Voltage-controlled 2π Liquid-crystal Terahertz Phase Shifter with Indium-tin-oxide (ITO) Nanowhiskers as Transparent Electrodes

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Abstract

Phase shift exceeding 2π at 1.0 THz with high transmittance was achieved in liquid-crystal THz phase shifters of three different designs. Indium-tin-oxide (ITO) nanowhiskers (NWhs) were employed as transparent electrodes. The driving voltage required for a 2π wave plate is as low as 5 Vrms.

1. Introduction

During the last three decades, remarkable progress has been made in sub-millimeter or terahertz (THz) technology. In general, THz studies range from bio-medical applications, THz wave 3D imaging, tomography, and investigations of ultrafast dynamics in materials [1]. To meet the demands of the exploding THz field, many novel quasi-optic components have been reported, such as phase shifter, phase grating, modulator, polarizers, and filters. In particular, a number of tunable THz devices by using liquid crystals (LCs) have attracted considerable attention [2-4]. In our previous work, phase shift exceeding 2π at 1 THz was achieved by using electrically controlled birefringence in a homeotropically aligned (E7) 1.83 mm-thick LCs cell, in thickness with root-mean-square voltages, 100 V (rms) [4]. Sputtered indium-tin-oxide (ITO) films, widely used as electrodes in visible range, are opaque in the THz frequency range [5, 6]. Therefore, two copper pieces separated by ~ 11 mm at two sides of LCs cell were used as spacers and electrodes [4].

Recently, ITO nanomaterials, e.g. nanocolumn, nanorods (NRs), nanowires, and nanowhiskers (NWhs), are reported to have omnidirectional, broadband anti-reflective (AR) characteristics in the visible and near-infrared, as well as superhydrophilicity that are attractive for use in solar cells, light emitting diodes (LEDs), and displays. Recently, we showed that the ITO NWhs also exhibit superb THz transparency (~82%), DC mobility (~92 $cm^2V^{-1}s^{-1}$), and comparable conductivities (~ 245 $\Omega^{-1}cm^{-1}$) to sputtered ITO thin films [5, 6].

In this work, we report three different designs of electrically tunable THz liquid-crystal phase shifters capable of 2π (360°) phase shifts using ITO NWhs as electrodes. The devices can be operated at relatively low voltage and exhibit high-transmittance in the THz frequency region.

2. Design and Operation Principles

The configurations of three devices with different numbers of layers of ITO NWhs are shown in Fig. 1. The LC (MDA-00-3461 by Merck) was sandwiched between fused silica substrates which were deposited with or without ITO NWhs as electrodes. The ITO NWhs were prepared by the electron-beam glancing-angle deposition (GLAD) method.

Here, Photoconductive (PC) antenna-based THz time-domain spectroscopy (THz-TDS) as described in our previous works were used to characterize these samples in the frequency range between 200 GHz and 1.2 THz [5, 6].

For biasing, we applied a sinusoidal-wave ac voltage at 1 kHz to the electrodes. Before turning on the voltage, the MDA-00-3461 molecules are in the initially stable state and parallel to the substrates. Due to the Fréedericksz transition, MDA-00-3461 molecules will be reoriented toward the applied electric field as the bias is increased beyond the threshold field given by $E_{th}= \pi\cdot(k_1/(\varepsilon_0\cdot\Delta\varepsilon))^{1/2}/d$, where $\varepsilon_0 = 8.854\times10^{-12}$ F·m^{-1}, $\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp} = 11.2$, $k_1 = 12.6\times10^{-12}$ N, and d are free-space permittivity, dielectric anisotropy, splay elastic constants, and the distance between two electrodes, respectively. After numerically finding the maximum tilt angle which exists at every layer due to the weak boundary of substrates for LCs in the cell, we can write the phase shift due to the effective birefringence can be given by $\delta = 2\pi\cdot f\cdot d\cdot\Delta n_{\mathrm{eff.Max}}/c$, where f and c are the frequency of THz radiation and the speed of light in vacuum, respectively.

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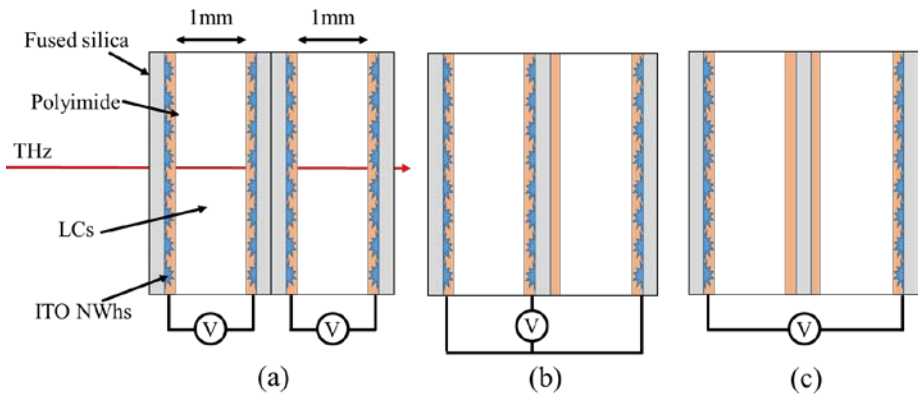

Fig. 1. Schematic diagram of (a) four-layer, (b) three-layer, and (c) two-layer ITO NWhs 2π THz phase shifter.

3. Results and Discussions

In Fig. 2(a), we plotted the phase shift as a function of driving voltage. Over 360° of phase shift were achieved at 1.05 THz when the phase shifter using ITO NWhs was driven at lower than 5 V (rms). This is an improvement of nearly 20 times. In Fig. 2(b), we have also plotted the experimentally measured transmission of all phase shifters as a function of frequency from 0.2 THz to 1.2 THz. Here, because of the smaller distance between two electrodes than phase shifter of two-layer ITO NWhs (blue line), the four-layer (black line) and three-layer (red line) devices possess the lower threshold voltage and steeper change in the phase shift. However, in the THz frequency range 0.2~1.2 THz, the phase shifter with two-layer ITO NWhs exhibited higher transmittance than others due to the smaller absorption caused by fewer ITO NWhs electrodes.

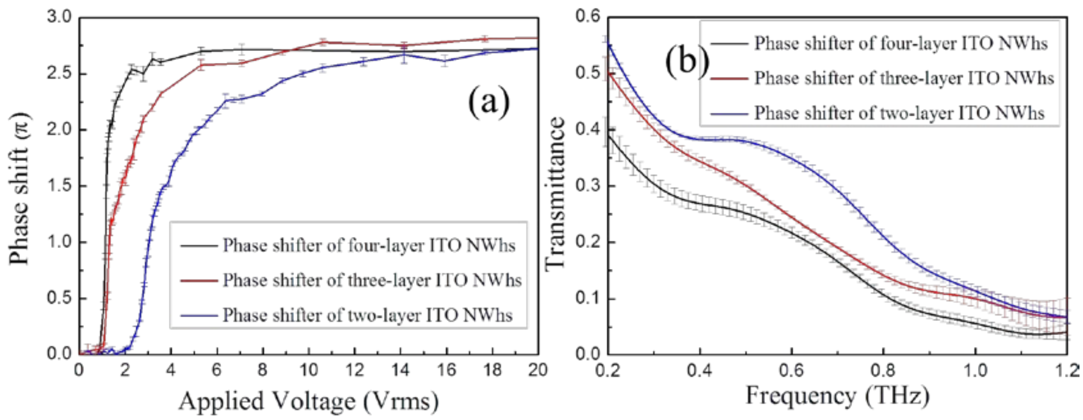

Fig. 2. (a) voltage controlled phase shifts at 1 THz, and (b) transmittance for three different 2π THz phase shifters based on multi-layer ITO NWhs.

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