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Development of Advanced Terahertz Optics Using Liquid Crystals

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***Abstract*—Liquid crystal devices manufactured with a commercially available material (E7) have been characterized with THz time-domain spectroscopy up to 4.5 THz. These LCDs were used to modulate the power output of a 3.4-THz quantum-cascade laser, attenuating the THz power through the device by up to 40% dependent both on the liquid crystal layer thickness and bias voltage applied.**

I. INTRODUCTION

LIQUID-CRYSTALS (LCS) are widely used in adaptive and controllable optics, enabling dynamic beam focusing, and power modulation in infrared and visible systems. Similar approaches are highly desirable in the terahertz (THz) band — for example, to compensate for source-power fluctuations, or atmospheric turbulence. However, to date, there have been very few studies of LC materials or devices above 1 THz. Here, we present the first controllable LC attenuators designed for operation in the >1 THz band and demonstrate their potential use in controlling the emission power from a 3.4-THz quantum cascade laser (QCL) with modulation depths in excess of 40%.

II. RESULTS

Typical materials for the manufacture of liquid crystal devices, such as glass slides for the substrates [1] and indium tin oxide (ITO) for the electrode layer [2], are ideal for visible wavelengths but show strong absorbance in the THz regime. To ensure that the LCDs were transmissive at THz frequencies, different materials had to be considered. Fused quartz slides were chosen as the window substrate owing to its transmission properties in both the visible and THz frequency regions. A conductive polymer, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), was chosen for the electrode layer which provides a transmittance of up to 83.5% at 1.22 THz and a conductivity comparable to a sputtered ITO thin film [3]. The commercial nematic LC material, E7, was used owing to its ready availability and relatively large THz birefringence and hence anisotropy [4]. A long-chain polyimide (SE-3510) layer was used to ensure liquid crystal alignment within the device. The LCDs were assembled using standard LC fabrication techniques in a parallel plate arrangement, shown in Figure 1, and wires were connected to the electrode layers. A 5 kHz sinusoidal voltage (V_{rms}) was applied to the electrodes, causing the LC director to begin to reorient perpendicular to the windows. Two devices were investigated, with LC thicknesses of 13 µm and 100 µm respectively.

THz time-domain spectroscopy was used to characterize the materials over a 0.3–8 THz bandwidth [5] at a range of voltages. The complex refractive indices of the LC material

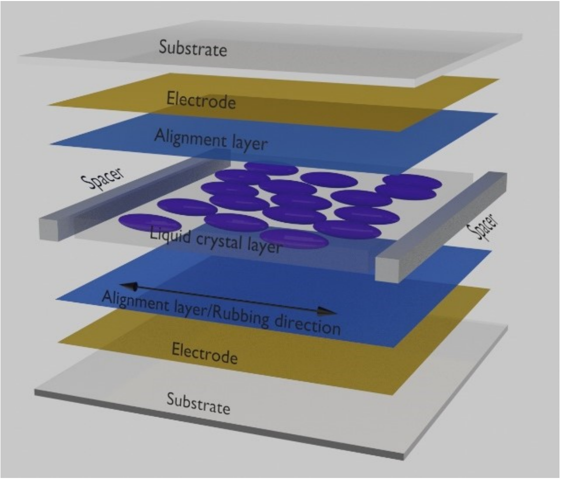

Fig. 1. Illustration of the structure of a conventional homogenous (planar) liquid crystal device with a parallel plate electrode.

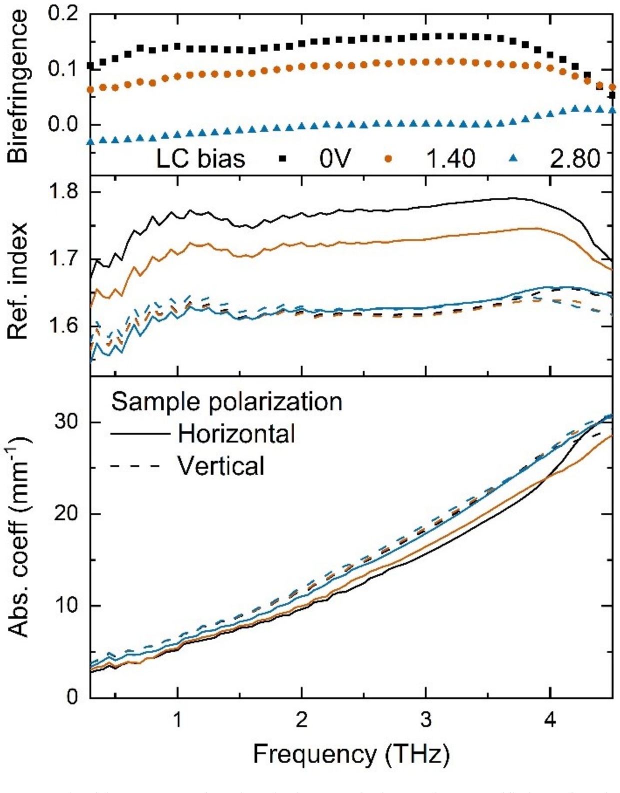

Fig. 2. Birefringence, refractive index, and absorption coefficient for the 100 µm LCD unbiased (black) and biased (V_{rms}) at 1.4 V (orange) and 2.8 V (blue).

were extracted numerically from the THz-TDS signal. This was performed by the fitting of a transfer function using the data processing tool Nelly [6]. By using reference data from the constituent components of the liquid crystal cells, the refractive indices and thicknesses of the fused quartz, PEDOT:PSS electrode layers and polyimide alignment layers were deduced and used to calculate the transfer function of the THz radiation passing through the LCD. This allowed for the complex refractive index of the liquid crystal material, E7, to be determined. Data are shown in Figure 1 for the 100 µm thick LCD.

A clear difference between the two liquid crystal axes is observable in the refractive index and absorption coefficient data shown in Figure 2. A birefringence of ~0.16 was determined within the range 1–4 THz for the unbiased LC material, tending towards zero as the bias voltage was increased. Data are limited to below 4.5 THz owing to a phonon present in fused quartz at ~5 THz. However, this still provides a large useable bandwidth for a wide variety of THz sources.

A linearly polarized, collimated beam from a 3.4-THz QCL [7] was passed through the LC device, which was orientated with the director parallel to the polarization direction and the transmitted power was measured using a helium-cooled bolometer. Modulation depths of 5% and 40% were achieved by adjusting the bias on the 13 µm and 100 µm devices respectively (Figure 3a and b). It was observed that when the LC director was perpendicular to the polarization direction of the THz radiation there was no change in the THz transmission in the device for increasing bias voltage. The modulation speed depends on bias voltage, with minimum fall times of 0.9 ± 0.1 s for a 2.5 V_{rms} bias, and 5 ± 0.2 s at a 14 V_{rms} bias for the respective devices. Rise times increase with modulation depth: on the order of a few seconds, or upwards of 400 seconds for the respective devices. The modulation depths and speeds were independent of the THz source power.

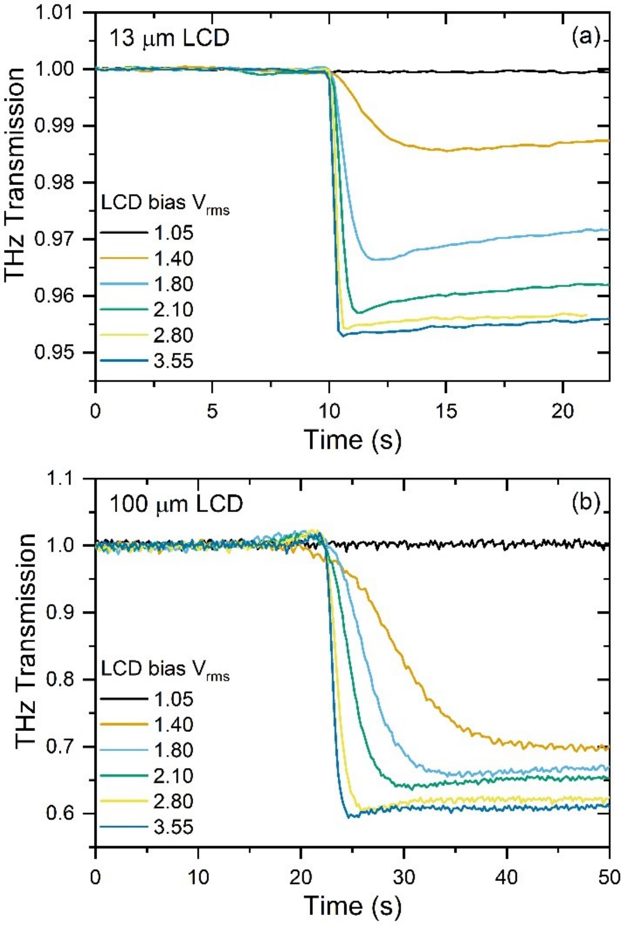

Fig. 3. Change in THz transmission through (a) the 13 µm LCD and (b) the 100 µm LCD at various bias voltages. Data was normalized to the THz transmission through the unbiased LCD.

III. CONCLUSIONS

We have characterized the liquid crystal material E7 up to 4.5 THz and have demonstrated that these liquid crystal devices can be used to modulate the power output of THz sources such as QCLs. Whilst power modulation offers immediate potential, liquid crystals that are birefringent at THz frequencies present opportunities for the development of THz optics such as variable wave plates, wave shifters, and wave modulators.

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