Wideband Multi-polarization Reconfigurable Antenna based on Non-uniform Polarization Convert AMC Reflector

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Abstract **–** A novel design of wideband multi-polarization reconfigurable antenna is proposed, based on a non-uniform polarization convert artificial magnetic conductor (AMC) reflector. The proposed antenna consists of a radiator element and an AMC reflector. Firstly, a modified polarization convert AMC reflector is designed. The non-uniform AMC reflector causes an enhancement of 3 dB axial ratio (AR) performance. Secondly, a wideband linearly polarized monopole antenna is presented as the main radiator, utilizing the broadband characteristic of a C-shaped monopole. The polarization reconfigurability of the proposed antenna can be achieved by properly rotating the AMC reflector, which can be switched between linear polarization (LP), left-hand circular polarization (LHCP), and right-hand circular polarization (RHCP). A prototype of the proposed antenna is fabricated and experimented with to validate the theoretical performance. The measured results show a -10 dB impedance bandwidth of 42.7% and 44.4% for LP and CP modes, respectively, and a 3 dB AR bandwidth of 20% for CP modes. In addition, the measured peak gain reaches 8 dBi/dBic. A good agreement is shown between the simulation and measurement, pointing to the good performance of the proposed antenna.

Index Terms **–** Non-uniform metasurface (MS), polarization convert AMC reflector, polarization reconfigurability, wideband.

I. INTRODUCTION

With the rapid development of mobile and satellite communications, lots of multifunctional antennas have been investigated in recent years, such as frequency reconfigurable antennas, pattern reconfigurable antennas, polarization reconfigurable antennas, or hybrid reconfigurable antennas [1]–[25]. Since circular polarization has the characteristic of reducing the effect of multipath loss, modern wireless communications require antenna polarization diversity to strengthen the communication quality, especially for satellite communications [3], [4]. Moreover, to meet more wireless communication applications needs, a wideband characteristic of the antenna is needed. Thus, the antenna, which combines performances of wideband and multi-polarization simultaneously, has attracted more and more attention.

Conventionally, the approach of antenna reconfigurability includes embedding RF or optical switches in slots on radiator patches or the ground plane to change the antenna current distribution and make different polarization modes [5]–[14]. In [5]–[7], three tri-polarization reconfigurable patch antennas are presented; they have simple geometries, but all obtain a narrow operating bandwidth of 2%, 8%, and 3%, respectively. On the contrary, a tri-reconfigurable antenna makes a large 3 dB axial ratio (AR) bandwidth of 50% caused by a C-shaped radiator [8], but the optical switch is not easy to apply to modern communication systems. Some other works unfortunately have polarization reconfigurability, switching only within linearly polarized (LP) modes or circularly polarized (CP) modes [9]–[12]. Other works realize polarization diversity by controlling switches inserted in the slot on the ground plane [13], [14].

Another method for a polarization reconfigurable antenna is to design a multipath phase-shift network, which can change the phase difference between the feeding points and lead to polarization diversities [15]–[10]. In this method, it is easy to offer a phase difference and then achieve polarization diversity. For example, in [15] and [18], a tri-polarization reconfigurable antenna and a quad-polarization reconfigurable antenna are proposed,

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but they obtain a narrow 3 dB AR bandwidth of 17% and 12%, respectively. Obviously, the shortcoming of this method is that a wideband phase-shift network is challenging to implement, and many lumped components are used, which causes cost increases.

It's worth noting that, as a novel design, some multi-polarization antenna investigations about metasurface (MS) for polarization diversity have been presented [20]–[25]. Compared with conventional works, the polarization reconfigurable antenna based on MS has the advantage of a low profile. In [20], a CP reconfigurable antenna based on non-uniform MS with a low profile and broadband is investigated, controlled by RF switches. Unfortunately, this antenna can't work in LP mode. In [23], a multi-polarization reconfigurable antenna based on polarization convert MS is proposed with a bandwidth of 30%, switching polarization states by rotating the MS. Compared with RF switches, this method can reduce the loss of bias circuits and lumped components.

In this paper, a wideband multi-polarization reconfigurable antenna based on a polarization convert artificial magnetic conductor (AMC) reflector is proposed. Different from the previously published design, this antenna is beneficial for a simple polarization switching strategy and a reduction of loss, selecting polarization modes by properly rotating the AMC reflector without any switches. Meanwhile, compared to the conventional metal reflector, the AMC reflector leads to an improvement of the antenna gain with a low profile. Eventually, the proposed antenna acquires multi-polarization working modes and a profile decline of 33.3% compared to conventional mental reflectors with a profile of $1/4\lambda 0$ (at $f0$ = 5 GHz).

II. ANTENNA DESIGN PRINCIPLE

As depicted in Fig. 1, the proposed antenna includes an AMC reflector and a C-shaped radiator. The wideband performance of the C-shaped radiator has already been validated by previous work [8]. There is a modified C-shaped monopole to offer a wideband incident wave source. The modified C-shaped patch and ground plane are printed on top and bottom of a 1.524 mm Rogers 4003C substrate with a relative permittivity of 3.38. In others, an improved AMC reflector is placed H = 10 mm below the radiator to achieve polarization reconfigurability and radiation directionality. The AMC reflector consists of 6×6 MS units fabricated on a 2 mm R4 substrate with a relative permittivity of 4.4. To explain the design principle of the proposed antenna, a detailed analysis of the AMC reflector and C-shaped monopole are discussed as follows.

A. Polarization convert AMC reflector analysis

The geometry of the proposed AMC unit is illustrated in Fig. 2, in which its cell is a shuttle-shaped patch etched with a crossed slot. An equivalent circuit is provided to explain how the AMC reflector realizes polarization conversion. Along the diagonal corners, the orthogonal surface impedance component, marked Z_u and Z_v, of the AMC unit can be approximately calculated as

$$\begin{aligned} Z_u &= 2R_1 + 2j\omega(2L_1) + 2/(j\omega C_1) \\ &\quad + 1/(j\omega C_2) \\ &= R_u + jX_u \text{ and} \end{aligned} \tag{1a}$$

$$\begin{aligned} Z_v &= 2R_2 + 2j\omega(2L_2) + 2/(j\omega C_3) \\ &\quad + 1/(j\omega C_4) \\ &= R_v + jX_v, \end{aligned} \tag{1b}$$

where $R1$, $L1$, $C1$, and $C2$, are the resistance, inductance, and distributed capacitance of the AMC unit in the u-direction, respectively, and $R2$, $L2$, $C3$, and C4 are in the v-direction. Further, according to the Euler formula, (1) can be simplified as follows

$$Z_u = |Z_u|\angle\varphi 1 = |Z_u|e^{j\varphi 1} \text{ and} \tag{2a}$$

$$Z_v = |Z_v|\angle\varphi 2 = |Z_v|e^{j\varphi 2}. \tag{2b}$$

What can be known is that the resistance, inductance, and distributed capacitance of the AMC unit are related to the triangle truncation and the crossed slot. Thus, by adjusting the size of the triangle truncated and the crossed slot, a phase difference can be achieved between Z_u and Z_v.

Assuming that the incident source is a linearly polarized plane wave along the x-axis, so the incident $\boldsymbol{E}$-field is also along the x-axis named $\boldsymbol{E}_{ix}$. Here, $\boldsymbol{E}_{ix}$ is broken into two orthogonal components, $\boldsymbol{E}_{iu}$ and $\boldsymbol{E}_{iv}$. By supposing that the magnitude of the two orthogonal $\boldsymbol{E}$-field

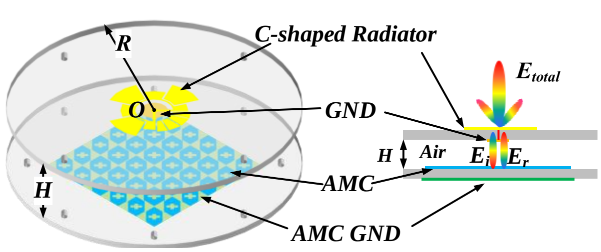


Fig. 1. The overall prototype of the proposed antenna.

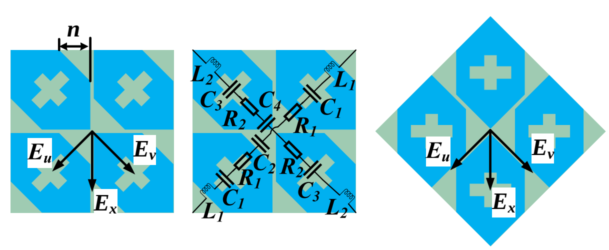


Fig. 2. The geometry of the proposed AMC.

components is $|E_m|$ and the phase is ö3 and ö4, $\boldsymbol{E}_{iu}$ and $\boldsymbol{E}_{iv}$ can be denoted by the following:

$$E_{\text{iu}} = |Zm|e^{j\varphi 3} \text{ and} \tag{3a}$$

$$E_{\text{iv}} = |Zm|e^{j\varphi 4}. \tag{3b}$$

When $\boldsymbol{E}$-field components $\boldsymbol{E}_{iu}$ and $\boldsymbol{E}_{iv}$ are incident on the AMC reflector, respectively, numerous electrons on the surface of the AMC unit will be excited and move along the u-direction and v-direction, respectively, generating induced currents, thus forming the reflected $\boldsymbol{E}$-fields $\boldsymbol{E}_{ru}$ and $\boldsymbol{E}_{rv}$ individually. If there is no energy loss in reflection, the reflected and incident $\boldsymbol{E}$-field are equal in magnitude. Furthermore, the phase of the reflected wave is equivalent to the combination of the phase with the incident wave, the phase of the AMC surface impedance along the incident wave direction, and the phase difference generated by the air gap. Therefore, the reflected $\boldsymbol{E}$-field components can be roughly described as follows

$$E_{ru} = |Zm|e^{j(\varphi 1+\varphi 3+\Delta\varphi)} \text{ and} \tag{4a}$$

$$E_{rv} = |Zm|e^{j(\varphi 2+\varphi 4+\Delta\varphi).} \tag{4b}$$

Eventually, the composite $\boldsymbol{E}$-field components can be roughly described as follows:

$$E_u = |Zm|\left[e^{j\varphi 3} + e^{j(\varphi 1+\varphi 3+\Delta\varphi)}\right] \text{ and} \tag{5a}$$

$$E_v = |Zm|\left[e^{j\varphi 4} + e^{j(\varphi 2+\varphi 4+\Delta\varphi)}\right]. \tag{5b}$$

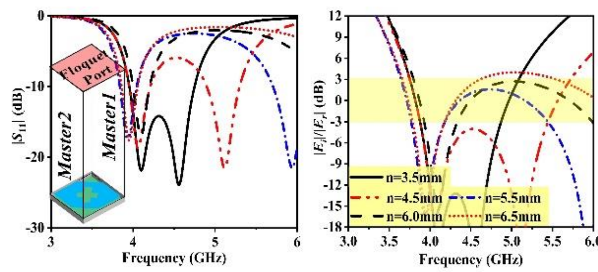
Since $\boldsymbol{E}_{iu}$ and $\boldsymbol{E}_{iv}$ are symmetric to $\boldsymbol{E}_{ix}$, these two orthogonal $\boldsymbol{E}$-field components have the same phase, meaning that ö3 is equal to ö4. And appropriately optimizing the AMC unit, a 90° phase difference can be obtained between Z_u and Z_v, assuming ö1 leads ö2 by 90°. As a result, (5a) and (5b) can be simplified as (6a) and (6b).

$$E_u = |Zm|\left[e^{j\varphi 4} + je^{j(\varphi 2+\varphi 4+\Delta\varphi)}\right] \text{and} \tag{6a}$$

$$E_v = |Zm|\left[e^{j\varphi 4} + e^{j(\varphi 2+\varphi 4+\Delta\varphi)}\right]. \tag{6b}$$

Thus, the composite $\boldsymbol{E}$-field $\boldsymbol{E}_{total}$ is a CP wave, which is combined by two $\boldsymbol{E}$-field components with identical magnitudes and a 90° phase difference. In addition, because the phase of the $\boldsymbol{E}$-field component in the u-direction leads the v-direction, the antenna will work in left-handed circularly polarized (LHCP) mode. As shown in Fig. 2, when the AMC unit is rotated by -45° or 45°, the AMC is symmetric about the x-axis. Thus, there is an in-phase or anti-phase of the surface impedance between the u-direction and v-direction. Accordingly, the composite $\boldsymbol{E}$-field $\boldsymbol{E}_{total}$ is an LP wave. Moreover, when the AMC unit is rotated by 90°, the polarization of the proposed antenna will be in right-handed circularly polarized (RHCP) mode.

Ansoft HFSS simulates the AMC unit with the Floquet port to verify the analysis. The width of the triangle truncation on AMC units is defined as parameter n. Its effect on the reflected characteristic of the proposed AMC unit and the polarization convert performance is given in Fig. 3. With the increase of n, the high-frequency resonance point of the AMC unit will move toward the high frequency, whereas the low frequency remains almost constant. Meanwhile, the impedance matching would deteriorate. In addition, for better CP performance, the magnitude ratio between the incident $\boldsymbol{E}$-field and the reflected must be within ±3 dB. As shown in Fig. 3 (b), while n increases, the magnitude ratio varies, and the broadest 3 dB magnitude ratio bandwidth is obtained when n is equal to 6 mm. Considering the performance of the impedance matching and the CP, there are two AMC units with different truncations, n = 4.5 mm and 6 mm, respectively, to build a non-uniform AMC reflector.



(a) (b)

Fig. 3. The effect of parameter n on the AMC unit: (a) Reflection coefficient $|S_{11}|$, (b) the magnitude ratio between the incident E-field and reflected E-field.

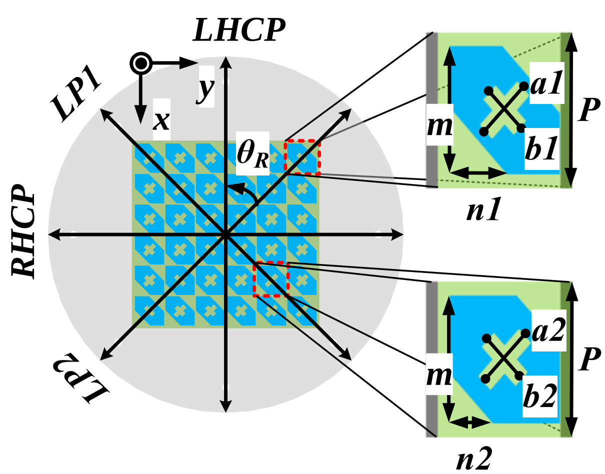
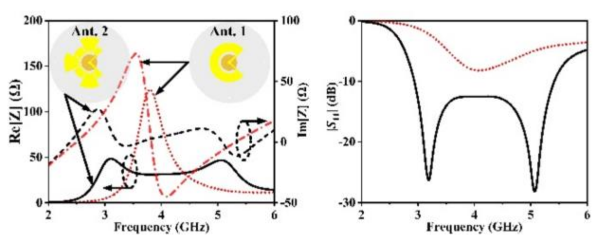


Fig. 4. The phototype of the proposed AMC reflector (design parameters: m = 11.5 mm, P = 12 mm, $n1$ = 6 mm, $n2$ = 4.5 mm, $a1$ = 5.5 mm, $a2$ = 6 mm, $b1$ = 4.5 mm, $b2$ = 5 mm).

B. C-shaped monopole antenna with the AMC reflector

Given the polarization conversion characteristic of the proposed AMC reflector, a modified C-shaped monopole is designed and introduced to offer an incident *x*-LP wave source, positioned at the top of the reflector.

As shown in Fig. 5, for Ant. 1, the impedance matching is poor, in which the real part of the impedance is not close to 50 Ù, and the imaginary part is not near 0 Ù within a certain bandwidth. There is a resonance only near 4 GHz, noted f_1. To improve impedance matching and bring multi-resonance, the C-shaped patch edge is slotted and placed into three parasitic stubs in a fan shape, labeled Ant. 2. Due to the slotting, the current length of the resonant frequency f_1 will be expanded so that the resonance frequency is scaled down and recorded as f_2. The parasitic stubs, with the induced current, will create a new resonance, marked f_3, achieving multi-frequency resonance. As a result, two resonant frequency points near 3 and 5 GHz are generated and bring a wide impedance bandwidth ($|S_{11}| <$ -10 dB) of about 60%.



(a) (b)

Fig. 5. The performance of two C-shaped monopoles: (a) Impedance, (b) $|S_{11}|$.

Then the proposed AMC reflector is applied below the C-shaped monopole antenna, about 0.15ë, to realize directionality and polarization reconfigurability. To reduce the crossed polarization, especially in CP modes, a set of fan-shaped parasitic stubs are added at the notch of Ant.2. The added parasitic stubs will be excited and generated with a polarization mode consistent with the antenna, so the main polarization is enhanced, which implies a <u>reverse</u> weakening of the cross-polarization, as shown in Fig. 6. The final design of the C-shaped monopole antenna, shown in Fig. 7, contains a C-shaped patch with seven parasitic fan stubs and a circular ground plane with two additional rectangle stubs.

Eventually, when holding the C-shaped monopole antenna still and rotating the AMC reflector counterclockwise by -45°, 45°, 0°, and 90°, the antenna can work on *x*-LP1, *x*-LP2, LHCP, and RHCP modes, respectively.

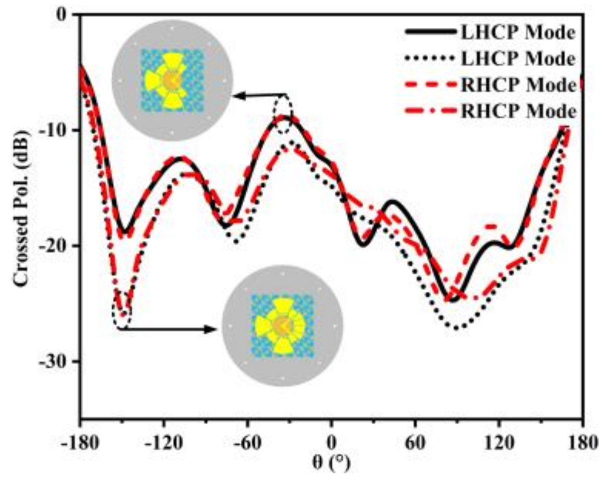


Fig. 6. The effect of the small fan parasitic stubs.

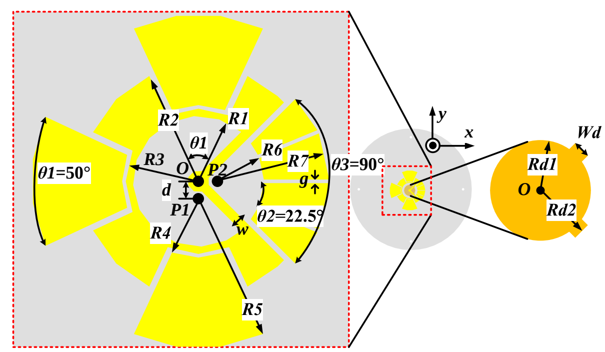


Fig. 7. The phototype of the C-shaped monopole (design parameters [millimetres]: *R1* = 9, *R2* = 16, *R3* = 10, *R4* = 8.5, *R5* = 21, *R6* = 7, *R7* = 16, *Rd1* = 6.5, *Rd2* = 7.5, *w* = 1.3, *d* = 2, *g* = 0.5, *Wd* = 2.3).

III. SIMULATED AND EXPERIMENTAL RESULTS

The proposed antenna is designed and optimized by Ansys HFSS and then fabricated and measured to verify the performance by the ROHDE&SCHWARZ ZVB-8 vector network analyzer and multi-probe antenna testing system. The manufactured antenna and far-field experiment setup are shown in Fig. 8.

Figure 9 illustrates simulated and experimental reflection coefficients $|S_{11}|$ in different polarization modes. The experimental -10 dB overlapped impedance bandwidth of 42.7%, covers 3.5 GHz to 5.4 GHz in both LP modes. It obtains 44.4% of the measured -10 dB impedance bandwidth for the CP modes and covers between 3.5 GHz and 5.5 GHz. The measured impedance matching of the antenna decreases slightly at high frequency due to manufacturing error. The experimental results are in good accordance with the simulation results.

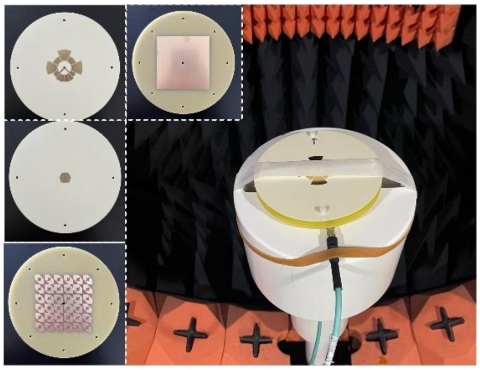


Fig. 8. Photographs of the manufactured antenna and experiment setup.

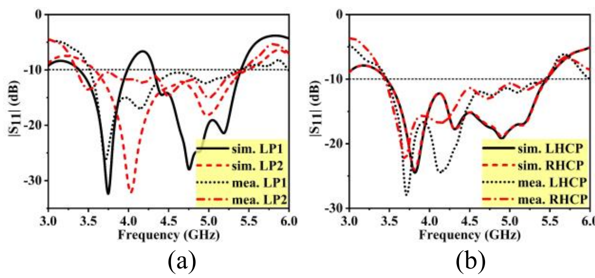


Fig. 9. The simulated and measured reflection coefficient $|S_{11}|$: (a) LP modes and (b) CP modes.

Figure 10 shows the simulated and measured axial ratio and gain in different polarization modes. When working in LP modes, the axial ratio of the antenna is larger than 25 dB within operating bandwidth. In addition, the measured peak gain reaches about 8 dBi. When working in CP modes, an overlapped 3 dB axial ratio bandwidth of 20%, covering 4.5 GHz to 5.5 GHz, shows good agreement with the simulation. Similarly, the measured peak gain is about 8 dBic for CP modes. Compared with the simulations, there is a 2 dB loss of the measured gain, which is caused by the error of fabrication and the loss of dielectric material. The measured and simulated normalized radiation patterns of the proposed antenna at 4.8 and 5 GHz are illustrated in Figs. 11 and 12 for CP and LP modes, respectively. The simulated results match well for all states with good directivity.

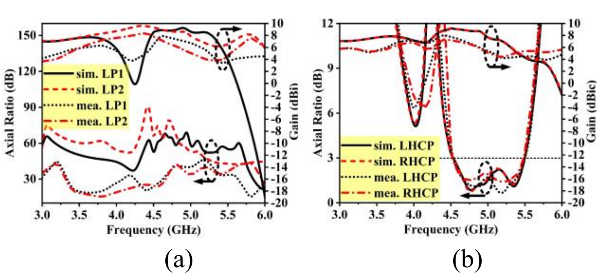


Fig. 10. The simulated and measured results of axial ratio and gain: (a) LP modes and (b) CP modes.

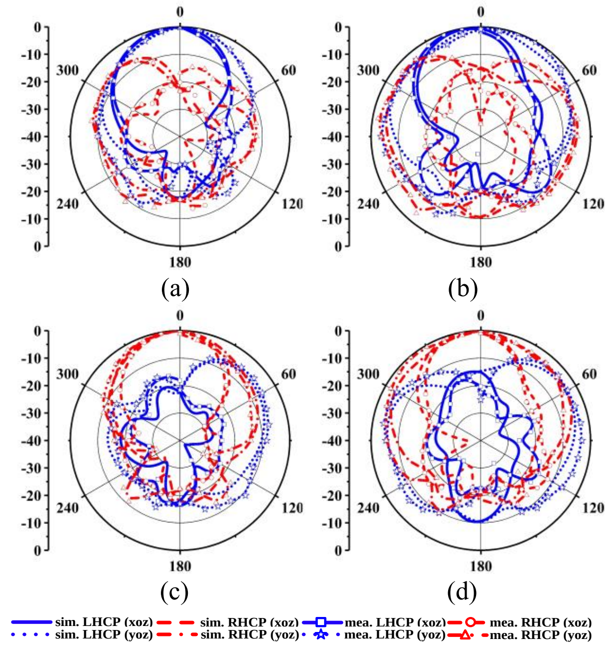


Fig. 11. The simulated and measured normalized radiation pattern: (a) LHCP at 4.8 GHz, (b) 5.2 GHz, (c) RHCP at 4.8 GHz, and (d) 5.2 GHz.

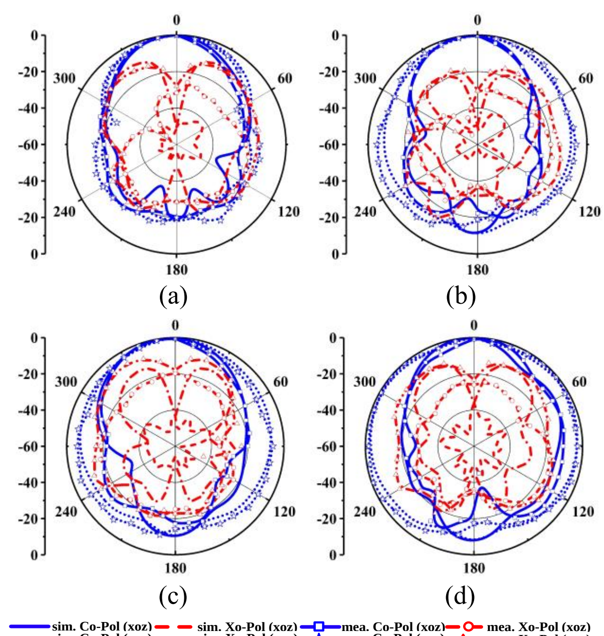


Fig. 12. The simulated and measured normalized radiation pattern: (a) LP1 at 4.8 GHz, (b) 5.2 GHz, (c) LP2 at 4.8 GHz, and (d) 5.2 GHz.

Table 1 shows a performance comparison with other polarization reconfigurable works. The proposed antenna has a wider -10 dB impedance bandwidth of over 40% and more operating modes. Meanwhile, this work has a simple polarization switch strategy by rotating the MS, with no RF switches applied. In addition, the 3 dB axial ratio bandwidth and peak gain of the proposed work have shown good performance.

Table 1: Performance comparison with other works

Ref.	**Modes**	**Impedance Bandwidth (%)**	**AR Bandwidth (%)**	**Peak Gain (dBi/c)**
[11]	2 CP	41.1	34	12
[12]	2 CP	5	4	5.2
[21]	2 CP	36	21.5	15.5
[22]	1 LP2 CP	LP: 17.1 CP: 8.7	8.7	LP: 9 CP: 8.3
This work	2 LP2 CP	LP: 42.7 CP: 44.4	20	LP: 8 CP: 8

IV. CONCLUSION

This paper proposes a design for a polarization reconfigurable antenna based on a rotating AMC reflector. The proposed antenna is composed of two parts, an AMC reflector and a C-shaped monopole. By turning the AMC reflector at $\pm 45°$, $0°$, and $90°$ clockwise, respectively, the antenna could switch the polarization state among x-LP, LHCP, and RHCP. Compared to other previous polarization reconfigurable antennas, it reduces the application of the DC bias circuits with a simple polarization switching strategy. The proposed antenna has a wide operating bandwidth of 42.7% and 20% for LP and CP modes, approximately covering 3.5 to 5.4 GHz and 4.5 to 5.5 GHz, respectively. Furthermore, the maximum measured gain reaches 8 dBi(c). It could be applied to 5G mobile communication systems, satellite communications, and other polarization-diverse applications.

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