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A Magneto-Electric Dipole Antenna With Switchable Circular Polarization

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ABSTRACT A polarization reconfigurable magneto-electric (ME) dipole antenna with broad bandwidth is proposed and investigated. Two crossed dipoles through a 90° phase delay line, constituting a sequentially rotated configuration, is used to feed the ME dipole. By manipulating the states of four p-i-n diodes which are inserted in the crossed dipoles, the antenna is able to switch the polarization between two orthogonal circularly polarized states. To verify the performance, the proposed antenna is designed, constructed, and tested. Measurements reveal the design obtains an effective bandwidth of 33.3% and a gain of approximately 8.2 dBic for both polarization states. Besides, stable unidirectional radiation patterns with front-to-back ratios higher than 25 dB are also achieved.

INDEX TERMS Switchable polarization, wide bandwidth, magneto-electric dipole.

I. INTRODUCTION

ANTENNAS with switchable polarization are of great interest in high-speed and highly reliable communication systems, because of their advantages such as mitigating polarization mismatch losses, increasing the system capacity and enhancing the system stability. In the last decade, an enormous amount of research effort has been made to develop polarization reconfigurable antennas [1]–[8]. Among them, patch antennas [1]–[4] or slot antennas [5]–[8] are widely used due to their advantages of low cost and ease of integrating with reconfiguration mechanisms. For example, a low-profile polarization reconfigurable circular patch antenna was presented in [1]. By controlling the orientation of a C-shaped slot etched on the circular patch, different polarizations are achieved. And in [5], a cavity-backed slot antenna with frequency, polarization, and radiation pattern agility was proposed. By varying the states of p-i-n diodes which are inserted in two crossed slots, the antenna is able to switch the polarization between linear polarized (LP) and circular polarized (CP) states. Nevertheless, bandwidths of these designs [1]–[8] are not wide enough and the gains are relatively low. Moreover, a simple structure and a stable performance between different polarization states are also of great concern. In consequence, a suitable antenna candidate with high performance is quite demanded to be used to design polarization reconfigurable antennas.

The magneto-electric (ME) dipole antenna which combines a magnetic dipole and an electric dipole, was first presented in 2006 [9]. As a complementary antenna, it is able to obtain a wide impedance bandwidth, excellent unidirectional radiation patterns and a high gain. Therefore, it is a great candidate for designing reconfigurable antennas. During the last several years, many different reconfigurable ME dipole antennas, focused on frequency [10], beamwidth [11], and polarization [12]–[15] reconfigurabilities have been reported. In [12], a polarization reconfigurable ME dipole antenna was put forward by Wu and Luk. The design was capable of providing two orthogonal LP states. Yet CP radiation is unavailable in this design. Later, antennas which can switch between two circular polarizations were proposed in [13]–[15]. However, effective bandwidths of these designs are all no more than 16%. Therefore, a wideband ME dipole antenna with the ability of switching polarization between two CP states is of great interest. It is worth mentioning that although some wideband polarization reconfigurable antennas have been presented in [16]–[18], these works are designed based on dipole antennas [16], [17] and water antennas [18]. Compared with these types of antennas, ME dipole antenna has more stable unidirectional radiation patterns across the operating band owing to its complementary property. Therefore, a wideband polarization reconfigurable ME dipole antenna is meaningful.

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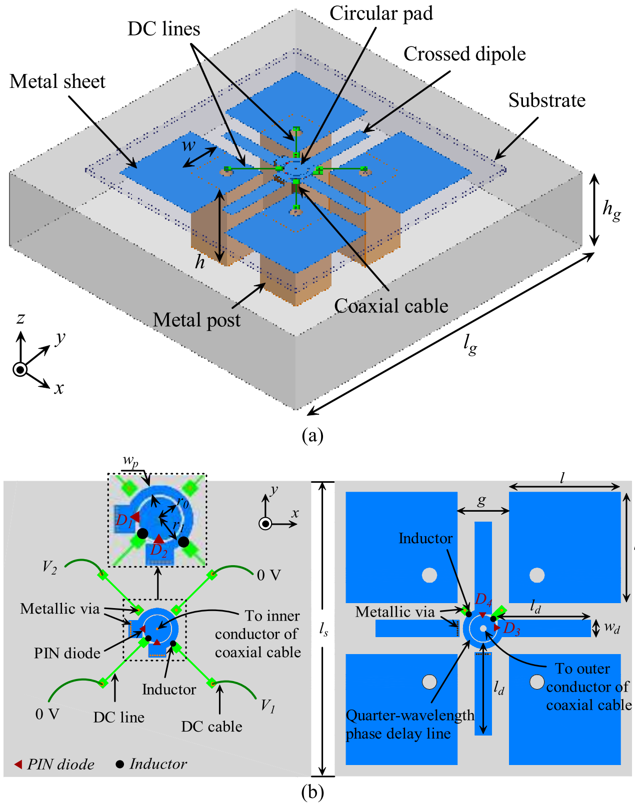

FIGURE 1. Configuration of the proposed polarization reconfigurable ME dipole antenna:(a) 3D view; (b) top side (left) and bottom side (right) of the substrate.

TABLE 1. Dimensions of the proposed antenna.

Parameters	l_g	h_g	l_s	l	w
Values/mm	120 $0.8\lambda_0$	27 $0.18\lambda_0$	88 $0.59\lambda_0$	30 $0.2\lambda_0$	15 $0.1\lambda_0$
Parameters	h	l_d	w_d	g	w_p
Values/mm	27 $0.18\lambda_0$	25 $0.17\lambda_0$	4.5 $0.03\lambda_0$	14 $0.09\lambda_0$	1.5 $0.01\lambda_0$
Parameters	r_0	r_1			
Values/mm	3.1 $0.02\lambda_0$	4.1 $0.03\lambda_0$			

λ_0 is the free-space wavelength at 2 GHz.

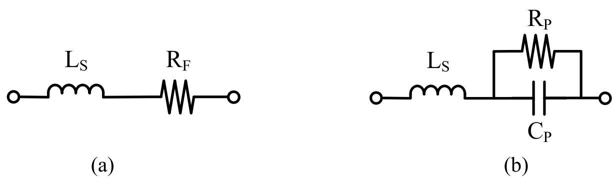

FIGURE 2. Equivalent circuits of the p-i-n diode: (a) ON state; (b) OFF state.

TABLE 2. Values of elements of equivalent circuits.

Element	Value
Ls	0.6 nH
R_f	1.2 Ω
R_p	5 kΩ
C_P	0.15 pF

In this letter, a wideband ME dipole antenna which can switch between two orthogonal CP states is proposed. A pair of crossed dipoles through a 90° phase delay line, constituting a sequentially rotated configuration, is used to feed the ME dipole. Four p-i-n diodes are inserted in the crossed dipoles. The antenna is able to switch the polarization between left-hand (LH) and right-hand (RH) CP states by manipulating the states of these four p-i-n diodes. Besides, the antenna can also obtain wide bandwidths for both impedance and axial ratio (AR), stable gains and stable unidirectional radiation patterns owing to the merits of the ME dipole.

II. ANTENNA DESIGN

A. ANTENNA CONFIGURATION

For the proposed polarization reconfigurable ME dipole antenna, the antenna configuration is depicted in Fig. 1. Table 1 illustrates the detailed dimensions. The antenna is primarily composed of four horizontal metal sheets, four vertical metal posts, two crossed dipoles, a semi-rigid coaxial cable and a cavity-shaped reflector. The metal sheets and metal posts combine together as an ME dipole which is fed by a pair of crossed dipoles. Both the metal sheets and crossed dipoles are printed on the substrate (Taconic RF-30, thickness = 1 mm, $\varepsilon_r = 3.0$). Each crossed dipole possesses a rounded quarter-wavelength microstrip line as a phase delay line to produce a sequentially rotated configuration. The crossed dipoles are connected with the center circular pads and then the inner and outer conductors of the semi-rigid coaxial cable via four p-i-n diodes (model *Infineon BAR50-02L*).

Each diode is able to be in ON state with a DC voltage which supplies a biasing current of higher than 100 mA, whereas it becomes OFF state under zero-bias. The equivalent circuits of the p-i-n diode are described in Fig. 2, and the values of the elements at the chosen biasing condition (biasing current = 100 mA) are given in Table 2. The cathodes of D_1, D_3 are soldered to the crossed dipoles and the anodes of them are soldered to the center circular pads. On the other hand, the anodes of D_2, D_4 are soldered to the crossed dipoles and the cathodes of D_2, D_4 are soldered to the center circular pads. As shown in Fig. 1, by using four printed horizontal DC lines, the circular pads and two crossed dipoles are supplied with DC voltages of 0 V, U_1 and U_2, respectively. 47-nH inductors (model *Murata LQW18A*) are used to isolate the RF signals from the DC circuits. To further control the effects of the DC circuits on the antenna performances, four DC wires, which are hidden inside the metal posts and beneath the cavity-shaped reflector, are used to connect to the DC lines.

TABLE 3. States of diodes for different polarization states.

Polarization	D_1	D_2	D_3	D_4
RHCP	ON	OFF	ON	OFF
LHCP	OFF	ON	OFF	ON

Then the voltage can be supplied to the wires to control the states of four p-i-n diodes.

B. OPERATING PRINCIPLE

As mentioned above, by manipulating the states of four p-i-n diodes, the ME dipole antenna is able to switch the polarization between LHCP and RHCP states and the specific results are summarized in Table 3. To better understand the design idea, this part analyzes the operating principle of the antenna as follows. As is well known, ME dipole is a complementary antenna which combines an electric dipole and a magnetic dipole together. The electric dipole is owing to two pairs of metal sheets and the magnetic dipole is attributed to the apertures between the metal sheets. To obtain a CP radiation, two orthogonal modes with equal magnitude and 90° phase difference is needed. Besides, by controlling the sequential phase between two modes, the antenna can switch the polarization between two orthogonal CP states. In this design, two crossed dipoles through a 90° phase delay line, constituting a sequentially rotated configuration, is used to feed the ME dipole and four p-i-n diodes are inserted in the crossed dipoles. When $U_1 = U_2 = -1.5$ V, D_1, D_3 are ON whereas the other two diodes are in OFF state, which leads the crossed dipoles with a sequential phase as indicated in Fig. 3(a). Accordingly, RHCP performance is obtained for the crossed dipoles as discussed in [19]. Because the crossed dipoles are used as the feeding source, therefore, the ME dipole antenna can be excited with RHCP radiation. To further understand the operating principle, Fig. 4 illustrates the simulated current distribution on the metal sheets and the electric field over the apertures between the metal sheets. Two orthogonally polarized ME dipole modes with 90° phase difference can be distinguished from the simulated results. At time t = 0 and T/2 where T is a period of time, *x*-direction current is dominant on the metal sheets, and *x*-direction electric field is dominant over the aperture along *y*-direction. This means an electric dipole in *x* -direction and an equivalent magnetic dipole in *y*-direction are excited at the same time as marked in Fig. 4 (a) and (c). Likewise, when time t = T/4 and 3T/4, it can be observed that *y*-direction current is dominant on the metal sheets, and *y*-direction electric field is dominant over the aperture along *x*-direction. At this time, an electric dipole in *y* -direction and an equivalent magnetic dipole in *x*-direction are served as radiating sources as marked in Fig. 4 (b) and (d). As a result, an ME dipole antenna with RHCP radiation is achieved. In addition, due to the performance of the ME dipole structure [9], [20], wider impedance and AR bandwidths can be achieved compared with the CP crossed-dipole antenna in [19]. Section III gives specific results for verification. On the other hand, when $U_1 = U_2 = +1.5\ V, D_1, D_3$ are OFF whereas the other two diodes are ON, which leads the crossed dipoles with a sequential phase as indicated in Fig. 2(b). Then LHCP performance is achieved. Hence, by manipulating the states of the p-i-n diodes, the proposed design is able to switch the polarization between two orthogonal CP states.

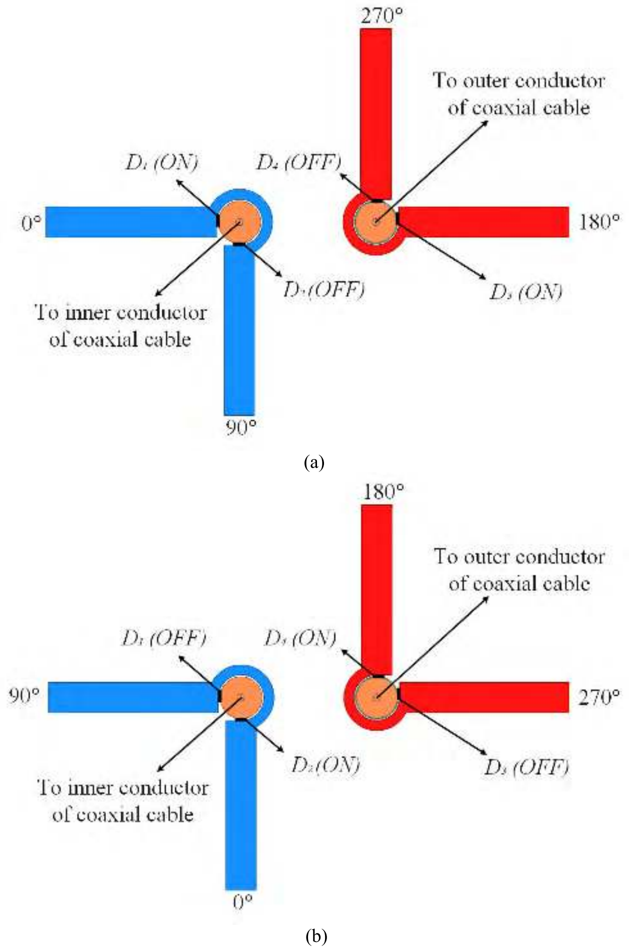

FIGURE 3. RHCP and LHCP states of the crossed dipoles: (a) RHCP state; (b) LHCP state. (Red and blue lines represent the two crossed dipoles, respectively.)

III. RESULTS

The fabricated antenna shown in Fig. 5 was measured to demonstrate its performance. The simulated results were obtained by software Ansys HFSS and measurements were completed by an Agilent E5080A network analyzer and a near-field measurement system.

Simulated and measured return losses and ARs in two states are depicted in Fig. 6. It is observed that the measured impedance bandwidths for $S_{11} \leq -10$ dB are of 46.7% from 1.59 to 2.56 GHz in the LHCP state and of 39.4% from

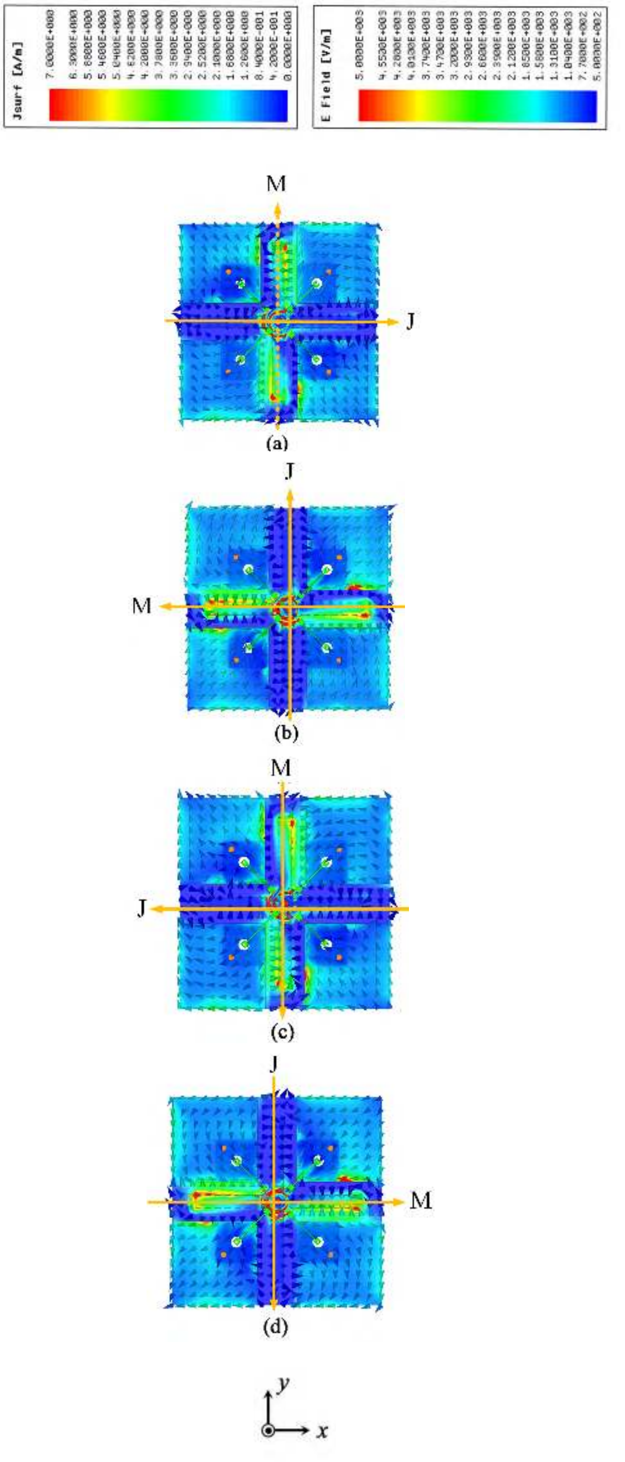

FIGURE 4. Current and electric field distributions on the proposed antenna over a period of time: (a) t = 0; (b) t = T/4; (c) t = T/2; (d) t = 3T/4.

1.73 to 2.58 GHz in the RHCP state. The measured AR bandwidths for AR ≤ 3 dB are of 46.7% from 1.72 to 2.46 GHz and of 39.4% from 1.74 to 2.52 GHz in two states, separately. Hence, the effective bandwidth of this design is 33.3% from 1.74 to 2.46 GHz. The discrepancies of the measured

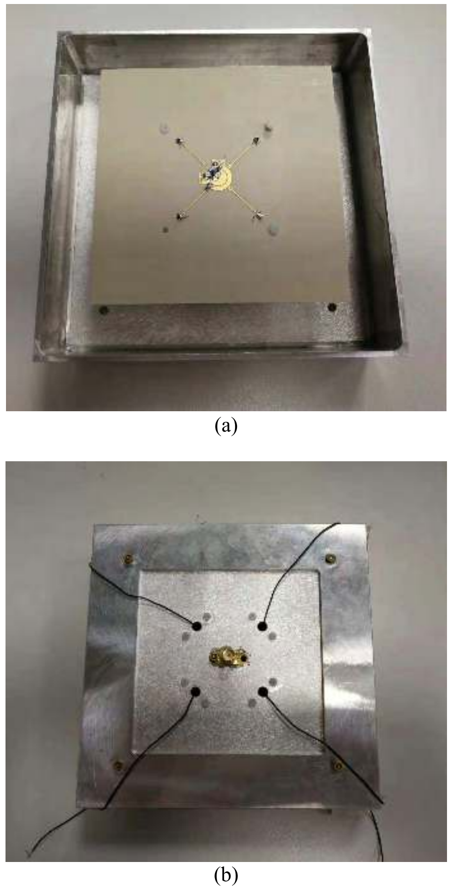

FIGURE 5. Fabricated antenna: (a) top side; (b) bottom side.

TABLE 4. Comparison between proposed and other reported polarization reconfigurable me dipole antennas.

Ref.	Antenna Type	Effective BW %	Gain (dBic)	Size
[13]	ME dipole	7.9	9	$0.91\lambda_0 \times 0.91\lambda_0 \times 0.24\lambda_0$
[14]	ME dipole	3.6	8.2	$0.84\lambda_0 \times 0.84\lambda_0 \times 0.24\lambda_0$
[15]	ME dipole	16	8.2	$1.0\lambda_0 \times 1.0\lambda_0 \times 0.27\lambda_0$
[21]	ME dipole	33.9	8.2	$0.8\lambda_0 \times 1.05\lambda_0 \times 0.21\lambda_0$
This Work	ME dipole	33.3	8.2	$0.8\lambda_0 \times 0.8\lambda_0 \times 0.18\lambda_0$

impedance bandwidths and AR bandwidths between two states are mainly due to the fabrication tolerance.

Fig. 7 shows the simulated and measured broadside gains of the proposed antenna. It can be seen that the measured gains are from 7.4 to 8.9 dBic and 7.7 to 8.8 dBic over the effective band in two states, respectively.

Fig. 8 gives the simulated and measured radiation patterns. Unidirectional radiation patterns with front-to-back ratios

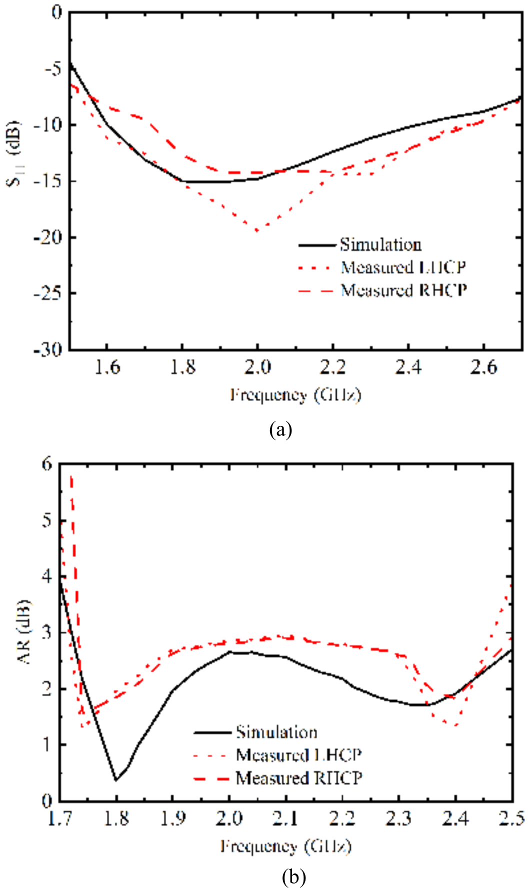

FIGURE 6. Simulated and measured return losses and ARs: (a) return losses; (b) ARs.

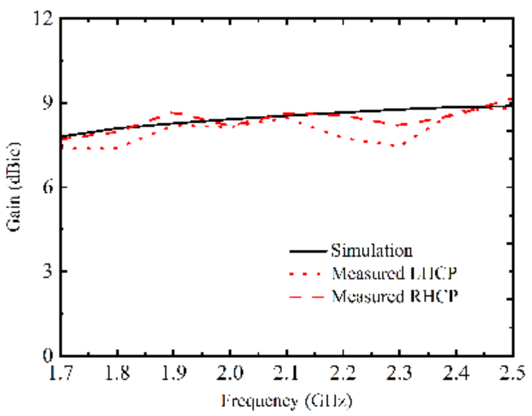

FIGURE 7. Simulated and measured broadside gains.

larger than 25 dB are achieved. Besides, the radiation patterns are symmetrical and stable across the effective band, demonstrating the superiority of ME dipole antenna. Owing to the influence of additional DC wires during the measurement, the back radiations between the simulated and measured results are slightly different.

Table 4 lists a comparison between our work and other reported polarization reconfigurable ME dipole antennas. Compared with the designs presented in [13]–[15], our work has a much wider effective bandwidth and a more compact size. Compared with the antenna presented in [21], our work has a more compact size.

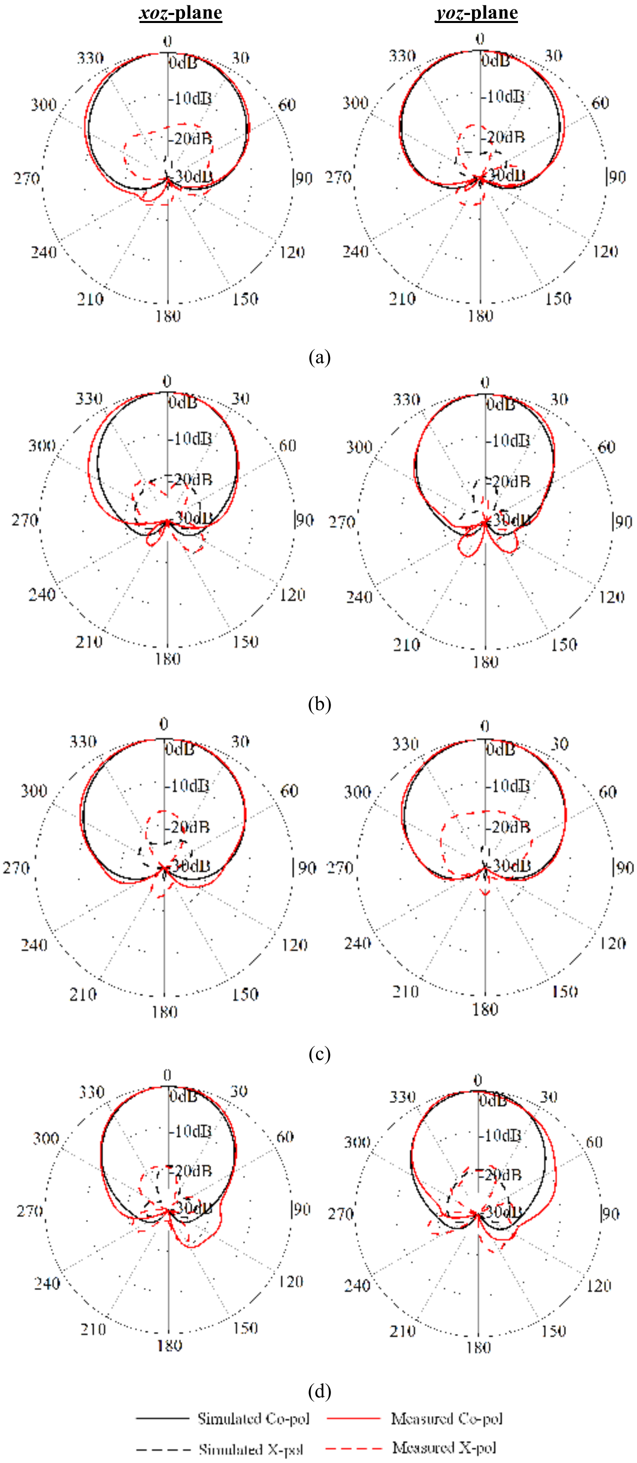

FIGURE 8. Simulated and measured radiation patterns in two states: (a) 1.84 GHz in LHCP; (b) 2.4 GHz in LHCP; (c) 1.84 GHz in RHCP; (d) 2.4 GHz in RHCP.

IV. CONCLUSION

A novel polarization reconfigurable antenna with switchable circular polarization has been proposed. By manipulating the states of four p-i-n diodes inserted in the crossed dipoles, the antenna can switch its polarization between LHCP and RHCP states. To verify the design idea, the proposed antenna was constructed and tested. The measurements demonstrate that the design has a wide effective bandwidth of 33.3%. Besides, a gain of approximately 8.2 dBic for both polarization states and unidirectional radiations are also realized. With these merits, this design is able to be applied in wireless communication systems.

REFERENCES

[1] K. M. Mak, H. W. Lai, K. M. Luk, and K. L. Ho, "Polarization reconfigurable circular patch antenna with a C-shaped," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1388–1392, Mar. 2017.

[2] W. Lin and H. Wong, "Multipolarization-reconfigurable circular patch antenna with L-shaped probes," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1549–1552, 2017.

[3] W. Lin and H. Wong, "Wideband circular-polarization reconfigurable antenna with L-shaped feeding probes," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2114–2117, 2017.

[4] W. Lin and H. Wong, "Polarization reconfigurable aperture-fed patch antenna and array," *IEEE Access*, vol. 4, pp. 1510–1517, 2016.

[5] L. Ge, Y. Li, J. Wang, and C.-Y.-D. Sim, "A low-profile reconfigurable cavity-backed slot antenna with frequency, polarization, and radiation pattern agility," *IEEE Trans. Antenna Propag.*, vol. 65, no. 5, pp. 2182–2189, May 2017.

[6] Y. Li, Z. Zhang, W. Chen, and Z. Feng, "Polarization reconfigurable slot antenna with a novel compact CPW-to-slotline transition for WLAN application," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 252–255, 2010.

[7] S.-G. Zhou, G.-L. Huang, H.-Y. Liu, A.-S. Lin, and C.-Y.-D. Sim, "A CPW-fed square-ring slot antenna with reconfigurable polarization," *IEEE Access*, vol. 6, pp. 16474–16483, 2018.

[8] M. K. Fries, M. Grani, and R. Vahldieck, "A reconfigurable slot antenna with switchable polarization," *IEEE Microw. Wireless Compon. Lett.*, vol. 13, no. 11, pp. 490–492, Nov. 2003.

[9] K.-M. Luk and H. Wong, "A new wideband unidirectional antenna element," *Int. J. Microw. Opt. Technol.*, vol. 1, no. 1, pp. 35–44, Jun. 2006.

[10] L. Ge and K. M. Luk, "Band-reconfigurable unidirectional antenna: A simple, efficient magneto-electric antenna for cognitive radio applications," *IEEE Antennas Propag. Mag.*, vol. 58, no. 2, pp. 18–27, Apr. 2016.

[11] L. Ge and K. M. Luk, "A three-element linear magneto-electric dipole array with beamwidth reconfiguration," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 28–31, 2015.

[12] F. Wu and K. M. Luk, "A reconfigurable magneto-electric dipole antenna using bent cross-dipole feed for polarization diversity," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 412–415, 2017.

[13] F. Wu and K. M. Luk, "Single-port reconfigurable magneto-electric dipole antenna with quad-polarization diversity," *IEEE Trans. Antennas Propag.*, vol. 65, no. 5, pp. 2289–2296, May 2017.

[14] F. Wu and K. M. Luk, "Wideband tri-polarization reconfigurable magneto-electric dipole antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1633–1641, Apr. 2017.

[15] L. Ge, X. Yang, D. Zhang, M. Li, and H. Wong, "Polarization-reconfigurable magnetoelectric dipole antenna for 5G Wi-Fi," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1504–1507, 2017.

[16] J.-S. Row and Y.-H. Wei, "Wideband reconfigurable crossed-dipole antenna with quad-polarization diversity," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 2090–2094, Apr. 2018.

[17] 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, Dec. 2017.

[18] Z. Hu, S. Wang, Z. Shen, and W. Wu, "Broadband polarization-reconfigurable water spiral antenna of low profile," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1377–1380, 2016.

[19] J. W. Baik, K. J. Lee, W. S. Yoon, T. H. Lee, and Y. S. Kim, "Circularly polarised printed crossed dipole antennas with broadband axial ratio," *Electron. Lett.*, vol. 44, no. 13, pp. 785–786, Jun. 2008.

[20] M. Li and K.-M. Luk, "Wideband magnetoelectric dipole antennas with dual polarization and circular polarization," *IEEE Antennas Propag. Mag.*, vol. 57, no. 1, pp. 110–119, Feb. 2015.

[21] Y. Shi, Y. Cai, X.-F. Zhang, and K. Kang, "A simple tri-polarization reconfigurable magneto-electric dipole antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, pp. 291–294, 2018.

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