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A Dual-Polarized, Direction Diagram Reconfigurable, Liquid Metal Antenna

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Abstract—In this paper, we present a dual-polarized, pattern reconfigurable, liquid metal dipole antenna. The proposed design consists of a pair of $\pm 45^\circ$ polarized reconfigurable dipole antennas, two vertically placed feeding structures with filtering branches, and a resin frame for injecting liquid metal to adjust the pattern. By introducing a U-shaped structure, a better impedance matching performance is achieved in two bands. The polarization can be switched by injecting liquid metal into different dipole microfluidic channels. By controlling the liquid metal reflector around the magnetic dipole, the reconfigurable pattern of $+45^\circ$ polarized antenna can be realized at 0°, 180° and 90° on the plane of phi = 90°, and the reconfigurable pattern of -45° magnetic dipole antenna can be achieved at 0°, 90° and 270° on the plane of phi = 0°. The basic antenna operates with linear polarization around 4.8 GHz. The VSWR is less than 1.5. In the radiation pattern of the antenna, the port isolations of the two crossing ports are S_{12} and S_{21}. S_{21} port isolation is more than 35 dB. The antenna has good pattern reconfigurable characteristics, and the simulation results of the antenna indicate good radiation directivity. Moreover, the height of the proposed antenna is 0.0625λ at 4.8 GHz. The good performance of the antenna makes it a candidate for base station systems below 5G sub-6 GHz.

1. INTRODUCTION

With the development of science and technology, the progress of communication technology and the continuous improvement of the modernization level of urban and rural construction, the fifth generation of mobile communication technology has gradually entered our life [1]. At present, polarization reconfigurable antennas account for a large number of reconfigurable antennas. Polarization reconfigurable antenna can not only eliminate the multi-path fading effect of the antenna, but also increase the frequency multiplexing of the antenna [1]. So polarization reconfigurability has become a hot spot in the research of reconfigurable antennas. However, in polarization reconfigurable methods, few antennas can be achieved to control beam direction or width. So, we turn to pattern reconfigurability.

In the antenna system, reconfigurable method has a certain position. Because the application of reconfigurable method can improve channel capacity and eliminate a polarization mismatch of the antenna [2], researchers pay more attention to the field of reconfigurable antenna. In general, the pattern reconfiguration feature of the antenna is achieved by antenna arrays which phased each other, and they may be too large and complex to satisfy some requirements of many applications [3]. A pattern reconfigurable microstrip parasitic array based on the Yagi-Uda antenna radiation principle is presented in [4]. In [5], an antenna used four open circuit switches over a high-impedance surface to realize pattern reconfigurability. Communication system requires a base station antenna. For example, the base station antenna needs to use the dual polarization method with plus and minus 45° polarizations as the antenna polarization mode, which makes the radiation antenna beam of the dual-polarized antenna adjustable in

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a certain scope [6]. The design in [7] used a cross-dipole antenna and an artificial magnetic conductor, and it got a better result of achieving matching performance in two bands.

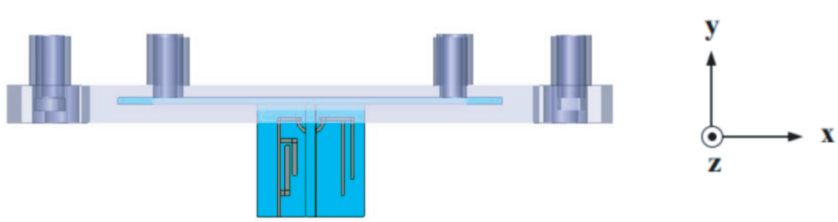
However, few designs broaden a beam of the antenna obviously [8]. For example, the design in [9] used a shape memory alloy bimorph-actuated switch for antenna reconfiguration. Or some researchers achieve a reconfigurable antenna with special materials, like using the PIN diodes by FR-4 based low profile material [10]. A single PIN diode can also achieve frequency reconfigurability [11]. Ref. [12] proposed a new reconfigurable antenna loaded with three meta material super-strates and parasitic patches. The most reconfigurable antennas rely on special materials and PIN diodes. We also found a gap in the field of reconfigurable antennas.

Cross polarization is a very important parameter in the antenna of communication base station. At the same time, the cross-dipole antenna is widely used in dual-polarized design because of its wide frequency band and simple structure. A large part of the pattern reconfigurable antennas are about shifting the main beam, like [13]. Based on this, we developed a new type of antenna structure in this paper. It realized the antenna direction diagram reconfiguration. Especially, using a slotted coupled microstrip line feeding way and injecting liquid metal into the cylinder on the antenna splint widens the beamwidth of antenna pattern. All these achieve good radiation effect.

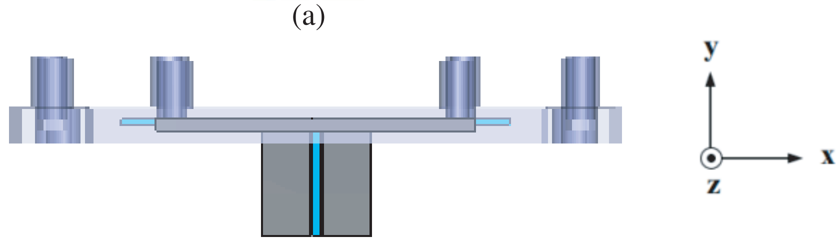
As for future development, there is also a great demand for pattern reconfigurable antennas in the field of wireless communication. Moreover, the direction diagram reconfigurable antenna system based on beam switching and broadening can also have a bright future in 5G-based stations [14]. The specific antenna structure is in Section 2 of the paper. Section 3 is for detailed simulation results analysis and Section 4 for summary and outlook.

2. ANTENNA DESIGN

Reference [15] proposed a reconfigurable antenna with a patch slot ring to switch the pattern in directions. The design [16] achieved two-bands by controlling PIN diodes. The antenna in [17] provides dual-polarized 25° beam steering in the elevation plane. However in the experimental results, the beam position in far-field patterns cannot be changed, and we cannot also see a significant beam broadening. Therefore, we improve the beamwidth of antenna radiation.



(a)



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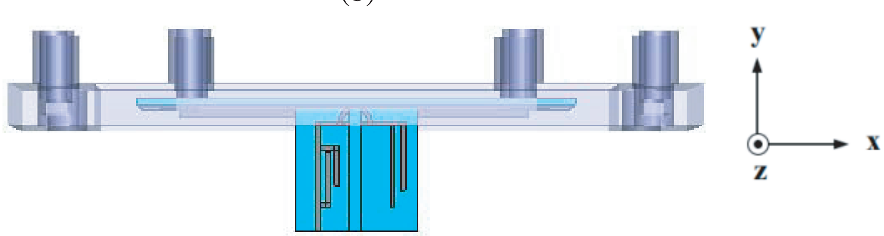

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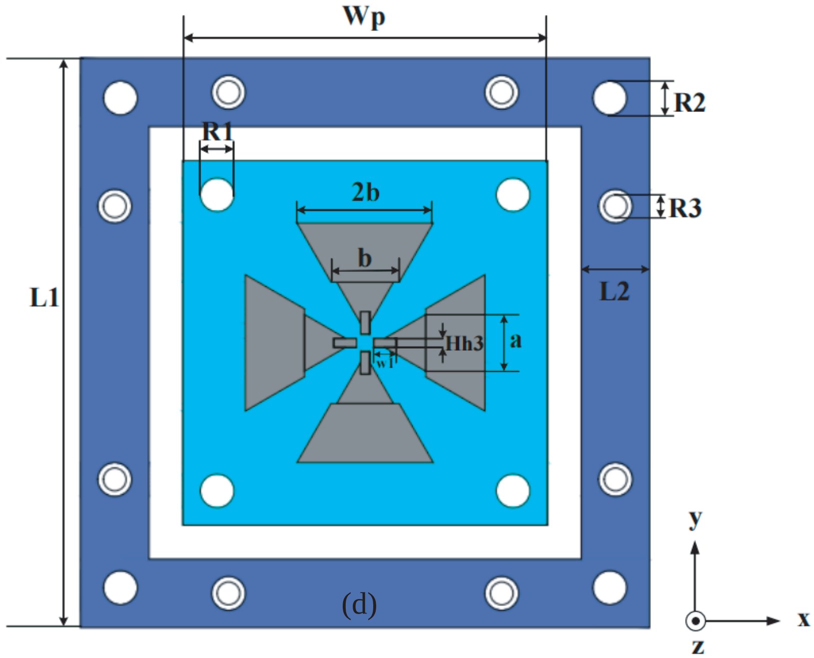


Figure 1. The 3D structure of the design. (a) The front view of the antenna and splint. (b) The left view of the antenna and splint. (c) The right view of the antenna and splint. (d) The top view of the antenna and splint.

The antenna in this article is composed of four parts: cross-dipole feed network, radiation patch, dielectric substrate, and antenna splint. Figure 1 shows the overlook plane size of the antenna. There are two reconfigurable dipoles with cross-feed structures used to feed. A square substrate is above the two cross dipoles with permittivity of 4.4 and thickness of 0.5 mm. The metal material near the patch and the feed microstrip line is copper. Copper patches of isosceles triangle and isosceles trapezoid are designed on the substrate to improve the radiation directivity of the dipole.

On the four corners of the square, we took out a radius of 1.5 mm column from each corner. To accommodate the liquid medium and liquid metal, we designed a container. As shown in Figure 2, the container is a hollow cylinder on the splint of the antenna. The hollow cylinder is added to the splint of the antenna to facilitate the injection of liquid metal. As shown in Figure 1(b), two cylinders on each side of the splint communicate with each other and are connected by a rectangular pipe, which is a liquid metal injection area. The rectangular pipe is $26\,\text{mm} * 2\,\text{mm} * 1\,\text{mm}$. Using liquid metal column

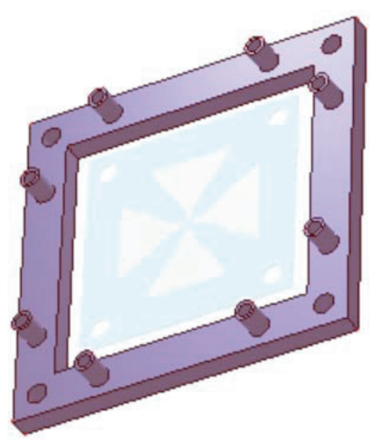


Figure 2. The structure of the antenna splint.

increases the sensibility of the folded dipole antenna, but at the same time, it also changes the radiation pattern of the cross dipole. Meanwhile, the injection of liquid metal is also an important way to broaden the beamwidth of the antenna pattern.

The distance between the antenna splint and the radiation patch is 3 mm. Antenna external splint uses transparent photosensitive resin material ($\varepsilon_r = 3.5$). The material itself has the advantage of smooth surface details, strong expressiveness, excellent waterproof ability, and strong dimensional stability. The printed model is nearly colorless, so it works well on the antenna of this article. The feeding mode of antenna adopts coupling feed of microstrip line. Part of the feeder is connected to geosyncline behind, and part of the feeder itself is used for coupling feed. We can see the cross structure of the feed structure, and the reconfigurability is achieved by using two crossed dipoles. Feeding structures contain two parts: U-shaped structures and branch structures. They were connected to form the feed structure of the antenna. The two cross feed structures are used to feed the reconfigurable dipole, and the ports are connected to the SubMiniature version A (SMA) to use. All the thicknesses of the feeding section are 0.035 mm.

Electromagnetic fields can be excited between the metal patch and the ground in the antenna radiation structure, and then produce outward radiation through the gaps between the patch and the ground. The metal reflection structure can improve the high-frequency radiation orientation map characteristics. The side-view (radiation) structure of the antenna is shown in Figure 3. More detailed parameters are listed in Table 1.

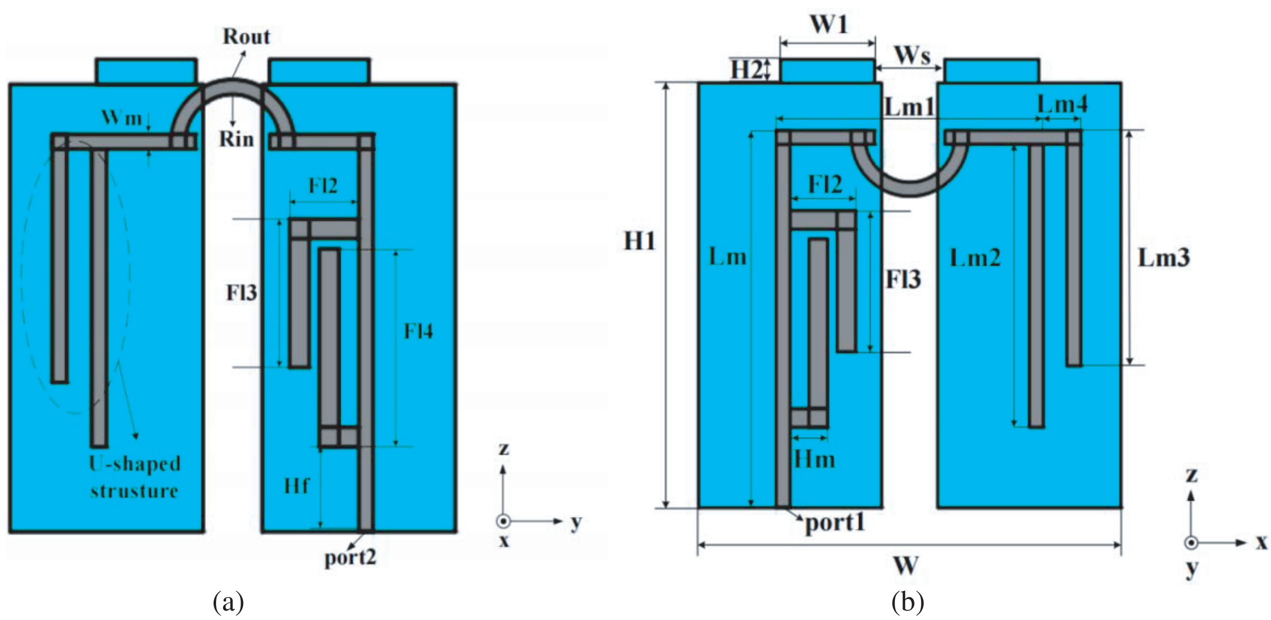


Figure 3. The structure of the reconfigurable antenna: (a) Radiation structure. (b) Side view of the design.

Table 1. Parameters of the proposed antenna.

Parameter	L_1	L_2	W_p	W_1	W_s	a	b
Value (mm)	50	6	32	2	1.5	5	6
Parameter	R_1	R_2	R_3	H_{h3}	H_1	H_2	H_m
Value (mm)	3	3	2	0.4	9	0.5	0.035
Parameter	L_m	L_{m1}	L_{m2}	L_{m3}	L_{m4}	F_{l2}	F_{l3}
Value (mm)	8	5.7	6	5	0.8	1.4	3
Parameter	F_{l4}	H_f	W	W_m	R_{out}	R_{in}	
Value (mm)	4	1.7	9	0.3	1.25	0.95	

In addition, liquid metal is applied in the antenna design. In the simulation of this paper, the metal is Perfect Electronic Conductor (PEC), which is a common metal medium, and its dielectric constant is relatively stable in the frequency band of 4.3–5.1 GHz.

During the simulation, we used the way of adding metal blocks to imitate the effect of actually adding liquid metal. And we carried out simulation through simulation software (CST ver. 2019).

3. RESULTS AND ANALYSIS

By studying the direction of the design principle of reconfigurable, theoretical analysis shows that the liquid metal injection can increase the antenna directivity and radiation intensity, and at the same time, it can also broaden the antenna radiation pattern of plus or minus 45° beamwidth. So we can know whether the antenna radiation pattern of the beamwidth is related to the injection of liquid metal or not.

From the analysis of S parameters, we can conclude that the antenna structure can cover the frequency range from 4.3 GHz to 5.1 GHz, especially at 4.8 GHz, and the antenna has a good impedance matching ability. The gain of the antenna is 2.51 dBi which is near the gain of half-wavelength dipole. The figure below clearly shows the input return loss (S_{11}, S_{22}), isolation (S_{12}), and gain (S_{21}) of the two antenna ports respectively and between them.

Figure 4 shows the performance of the antenna without liquid metal injection. From Figure 5 we can see that the S parameter of the two ports of the antenna is greater than 10 dB, and the port isolation is greater than 20 dB in the working band. From Figure 5, it can be observed that the impedance matching of the antenna is very good at the resonant frequency of 4.8 GHz. At 4.8 GHz, the corresponding value of S_{11} is -14.9 dB. These all indicate that the coupling between the ports of the antenna is smaller, and the antenna performance is better. From Figure 6, we can see that the overlapped -10 dB impedance bandwidth stretches from 4.47 GHz to 5.08 GHz when we added liquid metal in the x-axis direction and from 4.48 GHz to 5.13 GHz when liquid metal is injected in the y-axis direction. Of course, it can be seen from the figure that the addition of liquid metal does not have a significant effect on the S_{11} result of the antenna, because the addition of liquid metal has a certain coupling effect, which does not have an obvious effect on the frequency of the antenna. In order to prove the advantage of the directional graph reconfigurable antenna, the frequency band should be as consistent as possible.

Figure 7 shows the simulated far-field azimuth patterns at 4.8 GHz of port 1 without liquid metal injection in the positive and negative direction of y-axis. We can also see the horizontal and vertical

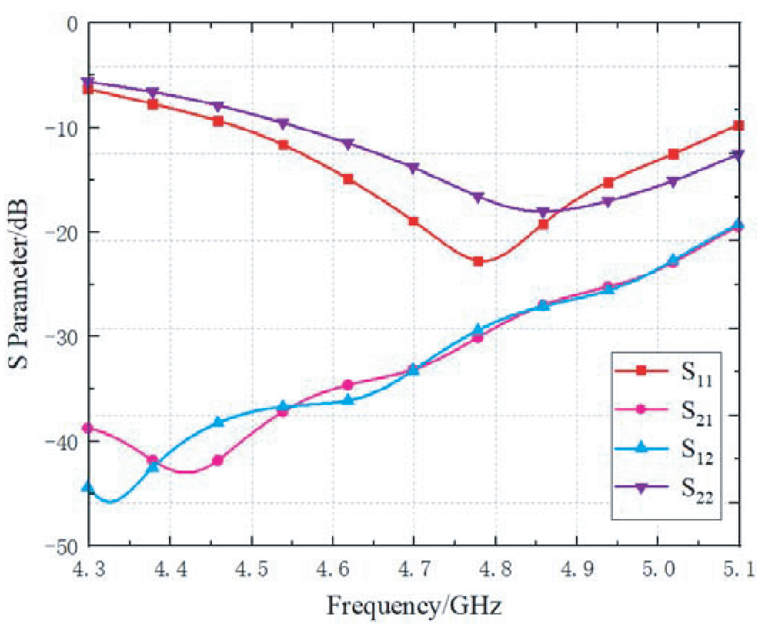


Figure 4. S parameter of the antenna without liquid metal injection.

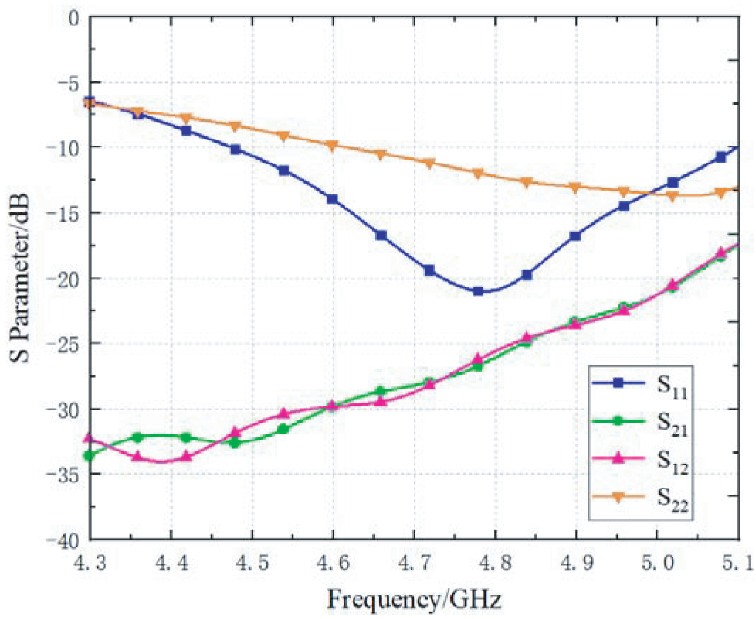


Figure 5. S parameter of the antenna used liquid metal.

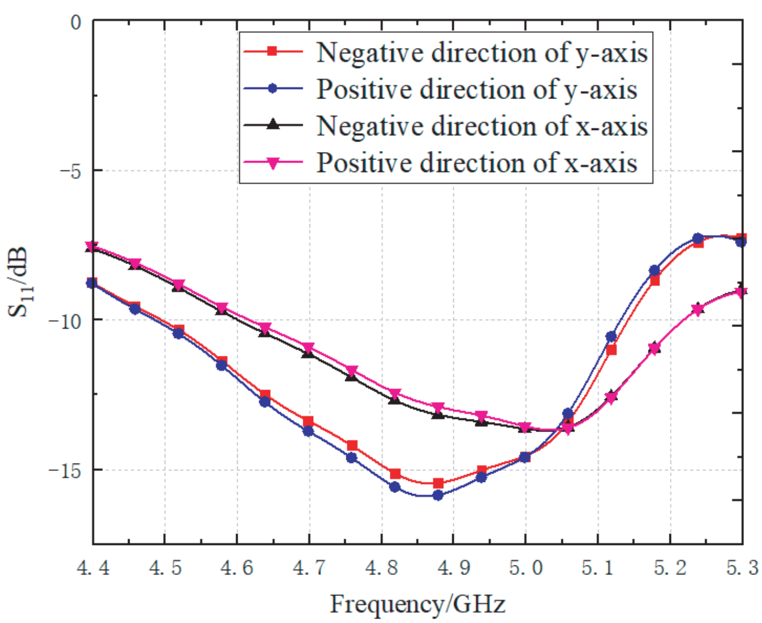


Figure 6. Measured $|S_{11}|$ of the antenna in different direction of placing liquid metal as a function of frequency.

radiation directions of antenna about port 1. Compared with the antenna without liquid metal injection, the beamwidth is broadened from 78° to 204°, and the main lobe direction is changed from 89° to 40° at phi = 90° of port 1 in the direction of y-axis. It is significant to change the radiation direction of the antenna and expand the radiation range of the antenna through injecting liquid metal. The polarization isolation of antenna is more than −15 dB. Figure 8 gives far-field patterns at 4.8 GHz without liquid metal injection in the positive and negative direction of x-axis. It can be concluded that injecting liquid metal has an influence on port 2 of phi = 0°, and the beam width is widened to 206° in the direction of x-axis. Figure 9 compares port 1 and port 2 using liquid metal in different directions and measures

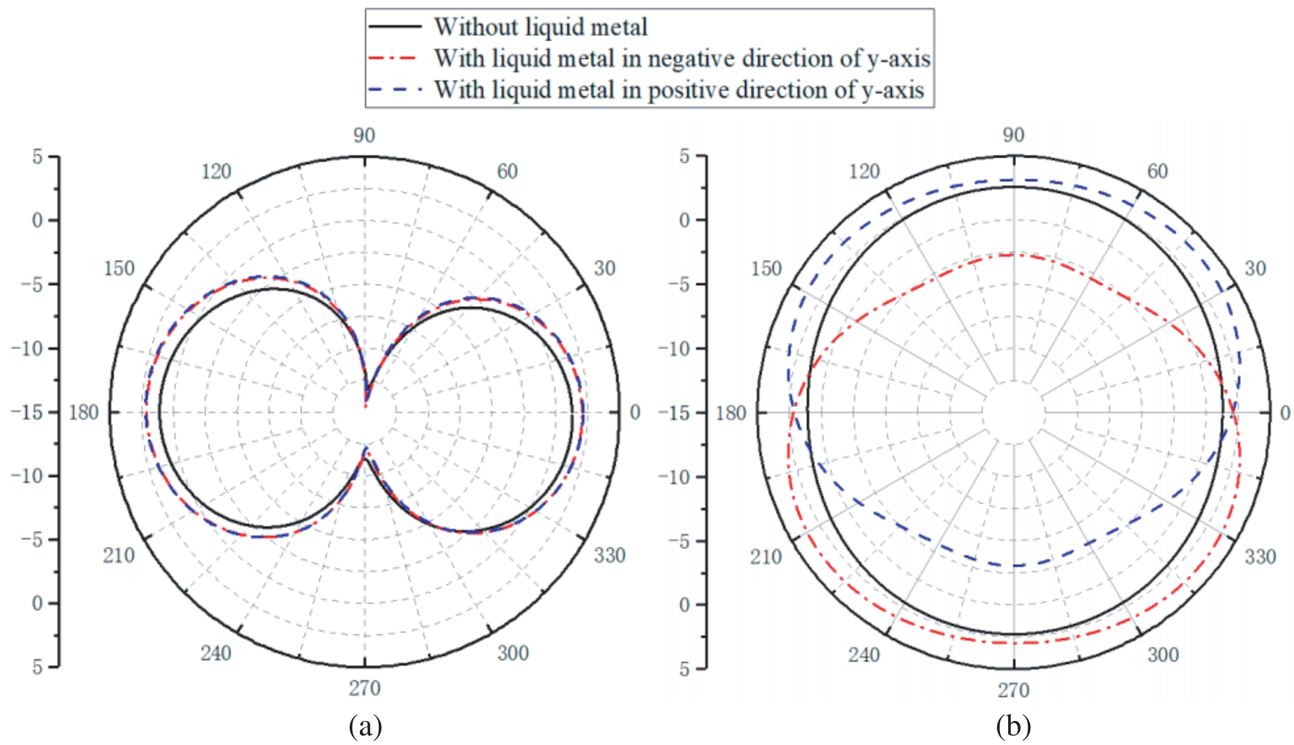


Figure 7. Measured antenna's radiation patterns of Port 1. (a) Phi = 0°, no liquid metal injection and liquid metal injection. (b) Phi = 90°, no liquid metal injection and liquid metal injection.

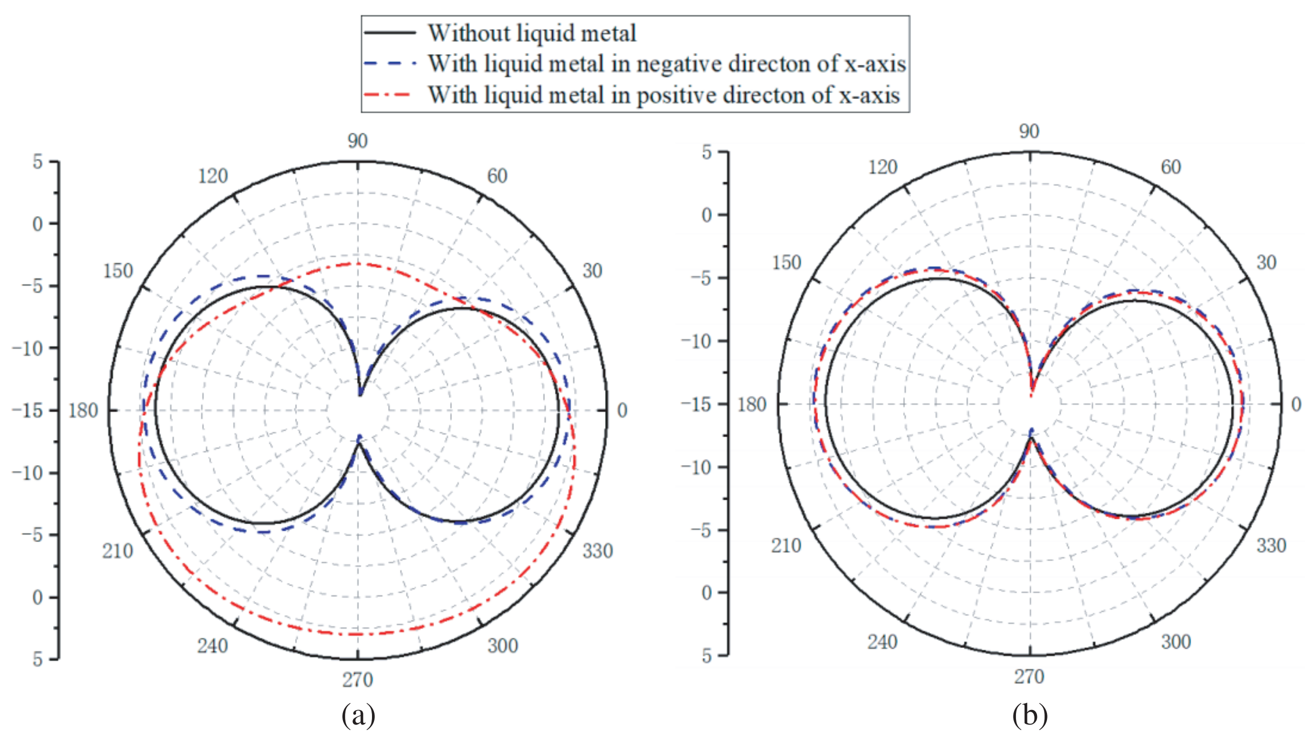


Figure 8. Measured antenna's radiation patterns of Port 2. (a) Phi = 0°, no liquid metal injection and liquid metal injection. (b) Phi = 90°, no liquid metal injection and liquid metal injection.

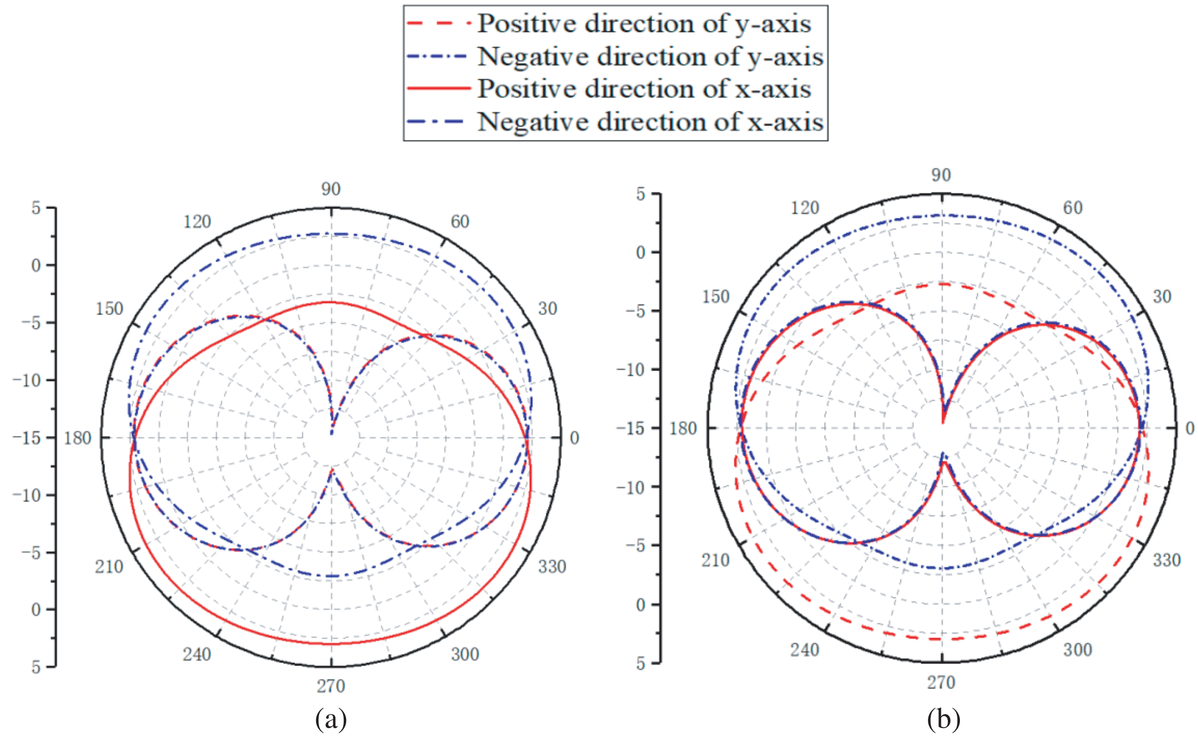


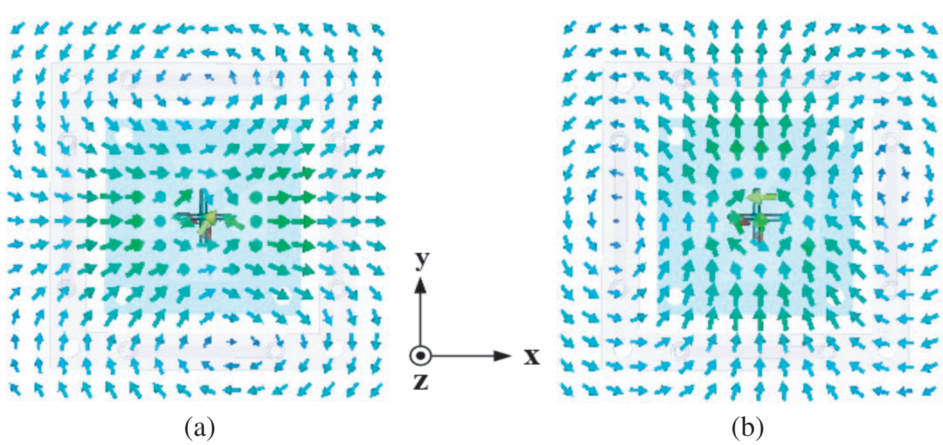
Figure 9. Measured antenna's radiation patterns of antenna in different direction of liquid metal at 4.8 GHz. (a) Phi = 0°. (b) Phi = 90° (The above results are the results of simulation software.)

radiation patterns of the antenna using liquid metal in different directions of 4.8 GHz. Clearly, the injection of liquid metal significantly changes the radiation direction of the antenna, which expands the radiation range and intensity of the antenna, and greatly reduces the loss of the antenna.

It can be concluded that the proposed antenna has stable pattern reconfigurability after injecting liquid metal. The gains of the back lobe and side lobe are both low while the main lobe is high.

Electric field distribution patterns are shown. There is a contrast between no liquid metal injection and liquid metal injection in different directions at 4.8 GHz of port 1 and port 2. We can see the changes of current distribution after injecting liquid metal in different directions. The location of the liquid metal has been indicated.

Figures 10(a) and (b) show the current distributions of the dipole antenna at 4.8 GHz without liquid metal injection of port 1 and port 2, respectively. We can clearly see the dual polarizations of the antenna in the absence of liquid metal. Figures 10(c) and (d) describe the current distribution in the positive direction of the coordinate axis with liquid metal injection at port 1 and port 2. Figures 10(e)



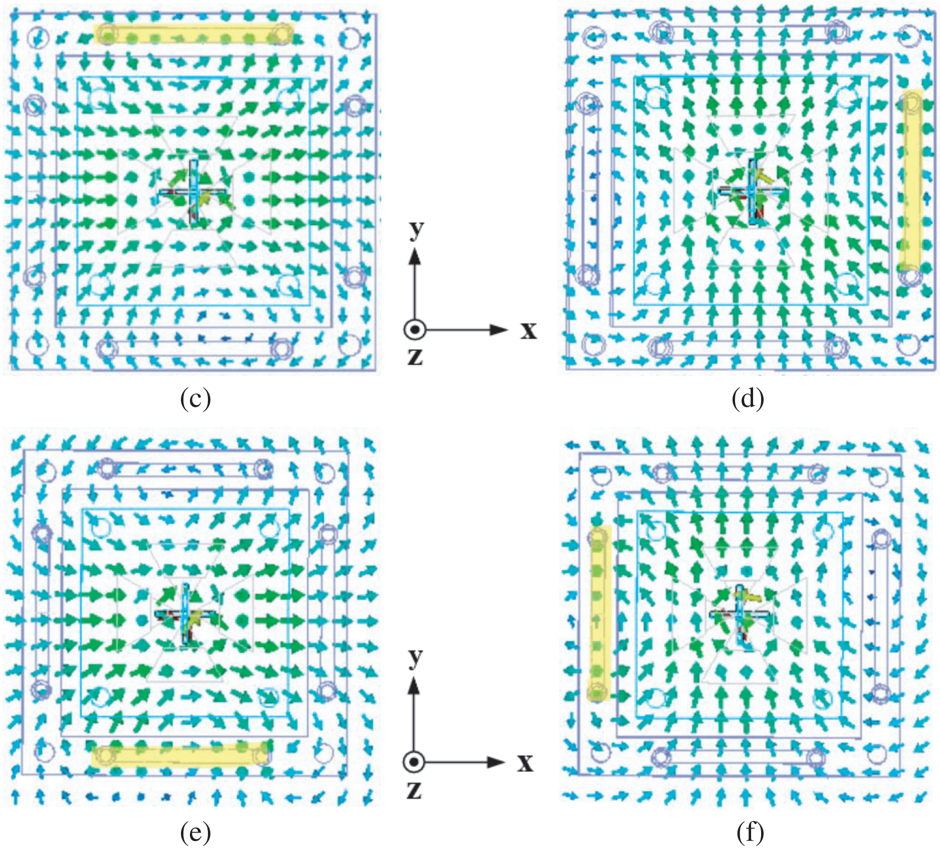


Figure 10. Current distribution of the cross dipole antenna at 4.8 GHz. (a) Without liquid metal injection at Port 1. (b) Without liquid metal injection at Port 2. (c) In the positive direction of y-axis at port 1. (d) In the positive direction of x-axis at port 2. (e) In the negative direction of y-axis at port 1. (f) In the negative direction of x-axis at port 2.

and (f) respectively describe the current distributions in the negative direction of the coordinate axis in the presence of liquid metal injection at port 1 and port 2. At the same time, it can be seen that the electric field distributions in the two across dipole arms are in the same direction, which increases the directivity and radiation intensity of the antenna. In the different directions of x-axis and y-axis, the electric field distributions are reversed. Also the radiation intensities of the antenna are different in the two axis directions. Only the above explanation is shown because the current distribution is not the focus of our research.

4. CONCLUSIONS AND FUTURE WORK

In this paper, a new type of dual-polarized, direction diagram reconfigurable antenna controlled by liquid metal is proposed. The reconfigurable antenna operates in the relative frequency tuning range from 4.3 GHz and 5.1 GHz. The injection of liquid metal changes the radiation direction and the beamwidth, and the changes are obvious. Port isolation between the two cross ports of the antenna is greater than 20 dB, and the polarization isolation of port 1 is more than −15 dB. The gain of the antenna is 2.51 dBi at the operating frequency of 4.8 GHz by injecting liquid metal. The antenna can increase the radiation range and reduce the loss. Meanwhile, the gain of the reconfigurable antenna is stable in the effective operating frequency band. In addition, the above simulation results show that the antenna has stable performance, so it is not only suitable for 5G-based station communication system, but also suitable for future 6G-based station antenna, which is also worth studying in the future.

REFERENCES

1. Zhang, M., "Research on flexible and reconfigurable liquid metal antenna," Beijing University of Ports and Telecommunications, Beijing, 2021.
2. Yang, X., Y. Liu, H. Lei, Y. Jia, and Z. Zhou, "A radiation pattern reconfigurable Fabry Pérot antenna based on liquid metal," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 11, 7658–7663, 2020.
3. Mubasher, F., S. Wang, X. Chen, and Z. Ying, "Study of reconfigurable antennas for MIMO systems," IEEE, 2010.
4. Zhang, S., G. H. Huff, J. Feng, and J. T. Bernhard, "A pattern reconfigurable microstrip parasitic array," *IEEE Antennas & Propagation*, Vol. 52, No. 10, 2773–2776, 2004.
5. Deo, P., A. Mehta, D. Mirshekar-Syahkal, and H. Nakano, "An HIS-based spiral antenna for pattern reconfigurable applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 196–199, 2008.
6. Duan, R. Z., "Research on reconstructed antenna technology based on beam switching," Beijing University of Ports and Telecommunications, Beijing, 2019.
7. Nie, Z., H. Zhai, and L. Liu, "A dual-polarized frequency-reconfigurable low-profile antenna with harmonic suppression for 5G application," *IEEE Antennas and Wireless Propagation Letters*, Vol. 18, No. 6, 1228–1232, 2019.
8. Cai, X. T., A. G. Wang, and M. A. Ning, "Novel radiation pattern reconfigurable antenna with six beam choices," *The Journal of China Universities of Posts and Telecommunications*, Vol. 19, No. 2, 2012.
9. Geetha, M., K. Dhanalakshmi, and V. Vetriselvi, "A shape memory alloy bimorph-actuated switch for antenna reconfiguration," *Journal of Materials Science: Materials in Electronics*, Vol. 33, No. 7, 4426–4437, 2022.
10. Kumar, R. V., M. Vanitha, R. Thandaiah Prabu, and M. Bindhu, "Multiband miniaturisefrequency reconfigurable patch antenna using PIN diodes," *Wireless Networks*, Vol. 28, No. 6, 2485–2497, 2022.
11. Patela, S. K., S. P.Lavadiya, J. Parmar, K. Ahmed, S. A.Taya, and S. Das, "Low-cost, multiband, high gain and reconfigurable microstrip radiating structure using PIN diode for 5G/Wi-MAX/WLAN applications," *Physics of Condensed Matter Physics B*, Vol. 639, 413972, ELSEVIER, 2022.
12. Nguyen, T. K., S. K. Patel, S. Lavadiya, J. Parmar, and C. D. Bui, "Design and fabrication of multiband reconfigurable copper and liquid multiple complementary split-ring resonator based patch antenna," *Waves in Random and Complex Media*, 2022.
13. Huff, H. G., J. Feng, S. Zhang, and J. T. Bernhard, "A novel radiation pattern and frequency reconfigurable single turn square spiral microstrip antenna," *Microwave and Wireless Components Letters*, Vol. 13, No. 2, 57–59, IEEE, 2003.
14. Hossain, M. A., I. Bahceci, and B. A. Cetiner, "Parasitic layer based radiation pattern reconfigurable antenna for 5G communications," *IEEE Transactions on Antennas & Propagation*, Vol. 65, No. 12, 6444–6452, 2017.
15. Nair, S. and M. J. Ammann, "Reconfigurable antenna with elevation and azimuth beam switching," *IEEE Antennas & Wireless Propagation Letters*, Vol. 9, 367–370, 2010.
16. Yu, Z. and J. H. Liu, "Wideband and low-profile omnidirectional circularly polarized antenna with slits and shorting vias," *IEEE Antennas & Wireless Propagation Letters*, Vol. 15, 686–689, 2015.
17. Massoud, A. T. and J. T. Bernhard, "A dualband dual-polarized steerable pattern reconfigurable antenna," *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, IEEE, 2015.