I J C T A, 9(8), 2016, pp. 3437-3449

A Microstrip Dipole Antenna for Circular Polarization

N. Raja Mohamed* and C. Mahendran

ABSTRACT

A circularly polarized antenna is given by inserting 2 pairs of parallel dipoles in a sq. contour. Firstly, our study demonstrates that circular polarization can be achieved at the broadside by setting a ninety section difference between the vertical and horizontal paired-dipoles. Secondly, the principle of wide-beamwidth circularly-polarized radiation is represented underneath the similarity in polar and angle radiation pattern for a combine of parallel dipoles. Once the spacing between 2 parallel dipoles is studied, the similar radiation patterns in these 2 orthogonal planes are derived. As such, a circular polarization will be achieved by inserting the two pairs of parallel dipoles vertically and horizontally whereas setting a ninety section distinction between them. In final, a circularly-polarized printed antenna is intended and fictitious on one nonconductor substrate. The 2 arms of its four dipoles are fashioned on the lower and higher interfaces of the substrate, and that they are excited by a Coaxial feeding network. Experimental results show smart agreement with simulated ones in terms of radiation pattern/gain, axial quantitative relation and came loss. Especially, the 3-dB axial quantitative relation beamwidth at the central frequency of 5.2 & 5.8 GHz has extended to 126 in associate degree angular vary from -63^0 to +63^0. The fictitious antenna exhibits a low-profile property with the height of zero.0043 free-space wavelength.

Index Terms: Axial ratio, circularly polarized antenna, dipoles.

1. INTRODUCTION

Circular polarization (CP) and wide beam are required for an antenna for satellite communications. CP antennas are divided in two types in general. 1) Single-fed antenna [3–5] and 2) dual-fed antenna [2, 6–8]. There is no external feed network for a single-fed antenna. But the usable impedance and axial ratio bandwidths are usually narrow. For a dual-fed CP antenna, the circular polarization is generated by exciting two orthogonal resonant modes with a feeding network which provides equal amplitude and 90º phase difference. The feeding network is often realized by a hybrid or Wilkinson power divider.

In, a dual-fed, bidirectional radiated circularly polarized square-ring antenna is presented. The antenna has abroad impedance bandwidth (|S11| < "10 dB) of about 45.2% and a 3 dB axial-ratio bandwidth of about 8.7%. In [7], a CP antenna which consists two bowtie patch and two electric dipoles is proposed. The antenna achieves an impedance bandwidth (SWR < 1.6) of 41% and a 3-dB ratio bandwidth of 33%. In [8], a structural modification of turnstile antenna with cylindrical parasitic elements is introduced. The antenna has a 5-dB AR bandwidth of 12.3% and a stable peak gain of 7.6 dBi. In this paper, a broadband, wide-beam CP antenna is presented. The antenna is a crossed-dipole fed by a broadband 90º power divider. The axial-ratio bandwidth of the proposed antenna is larger than that of the antennas in [2–8]. The 3-dB beamwidth is larger than 88º over the whole working frequency band. The bandwidth of the proposed antenna is broadened by a novel matching structure. The matching structure is part of the antenna structure rather than additional lumped elements. The concept of the matching structure is discussed in detail in the following paper.

To address this vital issue in style of a CP antenna, a few effective techniques are projected within the recent years. In, a basic CP antenna was mounted on a three-dimensional square ground thus on increase its

* Alagappa Chettiar College of Engineering and Technology, Karaikudi-630003. India

3-dB AR beamwidth of CP radiation to concerning 113; but, this projected CP antenna inquire the peak of over and it's a poor low-profile property. To represent a CP antenna with wide AR beamwidth, lightweight weight and low profile, the add introduced a bifold conducting wall to cut back the peak of the CP antenna to concerning whereas keeping its 3-dB CP beamwidth as concerning 106. A pyramidical ground structure with a partially fenced in and flat conducting wall was adopted for sweetening of the specified CP beamwidth, however this approach unfortunately brought out a large antenna structure. In a few parasitic rings were introduced higher than the first ring CP antenna to realize the wide AR beamwidth. However, this approach enlarged the peak and hyperbolic the quality of the projected CP antenna.

On the opposite hand, a method was bestowed in [7] by stretching the material substrate on the far side the bottom plane of a patch antenna, therefore widening the CP radiation beamwidth. But, this system might launch surface waves within the substrate so on degrade its 3-dB AR information measure. In [8]–[10], the helix antennas with varied configurations were utilized to realize a wide AR beamwidth, however they suffered from problem in fabrication particularly at high frequency. In [11], a CP antenna with eighty five 3-dB AR beamwidth was reported and it's shaped up by group action 2 bowtie patch antennas with 2 trapezoidal shaped dipoles. During this context, the ninety 3-dB AR beamwidth could be achieved by mounting a solid solution disk on a ground plane [12]. In [13], the one hundred forty 3-dB AR beamwidth was gained by loading the top-hats and mounting a reflector on top of and below the two crossed dipole antennas, however this antenna is concerning in height. In [14], [15], the crossed and unsymmetrical barbed dipole CP antennas were developed with wide AR beamwidth, but their height is as massive as 0.2Ω

2. ANTENNA DESIGN CONCEPT AND STRUCTURE

The geometry of the proposed antenna is shown in Fig. 1. Detailed dimensions are given in Table 1. The proposed antenna consists of two crossed dipoles, two pairs of coaxial cables, a ground plane and two pairs of rectangular patches. The arms of each dipole are bent toward the ground plane to save the horizontal space and widen the beamwidth. Each dipole is fed by a balun. The balun is formed by the four coaxial cables. The outer conductors of the four coaxial cables are replaced by copper tubes with the same radius to strengthen the antenna structure. And the four arms are fixed as well as connected to the top end of these copper tubes respectively. Significantly, the inner conductor of the coaxial cable 1 and 3 (where the arm 1 and arm 3 is connected to) are connected to the outer conductors of the coaxial cable 2 and 4 (the copper

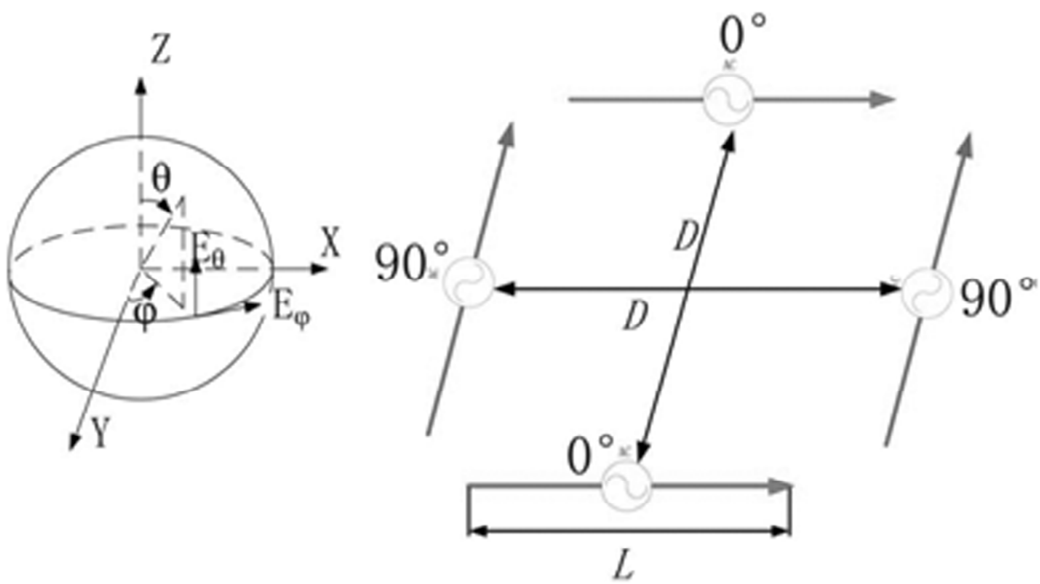


Figure 1: Schematic of the proposed circularly-polarized antenna consisting of two pairs of parallel dipoles in a square contour.

tube2 and 4) respectively. Moreover, the bottom ends of the four copper tubes are connected to the ground plane so as to be shorted together. The whole structure forms a balun. This balun integrates with the antenna well. Coaxial line1 and 3 are connected to SMA connectors which are underneath the ground plane and fed by a feeding network which provides equal amplitude and 90º phase difference across a wide bandwidth to realize circular polarization. Details of the feeding network will be illustrate later

Detailed dimensions of the proposed antenna (unit: mm).

Name	L1	L2	L3	W1	W2	W3	h
Value	12	15	18	5	5	5	38

The impedance bandwidth of the proposed antenna is broadened by the rectangular patches, which are attached to one end of the four arms of the dipoles. Based on the transmission line theory, it is pretty clear that a short transmission line (less than $\lambda/4$) which is terminated with an open circuit is capacitive and has a negative reactance $Zin = -jZ0 \cot \beta l$, where Z0 is the characteristic impedance of the transmission line, β

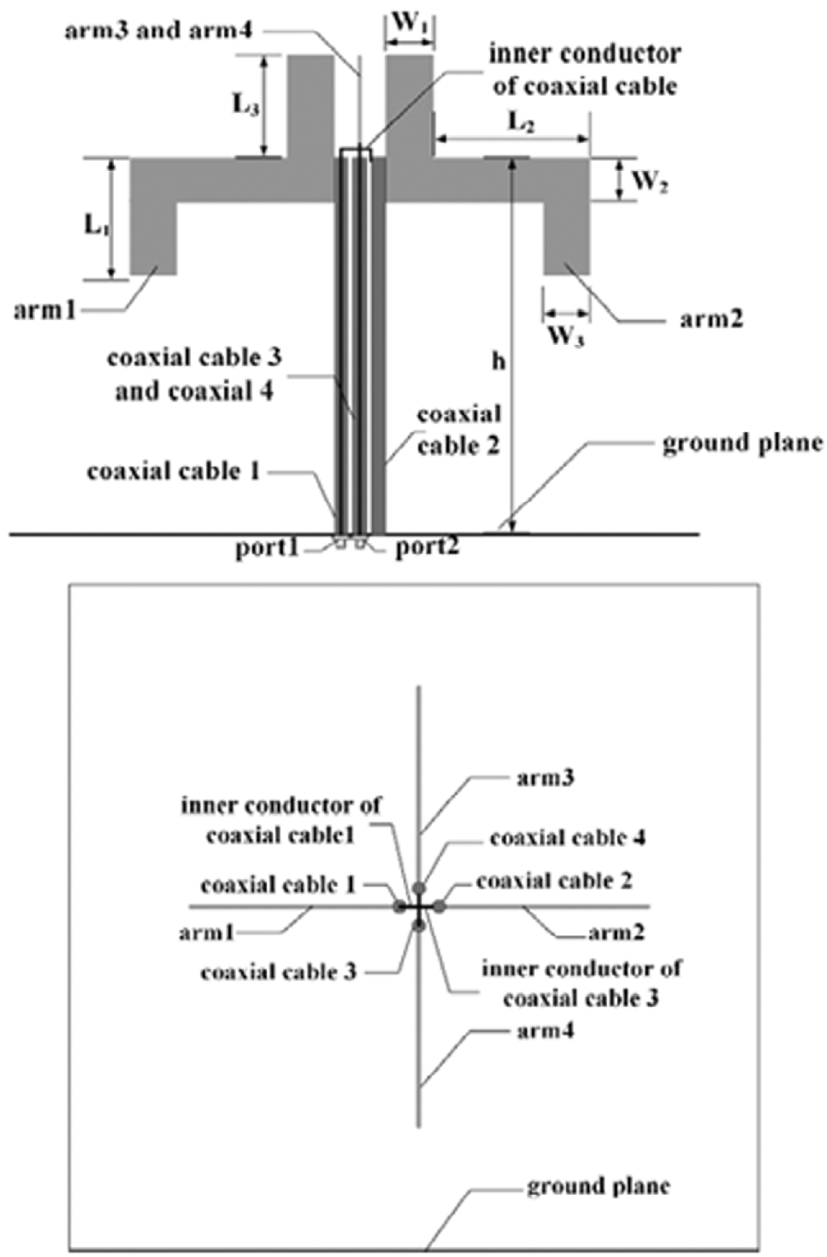


Figure 2: Geometry of the proposed antenna, side view and top view.

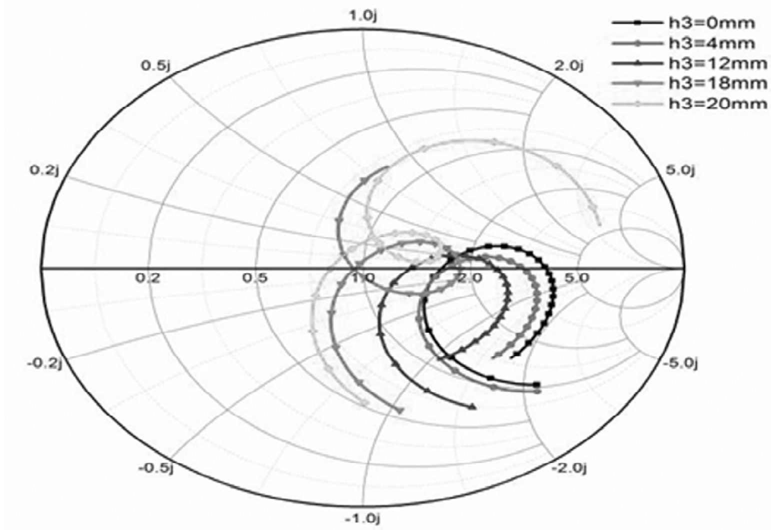


Figure 3: The impedance of the port 1 with different h3.

is the phase constant and l is the length of the transmission line. Thus the rectangular patches of the proposed antenna act as capacitors which are in parallel with the input impedances of the bent dipoles. The impedance of the antenna on Smith Chart while varying the parameter h3 when port 1 is excited and port 2 is terminated with a 50Ω resistor is illustrated in Fig. 2. It can be seen that the imaginary part of the impedance is increased with the increase of *h*3. When the length of the rectangular patch (*h*3) is very small, the absolute value of its reactance is very large. Such a shunt capacitor is can be viewed as open circuit thus it has little influence on the input impedance of port 1. As *h*3 increases, the absolute value of its reactance decreases and the influence of the rectangular patches on the impedance of the antenna become more and more apparent. The optimum value of *h*3 occurs at 18mm.

In this paper, a novel approach is presented to design a CP antenna with both low-profile and wide AR beamwidth. Two pairs of parallel dipoles are orthogonally placed in a square contour, and they are excited in the same amplitude and 90 phase difference. Our study shows that the wide AR beamwidth could be achieved if the spacing between two respective parallel dipoles is selected as 0.4α. Afterwards, a CP antenna, fed by a four port probe-to-microstrip network, is designed and fabricated on a dielectric substrate. The measured 3-dB AR beamwidth achieves as large as 126 at 5.2 GHz, while AR < 3DB, $|S_{11}|$ < -18DB and Gain > 5 DBi, and are gained over 5.2 GHz, which covers the GPS-band and CNSS-band.

2. PRINCIPLES OF PROPOSED CP ANTENNA

Fig. 1 depicts the schematic of the planned circularly-polarized antenna with 2 pairs of parallel dipoles in a very sq. contour. These four dipoles are all placed within the XY-plane. One pair of dipoles is destined within the coordinate axis, whereas another try of dipoles is within the coordinate axis. so as to induce the CP radiation in the broadside direction, i.e., Z-axis, these 2 pairs of dipoles are excited within the same amplitude and ninety part distinction. All of these four dipoles have a length of L and also the spacing between two several parallel dipoles is about as D. With the employment of this arrangement, the 2 orthogonal linearly-polarized radiations could be made, and their linear superposition are often expected to attain the required circular polarization

Now, let's start with mathematical demonstration on the rational of wide AR beamwidth for this proposed CP antenna. It is assumed in analysis that the current distribution on each of these four dipoles varies as a sinusoidal function. On a basis of classical antenna theory such as [16], the far-zone normalized electric field component in the polar axis, radiated by a pair of parallel dipoles along the X-axis in the XZ-plane, can be deduced as a function of the polar angle ⊖.

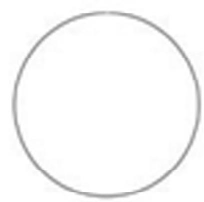
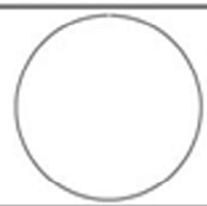
$$E_{\theta}(\theta) = \frac{\cos\left(k\ L\ \cos(\theta - \pi/2)\right) - \cos\ k\ L}{\sin(\theta - \pi/2)} \tag{1}$$

Where $k = 2\pi/Y_o$

Similarly, the far-zone normalized electric field component in the azimuthal axis, radiated by a pair of parallel dipoles along the Y-axis in the XZ-plane, can be derived as a function of the polar angle (⊖)

$$E_{\varphi}(\theta) = \cos\left(D/2 \times \sin(\theta)\right) \tag{2}$$

Table 1
Graphical Demonstration in Realization of Identical E⊖ And EΨ Radiation Pattern in The Xz-plane Used For The Proposed Cp Antenna

	Radiation pattern of a dipole		Radiation pattern of an in-phase binary array		Product of radiation pattern
$\lvert E_\theta \rvert$		×		=	
$\lvert E_\varphi \rvert$		×		=	

According to the feeding voltages of four dipoles as illustrated in Fig. 1, we can figure out that <EΨ. As such, superposition of these two orthogonal LP wave can radiate the perfect CP wave at the z-axis or ⊖ = 0^0 and the axial ratio (AR) at any polar angle (⊖) in the XZ-plane can be expressed as

$$AR(\theta) = \left|20 \times \log_{10}\left|\frac{E_{\theta}(\theta)}{E_{\varphi}(\theta)}\right|\right| \tag{3}$$

Obviously, the zero-dB AR can be achieved if from (3), but it is not a case. For a pair of parallel dipoles in the X-axis, the XZ plane is the E-plane. However, for a pair of parallel dipoles in the Y-axis, the XZ plane is the b H-plane. On one hand, the radiation pattern of an electric dipole looks like figure-8 shape in the E-plane and a figure-O shape in the H-plane. On the other hand, an in-phase binary array of isotropic radiators has the radiation pattern with a figure-O shape in the E-plane and a figure-8 shape in the H-plane. If the dipole-to-dipole spacing,, and the dipole length,, are properly selected, the E-and H-plane radiation pattern can achieve the identical shape in a wide angular range as graphically illustrated in Table I. It is a compulsory condition to achieve a wide CP beamwidth in the polar angle (⊖).

In this work, each dipole is designed with the length of $L = 0.5\lambda_0$ as usual. As illustrated in Fig. 2, the beamwidth of $|E_\theta|$ is almost unchanged regardless of varied spacing D. It can be simply understood from (1) that $|E_\theta|$ is not a function of D. However, the beamwidth of $|E_\phi|$ gradually becomes narrow and narrow as the spacing D increases from 0 to $0.2\lambda_0$, $0.4\lambda_0$, $0.6\lambda_0$, and $0.8\lambda_0$. Looking at (2) we can figure out that $|E_\phi|$ is a

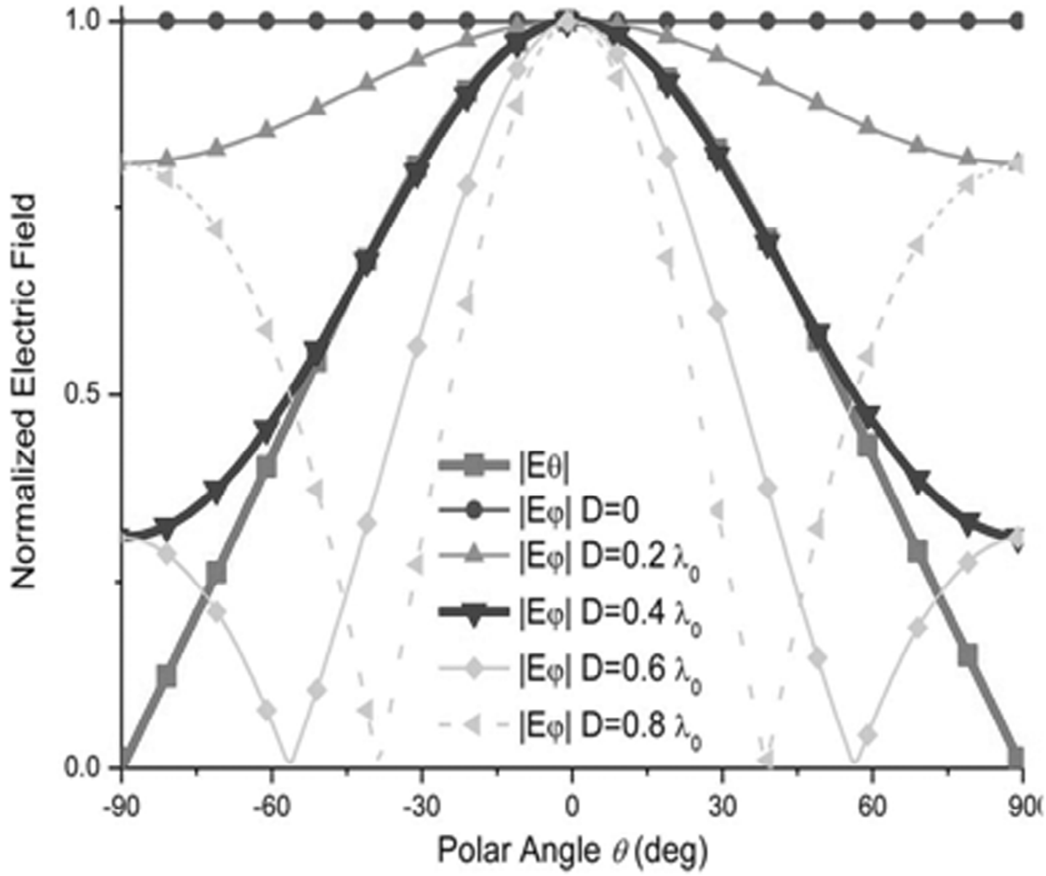


Figure 4: Calculated E⊖ and EΨ radiation pattern in the XZ-plane under varied Spacing for the proposed CP antenna in Fig. 1.

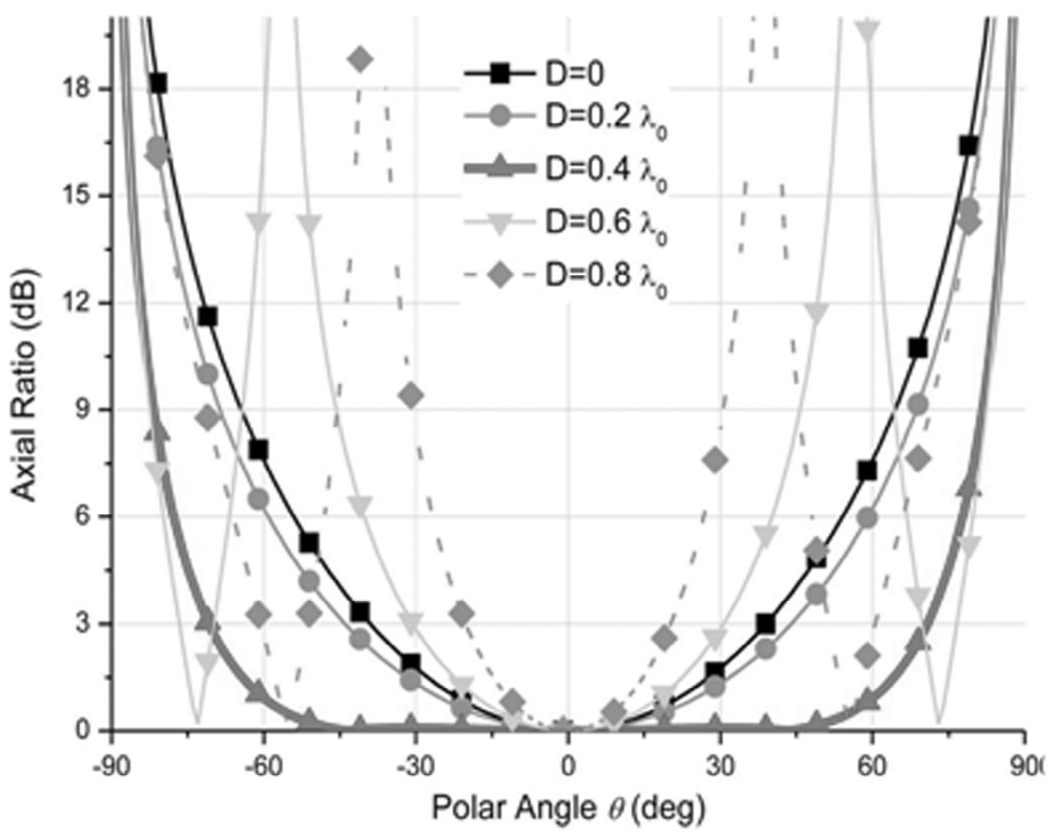


Figure 5: Calculated 3-dB axial ratio (AR) in the XZ-plane under varied spacing D for the proposed CP antenna in Fig. 1.

Table 2
3-DB Axial Ratio (Ar) Versus Varied Spacing D (Extracted From Fig. 3)

	$D = 0\ \lambda_0$	$D = 0.2\ \lambda_0$	$D = 0.4\ \lambda_0$	$D = 0.6\ \lambda_0$	$D = 0.8\ \lambda_0$
3-dB AR beamwidth	78°	88°	142°	62°	41°

cosine function of D. When D is extremely small or $D = 0$ in Fig. 2, the perfect flat pattern of $|E_\phi|$ shows an omnidirectional radiation property. At $D = 0.4\lambda_0$, the $|E_\phi|$ pattern (thick blue-line) becomes almost the same as the $|E_\theta|$ pattern (thick red-line) in a wide range of polar angle (θ) from –60° to + 60°. Beyond $D = 0.4\lambda_0$, the $|E_\phi|$ pattern becomes narrower than its $|E_\theta|$ counterpart in angular beamwidth.

Using (3), we can calculate the axial ratio (AR) in the XY-plane of the proposed CP antenna under the feeding voltages as shown in Fig. 1. Fig. 3 depicts the calculated AR under varied spacing. When $D = 0$, the proposed CP antenna in Fig. 1 becomes a crossed-dipole CP antenna as reported in [17], and its 3-dB AR beamwidth is approximately ranged in a polar axis from -39^0 to $+39^0$. At $D = 0.4\alpha_0$ this 3-dB AR covers a very wide range in the polar axis of -71^0 to $+71^0$. In particular, the beamwidth with almost zero-dB AR reaches to a range of -50 to 50. Beyond $D = 0.4\alpha_0$ this 3-dB AR beamwidth is gradually narrowed. Table II is tabulated to show the values of 3-dB AR beamwidth under to $L = 0$ to $0.2\alpha_0$, 0.4Y, $0.6\alpha_0$ and $0.8\alpha_0$. Again, we can see that a maximum 3-dB AR beamwidth of about 142 is achieved.

3. PROPOSED SCHEME

3.1. Design and Implementation of Printed CP Antenna

Based on the discussion in Section II, a circularly polarized (CP) printed antenna is proposed and constructed. Fig. 4 shows its geometry. This antenna is formed on a Rogers's 4003C substrate with the relative permittivity

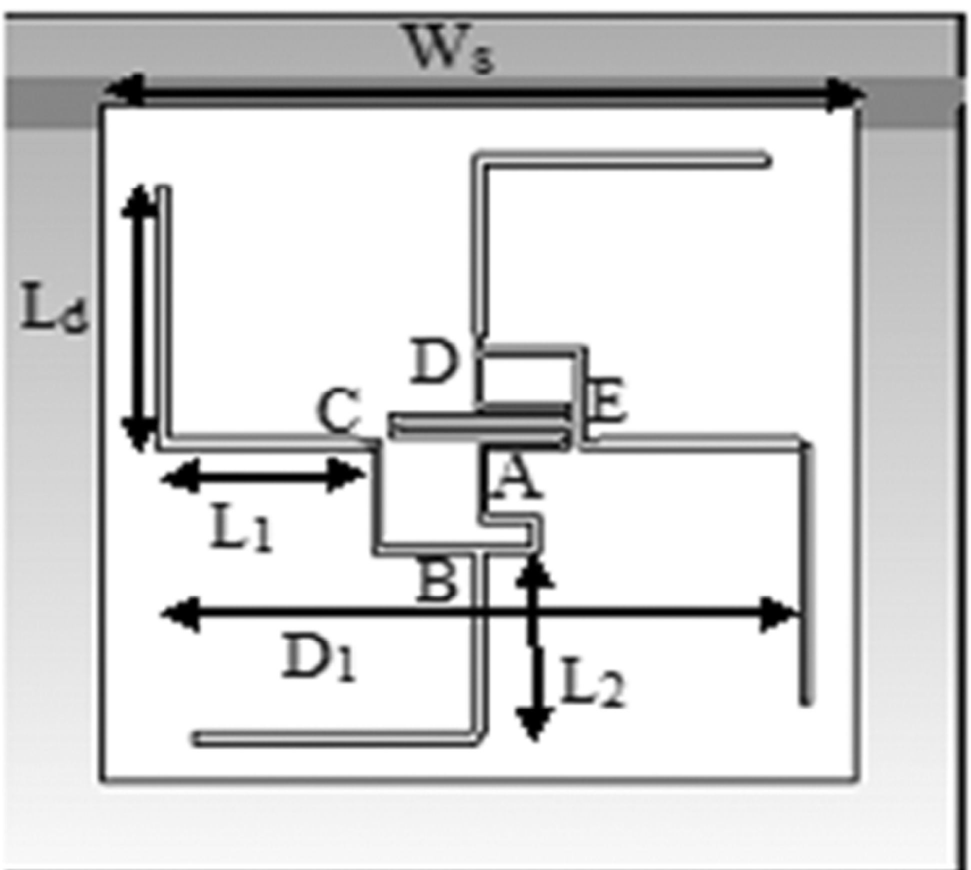


Figure 6: Overall configuration of the proposed CP antenna formed on the upper interfaces of a dielectric substrate.

of ε_r = 3.55 and the thickness of 0.813 mm that is about 0.00043Y$_o$at 5.2 GHz. Two pairs of parallel dipoles, spaced by, are orthogonally placed at the four sides of a square contour. The two arms of each dipole are formed on the upper and lower interfaces or layers of the substrate, and it is fed by a double-sided and balanced stripline as studied in [18]. The balanced stripline plays a key role as a balun and make the dipole to work at a balance mode. In this case, this double-sided dipole is slightly shorter than in its length. To gain a wide 3-dB AR beamwidth at maximum as discussed above with reference to Fig. 5 and Table II, the spacing between the two respective parallel dipoles is selected as about at 5.2 GHz. In the following, a coaxial feeding network shown in Fig. 7 will be investigated and designed with the target of zero-dB AR at the broadside direction, i.e., Z-axis in Fig. 1.

First of all, each dipole is designed with the input impedance of 70 at resonant frequency of 5.2 GHz by selecting its strip width as 1.5 mm. The four identical input impedances of these dipoles are considered as the load impedance of the four output microstrip-line ports of a 1-to-4 feeding and matching network as shown in Fig. 7. Next, this 1-to-4 network in Fig. 7 is designed using its equivalent transmission-line network in Fig. 7 based on the network theorem in microwave engineering [19]. In this design, our target is to equally distribute the input signal at the coax probe at Point A to the four micristrip-line output ports, namely, Point B, C, D and E. Meanwhile, the output signals, at Point B and C as well as Point D and E, should be designated with the 90 phase difference between them. As such the two pairs of vertical and horizontal parallel dipoles in Fig. 5 are equally fed in both amplitude and phase, respectively. Plus, there is a 90 phase difference between these paired vertical and horizontal dipole as inquired in Fig. 1. To meet the needs described above, the length of the double sided striplines, along the path of B to C and D to E, are selected as (is the guided-wavelength) and these two lines act as a 90 phase delay line. Since two neighboring dipoles, namely, are connected in shunt, the input impedance at their connecting points, i.e., Point B and D, looking to the dipole radiators becomes is 35. Next, a 59-Ω ¥$_g$/4 microstrip line is selected to transform 35

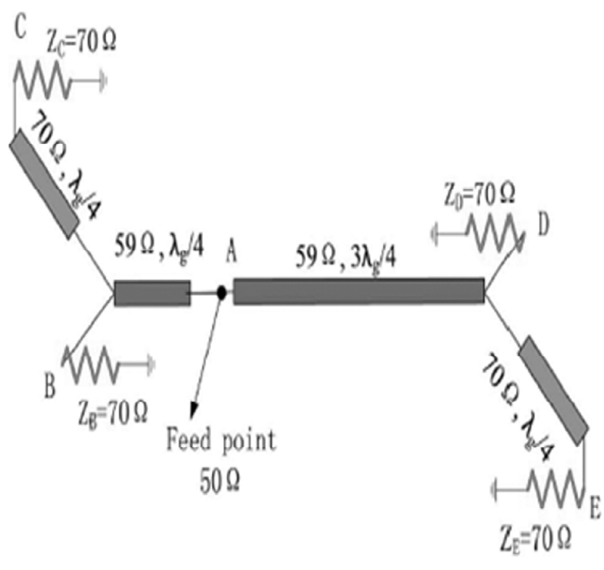


Figure 7: Coaxial Feeding network Equivalent transmission-line topology

Table 3
List of all The Dimensional Parameters for The Printed CP Antenna in Fig. 4

Parameters	Ld	Wd	D1	W1	W2	W3	Ws	Wg
Values (mm)	38	1.5	85	1.3	1	3	100	32
Parameters	L1	L2	AB	BC	AD	DE	BF	
Values (mm)	16	26.5	29.5	29.5	88.5	29.5	29	

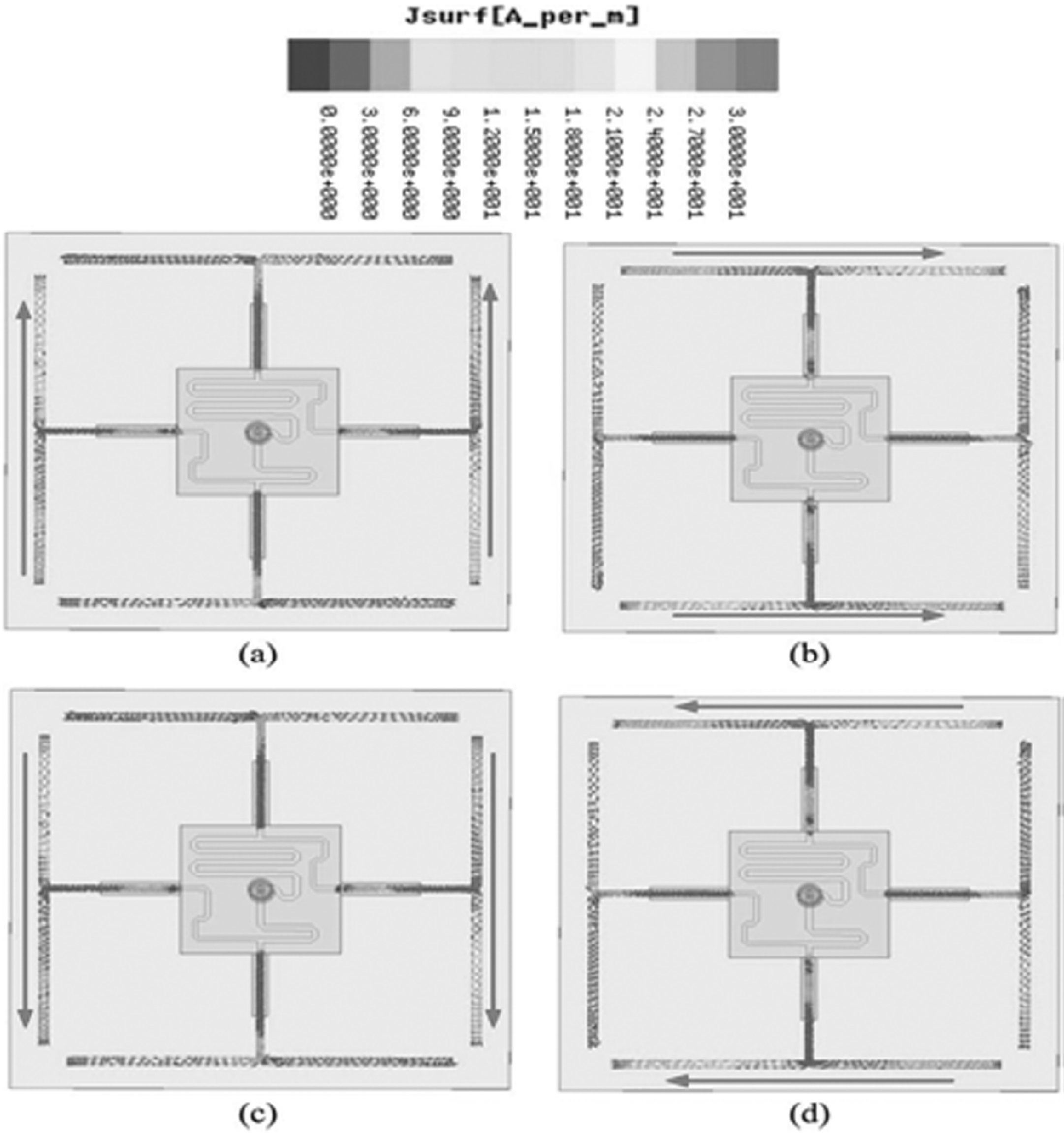


Figure 8: Simulated current distribution on the strip conductor of four dipoles at different time instances. (a) t = 0; (b) t = T/4; (c) t = T/2; (d) t = 3T/4.

at Point B to 100 at Point A, while a 59-Ω 3¥$_g$/4 microstrip line is employed to transform 35Ω at Point D to 100Ω at Point A. Since these two 100-microstrip lines are linked with the 50-coax probe, good impedance matching property can be achieved between the probe and microstrip line at Point A. After the design of the overall CP antenna shown in Fig. 4 is completed, all of its dimensional parameters can be determined and they are tabulated in Table III. To confirm that the CP wave could be radiated from this designed CP antenna in Fig. 6, the current distribution on the strip conductor of the four dipoles is simulated at different times, i.e., t = 0, T/4, T/2 and 3T/4, where T stands for the periodicity of electromagnetic wave at 5.2 & 5.8 GHz. The current distribution is simulated by the FDTD method. As shown in Fig. 6, the two pairs of dipoles are excited with almost the same amplitude and 90 phase difference, and they result to radiate the CP wave as a superposition of two orthogonal LP waves

4. RESULTS AND DISCUSSION

In this section, the overall layout of the designed CP antenna in Fig. 6 is simulated using the FDTD, and it is then fabricated to verify the predicted results and the proposed design approach in experiment. Fig. 9 depicts the photographs of the fabricated antenna prototype. Measurement on the reflection coefficient, radiation gain and radiation pattern of this antenna is executed by using the Agilent N5230A Network Analyzer and the near-field SATIMO antenna test system. Due to the rotational symmetry in placement of the dipoles, only the radiation characteristic in the XZ-plane is investigated in this work. Fig. 10 depicts the simulated and measured axial ratio (AR) as a function of the polar angle (⊖) at the central frequency of the designed CP antenna, i.e., 5.2 GHz. Both of them is found in good agreement with each other over a wide angular range. Under the usual 3-dB AR definition, the measured AR beamwidth has reached to 126, i.e., -63^0 to $+63^0$, as predicted in theory. This antenna radiates the so-called left-handed and right-handed circular polarization, in short, LHCP and RHCP, above and below the horizontal plane of the designed planar CP

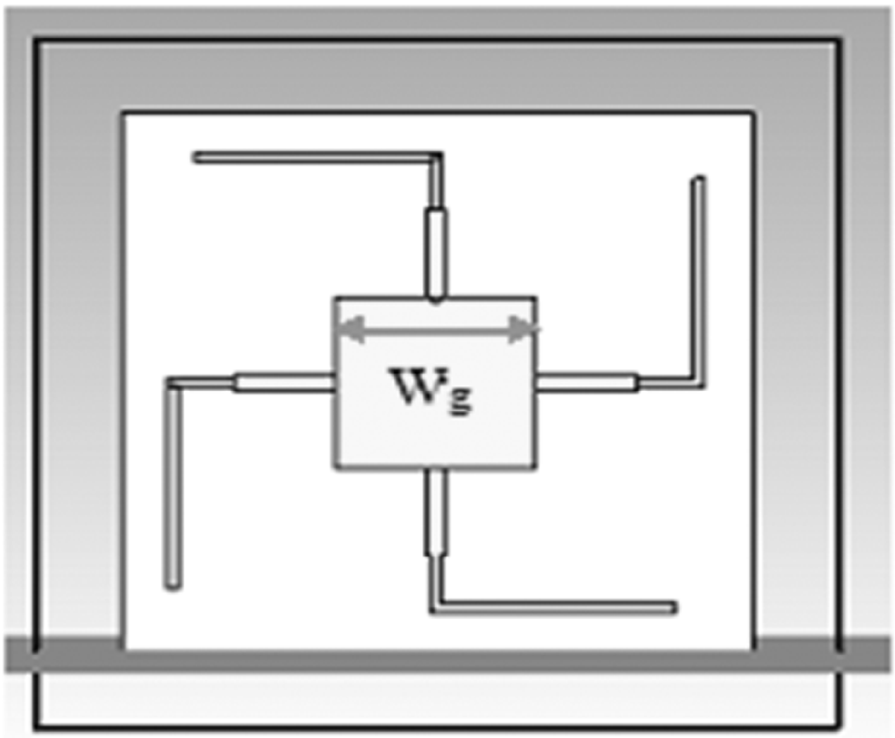


Figure 9: Overall configuration of the proposed CP antenna formed on the lower interfaces of a dielectric substrate.

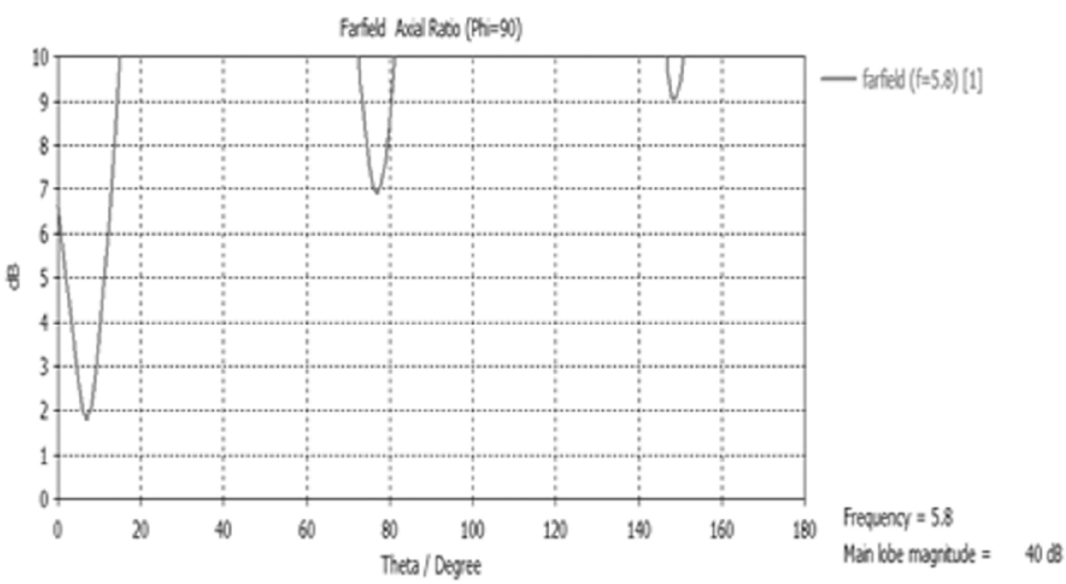


Figure 10: Simulated and measured axial ratio (AR) of the antenna in Fig. 9 with Respect to the polar angle (è) at 5.2 and 5.8 GHz.

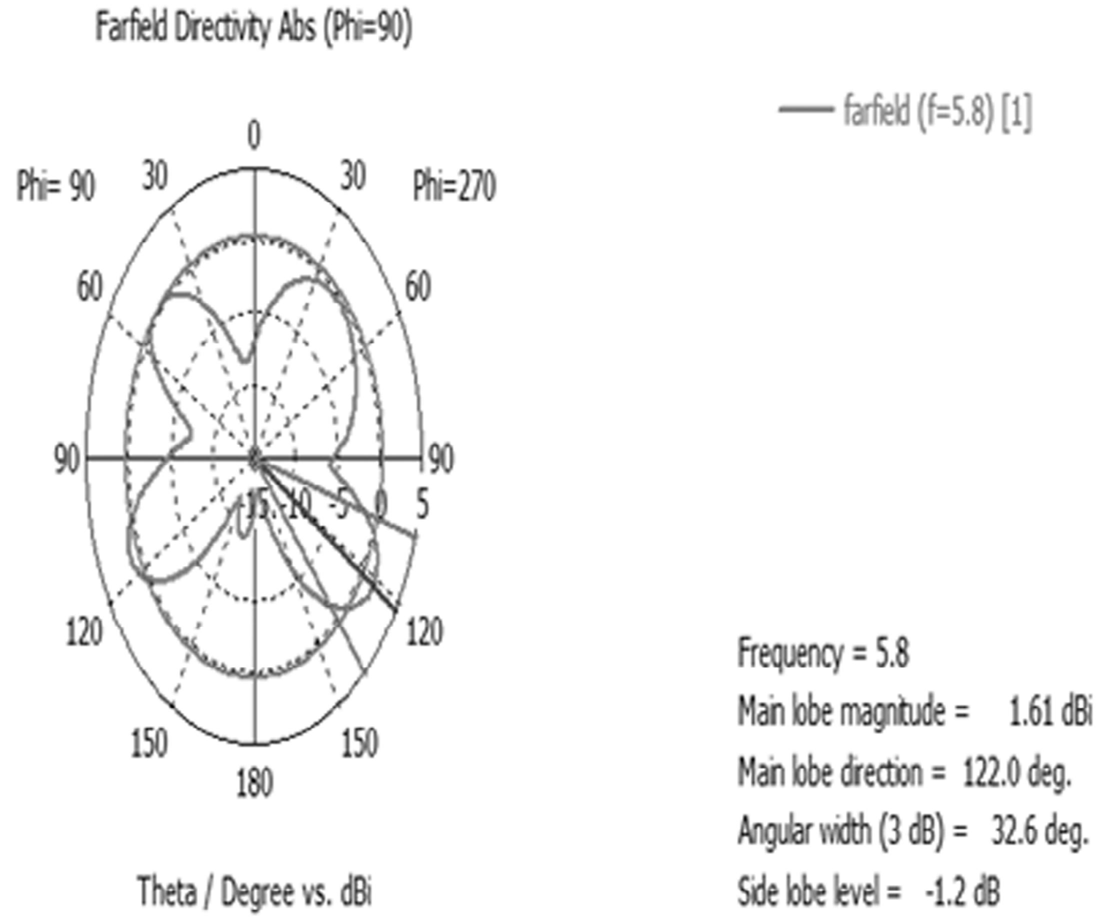


Figure 11: Simulated and measured radiation patterns at 5.2 GHz.

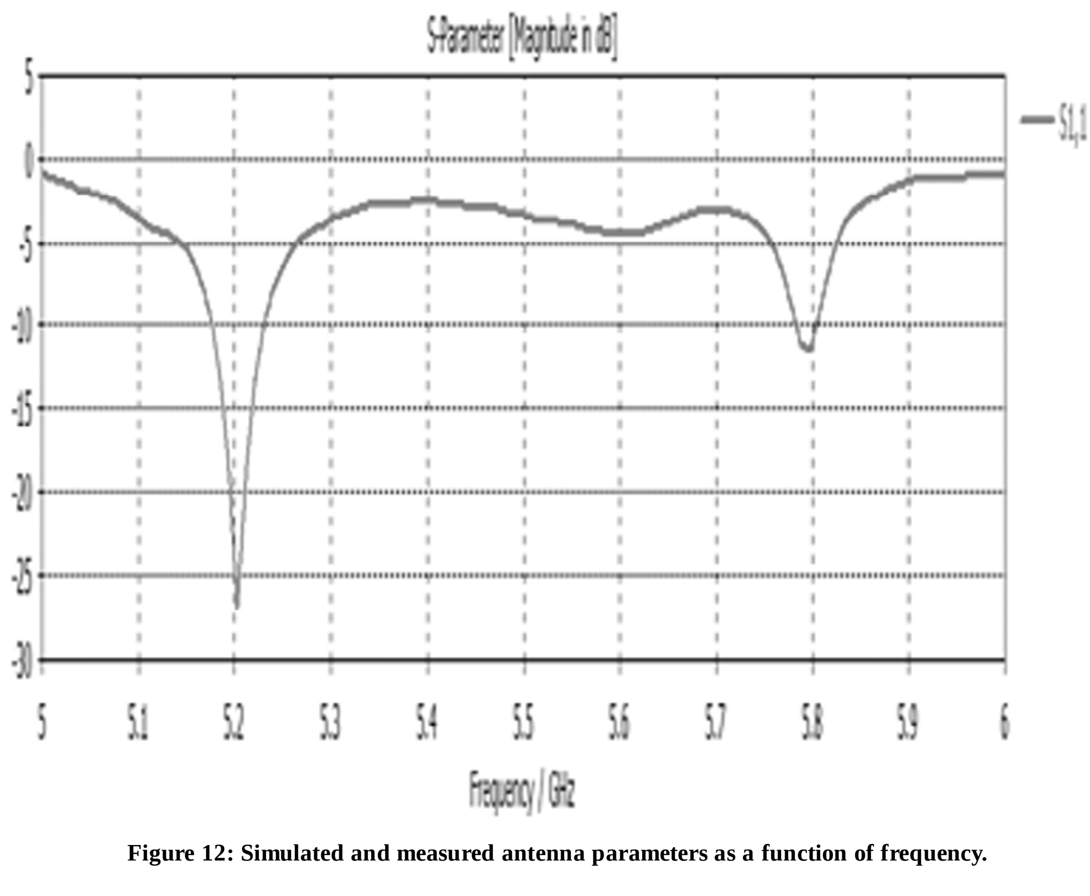


Figure 12: Simulated and measured antenna parameters as a function of frequency.

antenna in Fig. 9, respectively. Fig. 11 shows the simulated and measured radiation patterns at 5.2&5.8 GHz. Both of LHCP and RHLP patterns achieves almost the same configuration. In addition, the low cross-polarization in both sides is attained as illustrated in Fig. 10. Fig. 11 shows the simulated and measured results of $|S_{11}|$, peak LHCP radiation gain and axial ratios as a function of frequency. Measured results show a good agreement with the simulated ones. In the targeted band of 5.2 and 5.8 GHz, we have well achieved, AR< 3dB, $|S_{11}|$ < -18dB and Gain > $5dB_i$. Thereafter, the designed CP antenna can well cover the GPS-band and CNSS-band as demanded in wireless communications.

5. CONCLUSION

In this paper, a low-profile circularly polarized (CP) antenna with wide AR beamwidth has been proposed, designed and tested. After the principle of beamwidth enhancement has been intuitively explained and quantitatively demonstrated, a printed CP antenna with the two pairs of parallel dipoles has been implemented on a thin single-layer substrate with the height of about $0.00043Y_o$at central frequency of 5.2 GHz. By designing a coaxial feeding network, the two pairs of dipoles with orthogonal orientation have been confirmed to radiate good CP wave in a wide range of polar angle. As shown in both simulation and experiment, the 3-dB axial ratio of the proposed CP antenna can cover an extremely wide angular range with the beamwidth of about 126. Moreover, all the other measured results, such as reflection coefficient, radiation gain and axial ratio, are in good consistence with the predicted ones.

REFERENCES

[1] S. Gao, Q. Luo, and F. Zhu, Circularly Polarized Antennas. Hoboken-Piscataway, NJ, USA: Wiley-IEEE Press, Nov. 2013.

[2] C. L. Tang, J. Y. Chiou, and K. L. Wong, “Beamwidth enhancement of a circularly polarized microstrip antenna mounted on a three-dimensional ground structure,” Microw. Opt. Technol. Lett., vol. 32, no. 2, pp. 149-153, Jan. 2002.

[3] H. Nakano, S. Shimada, J. Yamauchi, and M. Miyata, “A circularly polarized patch antenna enclosed by a folded conducting wall,” in Proc. IEEE Conf. on Wireless Communication Technology, Honolulu, HI, USA, 2003, pp. 134-135.

[4] C. W. Su, S. K. Huang, and C. H. Lee, “CP microstrip antenna with wide beamwidth for GPS band application,” Electron. Lett., vol. 43, no. 20, pp. 1062-1063, Sep. 2007.

[5] S. I. Latif and L. Shafai, “Hybrid perturbation scheme for wide angle circular polarisation of stacked square-ring microstrip antenna,” Electron. Lett., vol. 43, no. 20, pp. 1065-1066, Sep. 2007.

[6] S. I. Latif and L. Shafai, “Circular polarisation from dual-layer squarering microstrip antennas,” IET Microw. Antennas Propag., vol. 6, no. 1, pp. 1-9, Feb. 2012.

[7] X. L. Bao and M. J. Ammann, “Dual-frequency dual circularly-polarised patch antenna with wide beamwidth,” Electron. Lett., vol. 44, no. 21, pp. 1233-1234, Oct. 2008.

[8] M. Caillet, M. Clénet, A. Sharaiha, and Y. M. M. Antar, “A broadband folded printed quadrifilar helical antenna employing a novel compact planar feeding circuit,” IEEE Trans. Antennas Propag., vol. 58, no. 7, pp. 2203-2209, Jul. 2010.

[9] K. Ding, Y. Wang, and X. Xiong, “A novel wide-beam circularly polarized antenna for SDARS applications,” IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 811-813, 2012.

[10] M. Amin, J. Yousaf, and S. Iqbal, “Single feed circularly polarised omnidirectional bifilar helix antennas with wide axial ratio beamwidth,” IETMicrow. Antennas Propag., vol. 7, no. 10, pp. 825-830, May 2013.

[11] K. M. Mak and K. M. Luk, “A circularly polarized antenna with wide axial ratio beamwidth,” IEEE Trans. Antennas Propag., vol. 57, no. 10, pp. 3309-3312, Oct. 2009.

[12] J. Ghalibafan, B. Rejaei, and N. Komjani1, “A circularly polarized antenna based on the unidirectional resonant modes of a ferrite disk,” IEEE Trans. Magnetics, vol. 50, no. 3, Mar. 2014.

[13] E. Choi, J. W. Lee, and T.K. Lee, “Modified S-band satellite antenna with isoflux pattern and circularly polarized wide beamwidth,” IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 1319-1322, 2013.

[14] S. X. Ta, I. Park, and R. W. Ziolkowski, “Dual-band wide-beam crossed asymmetric dipole antenna for GPS applications,” Electron. Lett., vol. 48, no. 25, pp. 1580-1581, Dec. 2012.

[15] S. X. Ta, I. Park, and R. W. Ziolkowski, “Multi-band, wide-beam, circularly polarized, crossed, asymmetrically barbed dipole antennas for GPS applications,” IEEE Trans. Antennas Propag., vol. 61, no. 11, pp. 5771-5775, Nov. 2013.

[16] C. A. Balanis, Antenna Theory: Analysis and Design, 3rd ed. Hoboken, NJ, USA: Wiley, 2005.

[17] J. W. Baik, K.J. Lee, and W.S. Yoon et al., “Circularly polarized printed crossed dipole antennas with broadband axial ratio,” Electron. Lett., vol. 44, no. 13, pp. 785-786, Jun. 2008.

[18] F. Tefiku and E. Yamashita, “Double-sided printed strip antenna for dual frequency operation,” in IEEE AP-S Int. Symp. on Antennas Propag. Dig., Jun. 1996, vol. 1, pp. 50-53.

[19] D. M. Pozar, Microwave Engineering, 4th ed. Hoboken, NJ, USA: Wiley, 2011.