A Low-Profile Broadband Circularly Polarised Wide-Slot Antenna with an Artificial Magnetic Conductor Reflector

Fangfang Fan, Xiao Fan, Xiaoyu Wang, and Zehong Yan

Science and Technology on Antenna and Microwave Laboratory
Xidian University, Xi'an, Shaanxi, 710071, China
fffan@mail.xidian.edu.cn, fanfanx17@163.com, wxyhongtongtong@163.com, zhyan@mail.xidian.edu.cn

Abstract ─ In this letter, a novel broadband circularly polarisation (CP) wide-slot antenna with an artificial magnetic conductor (AMC) as the reflector is presented. The wide-slot antenna is composed of a knife-shaped radiator and an improved ground plane. A broadband CP characteristic can be achieved by slotting the ground plane to make it an asymmetric ground shape. However, the average gain of the wide-slot antenna is only about 3 dBic because of bidirectional radiation. An AMC reflector is adopted to enhance the gain of the wide-slot antenna without introducing a high profile similar to the PEC reflector. In addition, the four metal plates are vertically placed around the antenna to broaden the axial ratio (AR) bandwidth of the antenna with the AMC reflector. The measurement results show that the 3dB AR bandwidth of the proposed CP antenna is 32.4% (2.35GHz─3.26GHz), the average gain is 6.5dBic in the AR bandwidth and the value of VSWR in the AR bandwidth is less than 2. The size of the antenna is $0.84\lambda_0 \times 0.84\lambda_0 \times 0.13\lambda_0$ at the centre frequency of 2.805 GHz. The proposed antenna has a low profile, broad AR bandwidth and high gain, thereby being a good candidate for various wireless communication systems.

Index Terms ─ Artificial Magnetic Conductor (AMC), broadband, Circular Polarisation (CP), low-profile, wide-slot antenna.

I. INTRODUCTION

With the rapid development of the wireless communication technology, researchers have been paying much attention to circularly polarisation (CP) antennas. CP antennas can transmit and receive electromagnetic waves of arbitrary polarisation and have strong anti-interference ability. The traditional microstrip CP antenna has a low profile. However, its CP bandwidth is very narrow due to its inherent high-Q nature. Many types of antenna have been developed to improve the CP bandwidth. Among them, planar monopole and wide-slot antenna are commonly used to achieve ultra-wideband circular polarisation. In the planar monopole design, many attempts have been made by employing various shapes of the monopole antenna, modifying ground plane or adding a parasitic stub to achieve a wider CP bandwidth [1─7]. In [1], the antenna employs a C-shaped monopole by adding an open-loop on the backside of the monopole and modifying the ground plane, a 65.2% 3dB axial ratio bandwidth (ARBW) is obtained [1]. In [2─4], the similar techniques as in [1] were used, achieving ARBWs of 63.3%, 63.61% and 53.92% for the antennas. In [5], a monopole antenna with a C-shaped patch and two triangular stubs was presented, and an ARBW of 104.7% was obtained. A compact monopole antenna was proposed in [6], the antenna consists of a P-shaped monopole and modified ground plane with a rectangular stub. Results demonstrated that the impedance bandwidth is 118.5% (S11< ─10dB) and the 3dB ARBW is 104.4%. Some reported wide-slot CP antennas are shown in [8─10]. In [8], a simple rectangular bracket-shaped parasitic strip was used to excite the CP modes; the 3dB ARBW can reach 49%. Two semicircular slots are etched in the ground plane to be used as the radiators [9], which has a wide 3dB ARBW of 74.3%. However, it was achieved at the expense of a relatively larger size and complex excitation mechanism of the CP modes. A U-shaped slot and two 50 Ω microstrip-fed ports were employed in [10] and can achieve dual circularly polarised radiation while providing an ARBW of 110.5%. The gains of the antennas proposed in the above literature are low, because these antennas have bidirectional radiation. Attempts have been made to increase the gain of these antennas. Placing a metal reflector under a wide-slot antenna enables the antenna to obtain unidirectional radiation, and the gain can be increased by almost 3 dB [11─14], but it results in a higher profile of about $0.25\lambda_0$. At the same time, the metal reflector would deteriorate the inherent wideband CP bandwidth. An artificial magnetic conductor (AMC) reflector is introduced inplace of a conventional metal reflector to reduce the profile of the unidirectional antenna. In [15─19], different AMC structures are introduced to increase the antenna gain while reducing its profile. However, these antennas are still large or the 3 dB ARBW is too narrow.

Submitted On: March 17, 2021
Accepted On: July 6, 2021

https://doi.org/10.47037/2020.ACES.J.360616

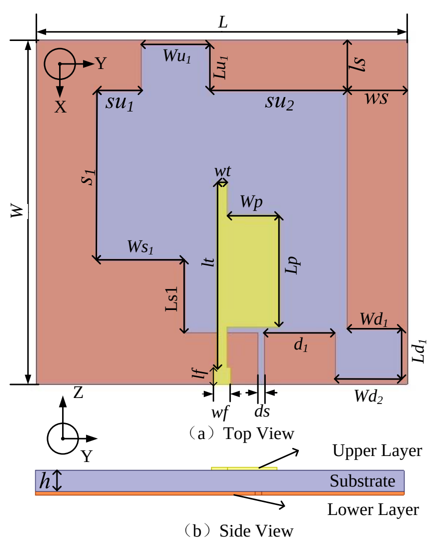
Hence, designing a wideband circularly polarised antenna with high gain and low profile is still a challenge.

In this letter, a novel broadband wide-slot CP antenna with high gain, wide CP bandwidth and low profile is proposed. Firstly, an ultra-wideband wide-slot CP antenna is designed. The wide-slot antenna has bidirectional radiation, which is why an AMC reflector is placed under the antenna to make it unidirectional and improve the gain of the antenna considerably. Then, four metal plates are vertically placed around the AMC reflector as in [20] to further broaden the ARBW of the antenna. The antenna is designed and simulated using the ANSYS HFSS. Finally, a prototype antenna is fabricated and experimented. The measured results verify the feasibility of the simulated antenna well.

II. ANTENNA DESIGN

A. Wide-slot antenna geometry

The geometry of the proposed wide-slot antenna is shown in Fig. 1. The antenna is fabricated on an FR4 substrate with a thickness of $h=1.6$ *mm*, a dielectric constant of 4.4 and a loss tangent of 0.02. The size of the substrate is $W \times L=65$ *mm* $\times$ *70 mm*. The radiation patch is on the upper layer of the substrate and it adopts a knife-shaped structure, which can improve the impedance matching and CP bandwidth. The lower layer of the substrate is a ground plane. Etching asymmetrical slots on the ground plane enables the antenna to generate two polarised waves perpendicular to each other with a phase difference of 90°, thereby forming circular polarisation.



(a) Top View

(b) Side View

Fig. 1. Geometry of the proposed wide-slot antenna. ($L=70$, $W=65$, $su_1=8.4$, $Wu_1=13$, $Lu_1=8.7$, $su_2=25.9$, $s_1=32$, $Ws_1=16.6$, $Ls_1=13.7$, $lf=3.1$, $wf=3.1$, $ds=1.2$, $d_1=13.35$, $Wd_2=12.5$, $Ld_1=9.4$, $Wd_1=10.2$, $Wp=9.9$, $Lp=21$, $lt=35$, $wt=1.9$, $ls=9.65$, $ws=11.35$). (Unit: mm).

B. Steps in realizing the wide-slot antenna

Six antennas labelled Ant.1─Ant.6 are developed and shown in Fig. 2 to explain the evolution of the broadband CP wide-slot antenna clearly. The VSWR and AR for the six antennas are compared in Fig. 3. Ant.1 is a conventional wide-slot antenna with a strip feedline on the upper layer and a rectangular slot on the lower layer of the substrate, which can radiate wideband linear polarised waves. To further improve the impedance matching of Ant.1, we introduce a rectangular stub with a size of $W_p \times L_p$ on the right side of the feedline, which is shown in Ant.2.

From Fig. 3 (a), we can see that the impedance bandwidth of Ant.1 has been broadened significantly, especially at the upper frequency after adding a rectangular stub. Then, to obtain CP performance, we adopt the method of slotting on the ground plane to obtain two near-degenerate modes. Firstly, an x-direction slit is employed in Ant.3 to change the current path in order to mainly reduce the low frequency AR, but its function in improving the low-frequency AR is not obvious. The slit benefits the impedance matching because of the improved coupling between the feedline and the wide-slot. Moreover, a rectangular slot of size $Ld_1 \times Wd_2$ is introduced on the right side of the slit in Ant.4 to further improve the AR performance at lower frequencies. This step greatly assists CP excitation at a lower-frequency as shown in Fig. 3 (b), because the rectangular slot can adjust the phase difference of the two near-degenerate polarised modes tending to 90° for CP radiation. However, the higher frequency band AR cannot meet the requirement. High-frequency AR should be reduced to extend the ARBW of this wide-slot antenna. In Ant.5, a rectangular slot of $Wu_1 \times Lu_1$ is etched on the top of the ground plane, and the position is approximately diagonal to the lower rectangular slot in Ant.4. These two slots introduce two perpendicular polarisation modes with almost a 90° phase difference at a higher frequency. Figure 3 (b) shows that the AR of Ant.5 is reduced at high frequencies. But the impedance matching in Ant.4 and Ant.5 especially at a lower frequency should be improved. A rectangular perturbation of size $Ls_1 \times Ws_1$ is introduced on the ground plane beside the knife-shaped radiation patch to further reduce the AR and improve the impedance matching. The VSWR was improved significantly compared with the VSWRs in Ant.4 and Ant.5, and the AR around 3 GHz was adjusted below 3 dB, that is to say, the rectangular perturbation acts as an important component in antenna performance in terms of wideband impedance matching and CP excitation. Thus, an ultra-wideband wideslot CP antenna (Ant.6) with good performance is generated. The impedance bandwidth with VSWR less than 2 is 94.6% (1.42 GHz─3.97 GHz), and the 3dB ARBW is 74.1% (1.41 GHz─3.07 GHz).

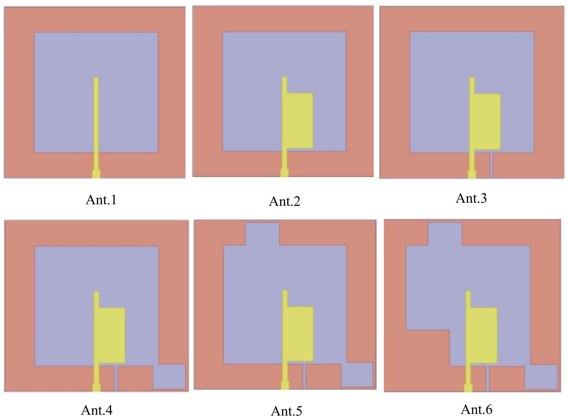
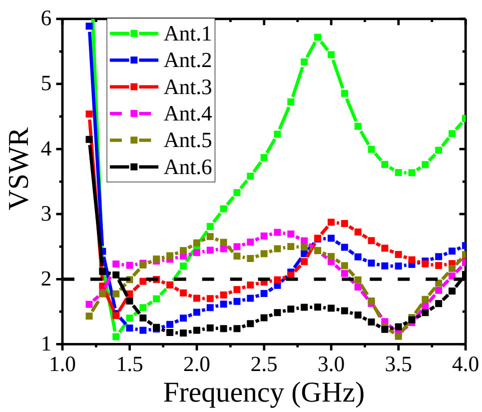
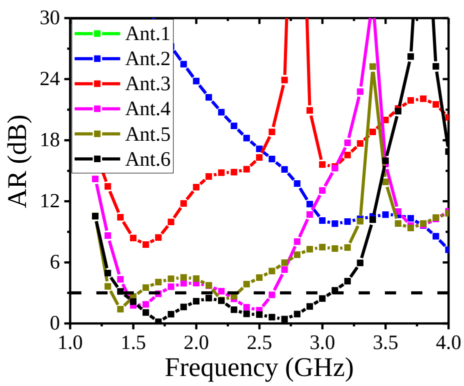


Fig. 2. Design steps of the proposed wide-slot antenna.



(a) VSWR



(b) AR

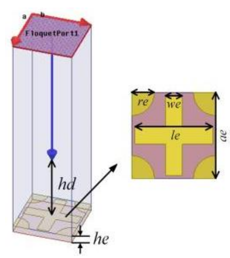
Fig. 3. Simulated results.

C. AMC structure design

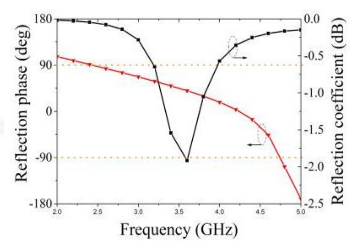
Generally, the gain of the wide-slot antenna is not high with the large slot, thereby introducing serious and unwanted backward radiation in wireless communication system applications. A large metal reflector can be added under the wide-slot antenna to enhance the gain of the antenna [12─13]. However, the profile of the overall antenna will be high, because the distance between the antenna and the metal reflector should be about $1/4\lambda_0$ in order to compensate for the 180° phase difference between the reflected and incident waves. With the reduction in the profile of the overall antenna taken into consideration, we adopt the AMC structure instead of the metal reflector.

AMC is an artificial electromagnetic periodic structure that can imitate the isotropic reflection characteristics of an ideal magnetic conductor. Generally, a subwavelength metal structure is printed on a dielectric substrate with a metal ground plane so that incident waves can achieve isotropic reflection characteristic effectively. In accordance with the principle of isotropic reflection, the reflected and radiated waves on the surface are superimposed in phase, so the distance between the wide-slot antenna and the AMC structure can be reduced to less than $1/4\lambda_0$.

Figure 4 shows the 3D model, reflection phase and coefficient results of the unit cell used in the proposed AMC structure after comparing the performance and size of several types of AMC unit cell. An FR4 substrate with a thickness of *he=1.6 mm* and a loss tangent of 0.02 is chosen, *hd* is the distance between the excitation source and the AMC unit cell. Crossed metal strips are placed in the centre on the upper layer of the substrate, with four quarter circles on the four corners. The lower layer of the substrate is a metal ground plane. The dimensions of the AMC unit cell are given in caption of Fig. 4.



(a) AMC 3D model



(b) Simulated results

Fig. 4. The 3D model and the simulated reflection phase and coefficient of the AMC unit. And the dimensions of the parameters are *ae=15*, *re=4*, *le=14*, *we=3*. (Unit: mm).

AMC structure after comparing the performance and size of several types of AMC unit cell. An FR4 substrate with a thickness of *he=1.6 mm* and a loss tangent of 0.02 is chosen, *hd* is the distance between the excitation source and the AMC unit cell. Crossed metal strips are placed in the centre on the upper layer of the substrate, with four quarter circles on the four corners. The lower layer of the substrate is a metal ground plane. The dimensions of the AMC unit cell are given in caption of Fig. 4.

Generally, the frequency band of the reflection phase on the AMC surface is defined as the isotropic reflection phase band [16]. From Fig. 4, we can see a frequency bandwidth of 2.35 GHz to 4.65 GHz with the reflection phase varying from 90° to −90°. The AMC unit satisfies the in-phase reflection characteristic in the frequency band of interest.

The parametric study has been done for the AMC unit cell in Fig. 5, we can conclude that the parameter *hd* influence the reflection phase obviously, which determines the phase difference between the incident and reflected wave, with the increase of *hd*, the zero reflection phase moves to the higher frequency, but the ±90° phase bandwith decreases. The parameter *le* influences the reflection phase a little, especially at the lower frequency, the reflection phase does not change.

Then, a 6×6 unit cell composing the AMC structure with a size of $90\,mm \times 90\,mm$ is placed under the wide-slot CP antenna, and the distance between them is reduced to about $0.14\lambda_0$ at the centre frequency of 2.805 GHz denoted as *hg=15 mm* as shown in Fig. 6.

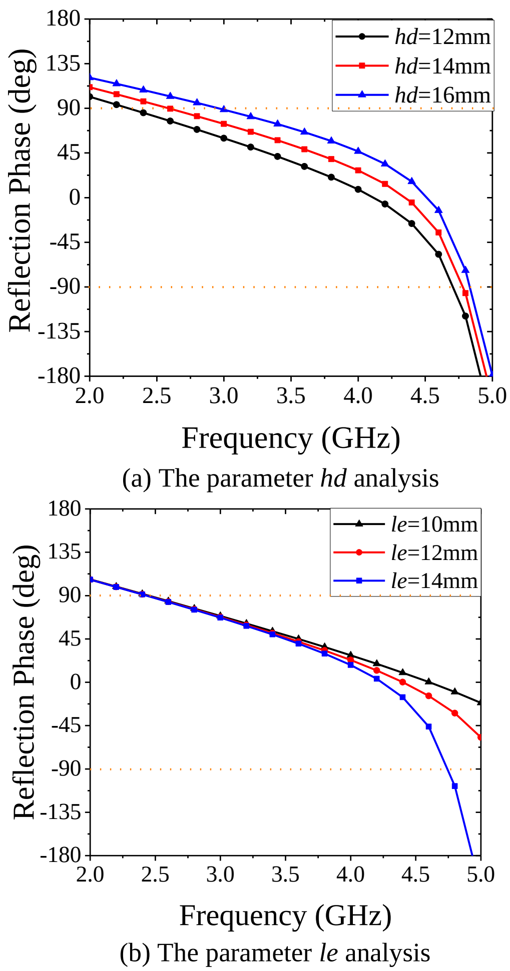


Fig. 5. The parametric analysis of the AMC unit cell.

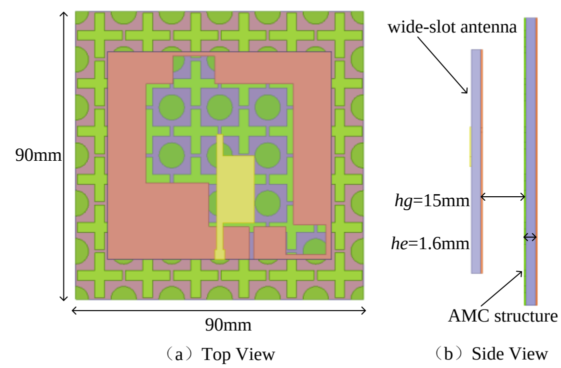
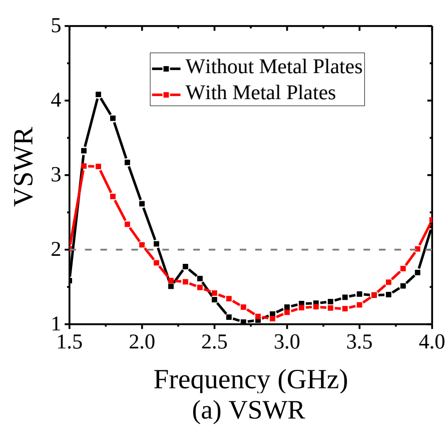
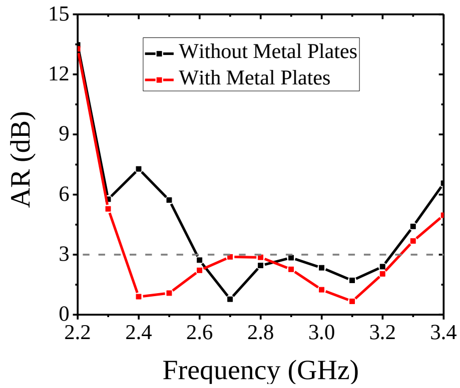


Fig. 6. Top and side views of the AMC antenna.

The simulated VSWR and AR results of the AMC antenna are given in Fig. 7, marked as the plots named without metal plates. The impedance characteristic is good, but the AR bandwidth decreases from 74.1% in Fig. 3(b) to 21.6% (2.6 GHz−3.2 GHz), because the AMC structure has an excellent isotropic reflection phase only near a certain frequency point. Moreover, the distance between the AMC structure and wide-slot antenna is different in wavelength for different frequencies. These conditions have a great impact on the reflected CP waves, thereby reducing the AR bandwidth considerably. Therefore, the AR bandwidth becomes narrower and the CP characteristic becomes worse after the AMC structure is introduced under the bidirectional radiating wide-slot antenna. To further enhance the bandwidth of AR, we introduce four vertical metallic plates around the AMC structure, similar to [20]. The height and length of each vertical plate is *16 mm* and *40 mm*, respectively. Four nylon mount posts with a diameter of *3 mm* are used to fix the antenna which are considered in the simulation.

To get a better insight of the polarization, the E-field of the antenna at 2.8 GHz for various phase (0°, 90°, 180°) observed from +z direction is shown in Fig. 8. The E-field rotates in a clockwise direction, which means a LHCP wave can be obtained.





(b) AR

Fig. 7. Simulated results for AMC antenna with and without vertical metal plates.

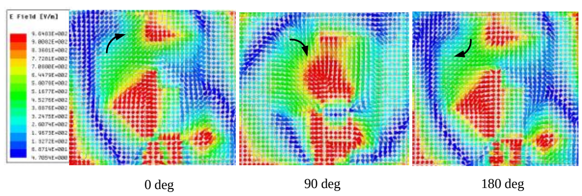


Fig. 8 The rotation of E-field at frequency of 2.8 GHz.

III. EXPERIMENTAL RESULTS

The photo of the fabricated wide-slot antenna with an AMC reflector and four vertical metal plates is shown in Fig. 9 (a). The wide-slot antenna is supported above the AMC structure by four nylon-66 dielectric posts. The performance of the prototype antenna was verified by measuring in a Microwave Anechoic Chamber. The simulated and measured VSWR and AR of the proposed antenna are shown in Fig. 9. The measured AR is generally consistent with the simulated result in the bandwidth of 32.4% (2.35 GHz-3.26 GHz), except that the ARs of two middle frequency points (2.7 GHz and 2.8 GHz) are slightly higher than 3 dB, and the VSWR is less than 2 in the entire ARBW and has an impendance bandwidth of 76% (1.8 GHz-4 GHz). Figure 10 shows the measured gain of the proposed antenna and the simulated gains. From the results, we can see that introducing the AMC reflector can increase the gain effectively. The gain increased by more than 3 dBic over most frequencies compared with the wide-slot antenna without the AMC reflector. The gain of the proposed antenna is greater than 5.5 dBic at the boresight with a peak gain of 7 dBic and an average gain of 6.5 dBic. The measured results prove that the proposed method can enhance the gain of the broadband wideslot CP antenna significantly, along with the decreased profile from $0.25\lambda_0$ to $0.14\lambda_0$. The measured normalised radiation patterns at three frequencies of 2.4 GHz, 2.8 GHz and 3.2 GHz are shown in Fig. 11. Evidently, the proposed antenna with the AMC reflector has a good and stable unidirectional radiation.

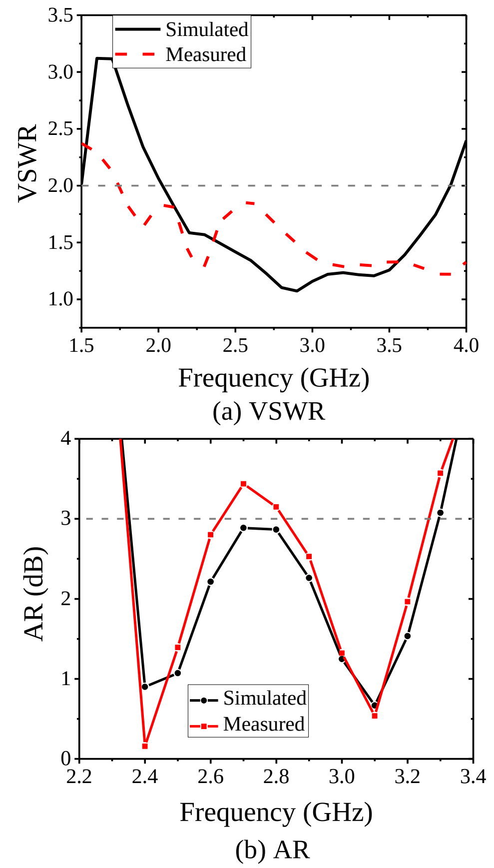


Fig. 9. Simulated and measured results for the proposed antenna.

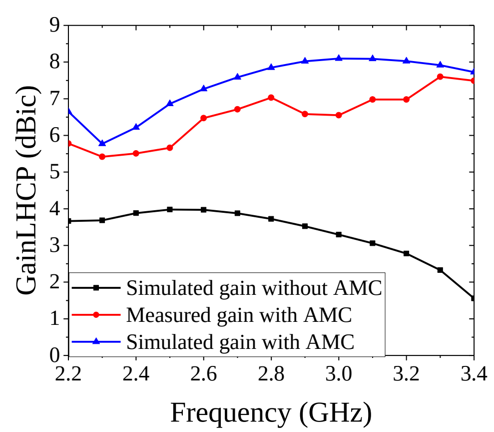


Fig. 10. Gain comparison between the antennas with and without AMC reflector.

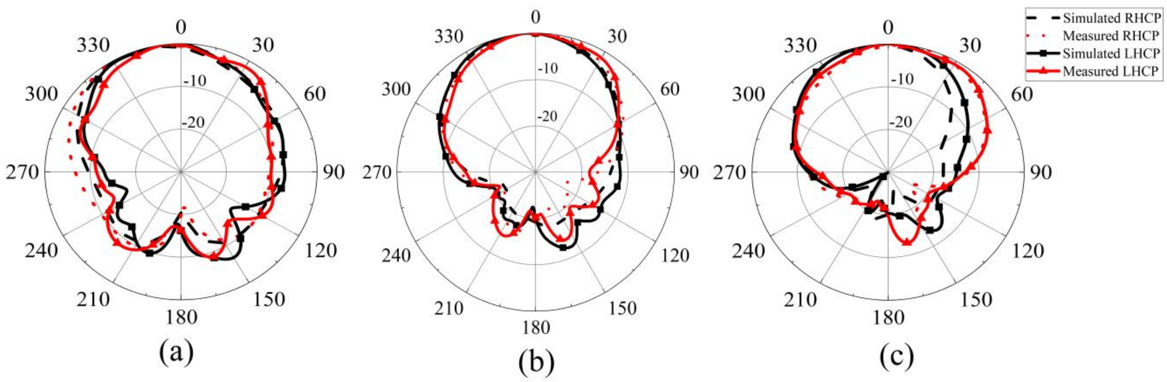


Fig. 11. Simulated and measured radiation patterns of the proposed antenna: (a) 2.4 GHz, (b) 2.8 GHz, and (c) 3.2 GHz.

Table1 summarises the measured performance of the proposed antenna and other similar previously reported antennas in terms of the overall size, ARBW, impedance bandwidth (IBW) and the gain of the antenna. The antenna size is calculated with respect to the CP center frequency. Although the proposed antenna does not have the smallest size, as in [15], it has a wider ARBW and higher gain. Except [15], the proposed antenna has the the smallest profile among the other antennas. The advantage of this design is that the broadband characteristics were achieved with a simple topology, low profile and high gain.

Table 1: Comparison between the proposed antenna and other similar previously reported antennas

Ref.	Size ($\lambda_0 \times \lambda_0 \times \lambda_0$)	ARBW (%)	IBW (%)	Gain (dBi)
[11]	1.23× 1.23 ×0.3	60.9	110	5.1@3GHz
[12]	0.65 × 0.58 ×0.32	80	82	6@4GHz
[13]	0.72 × 0.6 × 0.19	33.2	36.2	7.5@6GHz
[14]	0.54 × 0.54 ×0.08	4.1	15.9	5.5@2.7GHz
Prop.	0.84 × 0.84 ×0.13	32.4	76	7@2.8GHz

IV. CONCLUSION

A novel broadband wide-slot CP antenna with high gain and low profile is proposed, fabricated and measured. The overall antenna is composed of a wide-slot antenna, an AMC structure and four vertical metal plates. The wide-slot antenna can provide broadband CP characteristics, the AMC structure can enhance the gain while reducing the profile of the antenna, and the vertical metal plates can further broaden the ARBW. The measured results show that the proposed antenna can achieve an ARBW of 32.4% (2.35 GHz─3.26 GHz), and an average gain of 6.5 dBic with the profile of $0.14\lambda_0$ at the centre frequency of 2.805 GHz.

REFERENCES

[1] K. Ding, C. Gao, T. Yu, and D. Qu, "Broadband C-shaped circularly polarized monopole antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 2, pp. 785-790, Feb. 2015.

[2] K. Ding, Y. Guo, and C. Gao, "CPW-fed wideband circularly polarized printed monopole antenna with open loop and asymmetric ground plane," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 833-836, 2017.

[3] M. Samsuzzaman, M. T. Islam, and M. J. Singh, "A compact printed monopole antenna with wideband circular polarization," *IEEE Access*, vol. 6, pp. 54713-54725, 2018.

[4] M. Midya, S. Bhattacharjee, and M. Mitra, "Broadband circularly polarized planar monopole antenna with G-shaped parasitic strip," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 4, pp. 581-585, Apr. 2019.

[5] H. Tang, K. Wang, R. Wu, C. Yu, J. Zhang, and X. Wang, "A novel broadband circularly polarized monopole antenna based on C-shaped radiator," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 964-967, 2017.

[6] H. Alsariera, Z. Zakaria, and A. Awang Md Isa, "A broadband P-shaped circularly polarized monopole antenna with a single parasitic strip," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 2194-2198, Oct. 2019.

[7] N. Hussain, H. H. Tran, and T. T. Le, "Single-layer wideband high-gain circularly polarized patch antenna with parasitic elements," *International Journal of Electronics and Communications*, vol. 113, 2020.

[8] U. Ullah and S. Koziel, "A broadband circularly polarized wide-slot antenna with a miniaturized footprint," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 12, pp. 2454-2458, Dec.2018.

[9] T. T. Le, H. H. Tran, and H. C. Park, "Simple-

structured dual-slot broadband circularly polarized antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 3, pp. 476-479, Mar. 2018.

[10] R. Xu, J. Li, J. Yang, K. Wei, and Y. Qi, "A design of U-shaped slot antenna with broadband dual circularly polarized radiation," *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 3217-3220, 2017.

[11] J. G. Baek and K. C. Hwang, "Triple-band unidirectional circularly polarized hexagonal slot antenna with multiple L-shaped slits," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4831-4835, Sep. 2013.

[12] G. Li, H. Zhai, L. Li, and C. Liang, "A nesting-L slot antenna with enhanced circularly polarized bandwidth and radiation," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 225-228, 2014.

[13] U. Ullah, S. Koziel, and I. B. Mabrouk, "A Simple-topology compact broadband circularly polarized antenna with unidirectional radiation pattern," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 12, pp. 2612- 2616, Dec. 2019.

[14] K. Agarwal, Nasimuddin, and A. Alphones, "Wideband circularly polarized AMC reflector backed aperture antenna," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1456-1461, Mar. 2013.

[15] J. Li, H. Huo, J. Chen, S. Zhu, H. Shi, and A. Zhang, "Miniaturised artificial magnetic conductor and its application in unidirectional circularly polarised slot antenna design," *IET Microw. Antenna P.*, vol. 12, no. 12, pp. 1885-1889, 2018.

[16] A. Feresidis, G. Goussetis, and S. Wang, J. Vardaxoglou, "Artificial magnetic conductor surfaces and their application to low-profile high gain planar antennas," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 209-215, Jan. 2005.

[17] N. Hussain, M. Jeong, A. Abbas, T. Kim, and N. Kim, "A metasurface-based low-profile wideband circularly polarized patch antenna for 5G millimeter-wave systems," *IEEE Access*, vol. 8, pp. 22127-22135, 2020.

[18] N. Hussain, S. I. Naqvi, W. A. Awan, and T. T. Le, "A metasurface-based wideband bidirectional same sense circularly polarized antenna," *International Journal of RF and Microwave Computer-Aided Engineering*, no. 3, 2020.

[19] N. Hussain, M. Jeong, A. Abbas, and N. Kim, "Metasurface-based single-layer wideband circularly polarized MIMO antenna for 5G millimeter-wave systems," *IEEE Access*, vol. 8, pp. 130293-130304, 2020.

[20] Y. M. Pan, W. J. Yang, S. Y. Zheng, and P. F. Hu, "Design of wideband circularly polarized antenna using coupled rotated vertical metallic plates," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 42-49, Jan. 2018.