Electrically Controlled Room Temperature Terahertz Phase Shifter With Liquid Crystal

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***Abstract*—We present the use of electrically controlled birefringence in a nematic liquid crystal cell for phase shifting of electromagnetic waves up to terahertz frequencies. This device was operated at room temperature and a maximum phase shift of 4.07° was demonstrated at 1.07 THz when the interaction length was 38.6 μm. The driving voltage and corresponding field were 176.8 V (rms) and 589.3 V/cm, respectively.**

***Index Terms*—Liquid crystals, phase modulation, phase shifter, terahertz.**

I. Introduction

During the last two decades, submillimeter wave or terahertz (THz) technology has undergone remarkable growth with intense interests for their applications in time-domain far-infrared spectroscopy [1], [2], terahertz imaging [3] and terahertz ranging [4]. For these and future applications in THz communication and surveillance, quasioptic components such as phase shifters, modulators, attenuators and polarizers are indispensable. Recently, Libon *et al.* [5] demonstrated a tunable THz phase shifter based on optically induced change of the GaAs quantum well structure from a dielectric to a conducting material. Owing to their Lorentz-type dielectric function, parabolic quantum well structure has been used to enable efficient phase modulation of electromagnetic waves up to 4 THz [6]. Both of these quantum-well-type THz phase modulators, however, operated at temperatures far below room temperature. In the past, electrically controlled birefringence in a liquid crystal has been employed successfully for phase shifting of microwave and millimeter wave signals [7]. We have recently determined the complex index of refraction of a nematic liquid crystal (LC) 4'-n-pentyl-4-cyanobiphenyl (5CB) by THz time-domain spectroscopic (THz-TDS) technique [8]. It is shown that the birefringence of nematic 5CB is as large as 0.21 in the THz frequency range, while the absorption is negligible up to 1.2 THz. This indicates that 5CB in the nematic phase is potentially useful for device applications such as phase shifting in the THz frequency range. In this letter, we report the experimental demonstration, between 0.32 and 1.07 THz, of a room temperature, electrically controlled THz wave phase shifter using the birefringence of the LC material.

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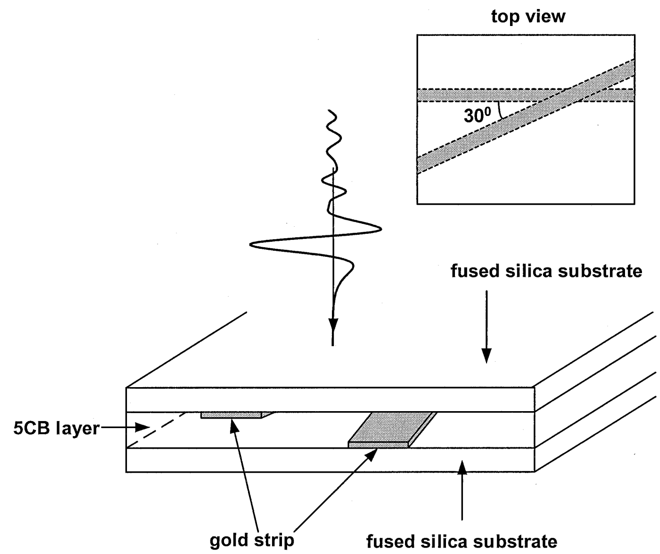

Fig. 1. Schematic diagram of a THz phase shifter using a LC 5CB cell. The inset shows the top view of 5CB cell.

II. Principle

Fig. 1 schematically illustrates the configuration of a variable phase shifter using a nematic LC cell for phase shifting of THz signals propagating in free space. The cell was prepared by sandwiching the commercial available LC, 5CB (Merck), between two fused silica windows as substrates. The thickness of the cell was $38.6 \pm 1.5\ \mu m$. Gold strips (one on each substrate), 3 mm in width and crossing at an angle of $\sim$ 30°, were deposited onto the inner surfaces of the substrates of the cell as electrodes. At the probing position, the strips were separated by about 3 mm. The cell was homogeneously aligned such that the director or optical-axis of the LC was parallel to one of the gold strips. An ac voltage at 1 kHz was applied to the electrodes. Consider a linearly polarized THz beam passing through the cell with LC having positive dielectric anisotropy. Without any bias field or if the bias field (root mean square value) is smaller than a threshold value, the transmitted THz beam will remain linearly polarized if the polarization of the incident THz beam is parallel or perpendicular to the LC director. Once the bias field is larger than a threshold value, this bias field will reorient the direction of LC toward the bias field direction, this phenomenon is called a Fréedericksz transition [9]. As a result, the effective refractive index of the LC layer will change. The phase shift due to the electrically controlled birefringence is given by

$$\delta = \frac{2\pi L f \Delta n_{eff}}{c} \tag{1}$$

where L is the LC layer thickness, f is the frequency of THz wave, $\Delta n_{\rm eff}$ is the average effective birefringence and c is the speed of light in vacuum.

III. Experiments and Results

The device was characterized by THz time-domain spectroscopy. The experimental setup has been described previously [8]. Briefly, the optical beam from a femtosecond mode-locked Ti:sapphire laser illuminated an inclined GaAs surface to generate the broad band THz signal, which was collimated and transmitted through the area between the two electrodes of the LC phase shifter. The transmitted THz signal was then detected by a probe beam from the same laser, using electro-optic sensing with a ZnTe crystal. The translation stage in our system is driven by a stepper motor with a 1 μm step resolution (equivalent to a temporal resolution of 6.67 fs). The measurements were done at room temperature (25 °C).

Fig. 2(a) shows the incident and transmitted THz waveforms through the LC phase shifter without and with a bias field. The spectral width and center frequency of the incident THz pulse was 0.68 THz and 0.37 THz respectively. The total scan range for the time delay was 9.32 ps. In Fig. 2(a), we show the data from 0.00 to 9.00 ps. An expanded view of Fig. 2(a) in the time window of 5.28 to 5.34 ps can be seen in Fig. 2(b), in which the phase shift is evident from the time shift of the waveforms. The transmitted THz wave spectra were then obtained from the time-domain THz waveform by fast Fourier transform (FFT) algorithm. The values obtained for the phase shift of the THz beam by the LC phase shifter at various frequencies are plotted as a function of the bias field in Fig. 3. The threshold voltage required to rotate the LC occurs at ~35.4 V (rms). The corresponding field was ~118.0 V/cm. When the driving field is smaller than the threshold value, the nematic LC director will maintain their original uniform alignment. Therefore, no phase shift was observed. When the bias field is larger than the threshold value, the effective refractive index of the LC will be changed until it is fully aligned with this field. The trend of phase shift versus bias field reflects this characteristic. That is, the phase shift rises above threshold and slowly approaches a steady state value. Under the same driving voltage, the terahertz wave experiences a larger phase shift at the higher frequencies in the 0.32 to 1.07 THz range. According to (1), the phase shift is proportional to the product of the effective index change $\Delta n_{\rm eff}$ and frequency of the electromagnetic wave. Since $\Delta n_{\rm eff}$ is ~0.21 in the range from 0.8 to 1.4 THz [8], we expect the observed phase shift to increase monotonically with frequency. The phase shift will reach a saturated value when the liquid crystal is completely aligned by the applied electric field. A maximum phase shift of 4.07° was obtained at 1.07 THz when the LC cell was driven at 589.3 V/cm. Still higher shift is expected if higher driving voltage is available.

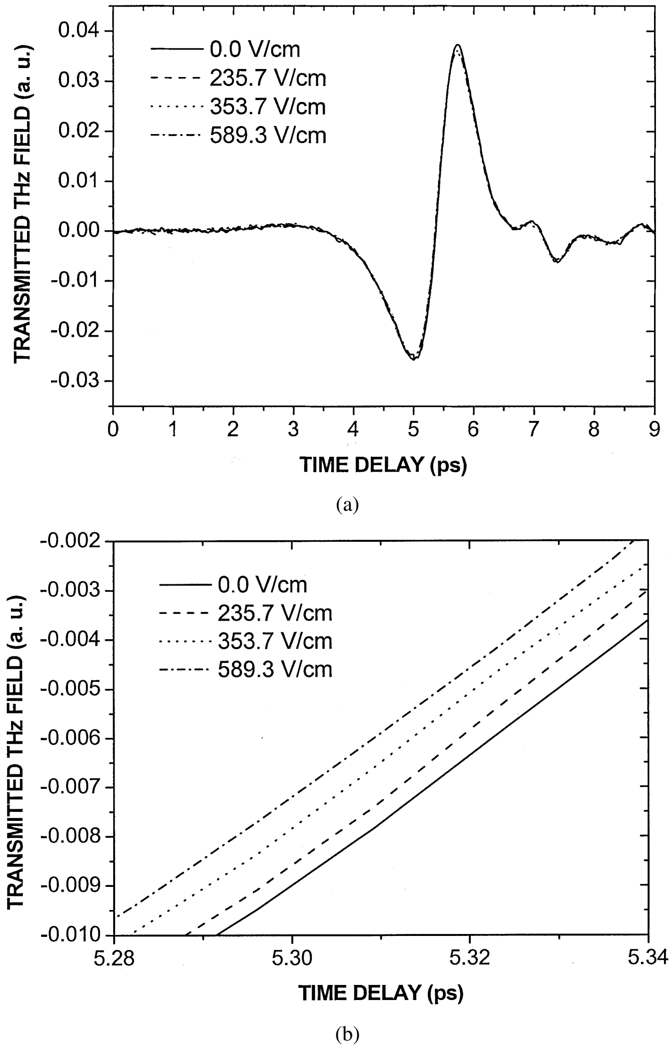

Fig. 2. (a) Measured terahertz waveforms transmitted through 5CB LC cell with various bias fields. (b) Expanded view of Fig. 2(a) in the time window of 5.28 to 5.34 ps.

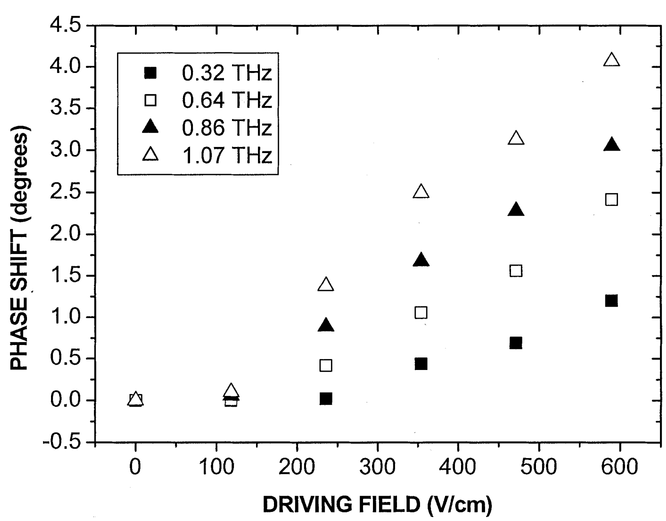

Fig. 3. Phase shift of the terahertz wave against bias fields applied to 5CB cell.

For a 38.6-μm-thick 5CB layer, with $\Delta n_{\rm eff} = 0.21$, the theoretical phase shift is $\sim 10.41°$ at 1.07 THz according to (1). This maximum value should occur when the nematic liquid crystal molecules are fully aligned with the applied field. By increasing the optical thickness of the liquid crystal layer to ~ 1.4 mm, a 2π phase shift at 1 THz could be realized.

IV. Conclusion

We have demonstrated a room temperature liquid-crystal-based THz phase shifter. The phase shift is achieved by electrical control of the effective refractive index of LC 5CB layer. A maximum phase shift of 4.07° was observed at 1.07 THz when the device was driven at 589.3 V/cm. In principle, the phase shift can be increased with a thicker LC cell and/or optimization of the electrode geometry.

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