I. INTRODUCTION

In recent years, fifth generation (5G) wireless mobile technologies have received increasing attention. This is because wireless communication systems operating at millimeter-wave (mmWave) frequencies provide significantly higher channel rates and capacity compared with their lower-frequency counterparts [1]. However, to realize this potential, you need directional, broadband, low-loss, and low-cost antennas that can be easily integrated with mmWave circuits in the transceiver package [2]. Typically, standard horn antennas are used as convenient measurement devices. However, it is difficult to integrate them with 5G devices due to their large size, hard platform, and high cost [3]. Recently, a planar-type antenna has shown the merits of offering a wide impedance bandwidth and being low cost and easy to maintain [4]. However, due to linear polarization (LP), polarization losses can be easily experienced. Circular polarization (CP) antennas are a good solution because they reduce fading problems due to the suppression of multipath interference by surrounding objects and the ground; they also provide good resiliency against polarization inconsistencies caused by a misalignment between transmitter (Tx) and receiver (Rx) antennas. The familiar quad rigid horn antenna with two ports can measure horizontal and vertical polarization, but it requires an RF switch, which requires an additional circuit design and a complex structure, as shown in [5]. To design a compact and

Design of 24–40 GHz Ultra-Wideband Circularly Polarized Monopole Antenna with a Defected Ground Plane

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Abstract

A new design method for an ultra-wideband circularly polarized microstrip-fed monopole antenna with a ground defect is proposed in this paper. To achieve ultra-wideband circular polarization performance, a parallelogram-shaped ground defect is employed in the bottom layer. The analysis of the ultra-wideband axial ratio (AR) and the impedance bandwidth of the proposed antenna is performed both in the top and bottom layers. A semi-circular aperture is designed to achieve impedance matching in the 24–40 GHz frequency range. Then, the AR bandwidth is discussed considering the surface current distribution produced by the parallelogram-shaped ground defect to rotate current in each orthogonal phase. A prototype of the proposed circularly polarized antenna with a 50% ultra-wide bandwidth (from 24 to 40 GHz), a 10-dB return loss, and a 3-dB AR was fabricated and measured. A 6-dBic right-hand circular polarization gain was also achieved.

Key Words: Axial Ratio, Circular Polarization, Monopole Antenna, Ultra-Wideband Width.
low-price antenna, it is necessary to create CP with a single feeding. Possible polarization misalignment between transmitting and receiving antennas leads to degraded performance when measuring antenna gain, axial ratio (AR), and efficiency. The type of polarization that is suitable for a measurement antenna for 5G device testing is CP, which provides the best performance compared to all linear polarizations. A large number of studies on CP in antenna arrays, right- or left-handed components, substrate-integrated waveguides (SIWs), and other structures has been conducted to provide small and efficient antenna modules.

Generally, a spiral antenna with a cavity is suitable for measuring a demanding broadband frequency range, high efficiency, CP, and so on. However, most of these characteristics are obtained at the balanced center-fed spiral, making the structure non-planar, complex, and large. As a result, many fabrication limitations may be encountered [6, 7]. Other CP antenna structures have been used in various planar configurations, such as arrays, SIWs, and monopoles. An SIW aperture antenna array structure exhibits high gain and is suitable for mmWave applications. An SIW antenna array with a CP mmWave fabricated in a single layer was proposed in [8–10]. A ring-shaped wideband CP antenna structure using multi-layer technology was presented in [11].

Due to the limitations of the waveguide cut-off frequency and less flexible SIW compared to a microstrip line (MSL) and a coplanar waveguide (CPW), the bandwidth of SIW CP is generally inferior to conventional transmission-line antennas. A CPW-fed monopole antenna employing a ground defect as a stub was reported in [12]. A single-fed CP stacked square microstrip antenna exhibiting wide impedance bandwidth (IBW) and axial ratio bandwidth (ARBW) was reported in [13, 14]. Printed planar shapes, such as circular, semi-elliptical, and rectangular patches, have resulted in linearly polarized compact omnidirectional antennas [15]. Typically, CP antennas operating in mmWave frequency bands cannot cover the entire 5G frequency range. As a result, they cannot be applied to over-the-air (OTA) test systems since the maximum achievable bandwidth of a wideband AR antenna is 20%.

In this paper, a new planar CP antenna employing a parallelogram ground defect is proposed. This antenna is capable of achieving a wideband AR and frequency range. The proposed design is based on a surface current flow analysis between the ground defect and the semi-circular in-band slab aperture. By combining a broadband aperture and a ground defect, the proposed CP antenna can be used to measure any device being tested in the mmWave frequency band. To validate the performance of the design concept, a prototype of the antenna was fabricated and measured. A detailed discussion of the proposed antenna is presented in the following sections.

II. ANALYSIS OF THE PROPOSED CIRCULARLY POLARIZED ANTENNA

1. Antenna Configuration

The structure of the proposed ultra-wideband CP antenna with a ground defect is shown in Fig. 1(a), and a cross-sectional cutaway view is shown in Fig. 1(b). The current distribution of the semi-circular aperture can be rotated according to each phase component. This can be achieved by inserting a parallelogram-shaped ground defect at the bottom layer with a 30° inclination with reference to the feeding line. The semi-circular aperture acts as both a transmitter and radiator, whereas the carving of the tilted quadrangle forms the physical circular current distribution of the proposed antenna through which energy mainly radiates. The design parameters of the proposed CP antenna are the radius of the semi-circular aperture $r_c$, the strip slab width $w_c$, the length $l_c$, the defect length $l_g$, width $w_g$, spacing $s_g$, the parallelogram angle $\theta_g$, and length $l_0$. A schematic diagram of the surface current distribution for different phase values in the range 0°–270° with a 90° step in the in-band is shown in Fig. 2.

![Fig. 1. Layout of the proposed CP antenna: (a) top view and (b) cross-sectional cutaway view.](image-url)

![Fig. 2. Schematic diagram of the surface current distributions for the proposed antenna at 28 GHz for different phase instants: (a) 0°, (b) 90°, (c) 180°, and (d) 270°.](image-url)
The surface current $J_A$ flowing in the aperture in the direction of the second quadrant is divided into two surface currents, $J_{gu}$ and $J_{gd}$ which flow in the ground defect, as shown in Fig. 2(a). When shifting by 90°, the rotation of the surface current in the antenna aperture is affected by the surface current, $J_{feed}$, flowing in the feed line, as shown in Fig. 2(b). In this case, it is assumed that the ground defect surface currents, $J_{gu}$ and $J_{gd}$, are weaker than the feed surface current, $J_{feed}$. Fig. 2(c) and 2(d) show the opposite direction of the surface current flowing in the aperture for the cases depicted in Fig. 2(a) and 2(b), respectively. The following relationships can be expressed for the surface currents, $J_{feed}$, $J_{gu}$, and $J_{gd}$:

\[ J_{A(a)} = J_{gu} - J_{gd} \]

\[ J_{A(b)} = J_{feed} + J_{gu} - J_{gd} \quad (J_{feed} > J_{g}) \]

\[ J_{A(c)} = J_{gd} + J_{feed} - J_{gu} \]

\[ J_{A(d)} = -J_{feed} - J_{gu} + J_{gd} \quad (J_{feed} > J_{g}) \]

The surface current distributions of the proposed antenna at 28 GHz were simulated using a 3D electromagnetic (CST Microwave Studio), as shown in Fig. 3. The eight design parameters of the proposed CP antenna are summarized in Table 1.

**Fig. 3. Simulated circular polarization direction of the proposed antenna at 28 GHz for different phase instants: (a) 0°, (b) 90°, (c) 180°, and (d) 270°.**

**Table 1. Proposed antenna design parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>4.7</td>
</tr>
<tr>
<td>$r_c$</td>
<td>1.1</td>
</tr>
<tr>
<td>$l_c$</td>
<td>2</td>
</tr>
<tr>
<td>$w_c$</td>
<td>1.2</td>
</tr>
<tr>
<td>$l_t$</td>
<td>2.7</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>$\pi/6$</td>
</tr>
<tr>
<td>$l_t$</td>
<td>11</td>
</tr>
<tr>
<td>$w_c$</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**III. PARAMETRIC STUDY**

Many parameters in the proposed antenna structure introduce complexity in the design process. In this section, the effect of some key parameters on the RL and AR is investigated by varying only one parameter at a time while keeping the other parameter values fixed. Parameters with a small impact, such as $w_c$ and $l_t$, are not examined since they can be determined after the design of other parameters of the proposed CP antenna. Further, $w_c$ is 4.5 mm in half-wavelength, which is the minimum spacing that is not coupled to the antenna.

1. Effects of $r_c + w_c$ and $l_t$

The proposed antenna is specially formed into a semi-circular strip slab of width $w_c$ and fed by a 50-Ω microstrip line. To achieve impedance matching, the strip slab, which is located between the radiator and the 50-Ω microstrip line (see Fig. 1), is used as an impedance transformer. The slab radius $r_c$ is determined by the lowest and highest operating frequencies of the antenna. The width of the strip slab $w_c$ and the antenna aperture radius $r_c$ are also determined by the lowest and highest operating frequencies and can be calculated with the following equations:

\[ w_c = \frac{\lambda_{g, high}}{4} = \frac{c}{4f_{high}\sqrt{\mu_0\varepsilon_r}} \]  

\[ w_c + r_c = \frac{\lambda_{g, low}}{4} = \frac{c}{4f_{low}\sqrt{\mu_0\varepsilon_r}} \]
In (5) and (6), \( c \) is the speed of light in the free space, \( f_{low} \) and \( f_{high} \) are the lowest and highest operating frequencies (24 GHz and 40 GHz, respectively), and \( \mu_e \) and \( \varepsilon_e \) are the equivalent magnetic permeability constant and dielectric constant, respectively. The wavelengths in (5) and (6), which correspond to the lowest and highest operating frequencies, are 12.2 mm and 1.1 mm, respectively.

The results in Fig. 4 show that impedance matching at the center frequency \( f_c \) is significantly affected by \( l_c \). When determining the lowest and highest operating frequencies, the radius of the semi-circular aperture, aperture length, and slab length affect each other. Therefore, these parameters need to be carefully adjusted. If \( l_c \) is too small (for example, \( l_c = 0.8 \text{ mm} \)), it cannot operate properly as an antenna in-band aperture. For better performance, \( l_c \) is set to 2 mm.

2. Effects of \( S_g \)

The microstrip line impedance of the feeding structure is maintained at 50 \( \Omega \) to provide a stable antenna feed. The parallelogram-shaped ground defect in the bottom layer significantly affects the impedance when a point in \( S_g \) is close enough to the 50-\( \Omega \) line on the top layer. Since the overlap position between the semi-circular aperture on the top layer and the laminated part of the bottom layer changes, resulting in a different surface current distribution flow, a stable energy source is needed. The 50-\( \Omega \) microstrip line meets a point in \( S_g \), where there is a ground defect in the bottom layer of the antenna. This is a key parameter for wideband operation. Fig. 5 shows RL results when \( S_g \) is varied. It can be observed that the RL is noticeably changed. As shown in the surface current flow in Fig. 5, if \( S_g \) becomes too large or too small, the surface current flow may not be smooth on the semi-circular antenna aperture. For effective impedance matching, \( S_g \) should be set to 2.7 mm.

3. Effect of \( \theta_g \) and \( l_0 \)

In this paper, the proposed ground defect shape improves CP performance. The surface current on the antenna aperture depends on the combination of the feeding length \( l_0 \) and the ground angle \( \theta_g \). Therefore, to obtain better CP performance for the proposed antenna, the parallelogram ground inclination must be optimized. The simulation results are presented in Fig. 6. It can be observed that the RL changes slightly with the variation of \( \theta_g \) and does not affect antenna performance. The AR also depends on the angle of the ground defect \( \theta_g \) for a fixed \( S_g = 2.7 \text{ mm} \). The ARBW exhibits a significant change in the 24–30 GHz range. The best performance can be obtained by adjusting the ground defect shape at the center frequency and selecting \( \theta_g = \pi/6 \) for \( S_g = 2.7 \text{ mm} \).

The ground defect spacing \( S_g \) is related to the parallelogram angle \( \theta_g \) and the microstrip line length \( l_0 \) through the following equation:

\[ S_g = \frac{l_0}{\tan(\theta_g)} \]
\[
I_0 = \frac{s_g}{\tan \theta_g}.
\]  

(7)

IV. SIMULATED AND MEASURED RESULT

Based on the above analysis, a prototype of the proposed antenna was fabricated on a TLY-5 substrate with \( \varepsilon_r = 2.2 \) and thickness \( b = 0.25 \text{ mm} \). Photographs of the fabricated antenna (with a connector) based on printed circuit board technology are shown in Fig. 7. A comparison between the simulation and measured RL and AR results is shown in Fig. 8. All measurements were conducted in a microwave anechoic chamber. The \( S \)-parameters were measured using a vector network analyzer. The maximum radiation points were measured in the broadside direction, and the AR was recorded at these points. In Fig. 8, it can be observed that in the 24–40 GHz frequency range (50% IBW), the maximum RL is more than 10 dB. In the 24–38 GHz frequency range (approximately 45.2% ARBW), the maximum AR is less than 3 dB and approximately 3.5 dB in the 38–39 GHz frequency range. The simulated and measured radiation patterns in the XZ and YZ planes at 28 GHz and 39 GHz are plotted in Fig. 9(a) and 9(b), respectively. A good agreement is observed between the measured and simulated results. The polarization at the topside of the antenna is the left-hand CP (LHCP). The results also show that the maximum radiation points are in the 0° angle directions. The radiation patterns in the YZ and XZ planes are almost identical. The simulated and measured antenna gains are shown in Fig. 10. The measured antenna gains at 28 and 39 GHz is -0.1 and 4.8 dBi, respectively. The discrepancy between the simulated and measured gain is within 1 dB, and it is caused by errors during the fabrication process and the high substrate loss tangent. A performance comparison of the proposed CP antenna with previously reported...
results is summarized in Table 2. The antenna reported in [8] shows even higher center frequencies; however, their IBW (31.8%) and ARBW (24.6%) are lower than the proposed antenna. Compared with [11], the IBW of the proposed antenna is in close agreement, but its ARBW is much wider. In addition, compared to [9, 13] uses sequential feeding networks. The ARBW of the proposed antenna is about 50% higher and is easier to fabricate, even if the antenna gain is higher. This comparison verifies that the proposed antenna exhibits outstanding performance and a simple structure. The remaining [10], [11], and [14] also show a narrower IBW and ARBW compared to the proposed antenna. In particular, [10] has a 63% lower IBW and [14] a 69% lower ARBW than shown by the proposed CP antenna’s result. In addition, the size comparison clearly confirmed that the proposed antenna is at least three to 256 times smaller than previous research. The proposed CP antenna exhibits a compact size and low gain; therefore, the low gain of the antenna is a trade-off that arises as the aperture becomes smaller.

V. CONCLUSION

A new ground defect CP antenna design exhibiting a wide ARBW and IBW based on a current distribution model was presented and demonstrated for mmWave wireless communication systems operating in the 24–40 GHz frequency range. By employing a parallelogram-shaped ground defect in its bottom layer, the antenna is capable of producing CP radiation in a wide bandwidth with good polarization purity. The proposed antenna is compatible with standard planar circuit technology and can be realized on a double-layer laminate, resulting in a low-cost and low-profile device. The simulation and measurement results demonstrated good antenna performance. Most importantly, the proposed antenna is capable of achieving CP, depending on the specific application. As a result, the use of multiple antennas with different polarizations integrated with RF systems is avoided. Furthermore, the proposed design can be easily adopted in 5G mobile and measurement systems and applied to a variety of mmWave circuits.

REFERENCES


![Fig. 10. Simulation and measurement antenna gain of the proposed CP antenna.](image-url)


