Progress In Electromagnetics Research C, Vol. 55, 35–42, 2014

A Monopole Antenna with Dual-Band Reconfigurable Circular Polarization

Shujie Shi*, Weiping Ding, and Kang Luo

Abstract—This paper describes a monopole antenna with dual-band switchable circular polarization (CP) sense in WLAN and WiMAX bands. The proposed antenna consists of a rectangular patch fed by a microstrip line and a ground plane embedded with a T-shaped slot integrated with PIN diodes. The slotted ground is capable of exciting CP sense around 2.45 GHz for WLAN and around 3.4 GHz for WiMAX, respectively. Two triangular strips are added to improve impedance matching. The CP sense of the proposed antenna can be reconfigured between the right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) by switching the states of PIN diodes in the slot. The lower band 3-dB axial ratio (AR) bandwidth is 8.6%, and the upper band 3-dB AR bandwidth is 20.8%, in which the return loss is less than −10-dB. Simulated analysis and measured results are carried out and good agreement is achieved.

1. INTRODUCTION

In recent years, due to the development of wireless communication, reconfigurable antennas have received much more attention. Reconfigurable antennas are gaining popularity as they can offer diversity performances to optimize communication quality and capacity. Frequency reconfigurable antennas [1–3] are particularly demanded for cognitive radios where the transceivers need the ability to change the operating frequency band. The switchable polarization antenna [4, 5] can be used to mitigate signal fading in multipath propagation environments and reuse frequencies to double transmission channels. Pattern reconfigurable antennas [6] are usually selected in multiple input multiple output (MIMO) systems, because they can adaptively change their radiation patterns depending on the wireless channel to improve the gain. As the CP antenna can reduce the loss caused by the polarization misalignment between the transmitting and receiving antennas, it is highly desired in mobile wireless communications [7, 8]. It makes sense that reconfigurable CP antennas are used in order to reduce fading and reuse frequencies in the modern communication systems.

It is possible to achieve reconfigurable CP for microstrip antennas fed by switchable networks [9]. It is a conventional approach to realize reconfigurable CP by simply using single-feed planar rectangular patch antennas with switchable corner truncations [10]. It is also possible to achieve switchable CP microstrip antennas with selectable shorting pins which are switched to the ground plane [11]. Moreover, it is widely used to achieve CP operation by adding stubs and slots to generate two orthogonal modes with equal amplitudes and 90° phase difference [12]. Hence, switchable slot and stub can be used to design reconfigurable CP antennas. Relatively in the scope of authors' knowledge, few works have been concentrated on designs with dual-band reconfigurable CP antennas.

In this paper, a dual-band reconfigurable CP antenna operating in WLAN and WiMAX bands is proposed. A T-shaped slot with PIN diodes is embedded on the ground plane of the antenna. In order

Received 11 October 2014, Accepted 13 November 2014, Scheduled 20 November 2014
* Corresponding author: Shujie Shi (shishujie1990@126.com).
The authors are with the Institute of Communications Engineering, PLA University of Science and Technology, 2 Biaoying at YuDao Street, Nan Jing, Jiangsu 210007, China.

to achieve CP sense reconfiguration, a pair of PIN diodes are integrated in the two arms of the T-shaped slot to activate or deactivate them respectively. Hence, the etched slot would be switched between the L-shaped and the inverted L-shaped, and the CP sense of the proposed antenna would be altered at both the lower band (around 2.45 GHz) for WLAN and upper band (around 3.4 GHz) for WiMAX. Unlike the conventional switchable polarizations studied in past literature, the proposed antenna can be switched by controlling the PIN diodes for LHCP and RHCP in two bands at the same time.

2. ANTENNA DESIGN

As shown in Figure 1, the proposed antenna is fabricated on a FR4 substrate with a dielectric constant of $\varepsilon_r = 4.4$ and a thickness of 1.6 mm. The overall dimension of the antennas is about $40 \times 40 \times 1.6\,\text{mm}^3$. In order to realize broadband impedance characteristic, the length L_0 of monopole radiator and the length $S_1 + S_2$ of the L-shaped slot are designed to generate two resonant modes at 2.45 GHz and 3.4 GHz respectively. The approximate values for them are a quarter-wavelength of referenced frequencies, given by

$$L \approx \frac{\lambda_g}{4} = \frac{\lambda_r}{4\sqrt{\varepsilon_{eff}}} = \frac{c}{4\sqrt{\varepsilon_{eff}}\,f_r} \tag{1}$$

where c is the speed of light, λ_r the free space wavelength of the resonant frequency f_r, and ε_{eff} the approximately effective dielectric constant. The effective dielectric constants for the rectangular patch and the L-shaped slot are respectively given by equations [13] below.

For microstrip lines and $W_0/h \geq 1$:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W_0}\right)^{-\frac{1}{2}} \tag{2}$$

where W_0 is the width of the microstrip line and h the thickness of the substrate.

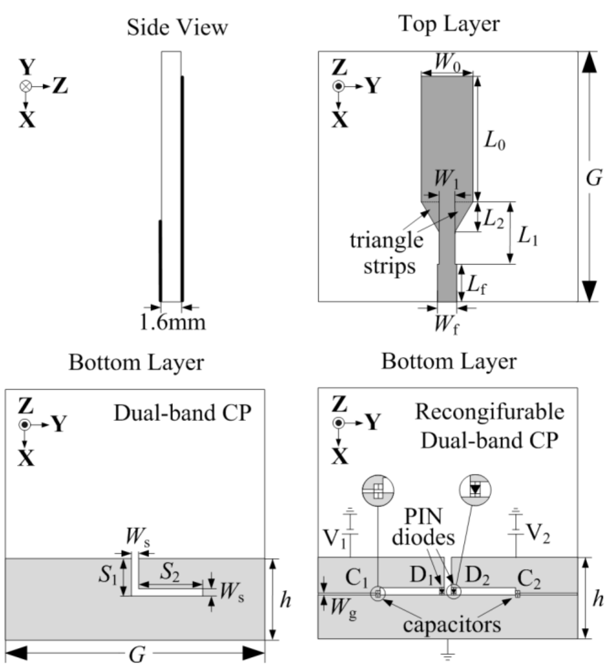


Figure 1. Geometry of the proposed antenna. (The dark/light grey indicates the microstrip on the front/back of the substrate.).

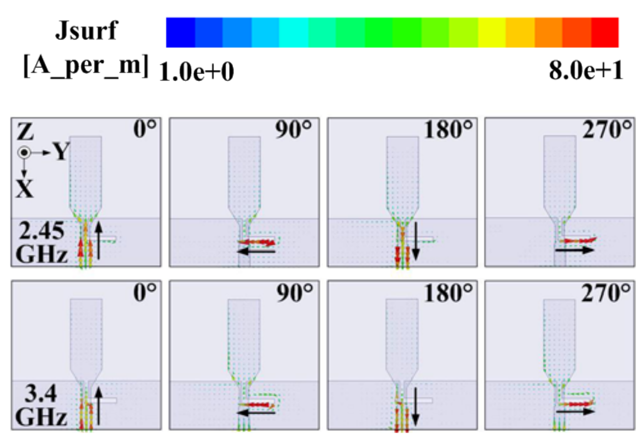


Figure 2. Current distributions of the proposed dual-band CP antenna with a slotted ground.

For slotlines and $3.8 \leq \varepsilon_r \leq 9.8$, $0.0015 \leq W_S/\lambda_r \leq 0.075$:

$$\varepsilon_{eff} = \left\{0.9217 - 0.277\ln\varepsilon_r + 0.0322(W_S/h)\sqrt{\frac{\varepsilon_r}{W_S/h + 0.435}} - 0.01\ln(h/\lambda_r)\left[4.6 - \frac{3.65}{\varepsilon_r^2\sqrt{W_S/\lambda_r}(9.06 - 100W_S/\lambda_r)}\right]\right\}^{-2} \tag{3}$$

where W_S is the width of the slotline.

The rectangular patch features vertical linear polarization mainly at 2.45 GHz. And the L-shaped slotted ground features horizontal linear polarization mainly at 3.4 GHz. Because the original monopole antenna is a wideband design, and the slot provides a minor resonance at 2.45 GHz, we can adjust parameters of the rectangular patch and the slot to make two orthogonal modes shift a little from the target frequency respectively to achieve 90° phase difference and equal amplitude, and to achieve CP operation at both frequencies.

Figure 2 shows the current distributions of each polarization at 2.45 GHz and 3.4 GHz. In both the lower and upper bands, the current rotates anticlockwise, and the antenna radiates in RHCP mode in $+z$ half space. Reference direction is always $+z$ direction when the polarization sense is discussed below. By flipping the L-shaped slot along the x-axis, the direction of the horizontal E vector (E_H) will be reversed, and the CP sense will also be altered from RHCP to LHCP.

Combining the L-shaped slot with the inverted L-shaped slot into a T-shaped slot and integrating two PIN diodes (SMP1320-079) in the slot to control the electrical property shape of the slot, we achieve a dual-band reconfigurable CP antenna, as shown in Figure 1. In order to isolate the direct current (DC) while maintaining continuity for the RF, a narrow slot is added to divide ground plane into three portions, and two capacitors are used to connect the three portions of the divided ground plane. When

Table 1. Summary of antenna polarization.

State	Bias Condition		Diodes		Polarization	
	V_1	V_2	D_1	D_2	2.45 GHz	3.4 GHz
State 1	0.7 V	-	ON	OFF	RHCP	RHCP
State 2	-	0.7 V	OFF	ON	LHCP	LHCP

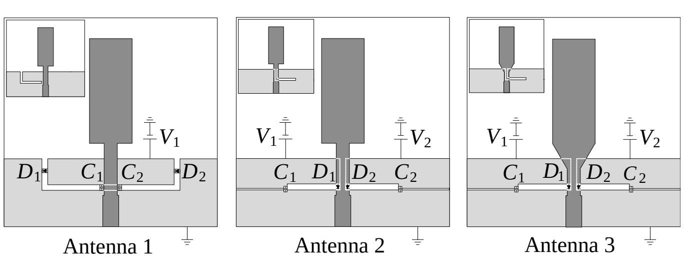


Figure 3. Three improved prototypes of the proposed antenna. (C_1 and C_2 denote capacitors. D_1 and D_2 denote PIN diodes.).

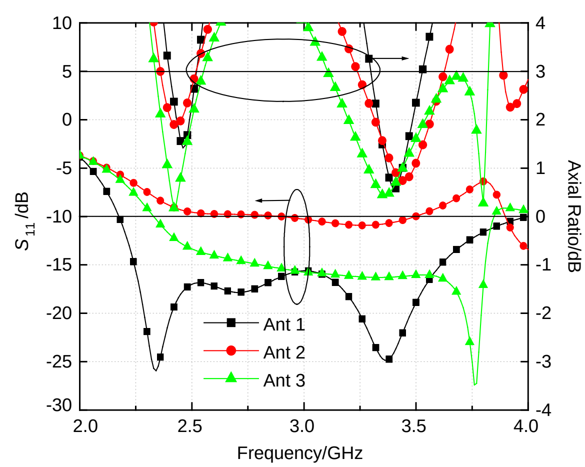


Figure 4. Simulated S_{11} and AR of Antenna 1, Antenna 2 and Antenna 3.

a positive voltage is applied, a diode is on and acts as a small resistor that can be regarded as a short circuit. Otherwise, when a negative voltage is supplied, a diode is off and acts as a small capacitor that can be regarded as an open circuit. A bias circuit is demanded to control the states of the diodes. Hence, when diode D_1 is on and diode D_2 is off, the left arm of the T-shaped slot is deactivated, and the right arm is activated. Consequently, the T-shaped slot acts as the L-shaped slot for generating RHCP at 2.45 GHz and 3.4 GHz. Similarly, when the diode D_1 is off and diode D_2 on, the T-shaped slot acts as the inverted L-shaped slot. And the antenna can excite LHCP at 2.45 GHz and 3.4 GHz. Table 1 summarizes the polarization control and operation of the reconfigurable antenna.

To clarify the improvement process, the three antenna designs are defined as follow in Figure 3: Antenna 1 includes a rectangular patch fed by a microstrip line and the U-shaped slotted ground integrated with two PIN diodes and two capacitors on the bottom layer; Antenna 2 contains a rectangular radiator fed by a microstrip line and a ground embedded with the T-shaped slot loaded with two PIN diodes and two capacitors; Antenna 3 adds two triangle strips attached to the junction between the rectangular patch and the microstrip feeding line to the design of Antenna 2.

Comparisons among Antenna 1, Antenna 2 and Antenna 3 can be observed from Figure 4. Comparing Antenna 1 with Antenna 2, we can see that the T-shaped slot design can enhance the AR bandwidth at both the lower band from 130 MHz to 180 MHz and upper band from 230 MHz to 390 MHz, and excite another CP sense at 3.93 GHz, but it causes the mismatching between the impedance bandwidth and the AR bandwidth.

Compared with Antenna 2, by adding two triangular strips, Antenna 3 enhances the AR bandwidth further and also improves the impedance bandwidth. Adding two triangular strips enlarges the AR bandwidth from 180 MHz to 230 MHz at the lower band and makes the upper CP band and another higher CP band merge into a broad CP band (720 MHz). Moreover, at the 3-dB AR bandwidth, it makes the return loss always less than −10-dB. It can be found that owing to the vertical slot in the center of the ground and two triangular strips, the vertical current can be strengthened at 3.4 GHz through the comparison between Figure 5(a) and Figure 5(b). Therefore, it makes amplitudes of the vertical E vector (E_V) and the horizontal E vector (E_H) more balanced to radiate better CP operation at 3.4 GHz. From Figure 5(c) and Figure 5(d), we can find that the new design introduces the current along the x-axis at 3.8 GHz to generate a new CP frequency band. In conclusion, the AR bandwidth of Antenna 3 is wider than Antenna 1.

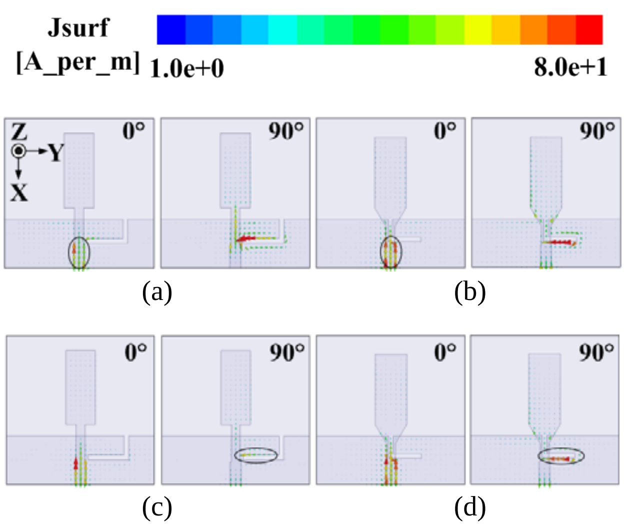


Figure 5. Current distributions of prototypes of Antenna 1 at (a) 3.4 GHz, (c) 3.8 GHz, and of Antenna 3 at (b) 3.4 GHz, (d) 3.8 GHz.

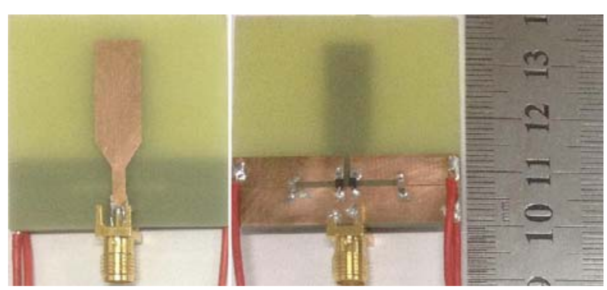


Figure 6. Photograph of the proposed dual-band reconfigurable CP antenna.

3. SIMULATION AND EXPERIMENT RESULTS

The proposed dual-band reconfigurable CP antenna is fabricated on an FR4 substrate. All the geometrical parameters are $G = 40\,\text{mm}$, $W_f = 3\,\text{mm}$, $L_f = 6\,\text{mm}$, $W_s = 1.2\,\text{mm}$, $W_g = 0.2$ mm, $W_0 = 8.5\,\text{mm}$, $L_0 = 19\,\text{mm}$, $W_1 = 2.4\,\text{mm}$, $L_1 = 10\,\text{mm}$, $L_2 = 5\,\text{mm}$, $h = 13\,\text{mm}$, $S_1 = 6\,\text{mm}$, $S_2 = 8.2\,\text{mm}$. According to datasheets of the components, the dimension of diodes is simulated as $0.7 \times 1.2\,\text{mm}^2$, and capacitors are simulated as $0.8 \times 1.2\,\text{mm}^2$. Figure 6 shows the front and back of the antenna. The anodes of the two diodes are upward, and the cathodes of them are downward. Effects of different values of S_1, S_2, L_1 and L_2 on the antenna performance are investigated. Figure 7(a) and Figure 7(b) show the effects of the slot length S_1 and S_2 on the reflection coefficient (S_{11}) and AR. It is found that the center frequency of S_{11} and AR decreases as S_1 increases, because as S_1 increases, the effective electrical length of the slot increases gradually.

However, the −10-dB bandwidth of S_{11} maintains relatively stationary, and the 3-dB bandwidth of AR is relatively sensitive to S_1. The other length dimension of slot S_2 has a similar influence on the antenna performance to S_1. Therefore, it can be seen easily that the center frequency of AR decreases as the total length of the slot increases. Then, we can mainly control the slot length S_1 and S_2 to determine the CP frequency bands of the antenna. Comprehensively evaluating the antenna performance at the lower and upper bands, the final values of S_1 and S_2 are 6 mm and 8.8 mm.

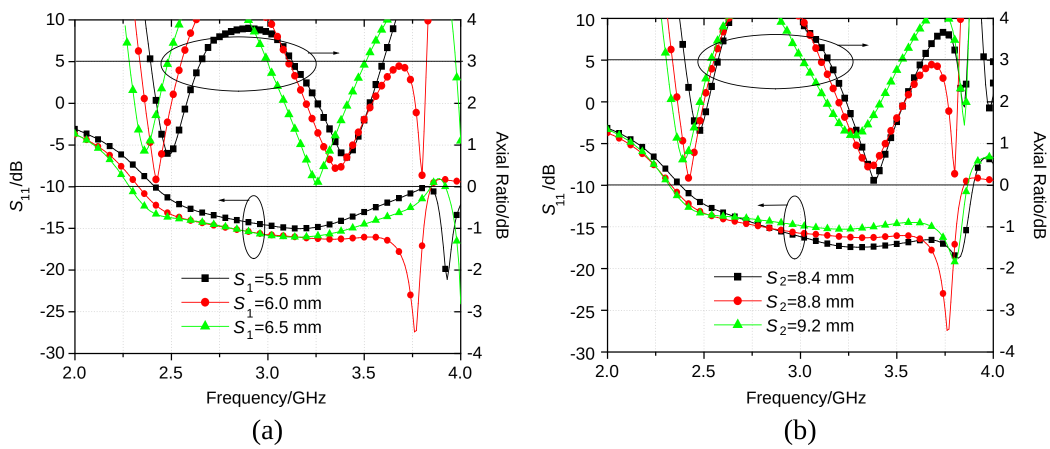


Figure 7. Effects of the slot length on the antenna performance. (a) Vertical length of the L-shaped slot (S_1). (b) Horizontal length of the L-shaped slot (S_2).

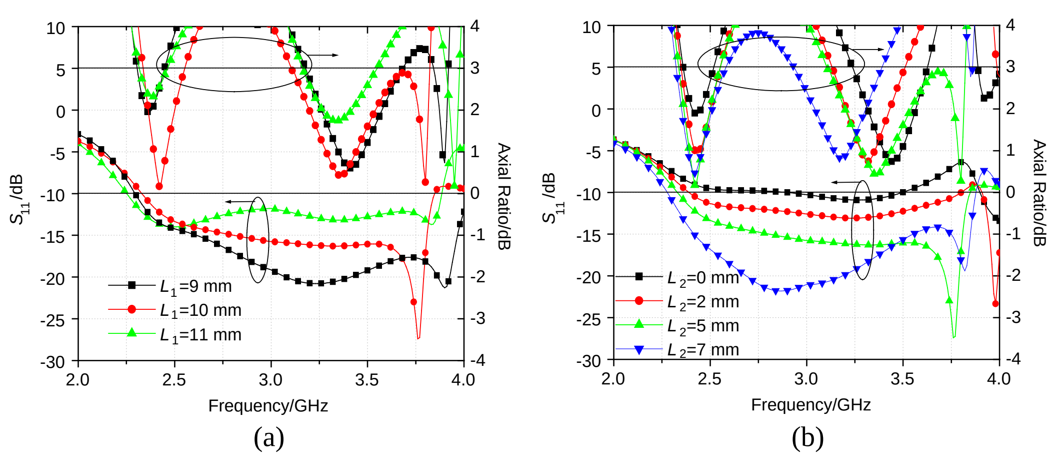
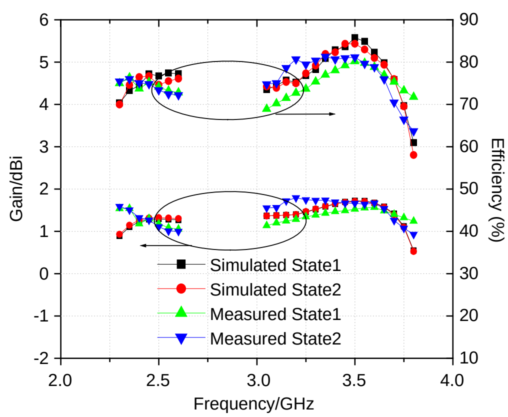


Figure 8. Effects of the feeding line's length and triangular strips' size on the antenna performance. (a) Length of the feeding line (L_1). (b) Size of triangular strips (L_2).

As depicted in Figure 8(a) and Figure 8(b), the length of the feeding line and the size of two triangular strips have significant influence on return loss and AR. Adjusting the feeding line length L_1 is equivalent to tuning the gap between the rectangular patch and the ground plane. L_2 is the main parameter of two triangular strips, which is added to improve impedance matching. By decreasing L_1 or increasing L_2, matching of the frequency bands (from 2.33 to 2.55 GHz and from 3.10 to 3.82 GHz) is considerably improved. This is because these two parameters can influence the coupling between the top metal and the ground. When these two parameters are fixed at $L_1 = 10\,\text{mm}$, $L_2 = 5\,\text{mm}$, the widest bandwidth of the proposed antenna can be achieved.

Simulated and measured frequency responses of the reflection coefficient for the two states of the proposed reconfigurable antenna are presented in Figure 9(a). The measured S_{11} is tested by using a vector network analyzer (Agilent N5230C). The measured −10-dB bandwidths of S_{11} for both State 1 and State 2 are about 1.6 GHz (2.3–3.9 GHz). Good impedance match is obtained. An anechoic chamber is used to measure AR and radiation pattern. Figure 9(a) and Figure 9(b) respectively show the axial ratio and gain curves for the two states of the reconfigurable antenna at two CP bands. The average efficiencies for both bands and both states are about 75% as depicted in Figure 9(a). For both states, simulated and measured values of 3-dB AR bandwidths and peak gains are provided in Table 2.

Figure 10 depicts the measured normalized radiation patterns of the two states of the reconfigurable antenna at both xz-plane and yz-plane at 2.45 GHz, 3.4 GHz and 3.8 GHz. It can be observed that good RHCP radiations are achieved for the operating bands around 2.45 and 3.4 GHz for State 1, and



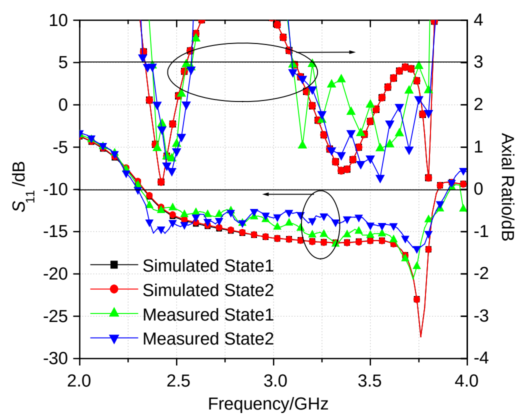


Figure 9. Simulated and measured performance of the antenna. (a) Gain and efficiency. (b) Return loss (S_{11}) and axial ratio.

Table 2. Simulated and measured values for both states.

State		Lower band		Upper band	
		3-dB AR bandwidth	Peak Gain	3-dB AR bandwidth	Peak Gain
1	Sim	220 MHz (2.33–2.55 GHz)	1.3 dBi (2.49 GHz)	720 MHz (3.1–3.82 GHz)	1.72 dBi (3.52 GHz)
	Mea	200 MHz (2.37–2.57 GHz)	1.6 dBi (2.325 GHz)	700 MHz (3.1–3.8 GHz)	1.57 dBi (3.6 GHz)
2	Sim	220 MHz (2.33–2.55 GHz)	1.33 dBi (2.49 GHz)	720 MHz (3.1–3.82 GHz)	1.71 dBi (3.52 GHz)
	Mea	230 MHz (2.35–2.58 GHz)	1.62 dBi (2.325 GHz)	710 MHz (3.1–3.81GHZ)	1.79 dBi (3.2 GHz)

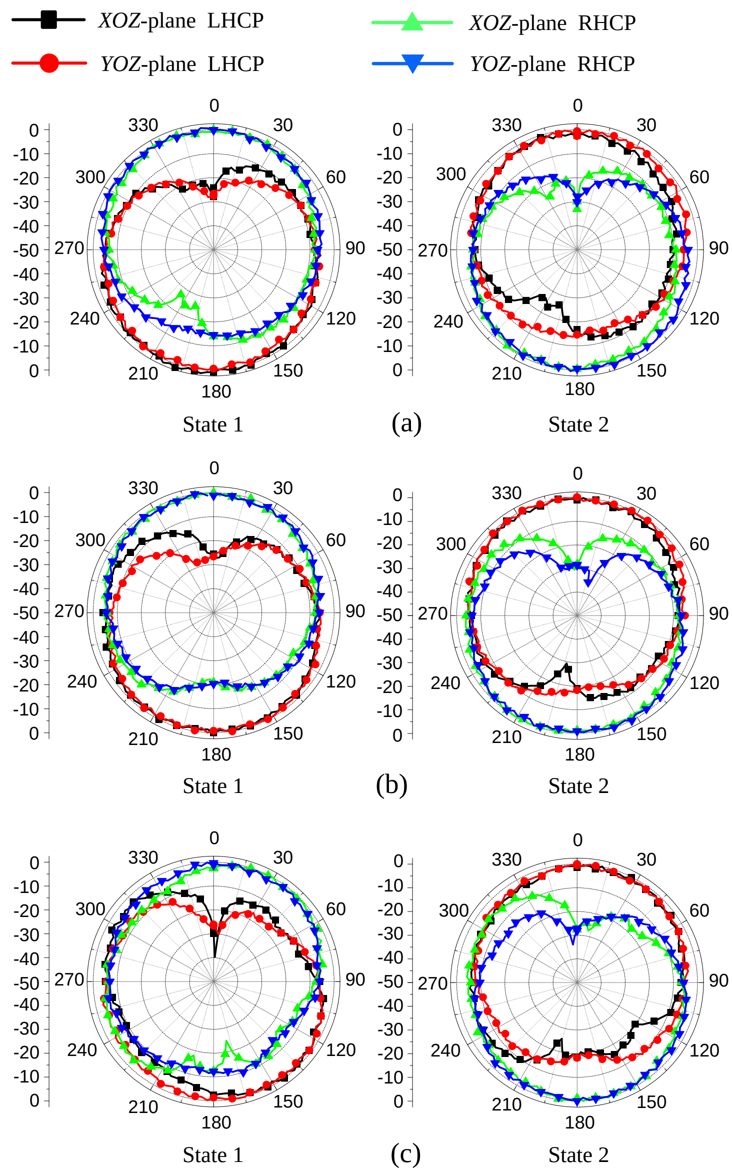


Figure 10. Measured normalized radiation patterns of the antenna. (a) At 2.45 GHz. (b) At 3.4 GHz. (c) At 3.8 GHz.

the contrary CP sense is obtained at the same operating bands for State 2. As shown in Figure 10, the radiation patterns at both sides of the antenna are similar with contrary CP senses, due to the bidirectional radiated monopole antenna structure [14].

4. CONCLUSION

In this paper, a dual-band reconfigurable CP antenna operating in WLAN and WiMAX bands is proposed. The switchable CP states are generated due to the reconfigurable slotted structure controlled by PIN diodes on the ground plane. As the antenna has the ability to switch the polarization state between LHCP and RHCP in two bands simultaneously, it can be used to reuse frequencies and increase the system capacity further in multifunctional applications. This proposed dual-band reconfigurable CP antenna can be used in multifunctional applications, such as multiple input multiple output (MIMO) systems, to reuse frequencies and doubles the system capacity.

REFERENCES

1. Boudaghi, H., M. Azarmanesh, and M. Mehranpour, "A frequency-reconfigurable monopole antenna using switchable slotted ground structure," *IEEE Antennas Wireless Propag. Lett.*, Vol. 11, 655–658, 2012.
2. Anagnostou, D. E. and A. A. Gheethan, "A coplanar reconfigurable folded slot antenna without bias network for WLAN applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 1057–1060, 2009.
3. Gheethan, A. A. and D. E. Anagnostou, "Broadband and dual-band coplanar folded-slot antennas (CFSAs)," *IEEE Antennas Propag. Mag.*, Vol. 53, No. 1, 80–89, Feb. 2011.
4. Boti, M., L. Dussopt, and J. M. Laheurte, "Circularly polarised antenna with switchable polarisation sense," *Electron. Lett.*, Vol. 36, 1518–1519, Aug. 31, 2000.
5. Kim, B., B. Pan, S. Nikolaou, Y.-S. Kim, J. Papapolymerou, and M. M. Tentzeris, "A novel single-feed circular microstrip antenna with reconfigurable polarization capability," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 3, 630–638, Mar. 2008.
6. Nikolaou, S., R. Bairavasubramanian, C. Lugo, I. Carrasquillo, D. C. Thompson, G. E. Ponchak, J. Papapolymerou, and M. M. Tentzeris, "Pattern and frequency reconfigurable annular slot antenna using PIN diodes," *IEEE Trans. Antennas Propag.*, Vol. 54, No. 2, 439–449, Feb. 2006.
7. Mak, K. M. and K. M. Luk, "A circularly polarized antenna with wide axial ratio beamwidth," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 10, 3309–3312, Oct. 2009.
8. Jou, C., J. W. Wu, and C. J. Wang, "Novel broadband monopole antennas with dual-band circular polarization," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 4, 1027–1034, Apr. 2009.
9. Tsai, J.-F. and J.-S. Row, "Reconfigurable square-ring microstrip antenna," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 5, 2857–2860, May 2013.
10. Sung, Y. J., T. U. Jang, and Y. S. Kim, "A reconfigurable microstrip antenna for switchable polarization," *IEEE Microw. Wireless Compon. Lett.*, Vol. 14, 534–536, Nov. 2004.
11. Li, W.-M., B. Liu, and H.-W. Zhao, "The U-shaped structure in dual-band circularly polized slot antenna design," *IEEE Antennas Wireless Propag. Lett.*, Vol. 13, 447–450, 2014.
12. Sung, Y., "Dual-band circularly polarized pentagonal slot antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 259–261, 2011.
13. Wadell, B. C., *Transmission Line Design Handbook,* Artech House, Norwood, MA, USA, 1991.
14. Chen, C.-H. and E. K. N. Yung, "A novel unidirectional dual-band circularly-polarized patch antenna," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 8, 3052–3057, Aug. 2011.