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Design and Fabrication of a Liquid Crystal-Based 94 GHz 360° Phase Shifter for Reflectarray Antennas

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Abstract—In this work, we propose a liquid crystal (LC)-based double-dipole phase shifter. By manipulating the electric field, we change the resonant frequency and phase of the electromagnetic wave by deflecting the orientation of LC molecules. We made the LC-based device with a 30×30 array of two parallel unequal dipoles on a Quartz substrate. The substrate has an area and thickness of $4 \times 4\,\mathrm{cm}^2$ and 480 μm, respectively. The experimental results show that the phase shift of 0°–385.4° is achieved at 94 GHz by changing the applied bias voltage on the LC layer from 0 V to 8.4 V. The phase shift is greater than 360° in the range 91.75–94.85 GHz. When the LC molecules are most significantly affected by the electric field, the maximum precision of phase shift is 4.08° with a bias voltage of 2 mV.

1. INTRODUCTION

The requirements of phased array antennas have increased enormously with the development of modern communication technologies [1–3]. Phase shifter is a crucial component in phased array antennas [4–6]. Phase shifters are used to adjust the reflection phase of each element of the array cell. Compared with traditional phased array antennas, reflective phased array antennas have the ability to significantly reduce the cost and processing difficulty in high frequency range [7, 8]. Recently, researchers have presented various reconfigurable reflection arrays based on liquid crystal (LC) [9, 10].

The LC is a tunable material, which is used in various frequency bands, such as microwave, millimeter wave [11], and terahertz bands [12–14]. The anisotropic properties of LC are used to dynamically adjust the phase of devices [15, 16]. In this study, an LC-based reflective phase shifter with 360° phase shift in 94 GHz is proposed. The test results show that the phase shift that the device can provide is 385.4° in 94 GHz, and bandwidths can reach 3.1 GHz for phase shift greater than 360°. It can provide a phase shift of 4.08° with the bias voltage of 2 mV.

2. DESIGN OF LCS BASED PHASE SHIFTER

The structure of the phase shifter unit cell is presented in Figure 1(a). The structure of this cell comprises two parallel layers of Quartz substrate and a sandwiched LC layer which has a height of 65 μm. Please note that Quartz has the permittivity of ε_r =3.78, loss tangent of 0.002, and thickness of 480 μm. The unit cell presented in Figure 1(b) is composed of double-dipole and a biasing line which is used as an electrode for applying the bias voltage to the LC substrate [17]. The patches and ground plane are made of copper and have a conductivity of 5.8×10^7 S/m. In order to control the orientation

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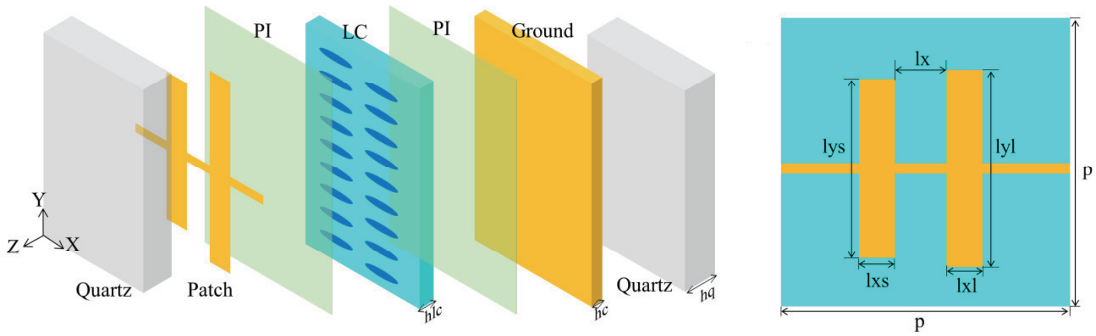


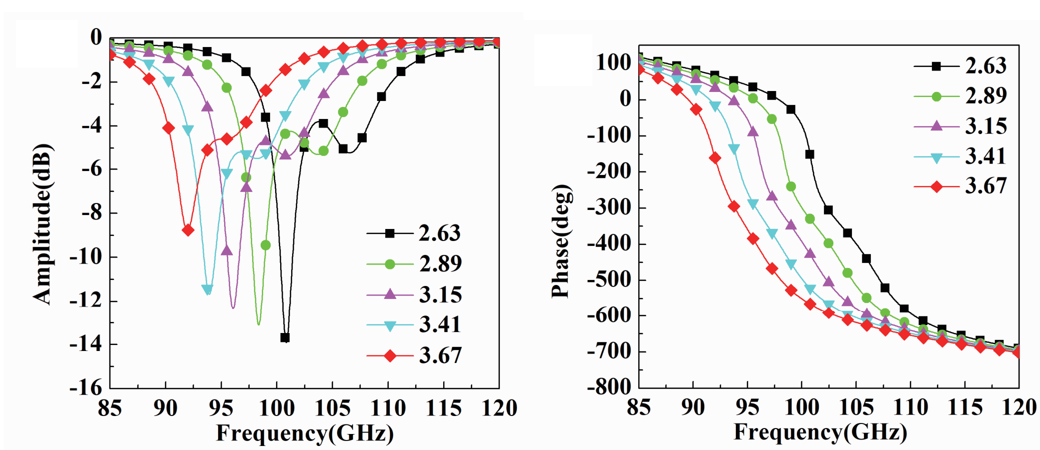
(a) (b)

Figure 1. Architecture of the LC-based phase shifter structure. (a) The 3D schematic diagram of the proposed phase shifter unit. (b) The front view of the unit cell.

of the LC molecules when no bias voltage is applied, the polyimide (PI) is spin-coated on the patches and ground plane as an alignment layer [18].

The parameters of the phase shifting unit cell presented in Figure 1(b) include p = 1090 µm, lxs = lxl = 150 µm, lx = 252 µm, lys = 738 µm, lyl=788 µm, hq = 480 µm, hlc = 65 µm, and hc = 0.5 µm. The LC material used in this phase shifter is HFUT-HB01 with $\varepsilon_\perp = 2.63$, $\tan(\delta_\perp)$ =0.02, $\varepsilon_\parallel = 3.67$, and $\tan(\delta_\parallel) = 0.015$ [19]. Initially, when no bias voltage is applied on LC, i.e., $V = 0$, the orientation of LC molecules is parallel to the metal ground plane due to the alignment imposed by the PI layer. We denote the initial permittivity of the LC substrate as $\varepsilon_\perp$. When we apply the bias voltage and it reaches saturation level, i.e., $V = V_{th}$, the LC molecules become parallel to the direction of electric field. At this stage, we denote the permittivity of the LC substrate $\varepsilon_\parallel$. Therefore, the tunable range of the LC permittivity is expressed as $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$.

Assuming that the unit cell is located in a periodic environment and illuminated by a y-polarized plane wave, the simulation is performed at an operation frequency of 90–140 GHz. Figure 2 shows the simulation results of the reflection amplitude and phase of LC-based phase shifter, when the permittivity varies in the range 2.63–3.67. As presented in Figure 2(a), the resonant peak gradually moves from 100.86 GHz to 91.9 GHz. Figure 2(b) shows the phase shift curve of the proposed device. We obtain the phase shift range of 360° for a 7 GHz bandwidth.



(a) (b)

Figure 2. The simulation results at different bias states of LC substrate permittivity. (a) Amplitude. (b) Phase.

In order to verify the performance of the proposed device in terms of phase shifting, we fabricate a prototype which consists of 30×30 cells. We print a copper patch pattern on the surface of a $4 \times 4\,\text{cm}^2$ Quartz plate, which is formed by means of evaporation, lithography, and other processes. The prototype and observations under a metallographic microscope are presented in Figure 3(a) and Figure 3(b).

Figure 3(c) shows the experimental environment and measurement system used in this work. When we apply a square wave of 1 kHz on the sample as a bias field, the phase and amplitude of the reflected wave for a different range of applied voltage amplitudes can be measured.

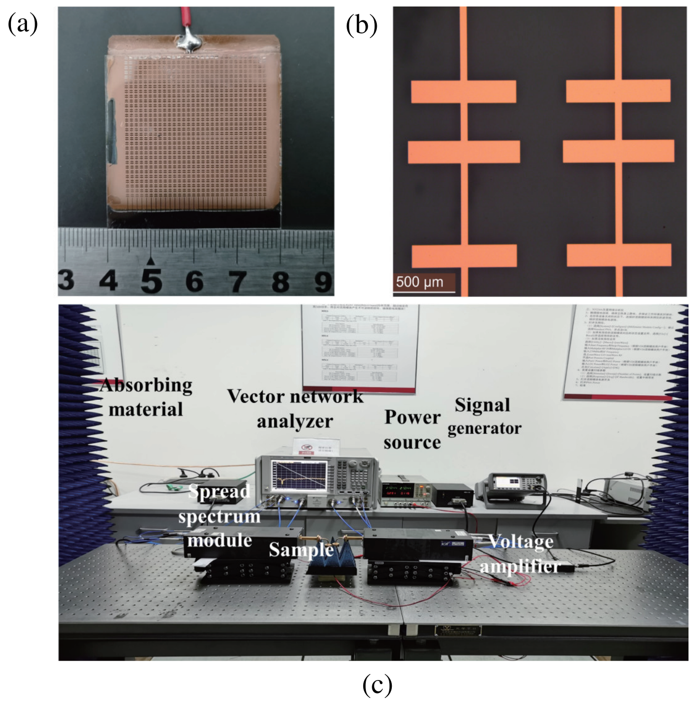


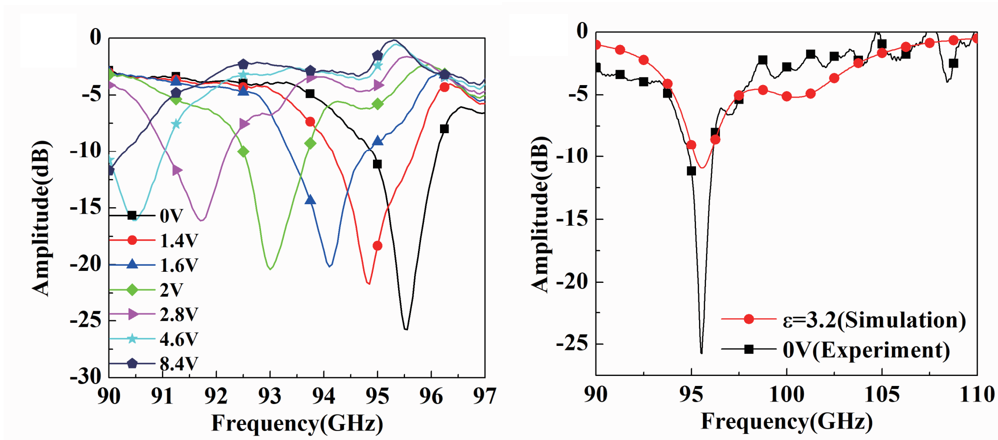
Figure 3. Manufacturing samples and test environment. (a) A photograph of the sample fabricated in this work. (b) The image of a unit cell under a metallographic microscope. (c) The experimental setup for performing measurements.

3. EXPERIMENTAL RESULTS AND NUMERICAL ANALYSIS

As shown in Figure 4(a), when the bias voltage is 0 V, the resonant peak is 95.55 GHz. It is notable that the measured resonant peak is left-shifted as compared to the peaks predicted in the simulation results. Due to testing constraints, we are unable to measure the data below 90 GHz. Since the thickness of the LC layer used in the proposed phase shifter is 65 μm, the region of LC substrate is inhomogeneous. Consequently, the initial permittivity of the LC is high. In Figure 4(b), we present the analysis of the experimental results of LC-based phase shifter by using the finite element method (FEM). The results show that the initial dielectric constant of the LC is 3.2. When the bias voltage applied on LC is 0 V, the resultant resonant peak obtained by measurement successfully matches the peak obtained in the simulations.

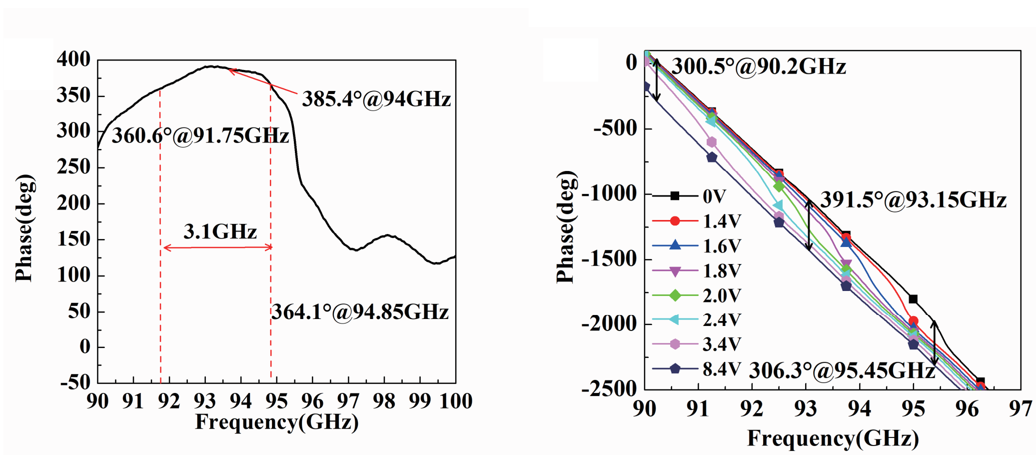
The max phase shift at different frequency points is shown in Figure 5(a). The proposed device realizes a phase shift greater than 360° within the range of 91.75–94.85 GHz, and a phase shift of 385.4° can be achieved at 94 GHz. The bandwidth above 360° reaches 3.1 GHz. According to the phase shift curve of different bias voltages in Figure 5(b), the device realizes a phase shift greater than 300° within the range of 90.2–95.45 GHz. The maximum phase shift is 391.5° at 93.15 GHz.

Usually, reflective array antennas consist of multiple elements. The distance from each element to the phase center is different. As a result, different phase compensations are required. It is noteworthy



(a) (b)

Figure 4. Measurement results for the amplitude of different bias voltages. (a) The variations in the amplitude. (b) A comparison of the simulation and experimental results of the initial state of LCs.



(a) (b)

Figure 5. Measurement results for the phase of different bias voltages. (a) The phase shift. (b) The variations in the phase when the bias voltage is changed.

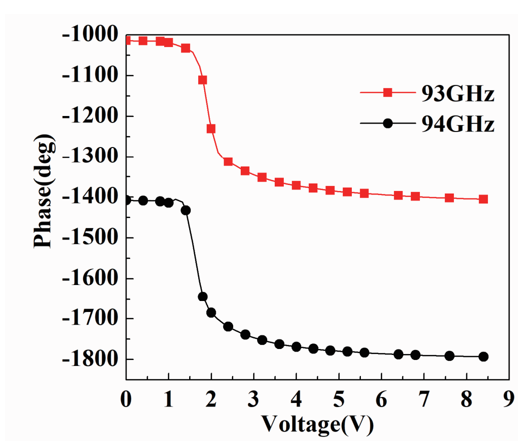


Figure 6. Phase as a function of the bias voltage.

that the tuning precision of the phase shifter plays a significant role in determining the precision of phase compensations required for each element of the array. This in turn has an effect on the beam scanning angle, gain, etc. of the antenna. Figure 6 illustrates the phase shift for different bias voltages at two different frequencies. The test results show that the changes in phase are most obvious when the bias voltage ranges between 1.85 V and 1.95 V. Therefore, in this work, we record the phase change of the phase-shifting unit at the minimum bias voltage that can be controlled by the signal generator. The experimental results are presented in Table 1, when the LC molecules are most significantly affected by the electric field, and the maximum precision of phase shift is 4.08° with a bias voltage of 2 mV. When the voltage increases from 1.904 V to 1.906 V, the resonant frequency point shifts left from 93.25 GHz to 93.2 GHz, and the effective dielectric constant of LC increases from 3.405 to 3.41.

Table 1. The relationship between the phase shift accuracy and the minimum applied voltage.

1.890 V–1.900 V (Step: 2 mV)								
Voltage (V)	1.886	1.888	1.890	1.892	1.894	1.896	1.898	1.900
Phase (deg)	−1230.13	−1230.62	−1232.09	−1235.14	−1236.40	−1238.21	−1239.78	−1243.86
Precision	/	0.4872	1.4660	3.0477	1.2661	1.8119	1.5697	4.0811

4. CONCLUSION

In this work, we design an LC-based double-dipole phase shifter at 94 GHz. We provide the simulated and measured results of the proposed device in detail. For the implementation of this work, we manufacture a 30×30 reflectarray prototype which exhibits phase shift in the range 91.75–94.85 GHz over 360°, when 0–8.4 V bias voltage is applied. We achieve a phase tuning mechanism by applying a range of different bias voltages, which regulate the effective permittivity of the LC layer. The experimental results show that the proposed phase shifter is capable of achieving a phase shift of 385.4° at 94 GHz, and the bandwidth above 360° can reaches 3.1 GHz. The maximum precision of phase shift is 4.08° with a bias voltage of 2 mV. The proposed phase shifter has the potential to be used in reconfigurable reflectarray antennas.

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