A Low-Profile Eighth-Mode SIW Antenna With Dual-Sense Circular Polarization, Enhanced Bandwidth and Simple Structure

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ABSTRACT A practical method, which based on eighth-mode substrate integrated waveguide (EMSIW), is investigated in this paper to design low-profile antenna with dual-sense circular polarization (CP) and enhanced bandwidth. First, an eighth-mode radiating cavities is presented and excited by single coaxial probe for size reduction and directional radiation. Then, two EMSIW antennas are placed symmetrically and a triangular parasitic patch is introduced between two EMSIW cavities. Attribute to the weakly coupled effect between the radiation aperture and triangular parasitic patch, dual-sense circular polarization characteristic and an additional resonance are acquired. When the triangular patch is transformed into a square parasitic patch, the current path on the parasitic patch is shortened, and a new resonance point is generated at 3.55 GHz. While the resonant mode of the two eighth-mode radiating cavities are almost unaffected and the CP bandwidth varies with the changed current path. Finally, a dual-sense CP EMSIW antenna with extended bandwidth and simple structure is designed and fabricated. The overall size of the fabricated prototype is only $0.57\lambda_0 \times 0.54\lambda_0 \times 0.02\lambda_0$ ($\lambda_0$ is the free-space wavelength at 3.4 GHz). Measured impedance bandwidth is 10.5% from 3.24 GHz to 3.60 GHz with an isolation up to 11.6 dB and a maximal gain better than 5.74 dBi in two ports is also achieved. Moreover, the characteristics of dual-sense CP and the cross-polarization suppression capability of up to 20 dB in the main beam are obtained in 3.48-3.60 GHz.

INDEX TERMS Eighth-mode substrate integrated waveguide, dual-sense circular polarization, parasitic patch, extended bandwidth.

I. INTRODUCTION

In recent years, modern wireless communication technology has developed vigorously, followed by an increasingly complex and congested electromagnetic environment. Taking into account the practically and economy of the antenna, the wireless communication market urgently needs novel antennas with miniaturization, high gain, multi-polarization, and large bandwidth to mitigate the negative effects caused by bulky structure, multi-path interference, polarization mismatch and high cost. The SIW technology, which combines printed circuit board and periodically arranged metalized vias, is gradually employed to design the antennas with low profile, low cost, high gain, dual-band, and circular polarization [1], [4].

Since the electric field line is parallel to the longitudinal symmetry axis of the SIW, after cutting the SIW along the longitudinal symmetry axis, the original field mode is maintained and the size of the SIW is greatly reduced. In this way, half-mode substrate-integrated waveguide (HMSIW) [5], [7], quarter-mode substrate integrated waveguide (QMSIW) [8], [10], eighth-mode substrate integrated waveguide (EMSIW) [11], [20] are designed with the advantages of miniaturization, compact size, low transmission loss, and high power capacity. Straightforwardly, the evolution process from SIW to EMSIW is given in Fig. 1. Based on this high-performance planar waveguide structure, attractive characteristics such as circular polarization, high gain, and multi-mode are realized. However, the two antennas in [6], [7] have the deficiency of narrow 3 dB axial ratio bandwidth (ARBW) less than 100 MHz and relatively complicated
structure, respectively. The sequential rotating feeding network increases the design difficulty in [8], [9], and the separate structure discards the advantages of compact antenna. On the basis of EMSIW, the complementary split-ring resonator (CSRR) technology is employed to design two antennas in [11], [12]. Attribute to the position of the CSRR and the bias voltage of the varactor diode, two electrically small antennas with the characteristic of adjustable resonance frequency are acquired. Interdigital capacitive slots are loaded on a double asymmetry EMSIW antenna in [13] to realize composite right/left-handed (CRLH) characteristic with enhanced gain and compactness. The measured gain up to 17.96 dBi and a maximum radiation efficiency of 96% suggest the fabricated antenna array can be utilized for full space scanning application. In [14], two coupled miniaturized EMSIW radiating cavities are combined with a feeding network to design a two-antenna system with enhanced bandwidth. Benefit to the coupling between the main resonator and the parasitic resonator, a measured bandwidth of 414 MHz, the shape of the parasitic patch changes, the gradual expansion of the bandwidth and the subsequent dual-sense circular polarization characteristics provide a new idea for the broadbandization and multi-polarization of multi-port EMSIW antenna. Finally, more than 10.5% impedance bandwidth displayed by the antenna prototype, measured gain up to 5.74 dBi, 3 dB axial ratio bandwidth of 120 MHz, port isolation up to 11.6 dB, simple structure and easy-to-process all indicate that the proposed antenna is extremely competitive for wireless communication.

II. EMSIW ANTENNA DESIGN AND RADIATION PRINCIPLE

As shown in Fig. 1, the evolution process from conventional SIW cavity to EMSIW is given. Assume that the length and width of the SIW cavity are L and W respectively, the electric and magnetic fields for the TE110 mode can be analyzed by the following formula [21]:

\[ E_x = E_0 \sin \frac{\pi x}{W} \sin \frac{\pi y}{L} \]  
\[ H_z = \frac{E_0}{\omega \mu L} \sin \frac{\pi x}{W} \cos \frac{\pi y}{L} \]  
\[ H_y = \frac{E_0}{\omega \mu W} \cos \frac{\pi x}{W} \sin \frac{\pi y}{L} \]  
\[ E_x = E_y = H_z = 0 \]

Among them, \( \omega \) is the angular frequency and \( \mu \) is the permeability of the material inside the SIW cavity. For SIW cavity, the resonant frequency of TE110 mode can also be calculated by (5).

\[ f_{110} = \frac{1}{2\pi \sqrt{\mu \varepsilon}} \sqrt{\left(\frac{\pi}{L}\right)^2 + \left(\frac{\pi}{W}\right)^2} = \frac{\sqrt{L^2 + W^2}}{2LW \sqrt{\mu \varepsilon}} \]
magnetic field distribution is characterized by being parallel to the cavity surface and perpendicular to the sidewall of the cavity. Furthermore, it can also be obtained from Fig. 1(a), (2) and (3) that the electric field distribution of the SIW cavity is symmetrical with respect to the A-A’, B-B’, C-C’, and D-D’ planes. In other words, the A-A’, B-B’, C-C’, and D-D’ planes are set as perfect magnetic walls due to the features of electric field distribution. Therefore, cutting the SIW cavity along the plane where the perfect magnetic wall is located will not only maintain the original electric field distribution, but also reduce the volume of the cavity. Through this approach, HMSIW, QMSIW and EMSIW are realized in Fig. 1(b), Fig. 1(c) and Fig. 1(d). Among them, EMSIW is designed by cutting along the plane where OC and OD are located, and its volume is only one-eighth of the SIW.

A. LOW-PROFILE EMSIW ANTENNA WITH SINGLE PORT

Based on the aforementioned analysis, a miniaturized, low-profile EMSIW antenna operating at 3.46 GHz is firstly investigated. The configuration of the presented EMSIW antenna is shown in Fig. 2 with optimal dimension given in Table 1. As shown in Fig. 2, a right-angled triangle patch is printed on the top surface of the employed substrate. For the substrate, the thickness of 1.575 mm, the permittivity of 2.2 and the tangent loss of 0.0009 are utilized. In addition, the periodically arranged metalized vias that meet the requirements of (6) and (7), and a metal floor printed on the bottom surface of the substrate together constitute the EMSIW antenna. Meanwhile, a coaxial probe is located inside the EMSIW radiation cavity, which excites the antenna by means of direct feeding from the back.

In view of the working mechanism of the proposed single-port EMSIW antenna, the discussion results of two crucial parameters W2 and dx are given in Fig. 3. As shown in Fig. 3(a), with the increase of W2, the resonance

\[
dr/dp \geq 0.5 \quad (6)
\]

\[
dr/\lambda_0 \leq 0.1 \quad (7)
\]

frequency point of the EMSIW antenna gradually moves to low frequency which is consistent with the description of the equation (5). Not only that, the amplitude of S11 changes very little during the frequency shift. On the contrary, it can be seen from Fig. 3(b) that the amplitude of S11 is sensitive to the change of dx. In other words, the position of the coaxial probe determines whether the antenna can achieve better impedance matching. Taking into account the resonant frequency point and reflection coefficient of the antenna, 20 mm and 3.8 mm are selected as the optimal values of W2 and dx respectively.

On purposed to verify the resonant frequency and radiation pattern of the designed EMSIW antenna, an antenna prototype shown in Fig. 4 is fabricated. A series of tests related to S-parameters, gain, radiation efficiency and radiation pattern
are launched. It can be concluded from Fig. 5(a) that the antenna works at 3.46 GHz with an acceptable reflection coefficient from 3.43 GHz to 3.49 GHz. Meanwhile, the measured gain and radiation efficiency are also depicted in Fig. 5(b), and a maximum gain of 3.56 dBi and a radiation efficiency of 85% are obtained at 3.46 GHz. Compared with the simulated results, not only the measured gain and measured efficiency are reduced by 0.4 dB and 10% respectively, but the $S$-parameter are also slightly shifted, which are caused by errors in processing and testing. The measured radiation pattern of the EMSIW antenna at 3.46 GHz is also presented in Fig. 6, and it can be found that two directional radiation pattern with 3 dB beam width of up to 80$^\circ$ and front-to-back ratio (FBR) of better than 15 dB are acquired in $xoz$ and $yoz$ planes.

Furthermore, the axial ratio is also measured and given in Fig. 7. The simulated result and the measured result show that the axial ratio within the resonance bandwidth fluctuates around 30 dB, which does not meet the requirement of 3 dB for circular polarization. To a certain, this also explains the phenomenon that the cross polarization in Fig. 6 is greater than $-10$ dB.

### B. TWO-PORT EMSIW ANTENNA WITH DUAL-SENSE CIRCULAR POLARIZATION

On the basis of the single-port EMSIW antenna analyzed in Section A, a two-port EMSIW antenna with dual-sense CP is proposed in this section to improve the characteristics of single polarization and narrow bandwidth. First, an inverted triangular parasitic patch is placed near the perfect magnetic wall OD of the single-port antenna, and a narrow gap is introduced to generate weak coupling effect with the EMSIW cavity. Then, a coupling current that can periodically rotation clockwise is obtained on the parasitic patch. At the same time, another single-port EMSIW antenna is located symmetrically on the right side of the original EMSIW antenna to generate the coupling current with the characteristics of counterclockwise rotation over time. The two mirror-symmetrical EMSIW antennas respectively dominate the rotation direction of the coupling current on the parasitic patch. It is worth noting that two coaxial probes are respectively located at the bottom of the corresponding antenna to provide the excitation signal required to generate the coupling current. Finally, a two-port EMSIW antenna capable of radiating left-hand circularly polarized (LHCP) waves and right-handed circularly polarized (RHCP) waves is acquired and the detailed configuration of the proposed antenna is also shown in Fig. 8 with optimal dimension given in Table 2. A Rogers 5880 substrate with a thickness of 1.575 mm is also employed to design the proposed two-port EMSIW antenna, and two EMSIW resonant cavities are placed symmetrically on the side close to the long side $L$ of the substrate. An inverted triangular parasitic patch is printed on the radiating aperture formed by the perfect magnetic wall OD. Two slits with the same dimension are etched near two right-angled edges of the parasitic patch to provide electromagnetic coupling. Feeding points 1 and 2 are

![Geometry of the proposed two-port dual-sense CP EMSIW antenna](image_url)

**TABLE 2. Dimensions of the Two-port Dual-Sense CP EMSIW Antenna.**

| Parameters | L  | W | hy  | hy₁ | dx  |
|------------|----|---|-----|-----|-----|
| Values/mm  | 50 | 48| 28.14| 28 | 7.2 |
| Parameters | dy | W2 | L1 | H  | gp  |
| Values/mm  | 15.5 | 20.7 | 39.6 | 1.575 | 1.2 |
located inside the two EMSIW resonators, which determine the LHCP and the RHCP, respectively.

On purpose to investigate the effect of different geometric parameters on the antenna performance, a parameter study is launched according to the principle of control variables. The width of the coupling slit between the EMSIW cavity and the parasitic patch is taken as the research focus, and the corresponding simulated results are also depicted in Fig. 9. As shown in Fig. 9(a), when $g_p$ increases from 0.6 mm to 1.8 mm in 0.3 mm steps, the reflection coefficient of port 1 shows that the additional resonance point 3.26 GHz which is introduced by parasitic patch and the original resonance point 3.46 GHz are moved to the intermediate resonance point 3.36 GHz. That is, the resonance bandwidth decreases with the increase of $g_p$. On the contrary, it can be seen intuitively from Fig. 9(b) that the isolation between the two ports gradually increases as $g_p$ increases. Although the antenna has excellent bandwidth when the $g_p$ is 0.6 mm, the port isolation of only 5 dB greatly reduces the network capacity and system throughput. Fig. 9(c) shows the curve of gain versus $g_p$. It can be seen that as $g_p$ increases, the gain of the antenna in port 1 gradually decreases, which caused by the decreased amplitude of the coupling current on the parasitic patch.

However, the radiation gain between 3.2 GHz and 3.6 GHz still maintains the same fluctuation trend. More importantly, the simulated result of ARBW at port 1 is also given in Fig. 9(d). And, it can be concluded that in the process of increasing $g_p$, the circular polarization resonance point gradually moves to low frequency, accompanied by a narrower 3 dB ARBW. Based on the above analysis, it can be obtained that $g_p$ as a key parameter, has a significant impact on S-parameter, radiation gain and ARBW. Therefore, 1.2 mm is finally selected as the optimal value of $g_p$ to obtain excellent performances, including a resonance bandwidth of up to 170 MHz, a 3 dB ARBW of 70 MHz, a radiation gain of 6.4 dBic and a port isolation of better than 10.3 dB.

According to Fig. 8, an antenna prototype shown in Fig. 10 is manufactured, and a series of tests are carried out to verify the characteristics of dual-sense CP and broadband. Meanwhile, the comparison of the specific results is also presented at Fig. 11. As shown in Fig. 11(a) and Fig. 11(b),
the reflection coefficients of the two ports from 3.29 GHz to 3.45 GHz both meet the requirement of $\leq -10$ dB. A higher isolation than 12.2 dB, which are basically consistent with the simulated results is also achieved. Since the measured results of axial ratio, gain, and radiation efficiency at the two ports are basically the same, only the measured results of port 1 are given in Fig. 11(c) and Fig. 11(d) for brevity. In detail, the 3 dB ARBW of port 1 is 2.3% from 3.37 GHz to 3.45 GHz, which shows a slight shift compared with the simulated results. At the same time, Fig. 11(d) shows the measured gain of 5.86 dBi at 3.4 GHz and a radiation efficiency of 90.9%. Compared with the simulated result, the measured results show a partial attenuation, which attributed to errors in the welding and measurement. Similarly, in order to intuitively illustrate the polarization type of the two-port EMSIW antenna, the simulated results and the measured results of the radiation pattern are given in Fig. 12. As shown in Fig. 12, when port 1 is excited, the main polarization of the two-port antenna in $xoz$ and $yoz$ planes both exhibits left-hand circular polarization with a FBR of 15 dB and a 3 dB beam width as high as 60°. Furthermore, it can be obtained that the cross-polarization amplitude with the right-handed circular polarization characteristic in the main beam direction is lower than $-20$ dB. Based on the symmetry of the antenna structure, it can be acquired that when port 2 is excited and port 1 is connected to a matching load, the main polarization of the antenna is characterized by RHCP, which is not given in the article for brevity.

C. DUAL-PORT DUAL-SENSE CP EMSIW ANTENNA WITH ENHANCED BANDWIDTH

In Section B, a dual-sense CP EMSIW antenna with low profile and high gain is designed, but the impedance bandwidth of the antenna is only 4.7%, which limits the application of the antenna. Traced back to Section B, it can be concluded that the introduction of the inverted triangular parasitic patch not only achieves circular polarization but also improves the antenna impedance bandwidth from 1.7% to 4.7%. Therefore, a square parasitic patch transformed from the inverted triangular patch is proposed in this section to expand the impedance bandwidth, while ensuring the feature of dual-sense CP. The configuration of the broadband antenna is shown in Fig. 13 with optimal parameters given in Table 3. Compared with the antenna described in Section B, the main difference is that the original inverted triangle parasitic patch is replaced by an innovative square parasitic patch. In order to highlight the effect of the square patch on the antenna performance, parameter study is carried out on the proposed antenna. It is worth noting that in the process of parameter analysis, only port 1 is excited and the port 2 is connected to a matching load. It can be found from Fig. 14 that as $gp$ increases from 0.7 mm to 1.9 mm, the two resonance points of the antenna at 3.23 GHz and 3.57 GHz both show a tendency that move to 3.40 GHz. Then, the two resonance points close to each other broaden the impedance bandwidth. At the same time, the port isolation within the resonance bandwidth deteriorates gradually, but still exhibits the characteristic of $\leq -10$ dB. As shown in Fig. 14(c) and Fig. 14(d), not only the $S$-parameter is sensitive to the coupling gap $gp$, but the antenna gain and 3 dB ARBW also show a certain degree of reduction with the increase of the gap width. Comparing the simulated results in Fig. 14, it can be concluded that the proposed antenna has an impedance bandwidth of 11.2% from 3.21 GHz to 3.59 GHz and an ARBW of 2.8% from 3.49 GHz to 3.59 GHz when $gp$ is 1.3 mm. Moreover, a maximum gain of 6.3 dBi accompanied with an isolation of $\leq -10$ dB is also acquired at 3.4 GHz.

Fig. 15 shows the surface current distribution of the single-port EMSIW antenna and the dual-port dual-CP broadband antenna to further explain the function of parasitic patch and
the principle of dual-CP polarization. It can be found from Fig. 15(a) that the radiation mechanism of the single-port EMSIW antenna at this time is represented by the energy radiating to free space from the hypotenuse of the triangular metal patch (the perfect magnetic wall OD). For the dual-port dual-CP antenna designed in this paper, the surface current distributions at 3.5 GHz and phase $\phi = 80^\circ$ are given in Fig 15(b) and Fig. 15(c). Two orthogonal E-fields with equal magnitudes are obtained at the hypotenuse of the two triangular metal patches. By adjusting the width of the gap between the parasitic patch and the EMSIW cavity, two orthogonal E-fields with equal magnitudes are excited and obtained on the two orthogonal sides of the square parasitic patch. The specific manifestation is that the currents mainly concentrated on the two right-angle sides close to the two EMSIW cavities which are shown in Fig. 15. Then, combination of these two orthogonal fields in the far field, a circular polarized wave is acquired. Furthermore, the corresponding electric field distribution and surface current distribution of the three antennas are also depicted in Fig. 16 to explain the working mechanism of circular polarization and enhanced bandwidth. For simplicity, three proposed antennas investigated in the second part are renamed Ant. 1, Ant. 2 and Ant. 3, respectively. Fig. 16(a) shows the electric field distribution of Ant. 2 and Ant. 3 at 3.40 GHz and 3.50 GHz, respectively. Compared with the EMSIW resonator, when Ant. 2 and Ant. 3 work at T/4 and 3T/4, the proportion of the electric field intensity on the parasitic patch gradually increases, which means that the resonance mode of the two antennas is dominated by the parasitic patch. Then, the bandwidth of the antenna is extended. As shown in Fig. 16(b), when port 1 is activated, the coupling current on the parasitic patch in one cycle follows the clockwise rotation rule. In other words, the Ant. 3 works in a left-hand circular polarization state. Similarly, when port 2 is excited, two E-fields with equal magnitudes and phase difference of 90$^\circ$ are also obtained on the square parasitic patch, but the coupling current shows periodic counterclockwise rotation, and the right-handed circular polarization characteristic is obtained.

It is also worth mentioning that the coupling effect between the square parasitic patch and the two EMSIW cavities plays a role in impedance matching and broadens the impedance bandwidth of the antenna. On the other hand, attribute to the orthogonal E-field with equal magnitudes on the parasitic patch, the large-area coupling current show clockwise or counterclockwise rotation, which greatly improves the purity of circular polarization.

The dual-port dual-CP broadband antenna is fabricated and the prototype is shown in Fig. 17. A series of tests are also carried out to verify the positive effect of the square parasitic patch. Fig. 18(a) shows the measured results of the reflection coefficient at the two ports and an impedance bandwidth of 10.5% from 3.24 GHz to 3.60 GHz is obtained, which is approximately the same as the simulated result. Attribute to the deviation in the welding, the measured port isolation within the impedance bandwidth is greater than 11.6 dB which is better than the simulated isolation of 10.4 dB in Fig. 18(b). The isolation of the dual-port antenna designed in this paper is less than 15 dB, which is mainly due to the following points:

First of all, the designed antenna is integrated in a plane of only $48 \times 50 \text{ mm}^2$ without any decoupling structure. When the antenna is working, the 3-D radiation patterns of port 1 and port 2 at 3.5 GHz are shown in Fig. 19. It is well known that when the main beam directions radiated by two antennas are opposite, there will be a relatively strong mutual coupling effect between two ports, resulting in poor isolation.
Furthermore, the surface current distribution of the two EMSIW cavities is also given in Fig. 20, when the two ports are excited separately. It can be seen from Fig. 20 that the current direction does not follow the mutual perpendicular behavior of the surface current on the square parasitic patch in Fig. 15(b) and Fig. 15(c). In fact, although the main radiation is dominated by the square parasitic patch when the antenna is working, the two EMSIW resonators are still included in the entire radiator. Due to the existence of the coupling gap, even if the surface currents on the parasitic patch are perpendicular to each other, the non-perpendicular characteristics of the current direction near the excitation port have almost no effect on the improvement of isolation.

Due to the symmetry of the antenna structure, only the far-field measured results of port 1 are given. As shown in Fig. 21(a) and Fig. 21(b), it can be seen that the fluctuation trend of the measured axial ratio, gain and radiation efficiency follows the simulated results. Then, taking into account the two ports, it is found that a ARBW of 3.4% from 3.48 GHz to 3.60 GHz, a maximum measured gain of 5.74 dBi at 3.45 GHz and a radiation efficiency of 88% are obtained. As shown in Fig. 22, detailed testing is also carried out for the far-field radiation pattern. The measured results are given in Fig. 23 to vividly explain the polarization diversity. When port 1 is excited, the main polarization of the broadband antenna still exhibits the feature of LHCP, which is the same as the antenna described in Section B. While, the cross-polarization of the fabricated broadband antenna shows the RHCP characteristic. Similarly, when the port 2 is excited, the co-polarization of the designed antenna exhibits RHCP characteristic which accompanied by a low cross-polarization of LHCP.
In detail, it can be obtained from Fig. 23 that the measured radiation patterns at 3.50 GHz in \(xoz\) and \(yoz\) planes both show directional radiation characteristic with a 3 dB beam width of 66°. However, in \(yoz\) plane, the main beam direction of the pattern deviates from the \(y\)-axis by 30°. This deterioration is caused by the enlarged coupling current on the square parasitic patch which dominates the radiation of the antenna. In Fig. 16(a), the simulated E-field distribution of the Ant. 3 at 3.5 GHz more intuitively explains the deterioration of the pattern at \(yoz\) plane.

### III. SUMMARY AND COMPARISON

To highlight the broadband and circular polarization performances of the proposed antennas, a summary of the simulated and measured results in terms of impedance bandwidth, 3 dB axial ratio bandwidth, port isolation, antenna gain, and radiation efficiency is tabulated in Table 4. For the three antennas proposed in the three sections, the measured results all show the characteristics basically consistent with the simulated results. First, a back-fed EMSIW antenna with a narrow bandwidth and directional radiation is proposed. On this basis, a two-port EMSIW antenna with dual-sense CP characteristics is obtained by combining two mirror-symmetric EMSIW antennas and introducing parasitic inverted triangular patches. Then, a method to transform the shape of the parasitic patch is proposed to achieve broadband characteristics, while retaining the circular polarization characteristics. Finally, a square patch is introduced to design the dual-sense CP two-port EMSIW antenna with an impedance bandwidth of 10.5%, ARBW of 3.4%, high gain, and high radiation efficiency. It is worth mentioning that the coupling gap between the EMSIW cavity and the parasitic patch has a significant impact on the impedance bandwidth, radiation gain, and circular polarization.

### IV. CONCLUSION

A simple structure dual-sense circular polarization broadband antenna based on the utilize of EMSIW technology is designed in this work. The proposed parasitic patch incorporated with two symmetrically placed EMSIW resonators to acquire the feature of circular polarization and wideband. As the shape of the parasitic patch and the dimension of the coupling slot change, the resonance bandwidth, polarization type, and radiation gain of the proposed antenna also change accordingly. In order to extend the impedance bandwidth and retain the circular polarization characteristics through the simplest and most feasible approach, a square parasitic patch is employed. Due to the coupling current on the square parasitic patch, the measured results show that the reflection coefficient at the two ports meet the requirement of \(<−10\) dB from 3.24 GHz to 3.60 GHz. Good advantages of simple structure, easy to implement, high isolation better

In Table 5, some reported EMSIW antennas are summarized and compared with the proposed work. In [11], [12], [15], [16], four miniaturized antennas are designed in conjunction by employing EMSIW and CSRR technologies, which achieve tunable resonance frequency and dual-band characteristics. But these antennas have the same disadvantage: the operating bandwidth is too narrow. In [14], [19], two EMSIW antennas with impedance bandwidths larger than 16% are proposed. Parasitic resonators and parasitic strips are introduced to improve the impedance bandwidth and axial ratio bandwidth. But the single polarization characteristic, measured gain below 5 dBi, and complex antenna structure are less competitive than the features of dual-sense CP, maximal gain of 5.74 dBi, and simple structure obtained in this research. In [20], a dual-polarized antenna is designed for 5G millimeter wave but the stacked structure of the 5-layer substrate and the complicated feeding method also weakened its practicality.

### TABLE 4. Summary of the Results of the Investigated Three Antennas.

| Antennas          | Single-port antenna | Two-port dual CP antenna | Two-port dual CP broadband antenna |
|-------------------|---------------------|--------------------------|----------------------------------|
| Simu. IMBW        | 2.0%                | 4.7%                     | 11.2%                            |
| Meas. IMBW        | 1.7%                | 4.7%                     | 10.5%                            |
| Simu. ARBW        | -                   | 2.1%                     | 2.8%                             |
| Meas. ARBW        | -                   | 2.3%                     | 3.4%                             |
| Simu. PI          | -                   | \(\geq 12.1\) dB         | \(\geq 10.4\) dB                 |
| Meas. PI          | -                   | \(\geq 12.2\) dB         | \(\leq 11.6\) dB                 |
| Simu. MG          | 3.96 dBi            | 6.27 dBi                 | 6.30 dBi                         |
| Meas. MG          | 3.56 dBi            | 5.86 dBi                 | 5.74 dBi                         |
| Simu. RE          | 95%                 | 95%                      | 95%                              |
| Meas. RE          | 85%                 | 89%                      | 90%                              |

IMBW represents impedance bandwidth; PI represents port isolation; MG represents maximal gain; RE represents radiation efficiency.

### TABLE 5. Comparison Between Reported and the Proposed Two-port Broadband CP EMSIW Antenna.

| Ref | IMBW (%) | ARBW (%) | Effi (%) | MG (dBi) | Size (\(\lambda_a^2\)) | PT |
|-----|----------|----------|----------|----------|------------------------|----|
| [11]| 1.55     | -        | 92       | 5.9      | 0.66×0.66×0.03         | -  |
| [14]| 16.2     | -        | 82       | 4.7      | 0.43×0.43×0.03         | LP |
| [15]| 2.34     | -        | 72.5     | 5        | 0.32×0.48×0.03         | LP |
| [16]| 2.42     | -        | 82.4     | 6.8      | 0.32×0.48×0.03         | -  |
| [19]| 18.5     | 8.7      | -        | 8.5      | 0.77×0.77×0.07         | LHCP |
| [20]| 23.9     | -        | -        | 4.5      | 0.35×0.49×0.16         | HP&VP |
| This work | 10.5 | 3.4 | 90 | 5.74 | 0.57×0.54×0.02 | LHCP & RHCP |

PT represents polarization type; \(\lambda_a\) represents the wavelength of the center frequency in free space; HP and VP stand for horizontal polarization and vertical polarization, respectively.
than 11.6 dB, maximum radiation gain of 5.74 dBiC and dual-sense circular polarization characteristics all suggest that the proposed two-port EMSIW broadband antenna is a good candidate for wireless communication. Such as 3.5 GHz wireless access communication, specifically 3400–3430 MHz uplink and 3500–3530 MHz downlink. The designed antenna can also be applied for 3.5-GHz WiMAX [22] and Band42. It is worth highlighting that, the scalability support of this method can continue to design a four-port EMSIW antenna for 5G on the basis of this paper.

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