AIP Applied Physics Letters

Room temperature terahertz phase shifter based on magnetically controlled birefringence in liquid crystals

Chao-Yuan Chen, Tsong-Ru Tsai, Ci-Ling Pan, and Ru-Pin Pan

Citation: Applied Physics Letters **83**, 4497 (2003); doi: 10.1063/1.1631064
View online: http://dx.doi.org/10.1063/1.1631064
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/83/22?ver=pdfcov
Published by the AIP Publishing

Room temperature terahertz phase shifter based on magnetically controlled birefringence in liquid crystals

Chao-Yuan Chen, Tsong-Ru Tsai, Ci-Ling Pan, and Ru-Pin Pan[a)]
Institute of Electro-Optical Engineering and Department of Electrophysics, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan 300, Republic of China

(Received 30 June 2003; accepted 8 October 2003)

We present the use of magnetically controlled birefringence in a nematic liquid crystal cell for phase shifting of electromagnetic waves in the range of terahertz frequencies. This device can be operated at room temperature. A maximum phase shift of 141° has been demonstrated at 1.025 THz and the results are in good agreement with theoretical predictions.
[DOI: 10.1063/1.1631064]

In the past decade, submillimeter 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 biomedical applications.[6] These applications require a variety of active and passive THz optical elements such as polarizers, attenuators, switches, modulators, and phase shifters, which are rarely explored up to now. Perforated flat plates that acting as dichroic filters or frequency selective surfaces in the THz range were reported by Winnewisser *et al.*,[7] however, they were not tunable. Among active devices that permit controlling the amplitude and phase of THz beams, there exist devices based on the optically excited carriers in semiconductors, of which the THz transmission properties are strongly affected by illumination[8,9] or carrier injection.[10,11] These quantum-well-based THz tunable phase shifters,[10–12] however, operated at temperatures far below room temperature.

The birefringence of liquid crystals (LCs) is well known and 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.[13,14] 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).[15,16] Significantly, we show that nematic 5CB exhibits relatively large birefringence (~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.[17] A maximum phase shift of 4.07° was achieved with a driving voltage of 177 V at 1.06 THz when the interaction length was 38.6 μm. A relatively long distance (>2 mm) between the electrodes was required to avoid blocking the THz beam. The thickness of the 5CB layer required to achieve a 2π phase shift at 1 THz would be very thick (>3 mm). This also presents a problem, as alignment of the LC becomes difficult with such thick cells.

In this letter, we demonstrate a room temperature THz phase shifter based on magnetically controlled birefringence in LCs. The magnetic field is used to effectively align and change the orientation of LC molecules and hence the effective index of refraction for THz waves.

A schmetic of the THz phase shifter is shown in Fig. 1. The LC phase shifter device consists of a homeotropic LC cell and a rotary magnet. The rotation axis is perpendicular to both of the polarization and the propagation directions of the THz wave. We define the magnetic inclination angle, θ, as the angle between the magnetic field direction and the propagation direction. The effective refractive index of LC for THz waves changes with the molecular orientation,[18] which is controlled by the angle θ. The phase shift, $\delta(\theta)$, due to magnetically controlled birefringence is given by

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

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

If the magnetic field is large enough, we can assume that the LC molecules are reoriented parallel to the magnetic field direction, the phase shift can then be rewritten as

$$\begin{aligned}\delta(\theta)&=2\pi L\frac{f}{c}\cdot\Delta n_{\mathrm{eff}}(\theta)\\&=2\pi L\frac{f}{c}\left[\left(\frac{\cos^2(\theta)}{n_o^2}+\frac{\sin^2(\theta)}{n_e^2}\right)^{1/2}-n_o\right],\end{aligned} \quad (2)$$

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

The LC cells have 5CB (Merck) sandwiched between fused silica plates with an area of 1 cm by 1 cm. The inner surfaces of the plates are coated with dimethyloctadecyl-(3-trimethoxysilyl)-propylammonium-chloride (DMOAP) to align the LC molecules perpendicular to the surfaces of the quartz plate.[19] To shift the THz wave phases, a Nd–Fe–B sintered magnet on a rotation stage is employed. The magnetic field at the center of the LC cell is 5100 G. The maximum possible magnetic inclination angle is 55°. Beyond that, the magnet in the present setup would block the THz

a)Electronic mail: rpchao@mail.nctu.edu.tw

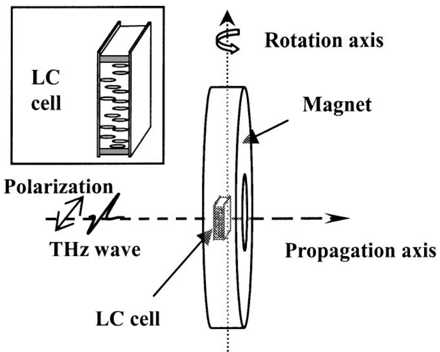

FIG. 1. Schematic diagram of a THz phase shifter using a LC cell.

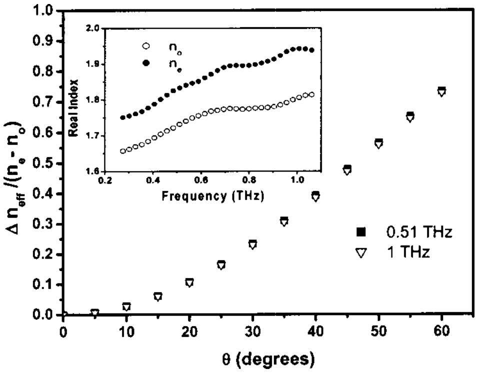

FIG. 3. Magnetic field induced refractive index change vs θ at 0.51 and 1 THz. The inset shows ordinary and extraordinary refractive indices of 5CB at 25 °C.

beam. Two LC cells, with nominal thicknesses of 1 and 1.5 mm, repectively, have been used in this work. The actual thicknesses measured are 0.95 and 1.32 mm, respectively.

The device is characterized by THz-TDS. The experimental setup has been described previously.[15] 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.[20] The measurements are done at room temperature (25 °C).

The temporal waveforms of the THz beam passing through the 1-mm-thick LC phase shifter at various magnetic inclination angles are illustrated in Fig. 2. The spectral width and center frequency of the incident THz pulse are 0.35 and 0.25 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 $\theta>0°$ show obvious time delay to the wave for $\theta=0°$. The spectral amplitude and phase of the transmitted THz wave were deduced by fast Fourier transform (FFT) algorithms.

If the magnetic field is parallel to the surface, the threshold field[18] required to reorient the LC molecules in our LC cell is 97 G, which is much lower than the field employed in this work (5100 G). This means that Eq. (2) is a reasonable assumption and can be used to predict the phase shifts. Although a field of 10 times of the threshold is usually large enough to have most of the molecules orient along the field, the much larger field used in our work is to make the LC orientation stable in cells as thick as 1.5 mm. Using Eq. (2) and the previously measured ordinary and extraordinary indices of refraction of 5CB in the THz range[15] (see inset of Fig. 3), the normalized magnetic-field-induced birefringence, $\Delta n_{\mathrm{eff}}/(n_e-n_o)$, vs θ at two frequencies is plotted in Fig. 3. At $\theta=60°$, as high as 75% of the maximum possible birefriengence is realized. The phase shift due to the LC phase shifter at various frequencies are deduced from the data in Fig. 2 by FFT algorithms and plotted as a function of the magnetic inclination angle in Fig. 4. We have also calculated and plotted the theoretically predicted phase shifts in Fig. 4 as the solid curves. 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 frequency of the electromagnetic wave. The THz wave is thus expected to experience a larger phase shift at the higher frequencies in the measured THz range. This is also confirmed in Fig. 4. The data for the 1.5-mm-thick cell at 1.025 THz are also show in Fig. 4. Maximum phase shifts of 108° and 141° have been obtained at 1.025 THz by using these two LC cells, respectively.

With the LC cells with different thickness, our results show that the dependence of the phase shift on the thickness of LC layer is also consistent with the theory. 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. Alternatively, newly developed liquid crystal material with high birefringence can be explored for this application.

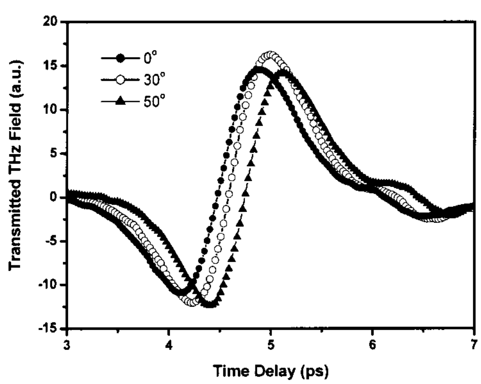

FIG. 2. Measured THz waveforms transmitted through a 1-mm-thick 5CB LC cell at various magnetic inclination angles.

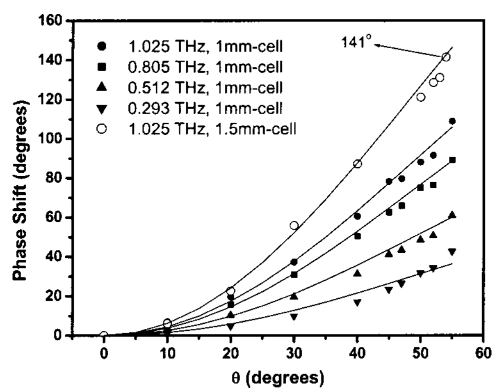

FIG. 4. Phase shift of the THz waves passing through the 1- and 1.5-mm LC cells vs the angle θ at various frequencies. The solid curves are from the theoretical predictions.

In the above experiments, we also find that the transmited THz field increases with the magnetic inclination angle when the angle is less than 40°. This can be explained simply by considering the Fresnel equations.[21] The ordinary and extraordinary refractive indices of 5CB are 1.77 and 1.90, respectively, at 0.8 THz. With the increasing θ, the effective refractive index of LC will increase from 1.77 to 1.90 (Ref. 15) and become closer to the refractive index of quartz substrate (1.95). The transmitted field will then increase according to Fresnel equations. The THz field decreases for $\theta > 40°$ due to partial blocking of the THz wave by the magnet.

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. The magnetic field also helps to align the LC for a cell as thick as 1.5 mm. Measured results are in good agreements with theoretical predictions. For the 1.5-mm-thick cell and the magnetic field inclined at 55°, the maximum phase shift realized is 141° at 1.025 THz. In principle, the phase shift can be increased by employing a LC cell with larger optical thickness and/or larger magnetic inclination angle. To achieve a 2π phase shift at 1 THz, we can increase the cell thickness to 3.18 mm with the same experimental setup used in this work. Alternatively, this can be realized with a 1.5-mm-thick LC cell with $\Delta n \sim 0.4$.

This work was supported in part by the National Science Council of R.O.C. under Grant Nos. NSC 89-2218-E-009-061, 90-2112-M-009-051, and -053 and the Pursuit of Academic Excellence Program of the Ministry of Education, R.O.C.

[1] P. H. Siegel, IEEE Trans. Microwave Theory Tech. **50**, 910 (2002).
[2] M. V. Exter, C. Fattinger, and D. Grischkowsky, Opt. Lett. **14**, 1128 (1989).
[3] D. Grischkowsky, S. R. Keiding, M. V. Exter, and C. Fattinger, J. Opt. Soc. Am. B **7**, 2006 (1990).
[4] B. B. Hu and M. C. Nuss, Opt. Lett. **20**, 1716 (1995).
[5] R. A. Cheville and D. Grischkowsky, Appl. Phys. Lett. **67**, 1960 (1995).
[6] A. J. Fitzgerald, E. Berry, N. N. Zinovev, G. C. Walker, M. A. Smith, and J. M. Chamberlain, Phys. Med. Biol. **47**, R67 (2002).
[7] C. Winnewisser, F. T. Lewen, M. Schall, M. Walther, and H. Helm, IEEE Trans. Microwave Theory Tech. **48**, 744 (2000).
[8] F. A. Hegmann, J. B. Williams, B. Cole, and M. S. Sherwin, Appl. Phys. Lett. **76**, 262 (2000).
[9] A. Chelnokov, S. Roeson, J.-M. Lourtioz, L. Duvillaret, and J.-L. Coutaz, Electron. Lett. **34**, 1965 (1998).
[10] I. H. Libon, S. Baumgärtner, M. Hempel, N. E. Hecker, J. Feldmann, M. Koch, and P. Dawson, Appl. Phys. Lett. **76**, 2821 (2000).
[11] T. Kleine Ostmann, M. Koch, and P. Dawson, Microwave Opt. Technol. Lett. **35**, 343 (2002).
[12] R. Kersting, G. Strasser, and K. Unterrainer, Electron. Lett. **36**, 1156 (2000).
[13] K. C. Lim, J. D. Margerum, and A. M. Lackner, Appl. Phys. Lett. **62**, 1065 (1993).
[14] D. Dolfi, M. Labeyrie, P. Joffre, and J. P. Huignard, Electron. Lett. **29**, 926 (1993).
[15] T.-R. Tsai, C.-Y. Chen, C.-L. Pan, R.-P. Pan, and X.-C. Zhang, Appl. Opt. **42**, 2372 (2003).
[16] R.-P. Pan, T.-R. Tsai, C.-Y. Chen, C.-H. Wang, and C.-L. Pan, Mol. Cryst. Liq. Cryst. (to be published).
[17] T.-R. Tsai, C.-Y. Chen, R.-P. Pan, C.-L. Pan, and X.-C. Zhang, IEEE Microwave Wireless Comp. Lett. (to be published).
[18] P. G. de Gennes and J. Prost, *The Physics of Liquid Crystals*, 2nd ed. (Oxford University Press, New York, 1983).
[19] F. J. Kahn, Appl. Phys. Lett. **22**, 386 (1973).
[20] Z. Jiang, M. Li, and X.-C. Zhang, Appl. Phys. Lett. **76**, 3221 (2000).
[21] E. Hecht, *Optic*, 3rd ed. (Addison Wesley–Longman, New York, 1998).