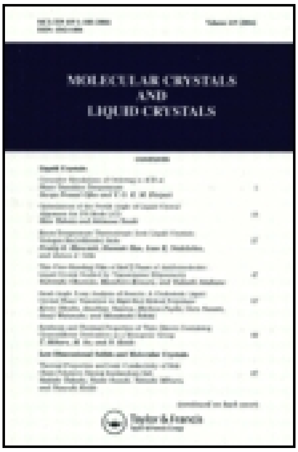

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Tunable Terahertz Filter Using an Etalon with a Nematic Liquid Crystal Layer and its Response Speed

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We demonstrate a tunable terahertz (THz) filter using an etalon with a nematic liquid crystal (NLC) layer. The etalon is composed of water-free fused silica glass plates and air layers, and contains a 75 μm-thick defect layer filled with homeotropically-aligned NLCs. Frequency tuning of the transmission peak is achieved by applying an in-plane electric field across the NLC layer: the transmission peak shifts from 1.025 THz to 1.013 THz. The obtained rise and decay times are 5.3 s and 12.2 s respectively and found to be 10 times faster than previous THz LC devices because of the thin NLC layer.

Keywords Etalon; nematic liquid crystal; response speed; terahertz; tunability

1. Introduction

In recent years, terahertz (THz) technology has received attention and developed remarkably, particularly in fields of THz generation and detection [1,2]. In order to realize THz devices, development of elements that enable control of THz waves are necessary. Nematic liquid crystals (NLCs) have been proposed as candidate materials for such devices because of its birefringence, electric field response and high transparency in the THz region [3,4]. There have been several devices using NLCs such as phase shifters [5,6], modulators [7], switches [8] and filters [9]. These devices required a thick NLC layer which is several 100 μm to few mm to control the propagating THz waves with a wavelength of about several hundred micro meters. This requirement enlarges the size of devices and also deteriorates the electro-optic performance: the response of the NLCs to the electric field is hindered to even minutes. Although a thin NLC layer could overcome this problem since

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the response speed of NLC is proportional to the thickness of the NLC layer [10], the thin NLC layer poorly affect the propagating THz waves because of luck of optical path length. An etalon which is an optical resonator consisting of two high-reflectance mirrors separated by a dielectric core material has potential to be resolution of the problem. It transmits at well-defined wavelengths related to the thickness and the refractive index of the core. The core thickness d is given by the expression $d = m\lambda/2n$ where the integer m is the mode number, λ is the transmission wavelength and n is the refractive index of core, respectively. As shown by the expression, the thin core could be obtained while possessing an ability of affecting the propagating THz waves. The NLC etalon consisting of two indium tin oxide (ITO)-coated mirrors was proposed as a THz filter [11] using only 150 μm NLC layer as the core. However, transmission amplitude of ITO in the THz region is very small [12].

Here, we propose the etalon consisting of no ITO, two dielectric mirrors composed of water-free fused silica glass plates whose absorption of THz waves is quite low and air layers. In the etalon, the NLC layer is used as the core material. Frequency tuning of the transmission peak is demonstrated when NLC alignment reoriented from homeotropic to planar alignment by applying an electric field. We also show that switching times of several seconds can be achieved because of the thin NLC layer.

2. Material Properties, Device Structure and Fabrication

We first measured the complex refractive indices of NLC (E47, Merck) in the 0.5–1.5 THz range at 20°C. We determined the real parts of ordinary and extraordinary complex refractive indices (n_o and n_e) of the NLC by measuring the time delay of linearly polarized THz waves passing through a 350 μm-thick NLC layer aligned planarly which was sandwiched between two fused silica substrates. Similarly, we determined the imaginary parts of ordinary and extraordinary complex refractive indices (κ_o and κ_e) by measuring the transmittance. We obtained ordinary and extraordinary complex refractive indices by rotating the cell against polarized incident THz waves. The complex refractive indices and birefringence are shown in Fig. 1. The refractive indices n_o varied from 1.53 to 1.56 and n_e varied from 1.67 to 1.69, respectively. The measured imaginary part κ_o varied from

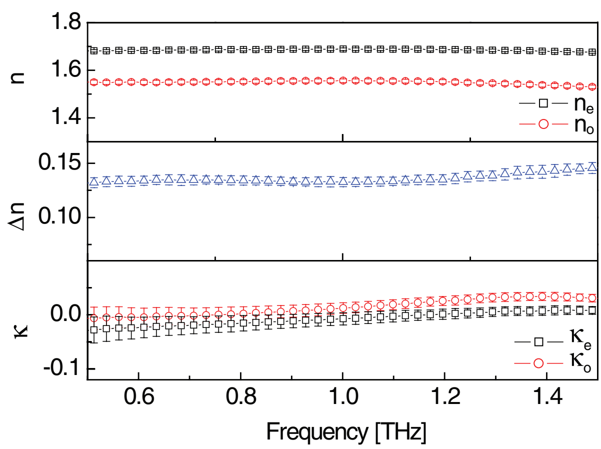

Figure 1. Complex refractive indices and birefringence of the E47 in the terahertz frequency range.

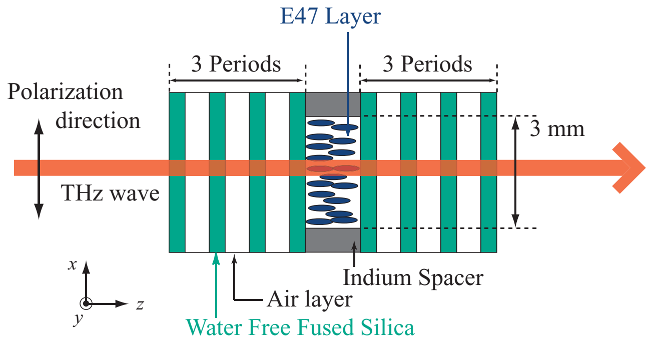

Figure 2. The cross-section of designed etalon structure.

−0.01 to 0.03 and κ_e varied from −0.03 to 0.01, respectively. The reason for the negative value of the imaginary part can be explained by the Fresnel equations which describe the transmittance of light passing through two materials which are in contact [14]. From the Fresnel equations, the transmittance of *s*-polarized and *p*-polarized light are described as $T_s = \sin 2\theta_i \cos\theta_t / \sin^2(\theta_i + \theta_t)$ and $T_p = \sin 2\theta_i \cos\theta_t / (\sin^2(\theta_i + \theta_t)\cos^2(\theta_i + \theta_t))$ respectively where θ_i is incident angle and θ_t is refraction angle respectively. In this experiment, θ_i was not zero since the THz waves were focused on the samples. The equations indicate that the large difference of refractive indices of two materials lead to low transmittance. The n_e was closer to the refractive index of fused silica which is 1.95 than reference, or air, then the transmittance increased according to the Fresnel equations.

The cross-section of device structure we designed is schematically shown in Fig. 2. The etalon was composed of alternating stacks of water-free fused silica glass plates and air layers for 7 periods, and contained the NLC layer in the center. Using refractive indices 2.05 and 1.0 in the THz region for the water-free fused silica glass plate and air respectively, the thickness of each layer was designed to be 37 μm and 75 μm respectively. The air layers were obtained by using 75 μm-thick Polyethylene terephthalate (PET) sheets which were punched the hole at the center. The NLC defect layer thickness was designed to be 100 μm using two 100 μm-thick indium spacers, and the water-free fused silica glass plates which sandwiched the NLC layer were coated with polyimide (JALS-2021-R2, JSR) to induce homeotropic alignment. The indium strips were separated by 3 mm and used as electrodes to apply an in-plane electric field. We observed the thickness difference between the design and the fabricated etalon. To detect what caused this difference, we measured the height profile of the PET sheet by laser microscope (VK-9710, KEYENCE). In Fig. 3, the picture and measured height profile of the PET sheet is shown and the burrs whose thickness was ∼15 μm were found to exist at the edge of the hole. The difference is attributed, therefore, to the burrs which made the air layers thicker and bended the water free fused silica glass plates leading to making the NLC layer thinner, or the air layer thickness found to be 90 μm and the NLC layer thickness found to be 75 μm. Thus, although the fabricated etalon had the difference with the design, we obtained the etalon with the thin NLC defect layer.

3. THz Transmission Properties of the Etalon

We measured the transmittance of the device by means of terahertz time-domain spectroscopy (THz-TDS) which is described in detail in refs. [2] and [13]. The incident THz wave was polarized along the short molecular axis (x-direction in Fig. 2). We applied an

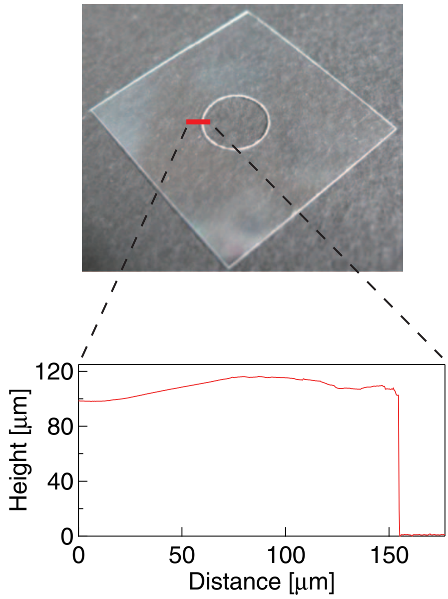

Figure 3. The picture of the used PET sheet which was punched at the center and its height profile of the burrs.

AC electric field (1.1 kHz) of 5 kV/cm between the indium spacers to reorient the NLC into planar alignment which was originally aligned homeotropically. Upon reorientation, the refractive index which the THz wave experiences shifts from n_o to n_e, and frequency tuning of the transmittance peak can be achieved. Figure 4(a) shows the experimental transmittance spectra where a shift in the transmission peak frequency from 1.025 THz to 1.013 THz is observed upon applying the electric field. The low transmittance region existing over 1.2 THz can be attributed to the absorbance of water vapor in the air. In addition, the low transmission peak amplitude was caused by spatially-distributed variation in NLC layer-thickness. As mentioned before, the transmission frequency of the etalon is decided by the expression $2ndf = mc$ where n is the refractive index of the NLC, d is the thickness of the NLC layer, f is the transmission frequency, the integer m is the mode number and c is the velocity of light, respectively. In other words, the incident THz waves whose diameter was ~3 mm felt the variation in the area and THz waves of many frequencies can pass which was decided by each variable NLC layer-thicknesses. As a result, the measured transmission peak reflected envelope of each transmission peaks and then the total transmittance decreased. The device was also numerically modeled by the 4×4 matrix method [15]. The fitting parameters of the NLC layer thickness of 75 μm and the air layer of 90 μm as mentioned before was adopted and good agreement with the measured spectra was obtained as shown in Fig. 4(b). Thus, 12 GHz frequency tune was achieved with only 75 μm-thick NLC layer.

4. Electro-Optic Response of the Etalon

We investigated the response speed of a 75 μm-thick E47 sandwich cell to evaluate the response speed of our device. The NLC molecules were homeotropically aligned, and

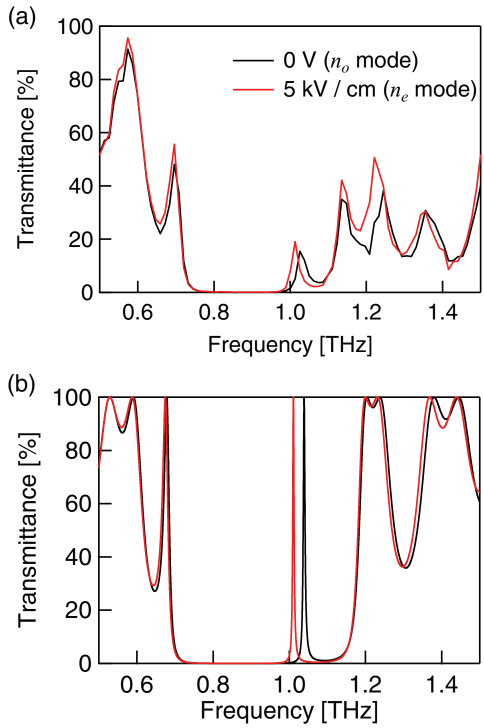

Figure 4. (a) Measured transmission peak shift of the etalon by applying voltage. (b) Calculated transmission peak shift of the etalon by change of alignment.

75 μm-thick aluminum strips which were used as both spacers and electrodes and were separated for 3 mm. The fabricated cell was placed between crossed polarizers and an electric field was applied at an angle of 45° to the polarization direction. When there was no electric field, there was no birefringence and so light could not pass through the analyzer. When the electric field was increased, the NLC molecules reorient to planar alignment leading to inducing birefringence and the incident light could pass through the analyzer. We turned on/off an electric field (1.1 kHz) of 5 kV/cm and measured the changing transmitted light intensity of a He-Ne laser (632.8 nm) through the analyzer. Rise and decay times defined as times when the intensity changes from 0.0 to 0.9 (arb. units) and from 1.0 to 0.1 (arb. units) respectively were estimated. Figure 5 shows measured time-dependent intensity and the rise and decay times were estimated as 5.3 s and 12.2 s respectively. Because of the thinner NLC layer, the response times were found to be 10 times faster than previous THz NLC devices [6]. This result pointed out that the thin NLC layer in the THz NLC devices was very effective to achieve fast response speed. The sharp intensity peak which is shown in Fig. 5(a) at around 0.02 s can be attributed to the optical bounce caused by the back flow effect [16]. When a strong electric field is applied rapidly, fast rotation of NLCs in the middle of the NLC cell generates a torque which makes NLCs near the substrates tilt in the opposite direction. Then the NLCs near the substrates turn back leading to optical bounce. Since this phenomenon is known to deteriorate response speed, eliminating the optical bounce could result in faster response speed [17].

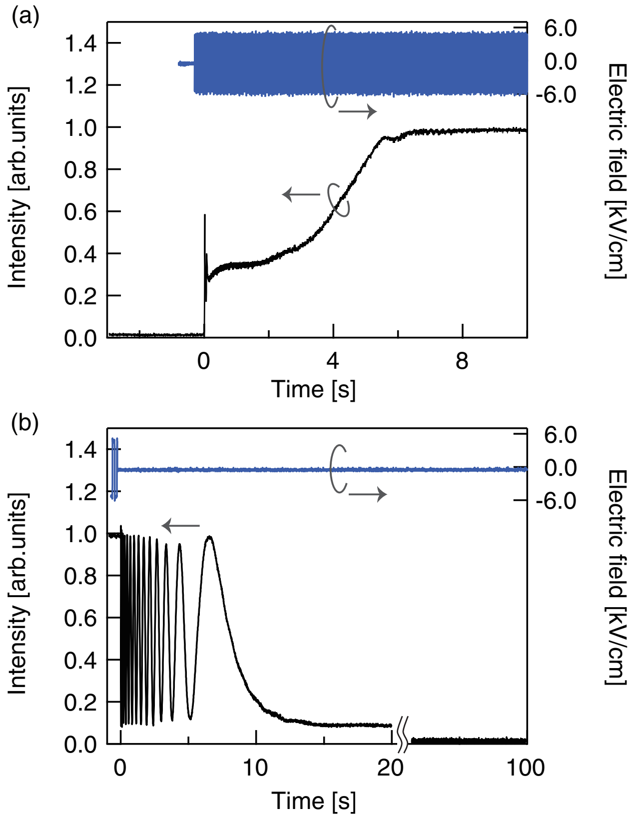

Figure 5. Measured rise time (a) and decay time (b) of the E47 homeotropic cell.

5. Conclusion

We demonstrated a tunable THz filter using an etalon with a 75 μm-thick homeotropically-aligned NLC layer. The transmission peak tuning from 1.025 THz to 1.013 THz was achieved. We also found the rise and decay times of the NLC layer to be 5.3 s 12.2 s respectively which is 10 times faster than previous THz LC devices because of thin NLC layer. In addition, eliminating the observed optical bounce could achieve faster response speed.

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