Progress In Electromagnetics Research C, Vol. 45, 73–85, 2013

A SPIRAL SLOT ANTENNA WITH RECONFIGURABLE CPW-TO-SLOTLINE TRANSITION FOR POLARIZATION DIVERSITY

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Abstract—A polarization reconfigurable spiral slot antenna with polarization states switched among left-hand circular polarization (LHCP), right-hand circular polarization (RHCP) and linear polarization (LP) is proposed in this paper. The antenna consists of a coplanar waveguide (CPW) input, a pair of reconfigurable CPW-to-slotline transitions, two separated same size single-arm spiral slot radiators, and four PIN diodes for reconfigurability. A good impedance match (VSWR $\leqslant 2$) for both linear and circular polarization is achieved from 2.1 to 2.9 GHz. The bandwidth for axial ratio AR $\leqslant$ 3 dB for both RHCP and LHCP states ranges from 2.27 to 2.66 GHz (15%). The simulation and measurement results agree well and hence sustain the reconfigurability of the proposed design.

1. INTRODUCTION

In recent years, reconfigurable antennas have received considerable attention in the fields of wireless communication systems, such as personal communications service (PCS) and wireless local area network (WLAN). Polarization reconfigurable antennas are able to expand the capability of the communication systems through frequency reuse and alleviate the harmful influence caused by multipath effects [1]. Polarization switching is commonly established by incorporating switching PIN diodes or RF-MEMS switches on the antenna topology [2, 3].

Circularly polarized (CP) antennas have been widely used in wireless and satellite communication systems to reduce multipath

Received 19 August 2013, Accepted 21 October 2013, Scheduled 28 October 2013
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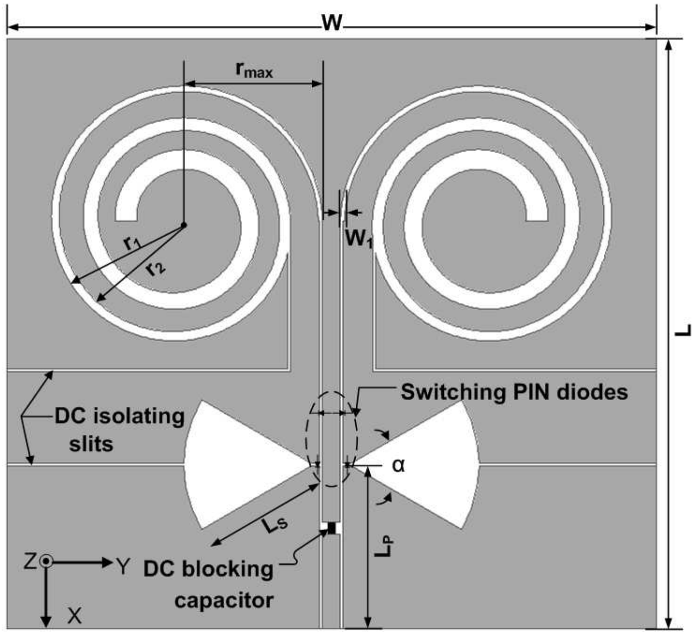
effects and the need for accurate polarization alignment between transmitting and receiving antennas [4]. Considerable previous work for polarization reconfigurability switched between circular and linear polarization or between two circular polarization have been proposed. In [1, 5–7], the structures to activate circular polarization (CP) wave are single-fed microstrip patch antennas with a perturbing structure. With a small part cut or added on a square, a circular, or triangle patch, the path of the current on the antenna is perturbed, thus circular polarization is achieved. Switching PIN diodes are employed to connect the perturbing structure to the patch. By controlling the *dc* biased states of the PIN diodes, reconfigurability for polarization is achieved. The limited 3 dB axial ratio bandwidth is a drawback of these antenna structures. Compared to these traditional techniques to realize circular polarization, printed slot antennas have the potential to improve the CP bandwidth without increasing the antenna size [8]. In [8], a compact U-slot microstrip patch antenna with reconfigurable polarization is designed. With different lengths of U-slot on the center of the patch, the antenna can excite two CP waves or one linear polarization (LP) and one CP. For all these polarization reconfigurable structures showed above, their base forms are single-fed microstrip antennas. Compared to these microstrip antennas, CPW-fed slot antennas have characteristics of a simplified configuration with a single metallic layer, smaller radiation loss and less dispersion [9]. In [10], a polarization reconfigurable CPW-fed square slot antenna with two T-shaped metallic strips controlled by PIN diodes is presented. By turning pin-diodes on or off, the antenna can switch between RHCP and LHCP, with a 11% 3-dB AR bandwidth. A CPW-fed two-arm Archimedean spiral slot antenna featuring wideband input impedance bandwidth with circular polarization (CP) is demonstrated in [11]. In spite of the narrower 3-dB AR bandwidth (2–3.4 GHz) in comparison to the traditional spiral antennas fed in the center of the spiral, the antenna structure is completely planar with the absence of balun. A spiral slot antenna fed by coplanar waveguide (CPW), using the magnetic flow in the spiral slots for broadband circular polarization demonstrates that single-arm spiral slot antenna exhibits the circular polarization characteristics [12], with a worse circular performance in comparison with the structure in [11]. Nevertheless, the structure in [11] provides a possibility for a polarization diversity antenna with compact CPW-fed structure in case that the sense of rotation of the two separate spiral slot radiators is opposite. Although there have been some researches on CPW-fed spiral slot antennas, as shown above, there is little literature on the polarization reconfigurable antennas based on the CPW-fed spiral slot antennas.

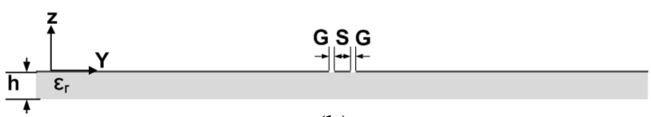
In this paper, a spiral slot antenna with a reconfigurable CPW-to-slotline transition is proposed to allow switching among left-hand circular polarization (LHCP), right-hand circular polarization (RHCP), and linear polarization (LP). The antenna structure proceeds from the CPW-fed spiral slot antenna and combines the CPW-to-slotline balun structure employed in [13], which concentrates on the pattern reconfigurability. The antenna covers the WLAN frequency band with good impedance bandwidths for both CP and LP modes from 2.1 to 2.9 GHz, and the 3-dB axial ratio bandwidth ranges from 2.27 to 2.66 GHz for the CP modes. The design of the antenna consists of four parts, i.e., a coplanar waveguide (CPW) input, two CPW-to-slotline transitions, two separated single-arm spiral slot radiators, and four PIN diodes for polarization reconfigurability. Relying on the different *dc* biased states of the PIN diodes, the proposed antenna can be fed by one of the three feeding configurations, namely the CPW feeding mode, the right-hand slot feeding mode, and the left-hand slot feeding mode. With the reconfigurable transition structure and the opposite polarization sense of the two spiral slot radiators, the antenna demonstrates switchable polarization states among left-hand circular polarization (LHCP), right-hand circular polarization (RHCP), and linear polarization (LP). The structure of the paper is as follows. In Section 2, the antenna configuration and the design concept for polarization are presented. In Section 3, simulated and measured polarization states of the antenna operated in all three feeding schemes are illustrated. In Section 4, a brief conclusion about the design is presented.

2. ANTENNA CONFIGURATION AND DESIGN CONCEPT

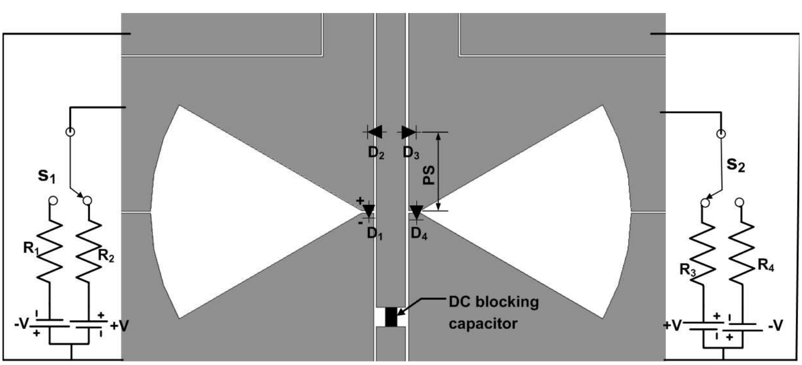
The configuration of the proposed polarization reconfigurable spiral slot antenna is shown in Fig. 1. As shown in Fig. 1(a), the antenna is composed of a CPW input, two CPW-to-slotline transitions, two separated same size single-arm spiral slot radiators, and four PIN diodes along with the associated *dc* bias network for polarization switching. The signal is fed to the CPW input line via a SMA connector. The characteristic impedance of the CPW line is designed to be 50 ohm, with dimensions $S = 3$ mm, $G = 0.3$ mm, which is matched to the SMA connector. The slotline impedance is around 80 ohm, which corresponds to a width of 0.3 mm in the design. The open-circuited radial stub of the CPW-to-slotline transition has a radius of 22 mm and a flared angle of 60°. Several thin slits are added to the far end of the open-circuited stubs and the appropriate positions



(a)



(b)



(c)

Figure 1. Configuration of the proposed antenna: (a) top view, (b) cross-sectional view, (c) PIN diodes arrangement and the associated *dc* biased network.

of the spiral slots for *dc* isolation. To block the DC current, a 10 pF capacitor is attached to the CPW line.

As shown in Fig. 1(c), in order to achieve polarization reconfigurability, two switchable CPW-to-slotline transitions with four PIN diodes are employed. Two PIN diodes are placed over the inputs of the open-circuited radial stub of the transitions, whereas the other two diodes are placed across the coupled slotlines of the CPW input. PS represents the distance between the input of the open-circuited radial stub and the position of the PIN diodes D_2, D_3. By controlling the bias states of PIN diodes, the feeding configuration is able to switch among the CPW feeding mode, the right-hand slotline feeding mode, and the left-hand slotline feeding mode. Accordingly, linear polarization, left-hand circular polarization (LHCP), and right-hand circular polarization (RHCP) are obtained in the frequency band of interest, respectively. The PIN diode in this paper is Infineon BAR89-02LRH PIN diode, with a package dimension about 1.0 by 0.6 mm^2. The *dc* bias voltage V is either 1.5 V or -1.5 V, which can be selected alternatively by a single-pole double-throw (SPDT) switch. The current-limited resistors R_1 to R_4 are 1 kΩ. The forward current of the diode I_F is given by

$$I_F = \frac{V - V_1}{R_1} = 0.8\,\mathrm{mA} \tag{1}$$

In (1), V_1 is the voltage across the diode for $I_F = 0.8\,\mathrm{mA}$, which is approximate 0.7 V according to the datasheet [14]. Hence a resistance of 3 Ω is extracted from the PIN diode datasheet [13] for the ON state in the simulation. On the other hand, the diode represents a parallel circuit with a capacitance of 0.16 pF and a resistance of $\sim 5\,\mathrm{k\Omega}$ for the OFF state.

As shown in Fig. 1(a), the reconfigurable transitions are followed by another section of CPW line, which is terminated by two separated same size single-arm spiral slot radiators. The left-hand and right-hand spiral slot radiators are of the same size and the opposite sense of rotation. The slot trace is as follows [11, 15]

$$\begin{aligned} r_1 &= r_{\max} + a\phi \\ r_2 &= r_{\max} - W_1 + (a + \mathrm{turnrate}/2/\pi)\phi \end{aligned} \tag{2}$$

where r_1 and r_2 are the outer and inner radii of the spiral slot respectively, and "a" is the growth rate, while "$r_{\max}$" is the maximum distance from the center to the border of the spiral. The lowest operating frequency f_l can be approximately by using the equation used for the conventional spiral antenna [16]

$$f_l = \frac{c}{2 * \pi * r_{\max}} \tag{3}$$

where c is the velocity of light. f_l in this design is approximately 2 GHz. W_1 represents the original width of the two spiral slots. The angle Φ ranges from 0 to — $2 * N * \pi$ with number of turn N. The spiral arm is tapered by gradually increasing the slots width for a better performance [11], as shown in Equation (2), where turnrate represents the increasing width per turn. Turnrate is set to be 1.2 mm, depending on the analysis in [11]. According to the general spiral slot antenna, the number of turn N is 1.5–3 for good radiation characteristics [12]. N is designed to be 2.5 through parameter study in the simulation process. To decide the whole size of the spiral slot, the maximum distance from the center to the border of the spiral ($r_{\max}$), the number of turn (N), the original width of slots (W_1) are the major elements.

In the left or right-hand slotline feed mode, one of the two spiral slot radiators is excited, the antenna radiates circular polarization wave in the active region [11]. It is well known that the polarization sense of the spiral is as same as the spiral winding direction from outer to inner arm. Therefore, for the left-hand spiral slot radiator, the polarization of the antenna is right handed circularly polarized when theta $= 0°$ and left handed circularly polarized in the opposite direction when theta $= 180°$, where theta is defined as angle from z to $-z$ axis in a spherical coordinate system for three dimensional space. For the right-hand spiral slot radiator, the polarization sense is opposite to that of the left-hand one. It is noteworthy in this paper that the defined states of the circular polarization, namely the RHCP and LHCP modes, are corresponding to the situation when theta $= 0°$. In the CPW feeding mode, both of the two spiral slot radiators are excited, thus a linearly polarized antenna is constructed.

Table 1. Bias conditions and polarization states for reconfigurability.

	switches		PIN diodes			
	S_1	S_2	D_1	D_2	D_3	D_4
CPW feeding (LP)	V	V	ON	OFF	OFF	ON
LEFT slot feeding (RHCP)	V	$-V$	ON	OFF	ON	OFF
Right slot feeding (LHCP)	$-V$	V	OFF	ON	OFF	ON

Table 1 summarizes the working configurations of the four PIN diodes for the three antenna feeding schemes and the corresponding polarization states (RHCP, LHCP and LP) in the frequency band of interest. When the diodes D_2, D_4 are turned off whereas D_1, D_3 are turned on, the right-hand slotline is shorted, and the left-hand spiral slot radiator is excited by the left-hand slotline mode, thus right-hand circular polarization is obtained. Likewise, when the diodes D_3, D_1 are turned off whereas D_2, D_4 are enabled, and the right-hand spiral slot radiator is excited by the right-hand slotline mode, so left-hand circular polarization is obtained. In either left/right-hand slotline feeding scheme, the unbalanced signal injected to the CPW input line will be transformed into a balanced slotline mode by the CPW-to-slotline transition [13]. The slotline feeding mode provides 180° out-of-phase for the spiral slot antenna, so there is no need for a balun circuit [12]. When the diodes D_2, D_3 are reverse biased whereas D_1, D_4 are forward biased, the antenna operates in the CPW feeding mode. The wave injected into the CPW input line propagates directly towards the left and right spiral slot antennas, in which case the two CPW-to-slotline transitions are disabled. Since the polarization sense of the two spiral slot radiators is opposite, the antenna radiates linear polarization wave.

3. SIMULATED AND MEASURED RESULTS

The antenna performance is first investigated by the EM full-wave simulator HFSS version 13.0 and then fabricated on a FR4 substrate with a dielectric constant of 4.4, loss tangent of 0.02, and thickness of 1.6 mm. The designed parameters of the antenna are: $G = 0.3\,\text{mm}$, $S = 3\,\text{mm}$, $W_1 = 0.5\,\text{mm}$, growth rate $a = 0.859\,\text{mm}$, number of turn $N = 2.5$, $r_{\max} = 24.3\,\text{mm}$, $L_S = 22\,\text{mm}$, $\alpha = 60^\circ$, $L_P = 28\,\text{mm}$, $PS = 7\,\text{mm}$. The overall dimension of the design, i.e., $L \times W$, is 100 by $110\,\text{mm}^2$.

A fabricated prototype of the proposed antenna along with the bias network and the connecting cables is shown in Fig. 2. The *dc* bias is provided by four batteries. The simulated and measured VSWR of the proposed antenna operated in the three polarization states are illustrated in Figs. 3(a), (b) and (c), respectively. The measurement was taken by a Wiltron-37269A network analyzer. As shown in Fig. 3, when the antenna operates in the three polarization states, the impedance bandwidth with VSWR less than or equal to 2.0 extends approximately from 2.1 GHz to 2.9 GHz, which can cover the WLAN band (2.4–2.484 GHz). It is worthwhile to note that the actual impedance bandwidth extends to more than 2.9 GHz, but the radiation efficiency in the higher frequency is low and the 3-dB axial ratio deteriorates for the RHCP/LHCP mode [11]. Hence, the antenna performance in the low frequency band of interest is considered. The

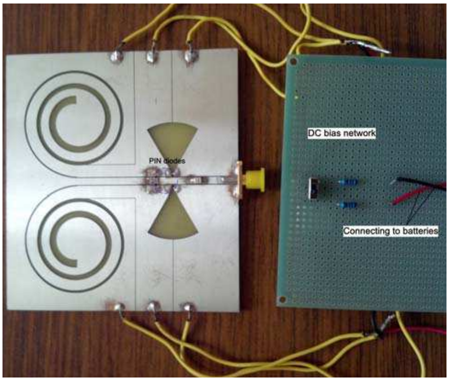


Figure 2. Prototype of the proposed reconfigurable antenna.

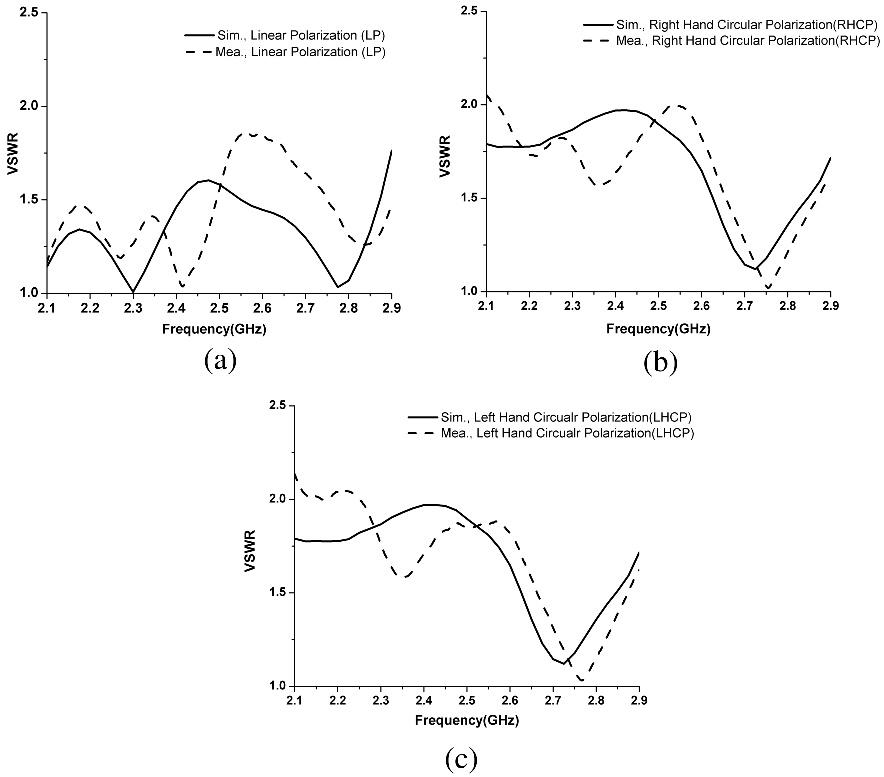
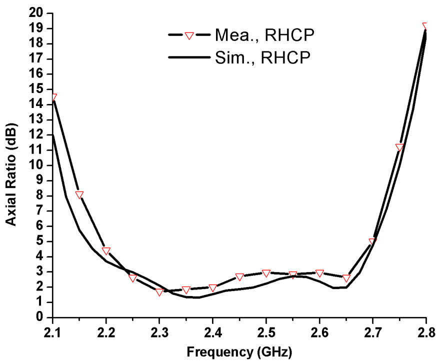


Figure 3. Simulated and measured VSWR for three modes: (a) LP, (b) RHCP, (c) LHCP.

manufacture errors for the slots of the radiation parts and the rough wielding of the PIN diodes affect the impedance of the antenna, which may lead to the disagreement between simulations and measurements.

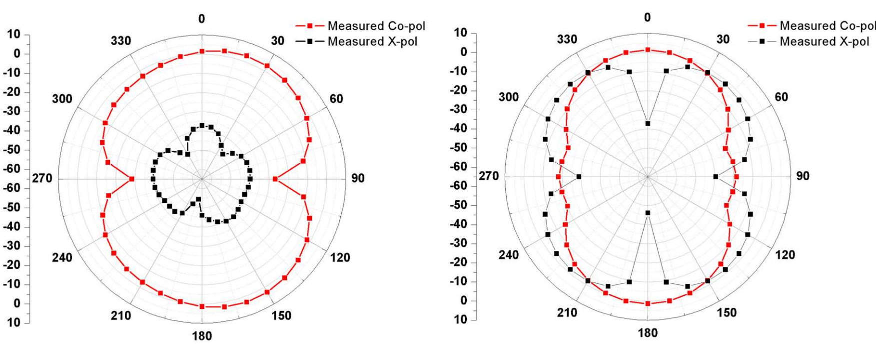
Figures 4(a) and (b) show the simulated and measured axial ratio results of the proposed antenna operated in the RHCP and LHCP modes, respectively. In both CP modes, the compared results are in good agreement. The measured 3 dB axial ratio bandwidth ranges from 2.27 to 2.66 GHz.

The measured radiation patterns of the proposed antenna operated in the LP, LHCP, and RHCP modes at 2.4 GHz are shown in



(a) (b)

Figure 4. Simulated and measured axial ratio for CP modes: (a) RHCP, (b) LHCP.



(a) (b)

Figure 5. Measured radiation patterns at 2.4 GHz for the LP mode: (a) x-z plane, (b) y-z plane.

Figs. 5–7. It can be observed from Fig. 5 that the cross polarization level for the linear polarization remains below −30 dB at the maximum radiation direction. As shown in Figs. 6–7, the proposed single-arm spiral slot antenna exhibits a well circular polarization performance with cross polarization level better than 16 dB. It has bi-directional radiation pattern with a slight angle shifting in its main direction. The shift is mainly due to the external feeding structure of the spiral antenna.

Figure 8 shows the gain and radiation efficiency of the proposed three operation modes. The maximum gain at three operation modes is 0.8–2.9 dB from 2.1 GHz to 2.9 GHz. The overall radiation efficiency of the antenna operated in the three modes is above 50%.

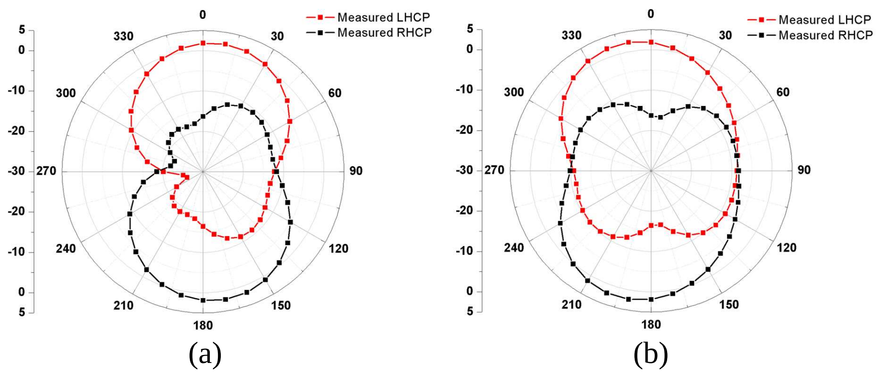


Figure 6. Measured radiation patterns at 2.4 GHz for the LHCP mode: (a) x-z plane, (b) y-z plane.

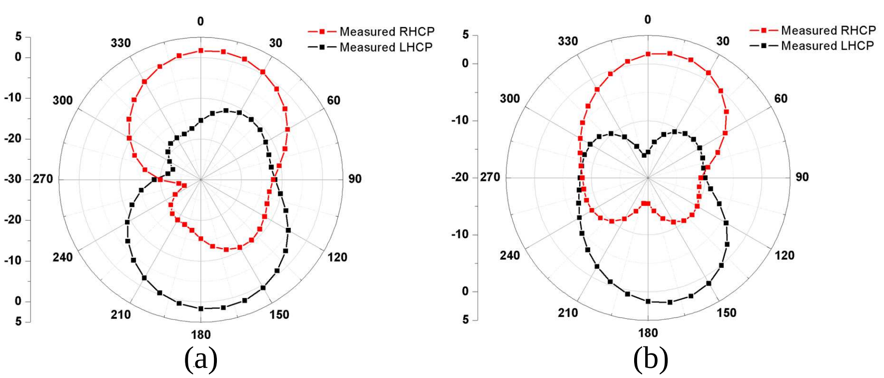


Figure 7. Measured radiation patterns at 2.4 GHz for the RHCP mode: (a) x-z plane, (b) y-z plane.

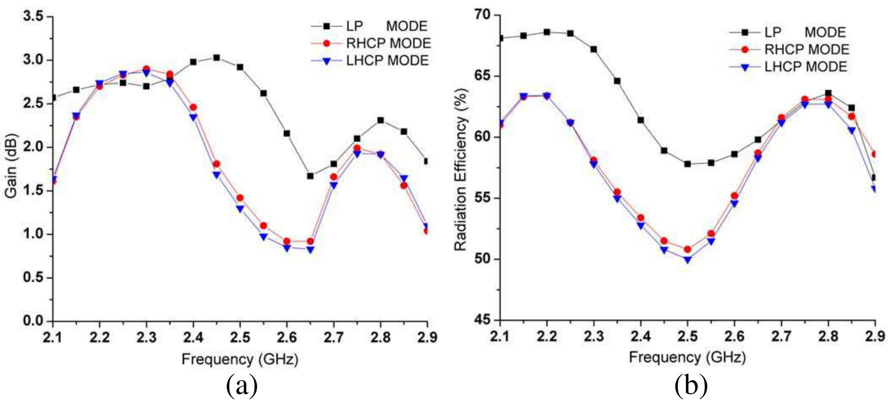


Figure 8. Measured (a) gain and (b) radiation efficiency of the proposed three operation modes.

4. CONCLUSION

A spiral slot antenna with a pair of reconfigurable CPW-to-slotline has been proposed and demonstrated for polarization reconfigurability. With the aid of four PIN diodes and the associated bias network, the antenna has the ability to alternatively switch its polarization states among linear polarization (LP), right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP). With the appropriate antenna geometry, the proposed antenna offers a measured impedance bandwidth extending from 2.1 to 2.9 GHz for all the three operation modes, which can cover the entire 2.4 GHz WLAN band. For the RHCP and LHCP modes, the bandwidths of the 3-dB axial ratio range from 2.27 to 2.66 GHz (15%). The measured LP radiations show that the antenna exhibits very low cross polarization level at the maximum radiation direction. The measured RHCP and LHCP radiations of the proposed single-arm spiral slot antenna at 2.4 GHz are also presented. It is demonstrated that, when the antenna is working in the left/right-hand slot feeding mode, the single-arm spiral slot antenna is proven to achieve a good circular polarization performance. The radiation efficiency of the proposed antenna operated in the LP and CP modes is above 50%. This antenna can be a candidate application in wireless communication systems for polarization diversity.

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