Voltage Controlled Liquid Crystal Terahertz Quarter Wave Plate

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***Abstract*—We demonstrate an electrically switchable THz quarter wave plate using nematic liquid crystals.**

I. INTRODUCTION

RECENTLY, Terahertz (THz) technology has experienced remarkable progress [1-4]. Nonetheless, essential quasi-optic components such as THz phase shifters are relatively under-developed. Previously, a tunable room-temperature 2π THz phase shifter using magnetically controlled birefringence in a sandwiched nematic liquid crystal (LC) cell was reported by our group [5-6]. It is,however, desirable to develop electrically controlled phase shifters. In our previous attempt, a maximum phase shift of 4.07° was achieved at 1.07 THz when the interaction length was 38.6 μm. The driving voltage and corresponding field were 177 V and 589 V/cm, respectively [7]. In this work, we report for the first time an electrically switchable THz quarter wave plate by changing the effective refractive index of the nematic liquid crystal, E7. The experimental results are in good agreement with continuum model of the LC [6].

II. PRINCIPLES AND SETUP

A schematic of the experimental setup is shown in Fig. 1. The key element is a homeotropically aligned nematic liquid crystal (E7 by Merck) cell [8]. The thicknesses of the E7 layer is 524 μm.

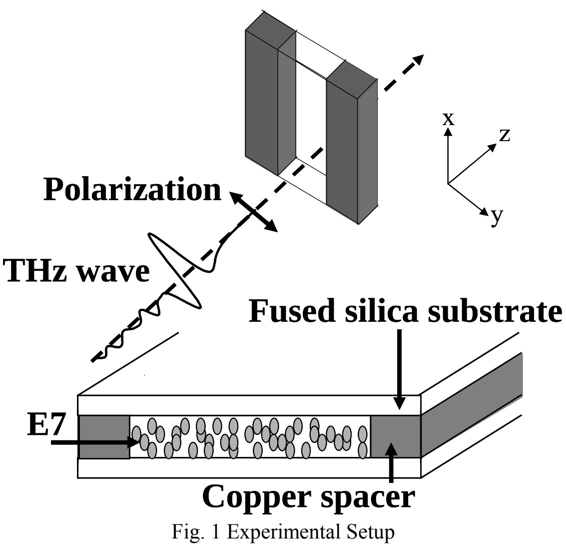

Fig. 1 Experimental Setup

Copper pieces (purity 99.94%) were as spacers and electrodes. The copper pieces were parallel to each other and separated by 11.9±0.3 mm. Since E7 has positive dielectric anisotropy, the liquid crystal director tends to be parallel to the direction of the external electric field. The device is characterized by conventional THz time-domain spectroscopic technique [9] using LT-GaAs photoconductive antennas.

When the driving voltage of the LC cell is zero or smaller than the threshold voltage (V_{th}), the LC director is mainly affected by the boundary alignment. Beyond the threshold voltage, the orientation of the LC sufficiently away from the inner surfaces of substrates is essentially determined by the applied electric field. The phase shift, $\delta(\nu)$, is given by

$$\delta(v) = \frac{2\pi f d}{c}\Delta n_{eff}(v) \, , \tag{1}$$

where d is the thickness of the LC layer, f is the frequency of THz wave, c is the speed of light in vacuum and $\Delta n_{eff}(v)$ is the change of effective birefringence.

An important parameter is the threshold voltage,

$$v_{th} = \pi \frac{L}{d}\left(\frac{k_3}{\varepsilon_a \varepsilon_o}\right)^{\frac{1}{2}}, \tag{2}$$

where L is the separated distance between two electrodes. k_3 and ε_a are the bend elastic constant and anisotropic dielectric constant of the LC, respectively. For E7, the threshold voltage is 26.9 V (rms).

Following Kahn [10], the field dependence of birefringence for $0<v-v_{th}<<v_{th}$ is given by

$$\Delta n_{eff}(v) = (n_e - n_o)\frac{n_o}{n_e}\left[\left(1+\frac{n_o}{n_e}\right)\left(\frac{v-v_{th}}{v_{th}}\right)\right], \tag{3}$$

where n_o and n_e are the ordinary and extra-ordinary refractive indices of E7. For $v-v_{th}>>v_{th}$, on the other hand,

$$\Delta n_{eff}(v) = (n_e - n_o)\left[1-\frac{2}{v}\left(\frac{k_3}{\varepsilon_a \varepsilon_0}\right)^{\frac{1}{2}}\frac{L}{d}\right], \tag{4}$$

III. RESULTS AND DISCUSSIONS

The temporal waveforms of the THz pulse transmitted through the LC cell for various driving voltages are shown in Fig. 2. An enlarged view is shown in the inset of Fig. 2. Increasing the applied voltage, the effective index of E7 will rise from 1.62 (n_o) to 1.79 (n_e).

The transmitted THz spectra are deduced from the temporal profiles of the THz pulse with fast Fourier transform (FFT) algorithms and spectral phase shifts are determined. According to Eq. (1), larger phase shift is expected at higher frequency. This is confirmed in Fig. 3, in which we plot the phase shifts from 0.20 to 1.00 THz by varying the driving voltages.

Fig. 4 shows the phase shifts as a function of driving voltage. The curves are theoretical predictions according to Eqs. (1) through (4) and in good agreements with the experiments, A maximum phase shift of 93.7° was achieved at 1.00 THz when the LC cell was driven at 125 V (rms). The theoretical phase shift is 91.8°. Because of the thick LC layer, the switching-off time is ~ 350 sec. Nonethelss, we have achieved an electrically switchable THz quarter wave plate. Although the electrically controlled LC THz phase shifter has many advantages, we should point out that it is difficult to tune the desired phase shift accurately from 26.9 to 35 V, near the threshold. From this perspective, continuously tunable magnetic controlled THz phase shifter in our previous work is superior [6].

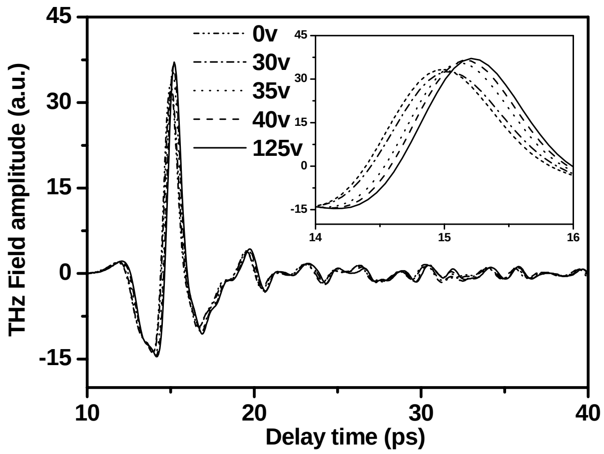

Fig. 2 The temporal waveforms of the THz pulse transmitted through the E7 cell at various applied voltages. The inset is the close-up from 14 to 16 ps.

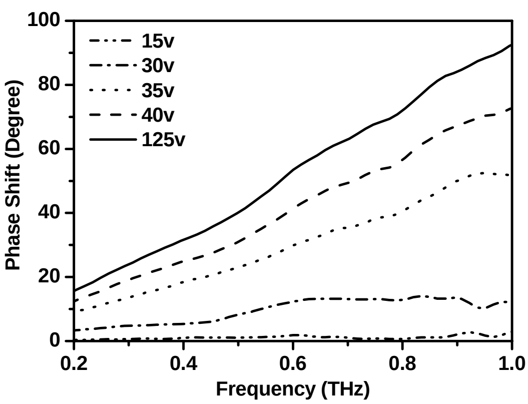

Fig. 3 The phase shift from 0.20 to 1.00 THz for several driving voltages of the LC cell.

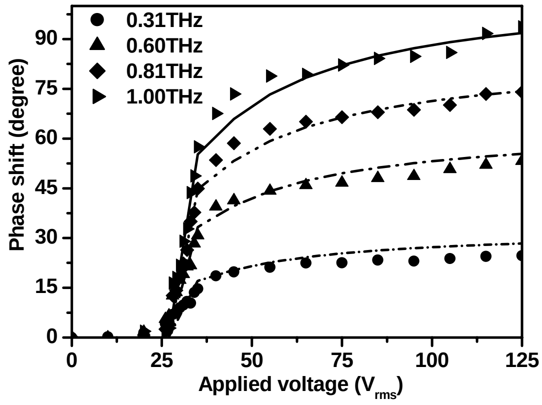

Fig. 4 The phase shift as a function of driving voltage for four frequencies. The curves are theoretically predicted phase shifts.

IV. CONCLUSION

A maximum phase shift of 93.7° at 1.00 THz is demonstrated using electrically controlled birefringence in a nematic liquid crystal, E7. The driving voltage required is 125 V (rms). This particular device can be considered an electrically switchable THz quarter wave plate..

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