International Journal of Microwave and Wireless Technologies, 2017, 9(5), 1155–1161.
doi:10.1017/S1759078716001240

RESEARCH PAPER

A novel single-feed reconfigurable antenna for polarization and frequency diversity

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A novel dual-band single-feed reconfigurable annular-ring slot antenna with polarization diversity is proposed. This antenna has the ability to switch frequency bands and polarization at the same time whereas applying a simple structure. It consists of two concentric circular slots and two tuning stubs on one side of the substrate and a 50 Ω microstrip feed line and two stubs on the other side. The proposed antenna can be switched between two resonant frequencies, 2.4 GHz (WLAN) and 3.5 GHz (Wimax). Furthermore, it can be switched between linear polarization (LP), left-hand circular polarization (LHCP), and right-hand circular polarization (RHCP) at the first frequency band, LHCP and RHCP at the second band. All these capabilities are achieved by applying only five PIN diodes on both sides of the substrate. Simulation and experimental results indicate that the proposed antenna demonstrates a good impedance bandwidth at the two frequency bands and satisfactory radiation pattern in five different states.

Keywords: Annular-ring slot antenna, Dual-band, Dual-polarized, Reconfigurable antenna

Received 20 May 2016; Revised 5 October 2016; Accepted 11 October 2016; first published online 5 December 2016

I. INTRODUCTION

Reconfigurable antennas owing to their alteration ability with changing the environment conditions have become very popular in recent years. Various wireless applications require different radiation and polarization characteristics, which can be provided by designing various antennas. However, the physical size of the system limits us to make the separate antennas for each application. Hence, the reconfigurable antennas as a good candidate for gathering the operating characteristics in a single antenna could be a new research gate for antenna researchers and engineers. Application areas that drive the development of such kind of antennas include multi-function wireless devices, multiple-input multiple-output systems, ultra-wideband systems, and anti-jamming secure communication to accommodate the ever-demanding requirements of such systems [1]. Reconfigurable antennas are divided into four main categories, those which exhibit reconfigurable return loss, reconfigurable radiation pattern and polarization, and different combinations of the previous categories. The communication signals reception can be improved by these antennas, with polarization agility and an exceptional ability of multipath fading reduction. Moreover, multi-band reconfigurable antennas are desirable in modern communication systems.

Conventional microstrip antennas have many benefits such as low profile, light weight, and conformable to planar surfaces. Besides, narrow bandwidth and spurious feed radiation due to low-efficiency, low-power, and high Q are their drawbacks.

The microstrip antennas with polarization diversity have been studied and their characteristics are reported in [2–4]. The antenna studied in [5] uses dual-feeding for reconfigurability, while an antenna with the simple feeding network is one of the main factors in wireless communication systems.

In order to achieve polarization switching in single-fed microstrip patch antennas, one simple method is changing the electrical characteristics by using PIN diodes. Several polarization reconfigurable antennas based on this method have been proposed [6, 7].

Some previous works present combinations of polarization and frequency diversities. Patch antennas with switchable slots having both frequency and polarization diversities [5, 8, 9] utilize dual-fed structures. Chung *et al.* [3] propose a reconfigurable single-feed microstrip patch antenna with frequency and polarization diversities using some PIN diodes and a U-slot, incorporated into a square patch. It does not provide polarization diversity in any of the resonant frequencies. All previous works do not propose antenna that can be switched between the two frequencies, and polarization at the same time using single feed or a few diodes, which are the subjects of this work.

The authors in [10] proposed a single-feed reconfigurable antenna that it can be switched between two frequencies and two states of circular polarization (left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP)) with seven diodes. In this paper, we present a novel single-feed reconfigurable annular-ring slot antenna for frequency diversity suitable for WLAN and Wimax applications. The suggested ring slot antenna has broad impedance bandwidth. Impedance matching is realized by applying

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Babinet's principle. This antenna can be switched between three states of polarization: linear polarization, LHCP, and RHCP at the first frequency band. Moreover, it has two states of circular polarization (LHCP, RHCP) at the second frequency. All of these configurations are achieved by just five PIN diodes. A single-feed, simple bias circuit, single-layered structure using just five PIN diodes control polarization and frequency at the same time is the significance of this work. The antenna is fabricated, and return losses and radiation patterns are tested. The experimental results show good agreements with simulation results obtained using the commercial package HFSS.

II. ANTENNA DESIGN

The proposed antenna is shown in Fig. 1. It has two concentric circular slots, which are printed on a 1.6 mm-thick FR4_epoxy substrate of relative permittivity 4.4. The microstrip feed line is placed on one side of the substrate and the annular slot is placed on the opposite side.

For conventional annular-ring patch antennas, the fundamental resonant mode (TM_{11} mode) for conventional annular-ring patch antennas takes place at a frequency whose wavelength in the ring nearly tally with the mean circumference of the ring [11]. That is

$$f = \frac{c}{\pi(R_1 + R_2)\sqrt{\varepsilon_{eff}}}, \tag{1}$$

$$\varepsilon_{eff} = 1 + q(\varepsilon dr - 1), \tag{2}$$

where c is the speed of light in the free space, f is the fundamental frequency of the conventional annular-ring antenna, $\pi(R_1 + R_2)$ is the mean circumference of the annular-ring antenna, ε_{eff} is the effective dielectric constant, εdr is the relative permittivity, and q is the correction factor considering the presence of the different dielectric materials on the two sides of the annular-ring patch. Here the radius and the widths of the annular slots for the first resonant frequency are (R_1, S_1) and for the second one are (R_2, S_2), respectively. Their primary values are calculated by the above formulas. HFSS software is applied to survey the characteristics of the proposed annular-ring antenna to reach optimum performance.

In order to have polarization diversity at the first resonance frequency, the outer ring is loaded with two stubs of width W_{st} and length l_{st}. Two PIN diodes are connected to each stub.

The microstrip feed line is broken into two fragments, that connected with a PIN diode (D_5). Inserting two paths with transformer in antenna feed line and two matching stubs with the length (L_{sf}) and width (W_{sf}), lead to have good impedance matching (50 Ω) for all states. Two open stubs with the length (L_{sb}) and the width (W_{sb}), which are connected by two PIN diodes (D_3, D_4); allow polarization diversity at the second frequency band.

A) Frequency diversity

The proper operating frequency can be obtained by varying the circumference of the annular-ring slot of the antenna. Hence, in order to operate at one frequency band, either inner or outer annular slot should be excited. To have frequency diversity, one PIN diode (D_5) is inserted in the feed line. When the PIN diode is biased (on-state), inner ring slot is excited for generating the second frequency band.

On the other hand, when the PIN diode (D_5) is in "off-state", the outer ring slot is excited and generates the first resonant frequency. The outer radius (R_1) is selected proportional to 2.4 GHz for the WLAN application, and the inner radius (R_2) is selected proportional to 3.5 GHz for the Wimax application. Therefore, the proposed antenna can operate with frequency diversity by only one PIN diode.

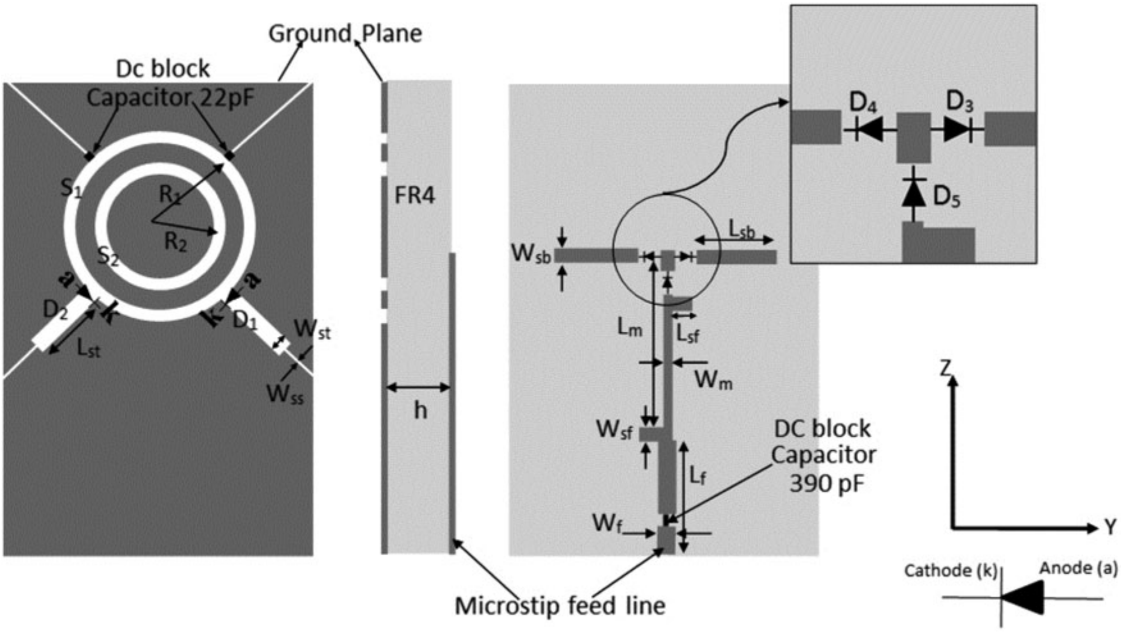


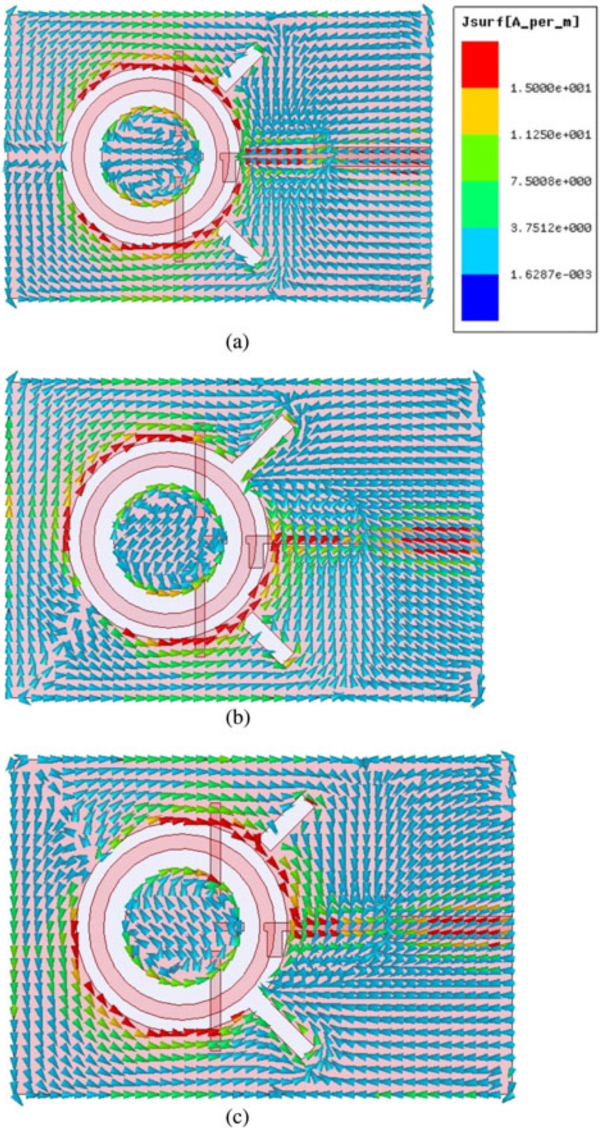
Fig. 1. Geometry of the proposed antenna.

Table 1. Different diode combinations and their associated operation status.

	D_5	D_1	D_2	D_3	D_4	Frequency	Polarization
Ant. 1	Off	Off	Off	Off	Off	F_L	LP
Ant. 2	Off	Off	On	Off	Off	F_L	LHCP
Ant. 3	Off	On	Off	Off	Off	F_L	RHCP
Ant. 4	On	On	On	Off	On	F_H	LHCP
Ant. 5	On	On	On	On	Off	F_H	RHCP

B) Polarization diversity

Generally, the annular-ring slot antenna operates in the fundamental TM_{11} mode. Circular polarization (CP) operation is excited by loading two stubs in the annular-ring slot. In this case, the fundamental TM_{11} mode can be split into two near degenerate resonant modes. Therefore, CP operation can be obtained and optimized by changing the tuning stub size. The two near resonant modes have almost equal amplitudes and 90° phase difference in CP operation. When a tuning stub is located at -45°, the LHCP operation can be obtained, and when the tuning stub is placed at -135°, the RHCP operation can be obtained. In addition, when none of the two tuning stubs is excited, the linear polarization can be obtained. By switching two PIN diodes (D_1 and D_2), the antenna can change between LHCP, RHCP, and LP at 2.4 GHz (Fig. 1).

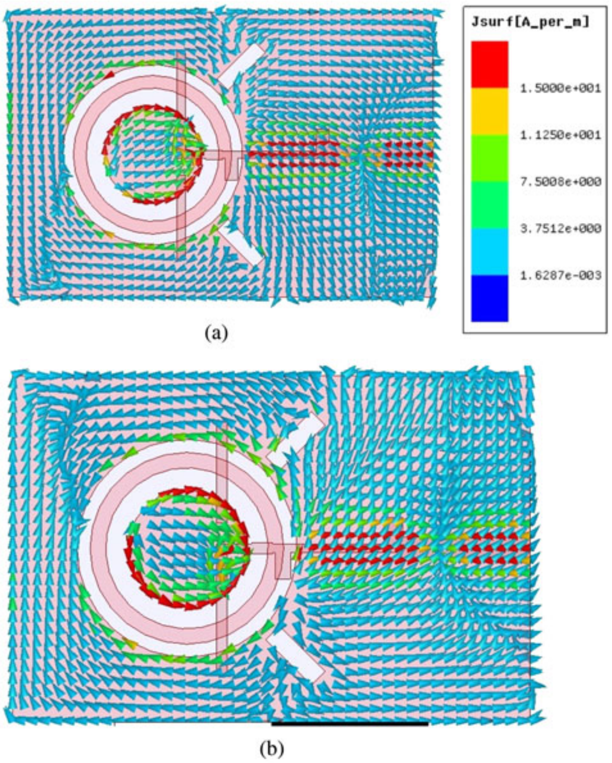


(a)

(b)

(c)

Fig. 2. Surface current distribution on the proposed antenna structure at 2.4 GHz: (a) Ant. 1, (b) Ant. 2., and (c) Ant. 3.



(a)

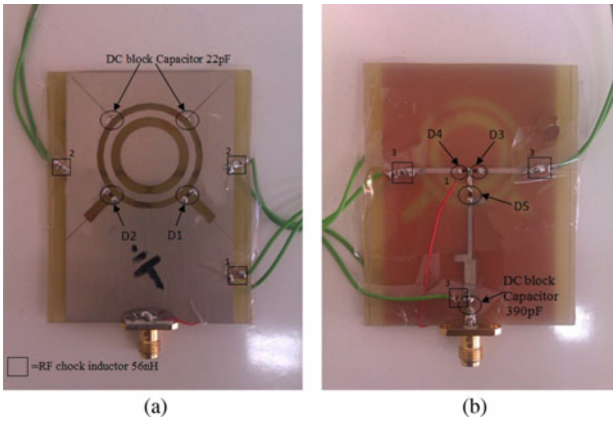
(b)

Fig. 3. Surface current distribution on the proposed antenna structure at 3.5 GHz: (a) Ant. 4 and (b) Ant. 5.

As mentioned before, to radiate CP, two orthogonal modes should be excited with the same amplitude and 90° phase difference. Generally, two orthogonal modes of the circular microstrip antenna can be excited in series with the microstrip feed line through the coupling of the ring slot. The magnitudes of the two orthogonal modes are related to the amplitudes of the vertical and horizontal directed currents under the ring slot. It means that by altering the current distribution in the microstrip feed line, the CP radiation of the ring slot microstrip antenna can be achieved. Based on this proposition, polarization diversity can be attained by adjusting the stub length.

In order to have polarization diversity between LHCP and RHCP at the second frequency band, two stubs perpendicular to feed line are used. When each of them is excited, LHCP or RHCP mode is achieved. The PIN diodes (D_3 and D_4) can be used for choosing the appropriate stub. Therefore, the proposed antenna can switch between LHCP and RHCP at 3.5 GHz. Different diode combinations and their associated operation status are summarized in Table 1.

Figures 2 and 3 show the surface current distribution on the suggested antenna structure at frequencies 2.4 and 3.5 GHz, respectively. The surface current distributions are obtained through HFSS. It is clear that outer of the slot



(a) (b)

Fig. 4. Photographs of the fabricated antenna prototype. (a) Front view and (b) back view.

Table 2. Details of design parameters (unit, mm).

Parameter	R_1	R_2	S_1	S_2	L_{sf}
Dimension	12.45	7.7	2	2.8	3.45
Parameter	W_{sf}	W_{st}	L_{st}	L_m	W_m
Dimension	2	2.5	10	23	1.1
Parameter	L_f	L_{sb}	W_{sb}	W_f	W_{ss}
Dimension	17.11	13.45	1.8	3.059	0.1

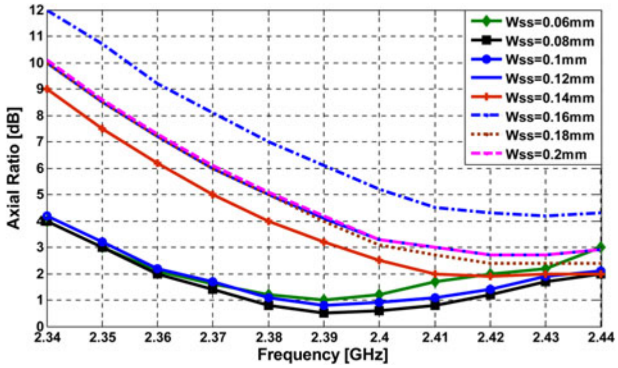


Fig. 5. The variation of the simulated axial ratio against parameter W_{ss} (RHCP).

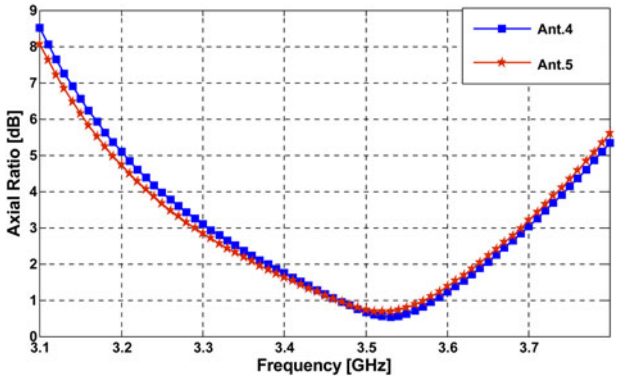


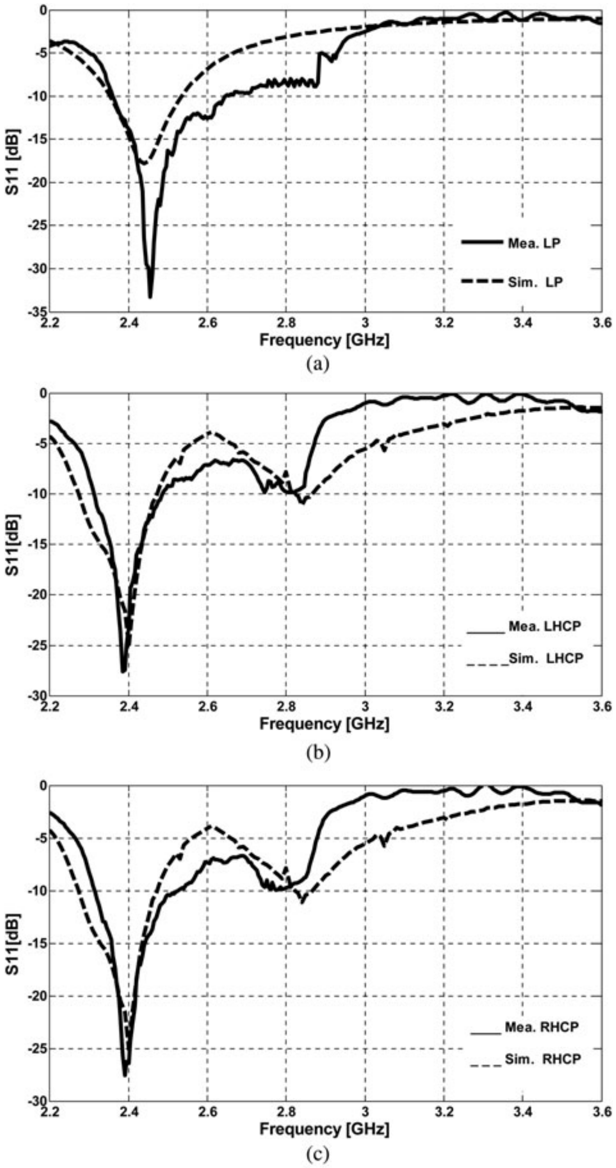
Fig. 6. Axial ratio of the proposed antenna at 3.5 GHz (Ant. 4 and Ant. 5.).

excited to the antenna operates at the lower frequency and inner one excited to have a higher frequency. Additionally, the antennas directional surface current vector illustrates its correct performance at polarization diversity.

C) Matching approach

The feed line consists of two open-stub shunt tuning circuits to achieve input impedance matching (50 Ω) for LHCP and RHCP polarizations at both resonant frequencies [12]. Length and width of these stubs (L_{sf}, W_{sf}) are tuned to obtain input impedance matching of the proposed antenna at all of states by using the parametric study of HFSS software.

The stubs' spacing is about 14 mm and symmetrical stubs are used to achieve the best antenna characteristics.



(a)

(b)

(c)

Fig. 7. Simulated and measured S_{11} of the proposed antenna at 2.4 GHz: (a) Ant. 1, (b) Ant. 2, and (c) Ant. 3.

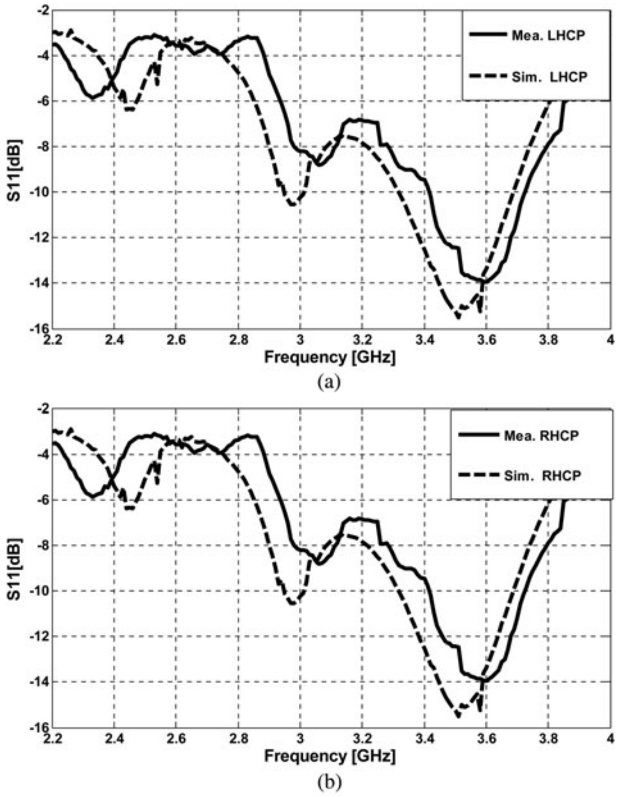


Fig. 8. Simulated and measured S_{11} of the proposed antenna at 3.5 GHz: (a) Ant. 4 and (b) Ant. 5.

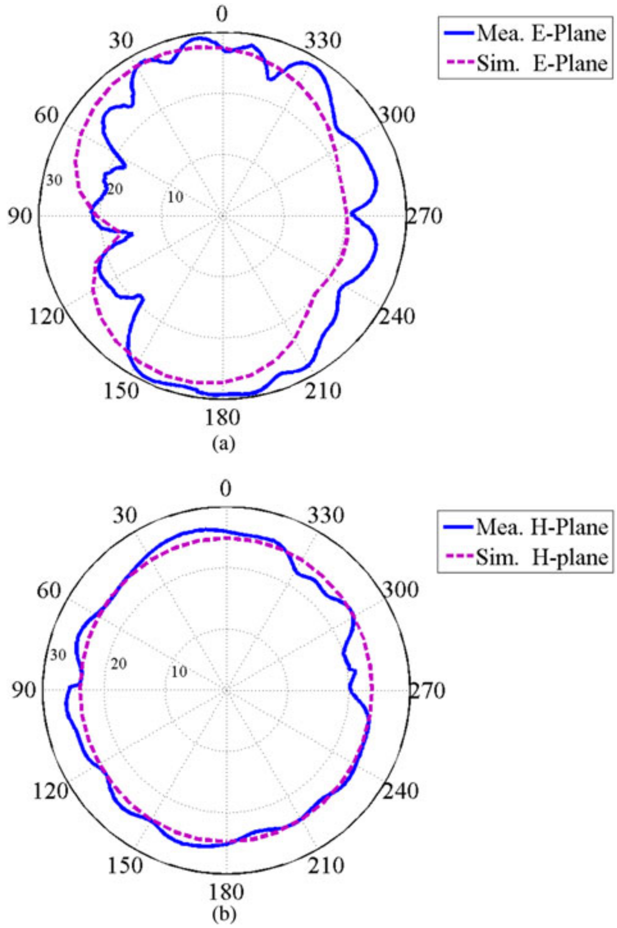


Fig. 9. Simulated radiation patterns of the proposed antenna for linear polarization at 2.4 GHz: (a) *E*-plane (*y–z* plane) and (b) *H*-plane (azimuth plane).

III. RESULTS

The PIN diode bias circuit composed of a DC blocking capacitor, radiofrequency (RF) chokes, and input voltage. One part of the ground plane and the centers of the feed stubs are connected to DC ground (marked with number 1 in Fig. 4). Two DC bias lines are indirectly connected to top part of the circular patch (marked with number 2 in Fig. 4). Three DC bias lines are connected to each matching stub, which supply DC current to PIN diodes as shown in Fig. 4 (marked with number 3 in figure). The equivalent RLC circuit models are used for the PIN diodes with the part number MA4P274-1141 T [13].

When the diode is on, the equivalent circuit is represented by a resistor ($R = 3\ \Omega$), when the diode is off, the equivalent circuit is represented by a capacitor ($C = 0.35$ PF). DC block capacitors of $C = 390$ PF are chosen to isolate the RF components from the DC. The RF chokes inductor isolate the RF signal from the DC signal. Therefore, six inductor of $L = 56$ nH were used as chokes. Photographs of the fabricated antenna prototype are shown in Fig. 4.

The ground plane is separated into four parts by using thin slits to supply the DC voltage. The DC voltage is applied directly through the divided ground plane.

Table 2 contains details of the design parameters. An acceptable CP operation is achieved by fixing its length (L_{st}) of tuning stub 10 mm and the width (W_{st}).

The width (W_{ss}) of thin slit is an important parameter. When W_{ss} is larger than 0.1 mm, RF signal will become discontinue on the ground plane and undesired resonance occurs. The optimized value of W_{ss} is 0.1 mm. The variation of the simulated axial ratio versus different values for W_{ss} at the first frequency band for the RHCP state is shown in Fig. 5.

Figure 6 shows the simulated axial ratio of the proposed antenna at the second frequency band in all states. The simulated 3 dB axial ratio bandwidth is 3.75% for the first resonant frequency and 11.42% for the second one.

The reflection coefficient (S_{11}) and radiation pattern shape of the proposed antenna have been simulated and tested. Details of the design parameters are summarized in Table 2.

Figure 7 indicates the simulated and measured reflection coefficient (S_{11}) of the antenna at the first frequency band for three states. These states included Ant. 1, Ant. 2, and Ant. 3, as described in Table 1. This figure illustrates that the antenna at these states works just at 2.4 GHz.

Figure 8 shows the simulated and measured reflection coefficient (S_{11}) of the antenna for the second frequency band. The results of this figure are for two other antenna states (Ant. 4 and Ant. 5) that are illustrated in Table 1. This figure shows that the antenna at these states works just at 3.5 GHz.

It can be seen that the measured impedance matching bandwidths are 14.28, 7.53, and 8.3% at the first frequency band for LP, LHCP, and RHCP, respectively, and they are 7.54 and 9.77% at the second frequency band for RHCP and LHCP, respectively.

The simulated and measured radiation patterns for both resonant frequencies are depicted in Figs 9–11. Figure 9

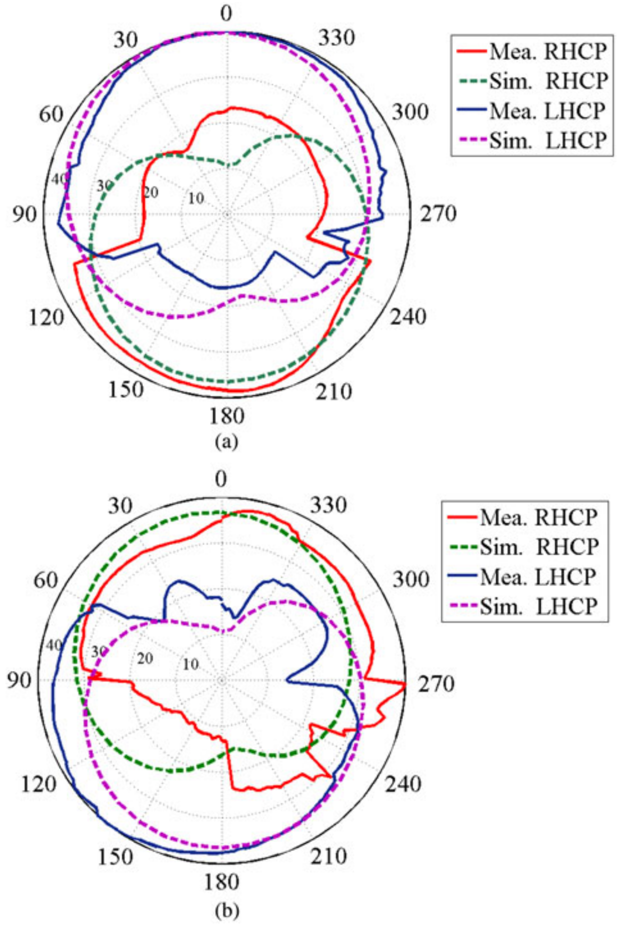


Fig. 10. Simulated radiation patterns of the proposed antenna for CP at 2.4 GHz: (a) Ant. 2 and (b) Ant. 3.

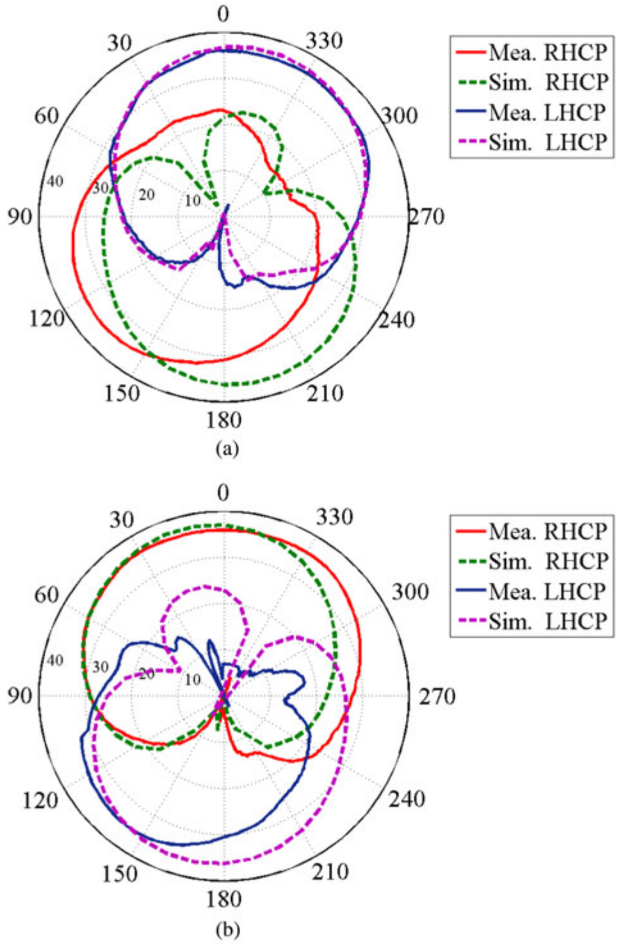


Fig. 11. Simulated radiation patterns of the proposed antenna for CP at 3.5 GHz: (a) Ant. 4 and (b) Ant. 5.

shows the radiation pattern of the proposed antenna for linear polarization at 2.4 GHz, it consists of E-plane and H-plane of the antenna. Figures 10 and 11 illustrate the radiation pattern of the proposed antenna for CP at both resonance frequencies.

The radiation patterns in the CP states were simulated at frequencies at where the minimum axial ratio occurs. Results show that broadside radiation patterns with good LHCP and RHCP characteristics are obtained at the resonant frequency.

The results of these figures indicate that the mentioned antenna works at different polarization by changing the states of diodes. This outcome is achieved from difference between LHCP and RHCP at various states.

For example, in case of Ant. 2, the difference between RHCP and LHCP is about 20 dB at 0o. Therefore, the antenna in this case works at LHCP mode.

Table 3 indicates the simulated peak gain and radiation efficiency of the antenna for all states. The radiation efficiency is obtained by calculating the ratio of the total radiated power of the antenna to the total input power. For all frequency bands of the interesting radiation, efficiency is between 76 and 80%. In addition, the average peak gain over all states at first resonant frequency is 1.47 dBi and at second one is 3.15 dBi.

Table 3. Peak gain and radiation efficiency results.

	Peak gain (dBi)	Radiation efficiency (%)
Ant. 1	1.67	77.55
Ant. 2	1.39	77.98
Ant. 3	1.36	76.86
Ant. 4	3.14	80.15
Ant. 5	3.16	79.49

IV. CONCLUSION

Design of a novel single-feed reconfigurable antenna for polarization and frequency diversity for WLAN (2.4 GHz) and Wimax (3.5 GHz) applications has been presented in this paper. This antenna has frequency diversity by using one PIN diode located in the feed line. Two stubs at the ground plane obtain the polarization diversity among linear polarization, LHCP and RHCP at the first frequency band. In addition, the proposed antenna can be switched between LHCP and RHCP at the second frequency band with two open stubs at the feed line. The simulated and measured results proved the true performance of our antenna agree very well as confirming the validity of our antenna.

ACKNOWLEDGEMENT

The authors would like to thank ITRC (Iran Telecommunication Research Center) for supporting this work under the contract number 15706.

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