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Tuneable Fabry–Perot etalon for terahertz radiation

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Abstract. An indium tin oxide-clad liquid crystal filled Fabry–Perot etalon structure has been shown to act as an effective narrow-band filter at terahertz frequencies. An applied voltage, which controls the alignment of the nematic liquid crystal allows the refractive index of the core to be tuned. Transmission spectra show well-defined resonant peaks which shift in position when the alignment is changed from planar to homeotropic. The measured transmission spectra agree well with the results of a multilayer optics model and the birefringence of the liquid crystals over this frequency range are determined as $\Delta n = 0.15(\pm 0.01)$ and $\Delta n = 0.08(\pm 0.01)$ for E7 and ZLI 2293, respectively.

Contents

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1. Introduction

Interest in the use of terahertz (THz) radiation is extensive and being able to manipulate such radiation with conventional low voltage electronics, in a similar manner to which light is controlled using liquid crystals, would be very advantageous. One such geometry which is extensively utilized at visible frequencies is the liquid crystal Fabry–Perot filter. A Fabry–Perot filter is a simple optical resonator consisting of two partially reflecting surfaces (generally dielectric stacks) separated by a dielectric core material. They transmit at well-defined wavelengths related to the reflector spacing and the refractive index of the core. In a liquid crystal Fabry–Perot etalon [1]–[4], the core region is filled with a uniaxial, optically anisotropic liquid crystal, the alignment and hence refractive index of which can be controlled by an applied voltage.

Before the application of liquid crystals at THz frequencies in devices such as Fabry–Perot etalons can be achieved, there are several practical issues to overcome. Firstly, with THz wavelengths $\sim$100 μm or more, wavelengths are of the order of the coherence length of a liquid crystal aligned by surface treatments alone. Previously, a liquid crystal has been successfully used as the active material in a magnetically tuneable Lyot filter for THz radiation [5]. However, as with other studies using liquid crystals at THz wavelengths [6, 7] strong external magnetic fields were required to align the liquid crystal over a thickness of several millimetres. In addition, the scattering losses associated with the thermal fluctuations of the liquid crystal material aligned over such thicknesses are significant. Secondly, the application of appropriate reflecting surfaces is highly problematic in this frequency range. At THz wavelengths, dielectric stacks would be rather thick and may lead to high insertion losses (although advances in the use of silicon and air multilayer stacks have recently been reported [8]). For the development of a liquid crystal Fabry–Perot interferometer one tends to consider the use of metallic mirrors, particularly as this will allow the application of the required voltages to the liquid crystal. However, this is not straightforward, as even metal layers as thin as 20 nm are almost completely opaque to THz radiation.

In this study, we show that an indium tin oxide (ITO)-clad liquid crystal filled Fabry–Perot etalon structure with a core thickness $\sim$150 μm acts as a tuneable effective narrow-band filter at THz frequencies. ITO has been used for many years as a transparent electrode for use in liquid crystal displays due to its high transmission in the visible range of the electromagnetic spectrum. However, in the THz range thin ($\sim$23 nm) layers of ITO, a poor conductor, is a good Fabry–Perot reflector. Importantly, it can also be used to apply an electric field across the liquid crystal layer, thereby allowing the modulation of the etalon transmission. Through experimental study and modelling, we characterize the THz optical properties of both the reflective ITO and the active liquid crystal core, and assess the birefringence of two liquid crystals (E7 (BL001) and ZLI 2293 (both from Merck, KGa)) in this frequency range.

For radiation incident on a Fabry–Perot etalon at normal incidence the resonant modes of the cavity are approximately given by the expression $2ndf = mc$, where n is the refractive index of the core, d is the core thickness, the integer m is the mode number and f is the frequency of the radiation. A core with a thickness in the region of 150 μm will act as a resonant cavity for radiation in the THz range (0.2–2.0 THz). Crucially, good alignment of a nematic liquid crystal can simply be achieved over this distance through the use of a thin surface alignment layer. In a planar aligned cell at zero volts the director (a vector describing the average molecular direction) is parallel to the cell substrate. In this case, with incident radiation polarized parallel

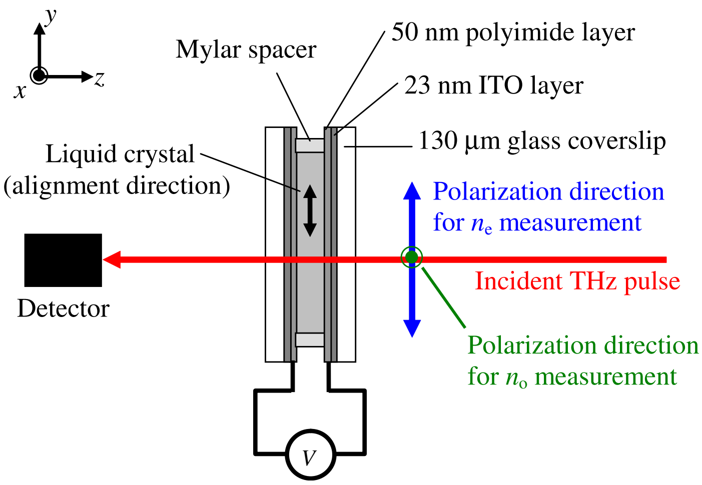

Figure 1. Schematic diagram of the planar aligned nematic liquid crystal cells used during the data-collection process.

to the director, the incident radiation senses the extra-ordinary index. When a voltage is applied across the etalon the liquid crystal layer aligns homeotropically (perpendicular to the substrate) and the ordinary refractive index is accessed. This means that the resonance transmission of the structure changes and also it allows measurements of both refractive indices.

2. Experimental method

Two $\sim$150 μm thick planar-aligned liquid crystal cells were constructed using 0.13 mm thick glass coverslips coated in a $\sim$23 nm layer of ITO as substrates. A 50 nm layer of polyimide (JSR AL-1254) was spun down on to each ITO surface and rubbed to induce strong planar alignment. The cells were then assembled using mylar spacers along each edge. One cell was filled at room temperature with E7 and the other with ZLI 2293 and both were then sealed. Examining the cells optically between crossed polarizers showed that in both cases a good planar monodomain was produced over the whole cell, and further a well-aligned homeotropic (vertical) state was produced when a 10 kHz 35 V_{rms} voltage was applied.

The E7 cell was mounted at normal incidence, with the rubbing direction parallel to the polarization of the incident beam (figure 1), in a THz time-domain spectroscopy (THz TDS) set-up similar to that described in [9]. This technique, with its ability to recover both amplitude and phase of transmitted radiation, allows access to both the real and imaginary parts of the refractive index (see below). The THz TDS data were collected in transmission with the cell shorted. A 10 kHz 35 V_{rms} voltage was then applied to the cell to produce homeotropic alignment and the data collection process was repeated. The cell was then rotated azimuthally through 90°, i.e. with the rubbing direction perpendicular to the incident polarization state, and the 0 V and 35 V_{rms} data collection was repeated. This procedure was then duplicated with the ZLI 2293 filled cell. By taking the Fourier transform of each set of data, the transmitted intensity versus frequency for each cell configuration was recovered. This was then normalized to the beam intensity collected without a sample in place to obtain the absolute intensity versus frequency data for each data

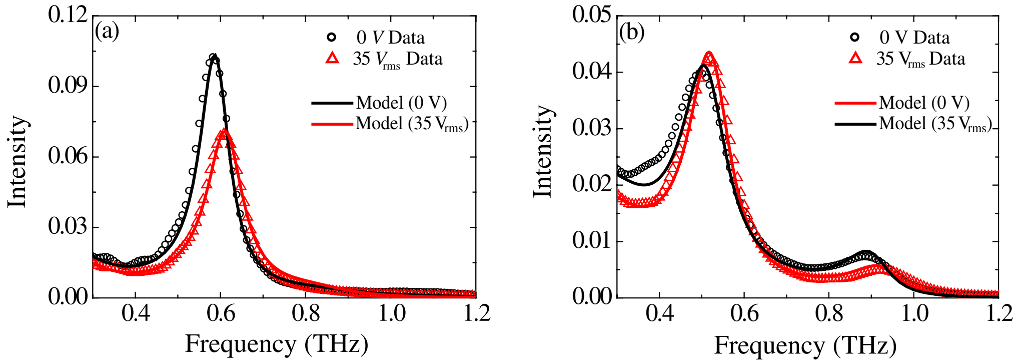

Figure 2. Measured and modelled normalized transmitted intensity versus frequency for planar aligned (0 V) and homeotropically aligned (35 V_{rms}) cells containing (a) E7 and (b) ZLI 2293.

set. To allow the dispersion of the glass and ITO to be independently determined the frequency-dependent transmission through a single glass coverslip, and then an ITO-coated glass coverslip were also measured separately and normalized using the THz TDS set-up.

3. Results and discussion

The data collected from the E7-filled cell is shown in figure 2(a). It is immediately evident that the structure is acting as a narrow-band filter at the position of the fundamental resonance of the system. A sharp, single transmission peak is seen at 0.588 THz for the 0 V (extra-ordinary) refractive index measurement. On switching the cell to the homeotropically aligned state this resonance position shifts upwards in frequency to 0.612 THz and noticeably reduces in intensity (due to differences in absorption along the ordinary and extra-ordinary axes). As expected from the uniaxial nature of the liquid crystal, these homeotropic data were identical to the 0 V and 35 V_{rms} measurements made with the director at 90° to the polarization direction (data not shown). In comparison, the data collected, with the incident polarization along the rubbing direction, from the ZLI 2293 cell at 0 V (figure 2(b)) shows a broader peak at 0.500 THz and a second, shallower resonance at 0.888 THz. On application of the 35 V_{rms} voltage, these resonances increase slightly in frequency to 0.517 and 0.908 THz, respectively. Compared to the E7 data the intensity of the ZLI 2293 is significantly lower, suggesting a much higher absorption of the THz radiation.

To obtain quantitative information about the ITO and liquid crystals at THz, we proceeded as follows: firstly, by solving the Fresnel equations [10] for the transmission spectra from the plain glass coverslip and then the ITO-coated glass coverslip, the dispersion of the glass and ITO were determined independently (figure 3). Figure 3(a) shows that the absorption of the glass increases rapidly with frequency. This limits the spectral range and absolute transmissions of the Fabry–Perot etalons. Figure 3(b) shows the measured dispersion of the 23 nm ITO layer. These data show good agreement with a simple Drude model [11] (lines in figure 3(b)) with a plasma frequency of 1600 THz and a damping constant of 50 THz.

To obtain the real and imaginary parts of the refractive indices of the liquid crystals the absolute intensity versus frequency data (figure 2) were fitted using a uniaxial multilayer

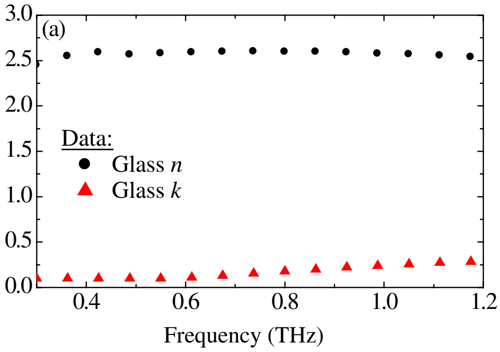

Figure 3. Measured dispersion over the spectral range used in the experiment of the refractive index and absorption of (a) glass and (b) ITO (including the results from the Drude model using the values given in the text).

Table 1. Summary of measured liquid crystal refractive indices at THz frequencies for E7 and ZLI 2293 and comparison with published values at visible and microwave frequencies (where available).

	E7			ZLI 2293		
Frequency	n_o	n_e	Δn	n_o	n_e	Δn
Visible [15, 16] (474 THz)	1.52 + 0.0007i	1.737 + 0.002i	0.217	1.500 + 0.0002i	1.639 + 0.001i	0.139
Terahertz (0.2–1.2 THz)	1.609 + 0.009i	1.761 + 0.006i	0.152	1.566 + 0.06i	1.644 + 0.05i	0.078
Microwave [17] (50–75 GHz)	1.654	1.780	0.136	–	–	–

optics model based on a 4×4 Berreman matrix [12] method. This technique calculates the transmission through a multilayer stack by solving Maxwell's equations at each interface, taking into account multiple reflections at each boundary. The refractive index of the core was described as a uniaxial material aligned along the y-axis when shorted and along the z-axis when the voltage was applied. As the glass and ITO parameters had already been determined independently and the optical effect of the ultra-thin polyimide layer was negligible, the only fitting parameters required were the complex refractive index and thickness of the liquid crystal core. The results of this modelling are shown as the solid lines in figures 2(a) and (b) and show reasonable agreement with the general features of the data. For the E7 liquid crystal, the best fit was obtained using a core thickness of $150(\pm 1)\,\mu$m with $n_o = 1.609(\pm 0.005) + 0.009(\pm 0.001)$i and $n_e = 1.761(\pm 0.005) + 0.009(\pm 0.001)$i and for the ZLI 2293, a core thickness of $195(\pm 1)\,\mu$m with $n_o = 1.566(\pm 0.005) + 0.061(\pm 0.001)$i and $n_e = 1.644(\pm 0.005) + 0.049(\pm 0.001)$i. These refractive index values, along with the birefringence ($\Delta n = n_e - n_o$) measured in the THz frequency range, are compared with published values for the liquid crystal birefringence at visible and microwave frequencies (where available) in table 1.

From table 1, it is clear that the absorption of the liquid crystals studied here is far more pronounced at THz than at optical frequencies. Indeed from the measurements in figure 2, the finesse of the cavity is estimated as only 5.70 and 5.45 for E7 at homogeneous and homeotropic alignment, respectively, and as 3.56 and 4.15 for ZLI 2293. These values, determined by the absorption in both the liquid crystal and ITO layers, fall well below those for optimized Fabry–Perot etalons designed for the visible range of the spectrum [13]. Moreover, the tuning range of our THz etalon is lower than at optical frequencies [14], determined by the birefringence of the liquid crystal core. Further from table 1, the birefringences of the liquid crystals studied here appear to increase strongly with frequency. It is therefore crucial for future applications of liquid crystal technology at THz frequencies that the minimization of the absorption and optimization of birefringence of these materials is addressed. In addition, by using a suitably strong surface aligner at the liquid crystal/ITO interface the thickness of the core may be increased to accommodate the higher order Fabry–Perot modes and increase the tunability.

4. Conclusions

In conclusion, an ITO-clad liquid crystal filled Fabry–Perot etalon has been constructed and has been shown to be an effective structure for controlling the resonant transmission of THz radiation. By exploiting the uniaxial nature of the liquid crystalline material, the position of the sharp transmission peaks has been tuned by 24 GHz for the E7 filled cavity and 17 GHz when filled with ZLI 2293. By comparing the measured absolute transmission as a function of frequency with model data, the birefringence of these materials has been measured as $\Delta n = 15(\pm 0.01)$ and $\Delta n = 0.08(\pm 0.01)$, respectively. This work shows that, by combining this novel ITO-clad Fabry–Perot etalon with a liquid crystalline material designed specifically to possess a high birefringence and low absorption in the THz range, a highly tuneable, narrow-band filter for THz applications should be possible.

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