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Electrically Tunable Room-Temperature 2π Liquid Crystal Terahertz Phase Shifter

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***Abstract*—Tunable phase shift up to 360° at 1 THz is demonstrated using electrically controlled birefringence in a vertically aligned nematic liquid crystal (E7) cell, 1.83 mm in thickness. The driving voltage and corresponding field required for a phase shift of 360° at 1 THz are 100 V and 90.5 V/cm, respectively.**

***Index Terms*—Liquid crystal (LC) devices, submillimeter wave phase shifters, tunable circuits and devices, ultrafast optics.**

I. INTRODUCTION

RECENTLY, terahertz (THz) technology and its applications have advanced rapidly [1]–[3]. Nonetheless, essential quasi-optic components such as tunable THz phase shifters are relatively under-developed. Several groups have demonstrated tunable phase shifters based on optically or electrically controlled carrier concentration in quantum-well structures [4]–[6]. These quantum-well-based THz phase shifters, however, have limited range of tunability and in general need to be operated at temperatures far below room temperature [4], [5]. Using magnetically controlled birefringence [7], [8] in a sandwiched dual nematic liquid crystal (NLC) cell, 3 mm in total thickness, a tunable room-temperature THz phase shifter capable of more than 360° of phase shift at 1 THz was realized [9], [10]. Following initial demonstration of less than 5° of phase shift in a homogeneously aligned 38.6-μm-thick NLC cell [11], we recently report electrically tunable phase shifts beyond 90° at 1 THz in a homeotropically aligned 570-μm-thick NLC cell driving at 125 V or 105 V/cm [12]. The operation of the device as a THz quarter-wave plate was also verified. Scaling of the electrically tuned liquid crystal (LC) phase shifter from 90° of phase shifter to 360° is not straightforward, however. It would require an NLC cell about 2 mm in thickness. For such thick cells, alignment of LC molecules in the bulk of the cell is not assured. The uniformity of electric field within the thick cell is also a concern. In this work, we demonstrate that the LC tunable terahertz phase shifter can indeed be scaled by increasing the cell thickness up to nearly 2 mm. Tunable phase shift up to 2π at 1 THz is realized.

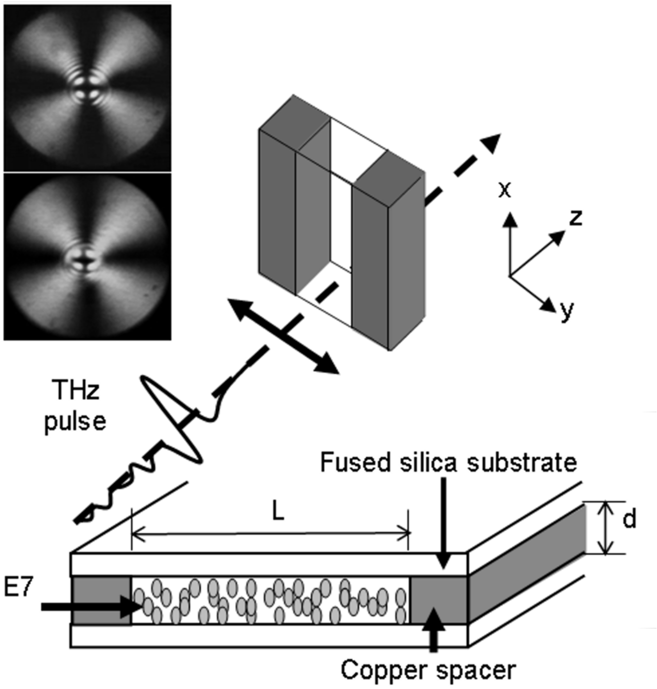

Fig. 1. Schematic drawing of the electrically tunable LC 2π THz phase shifter. Conoscopic patterns of 1.5-mm (upper inset) and 2-mm (lower inset) LC cells are shown. (Color version available online at http://ieeexplore.ieee.org.)

II. DESIGN AND OPERATION PRINCIPLES

The configuration of this device is shown in Fig. 1(a). The cell was constructed by sandwiching the E7 (Merck) layer between two fused silica substrates. Two copper pieces (purity of 99.94%) worked both as spacers and electrodes for the cell. They were parallel to each other and separated by $L = 11.0 \pm 0.3$ mm. The substrates were coated for vertical or homeotropic alignment [13]. The thickness d of the E7 layer is 1.83 mm. A square-wave ac voltage at 1 kHz was applied to the electrodes to avoid domain formation. The applied voltages quoted in this letter are all root-mean-square values.

The vertical alignment is confirmed by conoscopic measurements as shown in the inset of Fig. 1. Up to a cell thickness of 1.5 mm, the cell is well-aligned (top inset of Fig. 1). Although characteristic brushes and interference fringes can still be seen for the 2-mm-thick cell (lower inset of Fig. 1), the center part of the pattern changes slowly with time. The 1.83-mm-thick cell used in this work is near the limit of good alignment. This is sufficient for device application demonstrated in this work. The phase shifting properties of this device was characterized by

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a photoconductive-antenna-based THz time-domain spectrometer [14]. The measurements were done at room temperature (23 ± 0.5 °C).

The usual analysis of electrically controlled birefringence of an NLC cell used applied voltage. It implied that the expression $V = \mathrm{EL}$ is a good approximation. Because of the thick cell used in this work, the uniformity of the electrical field is a concern. We have, thus, taken a more general approach and formulated phase shift as a function of electrical field.

The threshold field (the Fréedericksz transition) required for reorienting the E7 molecules in the bulk of cell will be reoriented toward the applied electric field is $E_{\mathrm{th}} = (\pi/d)(k_3\varepsilon_a\varepsilon_0)^{1/2}$, where $k_3, \varepsilon_a = \varepsilon_{\|} - \varepsilon_{\perp} > 0$ and ε_o are the bend elastic constant, dielectric anisotropy, and electric permittivity of free space, respectively. For our device, we calculated that $E_{\mathrm{th}} = 6.4$ V/cm, with $d = 1.83$ mm, $k_3 = 17.1 \times 10^{-12} N$, and $\varepsilon_a = 13.8$ (from Merck). The phase shift $\delta(E)$ experienced by the THz beam transmitted through the cell biased at an electric field E is given by

$$\delta(E) = \int_0^d \frac{2\pi f}{c} \Delta n_{\mathrm{eff}}(E, z) dz \tag{1}$$

where f is the frequency of THz wave, c is the speed of light in vacuum, and $\Delta n_{\mathrm{eff}}(E, z)$ is the change of effective birefringence for NLC at a position z along the propagation direction of the THz beam. The effective birefringence can be written as

$$\Delta n_{\mathrm{eff}} = \left(\frac{\cos^2\theta}{n_o^2} + \frac{\sin^2\theta}{n_e^2}\right)^{-\frac{1}{2}} - n_o \tag{2}$$

where n_o and n_e are ordinary and extraordinary indices of refraction of NLC and θ is the reorientation angle of NLC molecules from the initial orientation. For $E > E_{\mathrm{th}}$, the angle θ at any point z in the cell can be computed using the relation [13]

$$\frac{z}{d} = \frac{E_{\mathrm{th}}}{\pi E} \int_0^\theta \left(\frac{1 + q\sin^2\theta}{\sin^2\theta_m - \sin^2\theta}\right)^{\frac{1}{2}} d\theta \tag{3}$$

where $q = (k_1 - k_3)/k_3$, and $k_1 (= 11.1 \times 10^{-12} N$ for E7) is the splay elastic constant of NLC. The angle θ_m is the maximum reorientation angle located at $z = d/2$. It is related to E/E_{th} by

$$\frac{E}{E_{\mathrm{th}}} = \frac{2}{\pi} \int_0^{\theta_m} \left(\frac{1 + q\sin^2\theta}{\sin^2\theta_m - \sin^2\theta}\right)^{\frac{1}{2}} d\theta. \tag{4}$$

In a uniform electric field approximation, E can be written as V/L. Equations (3) and (4) allow us to calculate the profile of molecular orientation in the cell for a given applied electric field [13].

III. RESULTS AND DISCUSSION

The temporal waveforms of the THz pulse transmitted through an empty cell and the device at several applied voltages are shown in Fig. 2.

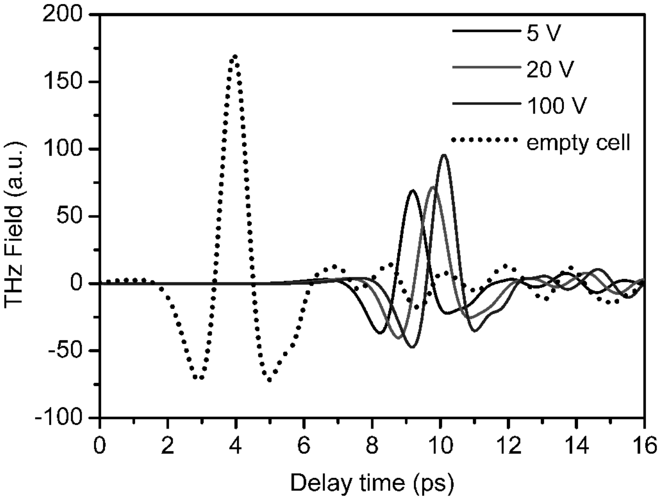

Fig. 2. Temporal waveforms of the THz pulse transmitted through the empty and LC cell at various applied voltages. (Color version available online at http://ieeexplore.ieee.org.)

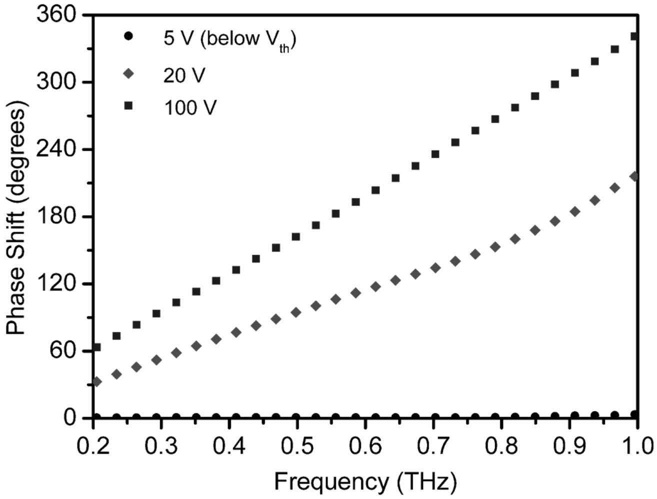

Fig. 3. Spectral phase shift for several driving voltages of the NLC cell. (Color version available online at http://ieeexplore.ieee.org.)

The dispersion of the LC cell due to the LC layer and fused silica substrates are negligible in the THz range. Transmittance of the LC cell was 34% for e-ray. Scattering and absorption account for the attenuation of the 1.8-mm-thick LC cell. The transmitted THz pulses exhibit clearly larger delay and higher peak field at higher applied voltages. This trend is explained by taking into account Fresnel reflections at the two interfaces between NLC layer ($n_o = 1.62, n_e = 1.79$ at 0.3 THz) [9] and quartz substrate ($n = 1.95$ at 0.3 THz). The theoretically calculated value was 1.11, assuming an ideal plane wave and neglecting scattering losses.

The transmitted THz spectra are deduced from the temporal profiles of the THz pulse with fast Fourier transform algorithms. The spectral phase shifts can then be determined. According to (1), a larger phase shift is expected at higher frequencies. This is confirmed in Fig. 3, in which we plot the phase shifts from 0.2 to 1.0 THz by varying the driving voltages. For a given voltage,

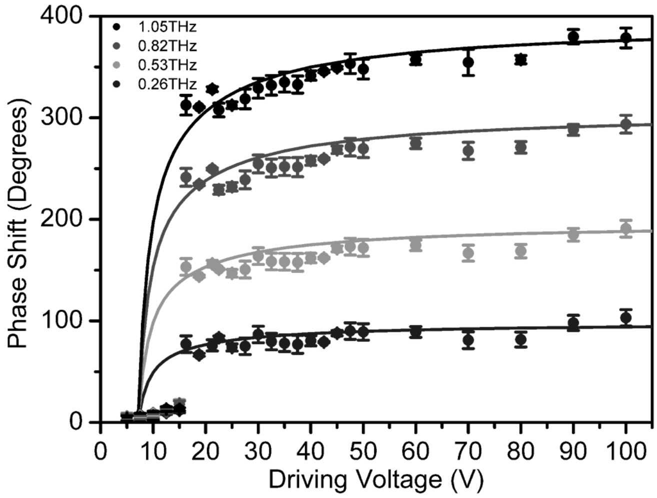

Fig. 4. Phase shift as a function of driving voltage for four frequencies. The curves are theoretically predicted phase shifts. (Color version available online at http://ieeexplore.ieee.org.)

the measured phase shift varied linearly with frequency, with a slope of 346.8°/THz at 100 V.

Fig. 4 shows the phase shifts as a function of driving voltage. Over 360° of phase shift was achieved at 1.0 THz when the cell was driven at 100 V or 90.5 V/cm. The theoretically predicted phase shift is 376°. The curves are theoretical predictions according to (1)–(4). Far above threshold, the NLC molecules are essentially aligned with the electrical field. The theoretical curves are in good agreement with the experiments. For applied voltage near and about threshold, the theoretical phase shift values tend to be larger than those of the experimental ones. The experimental threshold voltage and the corresponding field were found to be 16.3 V and 14.7 V/cm, respectively, higher than the theoretically predicted values, 7.1 V and 6.4 V/cm. This is reasonable, as the actual electric field reorienting the NLC molecules in the thick cell is lower than the average electric field given by V/L. We have calculated the field distribution in our device using FEMLab (a finite-element software by COMSOL, Inc.). Within more than 80% of the 1.0-cm-diameter THz beam area, the actual electric field is smaller than the average electric field. At the center of the cell, the actual electric field is 95% of V/L. Because the average electric field is used in the theoretical calculation, the theoretical phase shifts according to (1)–(4) will be larger than the experimental values. Furthermore, there are significant slow fluctuations of the NLC director for E smaller than or near E_{th} and a cell thicker than 1.5 mm. This is confirmed by long-term monitoring of the conoscopic pattern of the LC cell thicker than 1.5 mm. For $E > E_{\mathrm{th}}$, this is not so severe as the molecules are forcefully aligned along the direction of the applied electric field.

Although the electrically controlled NLC THz phase shifter has many advantages, we should point out that it is difficult to tune the desired phase shift accurately near the threshold. Further, the response of the device is slow, due to its thickness. It is, thus, not suitable for applications that require fast modulation. Instead, the device is excellent for instrumentation or apparatus that require a fixed phase with occasional fine tuning.

Equations (1)–(4) provide the needed mathematics for designing the LC THz phase shifter. First, an LC with large birefringence and acceptable loss in the frequency of interests is chosen. Using Δn, required d for the desired maximum phase shift is estimated. Cell thickness should fall within the range of acceptable thickness for good LC alignment. The threshold field and the phase shift versus operating voltage are calculated, as illustrated in Fig. 4.

IV. CONCLUSION

In summary, we have demonstrated an electrically tuned 2π THz phase shifter by using a 1.83-mm-thick vertically aligned NLC cell. A maximum phase shift of 360° at 1 THz has been achieved by using electrically controlled birefringence in an NLC driven at 100 V or 90.5 V/cm. The phase shift can be tuned electrically by controlling the effective refractive index of NLC layer. Measured results are in agreement with theoretical predictions.

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