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## Electrically induced anchoring transition in nematics with small or zero dielectric anisotropy

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### ABSTRACT

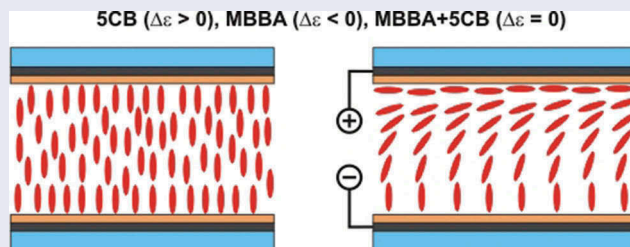
The orientational transitions induced by electrically controlled ionic modification of surface anchoring in liquid crystal cells based on the nematics with small or zero dielectric anisotropy  $\Delta\epsilon$  are considered. The type of director reorientation is shown to be independent of the sign of dielectric anisotropy and can be the same for the nematics with both negative and positive  $\Delta\epsilon$ . Besides, the orientational transition and corresponding switchable optical states do not depend on the  $\Delta\epsilon$  value and can be effectively realised even for the nematics with zero dielectric anisotropy.

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Nematic; ionic surfactant; anchoring transition; hybrid homeoplanar structure; dielectric anisotropy; electrooptics



## 1. Introduction

At present, the cells consisting of two parallel substrates filled with liquid crystal (LC) are widely used in modern optoelectronic devices. The macroscopic optical properties of the cells are mainly specified by the LC orientational structure which is highly sensitive to external forces. In the commercially available LC devices, the director reorientation and the corresponding switching of the optical states result from the Frederiks effect [1] under the action of electric field. The reorientation of director  $\mathbf{n}$  is caused by the external electric field  $\mathbf{E}$  which exerts the torque  $\mathbf{\Gamma}$  on the polarisation  $\mathbf{P}$  of LC [2]:

$$\mathbf{\Gamma} = \mathbf{P} \times \mathbf{E} = \epsilon_0 \Delta\epsilon (\mathbf{E}\mathbf{n}) \mathbf{n} \times \mathbf{E}, \quad (1)$$

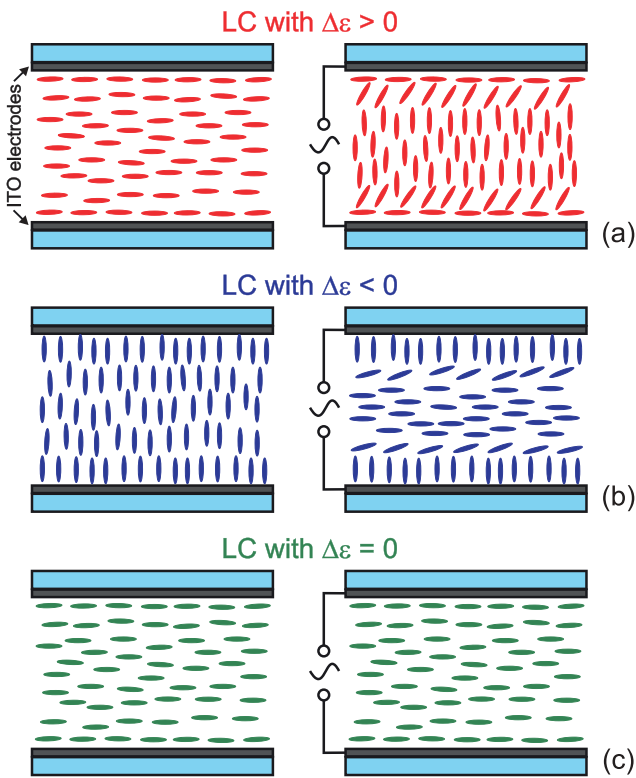
where  $\epsilon_0$  is the dielectric constant and  $\Delta\epsilon$  is a dielectric anisotropy of LC. Equation (1) makes it obvious that the dielectric anisotropy is the principal parameter which determines the characteristics of the LC

reorientation process, for example, the value of the Frederiks threshold field  $E_c$ :

$$E_c = \pi \sqrt{K/(\epsilon_0 \Delta\epsilon)}/d, \quad (2)$$

where  $K$  is an appropriate LC elastic modulus depending on the type of orientational transition, and  $d$  is a gap thickness of the LC cell. Moreover, the design of LC cell is specified by the  $\Delta\epsilon$  sign. Figure 1 shows the Frederiks effect within LC cells based on the nematics with different dielectric anisotropy. The ac electric field is applied perpendicularly to the LC layer.

If the nematic has a positive dielectric anisotropy, LC molecules are reoriented along the electric field (Figure 1(a)). In the cell based on the nematic with negative dielectric anisotropy, the electric field induces the reorientation of LC molecules perpendicularly to the field (Figure 1(b)). Consequently, the director orientation must be homeotropic in the initial state. Equation (2) implies that  $E_c \rightarrow \infty$  for LC with zero



**Figure 1.** (Colour online) The Frederiks effect in LC cells based on the nematics with positive (a), negative (b) and zero (c) dielectric anisotropy induced by the electric field. The initial LC orientations are shown in the left column. The right column represents LC orientations under the action of the ac electric field applied perpendicularly to the substrates.

dielectric anisotropy. It means that the reorientation of LC with  $\Delta\epsilon = 0$  caused by the Frederiks effect is principally impossible (Figure 1(c)). It should be noted that the director reorientation by means of the Frederiks effect occurs under the invariable anchoring of the LC molecules at the interface.

An alternative way to reorient LC is possible by modifying the LC surface anchoring with substrates by various external effects [3–11]. The methods of electrically induced modification of the surface anchoring seem to be the most interesting for practical application [8–11]. We are developing the method of electrically induced modification of surface anchoring of nematics by using ionic surfactants. The ionic-surfactant method was applied previously both to the polymer dispersed liquid crystals [12–15] and to the LC layer cells [16–18].

In this article, we investigate and compare the LC reorientation and corresponding optical response induced by the electrically controlled ionic modification of surface anchoring within LC cells based on the nematics with the different signs and values of dielectric anisotropy, including  $\Delta\epsilon = 0$ .

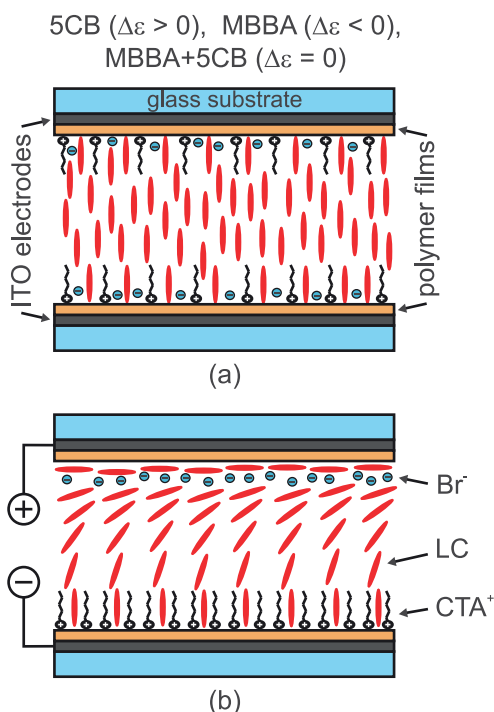
## 2. Materials and experimental techniques

The experiments were carried out with sandwich-like cells. These cells consisted of two glass substrates with transparent ITO electrodes coated with the 1.5- $\mu\text{m}$ -thick polymer films and 10- $\mu\text{m}$ -thick LC layer between them. The rubbed polymer films based on the polyvinyl alcohol (PVA) doped with glycerine compound (Gl) in the weight ratio PVA : Gl = 1 : 0.29 were used as orienting coatings. The utilised liquid crystal materials were the nematics LC 4-methoxybenzylidene-4'-n-butylaniline (MBBA) with  $\Delta\epsilon = -0.54$  at 25°C [19] and the MBBA-5CB mixture in the weight ratio 1 : 0.02, respectively. 5CB is 4-n-pentyl-4'-cyanobiphenyl with  $\Delta\epsilon = +13.3$  at 25°C [20]. The MBBA-5CB mixture had the zero dielectric anisotropy [8] and that was confirmed by our measurements of dielectric permittivity. The nematics were preliminary doped with ionic surfactant cetyltrimethylammonium bromide (CTAB) in the weight ratio LC : CTAB = 1 : 0.008. CTAB dissolved in liquid crystal dissociates into the positively charged surface-active ion  $\text{CTA}^+$  and the negative ion  $\text{Br}^-$ .

The optical textures of the nematic layer and their transformations under the electric field were studied in the crossed polarisers by means of the optical microscopy. Electro-optical response of the system consisting of LC cell placed between crossed polarisers was studied by using He-Ne laser ( $\lambda = 632.8 \text{ nm}$ ). The laser beam passed sequentially through the polariser, LC cell and analyser and was detected by the photodiode. The LC cell was placed so that the angle between the substrate rubbing direction and the polariser made 45°. The transmittance of the system was determined as  $T = (I_t / I_0) \times 100\%$ , where  $I_0$  is intensity of radiation after the first polariser,  $I_t$  is intensity after the second polariser.

## 3. Results and discussion

The polymer films specify the planar anchoring for the used nematics. However, the homeotropic director orientation within cell is formed in the initial state due to the ionic surfactant addition in the LC. It can be explained by the formation of surface-active  $\text{CTA}^+$  layers being adsorbed at the substrates. These layers screen the orienting influence of polymer walls and promote the LC molecules alignment perpendicularly to the substrates (Figure 2(a)). The application of dc electric field makes the electrode-anode substrate free from the layer of  $\text{CTA}^+$  ions and the planar anchoring proper to the polymer film restored (Figure 2(b)). As a result, the transition from the homeotropic director



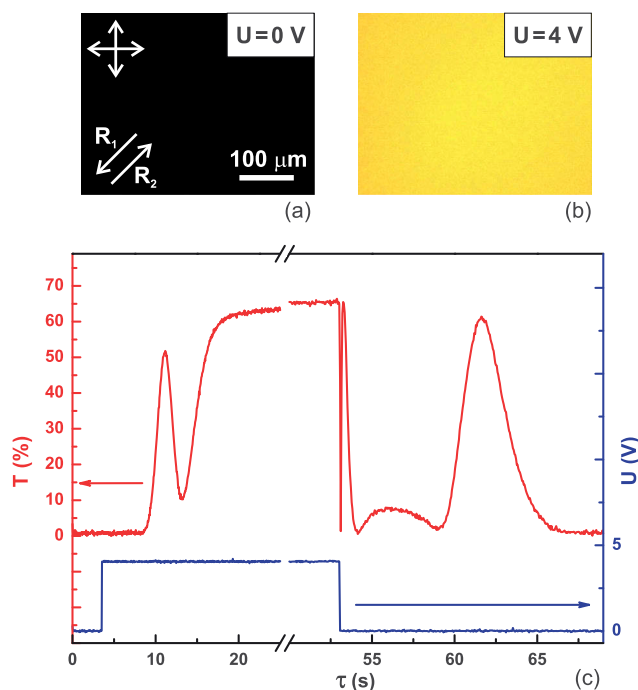
**Figure 2.** (Colour online) The scheme of the LC orientational transition induced by the electrically controlled ionic modification of surface anchoring. Under the dc electric field, LC is reoriented from the initial homeotropic configuration (a) into the hybrid one (b) independently on the sign and value of the dielectric anisotropy  $\Delta\epsilon$  of the used nematic.

configuration into the hybrid homeoplanar one occurs within the LC cell (Figure 2). This orientational transition has been investigated previously in the LC cell based on 5CB ( $\Delta\epsilon > 0$ ) doped with CTAB [16,17].

Since the main factor influencing the anchoring transition is the movement of the surface-active ions, the same variant of the director reorientation can be realised for the different LC independently of the sign and value of their dielectric anisotropy (Figure 2). For instance, the transition from the homeotropic director configuration into the homeoplanar one caused by the ionic modification of surface anchoring begins at  $U = 2.7$  V for the cell based on MBBA ( $\Delta\epsilon < 0$ ) doped with CTAB. This value is close to the threshold voltage ( $U_{th} = 2.8$  V) of 5CB cell operated by the ionic-surfactant method [16,17]. The reorientation of MBBA cannot be explained by the Frederiks effect (Figure 1 (b)) since the threshold field (Equation (2)) would be about 4 V for our cell [21]. Moreover, the estimation of phase retardation value reveals that it is approximately twice less than the one for the planar MBBA layer (Figure 1(b), right column) and corresponds to the hybrid configuration. The reorientation of LC director is not accompanied by the electrohydrodynamic

instability in the range of the control voltage  $2.7$  V  $\leq U \leq 4$  V. The domain structure was formed at the control voltage  $U \geq 4.1$  V. The on/off time of the MBBA cell under the action of rectangular electric pulse is tens of seconds and exceeds the same parameters for the 5CB cell ( $\sim 1$  s) [17].

It should be emphasised that the analogous transformation of the orientational structure (Figure 2) occurs for the nematic with zero dielectric anisotropy. Figures 3(a,b) demonstrate the change of the optical texture of the LC cell based on the MBBA–5CB mixture ( $\Delta\epsilon = 0$ ) doped with CTAB and placed between the crossed polarisers under the action of dc electric field. In the initial state, the optical texture of the LC layer is a uniform dark area independently of the sample rotation on the microscopic stage (Figure 3 (a)). It means that the director orientation within the cell is homeotropic. The dc electric field induces the modification of the surface anchoring which results in the formation of the hybrid LC structure. This transition leads to the increase of the light transmission of the system (Figure 3(b)). The reorientation induced by the ionic modification of the surface anchoring in the cell filled with MBBA–5CB mixture ( $\Delta\epsilon = 0$ ) has a



**Figure 3.** (Colour online) Optical textures of the LC cell based on the MBBA–5CB mixture ( $\Delta\epsilon = 0$ ) doped with CTAB in the initial state (a) and under the dc electric field 4 V (b); the square-wave optical response of the LC cell (the top curve) placed between the crossed polarisers and electric 4 V pulse (the bottom curve) (c). The polariser directions are shown by the double arrows.  $R_1$  and  $R_2$  are rubbing directions of the top and bottom substrates, respectively.

threshold character starting from 3 V which is approximately equal to the threshold voltages of 5CB cell [16,17] and MBBA cell operated by the ionic-surfactant method. The threshold character of the anchoring transition in LC is caused by the availability of the critical density of the adsorbed CTA<sup>+</sup> ions layer [22] below which the ionic layer does not screen the orienting influence of polymer coating [12]. Applying the dc electric field to the cell, one of the substrates begins to free itself from the layer of surface-active ions. Increasing the electric field to the threshold value, the surface density of ions decreases down to the critical value and the modification of the surface anchoring starts. At the control voltage  $3.0 \text{ V} \leq U \leq 4.1 \text{ V}$ , the optical texture of LC layer is a uniform light area (Figure 3(b)) without a domain structure which is formed at  $U > 4.1 \text{ V}$ . Thus the ionic-surfactant method provides an opportunity of the electrically controlled director reorientation of LC with zero dielectric anisotropy.

It should be noted that we had preliminary assembled the same cells as described in Section 2 but without CTAB. The response of the LC layers with both planar and homeotropic alignment to the applied AC electric field of 1 kHz was tested. The director reorientation was not observed up to  $U = 20 \text{ V}$ , at which the Williams domains were formed within LC layer with the initial planar-oriented structure. The spontaneous Frederiks transition [23] was not observed within the cell with homeotropic-oriented LC layer. These allow concluding that the observed changes of director orientation in the LCs doped with CTAB are caused by the ionic modification of surface anchoring.

Figure 3(c) shows the oscillogram of the square-wave response of the LC cell filled with the MBBA–5CB mixture and placed between crossed polarisers. The pulse amplitude is 4 V and its duration is 50 s. In the initial state, the cell transmittance is close to zero because of the homeotropic director orientation within the LC cell. The nematic reorientation into the hybrid state makes the light transmission of the system increased and saturated at near 66% after having successively passed through the maximum and minimum.

The dynamical characteristics of the optical response of the LC cell based on the nematic with  $\Delta\epsilon = 0$  depending on the value of applied electric pulse are presented in Figure 4. The delay time  $\tau_{\text{del}}$  defined as the time between the rising edge of the electric pulse and the start of system transmittance change decreases from 6.6 s to 4.5 s in the range 3.7–4.1 V of control voltage. The turn-on time  $\tau_{\text{on}}$ , defined as the time between rising edge of the electric pulse and the transmittance saturation, decreases from 29.3 s to 12.3 s in

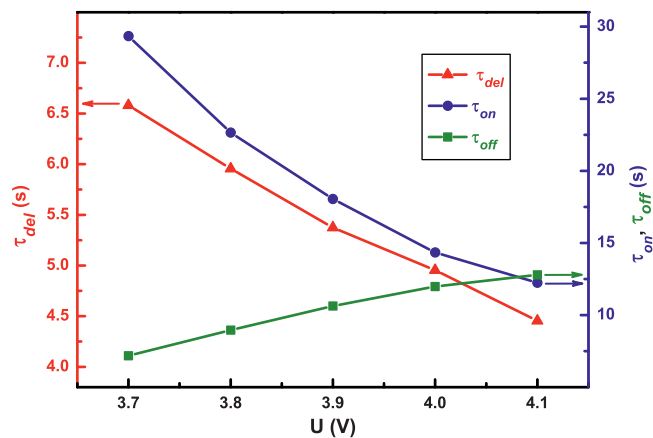


Figure 4. (Colour online) Delay time  $\tau_{\text{del}}$  (left axis), turn-on time  $\tau_{\text{on}}$  and turn-off time  $\tau_{\text{off}}$  (right axis) depending on the control voltage for the LC cell based on the MBBA–5CB mixture ( $\Delta\epsilon = 0$ ) doped with CTAB.

the same range of control voltage. Such dependences can be explained by the ion velocity rising resulted from the electric field increase. The turn-off time  $\tau_{\text{off}}$  defined as the time between the falling edge of the electric pulse and the relaxation of transmittance to the initial zero level, increases from 7.2 s to 12.8 s.

It should be noted that the ionic modification of the surface anchoring allows realising other variants of the LC orientational transition, for example, the transition from the hybrid homeoplanar director configuration to the twisted structure [18]. Apparently, this transition depends on neither the value nor the  $\Delta\epsilon$  sign. The use of this transition and optimising the form of the control electric pulse [18] allow considerably reducing the optical response time (down to milliseconds) for the electro-optical LC cells operated by the ionic-surfactant method.

#### 4. Conclusion

In conclusion, the orientational transitions induced by electrically controlled ionic modification of surface anchoring in nematics with small or zero dielectric anisotropy have been examined. It has been revealed that the external electric field causes the director reorientation from the homeotropic configuration into the hybrid one, which leads to switching of optical states of LC cell. This transformation depends on neither the sign nor the value of the LC dielectric anisotropy. That is, the same orientational transition can be realised for the nematics with  $\Delta\epsilon > 0$ ,  $\Delta\epsilon < 0$  and  $\Delta\epsilon = 0$  by applying approximately the same value of control voltage. Thus, the ionic-surfactant method provides an opportunity to study electrically induced anchoring

transitions and corresponding optical effects using all the variety of known nematics including LC with zero dielectric anisotropy.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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