Progress In Electromagnetics Research M, Vol. 74, 105–113, 2018

Circular Ring Shaped Polarization Reconfigurable Antenna for Wireless Communications

Manavalan Saravanan* and Madihally J. S. Rangachar

Abstract—A single fed polarization reconfigurable antenna is presented. The antenna comprises of a circular ring-shaped radiating element along with reconfigurable feed network located at its center which eliminates the need for additional space for reconfigurable feed network. A separate biasing network is placed to bias the pin diodes in the feed network for polarization reconfiguration and achieves three polarization states (linear, left-hand and right-hand circularly polarization). The antenna is designed to operate at 2.4 GHz ISM band. The antenna parameters are simulated using Ansoft high-frequency structure simulator and are validated using Agilent network analyzer (N9925A) and antenna test systems. The antenna achieves a good -10 dB impedance bandwidth of 85 MHz (2.40–2.485) GHz in linear state and 85 MHz (2.41–2.495) GHz in the circularly polarization states along with better cross-polarization isolation ($\geq$ 15 dB) in the operating bands and hence more suitable for modern wireless communications.

1. INTRODUCTION

Antennas with reconfigurable nature are most widely used in modern communication systems due to its ability to adapt to the system environment and also to the performance of the system. Especially polarization reconfigurable antennas plays a crucial role in remote sensing, missile tracking and guiding applications due to its ability to mitigate the effect of antenna orientation problems, avoiding fading loss and also to improve system capacity. In general, polarization reconfigurable antennas are designed based on reconfiguring the radiating element or by means of switching feed network using pin diodes, MEMS switches or varactor diodes. Lin and Wong [1] demonstrated a polarization reconfigurable antenna by reconfiguring the feeding network through sequential excitation by means of pin diodes in the feed network. In [2], an aperture coupled polarization reconfigurable antenna is proposed which consists of controllable RF switches on a cross aperture to excite the radiating element. A most common method of achieving polarization reconfiguration is by etching a slot on the radiating element and reconfiguring it by means of pin diodes [3] to connect the gap between the slots. A reconfigurable monopole antenna integrated with mushroom-like meta-surface to enhance antenna performance is demonstrated in [4]. The axial ratio bandwidth of the antenna is moved far from the resonant frequency of the antenna, even though the antenna achieves polarization diversity with a minimum number of diodes. Further, the use of pin diodes in polarization reconfiguration requires additional biasing circuit and has to be carefully designed in such a way that it should not affect antenna performance characteristics. Another approach is by using PIN diodes, RF switches, or by using varactor diodes polarization states are altered by modifying the feed network. Sun and Sun [5] suggested a reconfigurable antenna by reconfiguring the feed network to induce phase difference in the output ports. In [6], polarization diversity is realized by altering the feed network which provides different phase outputs by means of V-shaped coupling strip

Received 16 August 2018, Accepted 28 September 2018, Scheduled 11 October 2018

* Corresponding author: Manavalan Saravanan (msarawins@gmail.com).
The authors are with the Department of Electronics and Communication Engineering, Hindustan Institute of Technology and Science, Chennai, India.

in the feed network. In [7], a circularly polarized antenna with reconfigurable broadside and conical beams facilitated by a mode switchable feed network is presented. This method of reconfiguring feed network to realize polarization diversity needs extra space for feeding network, and it is also extremely dependent on performance characteristics and affects its performance drastically when it is not properly designed. Recently fluid dielectric materials are studied for polarization reconfiguration since they give better linear control over polarization [8, 9]. However, due to complexity in their control mechanism, it is difficult to integrate with most of the small devices and consumes additional space for the fluid tank. The radiation characteristics of the antenna are reconfigured by means of varactor diodes in [10]. The capacitance of the varactor diode is changed by varying the bias voltage which alters the performance of the antenna. A reconfigurable antenna array with an artificial magnetic conductor (AMC) ground plane is presented in [11]. The model utilizes pin diodes for reconfiguration and AMC as a reflector. Recently polarization reconfiguration is achieved by changing the feeding scenario manually [12]. This method is not feasible in real time applications where there is need to switch polarization at high speed which requires excitation of the same signal simultaneously in all ports that consumes much power.

Most of the conventional antenna consists of multiple substrates for placing additional feed network or utilizing the complex network for controlling reconfigurable system which makes the antenna profile thicker and also difficult to integrate with other circuit components. In addition to this antenna complexity, the conventional antennas utilize an increased number of switching elements which degrades the antenna performance especially antenna efficiency [13]. Hence there is a need to design a simple reconfigurable antenna on a single layer with a minimum number of switching elements. In this paper, a compact polarization reconfigurable antenna is presented. The antenna is designed on a single layer low-cost FR_4 substrate and utilizes only two miniature diodes for switching polarization. The antenna achieves three different polarization states based on switching of pin diodes. The reconfigurable feed network is placed within the gap region of the radiating element to reduce the antenna profile. The performance of the proposed antenna is validated through measurements and compared with other conventional antennas.

2. ANTENNA DESIGN PRINCIPLE

The geometry of the proposed antenna is shown in Fig. 1. A circular geometry is chosen for simplicity, and it has the advantage of a symmetrical shape. This helps in designing the LHCP and RHCP antenna geometry looking mirror images with each other and mitigates unnecessary shift in operating frequency between LHCP and RHCP modes. The antenna is modeled on a low-cost FR4 substrate of size 55 mm × 55 mm × 1.6 mm having a permittivity of 4.4 and loss tangent of 0.02. A circular ring-shaped radiating patch whose dimensions are shown in Fig. 1 is etched on the substrate, and a T-shaped reconfigurable feed network is placed at its center. The center of the radiating patch is shorted with the ground by means of vias to avoid DC saturation of pin diodes. Two pin diodes are integrated into the T-shaped network for polarization reconfiguration. A separate biasing network comprising blocking capacitor and RF choke inductor is used to bias the pin diodes. The antenna is fed by 50 Ω SMA connector.

3. PRINCIPLE OF OPERATION

Polarization reconfiguration of the antenna is achieved by switching the pin diodes (NXP BAP50-03, 50 mA, 50 V) placed in the T-Network. In general, the presence of pin diodes affects the performance of the antenna especially radiation efficiency. This is due to the presence of forward resistance, when the diode is in ON state. Hence a diode having a minimum forward resistance value is chosen for switching to minimize its effect on antenna performance. Further, the diodes are placed near the center of the antenna where current is minimum, and hence the effect of the diode on antenna radiation characteristics is minimized. In ON-state, the diode has a series resistance and inductance of 5 Ω and 1.8 nH, and in OFF-state, the diode has a shunt capacitance 0.35 pF with the reverse resistance of 500 kΩ.

The equivalent circuits of the pin diode at ON and OFF states are shown in Figs. 2(a) and 2(b). A separate DC biasing circuit for exciting pin diodes is shown in Fig. 2(c). The circuit comprises RF choke inductor (TDK MLG0603Q Series Multilayer SMD Inductor, 22 nH, 2.5 GHz, 6.150 mA, 1.2 Ω R_{dc}) to provide a DC bias path to the pin diode and also block the RF signal and a blocking Capacitor (AVX

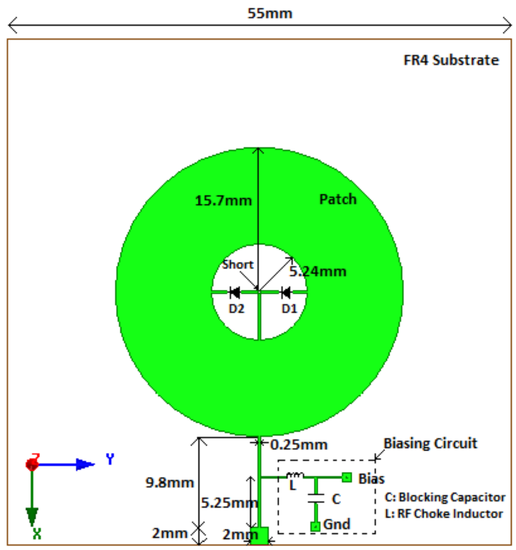

Figure 1. Antenna geometry.

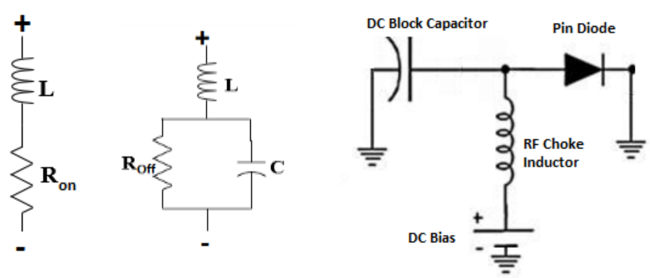

Figure 2. DC biasing circuit.

0402 Series Multilayer Ceramic Capacitors, 10 pf, 50 v) to avoid DC bias from reaching RF output. This isolates the RF element from DC input and hence avoids degradation of antenna performance. Further, the DC blocking capacitor and RF choke inductor are placed away from the radiating element near the feed line to avoid direct coupling with antenna radiating surface.

Table 1 shows different polarization states corresponding to pin diode switching conditions. Under no bias condition, both the diodes D1 & D2 are in OFF state, and the antenna resembles a circular ring patch as shown in Fig. 3(a) and radiates linear polarization. When a positive bias is applied, diode D1 is forward biased, and diode D2 is reverse biased, thus the T-shaped network reconfigured like a mirror image of 7 shape as shown in Fig. 3(b). This generates two orthogonal modes (E_x and E_y) with equal amplitude and +90° phase difference, and the antenna radiates left-hand polarization. Similarly, when a negative bias is applied, diode D1 is reverse biased, and diode D2 is forward biased, thus the T-shaped network reconfigured like inverted 7 shape as shown in Fig. 3(c). This generates two orthogonal modes

Table 1. Operating modes.

Modes	D1	D2	Polarization
1	OFF	OFF	LP
2	ON	OFF	RHCP
3	OFF	ON	LHCP

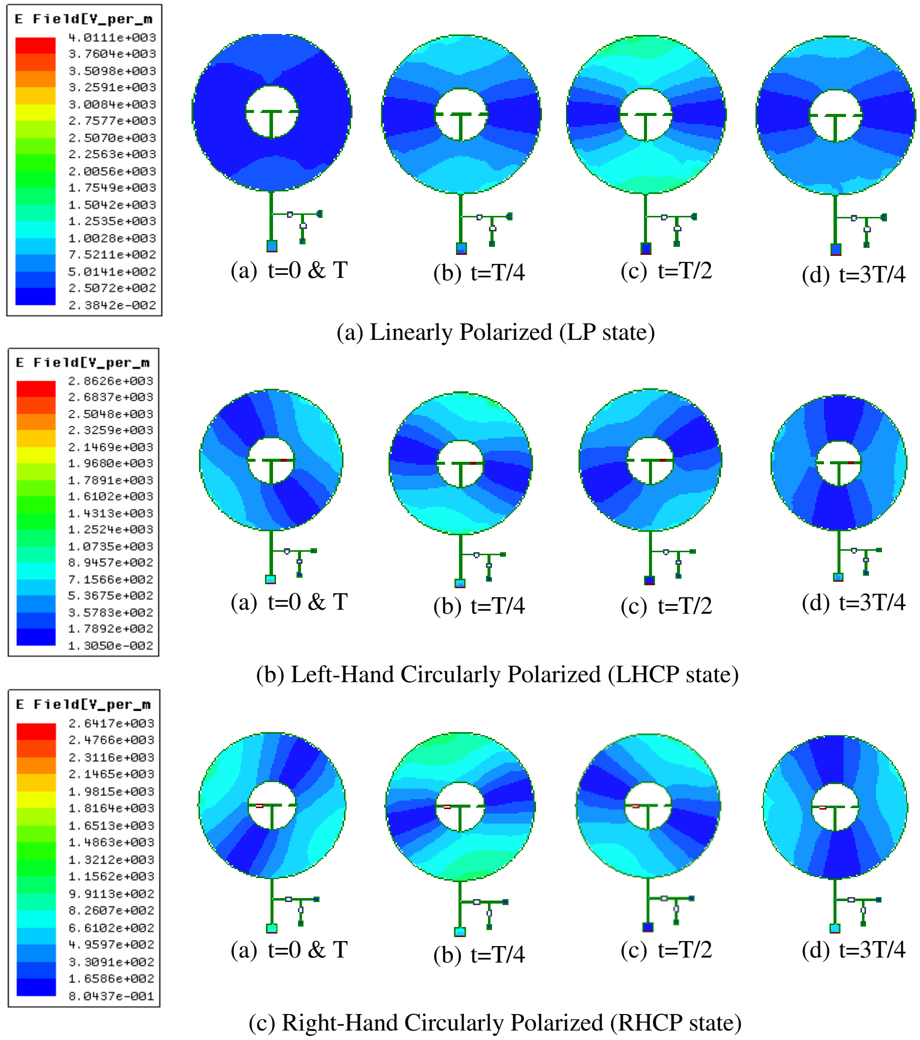

Figure 3. Surface current distribution.

(E_x and E_y) with equal amplitude and $-90°$ phase difference, and the antenna radiates right-hand polarization.

Figure 3 shows the current distribution on the antenna radiating element corresponding to different polarization states.

4. RESULTS AND DISCUSSION

In order to validate the performance of the antenna, the proposed model is fabricated on the FR_4 substrate and is integrated with pin diodes (NXP BAP50-03, 50 mA, and 50 V), inductor (TDK MLG0603Q Series Multilayer SMD Inductor, 22 nH, 2.5 GHz, 6.150 mA, 1.2 Ω R_{dc}) and capacitor (AVX 0402 Series Multilayer Ceramic Capacitors, 10 pf, and 50 v) as shown in Fig. 4. A 50 Ω SMA connector is used as an input port. Two DC biasing lines are connected with bias terminal and another with Gnd Terminal. Under different operating modes, the two DC lines are alternatively biased with positive or negative potentials.

The impedance characteristics of the antenna are measured using the network (N9925A) and are compared with simulated results and shown in Fig. 5.

It is observed that the antenna achieves a -10 dB measured impedance bandwidth (2 : 1 VSWR) of 85 MHz (2.40–2.485) GHz for LP state and (2.41–2.495) GHz for LHCP/RHCP state in the industrial,

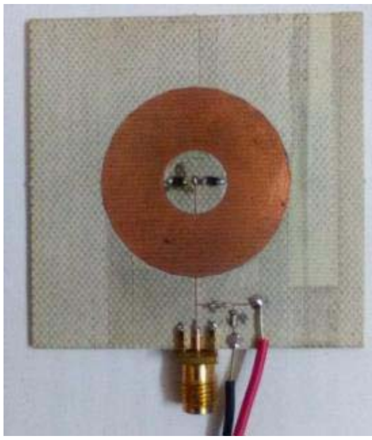

Figure 4. Fabricated prototype.

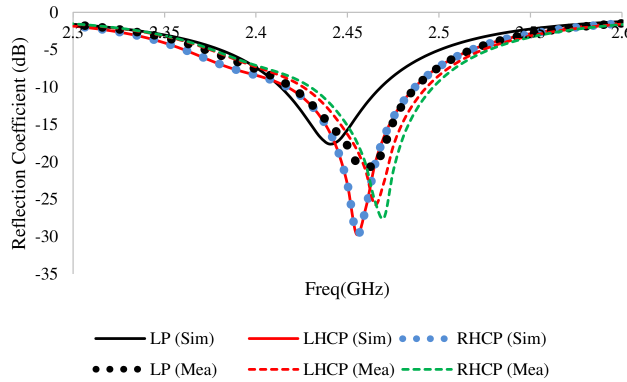

Figure 5. Reflection coefficient (dB).

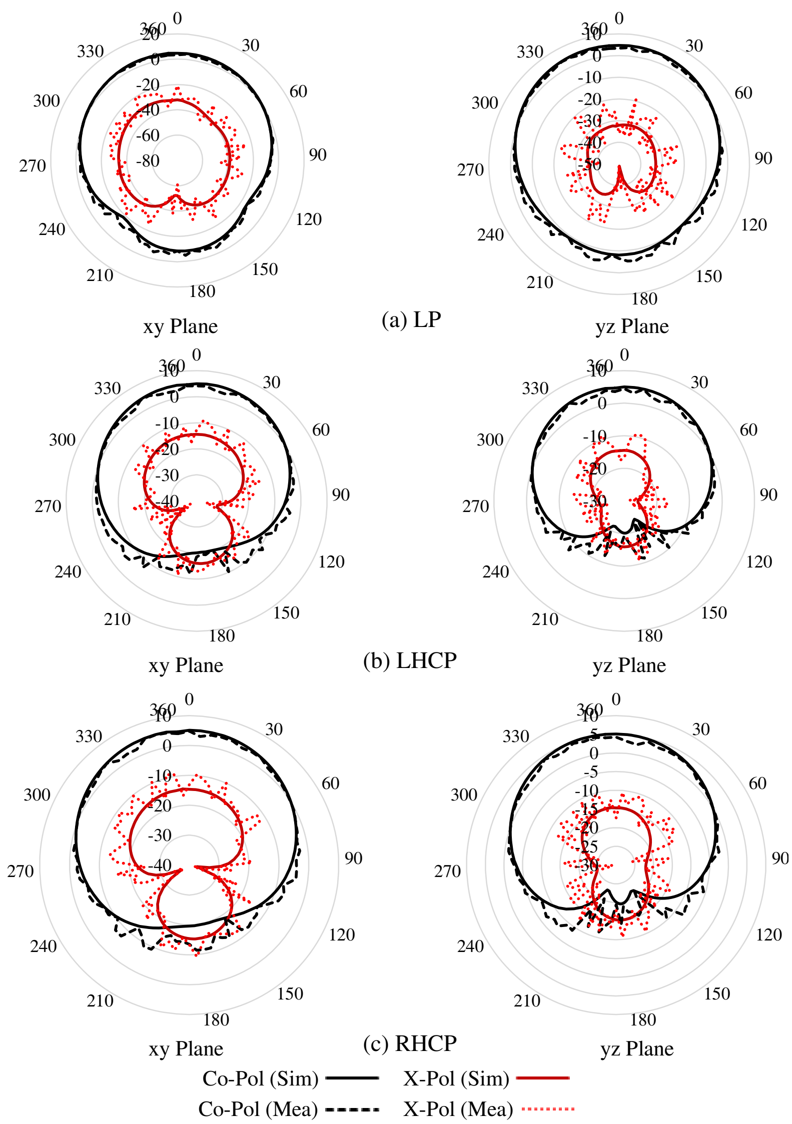

Figure 6. Radiation characteristics of the antenna.

scientific, and medical radio band (2.4 GHz ISM band) with minimum reflection coefficient of ≥ -20 dB.

Figure 6 shows the radiation characteristics of the antenna measured using antenna test systems. The antenna gives symmetrical radiation pattern around the zenith. A standard pyramidal horn antenna having a gain of 9 dB is used as a reference antenna. The antenna under test (AUT) is placed at the transmitter side and is rotated in the plane of polarization, and the output is recorded for all three modes. The distance between two antennas (R) is measured, and the gain is calculated using the Friis transmission equation given below

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r \qquad (1)$$

The antenna gives symmetrical radiation pattern and achieves a simulated gain of 6.82 dBi for linearly polarized state and 6.35 dBic for circularly polarized state (LHCP/RHCP). It gives a measured peak gain of 6.06 dBi for linearly polarized state and 5.74 dBic for circularly polarized state (LHCP/RHCP). In all the states the antenna achieves a minimum polarization isolation of ≥ 15 dB.

Figure 7 shows a variation of gain characteristics with respect to the operating band for different modes. It is observed that the antenna gives an almost flat gain response in their operating band.

Figure 8 shows a variation of axial ratio with respect to operating band for both LHCP and RHCP states. The antenna achieves minimum axial ratio in the direction of propagation at operating frequency and also achieves 3 dB axial ratio bandwidth of 90 MHz (2.41–2.50) GHz for both LHCP and RHCP configurations and covers 2.4 GHz band applications.

Figure 9 gives axial ratio beamwidth radiation characteristics for LHCP and RHCP states. It is observed that the antenna achieves a wider 3 dB axial ratio of 90° ($-30° \leq AR_{3\,\mathrm{dB}} \leq 60°$) in the

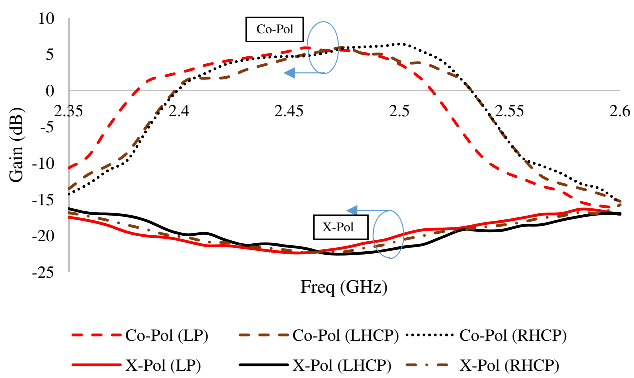

Figure 7. Measured gain across the operating band for different modes.

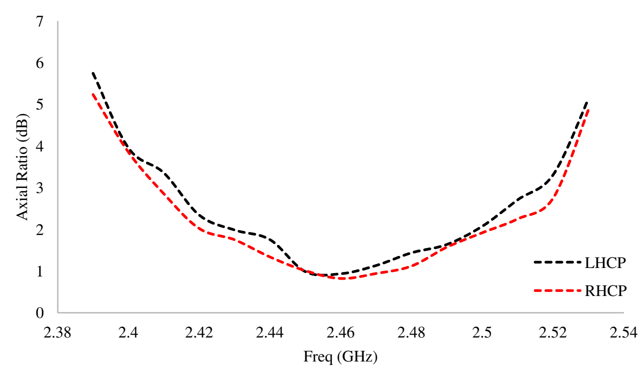

Figure 8. Variation of the Axial ratio (dB) against operating band (GHz).

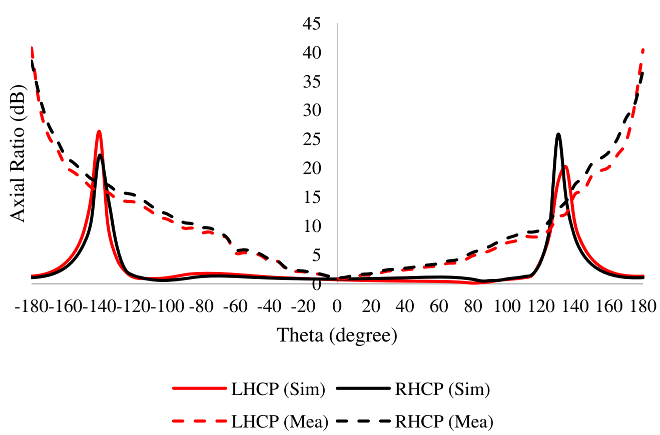

Figure 9. Variation of the Axial ratio (dB) against theta (degree).

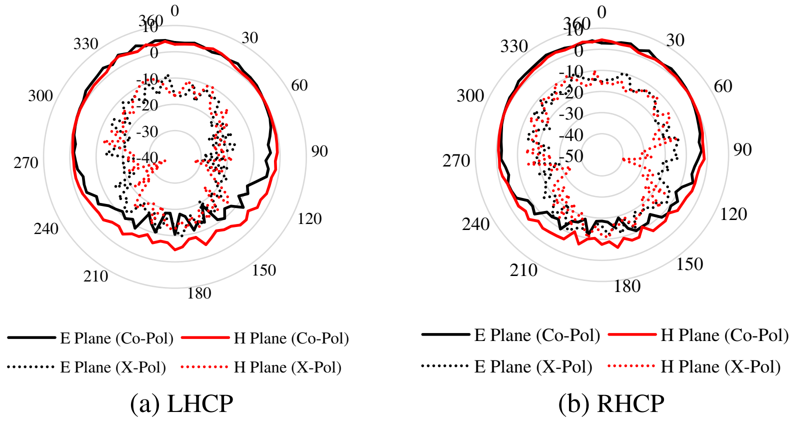

Figure 10. Radiation patterns measured at a frequency of minimum AR (a) LHCP and (b) RHCP.

operating frequency measured at the direction of propagation. Fig. 10 shows the radiation pattern measured at a minimum axial ratio corresponding to both modes.

The performance comparison of the proposed antenna model with other conventional models is given in Table 2. From Table 2 it is observed that most of the traditional antennas utilize an additional layer other than radiating element for reconfigurable feeding network circuit or mechanical rotation fluid control mechanism. This makes the antenna bulkier and difficult to integrate with other high-frequency circuits. In addition to this, these traditional antennas utilize complex feed mechanism systems or

Table 2. Performance comparison of proposed antenna with other conventional antennas.

Parameter	**Single/ Multi-Layer**	**Size (mm^3)**	**No. of Element**	**Gain**	**Impedance Band width**	**3 dB AR Bandwidth**	**3 dB AR Beamwidth**
[2]	Multi	420 × 120 ×4	4 Pin diodes	13.5 dBi	(2.25–2.47) GHz	NA (Since LP)	NA (Since LP)
[3]	Single	32 × 32 ×2.43	8 pin diodes	(6.31–7.3) dBic (CP) (6.42–7) dBi (LP)	(5.68–5.9) GHz and (5.18–5.26) GHz)	(5.08–5.12) GHz and (5.68–5.72) GHz	60° (LHCP, RHCP)
[4]	Multi	88 × 69 ×20.4	9 DPDT	(−1.2–5.3) dBi (LHCP) (−2.3–5.0) dBi (RHCP)	(1.21–2.09) GHz	(1.42–1.88) GHz	64° (LHCP) 46° (RHCP)
[5]	Single	100 × 100 ×1.6	8 Pin diodes	2.4 dBic (CP) 4.1 dBi (LP)	(892–972) MHz	(928–943) MHz	Not Reported
[7]	Multi	44 × 44 ×13	12 Pin diodes	5.8 dBic (CP)	(2.2–2.9) GHz	(2.45–2.65) GHz	60° (LHCP, RHCP)
[11]	Multi	100 × 100 ×0.79 (Single element)	4 Pin diodes	6.1 dBic (CP)	(1.24–2) GHz	(1.45–1.89) GHz	Not Reported
Proposed	Single	55 × 55 ×1.6	2 pin diodes	6.06 dBi (LP) 5.74 dBic (CP)	(2.41–2.495) GHz	(2.41–2.50) GHz	90° (LHCP, RHCP)

increased number of switching elements for reconfiguration. In the proposed antenna model, a simple structure with only two switching elements is used for reconfiguration. The reconfigurable feed network is placed in the radiating patch gap region to avoid unnecessary space required for feed network. The addition of an RF choke inductor and blocking capacitor to isolate the DC biasing circuit from the high-frequency RF element avoids degradation of radiation performances. The proposed antenna is compact, has single layer and achieves good gain characteristics in the operating band. Compared with traditional reconfigurable antennas mentioned in Table 2, the proposed antenna achieves a wider 3 dB axial ratio beamwidth with better cross-polarization isolation.

5. CONCLUSION

In this paper, a compact polarization reconfigurable antenna is presented. The antenna achieves polarization reconfiguration by means of pin diodes in the reconfigurable feed network. Compared to the conventional reconfigurable antenna, the proposed model utilizes the gap region in the circular ring for the reconfigurable network which eliminates the need of additional space required for reconfigurable feed network. The antenna achieves three different polarization states (LP/LHCP/RHCP) with a minimum number of switching elements with improved 3 dB axial ratio beamwidth of 90° and also achieves better gain characteristics along with cross-polarization isolation (≥ 15 dB) in the operating band than traditional reconfigurable antennas. Thus the antenna is better suitable for modern wireless application which prefers LP/CP antenna characteristics.

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