Electronically Tunable Liquid-Crystal-Based F-Band Phase Shifter

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ABSTRACT We propose an F-band phase shifter based on the nematic liquid crystals (NLCs). The proposed phase shifter is formed by a voltage-controlled cavity through introducing an NLC layer between a dipole structure array and a metal floor. Under the action of electric field, the orientation of the NLC molecules will be deflected. We adjust the resonant frequency and phase of the reflected electromagnetic (EM) wave by tuning the permittivity. The transmission characteristics and the LC parameters are calculated and analyzed for EM waves within the frequency range from 85 to 115 GHz. The LC-based device with a $30 \times 30$ array of two parallel unequal dipoles is printed on a quartz substrate, with $4 \text{ cm} \times 4 \text{ cm}$ area and $490 \mu\text{m}$ thickness. The experimental results show that phase shift of zero to 350.7° is achieved at 104.2 GHz by changing the applied bias voltage on the LC layer from 0 to 20 V. Considering the anisotropy and inhomogeneity of the LC, an improved electrification model is established and compared with the test results. The proposed phase shifter is expected to find several applications in millimeter wave and terahertz reconfigurable antenna systems.

INDEX TERMS Electrical control, F-band, liquid crystal, phase shifter.

I. INTRODUCTION

Over the past few years, the ever increasing applications of terahertz (THz) wave in aerospace, bio-sensing, wireless telecommunications, imaging, biomedicine and other fields have attracted extensive attentions [1]–[4]. However, with the development of reliable THz sources and detectors, one can not to reach to wider applications of THz waves without THz functional devices directly manipulating terahertz waves [5]. In recent years, several THz devices have been proposed such as modulators [6], filters [7], absorbers [8] and phase shifters [9]. Among these devices, phase shifters are the most critical components for the development of THz reflectarray antennas [10]. Currently, a variety of controllable phase shifting technologies have been proposed, including MEMS [11], flexible film metamaterials [12], ferroelectric films [13] and liquid crystals (LCs) [14]. Among these technologies, LCs are widely concerned for their excellent permittivity and wide tuning range in the THz band [15].

A microstrip reflectarray antenna is composed of a periodic set of resonator elements and a feed source. A phase shifter is used for each resonator element to adjust the scattering phase of each element to the incident wave, thereby realizing a beam-steering function [16], [17]. Conventional reflective array antennas achieve the phase compensation by controlling the structure of the resonance unit, and therefore, cannot provide a versatile beam-steering mechanism. As a tunable metamaterial, the molecular orientation of the nematic liquid crystals (NLCs) can be deflected by external electric or magnetic fields, thus changing their dielectric constants [18]–[21]. To take advantage of tunable properties of the LC permittivity, the dielectric substrate of the reflective phase shifter can be formed by liquid crystal materials. Thus, the phase of the reflected wave of each array unit can be controlled by an external electric field, thereby achieving continuous steering of the reflective array antenna beam. Recently, several LC-based phase shifters have been reported [22]. For example, an electrically tunable liquid LC shifter permeating NLCs into the resonant unit in the ka-band is proposed in [23]. In [24], a terahertz phase shifter with a phase-shifting
range of $2\pi$ was proposed possessing a response time of less than 1s. Perez-Palomino et al. proposed an LC phase shifter unit composed of three parallel dipoles at 100 GHz [25]. The LC phase shifter has a phase shift of $330^\circ$ at 104 GHz when the bias voltage reaches saturation. However, in order to achieve a larger beam scanning range for the reflective array antenna, the phase shifting capability of the phase shifter should be further improved.

This paper proposes a versatile tunable reflective phase shifter. The phase shifter is designed and experimentally verified at 100 GHz based on the electric tenability of the LC. The LC layer is filled between a reflective array composed of two parallel dipole patches and a metal ground plane. The dipole array is not only used to generate electromagnetic resonance, but also provides a bias voltage as the top electrode [26]. The proposed double dipole resonant unit has a lower driving voltage and can provide a larger phase tuning range compared to a single dipole. The test results show that the maximum phase shift that the device can provide is $350.7^\circ$, which is larger than the reported phase shifters in this frequency band. At 5 V bias voltage, it can provide a phase shift of $337.9^\circ$. Compared with existing reports, the device has a larger phase tuning range at 100 GHz.

II. DESIGN PROCEDURE

Fig. 1 (a) shows a 3D structure diagram of the proposed THz LC phase shifter. The phase shifter is a sandwich-like structure with quartz on the top as the upper substrate and LC on the metal floor as the substrate for the dielectric. The quartz under the metal floor supports the top electrode and encapsulates the LC. Furthermore, a copper pattern of two parallel dipole resonant unit is deposited on the lower surface of the quartz under the metal floor to induce the reorientation of the LC molecules. Once the bias voltage reaches to the saturation voltage, the orientation of the LC molecules becomes parallel to the direction of the electric field, and the permittivity of the LC reaches to the maximum value $\varepsilon_{//}$. Here, the tunable range of the LC permittivity is $\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$. Therefore, we can control the phase and amplitude of the resonance peak by applying the external electric field to adjust the dielectric constant within this range.

The LC phase shifter is analyzed using Finite Element Method (FEM) simulation under linearly polarized plane waves. The simulation assumes normal incidence of an $y$-polarization plane wave on the structure ($E$ parallel to dipole’s long edge) and the phase shift unit adopts the periodic boundary condition in the $x$-axis and $y$-axis directions, as shown in Fig. 1a. When the electromagnetic polarization direction is not parallel to the dipole, the device shows a very small phase shift and large loss. The conductivity of the copper used in the metal layer is $5.8 \times 10^7 \text{S/m}$. The upper and lower layers are both 490 um thick quartz, whose relative dielectric constant and loss tangent are $\varepsilon_{QL} = 3.78$ and $\tan(\delta_{QL}) = 0.002$. The specific parameters of the phase shifting unit cell, shown listed in Fig. 1(b) and Fig. 1(c), are as follows: $P_{x} = P_{y} = 1090 \mu m$, $L_{x1} = L_{x2} = 148 \mu m$, $L_{x3} = 253 \mu m$, $L_{y1} = 736 \mu m$, $L_{y2} = 786 \mu m$, $T_{q} = 480 \mu m$, $T_{p} = 60 \mu m$, $T_{i} \approx 90 \text{nm}$, and $T_{c} = 500 \text{nm}$. The LC mixture (HFUT-HB01) is filled inside the device, where the relative permittivity of the two limit states is as follows: $\varepsilon_{\perp} = 2.5$, $\varepsilon_{//} = 3.55$, $\tan(\delta_{\perp}) = 0.02$, and $\tan(\delta_{//}) = 0.02$ [28].

Variation of the amplitude and phase of the reflection coefficient of the LC phase shifter versus the permittivity is given in Figs. 2(a) and 2(b). It may be seen from Fig. 2(a) that, by increasing the permittivity of the LC from 2.5 to 3.55, its resonant peak gradually moves from 102.8 GHz to 93.1 GHz.
Fig. 2(b) shows the phase shift curve of the proposed device, where the maximum phase shift of 516° is achieved at 100.8 GHz.

In order to further verify the phase-shifting performance of the tunable device, the device is manufactured. First, a metal layer and a double dipole array structure are formed on the surface of the quartz substrate by means of evaporation, lithography and other processes. In order to align the LC, a layer of polyimide(PI) needs to be spin-coated on the surface of the quartz substrate and rubbed with a soft brush. Then, both edges of the upper and lower substrates were sealed with ultraviolet (UV) curable adhesive containing spaced microspheres of 60 µm. The diameter of the spaced balls determined the distance between the upper and lower substrates. Finally, the NLC material is injected into the LC cell and sealed again with UV glue. The fabrication process is characterized by the fabrication error of ±3 um, which is acceptable for the lithography process. Figure 3(a) shows the fabricated prototype, which is an array composed of 30 × 30 phase-shifting units. Figure 3(b) is a unit cell image of the sample under a metallographic microscope. The test equipment used to characterize the fabricated sample is shown in Fig. 3(c). The sample size is 4 cm × 4.4 cm, which is placed in a hole dug in the absorbing material. The spectral response of the sample is tested at the room temperature by a vector network analyzer (Agilent N5224A), an F-band module extender (N5262AW08) and two horn antennas (the frequency range is 90-140 GHz, the 3 dB bandwidth is 12 degree, and the gain is 21 dB). The $S_{21}$ of the vector network analyzer is the electromagnetic wave reflected from the sample. In addition, a 1 KHz square wave is used as the bias field during the measurement.

III. EXPERIMENTAL RESULTS AND NUMERICAL ANALYSIS

Fig. 4 shows the measurement results of the reflection coefficient of the double dipole phase shifter under different bias voltages. The device is designed assuming that the element is located in a periodic environment and is irradiated by linear polarization and normal incident plane wave. In fact, the bandwidths and phase shift of the device is reduced because the sample is not irradiated by the ideal linearly polarized wave during measurement and the sample size is limited.

As shown in Fig. 4(a), under the square wave bias voltage of 1 KHz, the amplitude and phase of 0 to 20 V reflected wave were measured. As the bias voltage gradually increases from 0 to 20 V, the resonant frequency shifts from 103.2 GHz to 93.5 GHz. The two extreme values of LC permittivity appear in 0 V and 20 V respectively. According to the phase shift curve of different bias voltages in Fig. 4(b), the device realizes a phase shift greater than 300° within the range of 103.5-106.1 GHz. The maximum phase shift was 350.7° at 104.2 GHz. Fig. 4(c) illustrates the phase shift under different bias voltages at three frequencies. The discrepancy of frequency and phase shift between measurement and simulation is mainly caused by the following reasons.
First, the dimensional error during the processing. Second, the anisotropy and inhomogeneity of the LC are not precise considered in simulation. Because the dipole patches are not enough to cover the entire LC surface in the device, it results in an uneven electrostatic field distribution. The uneven biased field causes non-uniformity in the LC and phase simulation error. In addition, due to the path loss, scattering loss and receiving loss during the test, the amplitude of the reflection coefficient of the test results is less than calculated value. If there is a large amplitude variation in the continuously tuned reflected wave, we can be avoided by selecting the appropriate tuning point or reducing the tuning range. The interplay between amplitude and phase modulation needs careful design [29].

One of the main advantages of LC-based devices is their low driving voltage. Table 1 shows the phase shift value at this frequency point under different bias voltages. Fig. 5 plots the variation of the phase shift at the maximum phase shift point 104.2 GHz.

**TABLE 1.** Values of phase shift at 104.2 GHz under different bias voltage.

| Voltage (V) | Phase Shift (deg) |
|------------|-------------------|
| 0          | 0                 |
| 1          | 3.7               |
| 1.2        | 10.8              |
| 1.4        | 23.9              |
| 1.6        | 43.6              |
| 1.8        | 67.9              |
| 2          | 132.8             |
| 2.2        | 253.7             |
| 2.4        | 283               |
| 2.6        | 299.7             |
| 2.8        | 310.4             |
| 3          | 326.6             |
| 5          | 337.9             |
| 20         | 350.7             |

**FIGURE 4.** Measurement results for the reflection coefficient of the double dipole phase shifter for different bias voltages. (a) Variation of the amplitude and resonance frequency versus the bias voltage. (b) Variation of the phase versus the bias voltage. (c) Phase as a function of the bias voltage.

**FIGURE 5.** The variation of the phase shift versus the bias voltage at 104.2 GHz.
FIGURE 6. Simulation results considering the reflection coefficient of liquid crystal anisotropy and heterogeneity. (a) Amplitude. (b) Phase.

with the bias voltage. By increasing the bias voltage from 0 V to 5 V, the phase is drastically changed as the bias voltage is not yet saturated. At a bias voltage of 5 V, the phase shift is 337.9°. As the bias voltage gradually increases from 5 V to 20 V, the LC molecules reach to the maximum deflection state, and the phase change tends to be gentle. The results show that the proposed device can still provide a wide phase tuning range at lower driving voltages.

In order to evaluate the introduced phase error without considering the anisotropy and inhomogeneity of the LC, we establish an improved model based on the principle proposed by G. Perez-Palomino et al. [30], [31]. According to the Palomino’s theory, the LC layer is divided into several regions as shown in Fig. 6 during the modeling process. The regions (NN) below and between the double dipole, where the electric field is strong, and the permittivity of the region is considered as ε∥. The electric field in the V region far from the dipole patch is weak, and the value of the dielectric constant is considered as ε⊥. Ni (i = 1, 2, 3, 4) is located between two dipoles and the edge of the cell, and the electric field is in the state of the electrified unsaturation. Hence, this region is non-uniform and divided into four sub-regions in modeling, where the LC molecules in each sub-region are homogeneous. Fig. 6 shows the comparison between the common model and the accurate model in two limit states. It can be seen from Fig. 6 that under the influence of the anisotropy and non-uniformity of the LC, the tuning range of the dielectric constant of the liquid crystal has decreased. In Fig. 6(a), the resonance points of the improved model are between the resonance points of the common model. This indicates that the tuning range of the dielectric constant of the LC is less than that set in the simulation above. Naturally, there is an error in the phase shift.

The results in Fig. 6(b) show that the maximum phase shift of the improved model is 398° at 100.8 GHz, and the anisotropy and inhomogeneity of the LC layer introduce a phase error of 118° compared to the common model. By comparing the accurate model with the measured results, we achieve the phase error of -47.3°.

The infinite period structure can be used for the preliminary design and optimization of the reflection characteristic. In order to reduce the phase error, a more accurate physical model needs to be used in the simulation, such as setting different liquid crystal parameters in different frequency bands. In addition, the measurement results can be better predicted by simulating a finite reflector array (the same size as the measured sample with quartz). The phase error also comes from the fabrication tolerance and the test accuracy. In the measurement, the device is not illuminated by the ideal linear polarization wave, and the size of the reflection array doesn’t satisfy the infinite periodic boundary condition, so the bandwidth and phase shift of the device are reduced. The output power of THz mixer is lower at a higher frequency. So the measurement is very sensitivity to noise and to the small change of environment. The processing precision of the sample should be improved and the quasi-optical system should be introduced in the test.

IV. CONCLUSION

We have proposed a tunable THz phase shifter based on the NLC. The full-wave simulation and experimental results of the proposed phase shifter is provided. A phase tuning mechanism is achieved by applying different bias voltages, regulating the effective permittivity of the LC layer. Experimental results show that the proposed phase shifter is capable of providing a phase shift of 350.7° at 104.2 GHz. Under the driving voltage of 5V, the phase adjustment range of the device is 337.9°, which is sufficient to provide a wide range of phase adjustment, so only sub-milliwatt power consumption is required. To reduce the phase error caused by the anisotropy and inhomogeneity of the LC layer, an accurate model is established based on the Palomino’s theory. In comparison to the ordinary model, the analytical results are more accurate. The device is expected to be widely applied to THz reflective array antenna systems.
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