Received 4 February 2021; revised 1 March 2021; accepted 1 March 2021. Date of publication 9 March 2021; date of current version 19 March 2021.

Digital Object Identifier 10.1109/OJAP.2021.3064996

A Circularly-Polarized-Reconfigurable Patch Antenna With Liquid Dielectric

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This work was supported in part by the National Natural Science Foundation of China under Grant 62001305; in part by the Shenzhen Science and Technology Innovation Committee, China, under Project JCYJ20180305124721920 and Project KQTD20180412181337494; in part by the Guangdong Provincial Department of Science and Technology, China, under Project 2020B1212030002; in part by the National Key Research and Development Program, China, under Grant 2019YFF0216602; in part by the Research Grants Council of the Hong Kong SAR, China, under Project CRF CityU C1020-19E; and in part by the Postgraduate Education Branch of the China Education Society of Electronics.

(Zhe Chen and Hao-Zhan Li contributed equally to this work.)

ABSTRACT A circularly-polarized-reconfigurable patch antenna based on fluidic control method is proposed in this paper. A liquid dielectric, ethyl acetate, is introduced to change the substrate of a patch antenna from homogeneous to inhomogeneous. Two orthogonal fundamental transverse magnetic (TM) modes are excited with a 90° phase difference in order to produce circularly polarized (CP) radiation. Then, the polarization of the proposed patch antenna is switchable between left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP) through the injection of the liquid dielectric to different channels in the substrate. For demonstration, the proposed antenna is designed at 2.4 GHz for radio frequency identification (RFID) application. According to the measured result, the proposed circular-polarization-reconfigurable patch antenna has a stable circularly polarized (CP) gain of 8 dBic and an efficiency of 90 % across the effective frequency band. Additionally, the measured overlapped impedance bandwidth of two polarization state is from 2.24 to 2.52 GHz which can fully cover the measured overlapped 3-dB axial ratio (AR) bandwidth from 2.38 to 2.43 GHz.

INDEX TERMS Liquid dielectric, polarization reconfigurable antenna, patch antenna, high gain.

I. INTRODUCTION

IN RECENT years, the application of polarization- reconfigurable antennas in satellite communications and RFID increases significantly. Most of the reported polarization-reconfigurable antenna designs prefer to integrate semiconductor switches such as p-i-n diodes, varactor diodes, and microelectromechanical systems (MEMS) [1]–[11] because these switches have superior dynamic features. The superior dynamic features can greatly support the requirement of agile switch-control in some wireless communication scenarios. However, the semiconductor reconfigurable method suffers from some drawbacks: i) they are not applicable to some high-power applications due to the power limitations of switches. ii) the additional power consumption of the direct current (DC) bias control network is significant because the DC power supply should be continuously provided to the working states. iii) the losses introduced by the semiconductor switches would affect the gain and total efficiency of the antenna.

Lately, some reconfigurable antenna designs with fluidic control method are reported. Although the dynamic feature of these liquid type reconfigurable antennas is inferior to that of the semiconductor switches, they can withstand higher power, work with smaller power consumption, and radiate with higher total efficiency. Liquid metal materials, such as eutectic gallium-indium (EGaIn), and dielectric liquid materials, such as water, organic solvents, and ionic liquids, have been used in reconfigurable antennas. Liquid metal alloys are introduced to integrate with patch antennas to realize linearly-polarized (LP) [12]–[13] and circularly-polarized (CP) reconfiguration [14]–[15], respectively. These liquid metal alloys are proper candidate to design reconfigurable antennas but their freezing point is generally above 0° which is not applicable in most low temperature environment. Water, as the most common liquid, has been proposed to design antennas since 1950s [16]. In recent decades, water antennas are designed for various applications [17]–[22]. Reconfigurable water antenna designs are one of the most concerned topics [23]–[27]. On the one hand, water is employed to constitute the radiator of reconfigurable antennas. For example, an Archimedean spiral antenna [23] and a dielectric resonator antenna (DRA) [24] are built up by water to achieve excellent CP reconfigurability. On the other hand, water is used to dynamically change the equivalent dielectric constant of the substrate and reconfigure the antenna performance [25]–[27]. Water antenna designs makes reconfigurability easily available. However, its practicality is still limited by its freezing point and more importantly water would introduce significant loss at high frequency band. It is important to find some low loss liquid dielectric which can be used at high frequency band. A low-loss transformer oil is employed to change the dielectric constant of substrate for frequency reconfigurable design in [28] and two kinds of ionic liquids are introduced for passive beam-steering in [29]. The ethyl acetate, as a liquid dielectric, is used to make up DRA and realize CP reconfiguration [31] at high frequency band. The profile of a DRA is normally high and not available in lowest profile requirement.

In this paper, a new type of patch antenna with an inhomogeneous substrate is proposed. The inhomogeneous substrate is composed of air and ethyl acetate which means the inhomogeneity of the substrate is dynamically controllable. The patch antenna with such inhomogeneous substrate can be easily excited two orthogonal fundamental TM modes with a 90° phase difference, therefore, CP radiation is achieved. Finally, the CP reconfiguration can be realized by dynamically changing the inhomogeneity of the substrate with fluidic control method. For demonstration, a patch antenna operating at 2.4 GHz for RFID application is designed, fabricated and measured. The measured overlapped impedance bandwidth of two polarization state is 11.8 % which can fully cover the measured overlapped 3-dB axial ratio (AR) bandwidth of 2 %. More importantly, the proposed circular-polarization-reconfigurable (CPR) patch antenna has stable circularly polarized (CP) gain of 8 dBic and high total efficiency more than 90% across the effective frequency band.

This paper is organized as follows. Section II introduces the design principle and fabrication of the CPR patch antenna. Then the antenna performances are presented in Section III. Finally, the conclusion is drawn in Section IV.

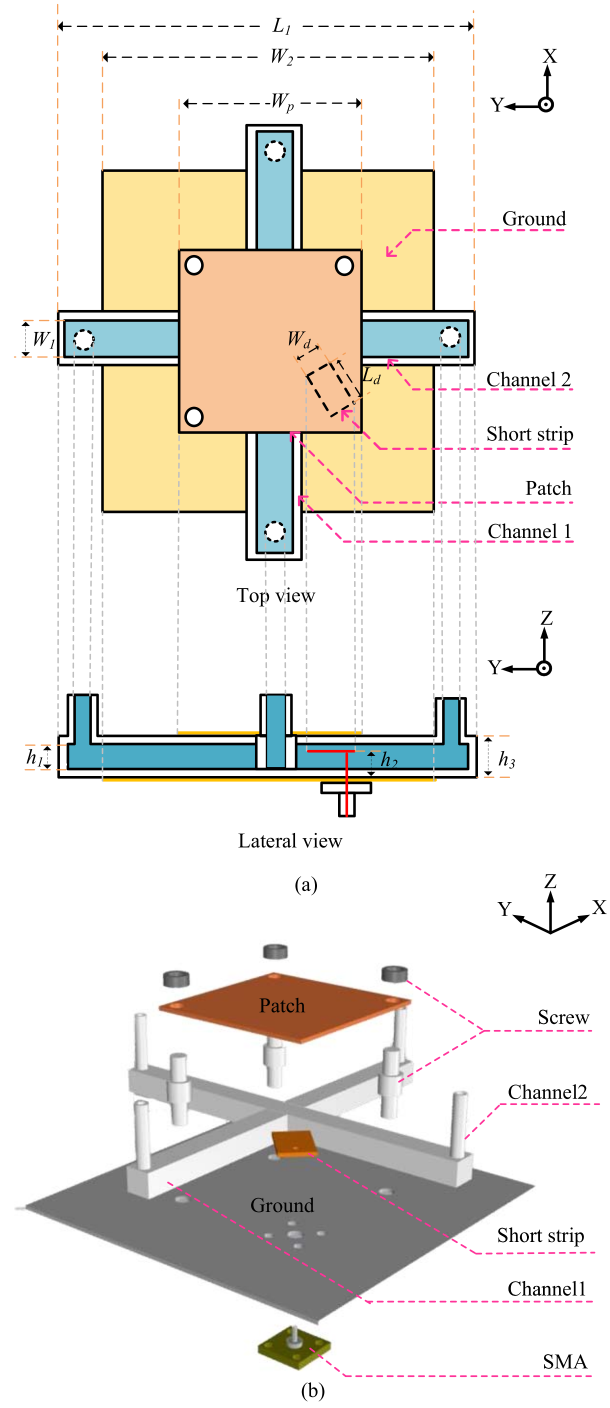

FIGURE 1. Geometry of the antenna: (a) top view and lateral view (b) exploded view.

II. ANTENNA DESIGN AND ANALYSIS

The geometry of the proposed CPR patch antenna is shown in Fig. 1. In this design, due to the integration of liquid dielectric the substrate is thicker than common patch antenna, therefore, L-shaped feeding structure is used to

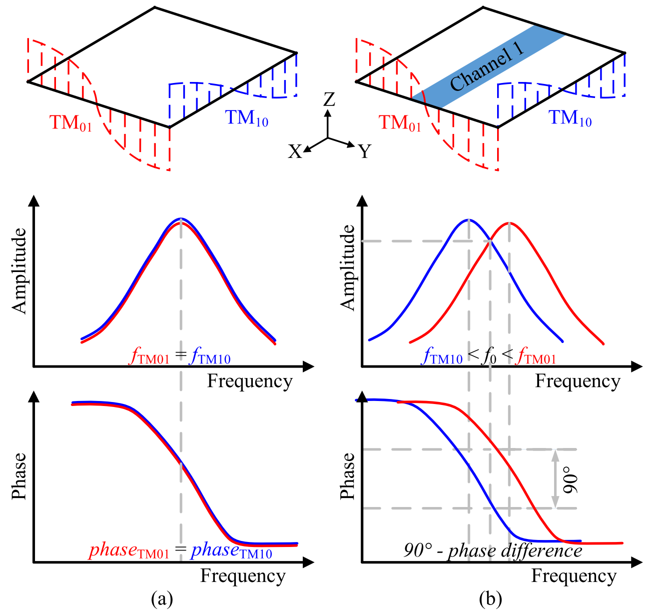

FIGURE 2. Analysis of the mechanism of circular polarization: (a) homogeneous substrate (b) inhomogeneous substrate.

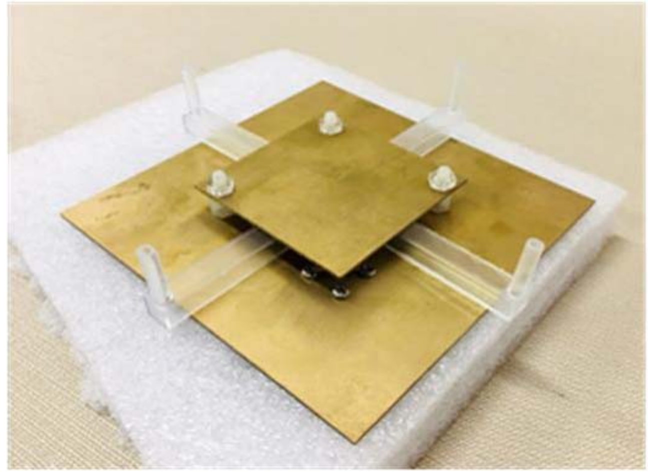

FIGURE 3. Photograph of the antenna prototype.

TABLE 1. Design parameters of the proposed antenna.

W_p	W_1	L_1	W_d	L_d
42 mm	3.6 mm	101 mm	9 mm	13.5 mm
W_2	h_1	h_2	h_3	
90 mm	5 mm	4.5 mm	6 mm	

broad the impedance matching bandwidth. The L-shaped feeding structure is composed by a probe and short strip as in Fig. 1 (a). The impedance matching can be adjusted by tuning the height of probe and the dimension of strip. Additionally, a cross-shaped microfluidic cavity fabricated by a 3-D printer Formlab 3 is between the patch and ground to hold the liquid dielectric as in Fig. 1 (a). The permittivity and loss tangent of the 3-D printing material are measured with DAK-TL-P base system in our lab ($\varepsilon_r = 2.8$ and loss tangent = 0.03 from 2 to 3 GHz). In Fig. 1 (a), the microfluidic cavity is composed of two channels: the one along *x*-axis is Channel 1, the other one along *y*-axis is Channel 2 and the intersection of these two channels are isolated. In Fig. 1 (b) the exploded view outlines the fabrication process in detail where 3 screws are utilized to fix the whole structure tightly.

In this design, the L-shaped feed is along one of the diagonals of the square patch, exciting two orthogonal fundamental TM modes — TM_{01} and TM_{10} whose electric field distribution are shown in Fig. 2 (a). These two modes are a pair of degenerate modes. Therefore, they would have similar phase and resonant frequency if the substrate of the patch antenna is homogeneous in Fig. 2 (a). The substrate become inhomogeneous when the liquid dielectric is injected into Channel 1 as in Fig. 2 (b). Consequently, the equivalent permittivity along *x*-axis increases while that along *y*-axis almost remain unchanged. As a result, the resonant frequency of TM_{10} mode shift to lower frequency whereas that of TM_{01} mode retained constant. If the volume of the liquid dielectric is appropriately optimized, these two degenerate modes would have same amplitude and 90° phase difference at f_0 ($f_{TM10} < f_0 < f_{TM01}$) as in Fig. 2 (b). In this way, this patch antenna radiates a LHCP electromagnetic (EM) wave as STATE 1. Since the antenna structure is symmetrical, the patch antenna would radiate a RHCP EM wave as STATE 2 when the liquid dielectric is injected into Channel 2. For brevity the mechanism analysis of RHCP radiation is not included here. At last, the CP sense of this proposed patch antenna could be switched by cyclically pumping the liquid dielectric between the two channels. The switch time is about 2 to 4 seconds.

The ethyl acetate is a sort of non-electrolyte which has low toxicity, stable dielectric constant and low-cost features. It is widely used as a solvent and diluent in chemical experiment or as a kind of additive in perfumes, paints, medicine, inks and other industries. Although the ethyl acetate is low toxicity and commonly used, we manipulate it carefully in our antenna fabrication and measurement. The injection and discharging of the ethyl acetate are processed in a dry environment at room temperature in the measurement. The operators are equipped with masks and gloves during the experiment. More importantly, the freezing point of ethyl acetate is below −89.3 °C which makes it could be applied at low-temperature environment. The dielectric constant and loss tangent of the ethyl acetate is measured with DAK-TL-P base system in our lab ($\varepsilon_r = 5.8$ and loss tangent = 0.05 from 2 to 3 GHz). Clearly, the ethyl acetate can be used at high frequency band due to its low loss property. The final dimensions of the proposed patch antenna are shown in Table 1.

III. RESULTS AND DISCUSSION

To verify our design, a CPR patch antenna is fabricated and measured. The photograph of the prototype is presented in

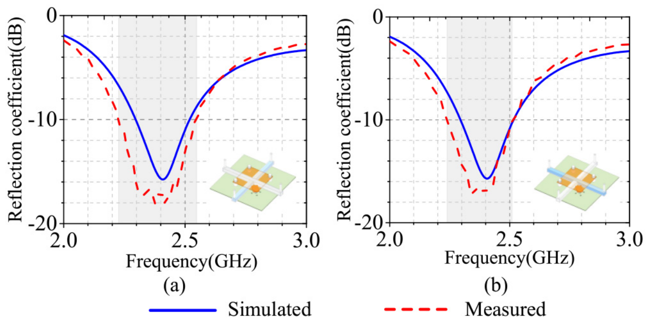

FIGURE 4. Measured and simulated reflection coefficients: (a) STATE 1: LHCP (b) STATE 2: RHCP.

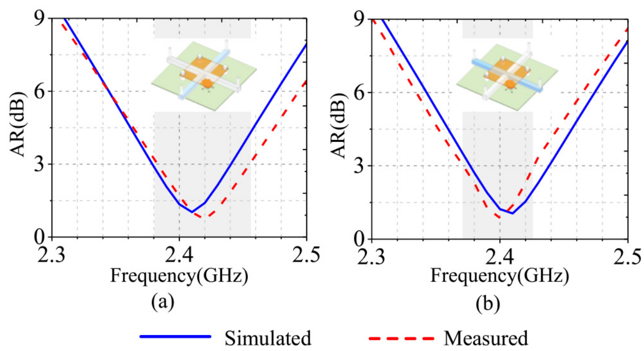

FIGURE 5. Measured and simulated axial ratios: (a) STATE 1: LHCP (b) STATE 2: RHCP.

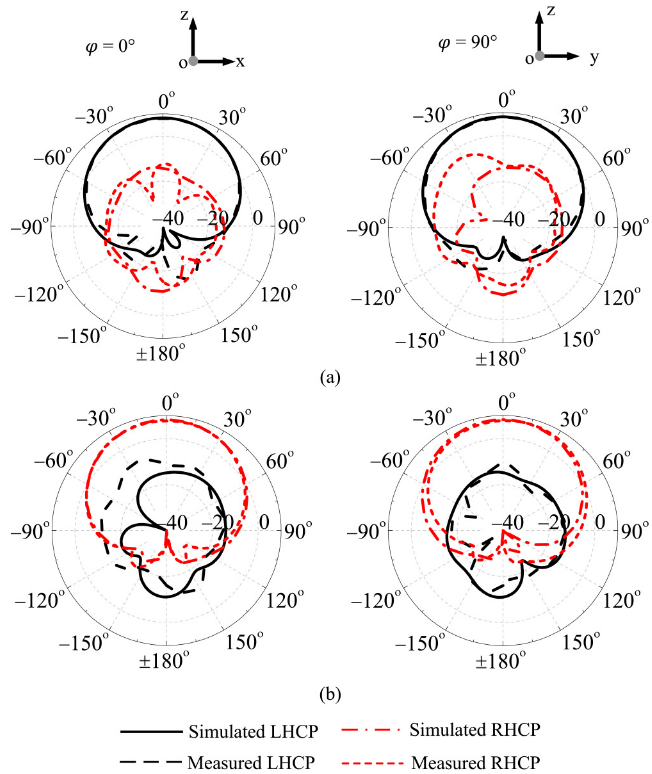

FIGURE 6. Measured and simulated radiation patterns at 2.4GHz: (a) STATE 1: LHCP (b) STATE 2: RHCP.

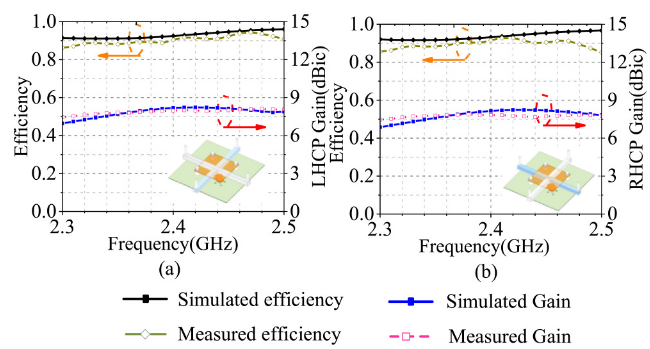

FIGURE 7. Measured and simulated total efficiencies and CP gains. (a) STATE 1: LHCP (b) STATE 2: RHCP.

Fig. 3. In the measurement, the reflection coefficients of the two CP states are measured by a Keysight PNA Network Analyzer N5224A. Meanwhile, the AR, radiation pattern, realized CP gain, and total efficiency of the two CP states are measured with a spherical near field measurement system SUNYIELD SY-16M.

A. REFLECTION COEFFICIENT AND AXIAL RATIO

Fig. 4 shows the measured and simulated results of reflection coefficient for the two CP states. It is shown a good agreement between the simulation and measurement. The measured impedance bandwidth of STATE 1 is 13.8 % from 2.22 to 2.55 GHz (reflection coefficient < -10 dB) in Fig. 4(a). The measured impedance bandwidth of STATE 2 is 11.8 % from 2.24 to 2.52 GHz in Fig. 4 (b). The overlapped impedance bandwidth of the two CP states is 11.8 % from 2.24 to 2.52 GHz.

The AR bandwidth is a key parameter to evaluate the performance of CP antenna. The measured and simulated ARs are matched well with each other in two states as shown in Fig. 5. The measured AR bandwidth of STATE 1 is 3.3 % from 2.38 to 2.46 GHz. The measured AR bandwidth of STATE 2 is 2.5 % from 2.37 to 2.43 GHz. The overlapped AR bandwidth of the two CP states is 2 % from 2.38 to 2.43 GHz. The overlapped impedance frequency band can fully cover the overlapped AR frequency band.

B. RADIATION PATTERN, TOTAL EFFICIENCY AND GAIN

Fig. 6 illustrates the radiation patterns at 2.4 GHz for the two CP states. Clearly, broadside radiation patterns have been obtained. For STATE 1, the LHCP is co-polarization while for STATE 2, the RHCP is co-polarization. The measured cross-polarization is higher than the simulated one, but the measured difference of the magnitude between co-polarization and cross- polarization is higher than 20 dB. As expected, the proposed CPR patch antenna can radiate RHCP and LHCP EM waves along z-axis in two states, respectively.

Fig. 7 displays the measured and simulated total efficiencies and CP gains of the two states. Although the measured total efficiencies are slightly lower than the simulation they are still higher than 90 % across the effective frequency

TABLE 2. Comparison for circular-polarized reconfigurable antenna performance.

Ref.	Turning Mechanism	Turning Frequency Range (GHz) (AR < 3 dB)	Total Efficiency	CP Gain (dBic)	Profile (λ_0)
[14]	EGaIn	LHCP (2.35 — 2.43) RHCP (2.38 — 2.48)	> 90 %	7.24 — 7.33	0.08
[15]	EGaIn	LHCP (2.27 — 2.83) RHCP (2.19 — 2.79)	43 — 66 %	1.63 — 3.64	0.04
[21]	Water	LHCP (1.27 — 2.12) RHCP (1.27 — 2.12)	40 — 80 %	~ 10.5	0.98
[23]	Water	LHCP (1.20 — 1.80) RHCP (1.20 — 1.80)	NULL	6.3 — 8.6	0.124
[24]	Water	LHCP (2.29 — 2.86) RHCP (2.30 — 2.92)	60 — 70 %	3 — 4	0.32
[25]	Water	LHCP (0.952 — 0.956) RHCP (0.952 — 0.956)	> 75 %	~ 6	0.04
[31]	Ethyl acetate	LHCP (2.31 — 2.72) RHCP (2.31 — 2.72)	>70 %	5 — 5.5	0.27
This work	**Ethyl acetate**	**LHCP (2.38 — 2.46)** **RHCP (2.37 — 2.43)**	**> 90 %**	**7.2 — 8.1**	**0.048**

band. Meantime, the measured CP gains match well with the simulation and remain stable at 8 dBic across the effective frequency band.

C. COMPARISON

The performance of the proposed CPR patch antenna is compared to the state-of-the-art in this area in TABLE 2. It is obvious that the proposed low-profile design has the highest total efficiency and most stable CP gain.

IV. CONCLUSION

A novel CP reconfigurable patch antenna has been investigated in this paper. The proposed design demonstrates how to control the polarization between LHCP and RHCP states with fluidic control method. After optimization, the proposed 3-D printed antenna has been fabricated and measured. Good agreement between the measured and simulated results was obtained. Compared with the state-of-the-art of liquid CP antenna designs, our design has a lower profile, higher total efficiency and more stable CP gain. For the potential application, the proposed design could be applied as a reader antenna in RFID application. In this design, ethyl acetate is applied in the high frequency band which has stable permittivity and low loss. This would provide a reference for the selection of liquid materials at high frequency range in the research of liquid antennas.

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