Progress In Electromagnetics Research M, Vol. 111, 199–208, 2022

A Novel Low Profile Circularly Polarized GNSS Antenna with Wide 3 dB Axial Ratio Beamwidth

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Abstract—A novel low-profile GNSS microstrip circular polarization antenna is proposed and analyzed. Circular polarization is realized by asymmetric structure patch, and an arc structure loaded on the main radiator can keep two modes orthogonal over a wide-angle range, so that the antenna has an extremely wide 3 dB axial ratio beamwidth (ARBW). The far-field AR beamwidths obtained are 232° and 212° respectively in the main plane of $\varphi = 0°$ and $\varphi = 90°$. In $\varphi = 45°$ and $\varphi = 135°$, 3 dB AR beamwidths are 241° and 244°, far exceeding the 120° required for satellite applications. In the whole CP band, 78.95% of the beam width exceeds 180°. The profile is only $0.0156\lambda_0$, which is suitable, especially, for portable wireless systems or devices. The return loss bandwidth of −10 dB is 5.13% (1.52 GHz–1.6 GHz), which covers BeiDou Navigation System B1 (1.561 GHz). The axial ratio bandwidth is 1.28% (1.55 GHz–1.57 GHz), and the in-band peak gain is 4.09 dBi.

1. INTRODUCTION

Circularly polarized (CP) antenna is an important part of navigation and positioning system applications. In some cases, CP antennas with a wide 3-dB axial ratio beamwidth (ARBW) are more important than some other characteristics, such as impedance and AR bandwidth [1]. For example, the satellite navigation and positioning system have high requirements on the axial ratio beamwidth of the antenna. Generally, 3-dB AR beamwidth is required to be greater than 120°, but only a narrow AR bandwidth is required. How to widen the ARBW of circularly polarized antennas has become a topic of great concern to many researchers, and there have been many breakthroughs in this field. Three-dimensional ground design is a feasible way to improve AR beamwidth. In [2], a Flower-Fractal microstrip patch antenna was proposed, and a hexagonal cavity was used to help the antenna to achieve a 3 dB AR beamwidth of 120°. Similar structures include three-dimensional ring-shaped ground plane [3], tapered-elliptical cavity [4], and dual-ring cavity [5]. These methods undoubtedly increase the antenna's overall size and manufacturing difficulty. Moreover, the AR beamwidth can be increased by introducing parasitic elements, e.g., square ring [6] and top-loaded monopole [7]. This is an efficient way, but parasitic radiators are mostly placed above the main radiator, greatly increasing the overall height of the antenna. In [8], an inverse S structure was adopted to achieve a 142° AR beamwidth. However, the antenna contained an integrated Barron resulting in an antenna height of 0.3λ. In terms of low-profile structure, researchers have made many efforts. Two pairs of parallel electric dipoles were used on both sides of the dielectric plate [9] to form a square structure, and 126° ARBW was achieved under the antenna profile of $0.0043\lambda_0$. Both antennas, however, produced unwanted bidirectional radiation patterns. And loading pins [10, 11] to expand the AR beam width. In [12], 3 dB ARBW can reach 180°

Received 16 May 2022, Accepted 22 June 2022, Scheduled 14 July 2022
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by using an asymmetric-microstrip antenna formed by integrating four unequal circles on corners of a square patch. Asymmetric CP antennas were used for Satellite Systems in [13] and 5G NR Applications in [14]. Using metasurface technology [15] to design wide AR beamwidth antennas has also become a new field.

The cost of Global Navigation Satellite System (GNSS) antennas is a fundamental design consideration driven by the market. The patch antenna is the proof of this because of its low profile, platform-compatible structure, small to medium size, and because of its low cost of simple feed [16]. A wide 3 dB AR beamwidth circularly polarized patch antenna for GNSS is designed in this paper. The 3 dB ARBW is greatly broadened by adding four arcs while using an asymmetric structure to achieve circular polarization. With the advantages of low profile and low cost, the excellent performance of the patch antenna will make it of high practical value in GNSS applications. The rest of this paper is arranged as follows. The second section describes the antenna structure and evolution in detail. In the third section, we show the antenna's wide beam performance and try to explain the realization of 3 dB wide AR beamwidth using the electric field and magnetic field. In the fourth section, the parameters of the proposed antenna are studied. To verify the simulation results, a prototype of the proposed antenna was fabricated and measured. In Section 5, the measurement results of the prototype are discussed, and the proposed antenna is compared with relevant antennas proposed in recent years. Finally, a summary of the antenna will be discussed in Section 6.

2. ANTENNA STRUCTURE AND DESIGN

2.1. Antenna Structure

The structure of the proposed antenna is shown in Figure 1. A coaxial probe is used to feed the antenna. The distance between the feed point and patch center is L_1. FR-4 material (permittivity $\varepsilon_r = 4.4$ and loss tangent $\tan\delta = 0.02$) was used as a dielectric substrate with width W and thickness h. The radiator is composed of a main radiator and four quarter arcs, where the side length of the main radiator is W_P. At the same time, two circles with radii R_1 and R_3 are respectively integrated on a pair of diagonal corners of the main radiator, and quarter-sector truncated corners with radii R_2 and R_4 are loaded on the other pair of diagonal corners. This asymmetric structure is the key to realizing circular polarization. The arc is obtained by subtracting the circles with radii R_6 and R_5. This structure can effectively improve the 3 dB axial ratio beamwidth. The main and arc radiators are in contact, as

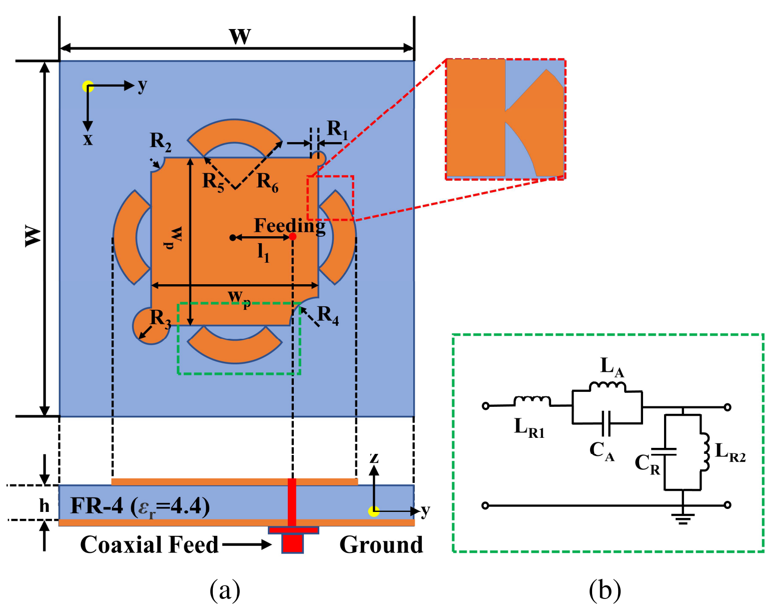

Figure 1. (a) Geometry of proposed CP antenna. (b) The equivalent circuit of a single branch.

shown in Figure 1. Figure 1(b) shows the equivalent circuit of a single branch at the green dashed box in Figure 1(a). The main radiator provides series inductance L_{R1}. Since the arc structure is in contact with the main radiator, it can be regarded as a capacitor C_A and an inductance L_A in series with the main radiator. Capacitance C_R and inductance L_{R2} are produced by coupling to the ground through the radiator [17]. The specific dimensions of the proposed antenna are shown in Table 1. The profile height is only $0.0156\lambda_0$, which has obvious low-profile characteristics.

Table 1. The specific dimensions of the proposed antenna.

parameter	w_p	R_1	R_2	R_3	R_4
dimension (mm)	37	1.1	2	2.7	4.2
parameter	R_5	R_6	l_1	W	h
dimension (mm)	9	14.1	11	100	3

2.2. Design Process

Figure 2(a) shows the evolution process of the designed antenna. The corresponding S_{11}, AR bandwidth, and 3 dB AR beamwidth at $\varphi = 0°$ are shown in Figures 2(b)–(d). First, design a common coaxial feed square patch, as shown in antenna 1 in Figure 2(a). At this time, it is only a linearly polarized patch antenna, and the center frequency f_c of the antenna is [18]

$$f_c = \frac{c}{2L_{eff}\sqrt{\varepsilon_{reff}}} \tag{1}$$

$$L_{eff} = L + 2\Delta L \tag{2}$$

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left[\frac{W}{h}+0.264\right]}{(\varepsilon_{reff}-0.258)\left[\frac{W}{h}+0.8\right]} \tag{3}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \tag{4}$$

where c is the speed of light in vacuum, L the side length of rectangular radiator, ε_r the dielectric constant of substrate, ΔL the length of correction, W the width of the patch, and h the width of the patch.

Replace a pair of diagonal corners of antenna 1 with two unequal circles to get antenna 2. Under such an asymmetric microstrip antenna structure, a pair of orthogonal modes with equal amplitude and a phase difference of 90° can be excited [12]. As a result, antenna 2 is a CP antenna, whose axial ratio is less than 3 dB at 1.76 GHz, and the AR beamwidth is 160°. Then, the other two corners of the square patch are removed by quarter-sector truncated corners of different sizes to form antenna 3, and the AR beam width is slightly widened by 10°. Finally, an arc radiator is placed on each side of the main radiator to form antenna 4 designed in this paper. An equivalent length L_{equ} of the proposed antenna can be approximated by

$$L_{equ} = L_1 + 2*(R_6 - R_5) \tag{5}$$

$$L_1 = w_p + (\pi - 2)R \tag{6}$$

$$R = (R_1 + R_2 + R_3 + R_4)/4 \tag{7}$$

where L_1 is the equivalent side length of antenna 3; w_p is the width of antenna 3; R_1 and R_3 are the radii of the two circles of the rectangular corners; R_2 and R_4 are the radii of the sectors embedded in the two rectangular corners; R_5 and R_6 are the radii of the inner and outer circles of the arc; R is the average value of R_1, R_2, R_3, and R_4. Assign the equivalent length L_{equ} to L in Equation (2), the

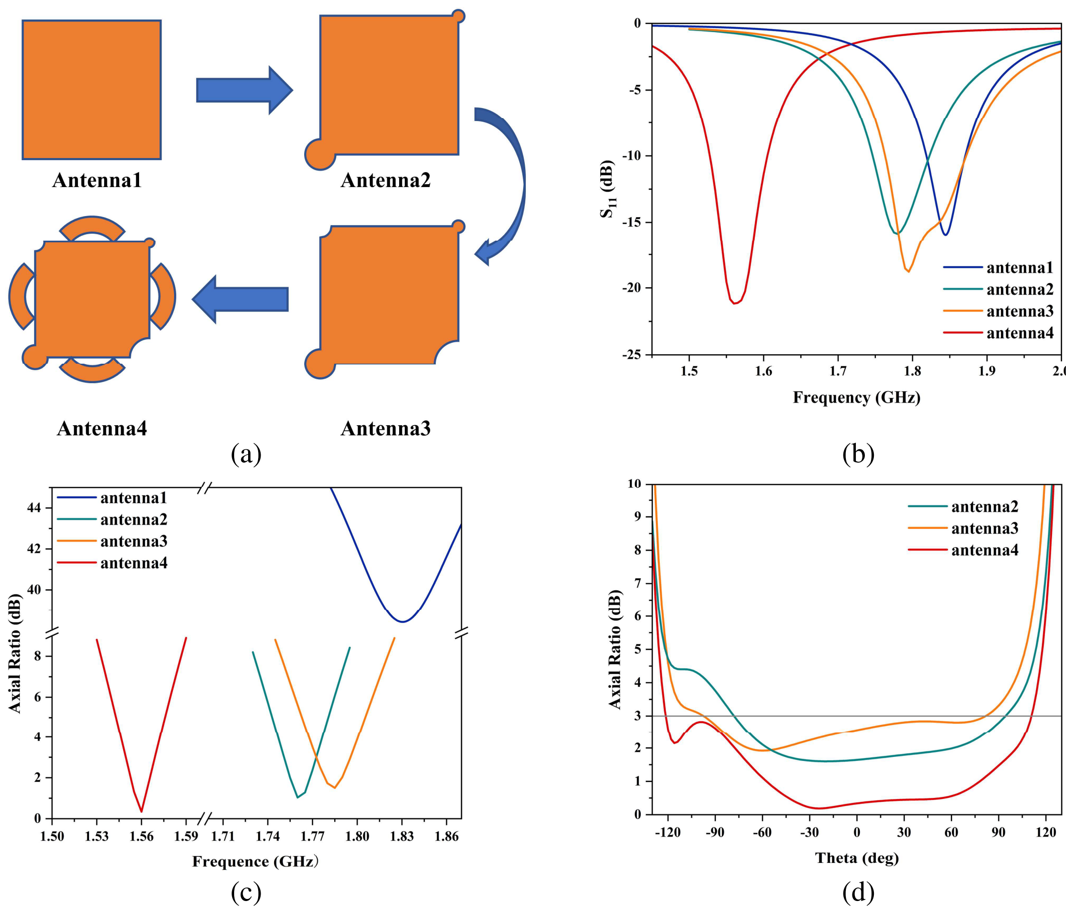

Figure 2. (a) Antenna design flow, (b) comparison of S_{11} of four antennas, (c) comparison of axial ratio performance of four antennas, (d) comparison of 3 dB ARBW of antenna 2, antenna 3 and antenna 4 at $\varphi = 0^\circ$ plane.

resonant frequency of the antenna can be calculated. The increase in side length causes the resonant frequency to move towards lower frequencies to the desired 1.56 GHz. After loading the arc structure, the AR beamwidth is greatly increased compared with antenna 2 and antenna 3, reaching a considerable 232°.

3. CIRCULAR POLARIZATION PERFORMANCE

In order to achieve circular polarization, it is necessary to excite the two orthogonal modes in some way and keep them with equal amplitude and quadrature-phase difference. This asymmetric patch structure can meet this requirement. By adjusting the size of the circle on the vertex, a good circular polarization performance can be obtained. Under the action of the arc structure, two modes can be kept orthogonal in a wide range of angles, so that the beam width of the axis ratio can be very wide. The surface current distribution of the patch antenna at 1.56 GHz, $\omega t = 0^\circ$, 90°, 180°, and 270° is shown in Figure 3. The current rotates counterclockwise, indicating that the polarization direction of the antenna is right-handed circular polarization (RHCP).

The electric and magnetic field intensity variations of antenna 2 and the proposed antenna are shown in Figure 4. The electric field distribution of the proposed antenna shows that a strong radiation area is provided by the arc structures. In terms of the magnetic field, for the CP antenna proposed in this paper, the magnetic field interacting with the arc structure and the main radiator enhances 3 dB ARBW. The radiator's center has an obviously strong magnetic field with a Gaussian distribution

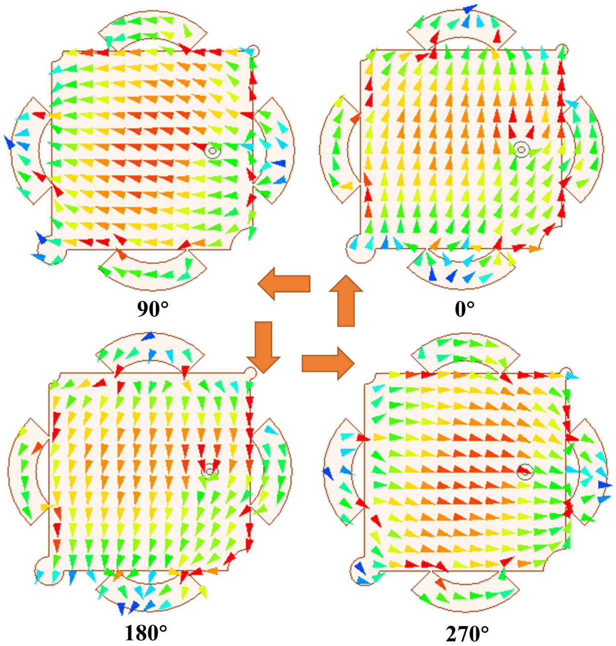

Figure 3. Surface current distribution of antenna 4 for $\omega t = 0°$, $90°$, $180°$, and $270°$.

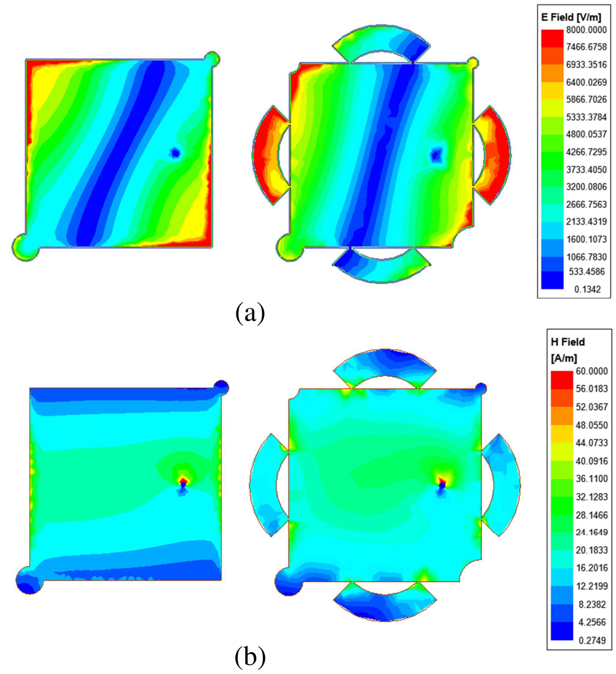

Figure 4. Variation of (a) electric and (b) magnetic field strength on antenna 2 and antenna 4.

exhibited in the main radiator [19]. Thus, its ARBW can exceed 240°, while antenna 2 has only 160°.

Figure 5 shows the ARBW and phase differences of the two far-field components ($\angle E_\theta - \angle E_\varphi$) in different radiation planes. It can be seen that the ARBW at $\varphi = 45°$ and $135°$ is wider than that at $\varphi = 0°$, which exceeds 240°. The ARBW is the narrowest at $\varphi = 90°$, and it still reaches 212°. The phase difference between E_θ and E_φ is relatively flat in these four planes and roughly remains at 90° in a wide-angle range.

In order to further verify the practicability of the proposed antenna, not only the AR beamwidths for different planes are observed, but the AR beamwidths over the entire circularly polarized frequency band are plotted in Figure 6. It indicates that the beamwidth of the proposed antenna exceeds 180°

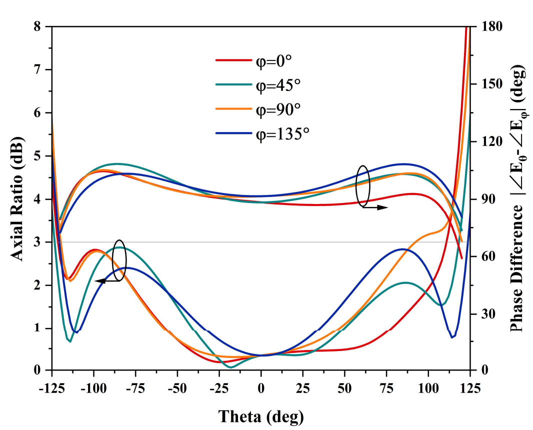

Figure 5. 3 dB ARBW and phase difference for $\varphi = 0°$, $45°$, $90°$, and $135°$.

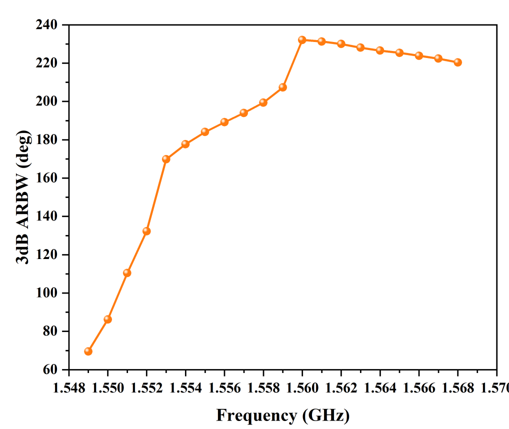

Figure 6. 3 dB ARBW and frequency diagram over CP band for $\varphi = 0°$.

in 78.95% of the circularly polarized frequency band. From different aspects, it is verified that the proposed antenna has very good circular polarization performance and strong practical value.

4. PARAMETRIC STUDIES

In this section, the parametric study of the designed antenna is carried out. In order to study the effect of various parameters on the radiation performance, especially the AR beamwidth, the S_{11} and AR performance of the antenna are studied. Due to the limited space of this paper, only one parameter is selected respectively for the main radiator and the arc part. One geometric parameter is changed at a time, and the rest remain unchanged.

It can be seen from Figure 7 that changing R_1 does not cause significant changes in S_{11} and axial ratio. Two planes $\varphi = 0°$ and $\varphi = 90°$ are selected to observe ARBW. The AR beamwidths at $\varphi = 0°$ are more than $200°$ for $R_1 = 0.9$ mm and 1.1 mm, and ARBW drops to $180°$ at $\varphi = 90°$ for $R_1 = 0.9$ mm. In summary, $R_1 = 1.1$ mm is the most appropriate value.

As the outer circle radius of arc structure (R_6) increases, the minimum axial ratio moves to a low frequency. As can be seen from Figures 8(c) and (d), the change of R_6 has a great impact on the AR beamwidths, while R_1–R_4 have a very limited effect on it. The arc structure is of great significance to broaden the beam.

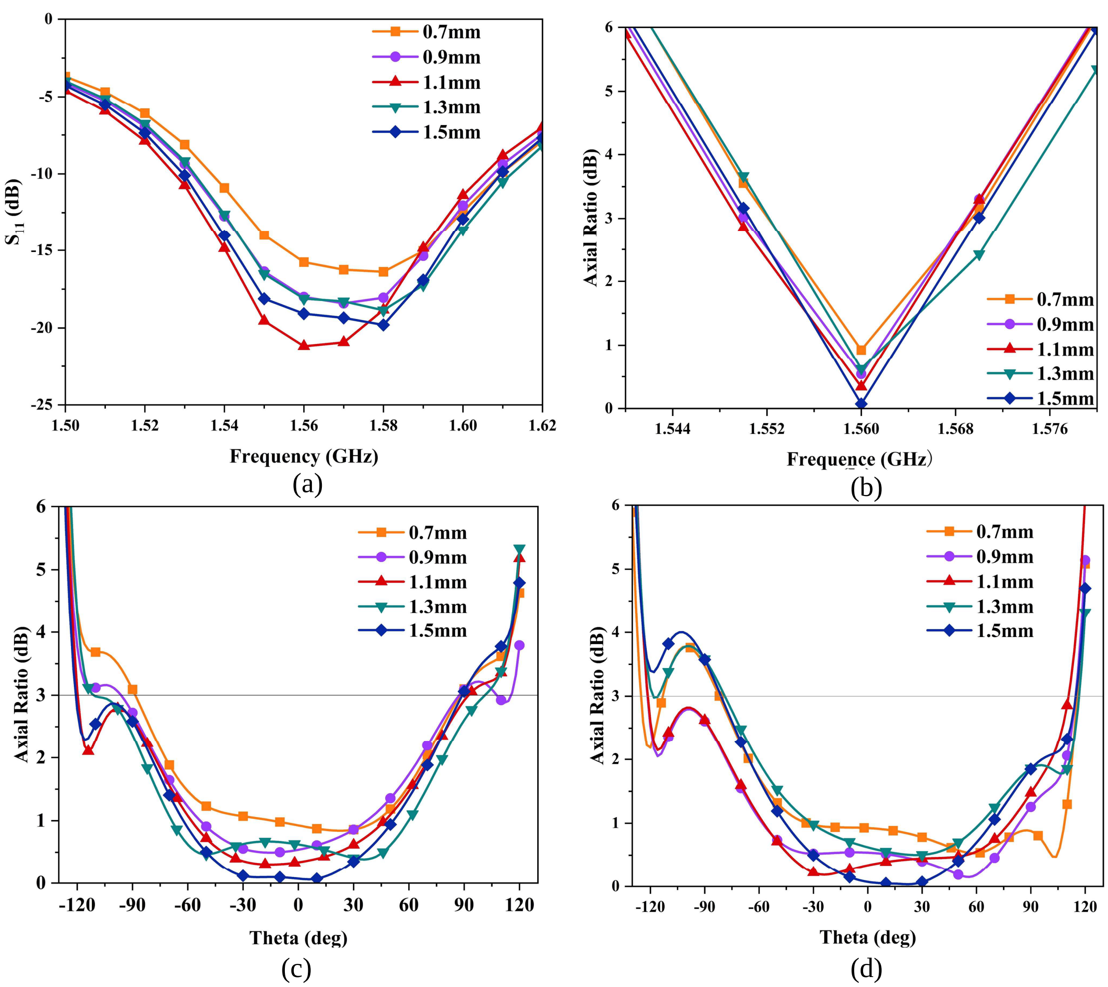

Figure 7. Comparison of (a) S_{11}, (b) axial ratios, (c) ARBW at $\varphi = 0°$, (d) ARBW at $\varphi = 90°$ under different sizes of R_1.

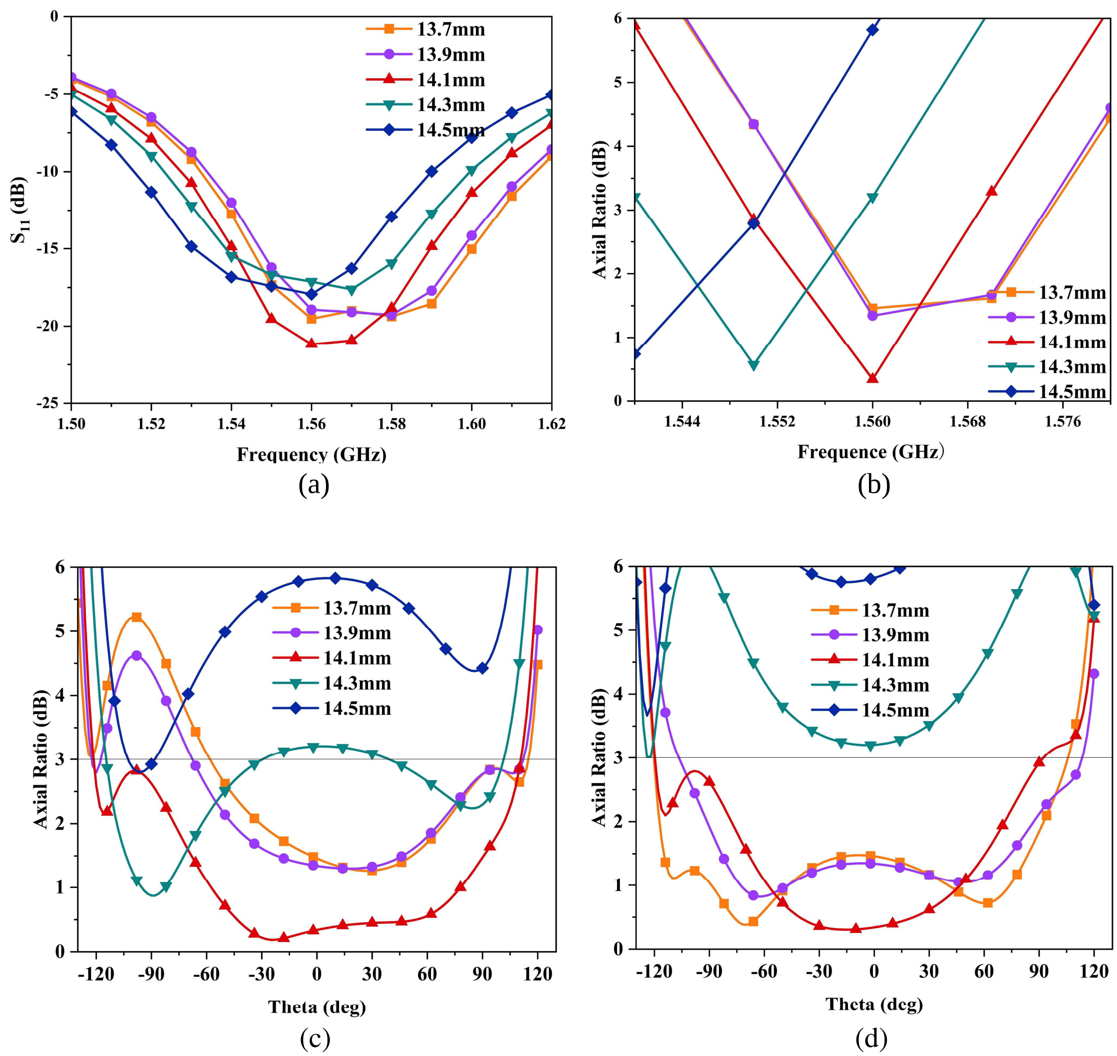

Figure 8. Comparison of (a) S_{11}, (b) axial ratios, (c) ARBW at $\varphi = 0°$, (d) ARBW at $\varphi = 90°$ under different sizes of R_6.

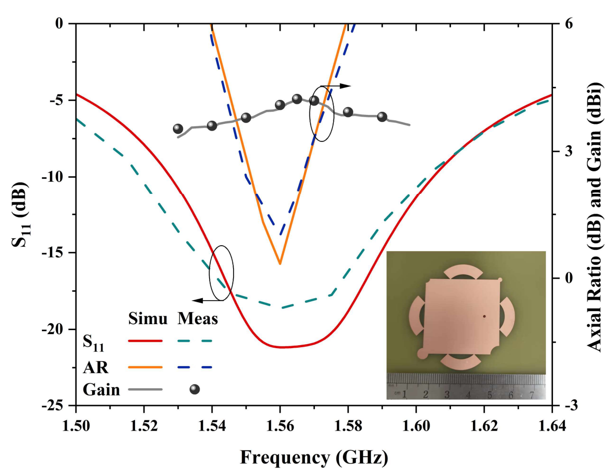

Figure 9. Simulated and measured S_{11}, axial ratio and gain.

5. SIMULATION AND MEASURED RESULTS

The proposed antenna was fabricated and measured for verification of the design. The simulated and measured results are shown in Figure 9. The measurements show an impedance bandwidth (IBW) of 5.13% [80 MHz (1.52 GHz–1.6 GHz)], CPBW of 1.28% [20 MHz (1.55 GHz–1.57 GHz)], an AR minimum of 1.2 dB, and a peak gain of 4.09 dBi. Figure 10 shows the simulation and measurement results of the radiation patterns for the E and H planes. Due to errors in antenna fabrication and measurement, there are some differences between simulated and measured LHCPs, which is still acceptable. A comparison

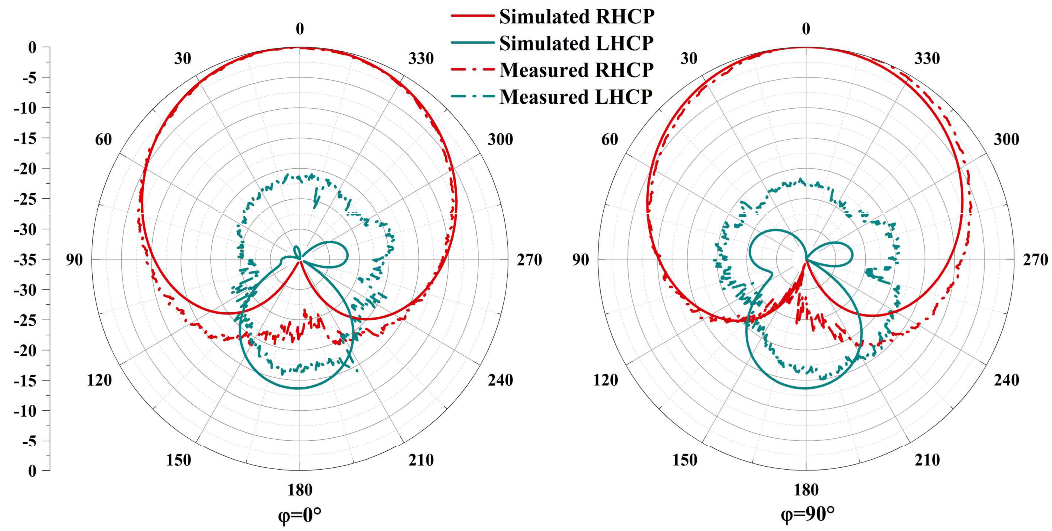

Figure 10. Simulated and measured radiation patterns (a) E plane, (b) H plane.

Table 2. The performance comparison between the proposed antenna and other relevant references.

Ant	relative profile (λ_0) @GHz	Feed method	10-dB RLBW (MHz)	3-dB ARBW (MHz)	3-dB ARBW (deg) $\varphi = 0°$	3-dB ARBW (deg) $\varphi = 90°$
[12]	0.016@1.578	probe feed	56 (3.55%)	24 (1.52%)	180	180
[15]	0.025@1.53	coupled feed	260 (17%)	220 (14.5%)	205	N/A
[19]	0.013@2.48	probe feed	85 (3.4%)	23 (0.93%)	226	198
[20]	0.008@1.57	CPW feed	400 (25.48%)	360 (22.93%)	N/A	N/A
[21]	0.013@2.421	probe feed	64 (2.6%)	22 (0.9%)	228	214
[22]	0.149@1.83	complex feed network	270 (14.75%)	N/A (N/A)	140	N/A
This work	0.0156@1.56	probe feed	80 (5.13%)	20 (1.28%)	232.2	212.2

of performance between the proposed antenna and other relevant papers is summarized in Table 2. It is obvious that the 3 dB axial ratio beamwidth (ARBW) of the proposed antenna is higher than that of other antennas in the table. Loading arc structure is a novel and effective way to broaden axial ratio beamwidth.

6. CONCLUSION

This paper proposes a novel low-profile GNSS antenna. When the asymmetric structure realizes circular polarization and four arc structures are loaded at the same time, the antenna has an extremely wide 3 dB axial ratio beamwidth, which is 232° and 212° in $\varphi = 0°$ and $\varphi = 90°$. In $\varphi = 45°$ and $\varphi = 135°$, the obtained ARBWs are 241° and 244°, respectively, far exceeding the 120° required for satellite applications. In the entire CP frequency band, the proportion of beamwidths exceeding 180° is as high as 78.95%. With extensive wide beam characteristics of low profile, low cost, simple antenna structure and feeding method, the antenna will have strong practicability and competitiveness in GNSS applications.

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