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A small footprint printed cross-dipole antenna with wide impedance bandwidth and circular polarization

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ABSTRACT

Wideband circularly polarized (CP) cross-dipole antennas with flat, cavity and artificial magnetic conductor (AMC) reflectors are proposed. Each proposed antenna consists of a pair of driven dipoles, a pair of vacant-quarter printed rings, and a 50Ω coaxial probe. The boomerang shape has been adopted in the crossed-dipole. This shape makes the design more compact, so it can be a good candidate in the antenna array because of reducing the mutual coupling. All numerical simulation works have been done using the ANSYS electromagnetic (EM) software based on the finite element method (FEM) algorithm. The presented crossed-dipole with a cavity has the best performance compared to ones with conventional flat and AMC grounds. However, the crossed-dipole with the AMC ground is a low-profile structure. Thus, the paper investigates and discusses the results of the proposed strctures thoroughly. The obtained impedance bandwidth (IBW) is 42% (5.1-7.85 GHz) and the axial-ratio bandwidth (ARBW) is 7.72% (5.86-6.32 GHz) for the crossed-dipole with the conventional flat ground (i.e., reflector). Furthermore, the IBW and ARBW for the antenna with the cavity reflector are 50.37% (5.08-8.5 GHz) and 26.4% (5.72-7.46 GHz), respectively. The antenna with the AMC ground has the characterstics of the IBW and ARBW as 38.16% (5.36-7.89 GHz) and 15.16% (5.79-6.74 GHz), respectively. All structures are designed to operate for the C-band and wireless local area networks (WLAN) applications.

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1. INTRODUCTION

The cross-dipole antenna (CDA) has attracted a lot of attention among researchers in the last decade owing to its capability to generate almost pure circular polarization at a wide range of frequencies. As known, antennas with circular polarization are in high demand since it can receive and transmit signals at any orientation in space. Thus, mobile wireless communications and satellite applications cannot indispensible of these types of antenna to guarantee a good connection between two wireless ends. Historically, the CDA was invented in the 1930s, following the invention from Brown which was the first CDA under the name of "turnstile antenna". After that, in 1940s, the "superturnstile" antenna was developed with a wider impedance bandwidth design compared with the previous ones [1], [2]. In the1960s, a new design of CDA used a single feed, where the CDA had arms with unequal lengths. This aids to balance the phase difference between the two components of electric fields to generate perfect circular polarization signals with an axial ratio close to 0 dB. In other words, the condition was that both dipoles had equal real part admittance but different input angle by 90° leading into generation of circular polarization [3]. In addition, in the 2010s, the CDA was fed with two separated ports, having 90° phase shift needed as a phase difference between the two ports, a process of generation of circular polarization signals [4].

The most important criteria in the CDA is the circularity of polarization because the circular polarization antennas are the solutions for prohibiting multipath effects and alleviating the polarization mismatch problems as known among the wireless communication community. Here, some examples for the use of the circular polarization antennas are recalled for the sake of integrity such as: navigation satellite system global position system (GPS), broadcasting services (BDS) and global navigation satellite systems (GNSS) [5]-[7], wireless local area network (WLAN) [8] and radio frequency identification (RFID) [9], [10], wireless personal area network [11] and worldwide interoperability (WiMax) for microwave access [12]. Therefore, the cross-dipole antennas are sophisticated for the present and future communication systems. Moreover, this type of antennas can generate isotropic, dual, omnidirectional radiation patterns with circular polarization capabilities. Also, the cross-dipole antenna is convenient for single and multiband as in [12], a wideband as well [13], and broadband operation as in [14].

In the recent years, different kinds of wide band CP have been designed and fabricated, utilizing many types of radiated structures [12]-[42]. For example, the CDA with dielectric resonant antennas were reported, covering a wide band of frequencies and being as a stair shape [15]; a rectangular CDA with two half split cylindrical dielectric waveguides, operating at the higher resonant order modes to increase the bandwidth and to enhance the circularity of polarization was proposed in [16]; exciting dual modes in the dielectric resonant antenna (DRA) by inserting a pair of L-shaped slots is found in the literature [14], providing a good circular polarization performance. Alternatively, antenna aperture backed to artificial magnetic conductors artificial magnetic conductors (AMCs) was proposed in [17] to improve the antenna performance and to reduce the overall size. As found in the literature and undoubtedly, antennas that can cover a wide range of frequencies with circular polarization characteristics are the CDA, thanks to its infrastructure, consisting of a pair of dipoles with 90 degree phase shift, in particular, the vacant-quarter ring as proposed in [18]. Hence, researchers made a lot of efforts in such type of antennas [18]-[38].

To make the antenna more usable, many modifications have been made to widen the circular polarization bandwidth using parasitic elements. The CDA was first designed in 2008 with strip-line transmission lines which had 15.6% axial ratio bandwidth ARBW in [18]. Baik *et al.* proposed in 2011 the same antenna design with open loop parasitic elements to enhance -10 dB the impedance bandwidth (IBW) and 3 dB ARBW in [19]. Subsequently, Feng *et al.* [20] have used a single parasitic cross-loop. A cross strip-dipole with a pair of dipoles to get wide band CP in [21], the same author enhanced his design by adding four square-slot patches to provide the broadband CP [22]. Nguyen *et al.* [23] have used a dual cavity structure to widen the CP wideband. Ta and Park has used in [24] a single cavity and magneto-electric (ME), which has good influences on the 3 dB antenna reflection (AR). Coupled rotated dipoles is presented in [25]. Also, a simple single parasitic element with utilizing a bias circuit to turn on-off the parasitic elements is introduced in [26], [27]. Other types and shapes to design the main arms of cross-dipole antennas to widen the ARBW and IBW were reported in [28]-[39]. Tran and Park [28] have used the bowtie shape with two slot-made etched on the main arms to make come up with a structure radiating at dual frequencies with the IBW and 3 dB ARBW of 57% and 51%, respectively. In [19], the same shape in the previous reference, the author has utilized four parasitic patches where the results are seemingly enhanced to have the IBW of 47.73% and 3 dB ARBW of 42.8%. More enhancements have been obtained on the IBW and ARBW compared to the previous references mentioned above. The obtained IBW and the 3 dB ARBW were 93.1% and 90.9%, respectively. This extraordinary enhancement is owing to using the sequentially rotated feeding lines and unequal cross-slots [29]. In addition, the trapezoidal bowtie CD antennas are presented in [31]. On the other hand, different shapes of radiating cross-dipole antenna arms have been reported as in [32] and are used with the elliptical shape, giving good results in front-to-back ratio (FBR), IBW and 3 dB ARBW when using the reflector cavity. Moreover, there are more different shapes are presented in [33]-[35]. The rectangular arm of the CDA, rectangular arms with extension in the other side of the substrate connected by via to decrease size of the antenna and four step rectangular patch with adding dielectric slab above the irregular ground plane (reflector) is also proposed. All of those antennas are designed for one aim which is to enhance the IBW and 3 dB ARBW.

Subsequently, the artificial magnetic conductor AMC is presented in the literature with the cross-dipole antennas to reduce the height which is equal to a quarter wavelength in conventional CDA. Using the AMC operates to alleviate the need to add this space between dipole’s arms and the ground to make the interference between signal radiating from the dipole’s arms and bouncing from the ground constructive. Then, the AMC has in-phase reflection, leading into adding the arms and ground adjacently. Additionally, the AMC gives new resonant frequencies, improving the impedance bandwidth [36]-[38]. The radiation arms were rectangular-shaped with parasitic strips to get a broadband AR where the two cross-asymmetric dual arms are used to radiate dual-band associated with T-shape slits etched on the unit cell patch of AMC structure. Most AMC structures use vias (pins) to connect the top conductor with the ground, but there is not few works using the AMC without vias.

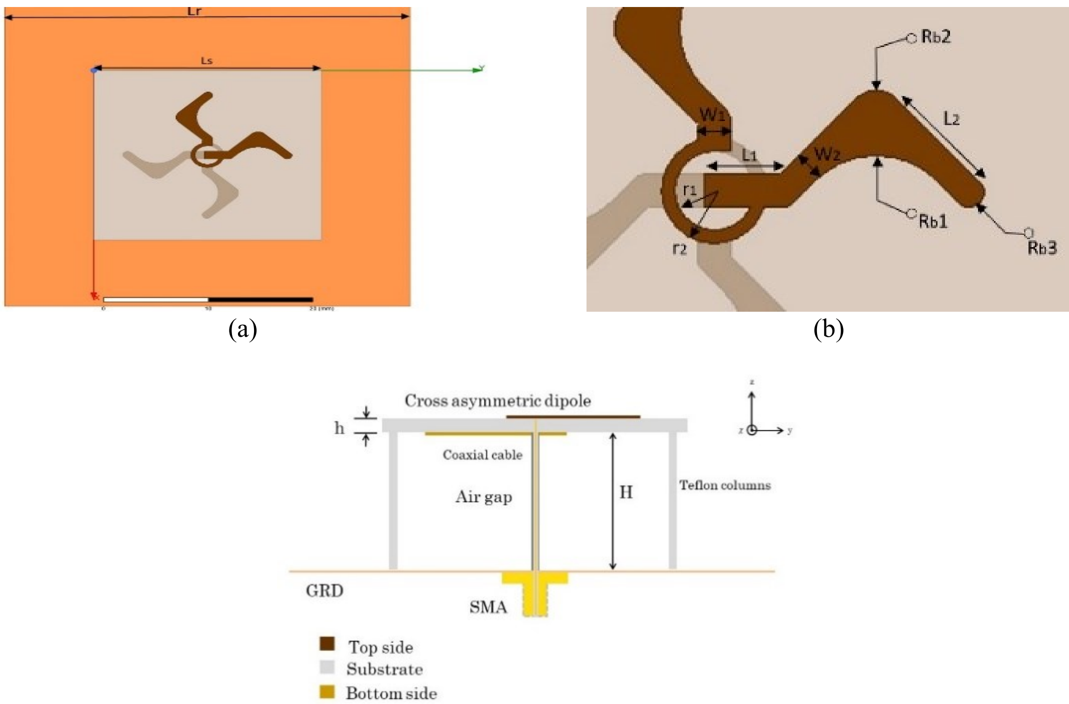
In this paper, we propose a new design of the printed cross-dipole antenna with new shapes called boomerang shapes for sub-5G applications. The proposed antenna has a very good impedance bandwidth and an acceptable 3 dB ARBW that are extremely useful for antenna arrays. Section 2 presents the process of the proposed antenna design. In section 3, the main keys of the antenna design is introduced. Finally, section 4 concludes this research paper.

2. ANTENNA DESIGN

2.1. Antenna configuration and antenna operation

The cross-dipole structure is adopted here in this research study because of its advantage as mentioned in the previous section. The classic shape in [18] was presented in many research efforts. Recently, a wideband CDA can be gotten after many modifying the main arms or by adding parasitic elements close to the main radiators to produce several resonance frequencies [19]-[22], [24]-[27], [29]-[31]. Here, the boomerang shapes to design dipole arms are employed. As will be seen later, the boomerang arms aid to make the structure resonating at several frequencies and leading into a wideband structure compared to other designs [28]-[35].

As depicted in Figure 1 and Table 1, the antenna is a pair of boomerang arms connected together by the feeding network as driven elements. The feeding network consists of a pair of vacant quarter rings [18]-[39], and they are used to connect the two cross boomerang arms with $\lambda_g/4$ length (λ_g is the guided wavelength at the design frequency). Each side of the substrate has a single vacant quarter ring printed on its faces. The substrate used in the design has 0.5 mm thickness where its type is FR4 (ε_r is 4.4 with loss tangent of 0.02). The semi-rigid coaxial cable of 50 Ω allows a 180° phase different between the two arms of each dipole. The inner conductor of the SMA is connected to the top arm and the outer conductor is connected to the bottom arm. The ground plane is placed on height H of $0.25\lambda_0$ (λ_0: free space wavelength at 6 GHz) from the main radiator. The ground is a square shape and its side length Lr is equal to $0.785\ \lambda_0$, in which this size is optimized to mitigate the ground effects on the antenna performance, and keeping the overall size is acceptable. Table 1 summarizes the antenna dimensions.



(a) (b)

(c)

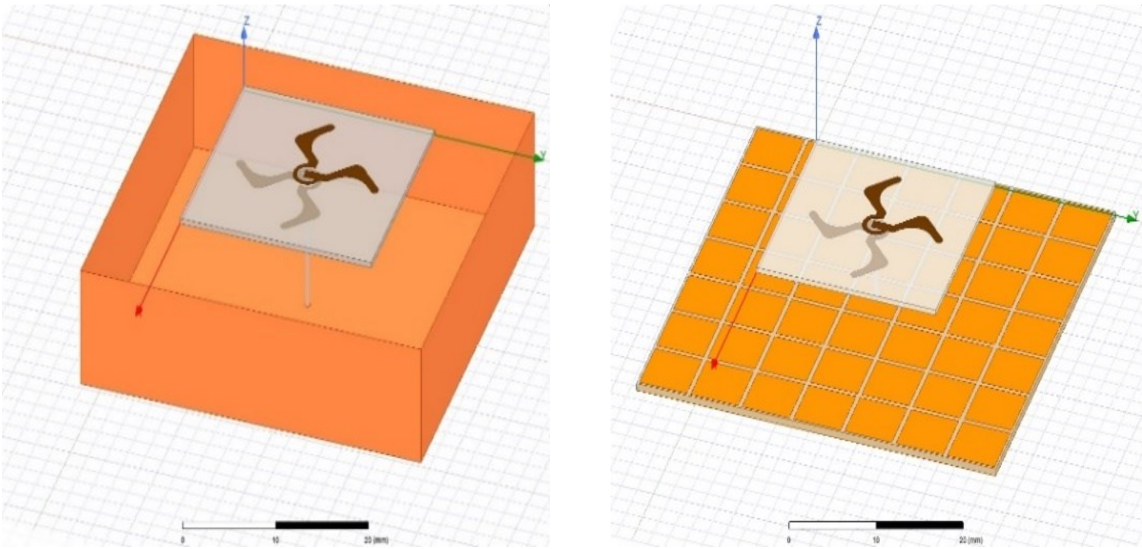
Figure 1. The geometrical structure of the proposed antenna type-I: (a) top view, (b) magnifying view of arms on the top and (c) side view

Table 1. A summary of the antenna dimensions (unit: mm)

Lr	Ls	W1	W2	L1	L2
39.25	22	1		2.3	3.55
r1	r2	Rb1	Rb2	Rb3	H
1.1	1.6	2.6	0.9	0.45	12.5

There are two equal input admittances for both arms of the two cross dipole antennas with a 90° phase shift difference to obtain the CP associated by coaxial cables and the phase sequence on the four arms will be $(0^{\circ}. 90^{\circ}, 180^{\circ} and\ 270^{\circ})$. The -10 dB IBW is 2.24 GHz with a center frequency of 6.38 GHz and 3 dB ARBW is 0.63 GHz with a center frequency of 5.9 GHz. Moreover, the most important property is the craving shape that introduces 25% length reduction than all the other CDA shapes. This reduction form is very useful in antenna arrays to increase space between antennas which in turn reduces the mutual coupling and increase the antenna efficiency.

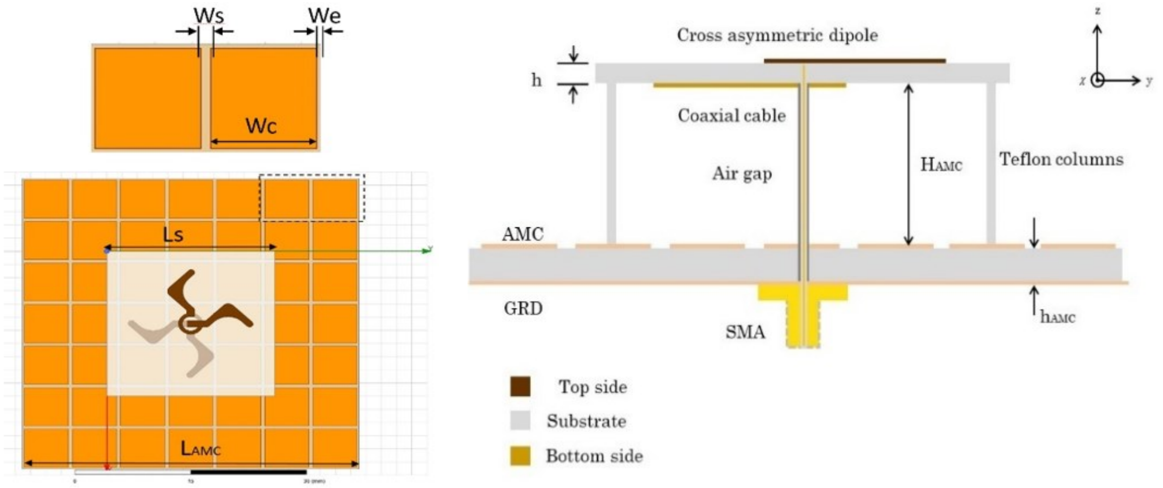
In general, the proposed antenna type-I offers good results. However, this antenna does not fulfill our goals in this research. Enhancing the performance while keeping or reducing the size is an outstanding key. The research is committed to do so. The first way is to employ a cavity with four side walls. Walls prohibit signals to spread in a wider space, so the resulting radiation beam becomes narrower and the gain becomes larger. This antenna is type-II as shown in Figure 2(a). It produces more consistent pattern and greater gain with a comparison to traditional reflector patterns [23]. The second enhancement is the use of an artificial magnetic conductor AMC, called antenna type-III, as depicted in Figure 2(b).



(a) type-II (b) type-III

Figure 2. 3D views of the geometrical structures of the proposed antennas

Cavity walls have height of 11.25 mm which is about $0.225\lambda_0$ at 6 GHz and the same reflector widths of the antenna type-I. These four walls are made of conducting materials. In order to use an alternative way but keeping the same antenna behavior when using bulky cavities is to use a 2D sheet of the AMC surface operating as a reflector. The resulting antenna is type-III, displayed in Figure 2(b). the AMC surface consists of 7×7 unit-cells, printed on the top side of the lower substrate, with a thickness of 0.708 mm where the martial type is Rogers RT/duroid 6010/6010LM (tm) (εr=10.2 and tanδ=0.0023). Each unit-cell has a side length of Wc=6 mm about $0.12\lambda_0$, the spacing between the cells is Ws=0.5 mm and the edge spacing is We=0.25 mm then the overall reflector size is 46×46 mm^2. The AMC reflector is placed with a height of HAMC=6 mm about $0.12\lambda_0$ less by 50% than the antenna Type-I and type-II in the vertical dimension. This is one of the aims to use the AMC surfaces (i.e., to make a small microstrip antenna) [39], as shown in Figure 3.



(a) (b)

Figure 3. The proposed antenna type-III: (a) top view and (b) side view

2.2. Antenna mechanism

The evolution of all proposed antennas presented here is demonstrated precedingly to show up the mechanism for improving bandwidths. The first two enhanced antennas with boomerang arms types-I and II use the cavity to stop or at least to highly mitigate the backward radiation, especially a cavity with side walls, while the proposed antenna type-III is the CDA boomerang type with an AMC reflector. The antenna type-III has good reflection coefficient compared to ones in [18]-[27]. It is a good alternative to other arm shapes like bowtie CDA which have a wide impedance bandwidth as known compared to other shapes of the CDA [28]-[39], see Table 2 that summarizes the comparison between the proposed antennas and preceding works in the literature.

Table 2. A comparison between the proposed antennas with previous works in the literature

Ref. Antenna	Size (λ0)	Antenna's Structure	Structure -10 dB IBW GHz	3-dB ARBW GHz	Max Gain (dBi)
[19]	1.05×1.05×0.24	Crossed dipole +Parasitic Loop Resonators	0.93	0.75	8
[20]	1.1×1.1×0.28	Crossed dipole + Cross loop + Squared cavity reflector	3.2	2.79	8
[22]	1.04×1.04×0.26	Crossed dipole + Parasitic elements+ Conventional reflector	1.41	1.23	7.2
[23]	0.57×0.57×0.24	Crossed dipole + Dual squared cavity reflector	2.8	2.5	8.5
[26]	0.79×0.79×0.27	Crossed dipole + Simple single parasitic element	2	1.7	8.2
[28]	0.88×0.88×0.23	Crossed dipole + Squared cavity reflector	1.42	1.4	9.6
[30]	1.1×1.1×0.4	Crossed dipole + bowtie dipole loaded with three of four sitparasitic	3.82	4.07	8.6
[32]	Circular ground plane	Crossed dipole +elliptical dipole +composite cavity	2.05	1.87	9
[33]	0.45×0.45×0.24	Crossed dipole + Conventional reflector	1.23	0.6	6.8
Proposed I	0.78×0.18×0.27	Crossed dipole boomerang arms	2.75	0.47	7.4
Proposed II	0.78×0.18×0.27	Crossed dipole boomerang arms + square cavity radiator	3.42	1.74	8.3
Proposed III	0.78×0.18×0.13	Crossed dipole boomerang arms + AMC reflector	2.53	0.95	7.7

3. DISCUSSION OF THE RESULTS

To analyze and evaluate the performance of the proposed antennas a high frequency structure simulator (HFSS) software from ANSYS Company was utilized. The HFSS relies on the finite element method FEM algorithm to analyze designs. As the electrical size of a structure increases, its time evaluation becomes larger and burden. The first step in the design is to make the antenna having good matching at the design frequency. A mechanism of the impedance matching is qualitatively, where the equivalent circuit model of the antenna is provided in Figure 4. The symbol Yin characterizes the total input admittance of the proposed antennas, YA means the antenna without the interlaced rectangular patches, whereas $C1$ and $C2$ mean the parallel-plate capacitors as seen in Figure 5.

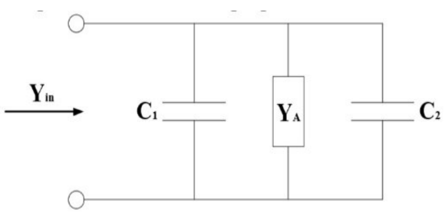


Figure 4. Equivalent circuit model of the antennas

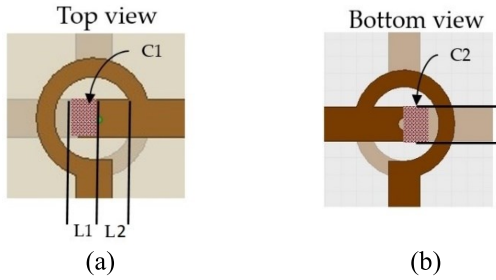


Figure 5. Structure of overlapped rectangular patch: (a) top view and (b) bottom view

The capacitance of parallel-plate capacitors $C1$ and $C2$ can be considered when the density of electrical charge on the plates is uniform, and neglect the fringing fields at the edges. From Figure 5, the input admittance of the proposed antennas can be indicated by (1).

$$Yin = YA + j\omega(C1 + C2) \approx YA + 1 \frac{2j\omega\varepsilon_r\varepsilon_0 WL1}{h} \quad (1)$$

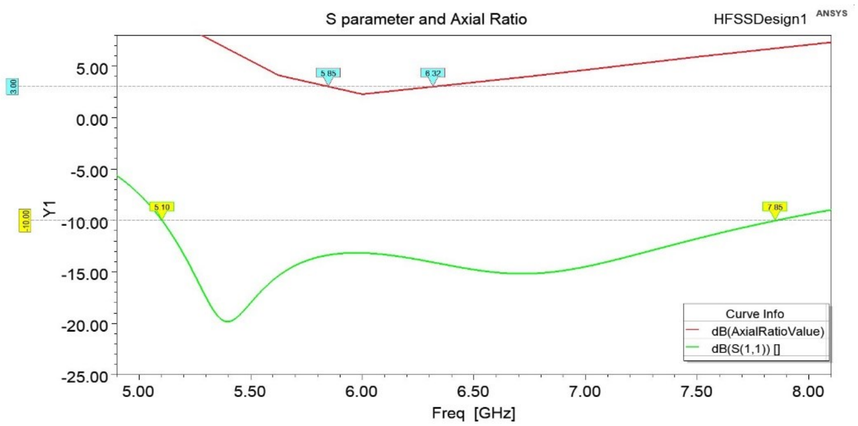
The approximation is derived from the small slot on the rectangular bottom patch that reduces the overlapping area of the condensers of the two parallel plates. It is shown in (1) that the rectangular patch width W and length L1 define the antenna input admittance Yin. Therefore, these two parameters can be tuned to the impedance characteristic of the antenna to achieve a good impedance.

The simulated |S11| -10 dB IBW and 3 db-AR results of the antenna type-I are presented in Figure 6(a). Firstly, as can be seen, we see the wideband impedance bandwidth of this antenna and also have an acceptable CPBW without loading any parasitic elements or doing any enhancement. It was about -10 dB IBW of 42.47% (5.1-7.85 GHz) and the 3 dB ARBW of 7.72% (5.85-6.32 GHz). In addition to that, the simulated gain was about 7.4 dBi with efficiency of 97.37%, and the overall size is about $(0.78\times0.78 \times0.27\lambda_0)$.

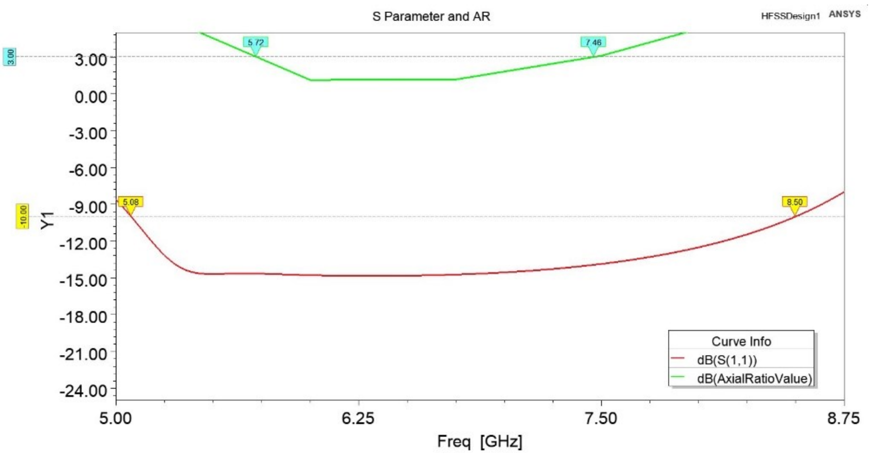
Then, the CDA with square-box cavity is analyzed where the back-lobe radiation is highly attenuated. In other words, this structure can offer better back-lobe reduction compared to the CDA that has only sheet reflector (i.e., flat ground plane). This increase in the efficiency is primarily due to surface wave suppression and the blocking of diffracted waves along the edge of the ground plane, so, the antenna type-II introduces very good results with wideband impedance bandwidth where the -10 dB IBW of 50.37% (5.08-8.5 GHz) and the 3 dB ARBW of 26.4% (5.72-7.46 GHz), as shown in Figure 6(b). The simulated gain was about 8.3dBi with efficiency of 97.65%. there is no change in the overall size.

Finally, the proposed antenna type-III is studied numerically to obtain its results. Before integrating the conventional CDA into the AMC, we should analyze and check the performance of the AMC layer. To do so, a single unit-cell is placed in a cavity structure to mimic its periodicity. This method aids to decrease the solution time and offers results close to the original structure. The AMC unit-cell can be modeled as an identical parallel resonator with a resonant frequency of f =1/(2π(LC)1/2), here C and L represent equivalent capacitance and inductance, respectively. The range of acceptable phases offered by the AMC is from -90° to 90° [36]. Figure 7 shows the reflection phase of the AMC structure. For further analysis of the parameter effect on the reflection coefficient phase, complete numerical analysis of the AMC cell has been conducted by simulation software HFSS. As can be seen, this phase range can cover a wideband of frequencies.

The overall 38.19% (5.36-7.89 GHz) and the 3 dB ARBW is about 15.16% (5.79-6.74GHz). The vertical size was reduced to half, thanks to the use of the AMC layer. It is clear that the IBW less than the IBW of the Antenna type-I due to the use of the AMC substrate martial. Generally, the AMC layer considers lossy type type because of its high permittivity but we can obviously see the enhancement in CPAR bandwidth, as shown in Figure 8.



(a)



(b)

Figure 6. Simulated results of the antenna reflection coefficient and AR: (a) type-I and (b) type-II

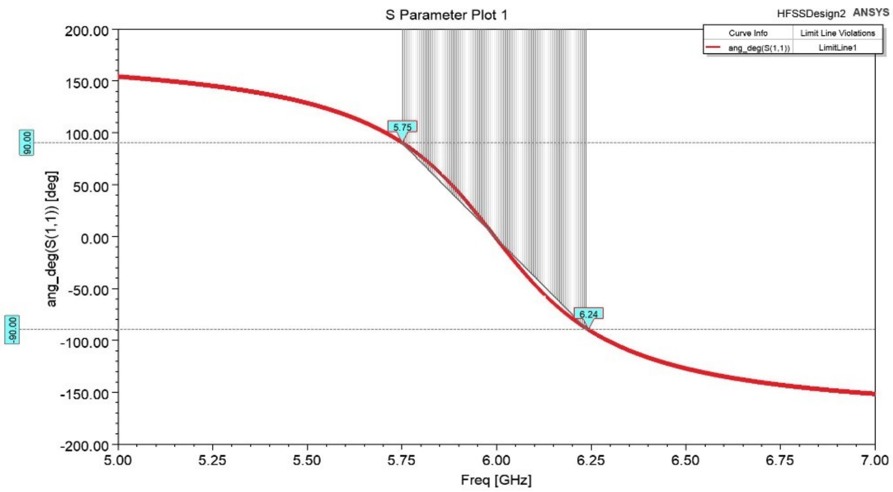


Figure 7. Reflection phase of the AMC structure

Figure 9 shows the simulated radiation patterns at 6 GHz in xoz-plane and yoz-planes. The patterns in xoz-plane are symmetrical to those in yoz-plane. The antenna generates unidirectional CP patterns in a boresight direction. The right-hand circular polarization (RHCP) is higher than the left-hand circular polarization (LHCP), generating exceptional RHCP radiation.

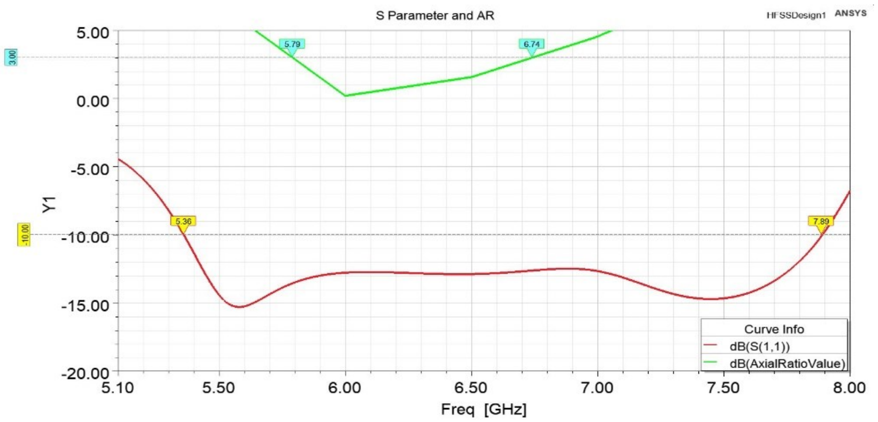
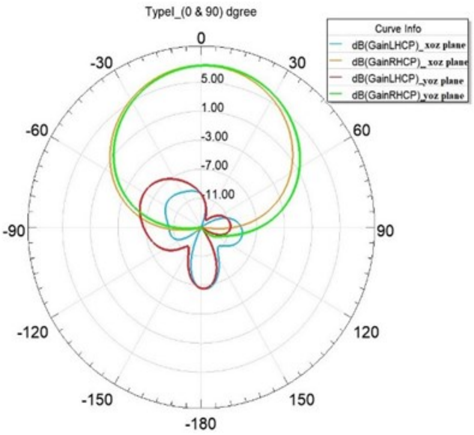
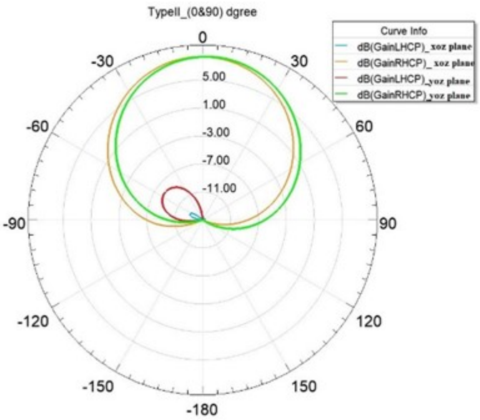


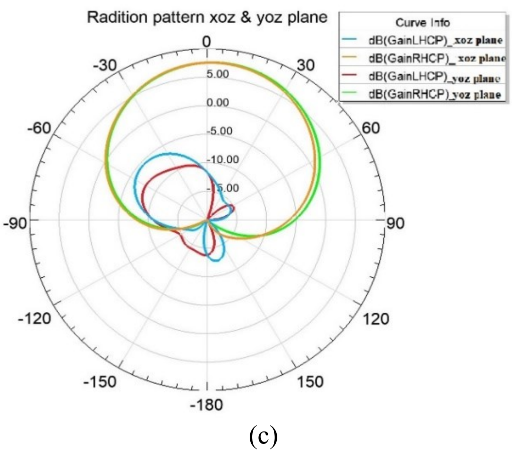
Figure 8. Simulated results of the antenna reflection coefficient and AR type-III



(a)



(b)



(c)

Figure 9. Simulated radiation pattern of the proposed CP CDA antenna at 6 GHz: (a) type-I, (b) type-II and (c) type-III

4. CONCLUSION

The proposed printed cross dipole antennas with new graceful arm's shape, consist of a pair of driven crossed boomerang dipoles that gives wideband circularly polarized (CP) cross-dipole antennas. It proposed three antennas, the best simulation results indicate for antenna III, that exhibits wideband CP characteristics with an impedance bandwidth (IBW) of 50.37% (5.08-8.5 GHz) and axial-ratio bandwidth (ARBW) of 26.4% (5.72-6.46 GHz) for cavity reflector. This antenna gave a good IBW and and gave the less length arm comparing with all others proposed CDA. So, the antenna has been more compact, this merit it will be very useful in array antenna by reducing mutual coupling and increasing the gain in antenna arrays.

REFERENCES

[1] G. Brown and J. Epstein, "A pretuned Turnstile antenna," *Electron*. vol. 18, pp. 102-107, June 1945.
[2] P. H. Smith, "Cloverleaf' antenna for F.M. broadcasting," *Proceedings of the IRE*, vol. 35, no. 12, 1947, pp. 1556-1563, doi: 10.1109/JRPROC.1947.230912.
[3] M. F. Bolster, "A new type of circular polarizer using crossed dipoles," *IRE Trans. Microwave Theory Tech.*, vol. 9, no. 5, pp. 385-388, Sept. 1961, doi: 10.1109/TMTT.1961.1125358.
[4] H. D. Hristov, H. Carrasco, R. Feick, and G. S. Kirov, "Broadband two-port X antenna array with flat reflector for polarization diversity applications," *Microwave and Optical Technology Letters*, vol. 52, no. 12, pp. 2833-2837, 2010, doi: 10.1002/mop.25616.
[5] J. Zhang, H. Yang and D. Yang, "Design of a New High-Gain Circularly Polarized Antenna for Inmarsat Communications," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 350-353, 2012, doi: 10.1109/lawp.2012.2191382.
[6] J. M. Baracco, L. Salghetti-Drioli, and P. de Maagt, "AMC low profile wideband reference antenna for GPS and GALILEO systems," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 8, pp. 2540-2547, 2008, doi: 10.1109/TAP.2008.927547.
[7] S. X. Ta, S. Member, H. Choo, I. Park, and R. W. Ziolkowski, "Multi-Band, Wide-Beam, Circularly Polarized, Crossed, Asymmetrically Barbed Dipole Antennas for GPS Applications," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 11, pp. 1-6, 2013, doi: 10.1109/TAP.2013.2277915.
[8] S. X. Ta, I. Park, and R. W. Ziolkowski, "Circularly polarized crossed dipole on an HIS for 2.4/5.2/5.8-GHz WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 12. pp. 1464-1467, 2013, doi: 10.1109/LAWP.2013.2288787.
[9] Y. F. Lin, Y. K. Wang, H. M. Chen, and Z.-Z. Yang, "Circularly Polarized Crossed Dipole Antenna With Phase Delay Lines for RFID Handheld Reader," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 3, pp. 1221-1227, 2012, doi: 10.1109/tap.2011.2180319.
[10] S. X. Ta, H. Choo and I. Park, "Planar, Lightweight, Circularly Polarized Crossed Dipole Antenna for Handheld UHF RFID Reader," *Microwave and Optical Technology Letters*, vol. 55. no. 8, pp. 1874-1878, 2013, doi: 10.1002/mop.27674.
[11] Y. L. Guoping Pan, "Isotropic Radiation From a Compact Planar Antenna Using Two Crossed Dipoles," I*EEE Antennas And Wireless Propagation Letters*, pp. 1338-1341, 2012, doi: 10.1109/LAWP.2012.2227450.
[12] S. X. Ta and I. Park, "Dual-band low-profile crossed asymmetric dipole antenna on dual-band AMC surface," *IEEE Antennas and Wireless Propagation Letters*, vol. 13. pp. 587-590, 2014, doi: 10.1109/LAWP.2014.2312950.
[13] J. Wen, Y. C. Jiao, Y. X. Zhang, and J. Jia, "Wideband circularly polarized dielectric resonator antenna loaded with partially reflective surface," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 29, no. 12, 2019, doi: 10.1002/mmce.21962.
[14] R. Kumar, "A new dual-mode wideband circularly polarized dielectric resonator antenna," *IEEE Antennas & PropagatIon Magazine*, 2019, doi: 10.1002/mmce.21150.
[15] S. Fakhte, H. Oraizi, R. Karimian, and R. Fakhte, "A New Wideband Circularly Polarized Stair-Shaped Dielectric Resonator Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1828-1832, 2015, doi: 10.1109/tap.2015.2392131.
[16] G. Varshney, V. S. Pandey, R. S. Yaduvanshi, and L. Kumar, "Wide Band Circularly Polarized Dielectric Resonator Antenna With Stair-Shaped Slot Excitation," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 3, pp. 1380-1383, 2017, doi: 10.1109/tap.2016.2635619.
[17] K. Agarwal, Nasimuddin, and A. Alphones, "Wideband Circularly Polarized AMC Reflector Backed Aperture Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 3, pp. 1456-1461, 2013, doi: 10.1109/tap.2012.2227446.
[18] J. W. Baik, K. J. Lee, W. S. Yoon, T. H. Lee, and Y. S. Kim, "Circularly polarized printed crossed dipole antennas with broadband axial ratio," *Electron*. *Lett.*, vol. 44, no. 13, pp. 785-786, Jun. 2008, doi: 10.1049/el:20080794.
[19] J. W. Baik, T. H. Lee, S. Pyo, S.M. Han, J. Jeong and Y. S. Kim, "Broadband circularly polarized crossed dipole with parasitic loop resonators and its arrays," *IEEE Trans. Antennas Propag.*, vol. 59, pp. 80-88, 2011, doi: 10.1109/TAP.2010.2090463.
[20] G. Feng, L. Chen, X. Xue, and X. Shi, "Broadband Circularly Polarized Crossed-Dipole Antenna with a Single Asymmetrical Cross-Loop," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, no. 2, pp. 3184-3187, 2017, doi: 10.1109/LAWP.2017.2767700.
[21] L. Wang, W. X. Fang, Y. F. En, Y. Huang, W. H. Shao, and B. Yao, "Wideband Circularly Polarized Cross-Dipole Antenna with Parasitic Elements," *IEEE Access*, vol. 7, pp. 35097-35102, 2019, doi: 10.1109/ACCESS.2019.2904658.
[22] L. Wang, W. X. Fang, W. H. Shao, B. Yao, Y. Huang, and Y. F. En, "Broadband circularly polarized cross-dipole antenna with multiple modes," *IEEE Access*, vol. 8, pp. 66489-66494, 2020, doi: 10.1109/ACCESS.2020.2981050.
[23] T. K. Nguyen, H. H. Tran, and N. Nguyen-Trong, "A Wideband Dual-Cavity-Backed Circularly Polarized Crossed Dipole Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 3135-3138, 2017, doi: 10.1109/LAWP.2017.2764923.

[24] S. X. Ta and I. Park, "Crossed dipole loaded with magneto-electric dipole for wideband and wide-beam circularly polarized radiation," *IEEE Antennas Wirel. Propag. Lett.*, vol. 14, pp. 358-361, 2015, doi: 10.1109/LAWP.2014.2363944.
[25] Z. Zhao, Y. Li, L. Wang, Z. Tang, and Y. Yin, "Design of broadband circularly polarized antenna via loading coupled rotated dipoles," *Microw. Opt. Technol. Lett.*, vol. 61, no. 2, pp. 425-430, 2019, doi: 10.1002/mop.31586.
[26] H. H. Tran, I. Park, and T. K. Nguyen, "Circularly Polarized Bandwidth-Enhanced Crossed Dipole Antenna with a Simple Single Parasitic Element," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 1776-1779, 2017, doi: 10.1109/LAWP.2017.2676165.
[27] H. H. Tran, N. Nguyen-Trong, T. K. Nguyen, and A. M. Abbosh, "Bandwidth Enhancement Utilizing Bias Circuit as Parasitic Elements in a Reconfigurable Circularly Polarized Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 8, pp. 1533-1537, 2018, doi: 10.1109/LAWP.2018.2853193.
[28] H. H. Tran and I. Park, "Wideband Circularly Polarized Cavity-Backed," *IEEE Trans. Antennas Propag.*, vol. 15, pp. 358-361, 2016, doi: 10.1109/LAWP.2015.2445939.
[29] D. Wu, Z. Y. Zhang, L. Ji, L. Yang, G. Fu, and X. Shi, "Wideband circularly polarized cross bowtie dipole antenna with axial-ratio bandwidth enhancement," *Prog. Electromagn. Res. C*, vol. 72, no. February, pp. 65-72, 2017, doi: 10.2528/PIERC17011503.
[30] G. Feng, L. Chen, X. Wang, X. Xue, and X. Shi, "Broadband circularly polarized crossed bowtie dipole antenna loaded with parasitic elements," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 1, pp. 114-117, 2018, doi: 10.1109/LAWP.2017.2777442.
[31] W. J. Yang, Y. M. Pan, and S. Y. Zheng, "A Low-Profile Wideband Circularly Polarized Crossed-Dipole Antenna with Wide Axial-Ratio and Gain Beamwidths," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3346-3353, 2018, doi: 10.1109/TAP.2018.2829810.
[32] L. Zhang *et al.*, "Single-feed ultra-wideband circularly polarized antenna with enhanced front-to-back ratio," *IEEE Trans. Antennas Propag.*, vol. 64, no. 1, pp. 355-360, 2016, doi: 10.1109/TAP.2015.2501844.
[33] J. Ren, X. Liang, J. Geng, W. Zhu and R. Jin, "A wideband circularly-polarized crossed dipole antenna," *2017 IEEE 6th Asia-Pacific Conf. Antennas Propagation, APCAP 2017 - Proceeding*, vol. 13, 2018, pp. 1-3, doi: 10.1109/APCAP.2017.8420986.
[34] Z. Yang, X. H. Wang, L. Kang, H. Wang, J. Bao and X. Shi, "A broadband circularly polarized antenna based on cross-dipoles," *Prog. Electromagn. Res. Lett.*, vol. 62, no. June, pp. 91-96, 2016, doi: 10.2528/PIERL16060601.
[35] W. Yang, Y. Pan, S. Zheng, and P. Hu, "A Low-Profile Wideband Circularly Polarized Crossed-Dipole Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 2126-2129, 2017, doi: 10.1109/LAWP.2017.2699975.
[36] W. He, Y. He, L. Zhang, and S. W. Wong, "An Improved Broadband Circularly Polarized Cross-Dipole Antenna with An AMC Reflector," *2019 IEEE Int. Conf. Microwaves, Antennas, Commun. Electron. Syst. COMCAS 2019*, pp. 2019-2021, 2019, doi: 10.1109/COMCAS44984.2019.8958315.
[37] S. X. Ta and I. Park, "Dual-band low-profile crossed asymmetric dipole antenna on dual-band AMC surface," *IEEE Antennas Wirel. Propag. Lett.*, vol. 13, no. January, pp. 587-590, 2014, doi: 10.1109/LAWP.2014.2312950.
[38] S. X. Ta and I. Park, "Artificial magnetic conductor-based circularly polarized crossed-dipole antennas: 1. AMC structure with grounding pins," *Radio Sci.*, vol. 52, no. 5, pp. 630-641, 2017, doi: 10.1002/2016RS006203.
[39] H. H. Tran, N. Nguyen-Trong, T. T. Le, and H. C. Park, "Wideband and Multipolarization Reconfigurable Crossed Bowtie Dipole Antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6968-6975, 2017, doi: 10.1109/TAP.2017.2766439.
[40] A. I. Al-Muttairi and M. J. Farhan, "Circular polarization reconfigurable antenna for mid-band 5G applications with a new reconfigurable technique," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no. 2, pp. 802-810, 2020, doi: 10.11591/ijeecs.v19.i2.pp802-810.
[41] A. Y. I. Ashyap *et al.*, "A wearable antenna based on fabric materials with circular polarization for body-centric wireless communications," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 18, no. 1, pp. 335-342, 2019, doi: 10.11591/ijeecs.v18.i1.pp335-342.
[42] A. Sabah and M. J. Frhan, "A new patch antenna for ultra wide band communication applications," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 18, no. 2, pp. 848-855, 2020, doi: 10.11591/ijeecs.v18.i2.PP848-855.