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A Simple Four-Beam Reconfigurable Antenna Based on Monopole

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ABSTRACT A simple pattern reconfigurable antenna based on monopole is presented in this paper. The antenna consists of four folded monopoles and a windmill-shape ground plane. The central patch is fed by a coaxial probe to decide which monopole is excited. Four reconfigurable modes can be achieved by changing the states of four PIN diodes mounted on the feeding lines. And the maximum radiation directions of the proposed antenna are deflected from $\varphi = 30°$, $\varphi = 120°$, $\varphi = 210°$, and $\varphi = 300°$ at azimuth plane in four operating modes. The proposed antenna is simulated, fabricated, and measured. The experimental results indicate that the antenna can achieve a measured 10-dB bandwidth of 25.7% (3.32–4.3 GHz), a 10-dB front-to-back ratio of 17.7% (3.6–4.3 GHz), and a stable average gain of 3.3 dBi within the operating band. These characteristics make the designed antenna fit for C-band satellite communication system.

INDEX TERMS Folded monopole, pattern-reconfigurable antenna, PIN diodes, windmill-like ground.

I. INTRODUCTION

Recent days we have witnessed rapid development and wide application of wireless communication technologies in various fields. Relatively pattern reconfigurable antennas are attracting more and more attention for its potential to enhance the overall system performance. Controlling an antenna's real-time radiation pattern can enable those systems to avoid noisy environments, prevent interference, improve system gain, improve security and save energy [1], [2].

The traditional method of changing antenna's radiation pattern is utilizing phased-array antenna technology [3]–[6]. By controlling the feeding phase of radiation elements, the direction of pattern of a phased-array antenna can be changed. However, some disadvantages such as complex design process, high cost, and great weight, would limit the applications of phased array antennas in communication systems to a great extent. Considering the problems mentioned above, in-depth study of pattern reconfigurable antennas has significant potential application prospect. In the open literatures, the realization of pattern reconfigurable antennas has several main ways at present, such as changing the structure of radiator, switching the feed network, switching connection states, and using special materials. The pattern-reconfigurable planar antenna proposed in [7] needs 4 PIN diodes to reconfigure the reflector, which can only achieve pattern reconfigurations in three states. The pattern reconfigurable antenna proposed in [11] consists of a radiation patch and a ground, showing heavy structure. The radiation-pattern-reconfigurable antenna proposed in [14] is bulky. The reconfigurable pattern antenna proposed in [15] is composed of a printed dipole, a series of HSR and a balun with a high height of $0.676\lambda_0$. The novel pattern-reconfigurable antenna proposed in [17] consists of a CDR and a grounded substrate with a large size and its bandwidth is narrow. The dual-polarized pattern reconfigurable antenna proposed in [18] consists of a radiating layer, a feeding layer, and a parasitic layer. 8 switches are used to achieve 4 switchable patterns. Two pattern reconfigurable antennas were proposed in [10] and [13], both of which consist of a central patch and several strips, whose sizes are larger than the proposed antenna. And the bandwidth of the antenna proposed in [10] is narrower than the proposed antenna. The pattern reconfigurable antenna proposed in [16] consists of a central patch and four sector coupling elements, whose bandwidth is narrow and its configuration is not compact. To sum up, those antennas shown in [11], [13], and [15] have larger size than the proposed antenna, the antennas shown in [10], [16], and [17] exhibit more complex configuration and narrower bandwidth than the presented antenna, the antennas shown in [7] and [18] use more numbers of switches for each reconfigurable state, the antenna shown in [14] obtains a bad front-to back ratio. Besides, there are many other antennas have similar structure and reconfiguration. However, none of them is as simple as the proposed antenna, which has a measured 10-dB bandwidth of 25.7% (3.32 - 4.3 GHz), a 10-dB front-to-back ratio of 17.7% (3.6 – 4.3 GHz), and a stable average gain of 3.3 dBi within the operating band.

In this paper, a new simple radiation pattern reconfigurable antenna is investigated to meet the demand of wideband, easy to fabricated, low profile and high front-to-back ratio. By controlling the on-off state of four PIN diodes integrated on the feeding lines, four reconfigurable modes can be realized with good characteristics.

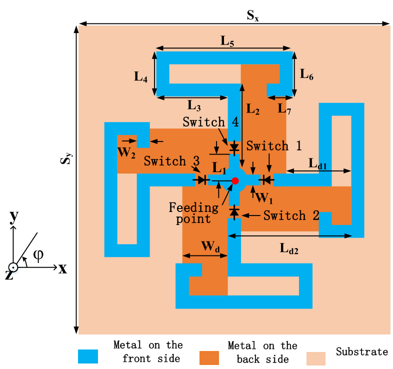
The operational principle detail and some parameter analysis are discussed in section II. Simulated results and measured results of the designed antenna are presented in Section III, with a concise conclusion and application of the antenna in Section IV.

II. ANTENNA DESIGN

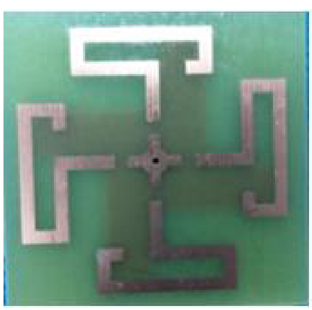
A. ANTENNA CONFIGURATION

The configuration and prototype of the proposed pattern reconfigurable antenna are shown in Fig. 1. The proposed antenna is mounted on an FR4 substrate with a relative permittivity of 4.4, a loss tangent of 0.02. And its size is 48 ($0.624\lambda_0$) mm$\times$ 48 ($0.624\lambda_0$) mm$\times$ 1.52 ($0.020\lambda_0$) mm (λ_0 is the wavelength of 3.9 GHz in free space.). It consists of four folded monopoles and a central patch which are printed on the top surface of the substrate. A windmill-shape ground plane is printed on the bottom surface of the substrate. The antenna is fed by a 50Ω coaxial line at the feeding point of the substrate center. Four PIN diodes (Switch 1-Switch 4) welded on the feeding lines between the central patch and four monopoles are utilized to decide which monopole is fed.

DC bias circuits are applied to bias the PIN diodes. The proposed antenna can realize the reconfigurability by changing the states of the diode switches. Fig. 2 gives the DC bias circuit of Switch 1, as the DC bias circuits of other switches are the same as Switch 1. The model of PIN diodes are BAR64-02V produced by Infineon. There is no need to add extra capacitors for no direct current flowing into the output devices such as the vector network analyzer. By changing the voltage of the DC power V_1 and V_2 to switch on-off state of PIN diodes, reconfigurable modes can be realized.



(a)



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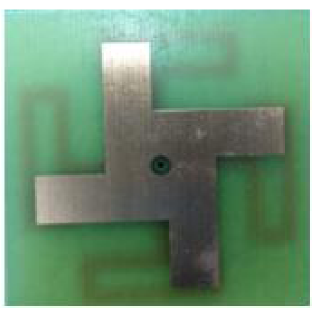
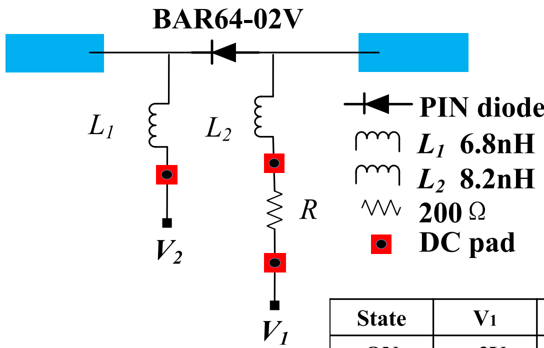


(c)

FIGURE 1. Configuration and prototype of the proposed antenna. (a) Geometry of the proposed antenna. (b) Front side view. (c) Back side view.



State	V_1	V_2
ON	+3V	0V
OFF	0V	0V

FIGURE 2. The biasing circuit for PIN diode operation.

B. OPERATING PRINCIPLE

The implementation mechanism of pattern reconfigurable antenna is introduced in this section. The reconfigurable functionality can be realized by changing the surface current distribution of the designed antenna. By the way, the operating principle remains coincident in four different modes.

From the current distribution diagram in four states shown in Fig.3, the current mainly focuses on the operating monopole. Referring to the Fig. 3 (a), it can be observed that when the antenna operates at state1, the current mainly distributes on the folded dipole in the direction of the +X axis. Similarly, we can notice that the current mainly distributes on the folded dipoles in the direction of the −Y axis, −X axis and +Y axis respectively as shown in Fig. 3 (b), Fig. 3 (c) and Fig. 3 (d).

When one of the PIN diodes is in conducting state with the other three PIN diodes disconnected, the folded monopole with the on-state PIN diode can be connected with central patch. So that it becomes the main radiator whose current is significantly stronger than the other three

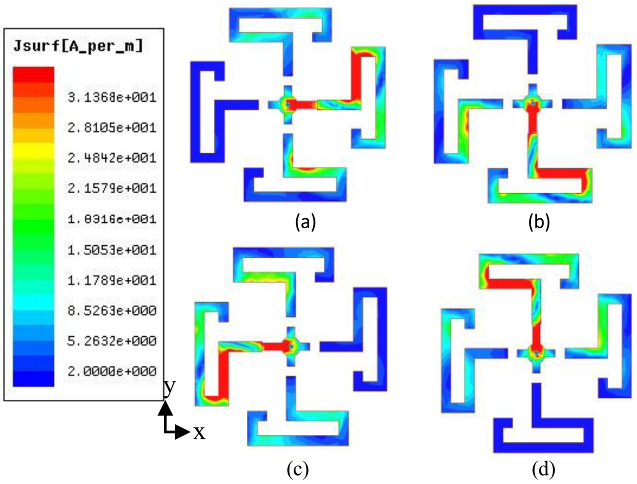


FIGURE 3. Simulation results of the current distribution at each reconfigurable state. (a) State 1. (b) State 2. (c) State 3. (d) State 4.

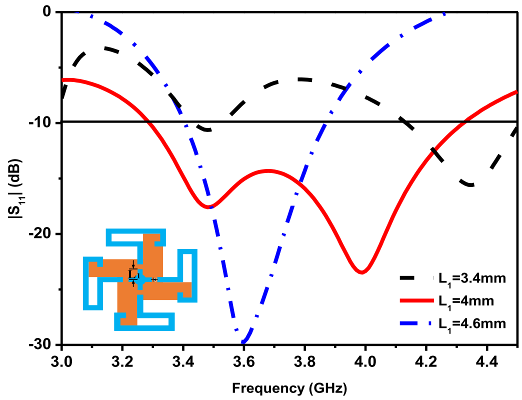


FIGURE 4. Dependences of $|S_{11}|$ of the diameter of L_1.

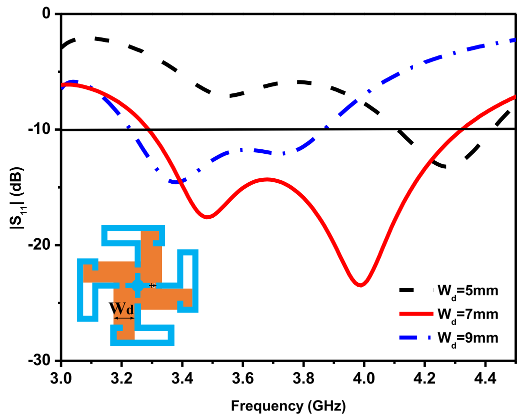


FIGURE 5. Dependences of $|S_{11}|$ of the diameter of W_d.

monopoles. Some weak electrical current also exists on the surface of other monopoles due to the coupling effect. According to the principle of Yagi antenna, three disconnected monopoles are equivalent to parasitic units, acting as reflectors. They reflect the radiation energy to the direction of the operating monopole with on-state switch, which make the proposed antenna have good directional pattern. Therefore, the radiation pattern can be deflected in four directions by changing the conduction conditions of four switches. Owing to symmetry of the antenna structure, the frequency band, radiation pattern and other properties maintain good stability when the states of the diodes change.

C. PARAMETRIC STUDY

A parametric study was performed to comprehend the influence on the performance of the proposed antenna. Taking state1 as an example, the parameters are optimized for antenna performance and listed in Table1 (λ_0 is the wavelength of 3.9 GHz in free space.).

The position of the diode switches would have significant effects on the impedance bandwidth performance, as illustrated in Fig. 4. When changing the length (L_1) of feeding line extended from the center point, the electrical length of the radiator would change. As a result, the resonant frequency and impedance bandwidth will change. The optimal value for the length of L_1 is found to be $L_1 = 4$ mm.

It can be observed that the parameter W_d mainly affects the $|S_{11}|$, as shown in Fig. 5. This is because the width of W_d has effect on the coupling between the monopole and windmill-shape ground. When the value of W_d increases, the lower resonant points will move towards the lower frequencies. When W_d is equal to 5 mm, the distance between two resonant points is too large, leading bad matching result $|S_{11}| > -10$ dB at the center of frequency band. When W_d increases from 5 mm to 7 mm, the resonance depth of the two resonant points is deepened for good impedance matching. The two resonant points getting close will lead to narrow bandwidth if W_d continues to increase. $W_d = 7$ mm is the optimized size from the above analysis.

Keep the total length of the folded monopole constant, we focus on one part of the folded monopole L_3, as is shown in Fig. 6. L_3 has influence on the reflection coefficient and the resonant frequency. This is because L_3 will affect the

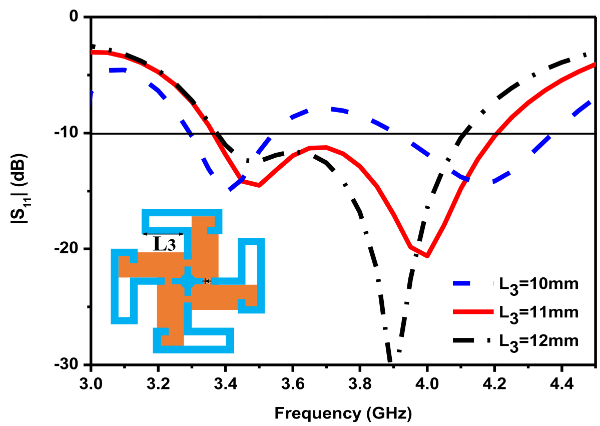


FIGURE 6. Dependences of $|S_{11}|$ of the diameter of L_3.

coupling between the monopole and the ground. The optimal value for the length of L_3 is found to be 11 mm.

Fig. 7 is the radiation pattern in azimuth plane versus "windmill" metal ground and square metal ground. It's obvious that the "windmill" metal ground can improve more effectively the directionality of the radiation pattern than square metal. The main reason for this analysis is the rectangular patch of the "windmill" metal ground acts as a reflector of the parallel monopole.

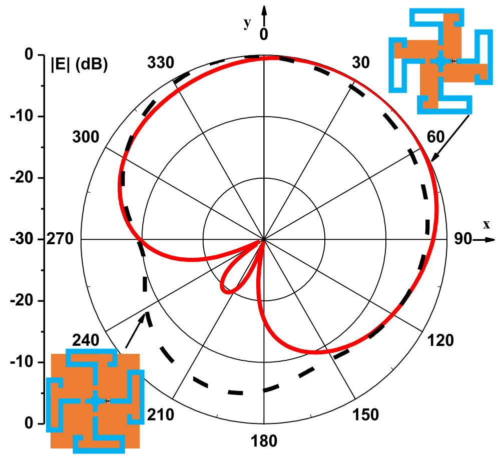


FIGURE 7. Effect of different ground shape on radiation pattern in xoy plane.

In Fig. 8, we focus on the radiation pattern in different shape of the monopole. When the shape of the monopole is changed from rectangle ring to circle ring, the operation band becomes narrow and the directionality becomes bad. So rectangle folded monopole is the optimal choice to meet the demands of small size and good radiation pattern.

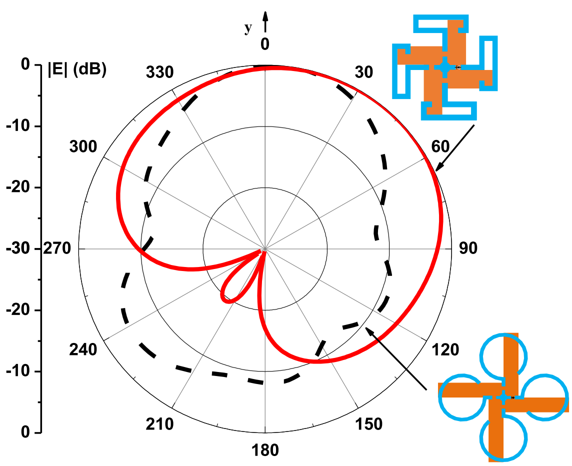


FIGURE 8. Effect of different monopole shape on radiation pattern in xoy plane.

The length of the rectangular patch of the "windmill" metal ground L_{d1} contributes the radiation performance. From the results shown of Fig. 9, the deterioration of the antenna's directional radiation can be caused by the length of the rectangular patch. Actually, the radiation pattern of the proposed antenna will be of good orientation when the optimized size of L_{d1} is 10 mm.

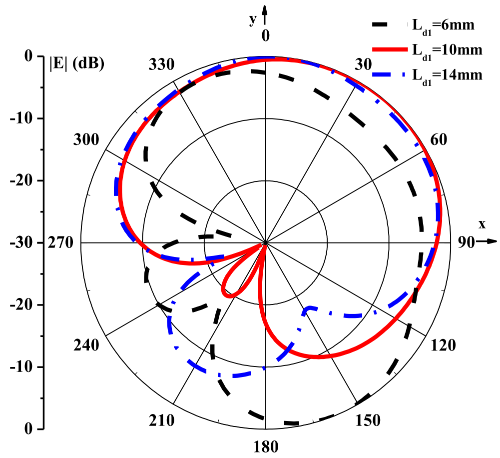


FIGURE 9. Effect of Ld1 on the radiation pattern in xoy plane.

TABLE 1. The optimized parameters of the proposed antenna.

Parameter	Size(mm)	Parameter	Size(mm)
S_x	48 ($0.624\lambda_0$)	L_6	8 ($0.104\lambda_0$)
S_y	48 ($0.6246\lambda_0$)	L_7	4 ($0.052\lambda_0$)
L_1	4 ($0.052\lambda_0$)	W_1	1.6 ($0.021\lambda_0$)
L_2	14 ($0.182\lambda_0$)	W_2	2 ($0.026\lambda_0$)
L_3	11 ($0.143\lambda_0$)	L_{d1}	10 ($0.130\lambda_0$)
L_4	8 ($0.104\lambda_0$)	L_{d2}	19 ($0.247\lambda_0$)
L_5	21 ($0.273\lambda_0$)	W_d	7 ($0.091\lambda_0$)

TABLE 2. Operating states of the antenna.

Operating states	Switch1	Switch2	Switch3	Switch4
State 1	on	off	off	off
State 2	off	on	off	off
State 3	off	off	on	off
State 4	off	off	off	on

III. RESULTS AND DISCUSSION

The proposed pattern reconfigurable antenna is designed and simulated by using Ansoft HFSS 13.0. The antenna can radiate four directions by changing the states of four PIN diodes. When one diode is forward-biased, the diode is in on-state, and when the diode is reverse-biased, it is in off-state. The four states of the pattern reconfigurable antenna are listed in Table 2.

To verify its performance, the complete antenna system is fabricated and assembled together. The fabricated antenna with DC bias circuit is shown in Fig. 10 (a). In the center of dielectric substrate, there is a non-metallic hole for coaxial line to excite the antenna. The inner core of coaxial line is welded to the middle of central patch, the outer core is welded on metal ground at the same time. Then the antenna can be tested by the other end of the coaxial line.

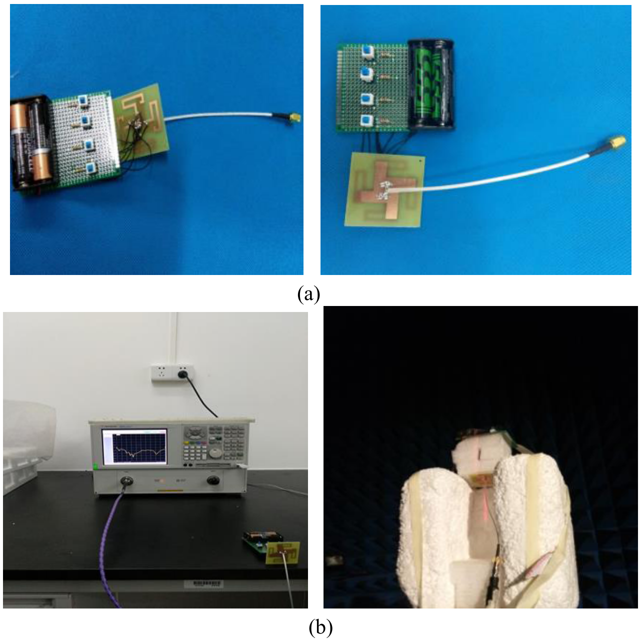


FIGURE 10. (a) The manufactured antenna with DC circuit. (b) Test in laboratory and dark room.

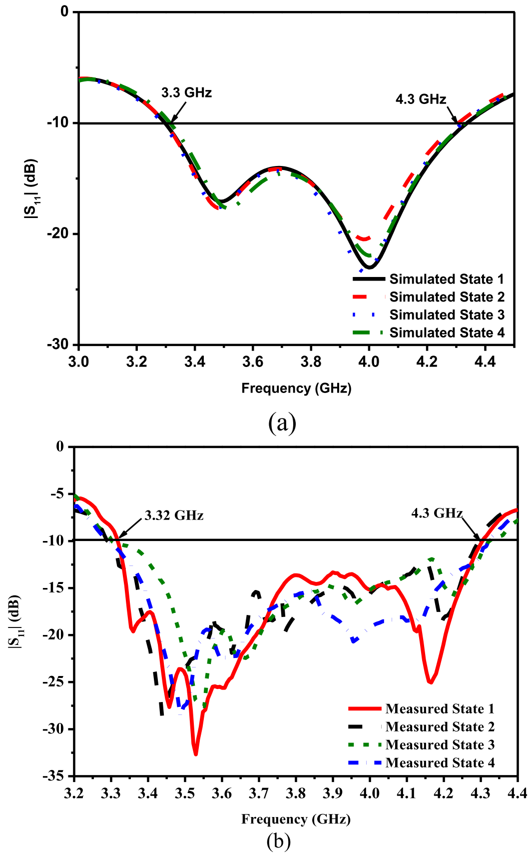


FIGURE 11. Simulated and measured $|S_{11}|$ of four states. (a) Simulated $|S11|$. (b) Measured $|S_{11}|$.

Fig. 10 (b) shows the tests in laboratory and dark room. In order to reduce the influence on the antenna radiation performance, the DC offset circuit is fixed by the hollow foam plate while measuring gain and radiation pattern. S-parameter is measured by an Agilent N5230A-420 2-port vector network analyzer. And the measured average gain and radiation patterns are obtained in China Electronics Technology Corporation Seventh Institute.

In Fig. 11 (a), the simulated reflection coefficient $|S_{11}| < -10$dB bandwidth is about 26.3% (3.3 - 4.3GHz) for all states. By comparison, the measured $|S_{11}| < -10$ dB bandwidth is given about 25.7% (3.32 - 4.3 GHz) in Fig. 11 (b). The phenomenon indicates good agreement between the simulation and measured results.

The simulated and measured results of radiation patterns in the azimuth plane (xoy-plane) are depicted in Fig. 12, when the proposed antenna is working in State 1, State 2, State 3, and State 4. Referring to the Fig. 12, the radiation patterns can be steered by switching the configurations (on/off) in the xoy plane. The maximum beam directions are deflected to $\varphi = 30°$, $\varphi = 120°$, $\varphi = 210°$ and $\varphi = 300°$ with suitable arrangements of the bias voltages, respectively. The radiation patterns are relatively stable and keep consistent shape in four working modes with other conditions unchanged. Fig. 13 shows the stimulated 3-D polar plots of the antenna's radiation pattern. The proposed antenna has a good directional characteristic, and the radiation pattern keeps stable in each operation state, which makes it suitable for the SatCom application.

Fig. 14 (a) and Fig. 14 (b) illustrate the simulated and measured gain for four states of the antenna in azimuth plane respectively. The simulated average gain is about 4.2 dBi while the measured one is about 3.3 dBi both in four different modes. The difference between measured and simulated results is due to the losses from coaxial cable and SMA connector which are not taken into account in simulation, and the insertion losses from the DC offset circuit.

In order to describe the directional characteristic of the antenna, simulated and measured front-to-back ratios (F/B) for the four states are depicted in Fig. 15 (a) and Fig. 15 (b). The 10-dB front-to-back ratio can reach 15.4% of the radiation pattern bandwidth from 3.6 GHz to 4.2 GHz. The measured results are little worse than the simulated ones because of the tolerances in the DC offset circuit and the PIN- diodes welded on the surface of the proposed antenna.

The folded monopole can be more coupled to the windmill-shape ground which acts as a reflector. In Table 3, the proposed pattern reconfigurable antenna is compared with other recent reported pattern reconfigurable antennas.

TABLE 3. Comparison between this work and other reconfigurable antennas.

Ref. No.	Volume	Reconfigurable states	Number of Switches	Impedance Bandwidth	pattern Bandwidth	FBR (dB)
[11]	$0.68\lambda_0\times0.68\lambda_0\times0.078\lambda_0$	3	4	0.1GHz 3.4%	0.1GHz 3.4%	/
[7]	$0.63\lambda_0\times0.57\lambda_0\times0.023\lambda_0$	3	4	3GHz 67%	3GHz 67%	>9.2
[15]	$0.72\lambda_0\times0.54\lambda_0\times0.676\lambda_0$	3	8	0.43GHz 15.2%	0.43GHz 15.2%	15.8
[18]	$1.17\lambda_0\times1.17\lambda_0\times0.08\lambda_0$	4	8	0.19GHz 5.6%	Not Mentioned	>10
[14]	$\lambda_0\times\lambda_0\times0.25\lambda_0$	4	4	1GHz 40%	1GHz 40%	>7.5
[19]	$0.48\lambda_0\times0.64\lambda_0\times0.02\lambda_0$	4	4	0.76GHz 34%	0.76GHz 34%	<10
[16]	$0.82\lambda_0\times0.82\lambda_0\times0.035\lambda_0$	4	4	0.16GHz 4.5%	Not Mentioned	/
[17]	$0.96\lambda_0\times0.96\lambda_0\times0.26\lambda_0$	8	8	0.16GHz 3.48%	Not Mentioned	10
[13]	$1.37\lambda_0\times1.37\lambda_0\times0.12\lambda_0$	8	8	1.5GHz 47.6%	2.5GHz 47.6%	>20
This Work	$0.624\lambda_0\times0.624\lambda_0\times0.02\lambda_0$	4	4	1GHz 26.3%	0.6GHz 15.8%	>10

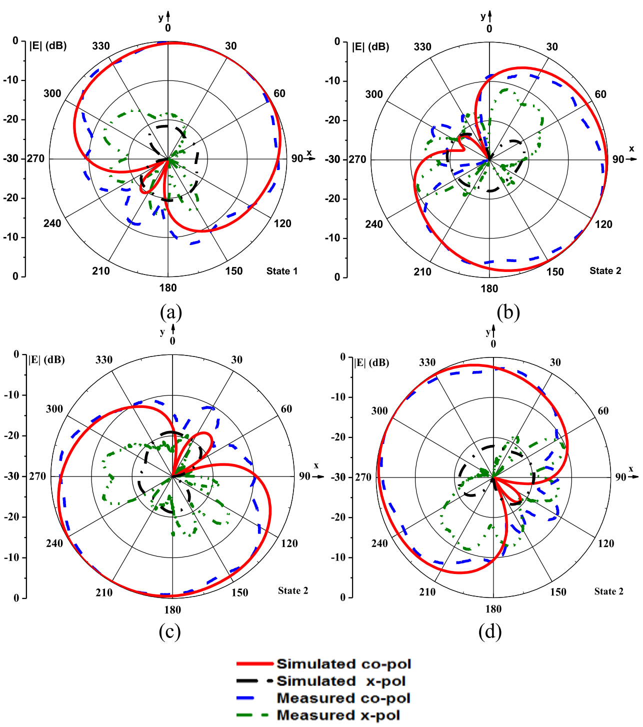


FIGURE 12. Simulated and measured radiation patterns in the xoy-plane. (a) State 1. (b) State 2. (c) State 3. (d) State 4.

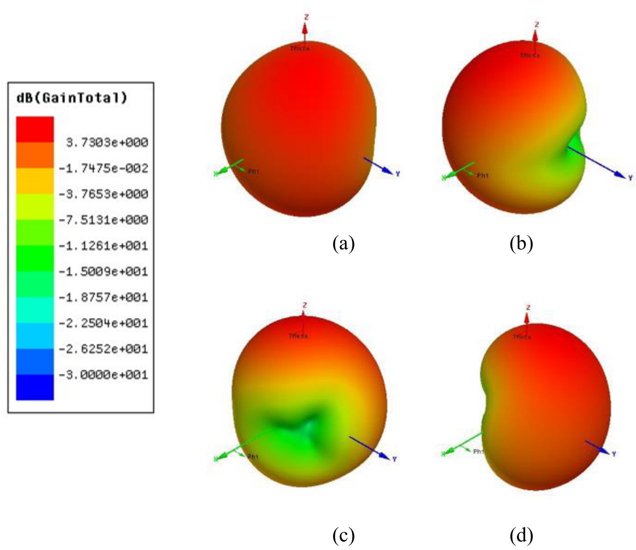


FIGURE 13. 3-D polar plot of the radiation pattern. (a) State 1. (b) State 2. (c) State 3. (d) State 4.

The pattern reconfigurable antenna with two reconfigurable modes proposed in [11] consists of two-element dipole array, the method of which is novel but its' operation band and radiation pattern is not good. The pattern reconfigurable ultra-wideband monopole antenna provided in [7] achieves three reconfigurable states by controlling 4 PIN diodes, but its gain is unstable and low (1.3-2.1dBi). The antenna shown in [15] has good front-to-back ratio by utilizing H-shaped structures to achieve reconfiguration, which need more PIN diodes for each directional states. The antennas shown in [11], [7], and [15] can operate in three reconfigurable

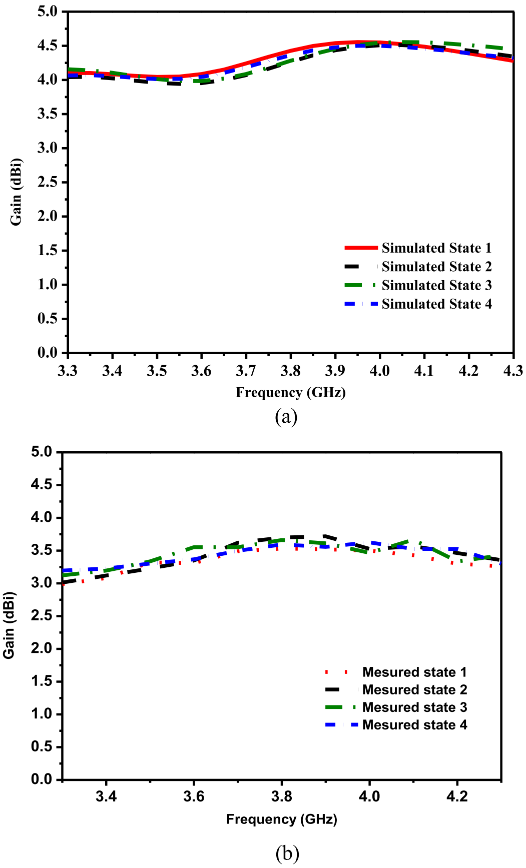


FIGURE 14. **Simulated and measured gain of the antenna. (a) Simulated gain. (b) Measured gain.**

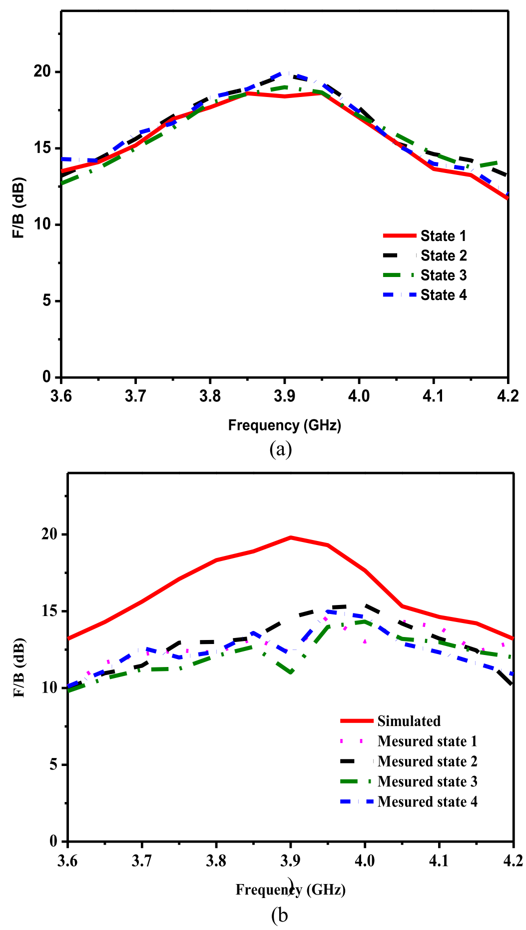


FIGURE 15. **Simulated and measured FBR of the antenna. (a) Simulated FBR. (b) Measured FBR.**

modes, whereas the proposed antenna possesses four reconfigurable states. The antenna proposed in [18] realizes low profile and high gain, with narrow bandwidth and large size. The antennas presented in [14] and [19] both obtain four reconfigurable states and realize the acceptable wideband. However, they have bad directionality, i.e. front-to-back ratios less than 10dB. By controlling the on/off state of four PIN diodes integrated on the feeding lines, four radiation pattern reconfigurable modes can be realized in [16], but its bandwidth is narrow while the proposed antenna has a wider bandwidth based on the same method. Basing on a cylindrical dielectric resonator, [17] shows an antenna which has narrow bandwidth and larger size. Reference [13] gets eight reconfigurable states by controlling 8 PIN diodes with good bandwidth and high gain, but its size is much larger than this work. Therefore, those antennas mentioned either need more switches for per reconfigurable modes, or have a large antenna size, or show bad front-to-back ratio/narrow bandwidth, which cannot well meet the requirements of simple structure, wide bandwidth and high front-to-back ratio. It is shown that the proposed reconfigurable antenna can achieve good characteristics in bandwidth, front-to-back ratio with simple structure, which makes it possible for wireless communication applications.

IV. CONCLUSION

In this paper, a simple planar pattern reconfigurable antenna for C-band satellite communication system is presented. By utilizing four switches between folded monopoles and feeding lines, the proposed antenna is capable of steering the radiation patterns. The maximum beam directions are deflected to $\varphi = 30°$, $\varphi = 120°$, $\varphi = 210°$ and $\varphi = 300°$ with suitable arrangements of the bias voltages, respectively. From the parametric study, it is learned that the parameters of the structure play an important part on the S parameters and the radiation patterns. The measured results show that the designed antenna has reflection coefficient ($|S11|$) < -10dB bandwidth of 25.7% (3.32 - 4.3 GHz). The 10-dB front-to-back ratio is of 15.4% (3.6 - 4.2 GHz). The measured average gain is 3.3 dBi in the operating band. The advantages such as planar structure, low cost, miniaturization and good stable directionality make it easy to be applied widely in wireless communication systems.

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