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Dual Frequency Liquid Crystals for Terahertz Power Stabilization

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Abstract—Liquid crystal (LC) devices have a wide range of applications in electrically controlled adaptive optical devices. However, these devices have much slower operating speeds in the THz band than in the visible band, owing to the need for thicker active layers. A new device was fabricated using a dual-frequency LC which overcomes the speed limitations by allowing both electrically driven switch-on and switch-off transitions. This device showed a transmission of $\sim 7\%$ at 3.4 THz, with modulation depths of 60%, along with a maximum modulation rate of 20 Hz.

I. INTRODUCTION

LIQUID CRYSTALS (LCs) are an important tool for adaptive optics, especially in the visible band where they are the most commonly used. LC devices are now available from the ultraviolet range all the way to the microwave regime.

In the case of nematic (rod-like) LCs, an applied AC electrical bias causes the constituent molecules to align with the generated electric field. This introduces a voltage controllable birefringence ($\Delta n = n_o - n_e$), and linear dichroism ($LD = A_{\parallel} - A_{\perp}$).

The controllable birefringence of LCs enables a range of potential applications in the Terahertz (THz) band, such as phase shifters [1] and beam steerers [2]. The controllable linear dichroism (i.e. a difference in absorption depending on the polarization of the incident light), allows for devices that can control the phase or attenuation of the light passing through. This effect, therefore, has potential for use in controllable THz attenuators, polarizers or power stabilization systems.

Owing to the much longer wavelength of THz radiation when compared to visible light, the thickness of the LC layer must increase significantly for the same effect. This increase has a major impact on the switching speed of subsequent LC devices, which are well approximated by the general equations [2.1,2.2],

$$\tau_{\text{off}} = \frac{\gamma_1 d^2}{K_x \pi^2}$$

$$\tau_{\text{on}} = \frac{\tau_{\text{off}}}{|(V/V_{\text{th}})^2 - 1|}$$

$$V_{\text{th}} = \left(\frac{K_x}{\epsilon_0 \Delta \epsilon} \right)^{1/2}$$

where γ_1 is the rotational viscosity of the LC, V_{th} is the threshold voltage for switching, $\Delta \epsilon$ is the dielectric anisotropy, and K_x is one of the LC elastic constants dependent on cell geometry. Typically for a cell with only a few microns of LC these switching times are on the order of milliseconds, but the off-time is inherently slow due to being a relaxation time of the molecules. With τ_{off} being proportional to the square of the LC thickness, d , this off-time rapidly increases into the seconds and beyond for the thicknesses required for THz devices. This is not

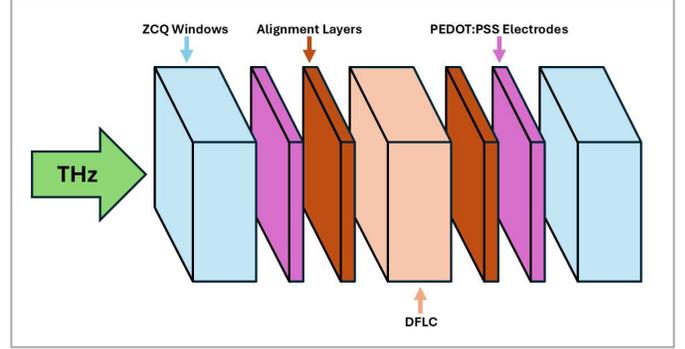


Fig. 1. Schematic of the cell design used for the measurements. For this specific device a second layer of PEDOT:PSS is used as the alignment material as it helps improve conductivity. Not to scale.

as significant a problem for τ_{on} as it is inversely proportional to the square of the bias applied, so a quicker switch can be achieved with a larger voltage. Nevertheless, the slow switch-off speed limits the overall response bandwidth for conventional nematic LC devices.

To solve the slow relaxation time, we exploit a different class of material, the Dual-Frequency Liquid Crystal (DFLC). A DFLC works almost identically to the usual LCs used in these devices, except that the material response to an applied AC bias inverts at a particular cross-over frequency. When a low frequency AC signal is applied to the cell (~ 1 kHz), the LC molecules align parallel to the applied electric field. However, increasing this frequency up to 20 kHz results in the molecules aligning perpendicular to the field. In contrast to standard nematic LCs, this allows an actively controllable “off” state.

II. RESULTS

The device considered in this work consists of a thin film of LC material, encapsulated within a THz transparent cell (see Figure 1). Almost all materials used to make visible light LC devices are opaque in the THz band, and as such, each part of the cell had to be carefully considered. For window materials, z-cut quartz (ZCQ) was chosen for its good THz transparency and chemical compatibility. The conductive polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) was used for the electrode layers in the device due to its ease of use and effectiveness in previous work [3]. The DFLC used in the cell (provided by Merck) is not optimized for the THz region but functions as a good proof of concept. A LC thickness of $\sim 120 \mu\text{m}$ was used.

The device was characterized with a 3.4 THz Quantum Cascade Laser (QCL) as a radiation source. The QCL was based on the active-region design in [4] and emitted an approximately linearly polarized beam with a power of 3.6 mW. The QCL was

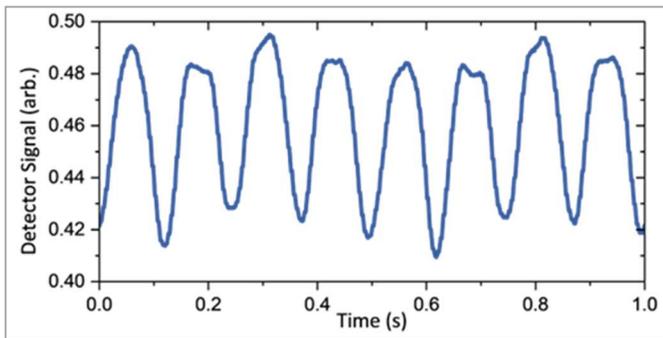


Fig. 2. Change in THz transmission for the fabricated DF-LC device operating at 8 Hz.

operated with a closed-cycle cryocooler (Sumitomo CH-204) and the beam was collected and focused onto the LC cell using a pair of off-axis parabolic mirrors. The LC cell was orientated such that the long axes of the molecules, in their relaxed state, were parallel to the electric-field vector of the incident beam. The transmitted THz signal was detected using an 8×8 patch-antenna-coupled TeraFET detector [5] with the output recorded on an oscilloscope.

A sinusoidal electrical bias was applied to the terminals of the LC cell using an arbitrary waveform generator, and a high-voltage piezo amplifier. An initial switching test was undertaken by applying a $100 V_{\text{rms}}$ 1 kHz signal to the LC cell.

The device showed a maximum transmission of $\sim 7\%$ with modulation depths of up to 60%. The dual-frequency properties of the cell were tested by applying a square-wave frequency-shift keying (FSK) scheme to the drive signal. This modulated the device between its on and off states (1 and 20 kHz drive, respectively) at a range of modulation frequencies. This allowed the THz signal to be modulated as the device switched states, as can be seen in Figure 2. The device achieved a maximum modulation rate of 20 Hz with a stronger bias field applied.

III. SUMMARY

In conclusion, we have demonstrated the use of a dual-frequency liquid crystal device to modulate the power of a THz QCL at 3.4 THz. This enables faster modulation than conventional nematic LC devices, up to a 20 Hz bandwidth, with a 60% modulation depth. These features open the doorway for active power stabilization of THz QCLs against thermal drifts, or as a variable attenuator for sensing applications.

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DATA AVAILABILITY STATEMENT

Data associated with this paper are freely available from <https://doi.org/10.5281/zenodo.15130793>

AUTHOR CONTRIBUTIONS

HG: Investigation, Writing — original draft, Visualization, Methodology; NKN: Investigation, Methodology; IK:

Resources; LHL: Resources; HFG: Conceptualization, Methodology, Supervision; ADB: Conceptualization, Methodology, Supervision; AV: Conceptualization, Methodology, Funding acquisition, Writing — review & editing.

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