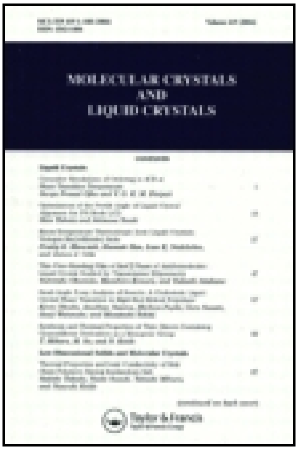

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TERAHERTZ PHASE SHIFTER WITH NEMATIC LIQUID CRYSTAL IN A MAGNETIC FIELD

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We report the phase shifter for terahertz waves utilizing magnetically controlled birefringence in a nematic liquid crystal cell. This device can be operated at room temperature. Two structures of cells were studied in this work. A maximum phase shift of 278° has been demonstrated at 1.0 THz. The results are in good agreement with theoretical predictions.

Keywords: nematic liquid crystal; phase shifter; terahertz waves

1. INTRODUCTION

Recently, sub-millimeter wave or terahertz (THz) technology [1] has undergone remarkable growth with intense interests for their applications in time-domain far-infrared spectroscopy [2,3], imaging [4], ranging [5] and bio-medical applications [6]. New THz optical elements such as polarizers, attenuators, modulators and phase shifters need to be developed for these applications. For tunable phase shifting application, Libon *et al*. [7] recently demonstrated a device based on optically induced change of the carrier concentration in GaAs multiple quantum well (MQW) structures. Control of the electron occupation and hence absorption of the THz radiation in MQW by an applied electric field has been used by Kersting *et al*. [8] to shift the phase of the THz wave. Gated two-dimensional electron gas in semiconductor nanostructures was proposed to change the phase of the THz carrier wave by up to 0.5 radians [9]. These quantum-well-based THz phase shifters, however, operated at temperatures far below room temperature.

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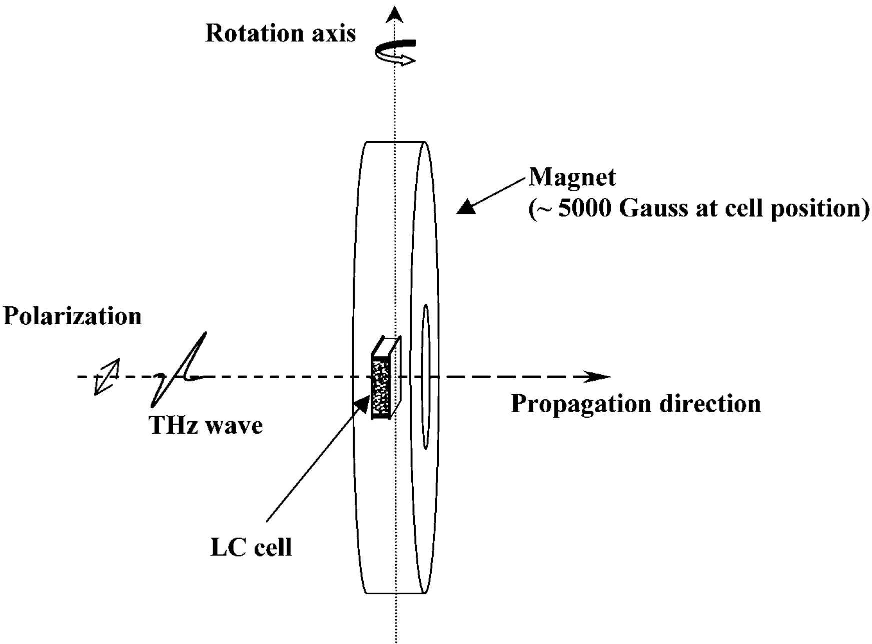

FIGURE 1 The schematic diagram of a THz phase shifter using a LC cell.

The large birefringence of liquid crystals (LCs) is well known and has been extensively utilized in optical systems for control and manipulation of visible, infrared and millimeter wave beams. Indeed, several groups have employed liquid crystals successfully for phase shifting of microwave and millimeter wave signals previously. [10,11] We have recently determined the complex index of refraction of a nematic LC 4′-n-pentyl-4-cyanobiphenyl (5CB) at room temperature by THz time-domain spectroscopy (THz-TDS) [12,13]. Significantly, the 5CB exhibits relatively large birefringence ($\sim$0.2) and small extinction coefficient ($<$0.1) at frequencies around 1 THz. This indicates that 5CB in the nematic phase is potentially useful for device applications such as phase shifting in the THz frequency range. An electrically controlled room temperature THz phase shifter with 5CB has also been demonstrated by the authors in a previous work [14]. However, that phase shifter need high driving voltage and the thickness of the 5CB layer required achieving a 2π phase shift at 1 THz would be about 1.7 mm. This presents a problem as alignment of the LC becomes difficult with such thick cells.

In this paper, we demonstrate a room temperature THz phase shifter based on magnetically controlled birefringence in LCs. A magnetic field

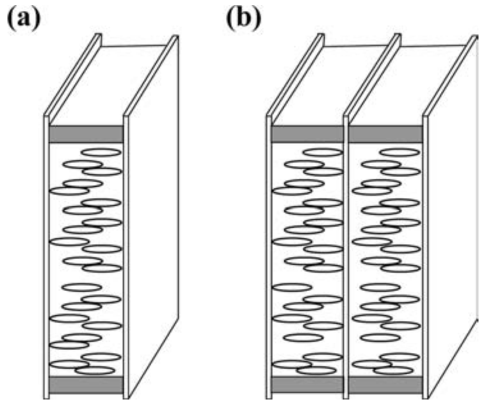

FIGURE 2 The structures of LC cells used in the THz phase shifter. The substrates are fused silica plates. The Teflon spacers are used for controlling the thickness. (a) The cell with one layer of LC, and (b) the cell with two layers of LC.

is used to orient the LC molecules and hence to vary the effective index of refraction for the THz waves.

2. THEORETICAL

The LC-based Phase THz shifter consists of a homeotropic LC cell and a rotary magnet as shown in Figure 1. The rotation axis is perpendicular to both of the polarization direction and the propagation direction of the THz wave. The magnetic inclination angle, θ, is defined as the angle between the magnetic field direction and the propagation direction. The effective refractive index of LC for THz waves changes with the LC molecular orientation [15], which is controlled by the angle θ. The phase shift, $\delta(\theta)$, due to magnetically controlled birefringence is given by

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

where L is the thickness of LC layer, Δn_{eff} is the change of effective birefringence, f is the frequency of the THz waves and c is the speed of light in vacuum.

We can assume that the LC molecules are reoriented parallel to the magnetic field direction when the magnetic field is large enough as in this work.

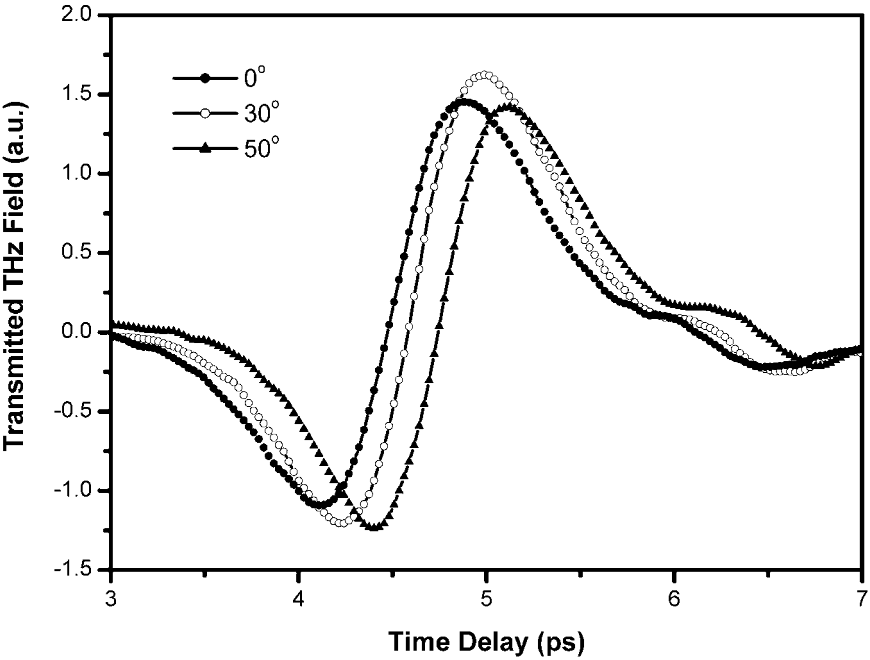

FIGURE 3 The measured THz waveforms transmitted through a 1-mm-thick 5CB LC cell at various magnetic inclination angles.

The phase shift, $\delta(\theta)$, in Eq. (1) can then be re-written as

$$\delta(\theta) = 2\pi L \frac{f}{c} \left\{ \left[\frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2} \right]^{-\frac{1}{2}} - n_o \right\}, \tag{2}$$

where n_o and n_e are the ordinary and extra-ordinary refractive indices of the LC.

The theoretical phase shift can be calculated if we know the n_o and n_e of LC and the thickness of the LC layer.

3. EXPERIMENTAL

Three LC cells have been used in this work. The structure of the first two cells is shown in Figure 2(a), and of the other one is shown in Figure 2(b). The nominal thicknesses of these cells are 1, 1.5 and 3 mm, respectively. The actual thicknesses measured by a vernier caliper are 0.93, 1.32 and 3.00 mm, respectively. The LC cells have 5CB (Merck) sandwiched between

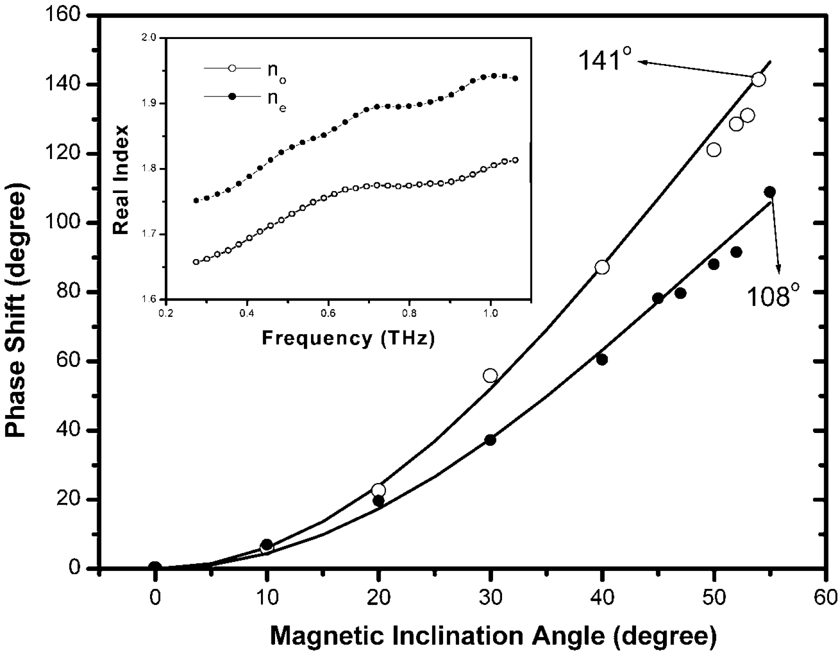

FIGURE 4 The phase shift of the THz waves passing through the 1-mm LC cell and the 1.5-mm cell versus the magnetic inclination angle θ at 1.0 THz. The solid curves are from the theoretical predictions. The symbols "●" and "○" show the measured data from 1-mm and 1.5-mm cells, respectively. The inset shows ordinary and extraordinary refractive indices of 5CB at 25°C.

fused silica plates with an area of 1 cm by 1 cm. s coated on The inner surfaces of the plates are coated with DMOAP (dimethyloctadecyl-(3-trimethoxysilyl)-propylammonium-chloride) for inducing the homeotropic alignment [16]. We employ an Nd-Fe-B sintered magnet on a rotation stage, which provide a rotatable magnetic field for tuning the phase shift of the THz wave. The magnetic field at the center of the LC cell is 0.51 Tesla. The achievable maximum magnetic inclination angle is 55°. Beyond that, the THz beam would be blocked by the magnet in the present setup.

We use THz-TDS method for characterizing the device. The experimental setup has been described previously [13]. Briefly, the optical beam from a femtosecond mode-locked Ti:sapphire laser illuminates a GaAs photoconductive antenna to generate the broad band THz signal, which is collimated and transmitted through the LC phase shifter. The transmitted THz signal is then detected by a probe beam from the same laser, using electro-optic sensing with a 4mm-thick (110) ZnTe crystal. [17]

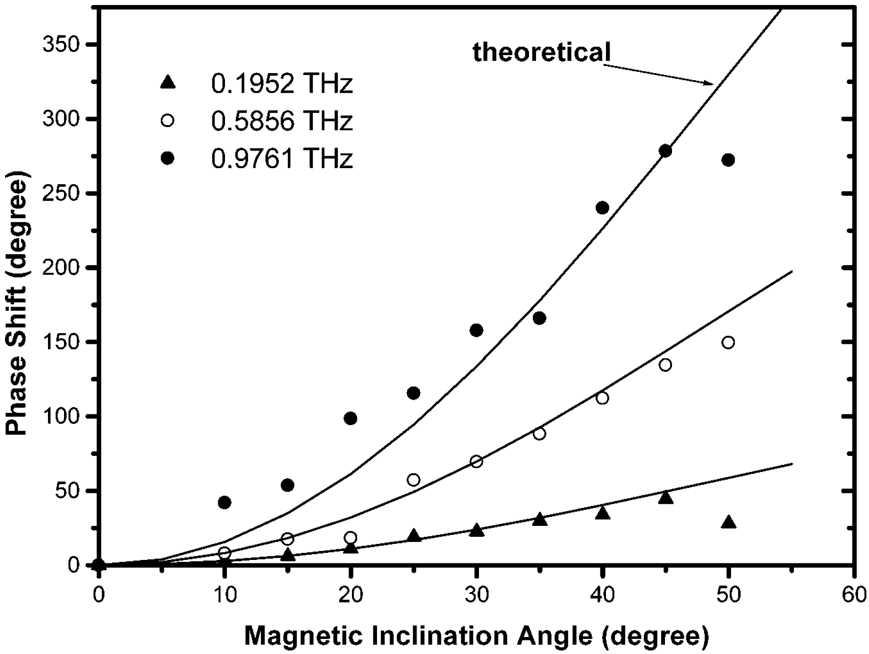

FIGURE 5 The phase shift of the THz waves passing through the 3-mm LC cell versus the magnetic inclination angle at various frequencies. The solid curves are from the theoretical predictions.

The temporal resolution in our system is 6.67 fs. The measurements are done at room temperature (25°C).

4. RESULTS AND ANALYSIS

The temporal THz profiles passing through the 1-mm-thick LC phase shifter at various magnetic inclination angles ($\theta = 0^\circ$, 30° and 50°) are illustrated in Figure 3. The center frequency and spectral width of the incident THz pulse are 0.25 THz and 0.35 THz, respectively. The total scan range for the time delay was 9.58 ps, although only the data from 3 to 7 ps are shown. The transmitted THz waves for $\theta > 0^\circ$ show obvious time delay to the THz wave for $\theta = 0^\circ$. The spectral amplitude and phase of the transmitted THz wave are deduced from the temporal waveforms by fast Fourier transform (FFT) algorithms. The deduced phase shifts at 1.0 THz due to the reorientation of molecules of the 1-mm-thick and the 1.5-mm-thick LC phase shifters are plotted as a function of the magnetic inclination angle in Figure 4, for various frequencies.

A threshold field of 96.7 gauss (for the 1-mm-thick cell) is required to reorient LC molecules in our LC cell when the magnetic field is perpendicular to the alignment direction [15]. That threshold is much lower than the magnetic field employed in this work ($\sim$0.51 tesla). This means that Eq. (2) is a reasonable assumption and can be used to predict the phase shifts. With Eq. (2) and the previously measured ordinary and extraordinary indices of refraction of 5CB in the THz range [13] (see the inset of Fig. 4), we have calculated and plotted the theoretically predicted phase shifts as the solid curves in Figure 4. They show good agreements with the measured data. According to Eq. (1), the phase shift is proportional to the product of the effective index change Δn_{eff} and the thickness of LC layer. This is also confirmed in Figure 4. A maximum phase shifts of 108° and 141° was obtained at 1.025 THz and $\theta = 55°$ by using the 1-mm-thick and 1.5-mm-thickness LC cells, respectively. For the 3-mm-thick LC cell, the measured phase shift with the theoretical values are plotted versus θ in Figure 5 for the frequencies at 0.1952, 0.5856 and 0.9761 THz. The THz waves experience larger phase shift at the higher frequencies as expected from Eq. (1). The measured data for this cell are also in good agreement with theoretical predictions. The maximum phase shift achieved was 278° at 1 THz and $\theta = 45°$.

5. DISCUSSION AND SUMMARY

In Figure 2, we also see that the transmited THz field increases with the magnetic inclination angle when the angle is less than 40°. This can be explained by the increasing transmittance at the glass-LC interface according to the Fresnel equations [18]. For example, the ordinary and extraordinary refractive indices of 5CB are 1.77 and 1.90, respectively, at 0.8 THz [13]. With the increasing θ, the effective refractive index of LC will increase from 1.77 to 1.90 and become closer to the refractive index of quartz substrate, which is 1.95. The transmitted field will then increase according to Fresnel equations. The THz field decreases for $\theta > 40°$ due to the partial blocking of the THz wave by the magnet.

Note that the dependence of the phase shift on the thickness of LC layer is also consistent with the theory in Figure 4. The thickness of the LC layer required to achieve a 2π phase shift at 1 THz is thus about 3.18 mm with the same setup used in this work. When the thickness of LC layer is more than 1.5 mm, the orientation of bulk LC molecules is usually unstable and has many domains. It can be improved by using sandwich structure as our 3-mm-thickn cell. Alternatively, newly developed liquid crystal material with high birefringence can be explored for this application.

For the 3-mm-thickn cell, the phase shift decreases with the magnetic inclination angle when the angle is more than 45°. This is probably caused by the nonuniform magnetic field across this cell, which is the thickest one in our experiments.

In summary, we have demonstrated a room temperature liquid crystal THz phase shifter. The phase shift is achieved by magnetically controlling of the effective refractive index of LC layer. Measured results are in good agreements with theoretical predictions. The maximun phase shifts of 108°, 141° and 278° are obtained by using 1-mm-thick, 1.5-mm-thick and 3-mm-thick cells, repectively. In principle, the phase shift of 2π can be achieved by employing a LC cell with larger optical thickness and/or larger magnetic inclination angle. Alternatively, this can be realized with a 3-mm-thick LC cell with Δn $\sim$0.26.

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