All-optical switching in a nematic liquid crystal twist cell

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Abstract: Continuous wave photorefractive-like all-optical switching was demonstrated using a twisted nematic liquid crystal cell composed of the liquid crystal 5CB (4-pentyl-4'-cyanobiphenyl) with polyvinyl alcohol (PVA) aligning layers. The nonlinear optical effect involved is due to optical control of surface charge on the polyvinyl alcohol alignment layer. The cell exhibits strong optical control of the Fredericksz transition by an argon ion laser. A mechanism is proposed involving the modulation of the charge double layer by photoinduced charge. Optical limiting in the milliwatt range was observed.

OCIS codes: (190.4710) Optical nonlinearities in organic materials; (190.4360) Nonlinear optics, devices

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1. Introduction

For a number of years, nematic liquid crystal cells have been investigated for various applications as nonlinear optical devices [1,2]. In particular, photorefraction in liquid crystals (LC) has been extensively studied because of its numerous applications including dynamic holography [1,2]. More recently, specific attention has been given to the effect of surface charging effects on the liquid crystal bulk orientation [3-10]. Surface charging can affect the bulk liquid crystal orientation through a number of mechanisms including screening of the internal electric field[3], alteration of the anchoring energy [7,8], and direct electric field effects [9]. In this paper, we present a new manifestation of these photorefractive-like effects in a non-holographic configuration.

The Friedericksz transition occurs when the energy of an applied electric field in a liquid crystal sample exceeds the elastic energy associated with liquid crystal alignment. We have shown that the Friedericksz transition can be controlled using a light beam [8]. Optical control of the Friedericksz transition may be easily investigated using a nematic twist cell placed between crossed polarizers invoking a basic pump-probe scheme. In a twist cell, the polarization of light is adiabatically rotated as the director twists in the plane between substrates whose polymer alignment layers are rubbed for planar alignment in orthogonal directions. When an electric field is applied between the substrates, eventually the electrical energy tending to align the director along the field (homeotropic alignment perpendicular to the substrates) exceeds the elastic energy responsible for the original twisted planar alignment.

In this work, we will further investigate optical control of the Friedericksz transition, and will demonstrate a concept for photorefractive-like all-optical switching for continuous wave lasers. We will also investigate a model for the optical switching mechanism. Specifically, we see that polyvinylalcohol (PVA) alignment layers lead to photosensitive alignment layers[3,10]. Pump-probe measurements of the optical shift of the Friedericksz transition by varying the applied dc voltage were studied in nematic twist cells. This concept was then applied at a fixed bias to produce a negative optical gating effect.

2. Experiment

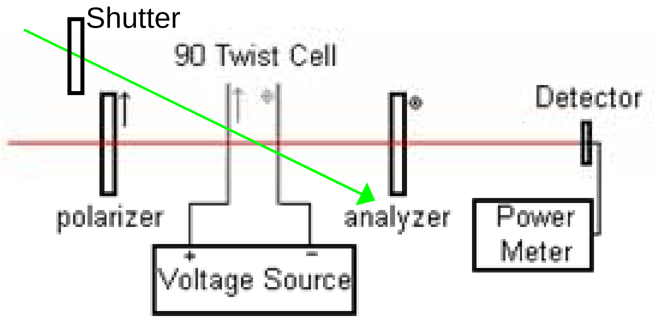

Fig. 1. Experiment layout. The pump laser (green) is an Argon ion laser (λ=488nm); the probe laser (red) is a HeNe laser (<1mW).

Friedericksz transition measurements were performed on 25μm thick liquid crystal nematic twist cells containing 5CB(4-pentyl-4'-cyanobiphenyl). Polyvinyl alcohol alignment layers several hundred nanometers thick were spin-cast from solution onto indium tin oxide coated (ITO) glass substrates, and baked at 80 ºC for 2 hours to eliminate solvent. The substrates were subsequently rubbed uniaxially with cloth and placed with rubbing directions perpendicular to each other, separated by 25 μm thick mylar, in order to achieve a twist-cell alignment. The cells were filled above the clearing point, 35ºC, and cooled slowly (6º/hr) to room temperature. Twist alignment was verified using polarizing microscopy.

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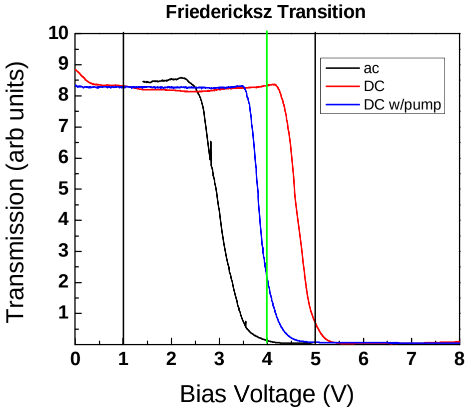

Fig. 2. Friedericksz transition measurements. Black line is ac (RMS) voltage, red line is dc voltage, and blue line is dc voltage with 730 mW/cm^2 pump applied. All three vertical lines correspond to the transient measurements shown in Fig. 5.

The experimental arrangement is shown in Fig. 1. Two initial measurements were performed on each cell. The twist cell was placed between crossed polarizers and probed with a low power (<1mW) 633nm HeNe beam. Transmission of the probe beam through crossed polarizers was measured as a function of bias voltage, for both ac and dc voltage as shown in Fig. 2. The Friedericksz transition was studied with and without the pump light using an Argon ion laser operating at 488 nm wavelength (transparent region of 5CB). The Argon pump beam is applied so that the beam does not pass through the polarizers. The shift of the Friedericksz transition with the applied pump laser radiation is also shown in Fig. 2.

The second measurement, the pump-probe gate measurement, involved pumping on the sample by the Argon ion laser at a wavelength of 488 nm. The experimental arrangement is the same as above (Fig. 1). The gate measurement is performed on a sample under a bias voltage determined by the transition measurements. The bias voltage is determined by the shoulder of the transition curve without the pump beam as indicated by the green vertical line if Fig. 2, but is fine-tuned to optimize the effect. Transmission of the probe beam through the sample between crossed polarizers is measured as a function of time. An electronically controlled shutter is opened allowing the argon laser to pump on the sample and is subsequently closed, while the transmission is continuously monitored with the probe beam.

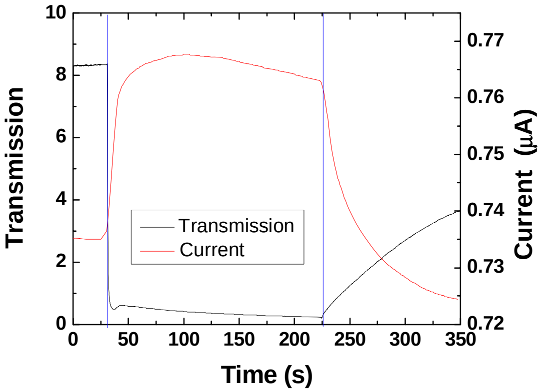

Fig. 3. Optical gate measurement. Pump applied (2.6W/cm^2) at the first vertical line, and turned off at the second vertical line. The bias voltage is 4.34V dc.

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A plot of probe transmission versus time is shown in Fig. 3, illustrating the gate effect. We see that over 90% photoinduced attenuation is attained. The first vertical line in this figure indicates time of application of pump beam. The second vertical line indicates the time at which the pump beam was extinguished. Also shown in Fig. 3 is the photoinduced current. It is seen that the dynamics of the photocurrent generally determines the dynamics of the gate effect. The speed was observed to be intensity dependent.

3. Discussion

In Fig. 3, it is evident that the pump beam is able to switch the sample from an aligned to a deformed state. Fig. 2 illustrates the operation of the optical gate device. The sample is biased at edge of the Friedericksz transition (green vertical line). After the pump beam is applied, the transition shifts (to lower applied voltage) as indicated so as to reduce the transmission at that bias voltage. The change in transmission is related to the steepness of the transition curve and the sensitivity of the curve shift to the pump intensity.

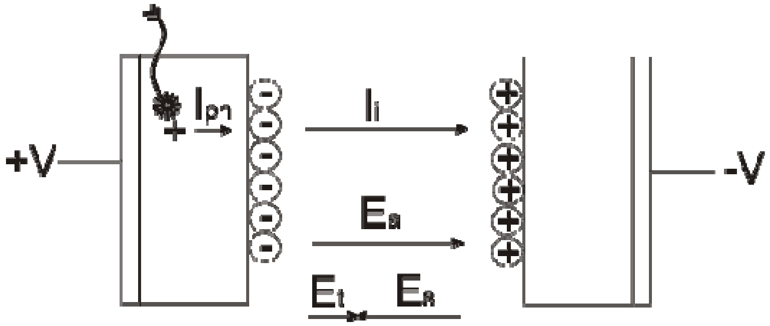

Fig. 4. Model of the observed effects. Charged layers are shown at the interface between the liquid crystal and the alignment layers.

We propose that the mechanism involves screening of the internal electric field by an interfacial charged double layer similar to those described earlier[3,10]. The proposed mechanism is summarized in Fig. 4. The application of a dc bias voltage results in a current I_i which is due, in part, to the drift of native ions. When the voltage is first applied, the internal field in the liquid crystal is approximately given by the applied field, E_a. The accumulated charge double layer markedly redistributes the electric field within the cell. It produces a screening field in the liquid crystal given by E_s, yielding a reduced effective field E_t. The electric field within the charge double layer at the interface is very large due to its thinness. Because the field in the bulk of the liquid crystal is reduced, a higher external field (applied voltage) is necessary to induce the Friedericksz transition. Upon irradiation with the pump, a photocurrent is induced, which partially neutralizes the screening charged layer, increasing the internal field and reducing the applied voltage necessary to induce the Friedericksz transition. Note that this model is consistent with the shift in the Friedericksz transition upon illumination in Fig. 2. We also measured the Friedericksz transition with an applied ac field (1kHz), which would not induce a charge double layer. We found that the Friedericksz transition under ac bias occurred at about 3V RMS, considerably lower than under dc bias. This transition is even lower than that under illumination indicating that the photocharge does not completely neutralize the screening charge layer. The nature of this photocurrent was described earlier[10], and was found to exist only in ITO/PVA/LC layered structure.

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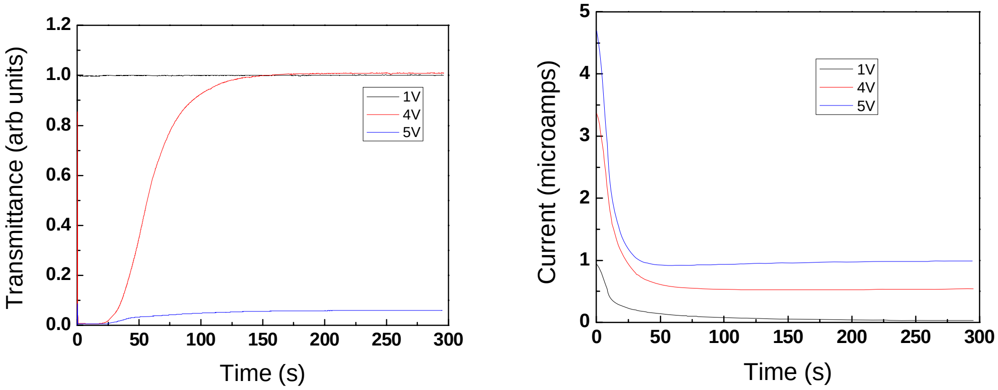

(a)

(b)

Fig. 5. Transient (a) optical transmittance (transmittance=1 at time=0 in all cases) and (b) current following application of a dc voltage as indicated.

In a set of experiments to test the model, we measured the transient transmitted intensity and cell current with the sudden application of a dc voltage with no pump beam. We chose three voltages to apply (see Fig. 2): 1) below the ac transition voltage (1V), 2) between the ac and dc transition voltages (4V), and 3) above the transition voltages (5V). The results are shown in Fig. 5. In case 1) the transmission stays high since applied voltage is below the Friedericksz transition for both dc and ac fields. In case 3), the transmission starts out high, and then reduces when the field is applied, as would be expected passing through the Friedericksz transition. In case 2), the transmission starts out high, then reduces as the voltage is applied which is above the transition with no charged double layer (similar to the ac case). However a strong transient current is observed in Fig. 5(b) as the double layer accumulates. As the charge layer forms, the current reduces as indicated in Fig. 5(b). Eventually, the transition corresponding to the dc case of Fig. 2 results from the screened internal field. This restores the transmission illustrating the shift of the transition from the lower voltage ac case (black curve in Fig. 2) toward the final dc curve (red curve in Fig. 2) at higher voltage as the charge double layer (and screening field) develops over time.

The charge double layer implies a strong electric field at the electrode that promotes photoinduced injection of charge. Similar effects have been reported with regard to increased injection and the screened internal field due to double layer formation in polymer light emitting devices.[11] As the pump laser radiation is applied to the sample, a photocurrent I_p flows in the direction indicated in Fig. 4. This charge either gets trapped near the interface or neutralizes the charged species already trapped at the interface. The shielding field inside the sample is reduced by reduction of the net interfacial charge due to these photogenerated carriers[3], thus increasing the net effective field across the sample bulk. The internal field energy now exceeds that necessary for the transition, thus reducing the transmission. Note that the sign of the initial current and photocurrent are the same, in agreement with our model.

The effect we observe might have potential applications with improved materials, such as optically addressed spatial light modulators, optical gates and optical limiters. We demonstrated the optical limiting effect by removing the probe beam of Fig. 1, and redirecting the pump beam along the path shown in Fig. 1 for the probe beam. The transmittance (I_{out}/I_{in}) was measured by collecting all of the transmitted light in a calibrated silicon detector for various values of I_{in} with an unfocused 1 mm radius incident beam. Measured transmittances were normalized to that measured at 10^{-4} mW incident power. The overall linear transmittance was low (<25%) due to the use of lossy polarizers (~60% transmission of light

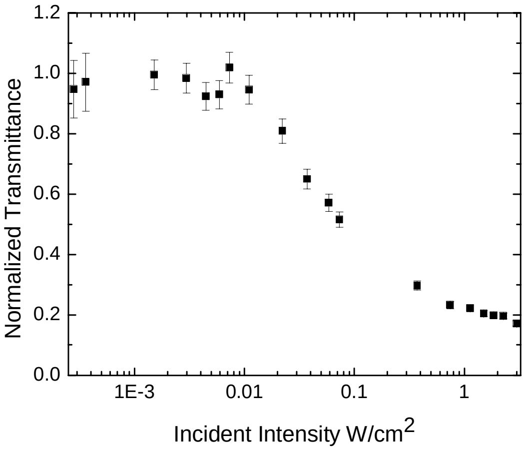

Fig. 6. Optical limiting and saturation. Data is normalized to the transmission at very low power (microwatt) input. The beam was not focused and had a 1 mm diameter.

polarized along each polarizer axis). The results shown in Fig. 6 indicate a linear region followed by a clear optical limiting region, as well as saturation at higher intensity. The maximum shift is determined by the saturation charge consistent with the Debye screening length in the cell. The optical limiting effect depends on the sensitivity of the shift to the input intensity, the steepness of the shift, as well as the maximum shift. Analysis of the data (transmission above and below the transition voltage) depicted in Fig. 2 indicates that off/on ratios of 10^{-2} are possible given a shift sufficient to generate the transmittance well above the Friedericksz transition, which is an order a magnitude greater than we were able to observe in this experiment.. Such a shift should be possible with a highly photoconducting alignment layer. By comparing the photocurrent and optical gating in Fig. 2, the speed of the effect generally follows the photoconductive dynamics. Speeds well below 1 second have been observed in good photoconducting polymers[12]. The data in reference [10] indicate the photocurrent in ITO/PVA/LC is particularly slow. The sensitivity, i.e. the voltage shift per applied pump intensity, will depend on photoconductivity of the alignment layer, with the current PVA/ITO/LC surface not being particularly photosensitive[10]. We expect that sensitivities orders of magnitude greater than observed in the photocurrent of Fig. 3 can be attained with highly photoconducting alignment layers due to much larger photoinduced charge generation.. The steepness of the transition depends on the surface anchoring and cell design. Studies are underway with photoconducting alignment layers, and much improved device behavior will be reported later. Additional studies aimed as further elucidating the mechanism are also underway.

In summary, we have reported on a new scheme for photorefractive-like all-optical switching under continuous wave illumination in a standard nematic liquid crystal twist cell geometry employing photosensitive alignment layers. This scheme can have applications in optically addressed spatial light modulators and in optical limiting devices.

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