Voltage-controlled liquid-crystal terahertz phase shifter with indium–tin–oxide nanowhiskers as transparent electrodes

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Indium–tin–oxide nanowhiskers were employed as transparent electrodes in a liquid-crystal terahertz phase shifter. Transmittance of the device was as high as ~75%. Phase shift exceeding $\pi/2$ at 1.0 THz is achieved in a ~500 μm-thick cell. The driving voltage required for the device operating as a quarter-wave plate was as low as 17.68 V (rms), an improvement of nearly an order of magnitude over previous work. © 2014 Optical Society of America

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During the last three decades, remarkable progress has been made in submillimeter or terahertz technology, which has made significant inroads to applications in fields ranging from biomedicine, three-dimensional imaging, tomography, and characterization of materials [1]. Subterahertz radio-over-fiber communication at data rates exceeding 20 Gb/s over a 25-km fiber link was also demonstrated [2]. To meet the demands of the exploding terahertz field, many novel quasi-optic components, such as phase shifters [3–6], gratings [7], modulators [8], polarizers [9,10], and filters [11–14], have been developed. In particular, a number of tunable terahertz devices employing liquid crystals (LCs) have attracted considerable attention [3–6,14]. In our previous work, phase shift exceeding $\pi/2$ at 1 THz was achieved by using electrically controlled birefringence in a 570-μm-thick homeotropically aligned (E7) LC cell, biased at a root-mean-square (rms) voltage of 125 V [4]. Sputtered indium–tin–oxide (ITO) films, widely used as electrodes in the visible range, are opaque in the terahertz frequency range [15,16]. Therefore, two copper pieces separated by ~11 mm on two sides of the LC cell were used as spacers and electrodes [4]. Later, Lin *et al.* demonstrated a $\pi/3$ phase shifter by using subwavelength metallic gratings as the transparent electrodes. Its operative voltage was as high as 130 V (rms) [6].

Recently, ITO nanomaterials, such as nanocolumns, nanorods, nanowires, and nanowhiskers (NWhs), were reported to have omnidirectional, broadband antireflective (AR) characteristics in the visible and near-infrared, as well as superhydrophilicity. These nanomaterials are thus useful as electrodes in solar cells [17], light emitting diodes (LEDs) [18], and displays [19]. In the terahertz band, we showed that ITO NWhs also exhibit superb transparency (~82%). Meanwhile, their DC mobility (~92 $cm^2\,V^{-1}\,s^{-1}$) and conductivities (~245 $\Omega^{-1}\,cm^{-1}$) are comparable to sputtered ITO thin films [15,16,20]. In this Letter, we report an electrically tunable terahertz LC phase shifter using ITO NWhs as transparent electrodes. The device can be operated at relatively low voltage and exhibits high transmittance in the terahertz frequency region. The operation of the device as a terahertz quarter-wave plate is verified. The voltage- and frequency-dependent characteristics of the terahertz phase shifter are discussed in detail. Experimental results are in good agreement with theoretical predictions by considering the minimum free energy condition.

The configurations of the two devices being investigated are shown in Fig. 1. The cells were constructed by sandwiching the LC (E7 by Merck) layer between two fused silica substrates which were deposited with either ITO NWhs or sputtered ITO thin films as electrodes. The latter were fabricated by DC reactive magnetron sputtering while the former were prepared by the electron-beam glancing-angle deposition (GLAD) method. Details of sample preparation can be found in our previous work [15,16]. For the phase shifter using ITO NWhs, the thickness of the substrate and the E7 layer

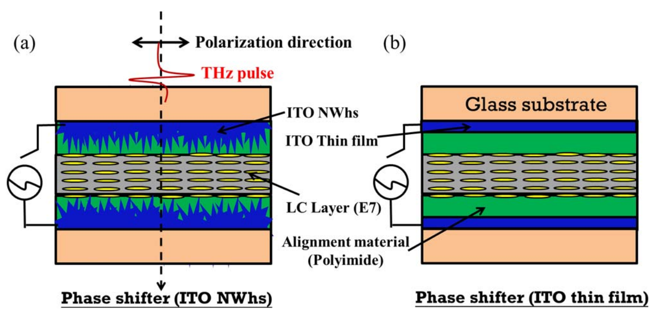

Fig. 1. Schematic diagrams of (a) ITO NWhs and (b) thin film-based LC phase shifter at terahertz frequency.

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were 1008 ± 8 and 509 ± 12 μm, respectively. The reference cell, coated with 200-nm-thick ITO sputtered thin film, employed substrates with thickness of 973 ± 8 μm, and a 524 ± 10 μm-thick LC layer. Inner faces of substrates deposited with ITO films or NWhs were further coated with polyimide for alignment of the LC molecules by the rubbing process. The cells were biased with sinusoidal signals at 1 kHz.

Before turning on the voltage, the E7 molecules are in the initially stable state and parallel to the substrates, as we illustrated in Fig. 1. Due to the Fréedericksz transition, E7 molecules will be reoriented toward the applied electric field as the bias is increased beyond the threshold field given by $E_{\mathrm{th}} = \pi(k_1/(\varepsilon_0 \times \Delta\varepsilon))^{1/2}/d$ [21], where $\varepsilon_0 = 8.854 \times 10^{-12}\ \mathrm{F} \cdot \mathrm{m}^{-1}$, $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp = 13.8$ [4], $k_1 = 11.1 \times 10^{-12}$ N [4], and d are free-space permittivity, dielectric anisotropy, splay elastic constants, and the distance between two electrodes, respectively. Here, $\varepsilon_\parallel$ and $\varepsilon_\perp$ are the dielectric constants along the preferred axis and perpendicular to this axis, respectively. The applied voltages quoted in this Letter were all rms values.

The boundary condition on the internal surfaces of substrates for the LC cell requires that the tilt angle of the director $\theta(0) = \theta(d) = 0$. Further, LC molecules are assumed to be originally aligned along the y direction. The condition for minimum free energy ($\delta U = 0$) can be written as [21]

$$(k_1 \cos^2\theta + k_3 \sin^2\theta) \times \left(\frac{d\theta}{dz}\right)^2 - \frac{D_z^2}{(\varepsilon_\parallel \sin^2\theta + \varepsilon_\perp \cos^2\theta)} = \text{constants}, \tag{1}$$

where k_3, θ, and, D_z are the bend elastic constant, tilt angle, and z component of the displacement field vector, respectively. Assuming the maximum tilt angle, $\theta_{\max}$, occurs at the center of the cell, the dependence of $\theta_{\max}$ on the applied voltage is given by [21]

$$\int_0^{\frac{\pi}{2}} \frac{\sqrt{(1 + \zeta \sin^2\theta_{\max} \sin^2\alpha)(1 + \rho \sin^2\theta_{\max})}}{\sqrt{(1 - \sin^2\theta_{\max} \sin^2\alpha)(1 + \rho \sin^2\theta_{\max} \sin^2\alpha)}} \mathrm{d}\alpha = \frac{\pi}{2} \frac{V}{V_{\mathrm{th}}}, \tag{2}$$

where $\zeta = (k_3 - k_1)/k_1$, $\rho = (\varepsilon_\parallel - \varepsilon_\perp)/\varepsilon_\perp$, and V is the applied voltage, whereas $\sin\alpha = \sin\theta_{\max}$. In addition, V_{th} is the threshold voltage and is equal to $E_{\mathrm{th}} d$. After finding the $\theta_{\max}$ at every applied voltage, the effective birefringence experienced by the terahertz wave transmitting through the LC cell can be written as [4]

$$\Delta n_{\mathrm{eff.Max}} = \left(\frac{\cos^2\theta_{\max}}{n_o^2} + \frac{\sin^2\theta_{\max}}{n_e^2}\right)^{-\frac{1}{2}} - n_o, \tag{3}$$

where n_e and n_o are extraordinary and ordinary indices of refraction of the LC, respectively. Due to weak anchoring of the ~500 μm-thick cell, we can write the phase shift due to the effective birefringence as $\delta = 2\pi f d \times \Delta n_{\mathrm{eff.Max}}/c$ [4], where f and c are the frequency and speed of propagation of the terahertz wave in vacuum. Here, the values of n_e and n_o for E7 are 1.690–1.704 and 1.557–1.581 at 26°C, respectively, giving rise to a birefringence of 0.130–0.148 in this frequency range [22].

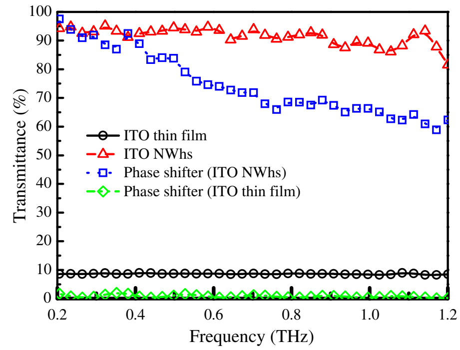

Fig. 2. Transmittance of ITO thin film, NWhs, phase shifter based on ITO NWhs, and thin film.

A photoconductive antenna-based terahertz time-domain spectroscopy (TDS), as described in our previous works, was used to characterize the terahertz phase shifters [15]. A pair of parallel wire-grid polarizers was placed before and after the devices under test to ensure the polarization of the terahertz beam. In Fig. 2, we have plotted experimentally measured transmittance of the two types of phase shifters. Transmission characteristics of ITO sputtered thin film and NWhs are shown as a reference. Transmittance of the substrate with ITO NWhs (~91.48%) is much higher than that with sputtered ITO thin films (~8.62%). The underlying basic physics for the huge difference is that terahertz radiation can more easily propagate through the air space among NWhs [15,16]. As a result, the transmittance of the phase shifter using ITO NWhs as electrodes (≥75%) is much higher than that using thin film (≤0.92%).

Recalling the relationship of phase shift and frequency, larger phase shift can be expected at higher frequencies. This is confirmed in Fig. 3, in which we plot the phase shifts from 0.2 to 1.2 THz by varying the applied voltages. For a given voltage, in general, the measured phase shift varied linearly with frequency. For the phase shifter based on NWhs, the slope of linear fit varies from 7.12/THz to 92.14/THz as the applied voltage is ramped from 1.48 to 17.68 V (rms).

In Fig. 4, we plotted the phase shift as a function of driving voltage. The fitting curves in Fig. 4 are theoretical predictions according to Eqs. (1)–(3). Far above threshold, the LC molecules are essentially aligned with the

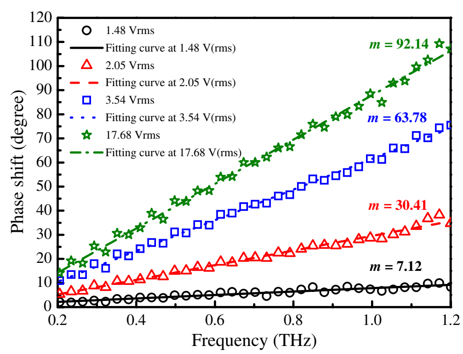

Fig. 3. Phase shift as a function of terahertz frequency for four driving voltages of phase shifter based on ITO NWhs.

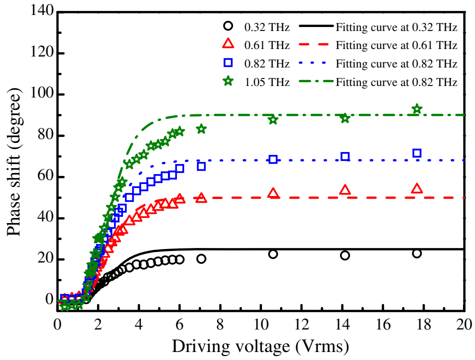

Fig. 4. Phase shift as a function of driving voltage for four frequencies of phase shifter based on ITO NWhs.

electric field. Here, the theoretical curves are in good agreements with the experiments. The thresholds for voltage and electric field, E_{th} and V_{th}, are determined to be 0.95 V (rms) and 18.60 V/cm, respectively. In the previous work [4], the threshold voltage and corresponding field were 27 V (rms), and 22.6 V/cm, respectively. Over 90° of phase shift were achieved at 1.05 THz when the phase shifter using ITO NWhs was driven at 17.68 V (rms) versus 125 V (rms) reported in previous work [4]. Therefore, the phase shifter using ITO NWhs can achieve the threshold of driving molecules and operate as a quarter-wave plate at much lower voltage—more than six times lower. The threshold electric fields are nearly the same, which is reasonable.

In summary, by applying the ITO NWhs obliquely evaporated by electron-beam GLAD as transparent conductors, we have demonstrated a tunable LC terahertz phase shifter and quarter-wave plate that exhibit desirable characteristics of high transmittance and low-operation-voltage. The transmittance of the device is as high as ~75%. Phase shift of more than $\pi/2$ at 1.0 THz is achieved in a -~509-μm-thick cell with low driving voltage, 17.68 V (rms). ITO NWhs are thus expected to be excellent choices as transparent conductors for optoelectronic devices not only in the visible but also in the terahertz band.

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