patterns and ARs are measured
in an anechoic chamber.

Fig. 7. Prototype of the proposed antenna. (a) Top view (b) Side view.

Fig. 8. Simulated and measured $|S_{11}|$ of the proposed antenna.

The simulated and measured $|S_{11}|$ are plotted in Fig. 8 and a good agreement
can be seen between the simulated and measured results. The measured impedance
bands ($|S_{11}| < -10$ dB) are ranging from 1.228 GHz to 1.660 GHz.

The simulated and measured ARs at the boresight direction are plotted in
Fig. 9. The measured AR bands (AR < 3 dB) are 36 MHz (1.252–1.288 GHz) and
52 MHz (1.528–1.580 GHz), with the relative bandwidth of 2.8% and 3.3%.
The simulated and measured radiation patterns at 1.268 GHz and 1.561 GHz are plotted in Fig. 10 and Fig. 11, respectively. At 1.268 GHz, the proposed antenna yields wide HPBWs of 122° and 126° in the XOZ and YOZ planes, while the measured 3 dB AR beamwidths are 123° and 141° in the XOZ and YOZ planes.
respectively, as shown in Fig. 12(a). At 1.561 GHz, the proposed antenna yields HPBWs of 123° and 129° in the XOZ and YOZ planes, while the measured 3 dB AR beamwidths are 152° and 212° respectively, as shown in Fig. 12(b). The measured antenna gains at the boresight direction for 1.268 GHz and 1.561 GHz are 3.0 and 4.1 dBi, while the measured antenna radiation efficiencies can reach up to 86% and 91% as shown in Fig. 13, respectively. Discrepancies between measured and simulated results are likely due to substrate and measurement errors.

Table I shows the comparison of performance of the proposed antenna with those of the previous antennas. As shown in Table I, the proposed antenna shows wide HPBWs with a relatively compact dimension compared with the other antennas.
Conclusions

A dual-band CP antenna with wide HPBWs for CNSS applications has been proposed and experimentally demonstrated in this paper. Four U-shape patches shorted to the ground are arranged sequentially to the center patch and fed by a compact SP feeding network. The dual-band CP operation is achieved by loading four parasitic arc-shape patches with one end shorted to the ground. The proposed antenna exhibits two overlapped impedance and AR bandwidths of 36 MHz (1.252–1.288 GHz) and 52 MHz (1.528–1.580 GHz), covering the CNSS-2 B3 and B1 bands. Meanwhile, the HPBWs at 1.268 GHz and 1.561 GHz are both greater than 122°. With these advantages, the antenna can be widely used in CNSS applications.

| Antenna Structure | Dual-bands or Single-band | Overall dimension ($\lambda_0^3$) | $-10\text{ dB } |S_{11}|$ bandwidth (%) | 3 dB AR bandwidth (%) | HPBWs (°) | Max Gain (dBic) |
|-------------------|---------------------------|-----------------------------------|-----------------------------|-----------------------|-----------|-----------------|
| Proposed antenna  | Dual                      | 0.34 × 0.34 × 0.09                | 29.5                        | 2.8                   | 122°      | 3.0             |
| Ref. [2]          | Dual                      | 0.20 × 0.20 × 0.076               | 2.3                         | 1.4                   | $\leq 100^\circ$ | 4.3             |
| Ref. [4]          | Dual                      | 0.49 × 0.49 × 0.16                | 6.3                         | 1.9                   | $\leq 80^\circ$ | 6.3             |
| Ref. [6]          | Dual                      | 0.12 × 0.12 × 0.35                | $\geq 10$                   | $\geq 10$             | 96°       | 4.4             |
| Ref. [7]          | Dual                      | 0.48 × 0.48 × 0.02                | 2.3                         | 0.6                   | 100°      | 3.9             |
| Ref. [8]          | Single                    | 0.7 × 0.7 × 0.18                  | 12.1                        | 3.3                   | 156°      | 3.5             |
| Ref. [9]          | Single                    | 0.7 × 0.7 × 0.02                  | 14.6                        | $\geq 15$             | 150°      | 2.5             |
| Ref. [11]         | Dual                      | 0.52 × 0.52 × 0.22                | $\geq 10$                   | $\geq 10$             | 135°      | 4.2             |

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