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Reconfigurable Polarization MIMO Dielectric Resonator Antenna

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Abstract—This paper introduces a reconfigurable polarization MIMO (Multi-Input Multi-Output) dielectric resonator antenna at a millimeter-wave frequency band. The proposed antenna consists of four single dielectric resonator antennas that are placed in configuration to form a MIMO antenna, and also this design is based on using the pin diode switching concept to control the antenna polarization. To modify the antenna structure for different polarizations, two pin diodes are used in the ground place of the MIMO antenna. The designed antenna operates at 4.35 GHz for polarization diversity applications of the modern wireless MIMO systems. The proposed antenna covers a bandwidth of 11.26% at the central frequency and provides circular and linear polarizations with a high gain of around 6.4 dB. The antenna performance in terms of reflection coefficient, gain, and axial ratio bandwidth in different modes (ON-ON, ON-OFF, OFF-ON, and OFF-OFF) is measured. The advantages of the designed antenna are simple structure (using two pin diode switches to modify antenna polarization), high gain, low profile, and light weight. According to the measurement and simulation results, the designed antenna displays good return loss and radiation performance. Using plexiglass as an antenna material which is very cheap and available in different dimensions is another advantage of the proposed antenna which reduces the fabrication cost.

1. INTRODUCTION

In recent years, with the development of wireless communication technologies, reconfigurable antennas, due to their ability to modify the antenna radiation pattern, resonance frequency, and polarization, have become a promising candidate for pattern/frequency and polarization diversity applications [1–4]. On the other hand, the reconfigurable antennas are made to eliminate or overcome some restrictions, and these antennas can adjust the system requirements and changing environmental conditions. There are many techniques such as material, electrical, optical, and mechanical changes that a reconfigurable antenna can achieve. Among different types of antennas, dielectric resonator antennas (DRAs) compared to patch antennas have a better performance at the mm frequency spectrum. DRAs can provide high gain, wide bandwidth, and polarization flexibility using field and current controlling mechanisms. Furthermore, DR antenna supports higher-order modes (TE, TM, and TEM) and has good isolation between co-pol and cross-pol at these modes. Due to mentioned radiation characterization, a reconfigurable DR antenna is a good candidate for wireless communication applications like software-defined radio, cognitive radio, and wireless MIMO systems [5–10]. MIMO is a technique used to achieve greater spectral efficiency and higher data rate for a certain bandwidth by using multiple antennas. Hence, the MIMO dielectric resonator antenna based on a reconfigurable front enhances the gain, data capacity, and diversity of wireless communication systems.

Recently, many types of reconfigurable frequency and polarization antennas have been designed and reported in [11–14]. In [11], a frequency and pattern reconfigurable antenna consisting of three switches has been presented. In the antenna structure, a lumped switch controls the operating bands,

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and two other switches control the beam switching of the antenna. A triple-band reconfigurable circularly polarized antenna with the capability of switching the polarization between right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) at three different frequencies has been designed in [12]. Polarization diversity characteristic is achieved using two pin diodes on the patch surface. [13] introduces a flexible pattern reconfigurable antenna consisting of two parallel parasitic branches embedded with two pin diodes. The designed antenna offers a 10 dB impedance bandwidth of 2.40–2.48 GHz with the capability of steering the beam in the direction and the azimuth plane. A polarization reconfigurable antenna using a change material technique has been investigated in [14]. The proposed metasurface antenna can be reconfigured to linear polarization with a gain of above 7.5 dBi, left hand and right-hand circular polarizations with the gain of 5 dBi.

As you know, the size of a dielectric resonator antenna depends on the resonant frequency of the antenna, and sometimes it is difficult to get the specific dielectric with specific dimensions. Also due to the high permittivity material which should be used in the fabrication of DRA, it usually has high fabrication cost. But in this paper, we use plexiglass compound as a DRA material which is very cheap and available in different dimensions, and the simple shape of the proposed antenna significantly reduces manufacturing costs. In this paper, two pin diode switches are used on the ground place of the proposed MIMO antenna to obtain the circular polarization and linear polarization without any considerable change in the operation frequency and radiation pattern. Depending on the location of the pin diode switches on the ground place and the placement of each dielectric resonator antenna, when two diode switches are in ON modes, the antenna has circular polarization. The designed antenna in another mode (OFF-OFF mode) provides the linear polarization with the same reflection coefficient results in all states which is one of the advantages of the proposed structure. In addition, easy fabrication, using two pin diode switches, compact size, and high gain are other advantages of the proposed antenna. In this paper, to achieve the optimized dimensions, the parametric study on the antenna operation is carried out, and the effect of the physical parameters of the antenna is described in four states of pin diode switches.

This paper consists of four sections. The first section provides an introduction to reconfiguration polarization dielectric resonator MIMO antenna. In the second section, the configuration of the proposed reconfigurable polarization MIMO DR (dielectric resonator) antenna is explained. The antenna analysis for four switch modes is carried out in the third section. A parametric study on the designed reconfigurable polarization antenna parameters is done in the fourth section. The conclusion and results are described in the last section.

2. SYSTEM CONFIGURATION

As the purpose is to design the reconfigurable polarization antenna, we need a special antenna structure and feeding network to produce circular and linear polarizations. For producing circular polarization, two orthogonal modes are needed. So, in the first step, a cylindrical dielectric antenna was considered as the antenna structure. To calculate the physical parameters of the cylindrical dielectric antenna, we first need to determine and calculate the resonant frequency of the antenna which is an important parameter of the antenna to design. The approximate calculation of this parameter for the $\mathrm{TM}_{01\delta}$ mode and $\mathrm{HEM}_{11\delta}$ mode can be expressed as follows [15, 16]:

The resonant frequency for $\mathrm{TM}_{01\delta}$ mode can be calculated by

$$F_{\mathrm{TM}01\delta} = \frac{c}{2\pi r\sqrt{\varepsilon_r + 2}}\sqrt{3.83^2 + \left(\frac{\pi r}{2h}\right)} \tag{1}$$

And the resonant frequency for $\mathrm{HEM}_{11\delta}$ mode is given by

$$F_{\mathrm{HEM}11\delta} = \frac{6.324}{r\sqrt{(\varepsilon_r + 2)}}\left\{0.27 + 0.36\left(\frac{r}{2h}\right) + 0.02\left(\frac{\pi r}{2h}\right)^2\right\} \tag{2}$$

where ε_r is the dielectric permittivity; c is the speed of the light in vacuum; r and h are the radius and height of the dielectric resonator, respectively.

The impedance bandwidth of the dielectric resonator antenna can be estimated by calculating the radiation Q-factor of the antenna.

The Q-factor for $TM_{01\delta}$ mode is given by

$$Q_{\text{rad}} = 0.00872 \times \varepsilon_r^{0.888413} \times e^{0.0397447} \left\{1 - \left(0.3 - 0.2\frac{r}{h}\right)\left(\frac{38-\varepsilon_r}{28}\right)\right\} \times \left\{9.498186\frac{r}{h} + 2058.33\left(\frac{r}{h}\right)^{4.32226} \times e^{-3.5} \times \left(\frac{r}{h}\right)\right\}, \quad (3)$$

and the Q-factor for $HEM_{11\delta}$ mode can be calculated by

$$Q_{\text{rad}} = 0.1007 \times \varepsilon_r^{1.3} \times \frac{r}{h}\left\{1 + 100 \times e^{-205\times\left(\frac{r}{2h} - \frac{1}{80}\times\left(\frac{r}{h}\right)^2\right)}\right\} \quad (4)$$

For both modes, the impedance bandwidth can be calculated by

$$\text{Impedance Bandwidth (BW)} = \frac{\text{VSWR} - 1}{Q_{\text{rad}} \times \sqrt{\text{VSWR}}} = \frac{\Delta f}{f_0} \quad (5)$$

in the next step, by calculating the physical parameters of the cylindrical dielectric resonator antenna, to optimize and improve the antenna parameters, the cross-shaped dielectric is added to the cylindrical DRA as shown in Fig. 1.

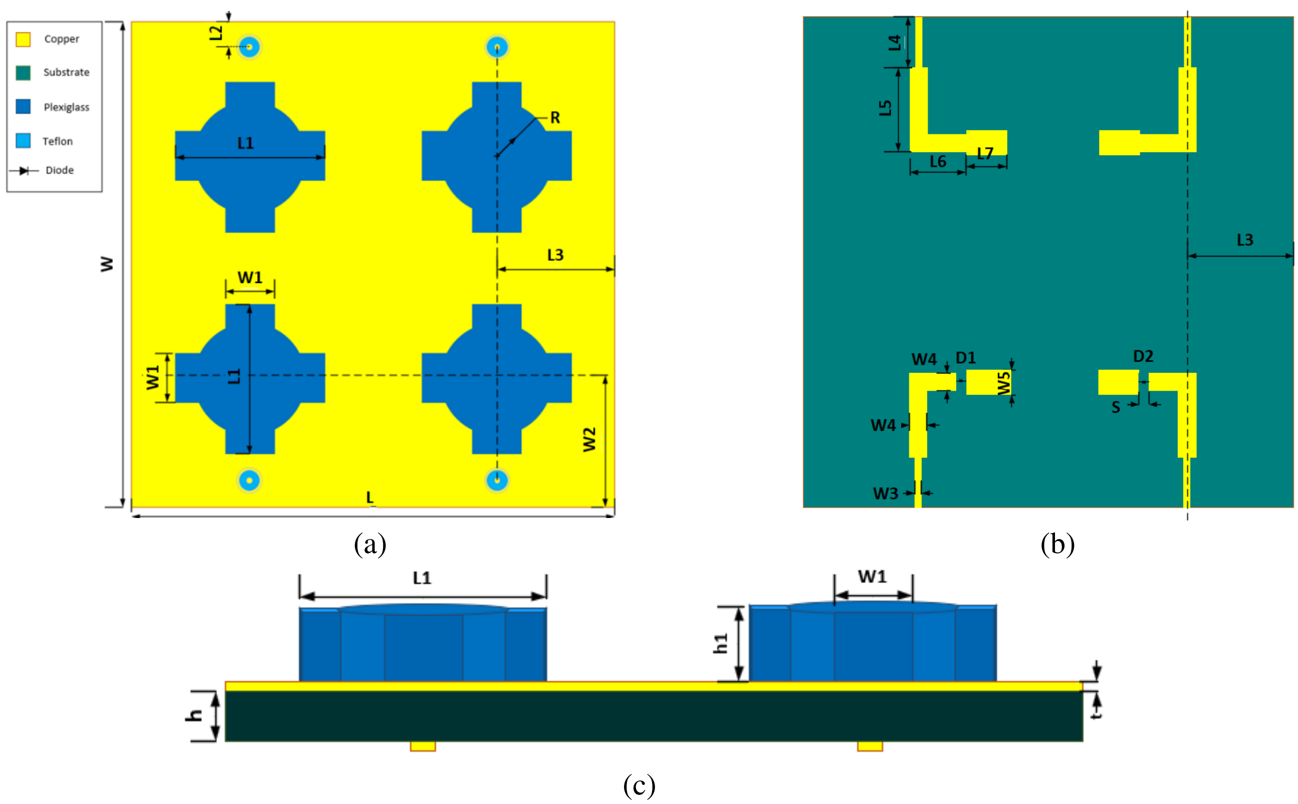
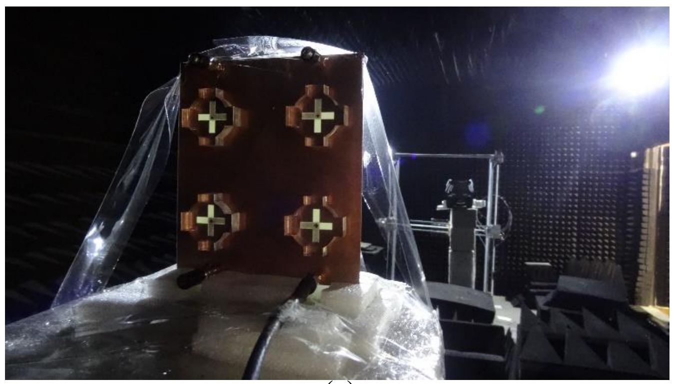


Figure 1. The simulation model of MIMO antenna in: (a) top view, (b) bottom view, (c) front view.

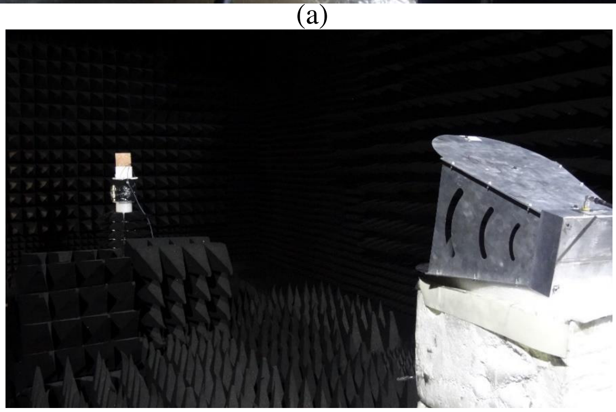
The top and bottom views of the simulation model and prototype of the MIMO DR antenna are shown in Fig. 1, which is designed on a Rogers RO4003 substrate with a relative permittivity of $\varepsilon_r = 3.55$ and a loss tangent of 0.0027 with a thickness of $h = 0.5$ mm. The antenna structure is shown in Fig. 1. As shown in Fig. 1, the antenna structure consists of four dielectric resonator antennas which are placed in 2×2 configuration and fed by a coaxial cable mechanism. The distance between the center of each antenna element in the vertical and horizontal directions is 70 mm. The proposed DRA using a plexiglass compound with a relative permittivity of 3.4 is etched on the substrate, and four L-shaped

Table 1. Dimensions of the MIMO antenna.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
L	124	L_6	12	h	0.5
W	140	L_7	10	h_1	10
L_1	36	W_1	12	t	0.035
L_2	4	W_2	37	r_i	0.6
L_3	27	W_3	0.9	r_o	1
L_4	11	W_4	4.0	S	2.0
L_5	28	W_5	4.4		



(a)



(b)

(c)

Figure 2. The prototype of the MIMO antenna in (a), (b) chamber room (3D fairfield radiation) and (c) antenna lab (s-parameter measurement.

strips are used in the ground of the MIMO antenna. To achieve a reconfigurable polarization antenna, two pin diode switches are used on the ground plane of the proposed antenna. The main advantage of the proposed structure is that by switching ON or OFF the pin diode switches which are modeled via a lumped element network, the linear or circular polarization is achieved. The final dimensions are shown in Table 1.

The polarization in the proposed antenna is controlled by using two pin diode switches (SMP1345-040) in the antenna feed structure which are modeled with the equivalent circuit (consists of an inductor, a resistor, and a capacitor) given in [14]. Due to the antenna structure shown in Fig. 1, when the VP is applied, the pin diode is forwarded-biased, and in OFF mode, the diode is reverse biased.

Table 2. Different pin diode's states.

Case	Switch one	Switch two
Case 1	ON	ON
Case 2	ON	OFF
Case 3	OFF	ON
Case 4	OFF	OFF

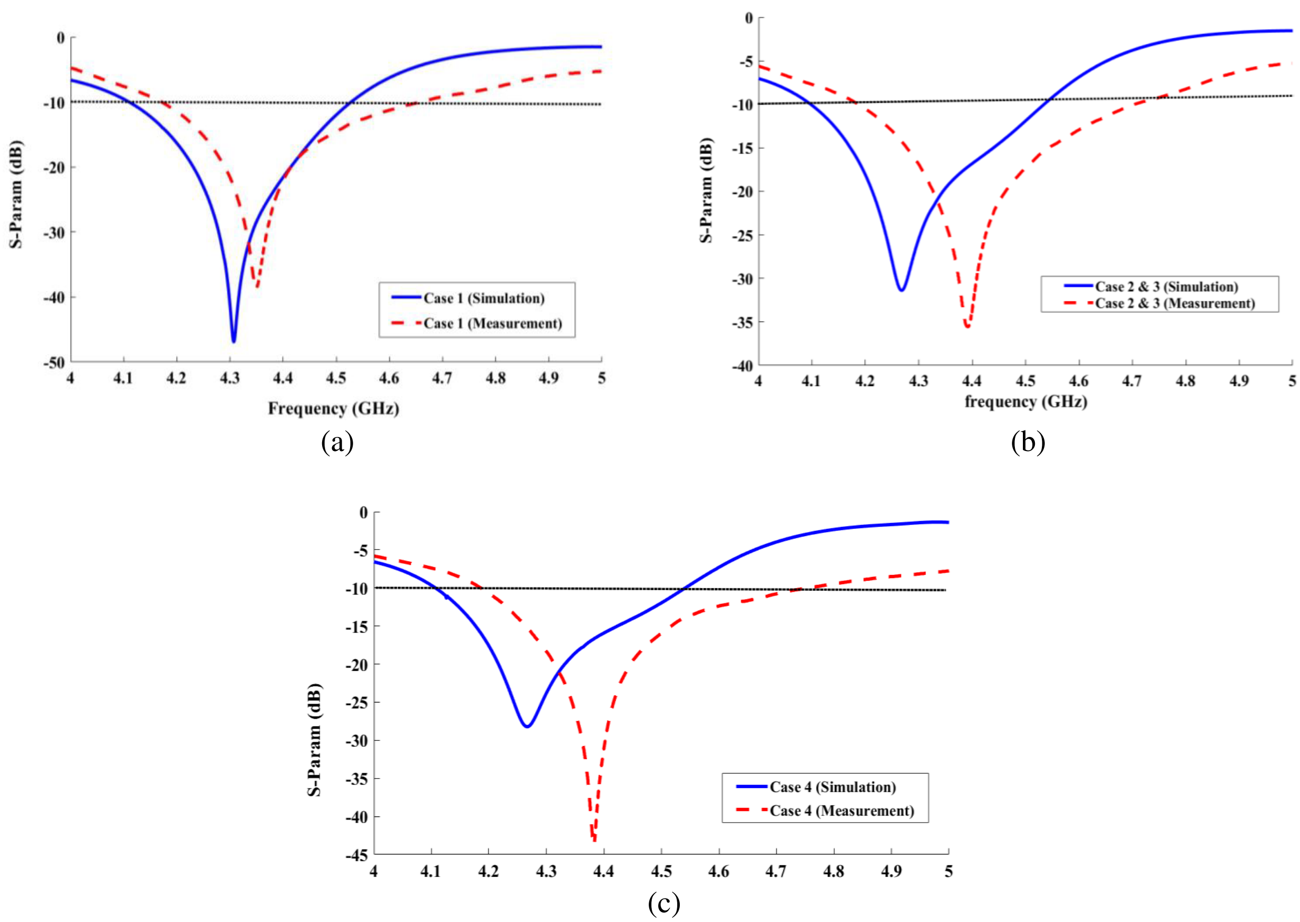


Figure 3. The simulated and measured return loss of the MIMO antenna in (a) state 1, (b) states 2 and 3 and (c) state.

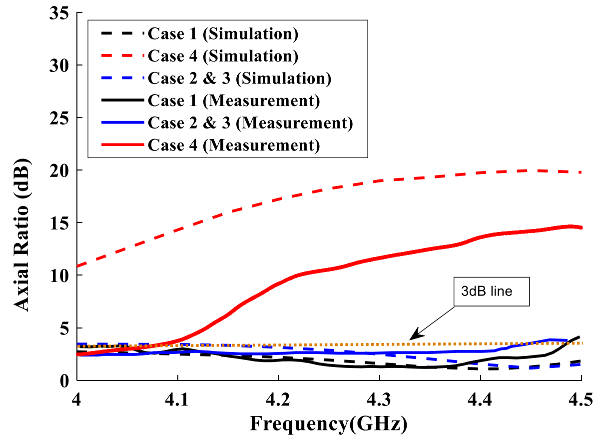


Figure 4. The simulated and measured axial ratio of the proposed antenna in all states.

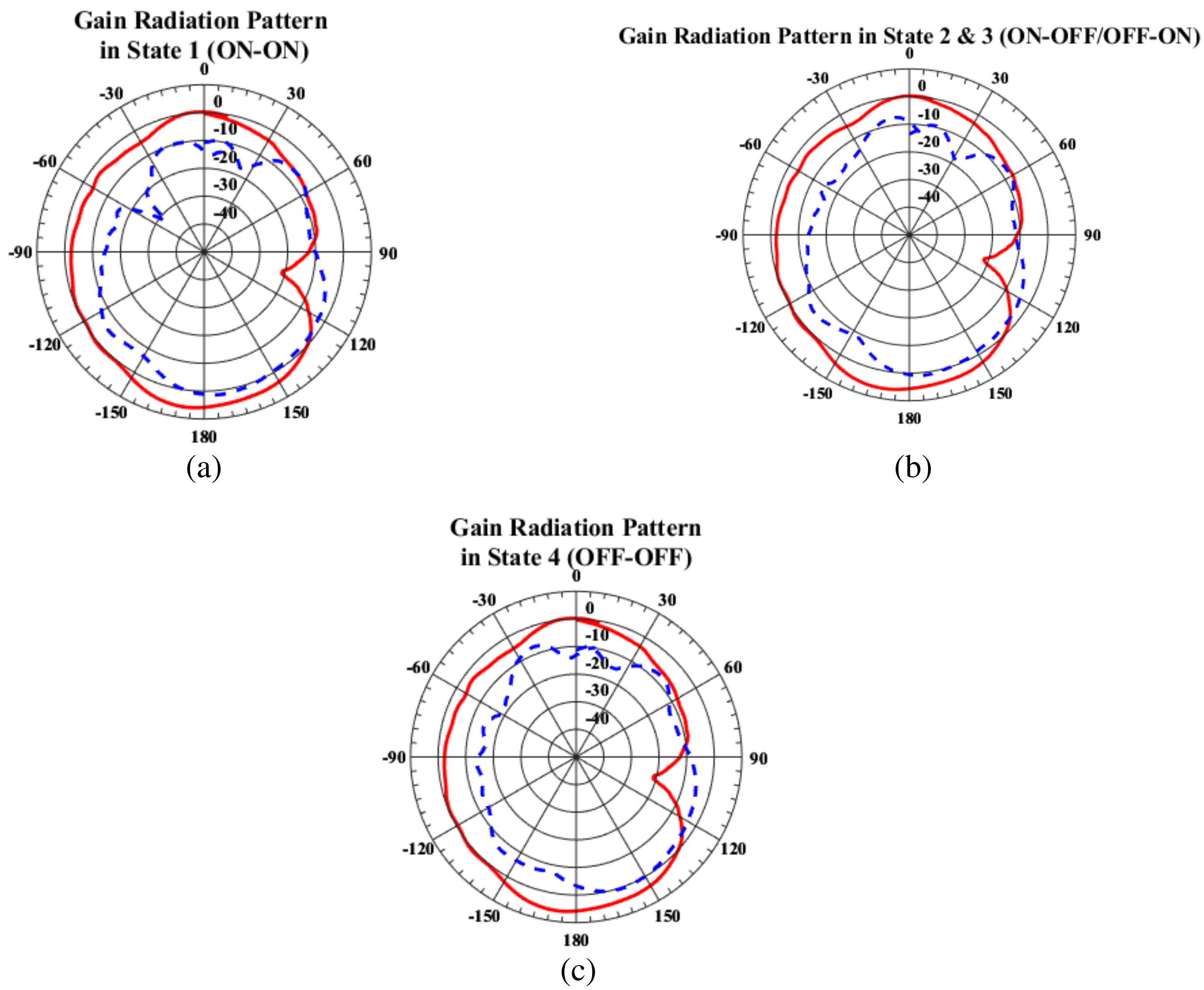


Figure 5. The measured antenna radiation pattern at the resonant frequency in (a) state 1 (ON-ON), (b) states 2 and 3 (ON-OFF & OFF-ON) and (c) state 4 (OFF-OFF) in YZ plane (Red solid line: Co-polarization and blue dashed line: Cross-polarization).

3. RESULTS AND DISCUSSIONS

In this section, the antenna simulation and measurement results in terms of reflection coefficient, polarization, and gain in all switch modes will be presented. The prototype of the MIMO antenna is shown in Fig. 2.

The performance of the proposed reconfigurable polarization MIMO DR antenna in terms of reflection coefficient, antenna gain, and axial ratio bandwidth is investigated in all switch states (Table 2) using Ansoft HFSS and CST simulator. As the pin diode switches are used to change the antenna polarization, the reflection coefficient results in all states should be the same which is an advantage of the proposed structure. In this regard, a plot of the simulated and measured S-parameters of the reconfigurable polarization DR antenna for all switch states are provided in Fig. 3. It can be observed that the proposed antenna resonates at 4.35 GHz frequency and has a wide 10 dB-impedance bandwidth

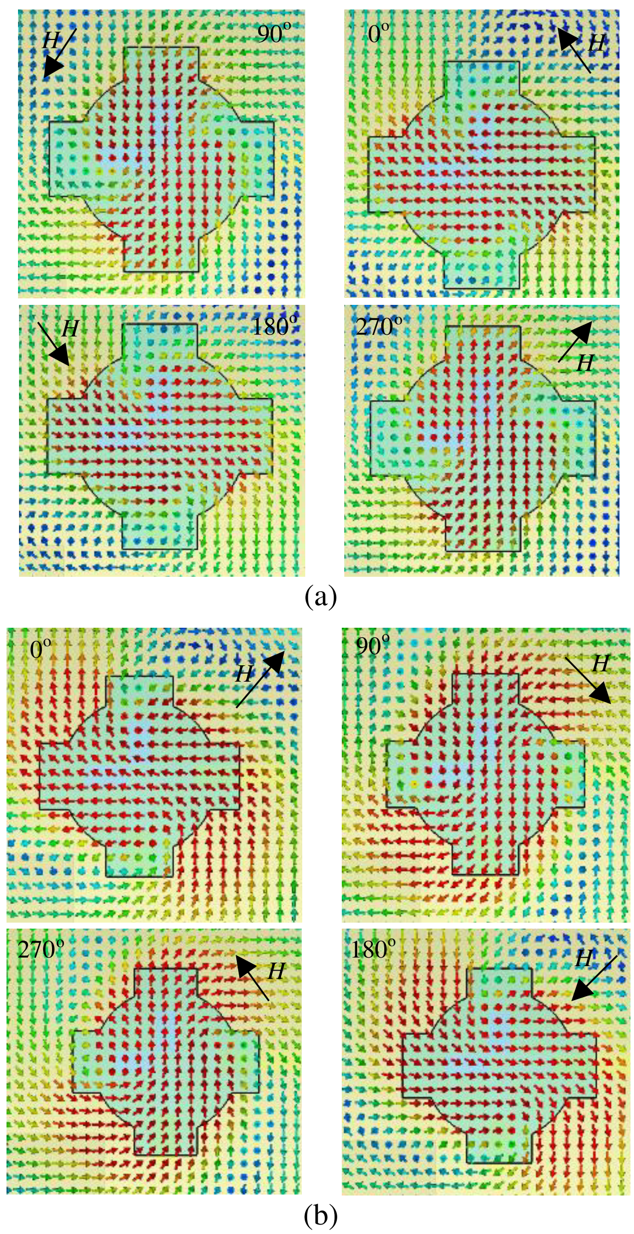
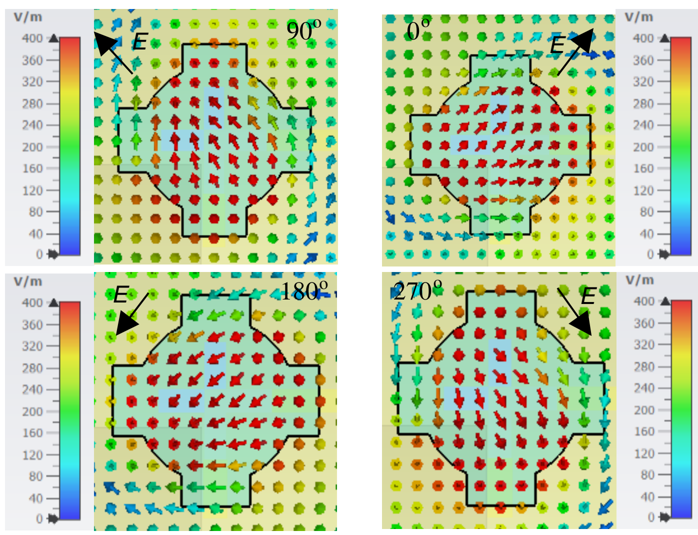


Figure 6. H-field distribution for (a) state 1 (RHCP) and (b) states 2&3 (LHCP).

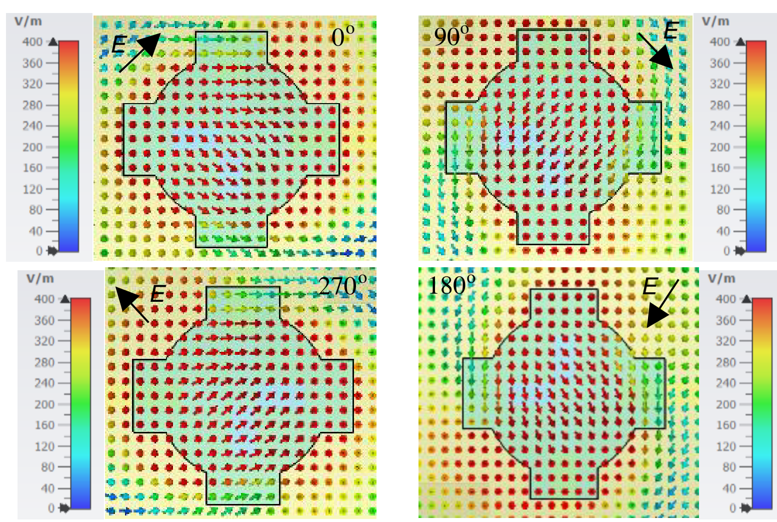
of 11.26% when two switches are ON. According to the measurement results in all states, it can be seen that the resonance frequency is shifted to the upper frequencies, and it usually happens because of the soldering, fabrication tolerance, and substrate parameters (permittivity and conductivity).

The selection of the structure is based on creating two orthogonal degenerate modes that are necessary for circular polarization. It is known that cylindrical shape and cross shape are proper choice to create degenerate modes. However, this structure is not standard, but with this antenna it is possible to excite or eliminate degenerate modes, and as a result, we can switch between linear and circular polarizations. With On or Off states of the switches on the feeding lines, it is possible to excite or eliminate degenerate orthogonal modes.

Figure 3 illustrates the simulated and measured axial ratios of the reconfigurable polarization MIMO DR antenna in circular polarization (cases 1, 2, & 3) and linear polarization (case 4). It can be observed that the proposed antenna provides the 3 dB axial ratio bandwidth of 8.7% (ON-ON state) at the frequency band. When two diodes are OFF, the resulting radiation polarization is linear. As seen in Fig. 4, the axial ratio plots of the antenna are the same on the states of 2 and 3 (switch 1: ON & switch 2: OFF, switch 1: OFF & switch 2: ON). Therefore, by changing the bias voltages which are applied



(a)



(b)

Figure 7. *E*-field distribution for (a) state 1 (RHCP) and (b) states 2&3 (LHCP).

on two pin diodes, the circular and linear polarizations can be achieved. A small difference between the simulation and measurement results may occur because of the soldering of the four SMA connectors outside of the ground boundary. The radiation patterns of the prototype reconfigurable polarization MIMO DR antenna for all cases are measured in the YZ plane and are shown in Fig. 5. Based on the H-field and E-field distributions that are shown in Fig. 6 and Fig. 7, for state 1 (ON-ON) the antenna polarisation is RHCP, and for states of 2&3 (ON-OFF/OFF-ON) is LHCP. In addition, according to the measurement results the proposed antenna attains the peak gain of 6.4 dB across the axial ratio bandwidth (which is shown in Fig. 8). It is necessary to mention that the maximum efficiency of the designed and fabricated antenna is 97.5%.

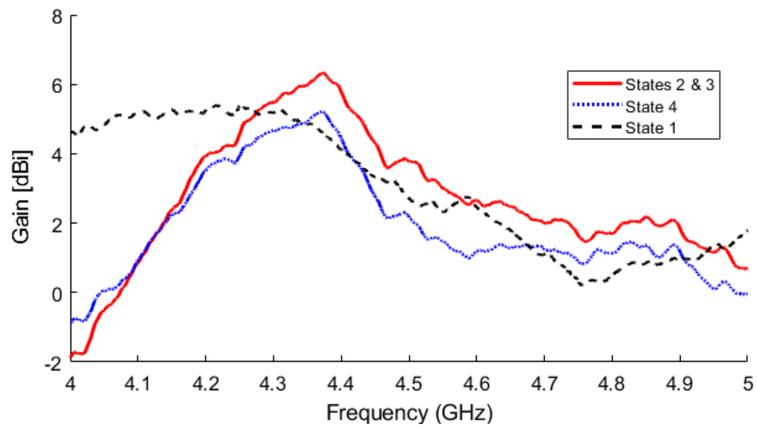


Figure 8. The measured gain of the proposed antenna in all states.

Table 3 presents the comparative study of the proposed reconfigurable polarization MIMO DR antenna with other existing reconfigurable polarization antennas in terms of antenna gain, impedance bandwidth, and axial ratio (AR < 3 dB) bandwidth. It can be seen in Table 3 that the proposed antenna presents higher peak gain, wider axial ratio (AR < 3 dB) bandwidth, and more polarization states than other works, and exhibits improved performance.

Table 3. Comparison between the proposed antenna and other existing structures.

Ref.	Impedance bandwidth	No of switches	gain	Axial ratio bandwidth	Polarization states
[11]	2.82%	8	7.13 dBi	2.82%	LP-CP
[17]	6.79%	4	6.2 dBi	2.36%	LP-CP
[18]	52.6%	2	2.7 dBi	3.5%–6.6%–2.4%	CP
[19]	4.16%	1	5 dBi	0.5%	LH/RH CP
[20]	3.16%	-	5.5 dBi	1.19%	LP-CP
[21]	23%	2	1.2 dBi	4.5%	LP-CP
[22]	23.7%	2	3.24 dBi	6.8%	LP-CP
[23]	9.23%	-	3.8 dBi	1.54%	LH/RH CP
[24]	5.54%	2	7 dBi	1.25%	LP-CP
This work	11.26%	2	6.4 dBi	8.74%	LP-CP

4. CONCLUSION

In this paper, a reconfigurable polarization MIMO DR antenna is designed, fabricated, and measured. We have used plexiglass compound as a DRA material which is cheap and available in different dimensions, and it has reduced the fabrication price. A good agreement can be observed between the simulation and measurement results. The proposed antenna using two pin diode switches is able to switch between linear and circular polarizations. The measurement results for all states (linear and circular polarizations) indicate that the designed antenna operates at the resonance frequency of 4.35 GHz with wide impedance bandwidth of 11.26% and has a maximum efficiency of 97.5%. The proposed antenna provides a high gain of 6.4 dB and is suitable for polarization diversity applications of modern MIMO systems.

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