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Extracting Material Properties from a Liquid Crystal Cell Using Terahertz Spectroscopy

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***Abstract*—Liquid crystal materials that demonstrate birefringence at terahertz frequencies present an opportunity for the development of adaptive terahertz optics. Liquid crystal devices often consist of several optical layers surrounding a thin liquid crystal film, which can make extraction of the material parameters challenging. Using broadband THz spectroscopy, we present a thin-film analysis of a liquid crystal device with a commercially available liquid crystal material (E7), up to 4 THz.**

I. Introduction

Liquid-crystals (LCs) are widely used at optical frequencies for adaptive and controllable optics, dynamic beam focusing, and power modulation, with similar devices highly sought after in the terahertz (THz) frequency range. However, to date there have been very few studies of LC materials or devices above 1 THz. Here, we present a study of a commercially available LC material (E7), using broadband THz spectroscopy, and discuss the data analysis challenges of extracting thin-film material parameters from a multi-layered structure.

II. Results

The liquid crystals devices discussed in this work were designed to be transmissive at THz frequencies, to allow characterization of the liquid crystal layer. Typical materials used for liquid crystal devices at visible wavelengths (see glass slide substrates [1] and indium-tin-oxide (ITO) electrode layers [2]) show strong absorbance in the THz frequency range. By using fused quartz slides as the window substrate, a conductive polymer, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), as the electrode layer [3], and a long-chain polyimide (SE-3510) layer to ensure liquid crystal alignment within the device, a THz transmissive cell was constructed. This LC cell was filled with a commercial nematic LC material, E7, which was chosen owing to its ready availability and relatively large birefringence at lower (< 2THz) THz frequencies [4]. The LCDs were assembled using standard LC fabrication techniques in a parallel plate arrangement, with wires connected to the electrode layers. A 5 kHz sinusoidal voltage (V_{rms}) was applied to the electrodes, causing the LC director to orientate perpendicular to the windows. Two devices are discussed here; a LCD manufactured without electrode layers and a 320 µm thick (nominal) LC layer used to characterize the material parameters of the E7 material, and a LCD with electrode layers and a 100 µm thick (nominal) LC layer used to investigate the effect of a LC bias on the THz transmission through the LCDs.

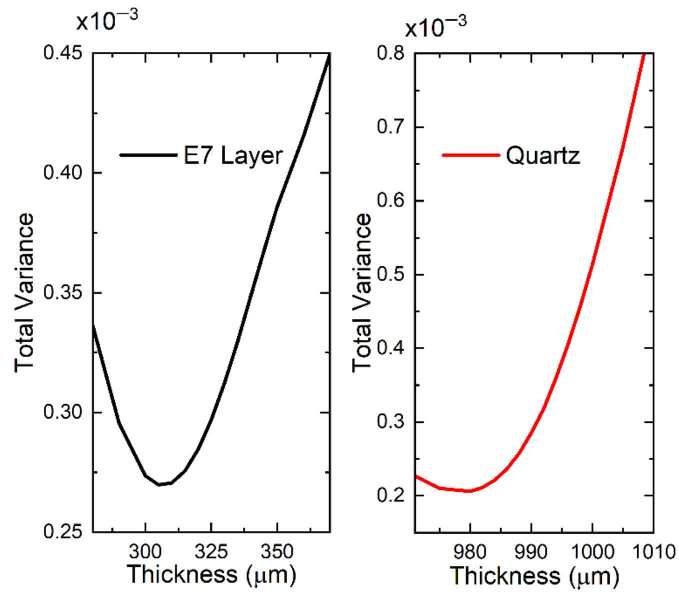

Fig. 1. Shows the thickness of the LCD layer (left pane) and fused quartz window (right pane) extracted from a total variance analysis of the THz-time domain signal [6]

THz time-domain spectroscopy was used to characterize LCDs over a 0.3–8.0 THz bandwidth [5] at a range of voltages, and the complex refractive indices of the LC material were extracted numerically from the THz-TDS signal. This was achieved in several steps. Reference data from the constituent components of the LC cells provided the complex refractive indices of the constituent layers. Subsequently, a transfer function of the THz radiation passing through the LCD was calculated, using the data processing tool Nelly [7, 8] and combined with a total variance analysis to establish the thicknesses of the individual layers in the LCD (see Figure 1.) [6] This allowed for both the thickness and the complex refractive index of the liquid crystal material E7, to be isolated from the main THz signal.

Figure 2 shows the data calculated for the 320 µm thick device, with the refractive indices and absorption coefficients of both the extraordinary and ordinary axes of the liquid crystal. This is shown as a shaded area, indicating the error on the measurement, estimated from a combination of an analysis of the effect of time-domain truncation on the extracted complex permittivity, with the uncertainty of the thickness of the liquid

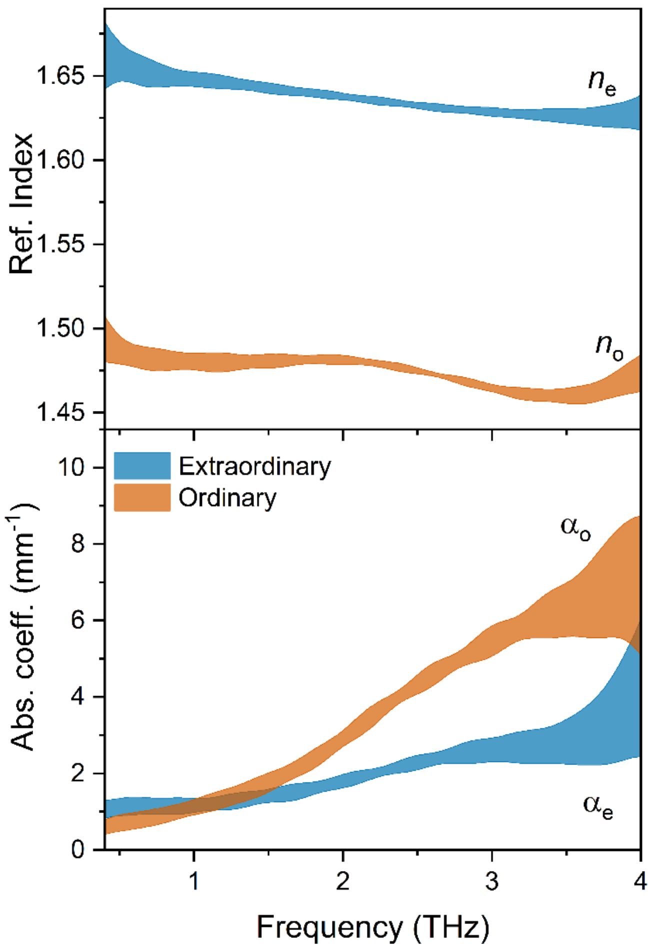

Fig. 2. Refractive indices and absorption coefficient of the extraordinary and ordinary axes of the E7 liquid crystal material, extracted from the terahertz time-domain measurements of a LCD with a 320 μm thick liquid crystal layer. The calculated values and errors are shown as a shaded region.

crystal layer, as well as repeat measurement.

The extraordinary and ordinary refractive indices are seen to be distinct from one another, suggesting reasonable mono-domain alignment of the LC layer, although the magnitudes of these refractive indices are slightly lower than measured previously [4, 9, 10]. The authors note that there is already a slight variation in the literature values depending on the LC layer thickness and data extraction method used. The use of total variance analysis in this work allows the thickness of the LCD layers to be determined *in situ*, whereas previous works have relied on nominal values. Both n_o and n_e remain relatively flat above 2 THz, which is consistent with behavior observed below 2 THz [4, 9, 10]. A phonon present in fused quartz centered at ~5 THz limits the measurable bandwidth to 4 THz.

The change in the THz transmission through the device was measured as a function of the bias voltage applied to the LC layer, relative to the transmission through the unbiased LC device. The THz transmission through the ordinary axis was seen to remain constant regardless of the bias voltage applied to the LC layer, as expected from the orientation of the LC molecules in the cell. The THz transmission was seen to decrease with increasing bias voltage along the extraordinary axis, which is shown in Figure 3 for the LCD with a 100 μm thick (nominal) LC layer. This is broadly explained by the linear dichroism between the extraordinary and ordinary axes of the LC material. Owing to the refractive index values of the window substrate and layer materials, the fused quartz windows act as an etalon, reflecting approximately 5% of the THz signal at each LC/electrode/quartz interface and 10% at the quartz/air interface. These reflections in the time-domain THz signal translate into oscillations in the frequency-domain, with a frequency dependence on the bias voltage applied to the liquid crystal layer. This is shown in Figure 3 as solid lines showing the full time-domain data (untruncated). By truncating the data to before the first etalon reflection, it is possible to minimize their effect on the resulting data, which is shown as dashed lines in Figure 3.

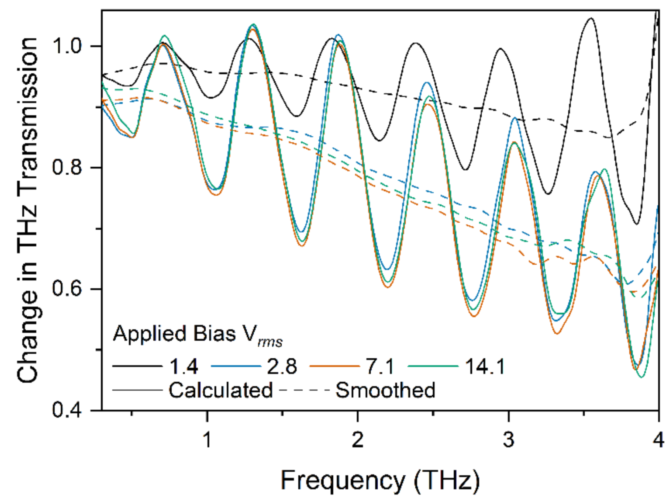

Fig. 3. Change in THz transmission through the extraordinary axis of the 100 μm thick LCD for untruncated (solid lines) and truncated (dashed lines) data at different LC bias voltages.

III. Conclusions

We have characterized the liquid crystal material E7 up to 4 THz, using a total variance analysis and a fitted transfer function of THz radiation passing through a LCD to extract the data for the thin liquid crystal layer. Biasing the liquid crystal device results in a change in THz transmission through the liquid crystal layer, caused by a combination of the linear dichroism of the liquid crystal material and the etalon reflections of the THz radiation at the LC/electrode/quartz interfaces.

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