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Pattern-Reconfigurable Cylindrical Dielectric Resonator Antenna Based on Parasitic Elements

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ABSTRACT A novel pattern-reconfigurable cylindrical dielectric resonator antenna is presented. By the incorporation of four p-i-n diode switches and four parasitic elements, the mode of dielectric resonator excited by the probe changed. The antenna's radiation patterns can be shaped to concentrate energy in four specific directions, while minimizing the gain in other unwanted directions without affecting the impedance bandwidth of the antenna for its complete symmetry in structure. The antenna switches its radiation patterns among four reconfigurable modes with orthogonal directions at azimuth plane covering a bandwidth of several 870 MHz and exhibiting a high maximum gain of 9.74 dBi. A fully functional prototype has been designed, fabricated, and tested. The measured results of the reflection coefficient, radiation patterns, and realized gain verify the effectiveness of the proposed pattern switching concept for cylindrical dielectric resonator antenna. These capabilities make the antenna suitable for smart wireless devices in next generation communication systems as it can enhance the radio frequency front-end flexibility and performance by adding pattern diversity, especially for muti-input-muti-output systems in multipath environments.

INDEX TERMS Cylindrical dielectric resonator antenna, pattern reconfiguration, parasitic elements.

I. INTRODUCTION

Dielectric resonator antenna (DRA) has been extensively studied since 1983 [1] , and increasingly used in wireless communication systems for its extraordinary advantages of light weight, compact size, high radiation efficiency, low loss and ease to excite [2], [3]. Hemispherical cylindrical and rectangular are the basic shapes of the DRA with different design flexibility and fundamental modes [4]–[6]. For a given dielectric resonator (DR), more modes can be excited by the selection of the feed and its location with different input impedance and radiation characteristics, which makes the DRA a good candidate for practical design consideration in malfunction or diversity systems [7]–[10].

At the same time, there is a significant topic to study and design reconfigurable antenna [11], which is able to alter its operating frequencies, polarizations, radiation patterns or combination of above to accommodate to dynamic system requirements [12]–[15]. According to the reconfigurable mechanisms, reconfigurable antennas can be classified into three groups, namely, those using material changes [16], and those using mechanical changes [17], and those using electrical devices, such as radio frequency micro electromechanical system (RF-MEMS), field effects transistors (FETs), varactor diodes and p-i-n diodes [18], [19]. Next wireless communication systems need the help of the recent reconfigurable antenna technologies for enhancements in multifunctional capability, signal quality, diversity gain and potential integration of various systems [20].

Newly, there have been some literatures published about frequency reconfigurable DRAs, using several frequency technique, such as controlling the lengths and positions of parasitic strips and slots, changing the height of colloidal dispersion and varying the differential feed by varactors [21]–[26]. Unfortunately, there is little polarization or pattern reconfigurable mechanism for DRA.

The work presented here introduces a simple, yet compact and novel reconfigurable DRA that can generate four directional radiation patterns. Four parasitic elements which connected the probe with p-i-n diode switches are etched orthogonally on the cylindrical DR at the central of probe, resulting on good impedance matching, large front-to-back ratio and high gain. By turning on one diode, the proposed DRA can steer the maximum beam direction to the direction of the excited parasitic element. The dc bias network to control the p-i-n diodes is simple as it just requires RF choke inductors and not requires dc blocking capacitors or vias.

Compared with pattern-reconfigurable DRAs in the published literature at present, the proposed DRA has many advantages. Firstly, compared to the designs in [27] and [28], the antenna has more reconfigurable pattern modes, higher gains and only one feeding port. Secondly, pattern reconfiguration is achieved over a wide bandwidth and no metalized via is required, compared to antenna in [29]. Lastly, the antenna doesn't need extra complex mechanical controller as in [30].

The following section describes the proposed antenna design along with the principle of operation and parametric study. The prototype of antenna, test and some key results are provided in Section III, followed by a concise summary and brief conclusion and prospect from the presented work in Section IV.

II. ANTENNA DESIGN

A. ANTENNA GEOMETRY

Fig.1 shows the proposed pattern-reconfigurable cylindrical DRA configuration, which is composed by five parts: one probe excitation, one ground plane, one cylindrical DR, four ortho-symmetric parasitic elements and four corresponding p-i-n diodes. The probe consists of the center pin of a coaxial transmission line that extends through the center of the ground plane with dimension of $d \times d$ mm^2 to the upper surface center of DR. The height and location of the probe relative to DR can adjust the amount of coupling and the mode excited. For ease of connection between the central probe to parasitic elements, a metal disc with a diameter of w is coating on the supine surface of DR. The cylindrical DR has a dielectric constant of 9.8, a radius of r and a height of h. For a given dielectric constant, the aspect ratio a/h determines resonant frequency and bandwidth of DRA. The dimensions and locations of parasitic elements affect the operating frequency and directional radiation performance. The detailed dimensions of the proposed antenna are listed in Table 1.

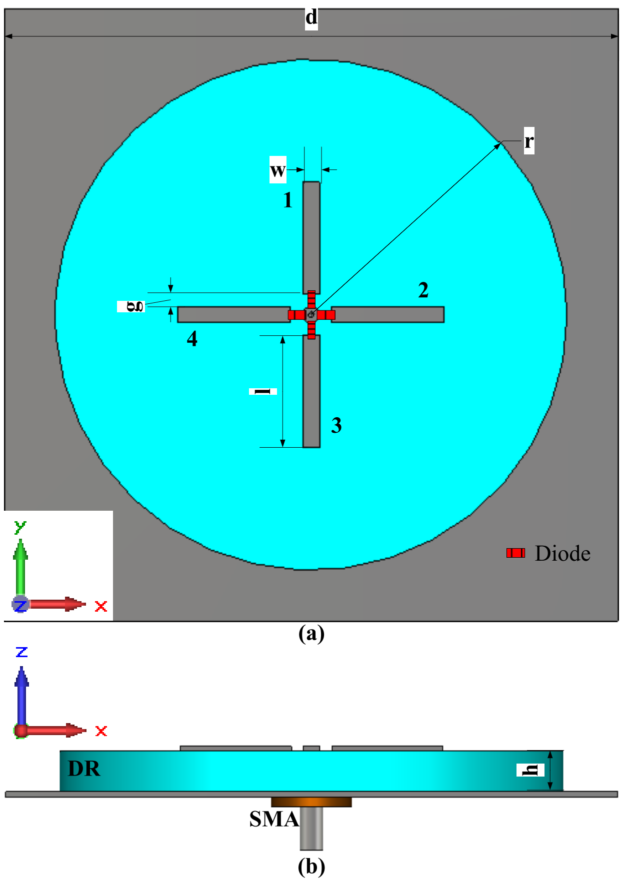

FIGURE 1. Geometry of the proposed pattern-reconfigurable cylindrical DRA: (a) top view and (b) side view.

TABLE 1. Final dimensions of the proposed antenna.

Parameters	r	h	w	l	g	d
Value(mm)	25	4.25	1.6	11	2	60

For clarifying the evolution process of the proposed antenna, three DRA prototypes are designed, as demonstrated in Fig. 2. Antenna I, a cylindrical DRA fed by a central 50-Ω coaxial probe excitation with the length equal to the height of the DR, can generate $TM_{0n\delta}$ modes. The $TM_{0n\delta}$ modes radiate like a short electric monopole, with omnidirectional radiation patterns at azimuth plane. For Antenna II, a rectangular parasitic strip connected to probe is added to achieve directional radiation pattern. In Antenna III, four ortho-symmetric parasitic strips are introduced to excite multiple beam control under different strips connecting to the central probe. Directional modes are achieved by connecting just one of the strips to the central disk, while the other three disconnect strips act as reflector elements.

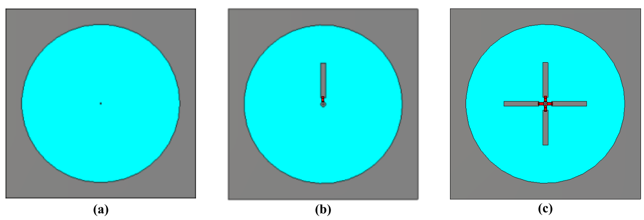

FIGURE 2. Evolution process of the proposed antenna: (a) Antenna I, (b) Antenna II, (c) Antenna III (the proposed antenna).

Simulated reflection coefficients for three antennas are plotted in Fig. 3. Antenna I operates at central frequency of 6.48 GHz with -10 dB impedance bandwidth of 300 MHz. Because of the introduction of parasitic strip, two resonant modes are excited simultaneously at 5.62 GHz and 7.06GHz. The frequency band excited by the cylindrical DR moves down and reaches up to 860 MHz, meanwhile, another frequency band at higher frequency for Antenna II is excited by parasitic element connected with probe. Antenna III operates at two frequency bands similar to Antenna II, but only lower band (980 MHz, 5.14-6.02 GHz) can be used for pattern reconfigurable DRA in this paper. The higher band has no

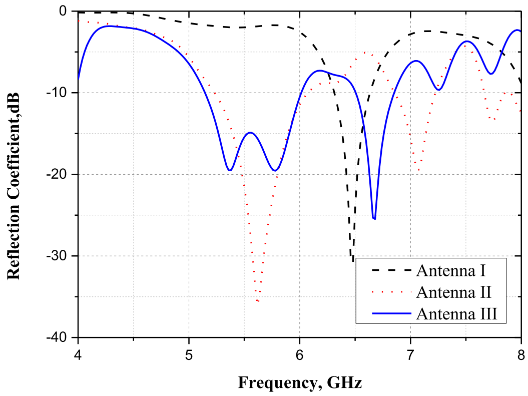

FIGURE 3. Simulated reflection coefficients of the three antennas.

virtual link with the resonant mode and characteristic of DR. It can be seen that the impedance bandwidth of the proposed antenna is relatively wide for the fusion of multi-resonant both from DR and from parasitic elements, and at the same time the antenna becomes compact for the reducing of electrical size from a different perspective.

B. FIELD DISTRIBUTION AND RADIATION PATTERN

The magnetic and electric field distributions of Antenna I at resonant frequency of 6.48 GHz are shown in Fig. 4 and Fig.5. For the combined effect of cylindrical DR (height, radius and dielectric constant) and probe, it works in $TM_{02\delta}$ mode with reference to field distributing. The mode subscribes respectively refer to field variations in the azimuth, radial and axial direction. The fields of $TM_{02\delta}$ mode have no variation in the azimuth direction and two maximum points in the radial directions. The value of δ is a number ranging between 0 and 1. The field distributions of $TM_{02\delta}$ mode indicate that it radiates like an electric monopole, with omnidirectional radiation pattern at azimuth plane.

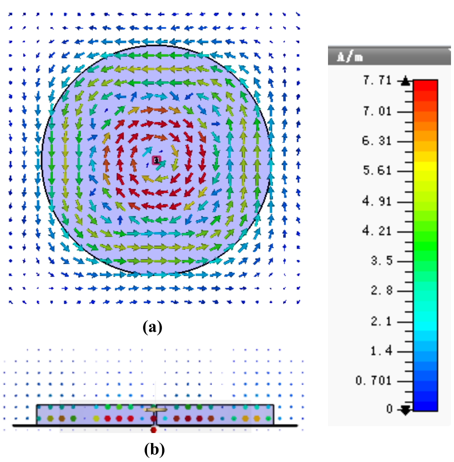

FIGURE 4. Magnetic field distributions of the $TM_{02\delta}$ of Antenna I: (a) top view and (b) cross-sectional view.

Fig.6 demonstrates the electric field distributions in top views of Antenna III at different modes under only one of parasitic elements connecting to the probe. When one of the p-i-n diodes is on, the length of probe coupling enlarged and the relative position to DR changed. For the cause of parasitic element directly connecting to the feed, the combined structure makes the original mode change significantly. The active parasitic element makes the amount of energy to build towards the element direction. The distributions in near field determine the radiation pattern in distant field. Obviously, when different switches are ON clockwise, the field distributions are transformed for rotation symmetry in azimuth, resulting in steerable main-beam radiation directions.

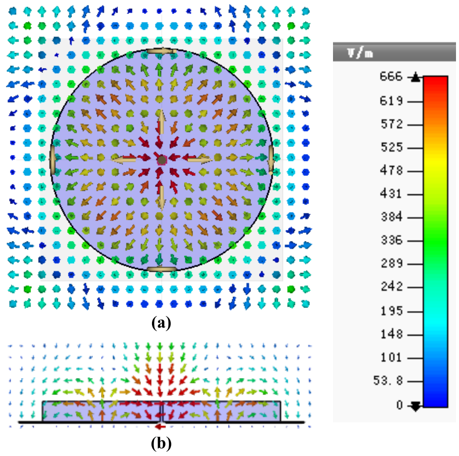

FIGURE 5. Electric field distributions of the $TM_{02\delta}$ of Antenna I: (a) top view and (b) cross-sectional view.

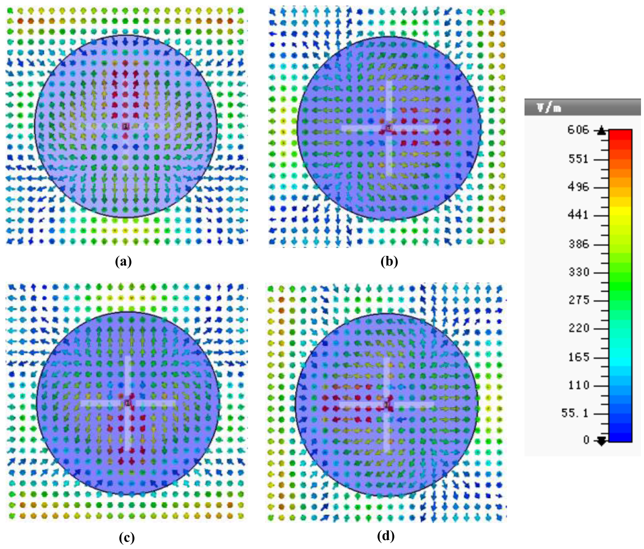

FIGURE 6. Electric field distributions in top views of antenna III: (a) Mode-1, (b) Mode-2, (c) Mode-3 and (d) Mode-4.

Simulated three-dimensional radiation patterns of the proposed cylindrical DRA at different modes are shown in Fig.7. Comparing Fig.6 and Fig.7, it is observed that the main beam direction is in according with the direction of the excited parasitic element.

The proposed DRA can generate reconfigurable directional radiation patterns by controlling only switches between probe and parasitic elements.

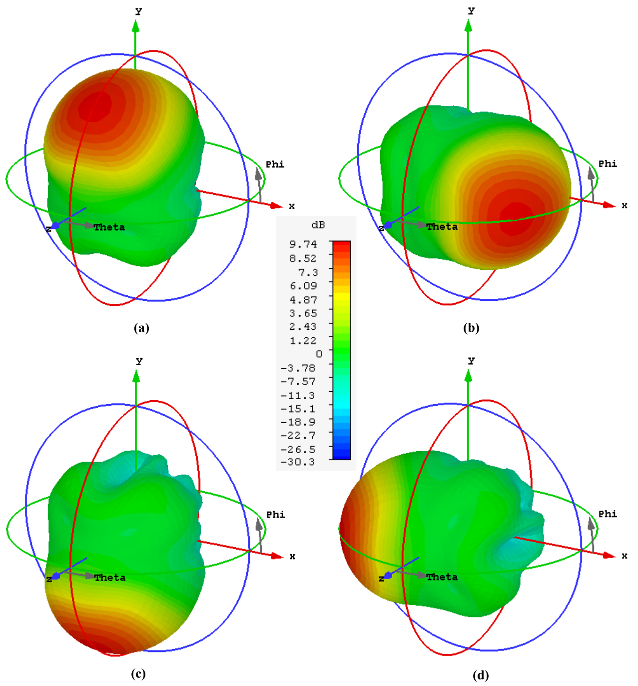

FIGURE 7. Simulated three-dimensional radiation patterns of the proposed DRA at (a) Mode-1, (b) Mode-2, (c) Mode-3 and (d) Mode-4.

C. PARAMETRIC STUDY

A parametric study was performed to understand how the dimensions of the parasitic elements affected the performance of the proposed DRA. Throughout this parametric study of simulations, ideal switches with metal bridges were instead of p-i-n diodes used for connecting between the central probe disk and parasitic element 1 in the $+y$ axis.

The first parameter studied was the width of the parasitic strip w. When the length of the strip is fixed at $l = 11$mm and the value of w changes from 1.2 to 2.0 mm, it is observed that the decreasing of w will slightly worsen both the impedance band and front to back ratio of radiation gain pattern cut in $\theta = 50°$ plane of the maximum radiation direction at 5.8 GHz as shown in Fig.8 and Fig. 9. Although the effect of

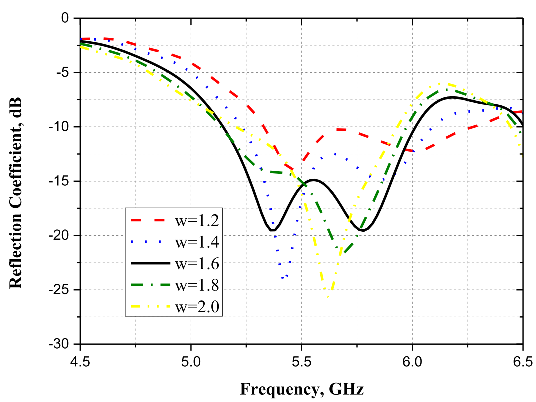

FIGURE 8. Effects of w on the reflection coefficient of the proposed DRA.

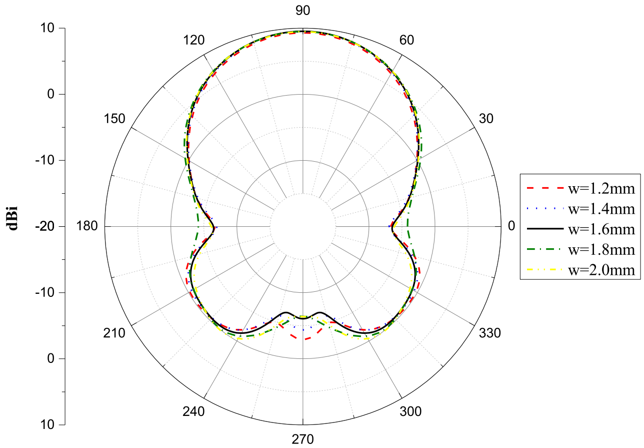

FIGURE 9. Effect of w on the radiation gain pattern cut along the $\theta = 50°$ plane.

the width is not crucial, care needs to be taken to guarantee that best optimum performance of the proposed antenna and $w = 1.6mm$ is chosen.

The second parameter optimized was the length of the strip l. It can be observed that the length of the strip affects the impedance bandwidth of the proposed DRA from Fig. 10. When changing the length of the strip, the probe used for exciting DR changed, which leads to resonant frequency and bandwidth changing accordingly. The effect of the strip length on the radiation pattern is depicted in Fig. 11. With the increasing of l, more directional radiation gains are produced in the $+y$ axis. Therefore, based on the above comprehensive analysis, a strip length of 11 mm is chosen to provide optimum performances for both impedance matching and directional radiation pattern.

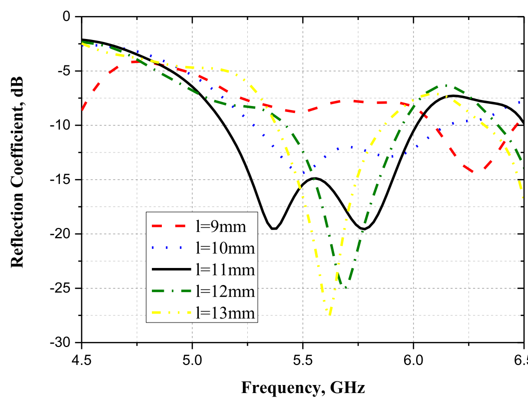

FIGURE 10. Effects of l on the reflection coefficient of the proposed DRA.

III. RESULTS AND ANALYSIS

The proposed antenna is numerically simulated by CST microwave studio which utilizes the finite integration technique for electromagnetic computation in this paper. To verify the pattern-reconfigurable cylindrical DRA design, a prototype of the proposed DRA is fabricated and measured. Fig. 12 presents photographs of the antenna with specific

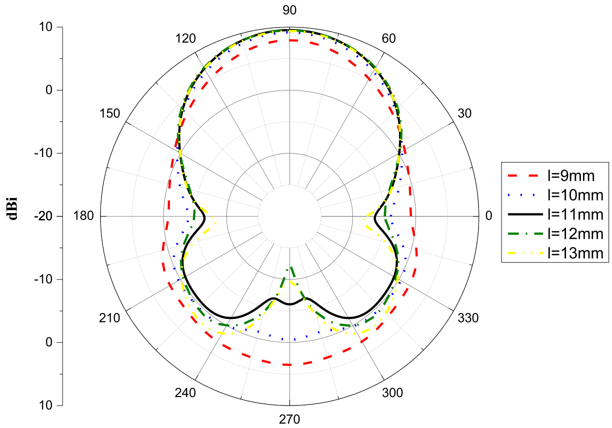

FIGURE 11. Effect of w on the radiation gain pattern cut along the $\theta = 50°$ plane.

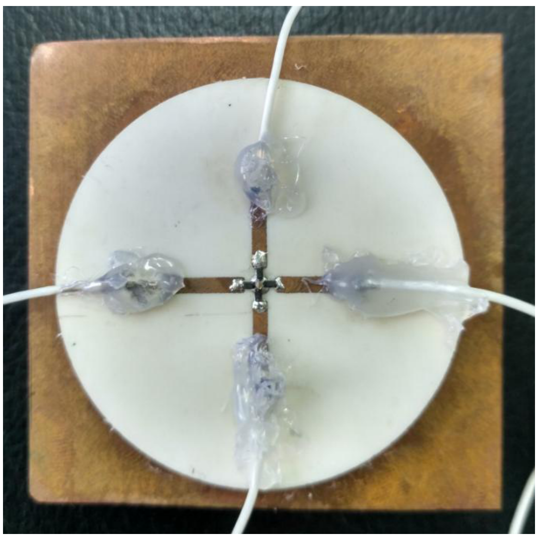

FIGURE 12. Prototype of the proposed pattern-reconfigurable cylindrical DRAs.

parameter values as shown in Table 1. In this paper, p-i-n diodes (BAR64-02 V) are used as switches to selectively connect the parasitic elements to the central feed probe for the corresponding modes, which need a forward voltage of 0.7 V and are modeled as a low forward resistance of 2.1 Ω at ON-state and a high reverse resistance of 3 kΩ in parallel with a capacitor of 0.15 pF at OFF-state. The dc-biasing network is fairly simple as there is no need to short slots in the antenna ground with dc blocking capacitors for RF continuity and just need a RF choke inductor of 100 nH between the end of parasitic and dc line for each diode of each mode. The impedance bandwidths are performed using Agilent-N5227A microwave network analyzer. A dc-block SMA connector was connected to the proposed antenna and the coaxial measurement cable.

Fig. 13 shows the simulated and measured impedance performances of the antenna at four pattern-reconfigurable modes. The simulated reflection coefficients of four modes are identical since the proposed antenna is geometrically

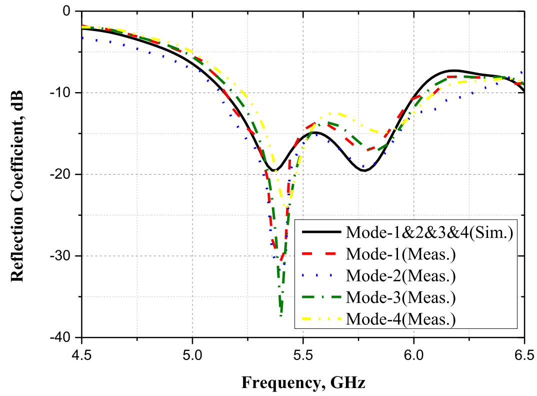

FIGURE 13. Simulated and measured reflection coefficient when the proposed antenna is operating in Mode-1, Mode-2, Mode-3 and Mode-4.

ortho-symmetrical with respect to the central of DR. However, the measured results are a little bit different due to the tolerances in the dc biasing network and the real diodes. In addition, the DR is a kind of aluminous ceramic with fast heat conduction, so it is not easy to weld and fix above it. For this reason, the soldering of the RF choke inductors and the diodes are not exactly identical and fix dc lines with the aid of hot melt adhesive. Therefore, this could have affected the ideal symmetrical properties of the prototype. The measured impedance bandwidths are slightly larger than the simulated one on account of reduction in quality factor brought by the introduction of air among DR, probe and ground plane.

The radiation patterns of the proposed pattern-reconfigurable DRA were measured in an anechoic chamber with the dimension of 10m×6m×6m. Fig. 14 depicts the simulated and measured far-field normalized radiation patterns

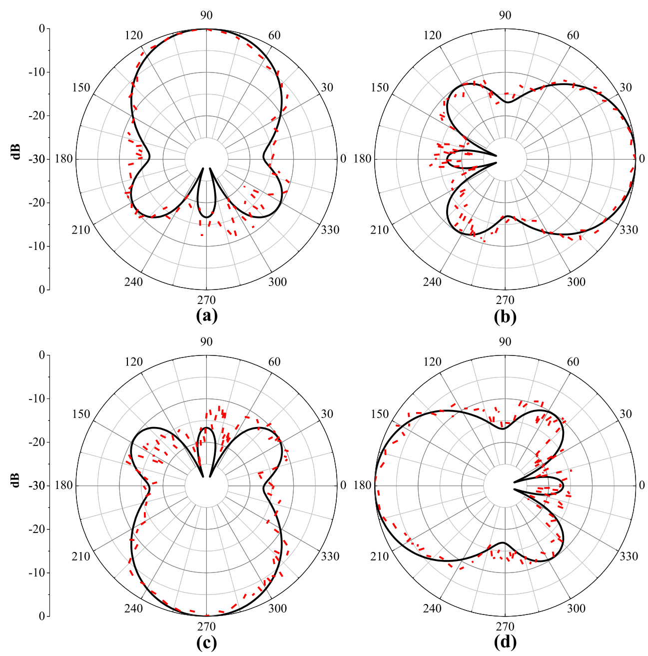

FIGURE 14. Simulated (solid line) and measured (dashed line) normalized radiation patterns at azimuth plane when antenna is configured at (a) Mode-1, (b) Mode-2, (c) Mode-3 and (d) Mode-4.

at azimuth plane, when the proposed antenna is operating at Mode-1, Mode-2, Mode-3 and Mode-4. It's obvious that the DRA can generate four identical directional modes with the maximum radiation direction of 90° between each mode, and each main beam direction is along the active parasitic element. The slight differences in the observed results are mainly attributed to the fabrication tolerances, the external dc wires coming from DC power supply and the antenna test positioning system. All the modes with operation at 5.8 GHz have the measured half power beam widths of 63° or so, and the measured gain ranges from 9.13 dBi to 9.87 dBi. Extra uncertainties in the gain measurements result from the standard gain horn curve published by manufacturer and slight differences in measuring the transmission coefficients in the anechoic chamber.

Performance comparisons between the proposed antenna and reported pattern-reconfigurable DRAs are indicated in Table 2. It is clear that, the gain of the proposed DRA with parasitic elements is higher than all the published pattern-reconfigurable DRA, benefiting from the combined action of the good directional radiation characteristic and high-order mode. As mentioned in the introduction, the antenna with four directional radiation modes has low complexity of reconfigurable mechanism with large bandwidth relatively. In the future research, more flexible beam-steering and wider bandwidth can be further enhanced.

TABLE 2. Performance comparison of pattern-reconfigurable DRAs.

Ref.	Beam No.	-10dB BW(MHz)	Reconfiguration Mechanism	Switch No.	Gain (dBi)
[28]	2	1000	SPDT	2	7.21
[29]	8	210	PIN	8	7.27
[30]	2	1620	Liquid	-	6.15
Our work	4	980	PIN	4	9.74

IV. CONCLUSION

A simple and novel design for a low profile pattern-reconfigurable DRA is presented. When the element attached above cylindrical DR connected to the probe reconfigured by switches, the antenna manipulates its main beam direction from one end-fire pattern to another opposite or orthogonal end-fire pattern. By optimizing the design parameters, a wide bandwidth of 870 MHz, a well front-back ratio of 10.2 dB and a high gain of 9.74 dBi are achieved. The test and simulation results are consistent. The proposed antenna can assist MIMO systems through the benefit of spatial diversity rather than frequency means, and be suitable for radio systems with plurality of applications at C band. To further develop this work, we intend to double the number of main beam directions only with same number of switches to this proposed antenna and further combine frequency and polarization reconfiguration capabilities to increase its flexibility and multi functionality. Switching solutions to provide better possible performance for specific requirements (such as single-pole double-throw switch) will be adopted to enhance the overall characteristics of this reconfigurable antenna.

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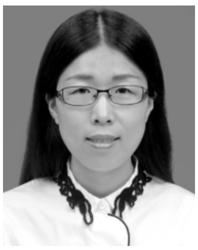

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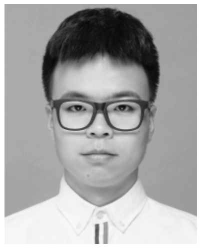
From 1982 to 1987, he was a Teaching Assistant with the Harbin Institute of Technology. From 1987 to 1992, he promoted as a Lecture, and then an Associate Professor. He was promoted as a professor in 2002. He has authored and co-authored over 100 publications (book chapters, journal papers, and conference articles). His research interests include in the field of electromagnetic theory, microwave devices, antennas and millimeter-wave imaging.



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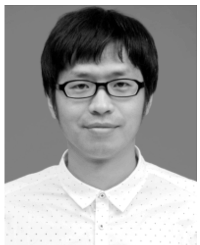

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