Electro-optical response of an ionic-surfactant-doped nematic cell with homeoplanar–twisted configuration transition [Invited]

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Abstract: This study is concerned with the optical response of an electro-optical material consisting of nematic liquid crystal as well as ionic surfactant as a dopant. The dopant is a key component to carry out the working of the resulting device through configuration switching. The operational principle is based on the surface anchoring transition induced by a steady electric field. The dynamic characteristics of the electro-optical cell can be considerably improved when the nematic layer is reoriented from the initially homeoplanar director configuration into the twisted state. Besides, a method to shorten the relaxation time is demonstrated by using a controlling pulse with a bipolar waveform.

OCIS codes: (160.3710) Liquid crystals; (120.2040) Displays.

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1. Introduction

The operational principles of modern liquid crystal (LC) devices are based on the classic Fréedericksz effect [1] which is characterized by reorientation of the LC director in the bulk under action of an applied electric field. Typically, the LC molecules coupled with the substrates of an electro-optical cell keep their orientation fixed owing to the persistent anchoring. Dubois-Violette *et al.* [2] and Ryschenkow *et al.* [3] proposed an alternative method to manipulate the LC reorientation by changing LC anchoring at the interface. Various external factors can control the anchoring, such as temperature [3–6], light radiation [7], and electric field [6,8]. The idea to use ionic surfactants to realize the electrically controlled anchoring transitions was firstly suggested by Petrov *et al.* [9]. Disappointing fact in their experiments was the electro-hydrodynamic instability caused by the intense ionic current at the steady voltage and this effect was dominant in the reorientation process. Recently, we have improved the ionic-surfactant method to control the LC orientation by inserting two special polymer films separating the nematic and indium–tin-oxide (ITO) electrodes [10]. It allows avoidance of the undesirable instability effect while achieves the LC reorientation resulting only from the anchoring transition. The study of electro-optical properties of such LC cells operated by the ionic-surfactant method has shown the response time to be about a second for the case of the homeotropic–homeoplanar configuration transition [11]. At that the alignment layers at both cell substrates were the same, providing the homeotropic anchoring in the field-off state. We have considered thoroughly the ionic/surface anchoring transition mechanism in LC cells with the initially homeotropic configuration in [10].

This paper aims at the improvement of dynamic properties of a LC cell composed of a nematic layer doped with ionic surfactant by employing another reorientation transition between the homeoplanar and twisted-nematic states.

2. Sample preparation and experiment

A planar cell consisting of two glass substrates with ITO coating on the internal sides was filled with a nematic LC doped with the cationic surfactant cethyltrimethyl ammonium bromide (CTAB) in the weight ratio 1: 0.008. The nematic used was 4-pentyl-4'-cyanobiphenyl (5CB). CTAB molecules within 5CB dissociate into Br^--anions and surface-active CTA^+-cations. The latter are adsorbed at the interface and, at the sufficient concentration, can form a layer specifying the homeotropic coupling condition for nematic molecules [12].

ITO-electrodes were covered with 1.5-μm-thick polymer films by a spin coater (HOLMARC HO-TH-05). These films served not only as aligning layers for LC molecules but also as protection layers to block the contact between surfactant ions and the electrodes. The top substrate was covered with a polyvinyl alcohol (PVA) film doped with glycerin (Gl) compound in the weight ratio 1: 0.432 whereas a pure PVA film was formed at the bottom substrate as shown in Fig. 1. The utilized CTAB concentration was minimal to provide the uniform homeotropic anchoring for 5CB molecules at the substrate with PVA–Gl film.

The polymer films on both substrates were rubbed by a machine (HOLMARC HO-IAD-BTR-01) to specify the desired alignment direction. The angle between the rubbing directions at the top and bottom substrates was 90°. The cell gap was 6 μm. The observation of optical textures was carried out by a polarizing microscope (Carl Zeiss Axio Imager.A1) equipped with an AxioCam MRc5 digital camera which allowed making photographs and dynamic videos of the reorientation processes. Microphotographs were taken in the crossed-polarizer scheme and the parallel-polarizer scheme as well. Single pulses of steady electric field applied to the cell were generated by a function generator (AKTAKOM ANP-3122).

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To study the dynamic response of the LC cell, a He–Ne laser (Linos, $\lambda = 0.633$ μm) was used. The laser beam passed in sequence through the polarizer, LC cell and analyzer and was detected by a photodiode. The beam diameter was about 1 mm. The measurements were taken in the crossed-polarizer condition. The LC cell was placed in a way so that the rubbing direction of the bottom substrate coincided with the transmission axis of either polarizer. The electric pulse applied across the sample and recorded by a USB-oscilloscope (DISCO Trade-M). The signal from the photodetector was recorded by the oscilloscope, too.

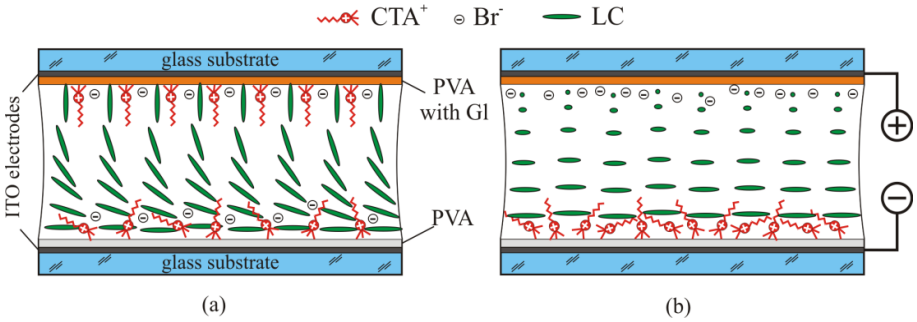

Fig. 1. Schematic of nematic structure transition from the homeoplanar director configuration to the twisted one. (a) Electric field is switched off. The boundary condition at the top substrate is homeotropic whereas the anchoring on the bottom substrate is planar. (b) At an applied steady voltage, the top substrate's anchoring changes from homeotropic to planar and yet the planar boundary condition remains invariable on the bottom substrate. The rubbing directions at the substrates are mutually perpendicular. CTA^+ are the surface-active cations of cethyltrimethyl ammonium; Br^- are the bromide anions.

The transmittance value presented below was determined as $T = (I_t/I_0)\cdot 100\%$, where I_0 is the intensity of radiation after the first linear polarizer; I_t is the intensity after the second polarizer.

3. Results and discussion

The transition from the homeoplanar director configuration to the twisted configuration within a LC cell filled with a mixture of nematic and ionic surfactant under action of a steady electric field is schematically shown in Fig. 1. The initial homeoplanar structure of the LC layer was formed due to the different orienting coatings at the top and bottom substrates (Fig. 1(a)). Both G1 and PVA components of polymer films specify the planar boundary conditions for LC [4,13]. However for the given CTAB concentration, the surface-active ions adsorbed at the top substrate with PVA–Gl film formed a layer screening the planar-orienting effect of the polymer coating and set the homeotropic anchoring for 5CB molecules. At the same time, the boundary condition remained planar at the bottom substrate covered with pure PVA film. Here, this property persisted in all the range of electrically variable surface density of CTA^+ ions. Apparently, it can be explained by stronger planar-orienting influence of pure PVA comparing with PVA–Gl composition.

The steady-state field made the top substrate free from the surface-active CTA^+ ions. As a result, it was the PVA–Gl layer that imposed the planar alignment of nematic molecules at this substrate (Fig. 1(b)). This transformation corresponded to the inverse mode of electrically induced anchoring transition in the ionic-surfactant method [14]. Eventually, the orientation transition from the homeoplanar to the twisted-nematic configuration occurred within the nematic layer since the rubbing directions of the substrates were mutually perpendicular.

Microphotographs of optical textures of the cell confirming the above-mentioned configuration transition are presented in Fig. 2. In the switched-off state the LC bulk under crossed polarizers appeared uniformly dark when the rubbing direction of the bottom

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substrate ($\mathbf{R_1}$) was parallel to the transmission axis of either linear polarizer (Figs. 2(a) and (c), top row). The maximum transmittance was observed at the polarization angle β = 45° between $\mathbf{R_1}$ and the transmission axis of the polarizer (Fig. 2(b), top row). The optical texture varying in this fashion with such sample orientation on the microscopic stage is a characteristic of the homeoplanar director configuration in the LC cell. It should be emphasized that the formation of the uniform untwisted planar structure, whose optical texture would change similarly, was impossible in this case because the rubbing directions of the substrates were mutually perpendicular.

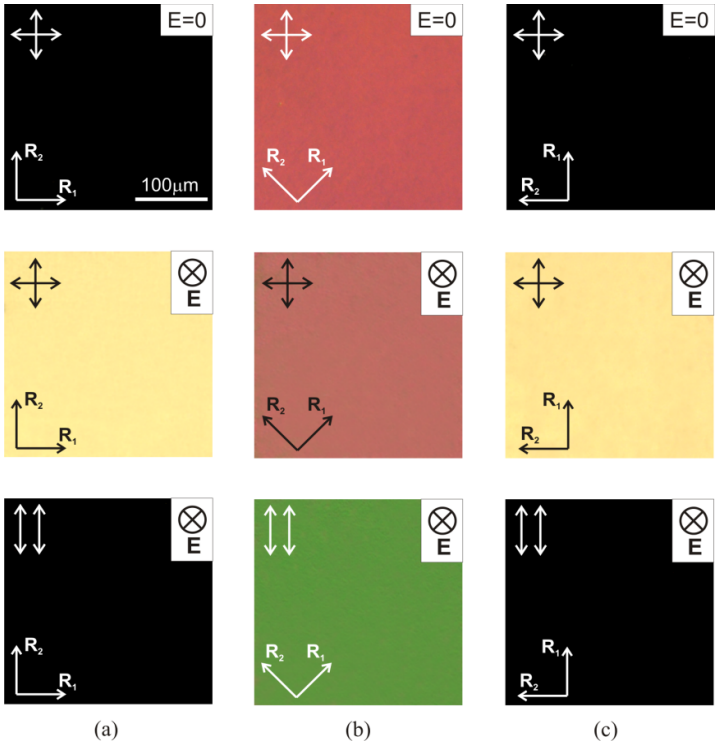

Fig. 2. Microphotographs of optical textures of the nematic 5CB layer doped with CTAB under crossed polarizers (top and middle rows) and in the parallel-polarizer scheme (bottom row) made at different β angles between the rubbing direction of the bottom substrate ($\mathbf{R_1}$) and the transmission axis of the polarizer. (a) β = 0°, (b) β = 45°, and (c) β = 90°. The top row corresponds to the initial state; the middle and bottom rows present the textures at the applied voltage of 3.3 V. Polarizer directions are represented by the double arrows. $\mathbf{R_2}$ is the rubbing direction of the top substrate.

Rectangular electric pulse of 3.3 V applied to the LC cell did not darken its optical texture at any azimuthal angle of the sample relative to the transmission axes of crossed polarizers (Fig. 2, middle row). However the transmittance was about zero for β = 0° or β = 90° in the parallel-polarizer scheme (Figs. 2(a) and 2(c), bottom row). That means the polarization of the linearly polarized light emerging from the LC layer turned about 90° angle, indicating the formation of the twisted-nematic structure within the LC cell.

The changes in transmittance as described above cannot be explained by the action of the classical Fréedericksz effect because here a nematic (5CB in this study) with positive dielectric anisotropy was used [15]. In accordance with the Fréedericksz effect, the application of a sufficient external electric field perpendicular to the 5CB layer plane would result in the homeotropic structure, yielding all dark textures under crossed polarizers (Fig. 2, middle row). This does not conform to the experiment. Thus, our observations are

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convincing evidence of the structural transition from the homeoplanar to the twisted alignment owing to the ionic modification of anchoring conditions at the anode-substrate.

Figure 3 depicts the oscillograms of optical response of LC cells switched by rectangular monopolar (Figs. 3(a) and 3(b)) and bipolar (Fig. 3(c)) voltage pulses. The amplitude and duration of the positive-polarity pulse were 3.3 V and 9.8 s, respectively, and those for the negative-polarity pulse were 2.2 V and 0.16 s, respectively.

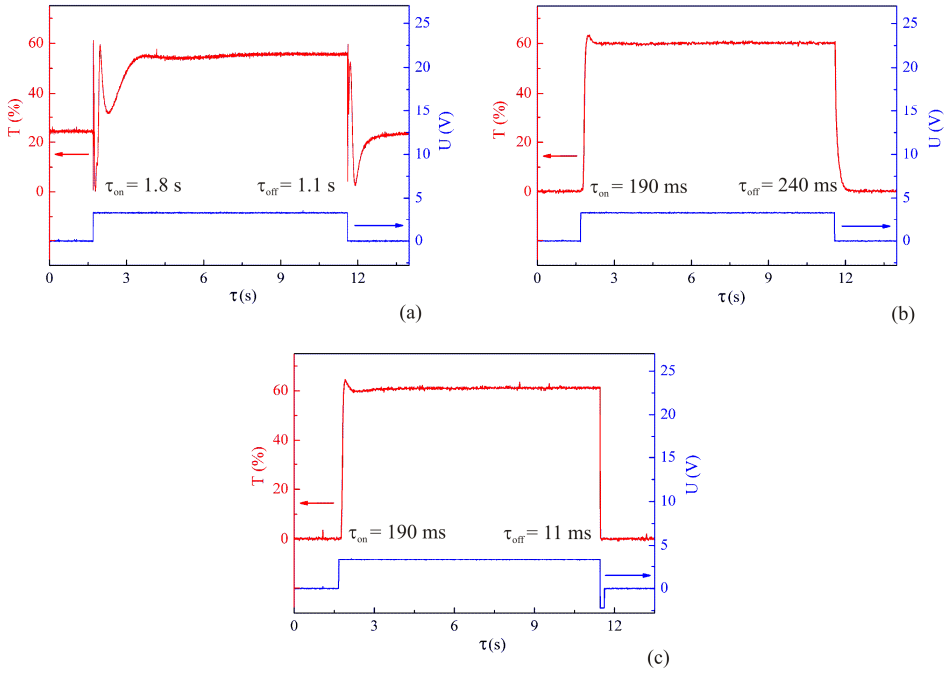

Fig. 3. Oscillograms of optical response of LC cells containing nematic 5CB doped with CTAB in the crossed-polarizer scheme. (a) A cell with β = 45° switched by a monopolar voltage pulse, (b) a cell with β = 0° or 90° switched by a monopolar voltage pulse, and (c) a cell with β = 0° or 90° switched by a bipolar voltage pulse. τ_{on} is the field-on time and τ_{off} is the field-off time.

Figure 3(a) shows the light transmittance (T%) change of a LC cell with polarization angle at β = 45° (see Fig. 2(b), top and middle rows). This oscillogram represents real dynamics of the reorientation process within the LC layer because the transmittance was varied due to electrically controlled phase retardation between two linearly polarized components of radiation propagated through the nematic. In this case, the response times (both the field-on time τ_{on} and the field-off time τ_{off}) were found to be the same as reported previously [10,11].

Figures 3(b) and 3(c) present the optical response of LC cell with guided-wave mode of light propagation where a single linearly polarized light component rotated along the twisted structure. In the field-off state, the rotation is absent, and the transmittance of the nematic cell with homeoplanar director configuration is close to zero in that the rubbing direction of the bottom substrate coincides with the transmission axis of one of the polarizers (see Fig. 2(a), top row). Affected by the positive-polarity pulse of electric field directed from the top substrate to the bottom one, the transmittance increases to 60%. The growth is attributed to the field-induced twisted-nematic alignment within the LC layer.

The analysis of the oscillograms (Figs. 3(b) and 3(c)) allowed estimating the dynamic characteristics of the optical response of LC cells with β = 0° or 90°. The field-on time was determined as the interval between the leading edge of the positive electric pulse and the

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90% level of maximum light transmission, and the field-off time was the interval between the falling edge of this pulse and the level of 10% maximum transmittance. The values τ_{on} and τ_{off} made 190 ms and 240 ms, respectively, when the cell was controlled by the monopolar pulse (Fig. 3(b)). These values are considerably smaller than the response times proper to Fig. 3(a) and those of the cell switched between the homeotropic director configuration and the homeoplanar one [10,11].

The LC-cell dynamic parameters can be improved further by varying the waveform of the electric pulse. For example, under the bipolar pulse τ_{off} was decreased to 11 ms (Fig. 3(b)). It was presumably due to the faster return of CTA^+ ions to the top substrate when the short pulse of negative polarity was applied immediately after the positive pulse. Thereby the restoration of the initial homeoplanar director configuration occurred more rapidly.

4. Conclusions

Liquid crystalline material based on ionic-surfactant-doped nematic has been, for the first time to the best of our knowledge, applied to realize the orientational transition from the homeoplanar director configuration to the twisted-nematic structure induced by a steady electric field. The LC cell's dynamic characteristics have been remarkably improved in comparison with the counterpart containing the same LC with the homeotropic–homeoplanar director configuration transition [10,11]. Besides, a method to shorten the relaxation time by varying the waveform of the controlling pulse has been demonstrated. It should be noted that both approaches considered are not exhaustive. Other obvious techniques to improve performance are also known. For example, thinning the LC layer, adopting a nematic material with lower viscosity, and so on. These methods will be tested in our next work.

The homeoplanar–twisted structural transition can be more advantageous in use due to the larger gray scale than that of the widely used twisted–homeotropic switching in commercially available twisted-nematic displays. For the twisted-nematic devices in the switched-off state, the polarization of light wave propagating through the twisted LC structure is generally slightly elliptical. That makes it impossible to decrease the transmittance to zero. For the LC cell under study, the initial configuration is homeoplanar and the linearly polarized light passing through the nematic layer (see Fig. 2(a) or (c), top row) keeps the same polarization. It favorably provides the opportunity to achieve the darker optical state and the higher contrast ratio for the cell as well.

In summary, a small additive of ionic surfactant in nematic can affect the structural and optical properties caused by electrically induced changes of boundary conditions. These changes are capable of initiating anchoring transitions and, consequently, various transformations of the director configuration in the whole LC bulk. At that some unique effects can be realized for LC cells operated by the ionic-surfactant method, for example, the structural multistability within both nematic and cholesteric droplets with radial director configuration in the unperturbed state [16]. For the conventional operation method the memory states are absent inside these droplets. The most impressive feature here is the possibility to reorient the LC independently of the value of their dielectric anisotropy $\Delta\varepsilon$. In principle the ionic-surfactant method allows operating the LC even with $\Delta\varepsilon = 0$. Thus, this hybrid material offers promising opportunities to design fundamentally novel types of display devices.

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