

# Surface-mediated light-controlled Friedericksz transition in a nematic liquid crystal cell

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Surface-mediated director reorientation in a pure nematic liquid crystal (LC) cell in the presence of both a dc and low-power optical field has been observed. A surface-dependent lowering of the Friedericksz transition voltage in a planar cell upon light irradiation was found. It is believed that this effect is due to a light-induced change in the near-surface ion concentration in the presence of a dc field and a photosensitive surface. Enrichment in the ion concentration near the surface causes a redistribution of the electric field in the cell and its localization near the surface. As a consequence, the energy of interaction between the LC and the dc field near the surface overcomes the anchoring energy and results in the director reorientation. © 2001 American Institute of Physics.

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## I. INTRODUCTION

Effects of director reorientation in liquid crystal (LC) cells using low-power light in the presence of an electric field has attracted considerable attention during the last decade because of possible applications in optical processing. Redistribution of the electric field in the cell due to a photo-induced change in the resistance of a photoconductive polymer aligning layer can be used for the development of spatial-time modulators.<sup>1,2</sup> A space-charge field generated by a spatially modulated incoming light in a photoconductive polymer was used for the recording of dynamic holograms.<sup>3,4</sup>

Another possibility of light-induced director reorientation in an electric field is to modulate electric charges in the LC. Sukhov *et al.*,<sup>5,6</sup> Khoo *et al.*,<sup>7,8</sup> and Minevitch *et al.*<sup>9,10</sup> have shown that doping of a photosensitive dye into a LC results in strong director reorientation under the simultaneous action of both a spatially modulated light and dc electric field. These effects are usually attributed to the light-induced modulation of electric charges in the LC bulk. Tabirian and Umeton<sup>11</sup> pointed out that not only light-induced bulk-localized charges, but also light-induced surface-localized charges will induce a strong reorientation of LC due to the field extending to the bulk.

Light-induced electric charges can also modulate the easy axis direction due to an electrochemical reaction on the aligning surface, which results in a strong permanent surface-mediated director reorientation in a dc field.<sup>12,13</sup> Another type of surface-mediated reorientation in a dc field was reported recently by Ikedo *et al.*<sup>14</sup> They observed that irradiation of a polyimide (PI) aligning layer with UV light induced a dynamic director reorientation from planar to homeotropic alignment in a dc field. The authors did not determine the physical cause of this effect, but stressed that it cannot be connected with a photochemical reaction on the PI surface.

In this article, we report on the observation of a *dynamic surface-mediated* director reorientation in a dc field with *visible* light. We propose a model for this effect involving a light-induced increase of the dc field near the surface due to desorption of ions from the surface by light absorption in a photosensitive aligning layer.

## II. MATERIALS AND BASIC EXPERIMENTS

We studied the action of He-Ne laser irradiation (wavelength,  $\lambda=0.63 \mu\text{m}$ , light intensity  $0 < \bar{I}_{\text{inc}} < 2 \text{ W/cm}^2$ ) on the Friedericksz transition in nematic twist cells filled with pure LC penty-cyanobiphenyl [(5CB), EM Industries]. This well-

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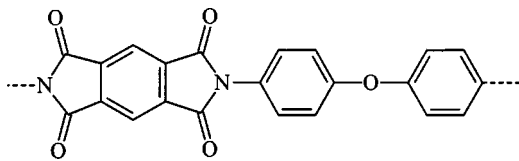


FIG. 1. Structure of oxidianiline-polyimide, ODAPI.

known LC is not photosensitive in the visible part of light spectrum. Its conductivity,  $\sigma_{LC}$ , was  $10^{-10} \text{ ohm}^{-1} \text{ cm}^{-1}$ .

The cells were constructed from two glass substrates whose inner surfaces were covered with transparent indium tin oxide (ITO) electrodes. The ITO substrates were coated with an aligning layer composed of the polymer oxidianiline-polyimide (ODAPI) (Kapton from Dupont is a commercial analog of ODAPI) as shown in Fig. 1. A solution of ODAPI was spin coated on the substrates, kept 10 min at  $60^\circ\text{C}$  to remove solvent and cured for 90 min at  $190^\circ\text{C}$ . The resulting layers had a thickness,  $L_{PI}$  in the range of  $0.12\text{--}0.16 \mu\text{m}$  providing a strong homogeneous alignment with a small (tens of degrees) tilt of the 5CB.

The twist cells were assembled so that the directions of the rubbing on the substrates were perpendicular to each other. The cells were filled with the LC either at room temperature or at the temperature above clear point,  $T_C = 34.5^\circ\text{C}$ . The cell thickness,  $L_{LC}$ , was  $20 \mu\text{m}$ .

The transmission,  $T$ , of the twist cells placed between a polarizer and an analyzer as a function of dc voltage,  $U_{dc}$ , was measured for different intensities of the incident light. The Friedericksz transition threshold,  $U_{dc}^{th}$ , was determined to be at the level of 10% of  $T_{max}$ . At low intensity,  $I_{inc} < 4 \text{ mW/cm}^2$ ,  $U_{dc}^{th} = 3.9 \text{ V}$ , while at higher  $I_{inc}$ , the Friedericksz transition threshold decreased to  $U_{dc}^{th} = 3.45 \text{ V}$  at  $I_{inc} = 174 \text{ mW/cm}^2$  as shown in Fig. 2. The dependence of  $U_{dc}^{th}(I_{inc})$  was monotonic and could be described with an exponential function as shown in Fig. 3.

In order to elucidate the possible mechanisms of this effect, the following additional experiments were performed.

(a) We measured the dependence  $T(U_{ac})$  at 1 kHz frequency. In this case, the threshold of the Friedericksz transition  $U_{dc}^{th} = 1.1 \text{ V}$  did not depend on the light intensity. The difference between  $U_{dc}^{th}$  and  $U_{ac}^{th}$  is due to the formation of

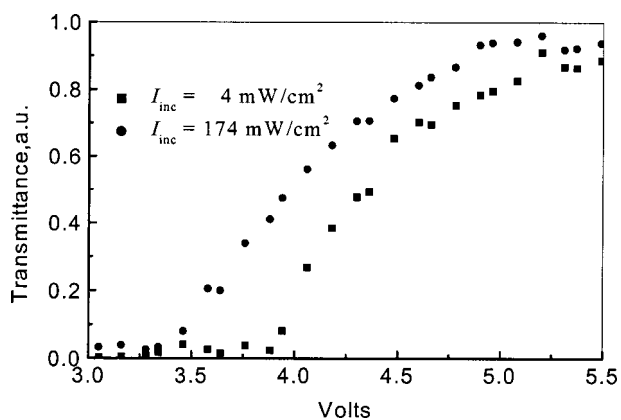


FIG. 2. Dependence of the LC cell transparency on applied voltage for two values of incident light.

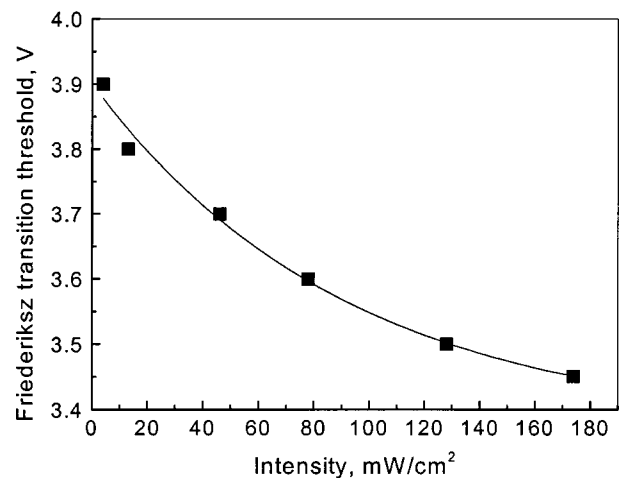


FIG. 3. Dependence of Friedericksz transition on the intensity of incident light.

electric double layers near the aligning surfaces arising from dc field induced separation of charged impurities in the LC.<sup>15</sup> Since the light-induced effect was observed with a dc field only, we can conclude that charged impurities in the cell must be involved.

(b) We repeated our original measurements where both aligning layers were substituted by either a rubbed commercial PI SE7492 (Nissan Chemical) or fluoro-polyvinylcinnamate (F-PVCN) irradiated with polarized UV light. The values of  $U_{dc}^{th}$  differed markedly from those measured with the ODAPI layers ( $U_{dc}^{th} = 3.2 \text{ V}$  for PI and  $U_{dc}^{th} = 4.0 \text{ V}$  for F-PVCN), and were found to be independent of the light intensity. A cell with one surface ODAPI and one surface PI SE7492 yielded  $U_{dc}^{th} = 9.3 \text{ V}$  accompanied by light-induced changes of the Friedericksz transition similar to the symmetric cell. At the same time, the replacement of the LC with commercial mixtures, E7 (BDH, Ltd.), ZLI 4801 (Merck), or 6CHBT and 1298 (Institute of Chemistry, Military University of Technology, Warsaw) did not eliminate the effect of light-induced change of  $U_{dc}^{th}$ . Therefore, we can conclude that the effect involves the action of light on the ODAPI layer and is aligning surface mediated.

(c) We measured the conductivity,  $\sigma_{PI}$ , of the ODAPI layer. A  $0.14 \mu\text{m}$  layer was prepared as described. A thin Al electrode was evaporated on its upper surface, and the value  $\sigma_{PI}$  was measured by the bridge method at 1 kHz in the range  $U = 0.1\text{--}5 \text{ V}$ . The value of  $\sigma_{LC}$  was found to be of the order of  $10^{-9} \text{ ohm}^{-1} \text{ cm}^{-1}$  which is comparable with the conductivity of the LC. The value  $\sigma_{PI}$  did not depend on the light intensity within 5% over the whole voltage range. Taking into account that  $L_{LC} \gg L_{PI}$  we can conclude, that redistribution of the electric field in the LC cell due to a possible light-induced change of the electrical resistance of the ODAPI layer<sup>16-18</sup> does not play a serious role in the observed effect.

### III. DISCUSSION AND ADDITIONAL EXPERIMENTS

Summarizing our experiments, one can conclude that the origin of the light-induced shift of the Friedericksz transition can be attributed to the redistribution of charged impurities

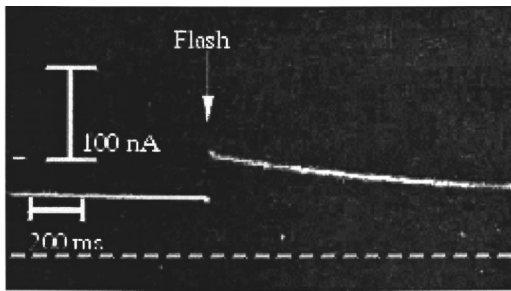


FIG. 4. Oscilloscope trace of the time dependence of photocurrent with a voltage  $U=3.3$  V applied. Dashed base line depicts zero dark current.

in the cell controlled by the light action on the ODAPI layer. It is well known that a surface distribution of ions will affect the anchoring of LC's on a substrate.<sup>19-21</sup> Additionally, we have previously demonstrated light induced changes in a surface charge distribution as a mechanism of photorefractive hologram formation.<sup>12</sup>

Light-induced redistribution of carriers must be accompanied by the appearance of a photocurrent. We observed the photocurrent response of the cell when irradiated by a short pulse (20  $\mu$ s) of a flash lamp of a visible spectrum range. Below the voltage of the Friedericksz transition, the photocurrent did not accompany the director reorientation and the amplitude of the photocurrent was of the order of the dark current  $I_{dark}$  as shown in Fig. 4. If the voltage applied was close to the voltage of the Friedericksz transition ( $U_{dc}^{th} - U \leq 0,1$  V), we observed that the photocurrent accompanied the director reorientation.

A photocurrent could be observed when no voltage was applied to the cell depending on its history. When the cell was flashed prior to the application of any voltage, the photocurrent,  $I_{hv}$ , was negligibly small. In contrast, when a voltage was previously applied to the cell, a photocurrent was observed even after the voltage was turned off as in Fig. 5. The amplitude of the photocurrent was an order of magnitude less than the steady "dark" current, and the direction of photocurrent was opposite to the direction of  $I_{dark}$  as observed when the initial voltage was applied. Figure 6 indicates that the amplitude  $I_{hv}$ , increased with the duration of the applied field as well as with the magnitude of the voltage. The important feature of this experiment was that the cell "remembered" the prior voltage application. After applying the voltage, the photocurrent response could be observed for many hours with its amplitude decreasing slowly with time

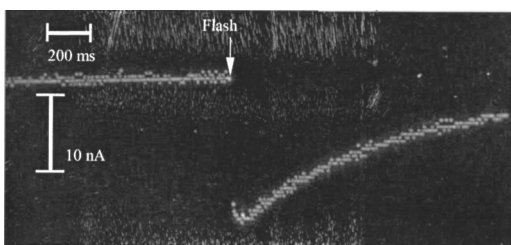


FIG. 5. Oscilloscope trace of the time dependence of photocurrent following the prior application of a voltage  $U=2.4$  V.

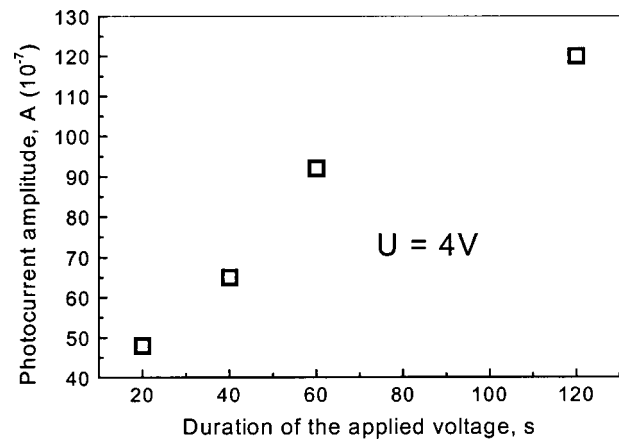


FIG. 6. Dependence of the photocurrent amplitude on the duration of the applied voltage.

as shown in Fig. 7. The photocurrent response decay could be accelerated by an increase in the repetition rate of the flash impulses as also seen in Fig. 7.

The "memory" of the cell to the electric field treatment indicates that the light-induced redistribution of the charges in the cell is governed by a process with a characteristic time of several hours. These experiments suggest that this process may be related to electrically and light-induced adsorption/desorption of ions from the aligning surfaces. We propose the following model, which is consistent with our observations.

Layers of adsorbed positive ions are formed on the ODAPI surfaces after filling the cell. This results in symmetric distribution of carriers throughout the LC bulk with respect to the middle of the cell as in Fig. 8(a). The light desorbs ions from the surfaces and changes the distribution of the carriers. With no applied field, the new distribution remains symmetric.

The application of an electric field breaks the symmetry of the carrier distribution and causes an additional adsorption of ions on one of the surfaces due to the drift of the charge across the cell. This results in a polarization of the cell shown in Fig. 8(b), which scales with the duration of the applied voltage. Subsequent irradiation leads to desorption of

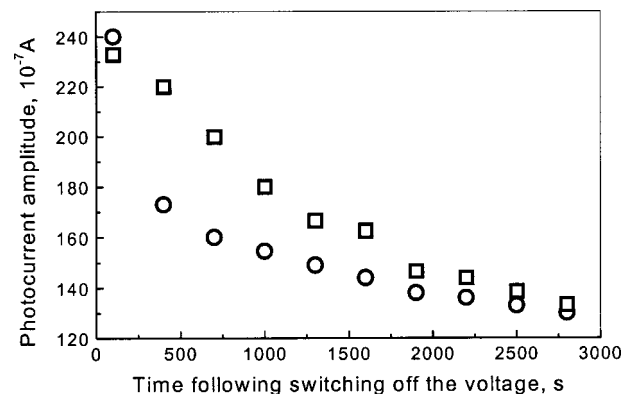


FIG. 7. Time dependence of the photocurrent maximum following voltage  $U=4$  V cut off. Circles: cell was flash irradiated 12 times between each measurement. Squares: no flashes.

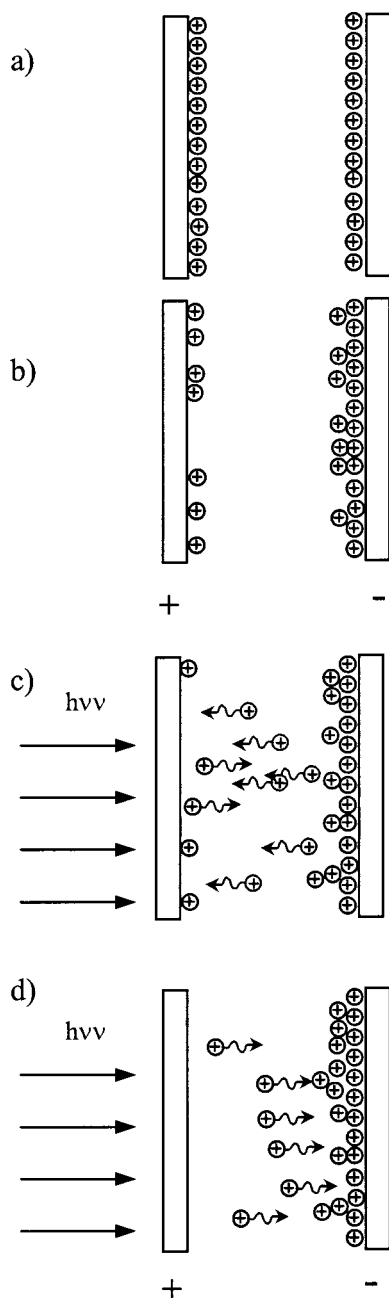


FIG. 8. Depiction of light-induced Fredericksz transition process (for simplicity, only positive ions are depicted): (a) ions are distributed symmetrically in a cell with no voltage or light applied; (b) application of an electric field results in breaking of the bilateral symmetry and development of polarization in the cell; (c) light-induced desorption causes a weak photocurrent to recover the original bilateral symmetry; and (d) simultaneous action of light and electric field results in a strong enrichment of ion concentration near the surface and director reorientation.

ions from the surfaces and the appearance of a photocurrent as shown in Fig. 8(c). The direction of the photocurrent is such that it recovers the original symmetry of the system, thus, opposite to the direction induced by the electric field. The asymmetric polarized state of the cell is long lived but not in thermodynamic equilibrium. Therefore, the photocurrent response gets weaker with time as the cell depolarizes. Light-induced ion desorption encourages this process.

In this model, light irradiation under an applied electric field results in a strong enhancement of the carriers and elec-

tric field near the surfaces as depicted in Fig. 8(d). This field disposes the LC to be oriented homeotropically. When the energy of interaction between the LC and this field near the surface (per unit area),  $F_E$ , overcomes the anchoring energy,  $W$ , the director reorientation occurs.

The microscopic origin of light-induced desorption of ions has not been established and will require further study. Nevertheless, it is reasonable to assume that heteroatoms of oxygen and nitrogen in ODAPI chains play an important role in the adsorption/desorption processes. Unshared valence electrons of heteroatoms are good adsorption sites for cations and the activation energy of the reversed desorption process does not exceed 2 eV, which is close to the energy of a He–Ne light quantum, and the value of voltage necessary to polarize the cell. Therefore, we speculate that light-induced desorption of  $H^+$  occurs due to energy transfer from light-induced excitons produced in ODAPI, to  $OH^-$  and  $ON^-$  groups.

We believe that these *photoelectrically-induced* surface phenomena may have application in devices for hologram recording and optical switching. Until now, we have recorded dynamic holograms using a He–Ne laser. The diffraction efficiency strongly depends on the hologram period  $\Lambda$  and the dc voltage, and had a maximum of about 5% when a voltage near to  $V_{dc}^{th}$  was applied. In addition, we have modulated the propagation of a probe beam through a twist cell using a He–Ne laser control beam, when a voltage slightly greater than  $V_{dc}^{th}$  was applied. The details of this device will be reported elsewhere.

#### IV. CONCLUSIONS

We observed a lowering of the Fredericksz transition voltage in a planar cell upon visible light irradiation. Our experiments suggest that the origin of the light-induced shift of the Fredericksz transition is attributed to the redistribution of the charged impurities in the cell volume as controlled by light-induced desorption of positive ions from the polymer alignment layer. This desorption of ions from the aligning surfaces results in an enhancement in the carrier concentration and an increase of electric field near the surfaces. As a consequence, the energy of interaction between the LC and the dc field near the surface overcomes the anchoring energy and results in the director reorientation.

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