Dielectric resonator antenna with reconfigurable polarization states

Amjad Iqbal12 ⋄ | Mohamed I. Waly3 ⋄ | Amor Smida34 ⋄ | Nazih K. Mallat5 ⋄

1 Centre for Wireless Technology, Faculty of Engineering, Multimedia University, Cyberjaya, Selangor, Malaysia
2 Department of Electrical Engineering, CECOS University of IT and Emerging Sciences, Peshawar, Pakistan
3 Department of Medical Equipment Technology, College of Applied Medical Sciences, Majmaah University, Al Majmaah, Saudi Arabia
4 Microwave Electronics Research Laboratory, Department of Physics Faculty of Mathematical, Faculty of Mathematical, Physical and Natural Sciences of Tunis, Tunis El Manar University, Tunis, Tunisia
5 Network and Communications Engineering Department, College of Engineering, Al Ain University, Al Ain, United Arab Emirates

Correspondence
Amjad Iqbal, Centre for Wireless Technology, Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor, Malaysia.
Email: amjad730@gmail.com

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Abstract
This study presents a simple and low-profile cylindrical dielectric resonator antenna (CDRA) for the fifth-generation (5G) band (3.5 GHz) with switchable polarization. The antenna can operate with linear or circular polarization (right-handed circular polarization [RHCP] or left-handed circular polarization [LHCP]) by changing the states of the PIN diodes below the CDRA, while keeping the same operating frequencies. The antenna operates at three modes (Mode 1, Mode 2, and Mode 3). It exhibits linear polarization in Mode 1, RHCP in Mode 2, and LHCP in Mode 3. The 10-dB bandwidths of 750 MHz (3.1–3.85 GHz), 950 MHz (3.03–3.98 GHz), and 960 MHz (3.03–3.99 GHz) are noted for Mode 1, Mode 2, and Mode 3, respectively. The 3-dB axial ratio bandwidth of 22.2% (3.09–3.86 GHz) and 21.4% (3.08–3.82 GHz) is achieved for Mode 2 and Mode 3, respectively. The reported antenna has high gain (>5.25 dBi for all operating modes) and high radiation efficiency (>79.8% for all operating modes). The proposed antenna is suitable for use in polarization diversity applications.

1 | INTRODUCTION

Polarization switchable antennas are often considered nowadays when the multistandard wireless communication system is required to realize polarization diversity. Different polarization schemes in the same frequency band can mitigate multipath fading losses thereby enhancing the system capacity and minimizing its size [1–4].

Various techniques have been used in the past to design polarization reconfigurable antennas. One method of generating switchable polarization is to use varying excitation ports. A number of antennas using this method have been recently reported by the researchers. In [5, 6], square slot antennas are designed, where the polarization is reconfigured by changing the excitation port, but the slot antennas [5, 6] have large dimensions and are difficult to integrate into the compact radio frequency (RF) front-ends. The second method of designing polarization switchable antennas is to modify the feeding networks. In [7], a sense polarization reconfigurable slot antenna is reported. The sense polarization reconfigurability is achieved by changing the states of the switches in the feeding network. The authors of [8] present a wideband polarization sense reconfigurable patch antenna, where reconfigurability between the left-handed circular polarization (LHCP) and the right-handed circular polarization (RHCP) is achieved by the reconfigurable feeding network. In [9], a compact CP antenna is designed with the aid of a microstrip patch and slots. The polarization in [9] can be interchanged between RHCP and
LHCP by changing the switching state of the diodes of the slots. By changing the state of the PIN diodes designed in balun feeds, the dipole produces horizontal and vertical polarization [10].

Microstrip antennas have disadvantages such as a narrow operating bandwidth and low radiation efficiency. Dielectric resonator antennas (DRAs), in contrast, possess the advantages of easy modes of excitation and wideband responses with high radiation efficiency [11–13]. It has around 10% wider bandwidth than a conventional patch antenna at 4 GHz [14]. A large number of frequency- and pattern-reconfigurable DRAs have been designed for multistandard RF front-ends [15, 16]. However, few studies have discussed the polarization reconfigurable DRAs. Recently, a DRA with multi-polarization schemes is reported in [17]. The circular polarization is achieved by incorporating cross slots in the ground plane, while the polarization states are controlled by the dimensions of the slots using PIN diodes. The antenna retains the impedance bandwidth of 20% for all polarization states; however, it has a very narrow 3-dB axial ratio (AR) bandwidth (1%) for circular polarization states. A polarization reconfigurable rectangular dielectric resonator antenna (RDRA) is reported in [18], where reconfigurability in the polarization states is achieved by controlling the dimensions of the modified cross-slot through electronically controlled PIN diodes. A polarization reconfigurable cylindrical dielectric resonator antenna (CDRA) with four unique polarization states is reported in [19], where reconfigurability in the polarization states is achieved by a tunable Wilkinson equal power divider. A cylindrical DRA with polarization diversity is designed in [20], but the nature of its switchable polarization made it impractical for use in multistandard systems. Additionally, some polarization reconfigurable antennas have been designed [21, 22], that use a liquid to change the state of polarization. In [21], reconfigurability in the polarization is achieved by injecting water into the different cavities of the dielectric resonator. In [22], ethyl acetate is injected into the DRA cavity to change the state of polarization between RHCP and LHCP. However, these antennas are big in dimensions and work only in static systems. Moreover, any change in the liquid properties can change the operating and CP bandwidth, so great care must be taken before injecting a liquid into the DRAs for polarization reconfigurability. Additionally, the pump for injecting liquid makes the system more complex. A multilayer wideband polarization reconfigurable DRA with lattice structure is proposed in [23]. The designed antenna has wideband CP bandwidth (21.1%), but its multilayer structure and large size restrict its application in compact RF front-ends. The authors of [24] reported a polarization reconfigurable RDRA. The polarization switching is achieved by adjusting the feed network, which is composed of Wilkinson power divider and tunable phase shift elements.

In this paper, the authors reported polarization switchable CDRA which can operate in linear polarization, RHCP as well as in LHCP, with same operating frequencies (5G band). The polarization can be controlled by changing the state of the PIN diodes connected between the ground plane and triangular parasitic patches.

2 | ANTENNA DESIGN

The geometry of the proposed CDRA is given in Figure 1(a) and 1(b). The dimensions of the parameters indicated in Figure 1(a) are given in the caption of the same figure. The CDR is a TMM10β material, having $\varepsilon_r = 9.9$ and tanδ = 0.002. The diameter of CDR is 21.7 mm and height is 10 mm. The CDR is placed on a 1.6-mm thick substrate of FR-4, having $\varepsilon_r$ of 4.4 and tanδ of 0.02. The CDR is excited through a rectangular slot, having dimensions of $W_s \times L_s$, while the slot is excited through a 50-Ω transmission line. The width of the transmission line is calculated for 50 Ω impedance using Equations (1) and (2) [25]. It is well known from the literature that slot is a resonant structure, but the dimensions and position of the slot are optimized so that it only excites CDR but does not generate its own resonance.

![Figure 1](image-url)

**Figure 1**: (a) Top view ($L = W = 40$ mm, $L_s = 20.3$ mm, $W_s = 17.9$ mm, and $L_t = W_t = 5.5$ mm); (b) 3D view; (c) equivalent circuit model of the PIN diode in OFF state, ON state, and basing circuit; (d) fabricated prototype, and (e) E- and H-field of HEM$_{11,6}^0$ and HEM$_{11,6}^2$ modes.
Parasitic patches of triangular shape are placed at each corner of the slot. Each parasitic patch is connected with ground through a PIN diode. Four PIN diodes ($D_1$, $D_2$, $D_3$, and $D_4$) are used for connecting each parasitic patch to the ground. PIN diode HPND-4005 is used in the fabricated prototype. The overall dimensions of each PIN diode are $640 \times 220 \times 220 \, \mu m^3$. Each PIN diode has a low insertion loss of 0.4 dB. Advantages of the used PIN diodes are not just limited to the low resistance value ($R = 4.7 \, \Omega$) and small capacitance value ($C = 0.017 \, pF$), but also its small geometry offers a minimum impact on the performance of antenna. The equivalent circuit of the PIN diode can be modelled as a series of connection of resistor ($R = 4.7 \, \Omega$) and inductor ($L = 0.15 \, nH$) for the ON state [26]. The OFF state of the diode can be modelled as a series of combinations of inductors ($L = 0.15 \, nH$) with parallel connected resistors ($R = 7 \, k\Omega$) and capacitors ($C = 0.017 \, pF$). The PIN diode is excited through a biasing circuitry. The biasing circuitry consists of a series of combinations of current limiting resistor ($R_c = 47 \, \Omega$) and RF isolator choke ($L_c = 68 \, nH$) [27], as shown in Figure 1(c). We used a forward bias voltage of 1.6 V for ON state and reverse bias voltage of 10 V for OFF state of the diode. The initial dimensions of the CDR for the HEM$_{116}$ mode are calculated using Equation (3) [28, 29].

$$e_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{b}{W} \right)^{-0.5}$$

(1)

$$Z = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \left[ \frac{W}{b} + 1.393 + 0.677 \times \ln \left( \frac{W}{b} + 1.444 \right) \right]^{-1}$$

(2)

where $\varepsilon_{eff}$ is the effective permittivity of the material, $\varepsilon_r$ is the relative permittivity of the substrate, $b$ is the thickness of the substrate, and $W$ is the width of the transmission line.

$$f(GHz) = \frac{4.7713 \times k_0 r_d}{h_d(cm) \times \varepsilon_r}$$

(3)

and

$$k_0 r_d = \frac{6.324}{\sqrt{\varepsilon_r + 2}} \left[ 0.27 + 0.36 \frac{r_d}{2h_d} + 0.02 \left( \frac{r_d}{2h_d} \right)^2 \right]$$

(4)

where $f$ is the resonant frequency in GHz, $r_d$ is the radius of the CDRA, $h_d$ is the height of the CDRA, and $\varepsilon_r$ is the dielectric constant of the CDRA which is 9.9.

Figure 2(a) shows the geometry of microstrip excited slot with and without DRA. When a stand-alone rectangular slot was excited with the aid of microstrip transmission line, the antenna shows minimal matching around 6.4 GHz. In the case of DRA loading, the antenna resonated at around 3.5 GHz, as shown in Figure 2(b). The AR in the presence and absence of DRA is shown in Figure 2. We noted that the slot below DRA is not directly generating circular polarization but assist in generating orthogonal modes in DRA. From the electric and magnetic field distribution in DRA (see Figure 1(c)), it is clear that the resonance in the antenna is because of the DRA. Also, Equations (3)–(4) support the results. Peak gains with and without DRA are compared in Table 1.

### Table 1: Peak gains comparison with and without DRA

| State | Modes | Mode 1 | Mode 2 | Mode 3 |
|-------|-------|--------|--------|--------|
| Without DRA | 1.51 dBi | 1.69 dBi | 1.68 dBi |
| With DRA | >5.89 dBi | >5.41 dBi | >5.38 dBi |

Abbreviation: DRA, dielectric resonator antenna.

3 | RESULTS AND DISCUSSION

The fabricated prototype of the polarization-reconfigurable DRA is illustrated in Figure 1(d). The microstrip transmission line, ground plane, and triangular parasitic patches were printed on FR-4 substrate using a chemical etching process. The lumped elements in biasing network and diodes are soldered using a narrow tip soldering iron. The CDR was fixed over the excitation slot using conductive glue. Figures 3, 5, and 7 show the simulated and measured reflection coefficient ($|S_{11}|$), AR, gain, and radiation efficiency of the antenna in various operating modes. The simulated and measured radiation patterns of Mode 1, Mode 2, and Mode 3 are shown in Figure 4, Figure 6, and Figure 8, respectively.
\section{Mode 1}

In Mode 1, all PIN diodes \((D_1, D_2, D_3, \text{ and } D_4)\) are in the OFF state. The simulated and measured results of Mode 1 are shown in Figures 3 and 4. In Mode 1, the CDRA is excited through a rectangular slot (acting as a horizontal magnetic dipole) \([30, 31]\) for generating the \(\text{HEM}^{1,16}_{+}\) mode of the CDR at 3.5 GHz. The current distribution of the ground plane of the antenna shows a somehow uniform current distribution around the corners of the slot, but most of the current lies on the terminating side of the transmission line which enhances \(\text{HEM}^{1,16}_{+}\) mode excitation, as shown in Figure 3(b). In this mode, the antenna resonates at 3.5 GHz with an absolute bandwidth of 750 MHz (3.1–3.85 GHz) and AR > 31 dB (linear polarization [LP]). The fabricated prototype is tested using vector network analyzer (VNA) model HP 8720D (50 MHz–13.5 GHz), in order to validate the reflection coefficient results obtained from HFSS. The fabricated model of the antenna was connected with VNA for reflection coefficient measurement after calibration of VNA using SOLT (Short-Open-Load-Through) calibration. The AR of the antenna was measured by using the dual-linear pattern method \([32]\). In LP mode, the measured 10-dB bandwidth of 720 MHz (3.12–3.84 GHz) and AR > 29.5 dB was observed. The simulated antenna gain and radiation efficiency are noted as 5.89–6.25 dBi and 87.5%–89.7%, respectively, for the whole operating frequency range in Mode 1. The radiation efficiency of the proposed antenna was measured using the quality factor (Q-factor) method \([33, 34]\). In this method, the antenna was placed on a metallic sheet and was excited through a probe. The unloaded Q-factor was measured without enclosing the antenna in radiation shield. In the second step, an unloaded Q-factor was measured when radiation shield was placed on metallic sheet by enclosing the DRA inside it. The radiation efficiency of the antenna was calculated by comparing the Q-factors of shielded and unshielded scenarios. The measured antenna gain and radiation efficiency are noted as 5.85–5.97 dBi and 85.3%–
antenna acted as a receiving antenna. The radiation pattern of the proposed antenna is broadside due to excitation of HEM\textsubscript{115} mode in CDRA. Backward radiation can be observed from the radiation pattern plot which is due to the effect of small ground plane. A narrow \( H \)-plane (\( \phi = 90^\circ \)) radiation pattern can be observed by reducing the size of ground plane. In our study, the \( \varepsilon_z \) (\( \phi = 0^\circ \)) and \( H \)-plane (\( \phi = 0^\circ \)) patterns are similar due to the fact of using an adequate ground plane.

### Table 2: Performance comparison of the CDRA for different modes

| Mode → | 1 | 2 | 3 |
|--------|---|---|---|
| State → | LP | RHCP | LHCP |
| Bandwidth (MHz) | Simulated | 750 | 950 | 960 |
| Measured | 720 | 980 | 950 |
| Peak gain (dBi/dBiC) | Simulated | >5.89 | >5.41 | >5.38 |
| Measured | >5.85 | >5.37 | >5.25 |
| Radiation efficiency (%) | Simulated | >87.5 | >82.5 | >79.8 |
| Measured | >85.2 | >82.5 | >80 |
| Axial ratio bandwidth (%) | Simulated | – | 22.2 | 21.4 |
| Measured | – | 19 | 21.7 |

Abbreviations: CDRA, cylindrical dielectric resonator antenna; LHCP, left-handed circular polarization; LP, linear polarization; RHCP, right-handed circular polarization.

### 3.2 Mode 2

In Mode 2, two diodes (\( D_1 \) and \( D_3 \)) are excited while the other two diodes (\( D_2 \) and \( D_4 \)) remain in the OFF state. By activating the PIN diodes (\( D_1 \) and \( D_3 \)), the diagonally placed triangular patches are excited, and the rectangular slot behaves like a corner truncated slot. The current distribution plot (Figure 5(b)) illustrates that the major portion of the current lies on the parasitic triangular patches connected with the excited PIN diodes (\( D_1 \) and \( D_3 \)). These activated diagonally placed triangular patches produce a \( 90^\circ \)-phase difference between the \( x \)- and \( y \)-polarized fields of the CDRA, which in turn generates additional path delay in the fields (causing circular polarization —RHCP). An additional mode of HEM\textsubscript{115} at 3.75 GHz is excited within the CDRA due to the diagonally activated triangular parasitic patches. The HEM\textsubscript{315} and HEM\textsubscript{515} modes of the CDRA are shown in Figure 1(d). Figure 5 shows the simulated and measured response of the CDRA in terms of the reflection coefficient, AR, gain, and radiation efficiency for CDRA in Mode 2. It is obvious from the reflection coefficient plot of Mode 2 that the CDRA has a 10-dB bandwidth of 950 MHz (3.03–3.98 GHz) with two resonances (3.39 GHz (HEM\textsubscript{115} mode) and 3.75 GHz (HEM\textsubscript{315} mode)). The 3-dB AR bandwidth of 22.2% (3.09–3.86 GHz) is observed for CDRA operating in Mode 2. In RHCP mode, the measured 10-dB bandwidth of 980 MHz (3.01–3.99 GHz) and 3-dB AR bandwidth of 19% dB (3.1–3.75 GHz) were observed, as shown in Figure 5(a) and (e). The CDRA has a reasonable gain (>5.41 dB/GHz for the whole operating band) and high radiation performance.
efficiency (>82.5% for the whole operating band). The measured antenna gain and radiation efficiency are noted as 5.37–5.55 dBi and 82.5%–87%, respectively, in the entire operating range, as shown in Figure 5(b) and (d). The simulated and measured RHCP and LHCP patterns of the antenna for both principal planes (\( \phi = 0^\circ \) and \( \phi = 90^\circ \)) at 3.5 GHz are shown in Figure 4. The measured RHCP and LHCP of the antenna are computed using Equations (5)–(6) by measuring the radiation pattern in horizontal (\( E_{\text{HP}} \)) and vertical plane (\( E_{\text{VP}} \)) [35].

\[
E_{\text{RHCP}} = \frac{1}{\sqrt{2}} (E_{\text{HP}} + jE_{\text{VP}}) \quad (5)
\]

\[
E_{\text{LHCP}} = \frac{1}{\sqrt{2}} (E_{\text{HP}} - jE_{\text{VP}}) \quad (6)
\]

We can see from the radiation pattern of Mode 2 that the RHCP pattern is \( \approx 32 \) dB stronger than that of the LHCP in the broadside direction (\( \theta = 0^\circ \)), as illustrated in Figure 6(a). In the \( \phi = 90^\circ \) plane, the beam is shifted from broadside direction because of the asymmetrical current distribution, due to the activation of diagonally placed parasitic triangular patches. Considering \( \phi = 90^\circ \) plane, the radiation pattern RHCP is \( \approx 32 \) dB stronger than that of the LHCP in the broadside direction, as shown in Figure 6(b).

### 3.3 Mode 3

In Mode 3, the PIN diodes \( D_2 \) and \( D_4 \) are activated while \( D_1 \) and \( D_3 \) are deactivated. The diagonally placed triangular parasitic patches connected with \( D_2 \) and \( D_4 \) are excited due to the activation of \( D_2 \) and \( D_4 \). The rectangular slot behaves like a truncated slot and the greater part of the current lies on the activated parasitic triangular patch, as shown in Figure 7(b). An additional HEM\(^{11}\delta \) mode is generated at 3.74 GHz due to the excitation of the diagonally placed excited parasitic triangular patches. Figure 7 shows the simulated and measured response of the CDRA in terms of the reflection coefficient, AR, gain, and radiation efficiency for CDRA in Mode 3. We see that the

#### Table 3 Performance comparison with other polarization reconfigurable DRAs (where \( \lambda_{1} \) is the wavelength at the lower band-edge frequency of the axial ratio plot and \( \lambda_{0} \) is the wavelength at the centre frequency)

| Refs. | Antenna size (\( \lambda_{1} \)) | DRA size (\( \lambda_{0} \)) | Polarization states | 10-dB FBW/3-dB AR FBW | Gain (dB/dBiC) | Radiation efficiency (%) |
|-------|-------------------------------|--------------------------|--------------------|--------------------------|-----------------|--------------------------|
| [17]  | NG 0.048                      | LHCP                     | 22%/12.2%          | 4                        | NG              |                          |
|       |                               | RHCP                     | 28%/12.2%          | 4                        | NG              |                          |
|       |                               | LP-1                     | 21%/-              | 5                        | NG              |                          |
|       |                               | LP-2                     | 27%/-              | 5                        | NG              |                          |
| [19]  | 0.49 \times 0.49 \times 0.13 0.005 | LHCP                     | 34.3%/30.4%        | 6.18                      | NG              |                          |
|       |                               | RHCP                     | 36.6%/32.9%        | 6.58                      | NG              |                          |
|       |                               | LP-1                     | 9.5%/-             | 6.48                      | NG              |                          |
|       |                               | LP-2                     | 6.3%/-             | 6.39                      | NG              |                          |
| [21]  | 1.12 \times 1.12 \times 0.27 0.047 | LP                       | 22.1%/-            | >3                       | >88             |                          |
|       |                               | RHCP                     | 23.8%/22%          | >2.8                      | >88             |                          |
|       |                               | LHCP                     | 22.1%/21.1%        | >3                       | >59             |                          |
| [22]  | 0.92 \times 0.92 \times 0.26 0.022 | RHCP                     | 35.6%/16.3%        | 5.5                       | >70             |                          |
|       |                               | LHCP                     | 35.6%/16.3%        | 5                        | >70             |                          |
| [23]  | 0.88 \times 0.88 \times 0.1 0.011 | LP                       | 30.1%/-            | 8.3                       | 86              |                          |
|       |                               | RHCP                     | 27.6%/20.7%        | 8.7                       | 83              |                          |
|       |                               | LHCP                     | 28.4%/21.1%        | 8.6                       | 84              |                          |
| [24]  | 0.55 \times 0.55 \times 0.14 0.007 | LHCP                     | 16.38%/16.35%      | 5.5                       | NG              |                          |
|       |                               | RHCP                     | 14.11%/19.22%      | 5.4                       | NG              |                          |
|       |                               | LP-1                     | 2.5%/-             | 5.6                       | NG              |                          |
|       |                               | LP-2                     | 4.6%/-             | 5.8                       | NG              |                          |
| This study | 0.41 \times 0.41 \times 0.11 0.005 | LP                       | 21.6%/-            | >5.89                     | >87.5           |                          |
|       |                               | RHCP                     | 27.2%/22.2%        | >5.41                     | >82.5           |                          |
|       |                               | LHCP                     | 27.3%/21.4%        | >5.38                     | >79.8           |                          |

Abbreviations: CDRA, cylindrical dielectric resonator antenna; LHCP, left-handed circular polarization; LP, linear polarization; NG, not given; RHCP, right-handed circular polarization.
reflection coefficient plot of Mode 3 has 10-dB bandwidth of 960 MHz (3.03–3.99 GHz) with two resonances (3.40 GHz [HEM$^{116}$ mode] and 3.74 GHz [HEM$^{116}$ model]). The 3-dB AR bandwidth of 21.4% (3.08–3.82 GHz) is observed for CDRA operating in Mode 3. The CDRA shows a reasonable gain (>5.38 dBi for the whole operating band) and high radiation efficiency (>79.8% for the whole operating band).

In RHCP mode, the measured 10-dB bandwidth of 950 MHz (3.07–4.02 GHz) and 3-dB AR bandwidth of 21.7% dB (3.08–3.83 GHz) were observed, as shown in Figure 7(a) and (c). The measured antenna gain and radiation efficiency are noted as 5.25–5.60 dBi and 80%–87.1%, respectively, in the entire operating range, as shown in Figure 7(b) and (d). The LHCP and RHCP patterns of the antenna for both principal planes ($\phi = 0^\circ$ and $\phi = 90^\circ$) at 3.5 GHz are shown in Figure 8. Figure 8(a) confirms the LHCP of the antenna since the LHCP pattern is $\approx 28$ dB stronger than that of the RHCP in the broadside direction ($\theta = 0^\circ$ and $\phi = 0^\circ$). In $\phi = 90^\circ$, the beam is shifted from the broadside direction because of the asymmetrical current distribution due to the activation of the diagonally placed parasitic triangular patches. Considering $\phi = 90^\circ$ plane, the radiation pattern of the LHCP is $\approx 28$ dB stronger than that of the RHCP in broadside direction, as shown in Figure 8(b).

Table 2 compares the simulated and measured results of the antenna under different operating modes. It is concluded that the antenna can operate in LP, RHCP, or LHCP, depending on the operating mode. Table 3 compares the proposed polarization switchable DRA with other polarization-reconfigurable DRAs. We see that the proposed antenna has minimal dimensions than any design in the reported literature. The 3-dB AR bandwidth of the proposed antenna is better than [17, 21–24]. The FBW of the proposed antenna is almost similar to the reported literature. The FBW of [19] is better than ours, but the large footprint, large number of diodes, and narrow bandwidth in the LP cases make this antenna unsuitable for compact systems where wide bandwidth is needed in the LP case. Also, the gain and radiation efficiency is greater than those reported in [21, 22]. Additionally, the pump size and liquid carrying channels increase the system’s complexity in [21] and [22]. The gain and radiation efficiency of the DRA in [23] are higher than the proposed DRA; however, its multilayer structure and large size limit its usefulness in compact systems. Moreover, a small misalignment in the layers may lead to different results.

4 | CONCLUSION

A cylindrical-shaped DRA has been designed in this study with switchable polarization. The different polarization (linear, RHCP, and LHCP) can be obtained by changing the state of the PIN diodes. The antenna operates with linear polarization in Mode 1, circular polarization (RHCP) in Mode 2, and circular polarization (LHCP) in Mode 3. The 10-dB bandwidth of 750 MHz (3.1–3.85 GHz), 950 MHz (3.03–3.98 GHz), and 960 MHz (3.03–3.99 GHz) is noted for Mode 1, Mode 2, and Mode 3, respectively. The 3-dB AR bandwidth of 22.2% and 21.4% was recorded for Mode 2 and Mode 3, respectively. The reported antenna has high gain (>5.25 dBi for all operating modes) and high efficiency (>79.8% for all operating modes). The proposed antenna is the best candidate for use in 5G multistandard wireless communication system to realize polarization diversity in order to mitigate multipath fading losses and thereby enhance the system capacity.

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ORCID

Amjad Iqbal https://orcid.org/0000-0002-8312-7087
Mohamed I. Waly https://orcid.org/0000-0003-4737-6833
Amor Smida https://orcid.org/0000-0001-9096-4337
Nazib K. Mallat https://orcid.org/0000-0003-0487-4015

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