Liquid-Crystal-based Electrically tunable THz Optical devices

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ABSTRACT

In this work, we report recent progress in liquid-crystal-based electrically tunable THz optical devices. 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. A sandwiched NLC cell about 2 mm in total thickness is used to increase the interaction length while minimizing Fresnel losses at the interfaces. A phase shift of 367º is demonstrated at 1.05 THz, significantly improving the dynamic response of the device.

Keywords: THz, Liquid-crystal devices, far Infrared, phase shifters

1. INTRODUCTION

In recent years, remarkable progress has been made in Terahertz (THz) photonics. With the development of solid-state femtosecond lasers and advanced optoelectronic THz-devices, a new era of fundamental and applied THz science is opening up. THz studies ranging from investigations of ultrafast dynamics in materials to medical, environmental sensing and imaging are actively explored.[1-3] For these and future applications in THz communication and surveillance, quasi-optic components such as phase shifters, modulators, attenuators and polarizers are indispensable. The large birefringence of liquid crystals in the visible is well known and has also been employed successfully for phase shifting of microwave and millimeter wave signals previously.[4] In the THz frequency range, we have shown that a nematic liquid crystal (NLC) 4'-n-pentyl-4-cyanobiphenyl (5CB) exhibits relatively large birefringence (~ 0.2) and small extinction coefficient at frequencies around 1 THz.[5,6] We recently demonstrated the first tunable room-temperature THz phase shifter capable of more than 360° of phase shift at 1 THz.[7,8] The device was based on magnetically controlled birefringence in a sandwiched dual NLC cell, 3 mm in thickness. Nonetheless, electrically controlled phase shifters are deemed desirable for many applications. A maximum phase shift of 4.07° was achieved at 1.07 THz when the interaction length was 38.6 μm in a homogeneously aligned NLC cell.[9] The driving voltage and corresponding field were 177 V and 589 V/cm, respectively. More recently, we report electrically tunable phase shifts beyond 90° at 1 THz in a homeotropically aligned 570 μm-thick NLC cell.[10] The operation of the device as a THz quarter-wave plate was verified. The experimental results were in good agreement with calculations using the continuum theory of the NLC. In our latest work, we demonstrate that the LC tunable THz 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.[11] The minimum thickness of the NLCs layer required to achieve a 2π phase shift at 1.00 THz would be 1.5 mm. This presents a problem, as alignment of the NLC becomes difficult with such thick cells.

In this work, we report recent progress in liquid-crystal-based electrically tunable THz optical devices. 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. A sandwiched NLC cell about 2 mm in total thickness is used to increase the interaction length while minimizing Fresnel losses at the interfaces. A phase shift of 367º is demonstrated at 1.05 THz, significantly improving the dynamic response of the device..

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2. DESIGNS AND OPTERATION PRINCIPLES

A schematic of the experimental setup is shown in Fig. 1. The key element is a homeotropically aligned nematic liquid crystal (E7 by Merck) single or sandwiched cell.

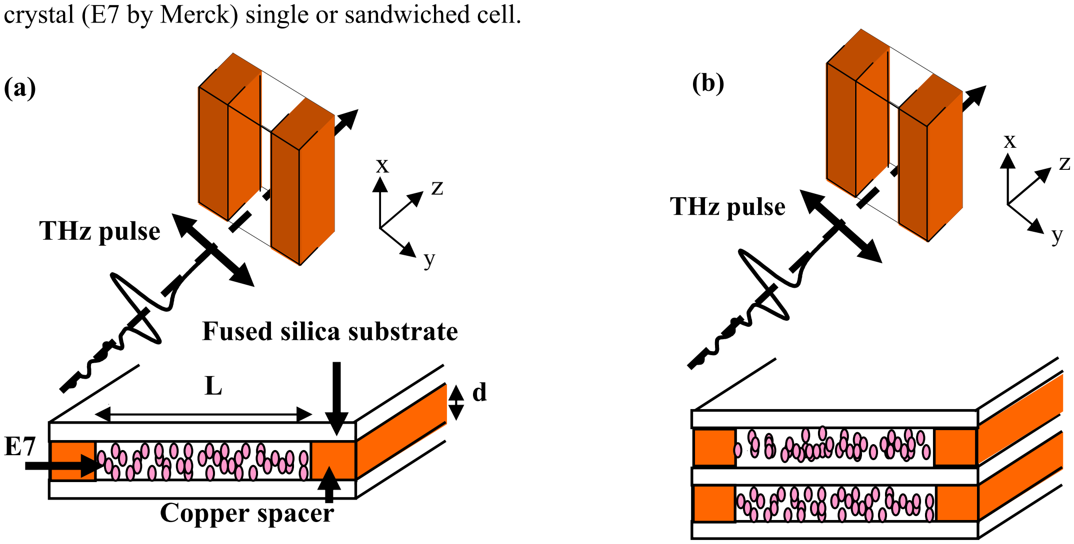
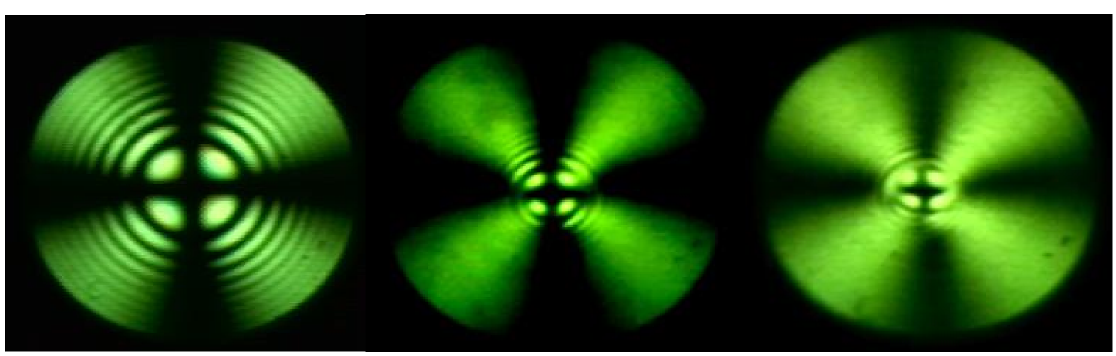


Fig. 1 Schematic drawing of the electrically tunable liquid crystal THz phase shifter. The THz wave propagation and polarization directions are z and y, respectively. (a) The cell with one layer of E7, and (b) the sandwiched cell with two layers of E7.

In Fig. 1(a), the thicknesses of the E7 layer is 1830 m for achieving a phase shift of 2π. In Fig. 1(b), the thickness of each E7 layer is 1012 μm. Vopper pieces (purity of 99.94%) were used both as spacers and electrodes for the cell. They are parallel to each other and separated by 10.2±0.3 mm. The substrates were coated with N,N-dimethyl-N-octadecyl- 3-aminopropyltrimethoxysilyl chloride (DMOAP) for vertical or homeotropic alignment.

It can be readily seen that an NLC cell about 2.0 mm in thickness would be required to obtain phase shifts of 2π at 1.00 THz. 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. To study the alignment effects induced by DMOAP-coated substrates on NLC molecules in such thick cells, a series of cells with different spacing was fabricated and visually checked using conoscopy. The conoscopic patterns for the homeotropic aligned NLC cells with spacing of 0.44 mm, 1.64 mm, and 2.10 mm are shown in Fig. 2 (a), (b), and (c) respectively.



(a) (b) (c)

Fig. 2 Conoscopic patterns of 0.44-, 1.64- and 2.10-mm LC cells are shown in (a), (b) and (c), respectively.

The stripe-like patterns in Fig. 2 are due to the phase difference between the ordinary and extraordinary rays with respect to the optical axis of NLC molecules at different incident angles. Up to a cell_thickness of about 1.5 mm, the cell is well-aligned. Although characteristic brushes and interference fringes can still be seen for the 2.10 mm-thick cell

(Fig. 2(c)), the center part of the pattern changes slowly with time. Thus NLC cells with thickness smaller than 1.5 mm is more practical for applications of LC-based devices in the THz frequency range. The 1.83mm-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 a photoconductive-antenna-based THz time-domain spectrometer (THz-TDS).[13] 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 = 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 $E_{th}=(\pi/d)(k_3/\varepsilon_a\varepsilon_0)^{1/2}$, where k_3, $\varepsilon_a = \varepsilon_{\parallel} - \varepsilon_{\perp} > 0$ and ε_o are the bend elastic constant, dielectric anisotropy, and electric permittivity of free space, respectively. For our device, we calculated that E_{th} = 6.4 V/cm, with d=1.83 mm, k_3=17.1×10^{-12}N and ε_a=13.8 (from Merck). For the sandwiched E7 cell, we calculated that E_{th} = 11.62 V/cm).

The phase shift, $\delta(E)$, experienced by the THz beam transmitted through the cell biased at an electric field E is given by

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

where f is the frequency of THz wave, c is the speed of light in vacuum and $\Delta n_{eff}(E,z)$ 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

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

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 $E>E_{th}$, the angle θ at any point z in the cell can be computed using the relation[14]

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

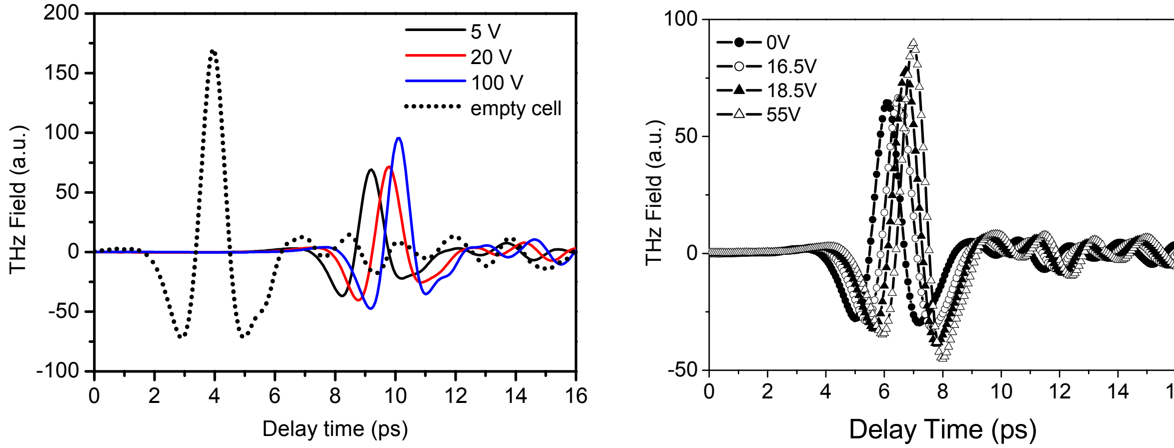
where $q=(k_1-k_3)/k_3$, and k_1 (= 11.1×10^{-12} N for E7) is the splay elastic constant of NLC. The angle θ_m is the maximum reorientation angle located at $z = d/2$. It is related to E/E_{th} by

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

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.[14]

3. RESULTS AND DISCUSSIONS

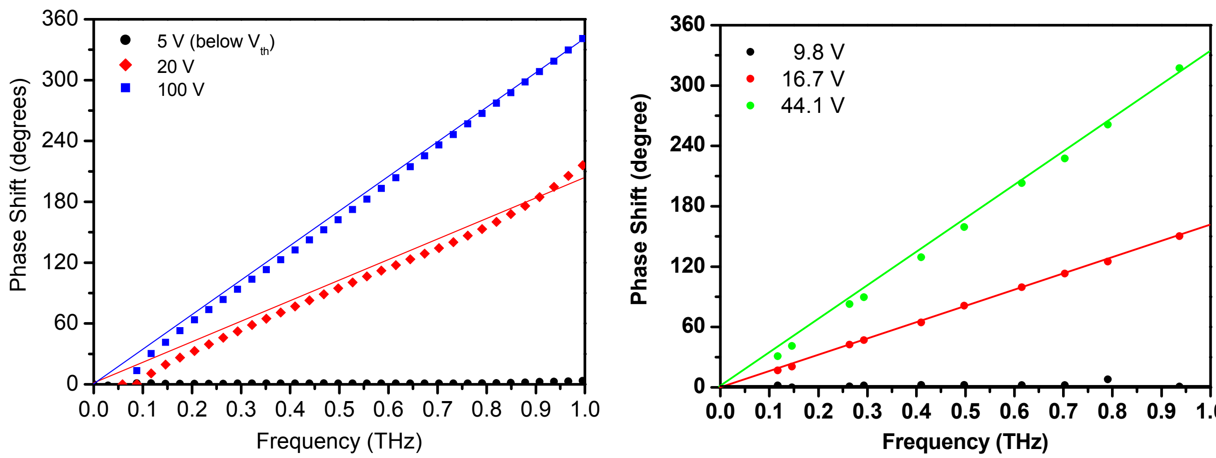
The temporal waveforms of the THz pulse transmitted through an empty cell and the single 1.83-mm-thick cell at several applied voltages are shown in Fig. 4(a). Similar curves are plotted for the sandwiched cell in Fig. 4(b). The dispersion of the LC cell due to the LC layer and fused silica substrates are negligible in the THz range. Transmittance of the LC cell was 34% for e-ray. Scattering and absorption account for the attenuation of both the 1.8mm-thick single LC cell as well as the sandwiched cwll. 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) and quartz substrate (n = 1.95 at 0.3 THz). The experimentally measured ratio of power transmittance for e-ray and o-ray is 1.37, which is almost identical to the theoretically calculated value of 1.03 for the sandwiched cell in Fig. 4(b).



(a) (b)

Fig. 4 The temporal waveforms of the THz pulse transmitted through the (a) single and (b) sandwiched LC cells at various applied voltages.

The transmitted THz spectra are deduced from the temporal profiles of the THz pulse with fast Fourier transform (FFT) algorithms. The spectral phase shifts can then be determined. According to Eq. (1), larger phase shift is expected at higher frequencies. This is confirmed in Fig. 5(a) for the single cell, in which we plot the phase shifts from 0.2 to 1.0 THz by varying the driving voltages. For a given voltage, the measured phase shift varied linearly with frequency, with a slope of 346.8°/THz at 100 V. Similarly, the measured phase shift versus frequency for the phase shifter with sandwiched cell is given in Fig. 5(b), with a slope of 362.6/THz at 45 V or 44.1 V/cm. Examining Fig. 5, clearly the phase shifter with sandwiched cell exhibits better linearity. Presumably this is due to better aligned liquid crystal molecules in the thinner cells in the latter case.



(a) (b)

Fig. 5 The spectral phase shift from 0.2 to 0.8 THz for several driving voltages of the (a) single and (b) sandwiched NLC cells.

Figure 6 shows the phase shifts as a function of driving voltage for the single 1.8-mm cell and the sandwiched cell, respectively.

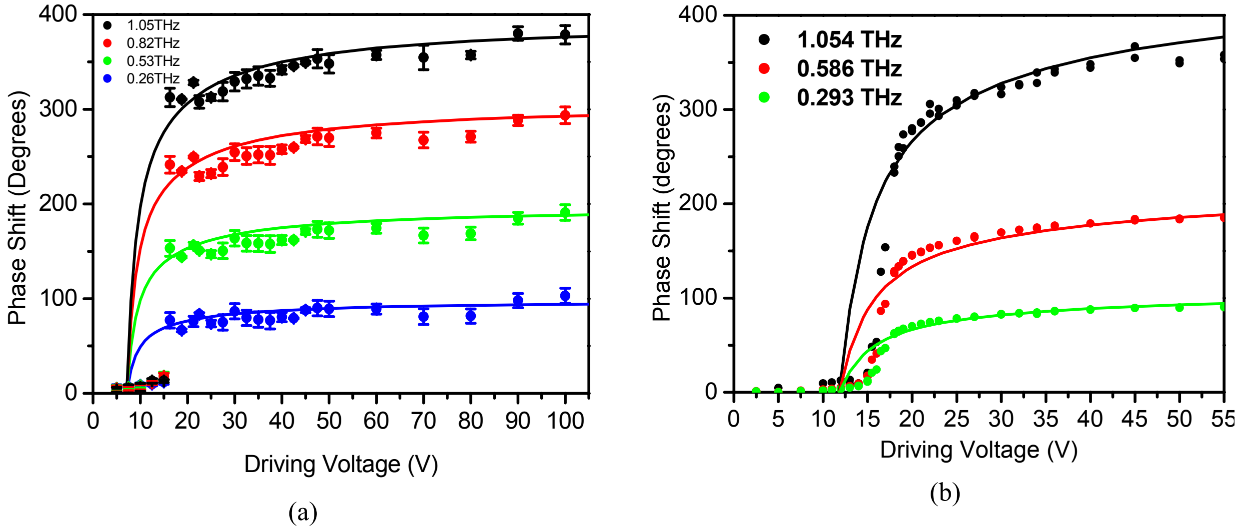


Fig. 6 The phase shift as a function of driving voltage for the single 1.8 mm-thick cell (a) and the sandwiched cell (b) at several frequencies. The curves are theoretically predicted phase shifts.

Over 360° of phase shift was achieved at 1.0 THz when the single 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 agreements 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 $E>E_{th}$, this is not so severe as the molecules are forcefully aligned along the direction of the applied electric field.

Similarly, a maximum phase shift of 367° was achieved at 1.05 THz when the sandwiched cell was driven at 44.1 V/cm. The theoretically predicted phase shift was 363.9°. The threshold field was found to be 13.73 V/cm, in fair agreement with the theoretically predicted value, 11.62 V/cm.

4. SUMMARY

We present recent progress in electrically-controlled liquid crystal THz optical devices from our group. An electrically tuned 2π THz phase shifter was realized by using a sandwitched-vertically aligned NLC cell with two layers each of a thickness, d=1.012 mm. A maximum phase shift of 367° was achieved at 1.05 THz when the cell was driven at 44.1 V/cm. The theoretically predicted phase shift was 363.9°. The threshold field was found to be 13.73 V/cm, in fair agreement with the theoretically predicted value, 11.62 V/cm . In comparison, a 2π THz phase shifter using a 1.83-mm-thick LC layer requires a driving field of 90.5 V/cm. The phase shift can be tuned electrically by controlling the effective refractive index of NLC layer. Further, the response of the device scales with the square of its thickness. In principle, the sandwiched structure should respond much faster. Measured results are in agreement with theoretical predictions.

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