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Wideband Multi-Linear Polarization Reconfigurable Antenna for Wireless Communication System

Kaisheng Yang, Na Kou, and Shixing Yu*

College of Big Data and Information Engineering, Guizhou University, Guiyang 550025, Guizhou, China

ABSTRACT: This letter presents a wideband multi-linear polarization reconfigurable antenna, which has the ability to switch among four linear polarizations at rotation angle of 45°, namely 0°, 45°, 90°, and −45°. Its main structure consists of three layers of substrates and a reflective cavity. Four pairs of crossed bow-tie dipoles are used as the primary radiators, and the polarization switching is realized by controlling the ON/OFF states of four pairs of PIN diodes between feeding source and the dipoles. In addition, circular ring and reflective cavity structures are used for enhancing the operating bandwidth, stabilizing the radiation patterns, and increasing the gain. Finally, the simulation and measurement results both demonstrate that the antenna exhibits an overlapped impedance bandwidth of 42.6% (2.4 GHz–3.7 GHz) for all polarization states, and it remains a steady radiation pattern within the operating bandwidth. With these features, the design can be used in wireless communication systems in the 5G sub-6 GHz band.

1. INTRODUCTION

Reconfigurable antennas [1] can adapt to different needs by adjusting configurations to achieve changes in operating bands [2], radiation patterns [3], and polarizations [4]. In particular, polarization reconfigurable antennas play an important role in solving the problem of polarization mismatch in wireless communication. The polarization reconfigurable antennas reported in the literature so far are mainly switched among three pairs of polarizations, including left/right circular polarizations [5], linear/circular polarizations [6], and multiple linear polarizations [7]. When receiving an arbitrary linearly polarized (LP) wave, polarization matching between two antennas is required, but this is difficult. Although circularly polarized antenna can capture any LP wave, the efficiency is limited to a maximum of 50%. In this case, multiple linearly polarized reconfigurable antennas may be a good choice for receiving random LP signals. In particular, multiple LP reconfigurable antennas have high potential applications in areas such as wireless biomedical systems and conformal antenna arrays.

How to design an effective polarization reconfigurable antenna is a key issue. The first thing to note is that while switching polarization states, it is necessary to maintain the stability of its operating frequency and radiation pattern. An effective method of switching polarization states is to change the position of the feed point through a controllable feed network [8]. Another feasible approach is to introduce RF switches on the antenna, thus changing the polarization state [9]. It is worth nothing that multi-linear polarization reconfigurable antennas have been proposed in recent years, but most of these designs only contain two LP states [10–19]. In [10–12], antennas for 5G mobile communication have been proposed, which only contain two polarization directions. At the same time, although they cover some of the frequency bands often used in 5G, the operating frequency bands are still very narrow. In [13–19], most of the antennas have three or four polarization modes, yet the line polarization states are only one or two. For example, in [13], the antenna is designed with four polarization states, yet the line polarization contains only horizontal and vertical polarizations, and the relative operating bandwidth (BW) for each polarization state is around 10% and even containing just one linearly polarized state in [14]. Furthermore, reconfigurable antennas with four LP states have been achieved in [20–22]. Nonetheless, these designs still present certain drawbacks such as intricate feeding networks [20] or using additional metasurfaces [21]. This results in a complex antenna without a substantial increase in functionality. In other cases, a relatively simple structure can be designed but leads to limited bandwidth [22], and its relative bandwidth is only 7%. At present, there are few designs which can achieve both four linear polarizations and a large relative bandwidth within an uncomplicated structure. In addition to containing four LP states, crossed dipole antennas can extend the operation bandwidth, and it is boosted to 37% in [23]. In [24], the number of polarization states can be increased to six LPs. However, these designs still have the obvious disadvantages of considerably narrow operating bandwidth, low gains, or high cross polarization.

To address the aforementioned challenges, this letter presents a wideband and high-gain reconfigurable antenna featuring four linear polarization diversities with a simple structure. It can realize four switchable linear polarization states of 0°, 45°, 90°, and −45° rotations, respectively. The primary radiator of this antenna comprises four pairs of crossed bow-tie dipoles arranged at 45° apart from each other to facilitate wideband operation. Polarization reconfigurability with four LPs at a 45° rotation is achieved by controlling the ON/OFF states of four pairs of PIN diodes. A circular ring is placed at the lower end

* Corresponding author: Shixing Yu (sxyu1@gzu.edu.cn).

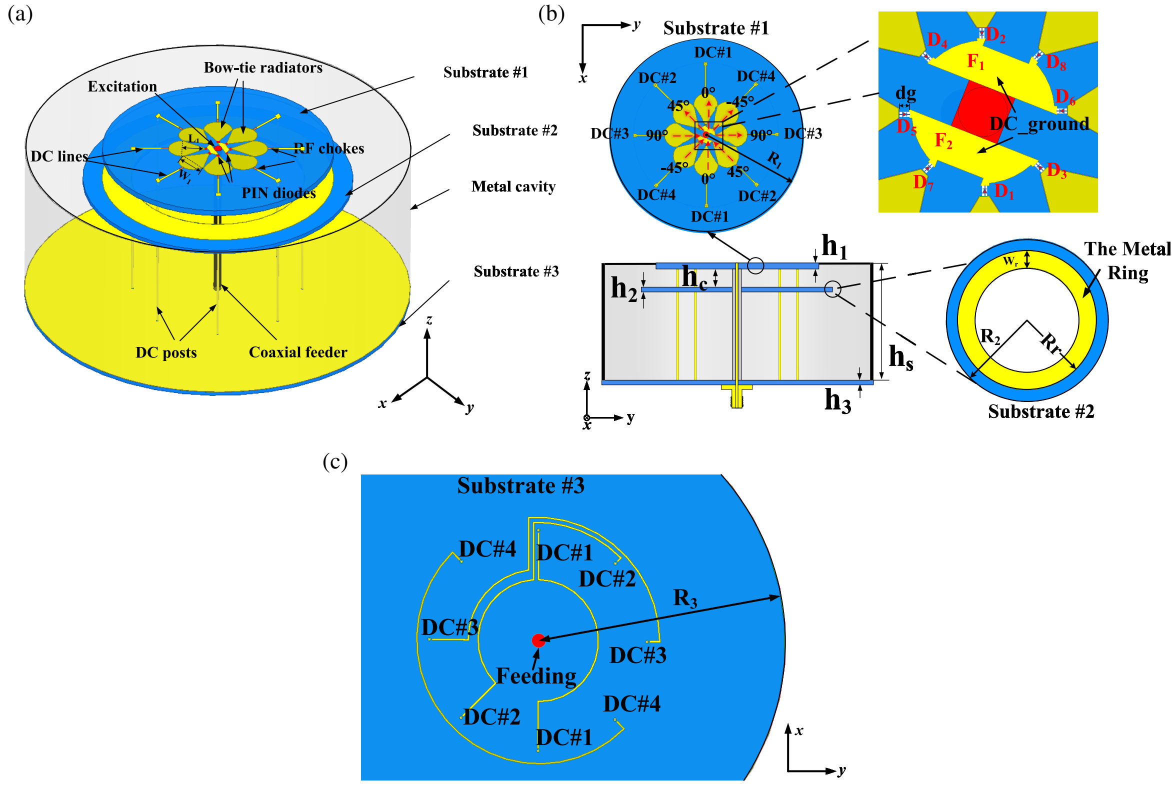

FIGURE 1. (a) Configuration of the reconfigurable antenna. (b) The side view of the antenna, and the detailed structure of substrate ♯1 and substrate ♯2. (c) The bottom view of the antenna. The parameters of the structure are: $L_1 = 9.4$ (length of the dipole), $W_1 = 3.7$ (width of the dipole), $W_r = 7.5$ (width of the ring), $h_1 = 1.6$ (height of the substrate ♯1), $h_2 = 1$ (height of the substrate ♯2), $h_3 = 1$ (height of the substrate ♯3), $hc = 8.5$ (distance between substrate ♯1 and substrate ♯2), $h_s = 3$ (distance between substrate ♯1 and substrate ♯3), $R_1 = 30$ (radius of substrate ♯1), $R_2 = 35$ (radius of substrate ♯2), $R_r = 30$ (radius of ring), $dg = 0.42$ (gap for PIN diode connection), $R_3 = 45$ (radius of substrate ♯3) (unit: mm).

of the dipole to stabilize the radiation pattern. We also use a cylindrical reflector cavity to enhance the gain. Both simulation and measurement results demonstrate that the designed antenna achieves a wide impedance bandwidth of 42.6% from 2.4 GHz to 3.7 GHz and a peak gain of 9.3 dBi. All simulations and parameter optimizations are performed using the ANSYS High Frequency Structure Simulator (HFSS 2021).

2. ANTENNA DESIGN AND STRUCTURE ANALYSIS

The structure of the proposed multi-linear polarization reconfigurable antenna is shown in Fig. 1(a). The structure mainly consists of three substrates and a reflective cavity. As can be seen from Fig. 1(b), on the top substrate, we use crossed bow-tie dipoles as the primary radiators since the bow-tie shape has been proven to achieve a larger overlapped bandwidth. In addition, the end of the bow-tie is modified into a fan shape which makes edges rounded to expand bandwidth compared to conventional triangular dipoles. The four pairs of bow-tie dipoles loaded with four pairs of PIN diodes are placed with rotation angle of 45° apart. Each pair of the bow-tie dipoles corresponds to 0°, 45°, 90°, and −45° linear polarizations, respectively. These dipoles are fed by two semi-circular patches (F1 and F2) which are connected to one coaxial line. Meanwhile, the two semi-circular patches will also serve as the DC ground for PIN diodes. At the end of each bow-tie dipole, narrow DC line with width of 0.4 mm is pulled out to connect the other end of PIN diode with a chock inductor (1 μH).

For substrate ♯2, a metallic circular ring serves a reflector to stabilize the radiation patterns. Furthermore, a metallic ground is located on substrate ♯3, and the DC lines of PIN diodes are printed under the substrate ♯3, as shown in Fig. 1(c). We utilize metal wires as the DC posts to connect the DC lines on substrate ♯1 and that on substrates ♯3. FR-4 ($\epsilon_r = 4.4$, $\tan\delta = 0.02$) is chosen as the materials for these three substrates. To increase the operating bandwidth of antenna, many methods have been proposed. Changing the shape of the radiation patch, adding parasitic units and backed cavities, etc. are commonly used [25–27]. The bow-tie shaped dipoles have been shown to have a wider bandwidth than ordinary dipoles, so we choose bow-tie shaped dipoles as the main radiators of this antenna and add a fan around the edge because of its good impedance match with the feed line. But the increased bandwidth in this way is not enough. Therefore, we add a ring and reflective cavity to continue to increase the bandwidth. In Fig. 2(a), we can see the

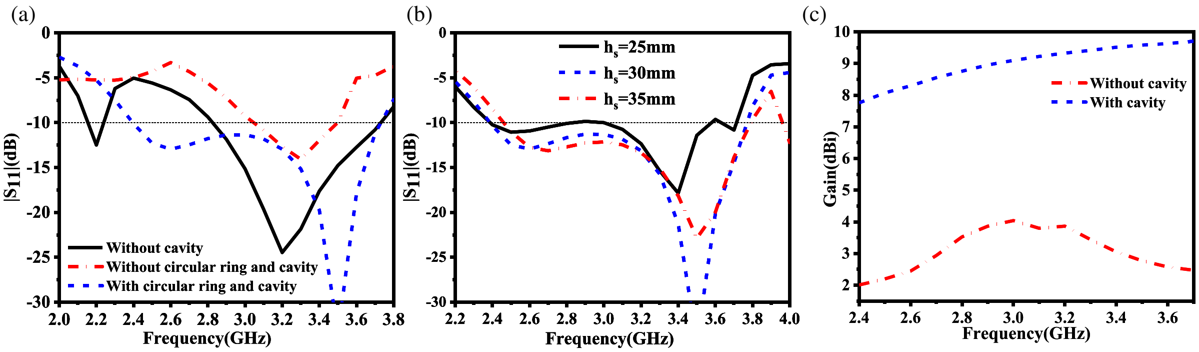

FIGURE 2. (a)Simulated $|S_{11}|$ in different cases, (b) effects of various H_s on $|S_{11}|$, (c) simulated gain in different cases.

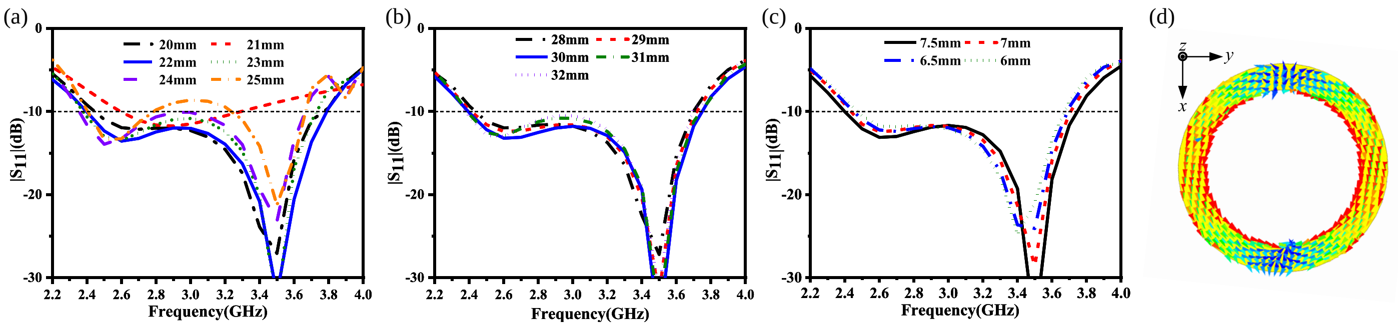

FIGURE 3. (a) Effects of various heights of ring on $|S_{11}|$, (b) effects of various R_r on $|S_{11}|$, (c) effects of various W_r on $|S_{11}|$, (d) parasitic current distribution on the circular ring at 0° polarization state.

bandwidth in different cases. If there are only dipoles, the optimal relative bandwidth of the antenna in that band is only 15% (3.1 GHz–3.5 GHz). The circular ring on the substrate ♯2 can be regarded as a parasitic unit of the antenna and causes the antenna to resonate at low frequencies, thus to increase the operating bandwidth. In this design, we make the resonant point of the dipole around 4.5 GHz and the resonant point of the ring at about 1.5 GHz. As a result, the antenna has two resonance points, and its bandwidth increases. A cylindrical cavity, which is about $\lambda_0/4$ away from the main radiators, also serves to extend the bandwidth. Ultimately, the relative bandwidth of the antenna can be expanded to 42% (2.4 GHz–3.7 GHz). Moreover, we can see from Fig. 2(b) that the height of the cavity has an effect on the bandwidth. Too low or too high a height will narrow the bandwidth, from which we choose an optimal height. At the same time, the introduction of a reflective cavity also increases the gain, as can be seen in Fig. 2(c). After loading the reflective cavity, the gain can be increased by about 5 dBi.

The parametric study has demonstrated that there are three moderately important parameters that influence the performance of the circular ring on S_{11}, as illustrated in Figs. 3(a), (b), (c). First, the performance of the antenna is largely affected by the height of the ring. Sightly higher or lower height will result in a narrower impedance bandwidth. Second, the radius of the circular ring has great impact on frequency. When the radius becomes larger, the frequency shifts towards the lower end of the frequency spectrum, and vice versa for the higher frequencies. Furthermore, the width of the ring has minor impact on antenna performance as well. We combine these parameters to select the best among them. At the same time, the circular ring can function to stabilize the radiation patterns when different polarization states are excited. For example, if the pair of dipoles at 0° starts working, a symmetrical coupling current on XZ plane is generated in the circular ring, as shown in Fig. 3(d). The ring can then be considered as a combination of dipoles on both the positive and negative sides of the XZ plane which have the same strength and phase. In this way, the ring can be equivalent to a dipole array and produce a wide range of radiation to strengthen the radiation intensity in this direction.

To switch the polarization direction of the proposed antenna, we can control the ON/OFF states of the four pairs of PIN diodes, expressed as (D_1, D_2), (D_3, D_4), (D_5, D_6), (D_7, D_8). The PIN diode has model number SMP1340-040LF from Skyworks Solutions, lnc. The equivalent circuit model of the PIN diode is demonstrated in Fig. 4. This model has a fast switch-

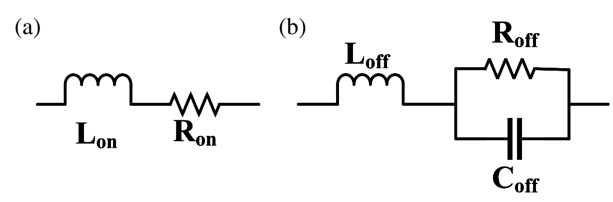

FIGURE 4. Equivalent circuit for the PIN diode in case of (a) ON state and (b) OFF state. ($L_{on} = 0.45$ nH, $R_{on} = 0.85\,\Omega$, $L_{off} = 0.45$ nH, $R_{off} = 5\,\text{k}\Omega$, $C_{off} = 0.21$ pF).

TABLE 1. Polarization by different states of p-i-n diodes.

Polarization	(D_1, D_2)	(D_3, D_4)	(D_5, D_6)	(D_7, D_8)
0° LP	ON	OFF	OFF	OFF
45° LP	OFF	ON	OFF	OFF
90° LP	OFF	OFF	ON	OFF
−45° LP	OFF	OFF	OFF	ON

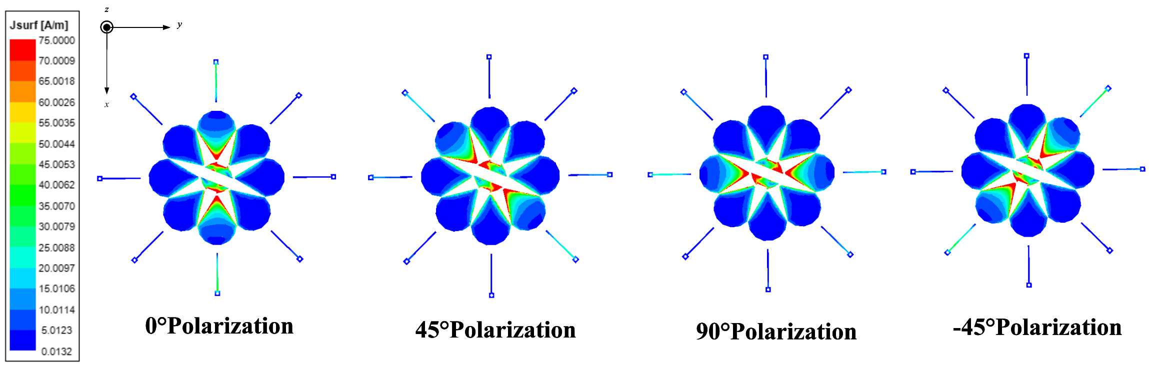

FIGURE 5. The current distributions of different states.

ing speed and relatively low cost. It is suitable for this design to maintain the stable frequency and radiation pattern in each polarization mode. Meanwhile, the switching of polarization state is also faster than the normal mechanical switching method. The details of PIN diodes placement in the structure can be seen in Fig. 1(b). These diodes are all located between feeding points and dipole arms which allows for selective excitation of a particular pair of dipoles. Next, in order to provide DC controlling voltage to the cathodes for each pair of diodes, four pairs of DC lines (from DC♯1 to DC♯4) are pulled out from bow-tie shape and threaded through the copper posts to the bottom of the substrate ♯3, as shown in Fig. 1(c). Meanwhile, the DC ground areas are connected to these DC lines through inductors to isolate the high-frequency signal from DC power. The correlation between specific polarization directions and the switching states of the diodes is illustrated in Table 1. The current distributions of the different states are shown in Fig. 5.

3. ANTENNA PERFORMANCE

The fabricated prototype of the proposed multi-linear polarization reconfigurable antenna is shown in Fig. 6. We use a 1.5 V battery for DC biasing and place it at the bottom of the substrate ♯3. Four Dupont threads are used to switch the ON/OFF states of four pairs of p-i-n diodes.

Firstly, the simulated and measured $|S_{11}|$ for all polarization states are represented in Fig. 7(a). The two results are basically in good agreement. Under each polarization state, the proposed antenna has a wide measured −10 dB impedance bandwidth of 42.6% from 2.4 GHz to 3.7 GHz.

Figure 7(b) illustrates the simulated and measured gains versus frequency for all polarization states of the antenna. From Fig. 7(b) we can see that under four polarization states, the proposed antenna maintains stable gains above 7 dBi across the op-

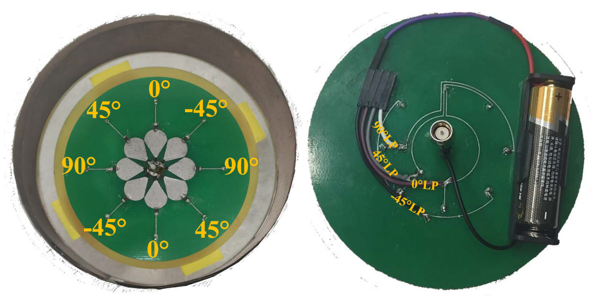

FIGURE 6. Top and bottom views of the fabricated antenna prototype.

erating bandwidth (from 2.4 GHz to 3.7 GHz). The value of the peak gain is close to 10 dBi, and the measured gains are slightly less than the simulated ones due to the losses of the p-i-n diodes and inductors. Meanwhile, the measured cross-polarized directivities are all less than the co-polarized ones by around 18 dB.

The radiation efficiencies of the antenna for the four linear polarization states are demonstrated in Fig. 8(a), and the efficiencies for all four states are above 80% in the operating frequency band. Then, the 3D radiation patterns for the four states are also shown in Fig. 8(b), which reveal that the antenna has four linear polarizations, while the 3D radiation patterns for each polarization are stable.

Then, the simulated and measured normalized radiation patterns for all polarization states at 2.4 GHz, 3.0 GHz, and 3.7 GHz in E-plane and H-plane are displayed in Fig. 9. The measured results agree well with the simulated ones, and both results indicate that the proposed antenna has stable radiation patterns of wide beam from 2.4 GHz to 3.7 GHz. Furthermore, the cross-polarization radiation patterns all remain in low levels with maximum value of −18 dB.

Through simulation and measurement, we can observe that the performances of antenna under 0° and −45° linear polariza-

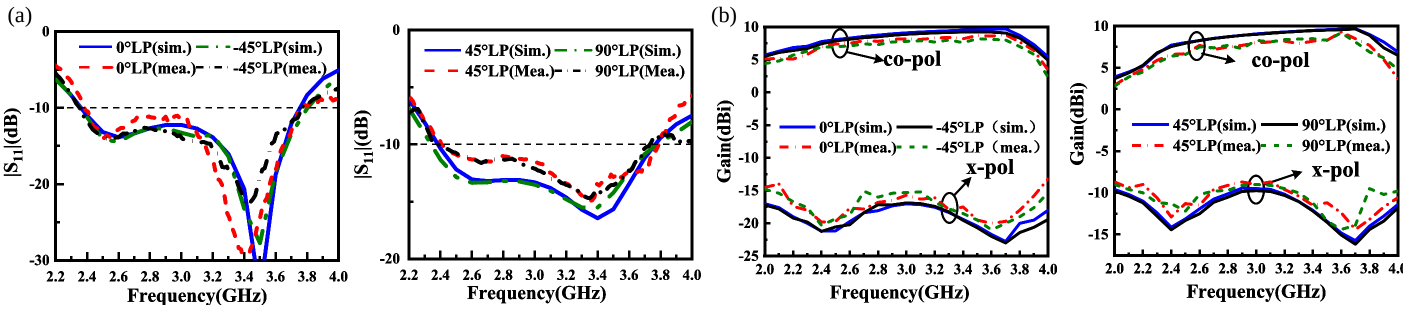

FIGURE 7. (a) Simulated and measured $|S_{11}|$ under four different linear polarizations. (b) Simulated and measured gains under four different linear polarizations.

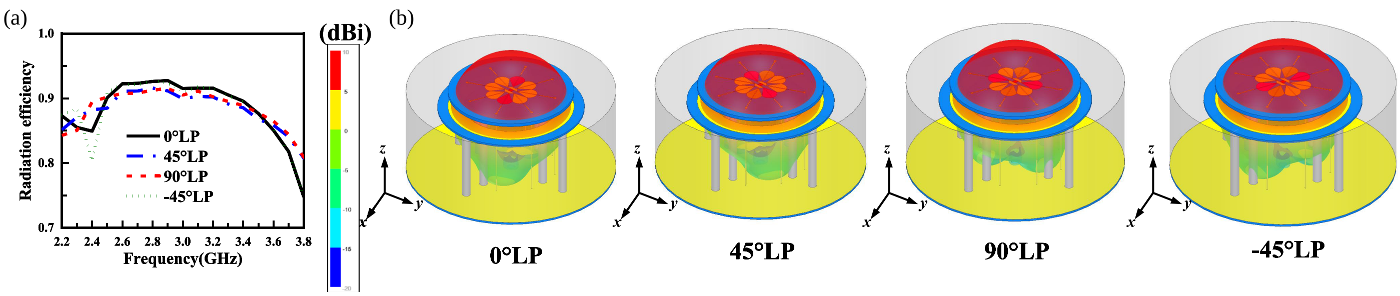

FIGURE 8. (a) Radiation efficiency under four different linear polarizations, (b) 3D radiation patterns under four different linear polarization.

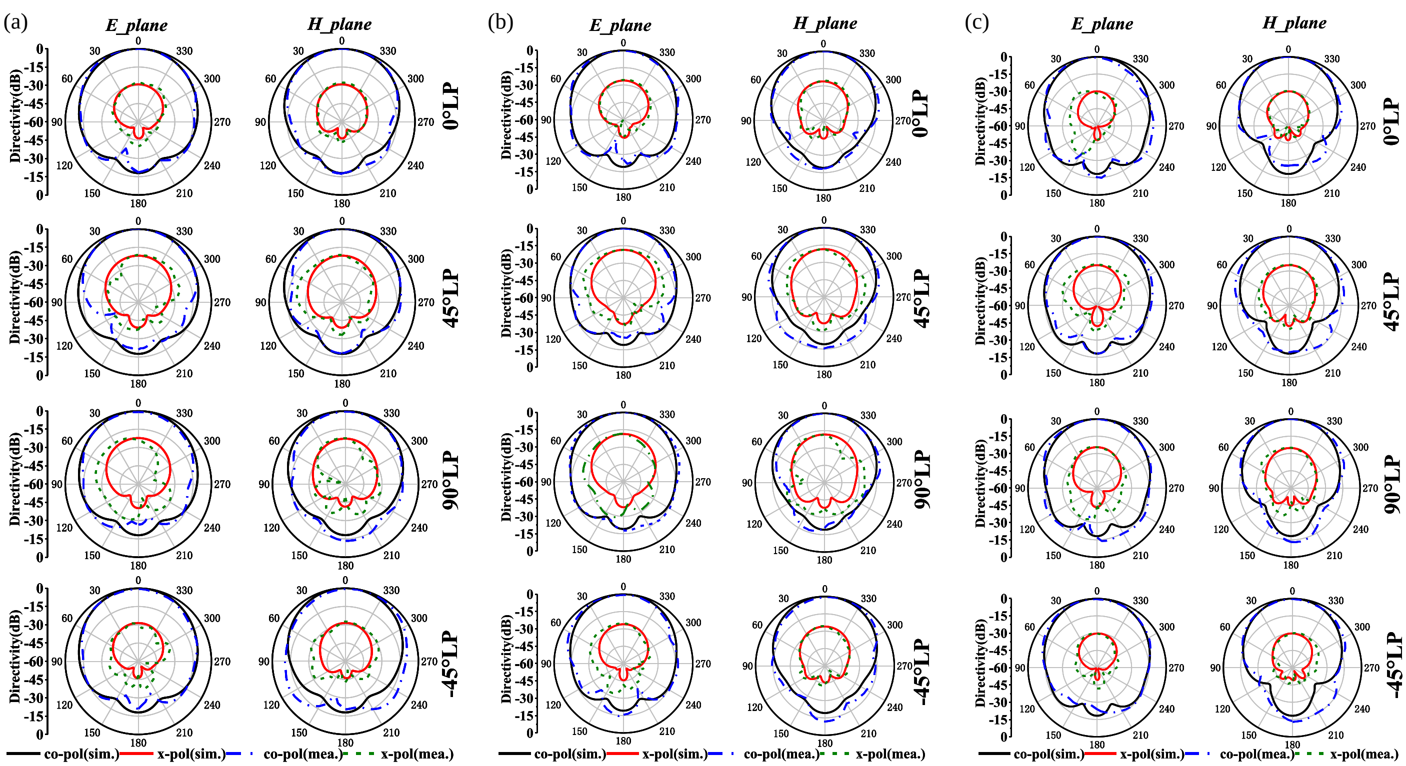

FIGURE 9. (a) Simulated and measured normalized radiation patterns at 2.4 GHz. (b) Simulated and measured normalized radiation patterns at 3.0 GHz. (c) Simulated and measured normalized radiation patterns at 3.7 GHz.

tion states are similar, and those under 45° and 90° LP modes resemble each other as well. Moreover, the cross-polarization levels of 0° and $-45°$ linear polarization modes are better than the other two modes. This situation can be explained by Fig. 10. Because the radiator structure is symmetrical, the results are always similar for 0° and $-45°$ and the same for the other two an-

TABLE 2. Performance comparison.

Ref.	Overall size (λ^3)	No. of LPs	Overlapped BW (%)	Peak Gain (dBi)
[12]	$0.75 \times 1.5 \times 0.1$	2	16	3
[13]	$3 \times 3 \times 0.6$	2	10	12
[14]	$1 \times 0.62 \times 2$	1	16	9
[15]	$0.57 \times 0.57 \times 0.06$	2	10.7	7.7
[16]	$0.8 \times 0.5 \times 0.25$	2	23.2	8
[17]	$0.7 \times 0.7 \times 0.05$	2	2.5	7
[18]	$0.7 \times 0.7 \times 0.19$	2	40	5
[19]	$0.44 \times 0.44 \times 0.17$	2	18.8	8.42
[22]	$0.57 \times 0.57 \times 0.07$	4	7	5.9
[23]	$0.95 \times 0.95 \times 0.3$	3	37	8.9
[24]	$1.04 \times 1.04 \times 0.03$	6	6.7	3.52
Prop.	$\mathbf{0.9 \times 0.9 \times 0.3}$	**4**	**42.6**	**9.3**

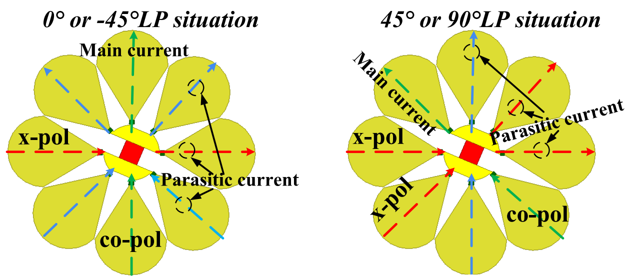

FIGURE 10. Directions of main and parasitic currents in the two situations.

gles. Furthermore, when a pair of bow-tie dipoles starts working, the parasitic currents appear on its neighboring dipoles. Under 0° or $-45°$ linear polarization situation, only one of the three pairs of parasitic currents opposes the direction of the main current. Therefore, this will reduce the cross-polarization level. However, under 45° or 90° linear polarization situation, two of three pairs of parasitic currents are in the opposite direction to the main current which leads to the increase of cross-polarization level.

Finally, the proposed multi-linear polarization reconfigurable antenna is compared with some previous studies, as indicated in Table 2. It is evident that the antenna proposed in this letter has the advantages of large operational bandwidth and high gain. Meanwhile, the antenna features four linear polarization modes with simple structure, making it suitable for applications in 5G and beyond wireless communication systems.

4. CONCLUSION

A multi-linear polarization reconfigurable antenna is presented in this letter. The antenna structure is composed of wideband bow-tie dipoles loaded with PIN diodes to realize reconfiguration of four different linear polarizations. We also use circular ring and reflective cavity structures to enhance the performances of radiation patterns and gain. Both simulated and measured results confirm that the antenna can achieve a wide overlapped BW from 2.4 GHz to 3.7 GHz for all polarization states. In addition, high gain, steady radiation patterns across the operating BW, and low cross polarization for each polarization state have been realized. The proposed antenna design is suitable for application in 5G, particularly within the sub-6 GHz band, as well as in future wireless communication systems.

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