A Reconfigurable Crossed Dipole Antenna for Polarization Diversity Using Characteristic Mode Theory

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Abstract ─ A novel printed crossed dipole antenna with reconfigurable circular and linear polarization is proposed. This antenna consists of a pair of L-shape elements and a narrow gap on each arm for inserting a conductive metal tab as an ideal switch in the center of the gap to control its on-off status. The theory of characteristic modes has been used to design and analyze the proposed antenna. Based on the presented idea, a prototype of such antenna has been constructed with the center operating frequency at about 2500 MHz. The experimental results have been presented and compared with those obtained from the simulation showing a good agreement. The antenna is low cost and possesses simultaneous circular and linear polarization which has not been reported in the literature for single-feed crossed dipole antennas.

Index Terms ─ Characteristic modes, circular polarization, crossed dipole, diversity, linear polarization, reconfigurable.

I. INTRODUCTION

The crossed dipole is a common type of antenna used in a wide frequency range for generating circular polarization.

Brown developed the first crossed dipole antenna in the 1930s under the name of "Turnstile Antenna" [1]. In 1961 Bolster introduced a new type of crossed dipole antenna with a single feed for circular polarization radiation [2].

Based on this idea, numerous single-feed circularly polarized crossed dipole antennas have been designed [3-6]. For recent wireless communications, a circular polarization (CP) technique is popularly used because of its insensitivity to transmitter and receiver orientations [7]. In addition, antennas with a reconfigurable polarization have been studied to avoid the signal fading loss caused by multipath effects. Recent reconfigurable crossed dipole antennas only cover circular polarization [8] and having circular and linear polarization simultaneously can improve antenna applications.

The theory of characteristic modes is one of the useful methods which are widely used for analyzing the antennas [9-10]. The theory of CM was first developed by Garbacz [11] and was later refined by Harrington and Mautz in the seventies [12-13]. Recently the theory of CM reemerged in designing antennas for modern applications such as crossed dipole antenna [14].

In this paper first, we provide a brief description of the theory of CM and its applications. Second, we introduce and analyze crossed dipole antenna in linear and circular polarization with CM theory. Finally, with the combination of the antenna structure in two types of polarizations a reconfigurable crossed dipole antenna with a switchable circular and linear polarization is presented. After implementation, we compare simulation and measurement results.

II. THEORY OF CHARACTERISTIC MODES

The theory of characteristic modes is presented here in brief. The characteristic modes or characteristic currents can be obtained as the eigenfunctions of the following particular weighted eigenvalue equation:

$$X(\overrightarrow{J_n}) = \lambda_n R(\overrightarrow{J_n}), \quad (1)$$

where the λ_n are the eigenvalues, (J_n) are the eigenfunctions or the eigencurrents, and R and X are the real and imaginary parts of the impedance operator:

$$Z = R + jX. \quad (2)$$

Modal significance (3) and characteristic angle (4) are other antenna characteristics using the eigenvalue information to extract resonance information,

$$MS_n = \left|\frac{1}{1+j\lambda_n}\right|, \quad (3)$$

$$\alpha_n = 180^\circ - tan^{-1} \lambda_n. \quad (4)$$

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The resonance of each mode can be identified by the maximum value of each modal significance curve corresponding to the characteristic angle that is equal to 180°. This means that the closer the modal significance to its maximum value or characteristic angle to 180°, the more effective the associated mode contributing to radiation.

If excitation is present the modal excitation and the modal weighting coefficient are calculated, giving an indication of how well the excitation will excite each mode and how presented in total current distribution.

III. ANTENNA DESIGN

The idea and the procedure for antenna design are presented in the following subsections. The crossed dipole antenna is analyzed in the forms of simple metal strip structures in linear and circular polarization according to CM theory. With the reference obtained from the above procedure, we propose a reconfigurable antenna with linear and circular polarization. This prototype antenna is simulated and constructed based on a dielectric substrate.

A. Linear polarization mode

Figure 1 shows the configuration of a simple crossed dipole antenna composed of two orthogonal L-shape metal strips with a vertical distance of 0.5 millimeters in air substrate and the length of each arm along x or y-direction is d1= d2 = 30 millimeters and the width of each arm is w = 1 millimeter.

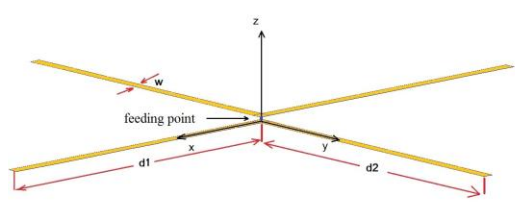


Fig. 1. Simple crossed dipole antenna.

The modal analysis of this structure is performed by the software for electromagnetic simulations (FEKO) [15] using characteristic modes request.

The core of the program FEKO is based on the method of moments (MoM). The MoM is a full wave solution of Maxwell's integral equations in the frequency domain. The FEKO solver supports RWG (Rao-Wilton-Glisson) [16] and higher order hierarchical basis functions. The procedure begins when the antenna surface is discretized using triangles. Then with the aid of the RWG method, the software extracts the Z impedance matrix.

This impedance matrix is used to calculate the eigenmodes and eigenvalues of the given antenna. This method is used stepwise at isolated frequency points through the predefined frequency range. The eigenvalues are the main parameters to calculate the additional modal parameters, e.g., modal significance and characteristic angle.

Figure 2 shows the variation of the modal significance and modal weighting coefficient with the frequency related to current modes (Jn) of the crossed dipole antenna.

It can be noticed that the modes 1 and 2 resonate around 2.4 GHz and mode 3 resonates at 2.6 GHz and other modes resonate at higher frequencies as indicated by their corresponding modal significance curves.

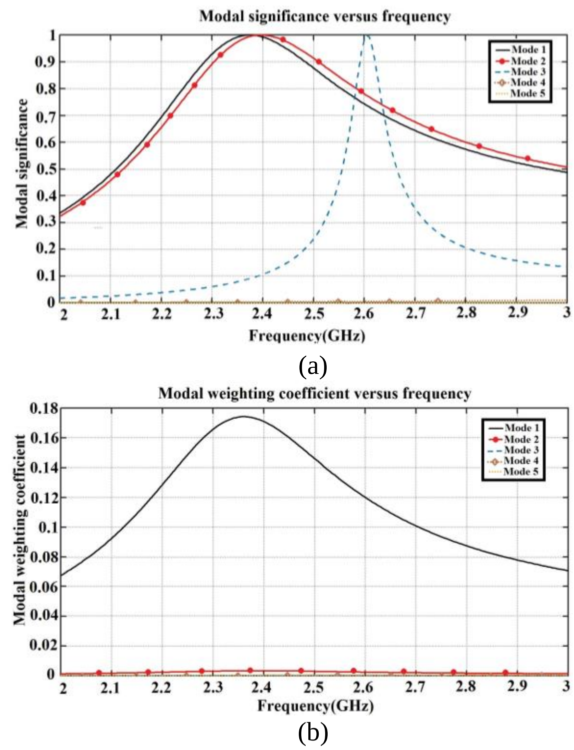


Fig. 2. Crossed dipole in linear mode: (a) modal significance, and (b) modal weighting coefficient.

Among these modes with feeding point in Fig. 1, only mode 1 radiates as seen in corresponding modal weighting coefficient curves, in other words, the antenna in Fig. 1 radiates in linear polarization mode.

Figure 3 shows the normalized electric field (En) at 2.4 GHz associated with the characteristic currents (Jn). It can be appreciated that far field produced by mode 1 is similar to the final far-field pattern of the antenna.

B. Circular polarization mode

It is a well-known fact that to get circular polarization, it is essential to combine two orthogonal and linearly polarized modes with the same current amplitude and with a phase difference of 90º.

This is simply achieved by combining modes 1 and 2. To produce the required phase shift of current the length of d1 (for both arms) can be increased making d`1=d1+a, causing the resonance frequency of mode 1 which moves to lower values and simultaneously shortens the length of the d2 (for both arms) making d`2=d2-a causing the resonance frequency of mode 2 that moves to higher values as seen in the curves of modal significance of Fig. 4.

Figure 4 also shows what happens to the curves of the characteristic angle and modal weighting coefficient. It can be seen that the characteristic angle curves corresponding to modes 1 and 2 have a phase difference of 90º at the point that both modes have exactly the same amplitude of the normalized current.

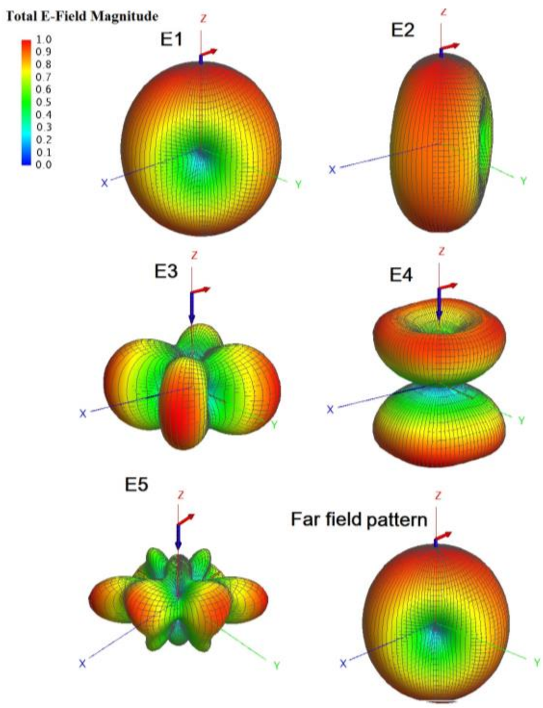


Fig. 3. Comparison of modal field and far-field pattern.

For a value of a = 2.5 mm the desired displacement between modes 1 and 2 is obtained. Moreover, as shown in Fig. 4, modal weighting coefficient curves (mode 1 and mode 2) have identical parts in final radiation power and other modes can be neglected in comparison to them. So there are two orthogonal modes that meet the required conditions for circular polarization.

Depending on which arms (increased or decreased), the polarization can be RHCP or LHCP.

Also, based on current distribution, we could assess this antenna. From Fig. 2 (b) and Fig. 4 (c), we learn that in linear mode, only mode one radiates although in circular mode, two modes (one and two) radiate simultaneously.

Figure 5 shows the current distribution in linear and circular modes. As we can see in linear mode, the current flow to all four antenna arms via antenna port, we get linear slant polarization.

In the circular mode, the current flow in two aligned arms in mode1, and other two arms in mode 2, with a phase difference of 90º, resulted in circular polarization [17-18].

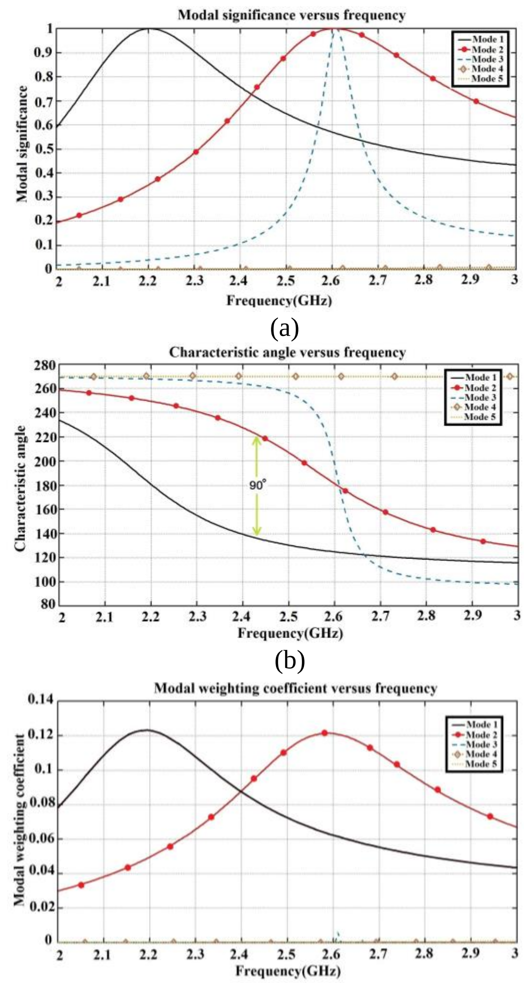


Fig. 4. Crossed dipole in circular mode: (a) modal significance, (b) characteristic angle, and (c) modal weighting coefficient.

C. Proposed antenna geometry

With the ideas explained in parts A and B, we propose the configuration of the antenna in Fig. 6. There are L-shape elements composed of two orthogonal arms on both sides of a dielectric substrate. On each arm, there is a narrow gap and a conductive metal tab or metal bridge as an ideal switch that can be inserted on each gap. A reflector is used for providing balanced feeding with a coaxial cable and a higher gain. The air gap between the ground-connected reflector and the crossed dipole is equal to $\lambda_0/4$.

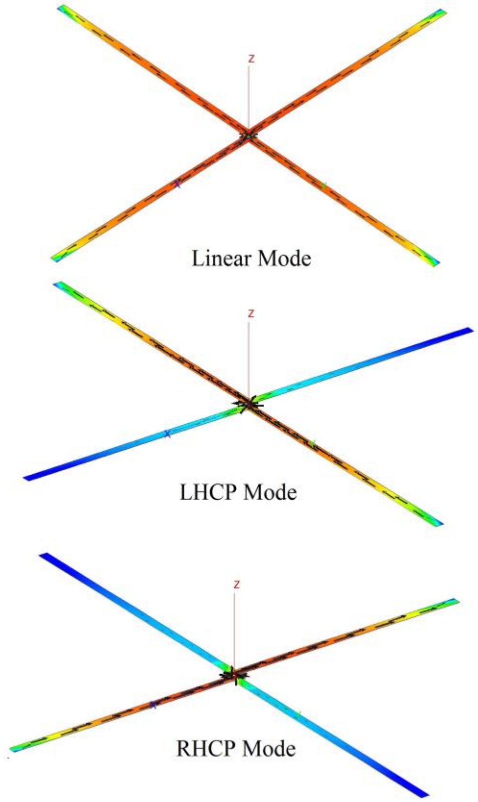


Fig. 5. Crossed dipole current distribution for linear mode in comparison to circular modes.

The states of the switches and the antenna polarization are summarized in Table 1.

Table 1: Antenna polarization corresponding to states of switches

Switch	D1	D2	D3	D4	Polarization
State 1	On	Off	On	Off	LHCP
State 2	Off	On	Off	On	RHCP
State 3	On	On	On	On	Linear Pol.

When D1and D3 are on and D2 and D4 are off, the antenna radiates on a left-hand CP (LHCP) mode and the opposite states of the diodes generate the radiation on a right-hand CP (RHCP) mode. When all switches are on, the antenna radiates on a linear polarization mode.

The proposed antenna is implemented on a substrate with a relative permittivity of 4.4 (FR4) and a thickness of 0.508 mm. Figure 8 shows the photo of an RHCP antenna.

Ideal switches that are on, in Fig. 6, are represented by conductive metal tabs on the gaps while those that are off are represented by leaving the gap unchanged. It has been shown that these simplified implementations of switches, provide acceptable representations for the actual switches [19-22].

The parameters of the crossed dipole shown in Fig. 6 are L_1 = 20.4 mm, L_2 = 3.1 mm, L_3 = 30 mm, G = 1.1 mm, W_1 = 1 mm, r_1 = 0.8 mm, r_2 = 1.5 mm, r_3 = 1.9 mm, and $\alpha = 45°$.There are two vias each with a diameter of 0.2 mm. The antenna is center-fed by a 50 Ω coaxial cable and is placed at a quarter-wavelength above a square reflector to obtain a directional CP or linear radiation pattern.

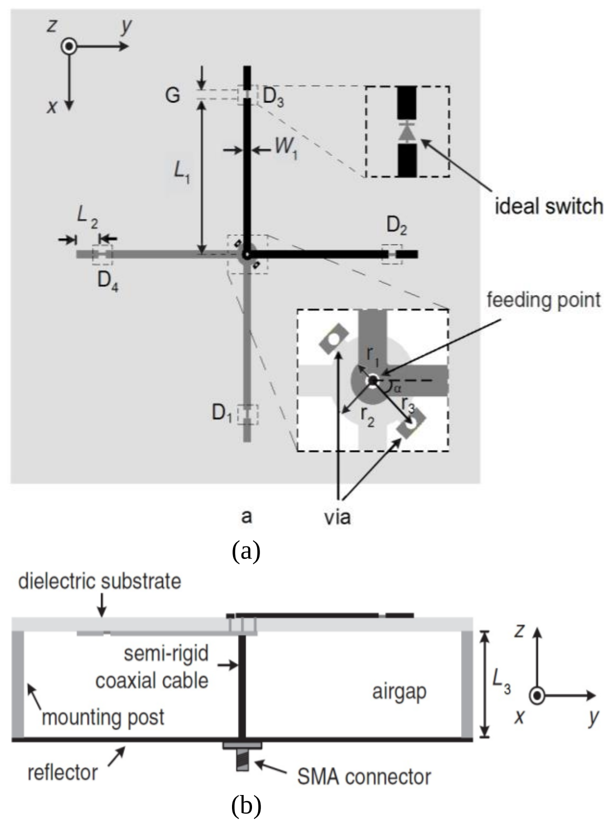
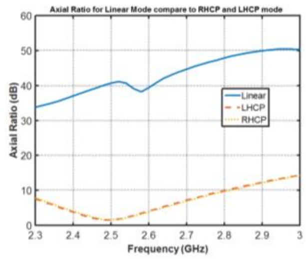


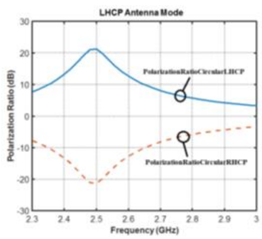
Fig. 6. The configuration of the proposed antenna: (a) top view, and (b) side view.

The antenna has one port for both linear and circular polarization. For isolation between linear mode and circular mode, we can consider the axial ratio. The axial ratio in the circular antenna (LHCP or RHCP) is about 3 dB and in the linear antenna is greater than 30 dB in the desired bandwidth.

HFSS computes the polarization ratio circular LHCP and polarization ratio circular RHCP at each selected aspect angle, so if the polarization ratio circular RHCP is high it means that we have RHCP antenna and vice versa. So the difference between the two graphs in each figure indicates the isolation between the two circular polarization in the antenna. Polarization ratio for RHCP antenna and LHCP antenna are shown in Fig. 7 so as we see in the figure there is proper isolation between RHCP and LHCP mode.



(a)



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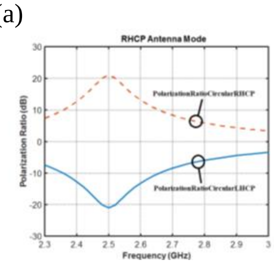


(c)

Fig. 7. (a) Axial ratio for linear mode compare to circular modes, (b) polarization ratio in LHCP antenna mode, (c) polarization ratio in RHCP antenna mode.

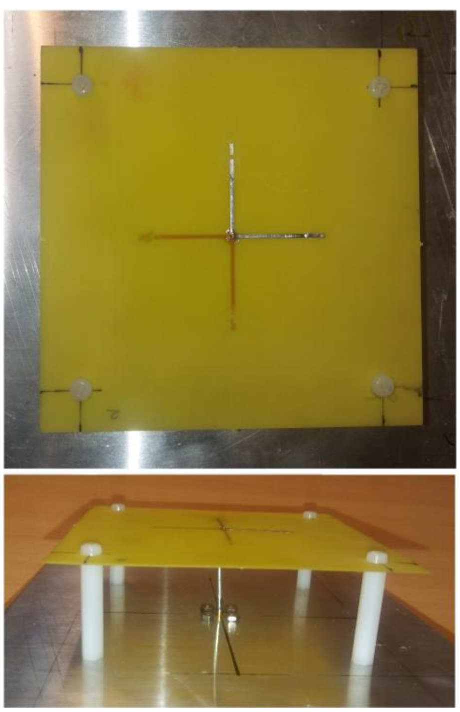
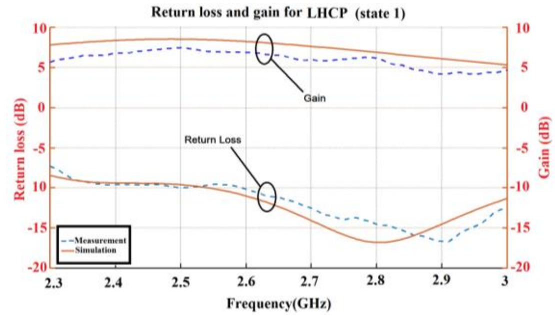


Fig. 8. Photos of RHCP crossed dipole antenna.

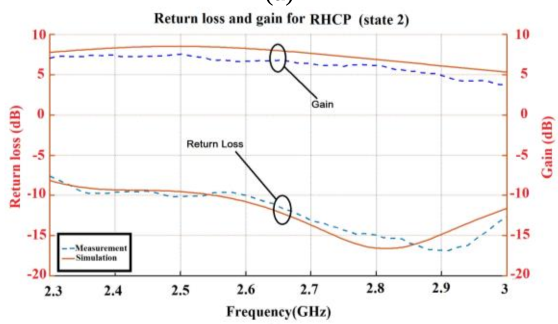
IV. RESULTS

The proposed antenna has been analyzed and optimized with the aid of the Ansoft HFSS and a prototype of the proposed design with the operating frequency at about 2500 MHz has been constructed and studied.

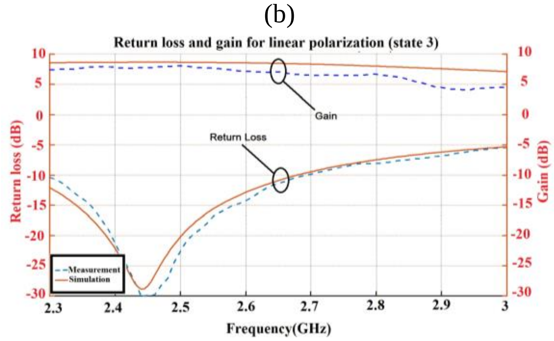
Figure 9 shows the simulated and measured return losses in three states based on Table 1. The measured data in general, agree with the simulated results.



(a)



(b)



(c)

Fig. 9. Return loss and gain: (a) LHCP, (b) RHCP, (c) Linear Polarization.

Figure 10 shows the simulated and measured axial ratio for circular polarization mode. The obtained 3-dB axial ratio bandwidth reaches 140 MHz (2500-2640 MHz) with a center frequency of 2570 MHz that is slightly shifted in respect to the center frequency at 2500 MHz at which a minimum axial ratio is expected. From the measured return loss shown in Fig. 9, it is evident that the return loss for circular polarization is about 10 dB and for linear polarization is better than 12 dB in 3-dB axial ratio bandwidth. Figure 9 also presents the measured antenna gain and the average antenna gain level is about 7 dBi in 3-dB axial ratio bandwidth.

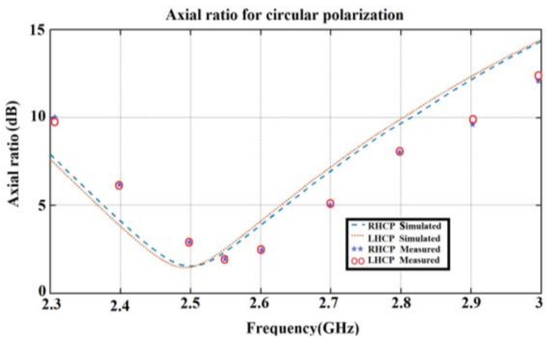


Fig. 10. Axial ratio for circular polarization.

Figures 11 and 12 show the simulated and measured radiation pattern in linear and circular polarization modes respectively. The radiation patterns have been measured in XZ-plane (Φ = 0°) and YZ-plane (Φ = 90°). It is also noted that the antenna has a slant polarization in linear mode.

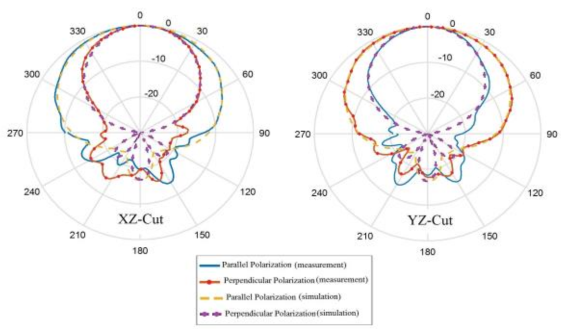


Fig. 11. Normalized radiation pattern in linear polarization mode.

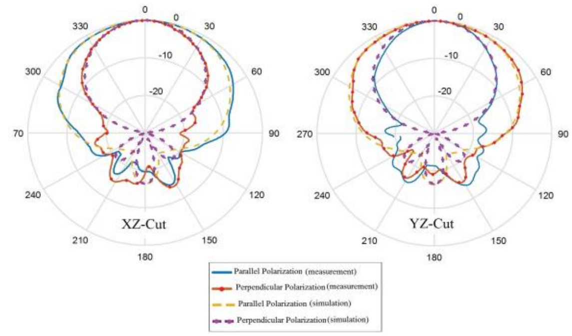


Fig. 12. Normalized radiation pattern in left-hand circular polarization mode.

A comparison of the performances of the proposed antenna and other crossed dipole antennas [8, 14] is shown in Table 2. According to this table, the proposed antenna can produce three polarizations including linear polarization, LHCP, RHCP and possesses better return loss in 3-dB axial ratio bandwidth.

V. CONCLUSION

This paper demonstrates a crossed dipole antenna by employing the theory of characteristic modes in a single coaxial feed. It has been shown that CM theory provides valuable information for mode excitation without any design complexity. The design in this paper illustrates that with changing lengths of antenna arms, we can excite desired modes and polarizations. The proposed reconfigurable antenna can produce LHCP and RHCP and linear polarization. It is expected that by applying this procedure on other CP antennas, we can achieve new design for polarization reconfigurable antennas.

Table 2: Comparison of the performances of crossed dipole antennas

Antenna Structure	**Size of Antenna (Without Biasing Circuit)**	**3-dB Axial Ratio Bandwidth**	**Return Loss in 3-dB Axial Ratio BW**	**Number of Polarizations**
Proposed antenna	$0.422\lambda_0 \times 0.422\lambda_0$ (at 2.57 GHz)	(2500-2640 MHz) 4.3%	10 dB (average)	Three (Linear Pol.-LHCP-RHCP)
Ref. [8]	$0.37\lambda_0 \times 0.37\lambda_0$ (at 2.16 GHz)	(2050-2270 MHz) 10.2%	7.4 dB (average)	Two (LHCP-RHCP)
Ref. [14]	$0.516\lambda_0 \times 0.448\lambda_0$ (at 289.25 MHz)	(296-282.5 MHz) 4.7%	-----	Two (LHCP-RHCP)

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