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[a]Kirensky Institute of Physics, Krasnoyarsk Scientific Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russia; [b]Institute of Engineering Physics and Radio Electronics, Siberian Federal University, Krasnoyarsk, Russia

ABSTRACT

A reorientation of cholesteric liquid crystal with a large helix pitch induced by the electrically controlled ionic modification of the surface anchoring has been studied. In initial state, the cholesteric helix is untwisted completely owing to the normal surface anchoring specified by the cations adsorbed at the substrates. As a result, the homeotropic director configuration is observed within the cell. Under the action of DC electric field, one of the substrates becomes free from the layer of surface active cations, therefore, setting the planar surface anchoring. The latter, in turn, leads to the formation of the hybrid chiral structure. The threshold value and dynamic parameters have been estimated for this process as well as the range of control voltages, which do not allow the electrohydrodynamic instabilities. The twisted hybrid director configuration observed in the experiment has been analysed by means of the simulation of polarisation change of light propagating through the cholesteric layer with asymmetric (planar and homeotropic) surface anchoring on the cell substrates.
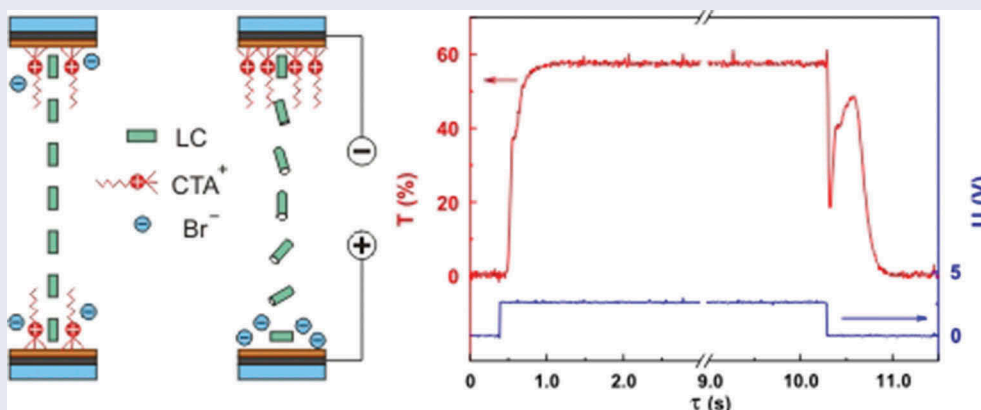
1. Introduction

Cholesteric liquid crystals (CLCs) are of great interest in various applications such as displays, light modulators, switchable diffraction gratings, liquid crystal lasers and others [1–5]. This is determined by specific optical properties resulting from the helical ordering of director [6]. Vast majority of the devices are operated by the Frederiks effect inducing the director reorientation within the CLC bulk under the electric field. In these applications, the cholesteric is generally placed between two flat substrates specially treated to specify a certain surface anchoring of liquid crystal (LC) at the interface,

which stays invariable during the process of director reorientation inside the cell bulk.

Besides, the LC reorientation can also be caused by the anchoring transition under the influence of external factors such as temperature, UV radiation or electric field [7–13]. Study of the director reorientation induced by the surface-anchoring modification is useful for both the basic investigations and application, since the LC orientational transitions, which are impossible under the Frederiks effect, can be realised.

The method of electrically controlled modification of the surface anchoring by using the ionic surfactants
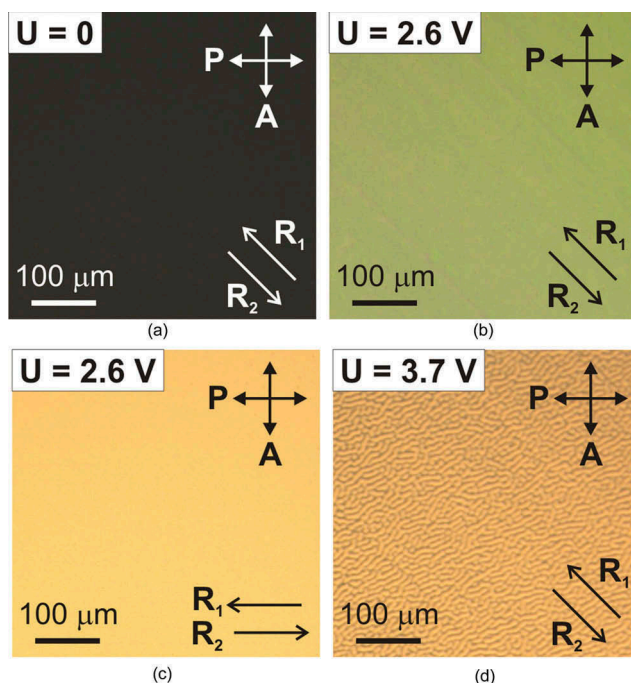
Figure 1. POM images of the optical textures of the cholesteric layer doped with the ionic surfactant made under different control voltages U and α angles between the rubbing direction of the bottom substrate (R_1) and the polariser (P): (a) $U = 0$ V, $\alpha = 45°$; (b) $U = 2.6$ V, $\alpha = 45°$; (c) $U = 2.6$ V, $\alpha = 0°$; (d) $U = 3.7$ V, $\alpha = 45°$. The cell gap thickness is $d = 8.1$ μm. Confinement ratio is $\rho = 0.4$. A is the analyser direction. R_2 is the rubbing direction of the top substrate.

has been developed for the nematic LC droplets [14–17], nematic layers [18–20] and cholesteric droplets. [21] For the nematic layers, the transitions from the homeotropic structure into the homeoplanar director configuration [18,19] and from the homeoplanar configuration into the twist structure [20] were found and studied.

The ionic-surfactant method is based on the change of surface-active ions concentration on the substrate under the action of DC electric field. The nematic is doped with the surfactant. The latter dissociates into ions, among which at least one is the surface active ion specifying, for example, the homeotropic anchoring [18]. The surface-active ions are adsorbed at the substrates. If their concentration is enough, they form the layers which can screen the planar-orienting effect of the substrates and stimulate the LC alignment perpendicularly to the substrates. Thus, the homeotropic director configuration is realised in the LC cell. Under the action of DC electric field, the ions dissolved in the LC shift to the appropriate electrodes. Therefore, the surface-active ion concentration decreases at one of the substrates and the planar anchoring, proper to the orienting coating, is restored here. As a result, the

transition into the homeoplanar director configuration occurs within the LC cell.

It is obvious that the orientational transition results in the change of light transmission of the system consisting of the LC cell placed between the crossed polarisers. For example, in the initial state, the system transmission is close to zero because of the absence of birefringence in the LC layer with homeotropic orientational structure. However, when the director is reoriented into the homeoplanar configuration, the light transmission increases, in case the orientation of LC at the substrate with planar anchoring mismatches any polarisers.

This paper is devoted to the development of the ionic-surfactant method to control the director orientation of the cholesterics with a large helix pitch.

2. Materials and experimental techniques

The experiment was carried out with sandwich-like cells. These cells consisted of two glass substrates with transparent indium tin oxide (ITO) electrodes coated with polymer films and the cholesteric layer between them. The polymer films based on the polyvinyl alcohol (PVA) doped with glycerine compound (Gl) in the weight ratio PVA : Gl = 1 : 0.383 were used as orienting coatings. The polymer films were deposited by spin coating and rubbed. The cell gap thickness d was set using teflon spacers and measured by means of the interference method [22] with the spectrometer. Cholesteric mixtures were prepared using the nematic 4-pentyl-4′-cyanobiphenyl (5CB) with positive dielectric anisotropy $\Delta\varepsilon$ and the chiral additive cholesterylacetate (ChA) in the weight ratios 5CB : ChA from 1 : 0.0030 to 1 : 0.0155, respectively. The nematic was preliminary doped with ionic surfactant cetyltrimethylammonium bromide (CTAB) in the weight ratio 5CB : CTAB = 1 : 0.002. CTAB dissolved in LC dissociates into the positively charged surface active ions CTA$^+$ and the negative ions Br$^-$. The helical twisting power HTP = 6.5 μm^{-1} of the additive ChA in the nematic 5CB was determined with the droplet method.[23] The used mixtures had pitch $10 \leq p \leq 51$ μm as calculated from $p = 1/(\text{HTP} \times c_w)$, where c_w is weight concentration of the chiral agent. The confinement ratio $\rho = d/p$ in LC cells was $0.16 \leq \rho \leq 0.85$.

The optical textures of the LC layer and their transformations under the electric field were analysed in the crossed polarisers by means of the polarising optical microscope (POM). Electro-optical response of the LC cell placed between crossed polarisers was studied with He-Ne laser ($\lambda = 632.8$ nm). The laser beam passed sequentially through the polariser, the LC cell, the analyser, and was detected by the photodiode. The LC

cell was placed so that the angle between the substrates rubbing direction and the polariser was $\alpha = 45°$ or $0°$. The transmittance of the system was determined as $T = (I_t/I_0) \times 100\%$, where I_0 is light intensity after the polariser, I_t is intensity after the analyser.

3. Results and discussion

Figure 1 demonstrates the change of optical texture of the cholesteric layer doped with the ionic surfactant under the action of DC electric field. In the given LC cell, the confinement ratio ρ is 0.4. When the electric field is switched off, the optical texture of the LC layer in crossed polarisers is a uniform dark area (Figure 1 (a)) independently of the sample rotation on the microscopic stage. Such an optical texture remains invariable until the $U = 2.3$ V. The latter was accompanied with the light transmission increase. In the range of control voltages 2.3 V $\leq U \leq$ 3.4 V, the optical texture of the cell is a uniform bright area (Figure 1 (b)). At that, the sample rotation relative to the crossed polarisers does not lead to the dark texture. The optical textures shown in Figure 1(b,c) prove this. Here, the angle α between the rubbing direction and polariser is 45° and 0°, respectively. Besides, at $\alpha = 0°$ (Figure 1(c)), the dark texture is not obtained either under the analyser rotation. At the control voltage $U = 3.5$ V, the domains began to form in the LC cell and they appear clearly at $U = 3.7$ V (Figure 1(d)).

The similar changes of optical texture were observed within the LC cells with $\rho = 0.16$ and 0.85 approximately under the same control voltage. The only difference of the initial texture of cholesteric layer with $\rho = 0.85$ is the presence of a small number of cholesteric bubbles [24,25]. However, after the application of AC voltage, the cholesteric bubbles disappear and the optical texture of LC layer is the uniform dark area.

The optical texture of the LC layer in the absence of electric field (Figure 1(a)) and its invariability at the sample rotation relative to the crossed polarisers indicates a complete untwisting of the cholesteric helix and the formation of the homeotropic director orientation within the cell due to the ionic surfactant CTAB added (Figure 2(a)). The cholesteric helix untwisting occurs as an effect of the normal anchoring of LC molecules with the substrates.[26] The formation of homeotropic or twisted structures within the cholesteric layer with rigid normal anchoring depends on the confinement ratio ρ. The transition threshold ρ_{th} value is defined by the equation [27]:

$$\rho_{th} = K_{33}/(2K_{22}), \qquad (1)$$

where K_{33} and K_{22} are elastic constants of the bend and twist deformations, respectively. When $\rho < \rho_{th}$, the helix pitch is completely untwisted inside the LC cell with rigid normal anchoring. The twist structure is formed at $\rho > \rho_{th}$. The typical materials have the threshold value ρ_{th} about 1 [28]. The samples under study have $\rho < 1$, which makes the helix pitch completely untwisted in the initial state.

When the DC electric field is applied, the surface anchoring on the electrode-anode substrate is modified, and the planar anchoring proper to the polymer orienting coating is restored at this substrate. The modification of the boundary conditions results in the reorientation of the LC structure and, consequently, in the change of the optical texture of the LC cell in the crossed polarisers (Figure 1(b)). Since the considered optical texture does not get dark completely during the sample rotation on the microscope stage relative to the crossed polarisers (Figure 1(b,c)), it means that the twisted orientation structure is formed within the LC layer. Thus, the optical textures of the LC layer presented in Figure 1(b,c) correspond to the hybrid-aligned cholesteric [29–33]. Its orientational structure is shown in Figure 2(b). It should be emphasised that the observable changes of optical texture cannot be
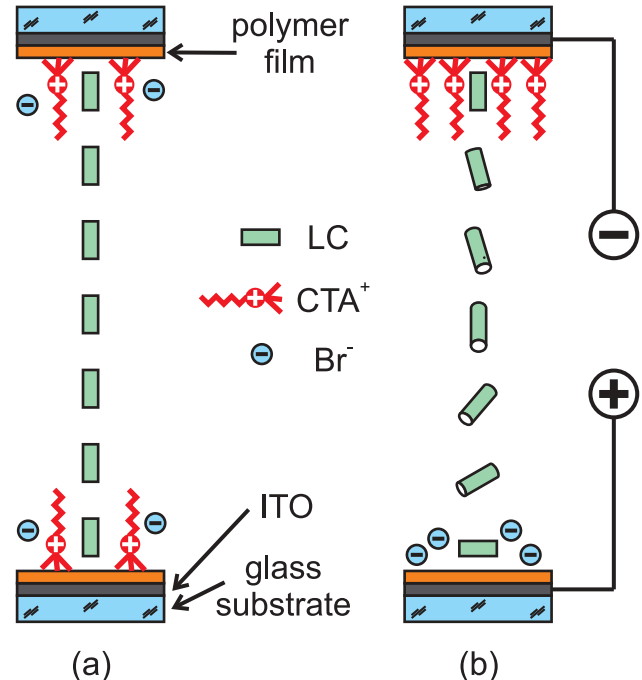

Figure 2. (Colour online) Scheme of the orientational transition induced by the DC electric field inside the LC cell filled with the CLC doped by the ionic surfactant. (a) The homeotropically aligned LC layer under the electric field off. (b) The cholesteric layer with a hybrid structure formed owing to the homeotropic-planar change of surface anchoring on the electrode-anode substrate.

induced by the Frederiks effect because the LC used in our experiment has positive dielectric anisotropy. In this case, the Frederiks effect could result only in the stabilisation of the initial homeotropic director configuration.

As mentioned above, the optical texture (Figure 1 (c)) does not become dark completely under the analyser rotation when the polarisation direction of incident light coincides with the substrate rubbing direction. It indicates that the light after passing through the layer of hybrid-aligned CLC is no longer linearly polarised. The light polarisation change for such a system has been simulated. First, the cholesteric orientational structure within the cell was calculated by means of the energy minimisation of elastic deformations of the director field [34] under asymmetric boundary conditions. The LC surface anchoring on one of the substrates was planar and on the other one was homeotropic. Then, applying the Berreman 4×4-matrix method [35], the light polarisation after the LC layer transmission was simulated. The following parameters of 5CB were used for the calculations: the elastic constants of the splay deformation $K_{11} = 5.7$ pN, the twist deformation $K_{22} = 3.5$ pN and the bend deformation $K_{33} = 7.7$ pN [36]; the extraordinary and ordinary refractive indices $n_e = 1.7002$, $n_o = 1.5294$ ($\lambda = 632.8$ nm), respectively [37]; the thickness of LC layer $d = 8.1$ μm, the helix pitch $p = 21$ μm, the confinement ratio $\rho = 0.4$.

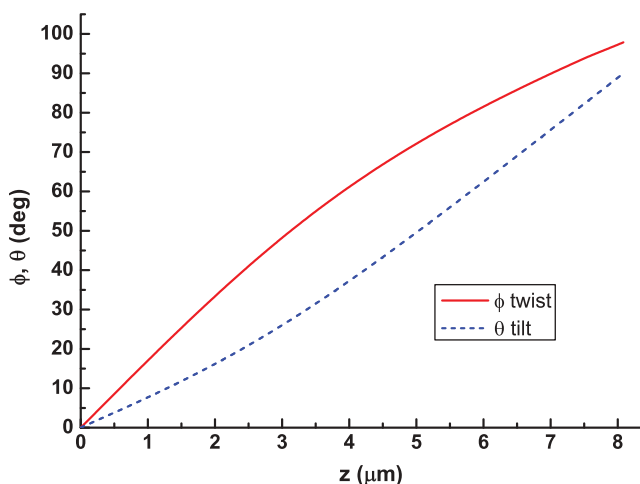Figure 3 shows the calculation data for the hybrid-aligned cholesteric structure. The simultaneous tilt and

Figure 3. (Colour online) Calculation data of tilt angle θ and twist angle φ of the director versus the z-coordinate perpendicular to the cell substrates for the structure of hybrid aligned cholesteric. z = 0 and z = 8.1 μm correspond to the substrates with planar and homeotropic surface anchoring, respectively. Thickness of the LC layer is d = 8.1 μm. The helix pitch is p = 21 μm.

twist of the director are seen to occur inside the LC layer. The total twist angle of director is 98°. The Berreman method simulation has revealed that the linearly polarised light beam ($\lambda = 632.8$ nm) passing through such a LC orientational structure gets elliptically polarised. The ratio of semi-major axis to semi-minor axis of the polarisation ellipse is 3.8. At that, the β angle between the polarisation direction of incident light and the semi-major axis of elliptically polarised light is 68° when leaving the LC layer.

We measured β angle depending on the control voltage value. The cell was placed between the crossed polarisers so that the rubbing direction of input substrate coincided with the polarisation direction of incident He-Ne laser beam. After that, the DC voltage was applied to the LC cell. When the light transmission reached the saturation, which corresponds to the formation of the hybrid-aligned CLC, the minimal light transmission of the system was found by means of the analyser rotation. In this case, the direction of semi-major axis of the elliptically polarised light was perpendicular to the analyser direction. In the range 2.6–3.2 V of control voltages, β angle changed from 62° to 64°, respectively. These data are in a good accordance with the calculated results.

Figure 4 shows the oscillograms of the square-wave response of the LC cell placed between crossed polarisers. The pulse amplitude is 2.6 V and its duration is 10 s. The oscillogram in Figure 4(a) corresponds to the situation, when the polarisation of incident light coincides with the rubbing direction ($\alpha = 0°$), and $\alpha = 45°$ for Figure 4(b). In the initial state, the light transmission of the system is close to zero because of the homeotropic director orientation. The applied electric pulse increases the light transmission caused by the formation of the hybrid-aligned cholesteric. If the polarisation of incident light coincides with the rubbing direction (Figure 4(a)), the light transmission saturation reaches 58%. The on-time τ_{on} defined as the interval between the rising edge of electric pulse and the increase of the transmittance up to 90% from the saturation value was 0.31 s. The off-time τ_{off} defined as the interval between the falling edge of electric pulse and the decrease of the transmittance down to 10% of the saturation value was 0.51 s. For $\alpha = 45°$, the transmittance saturation reached 51% (Figure 4(b)), $\tau_{on} = 0.13$ s, $\tau_{off} = 0.59$ s. Under the control voltages $2.6 \leq U \leq 3.2$ V, the on-time τ_{on} did not practically change. The off-time τ_{off} in the same range of voltages increased up to 1.75 s. It should be noted that the change of the control pulse form is able to lead to a significant improvement of the dynamic characteristics of LC cell with electrically controlled ionic modification of the surface anchoring.[20]
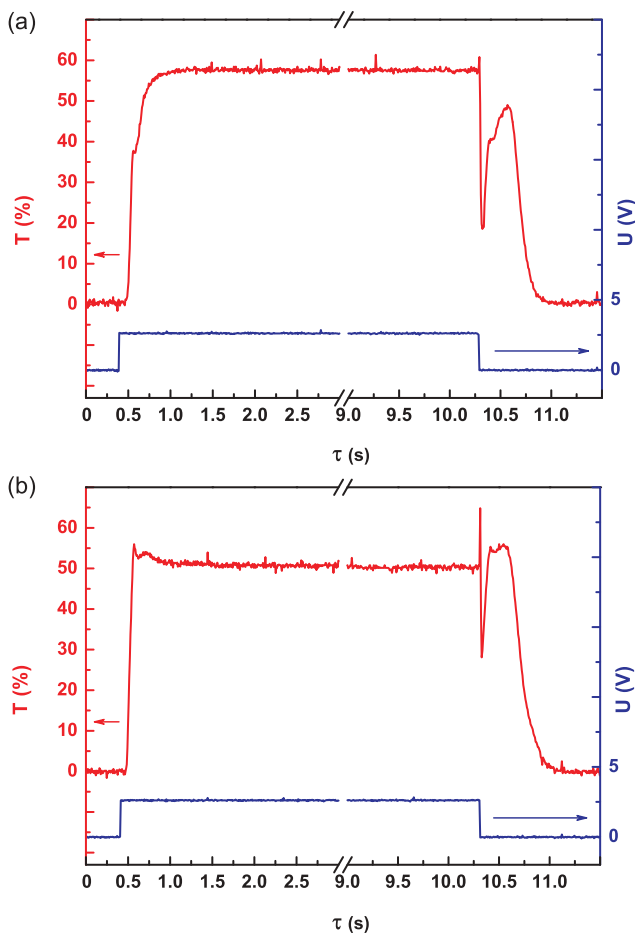
(a)

(b)

Figure 4. (Colour online) Optical response of the LC cell filled with the ionic surfactant-doped cholesteric in crossed polarisers at different α angles between the polarizer and the rubbing direction: (a) $\alpha = 0°$; (b) $\alpha = 45°$. Applied voltage amplitude is 2.6 V. Confinement ratio is $\rho = 0.4$.

4. Conclusions

The reorientation of cholesteric LC caused by electrically controlled ionic modification of the surface anchoring has been studied in the present paper. The reorientation has been examined for the cholesteric with the large helix pitch (10–51 μm), and the ratio of the LC layer thickness to the pitch changed in the range 0.16–0.85. It was shown that in the LC cell, the dc electric field induces the transition from the homeotropic director configuration into the twisted hybrid one. The director reorientation is found to have the threshold at 2.3 V. It proceeds without electrohydrodynamical instabilities under the control voltages 2.3 V ≤ U ≤ 3.4 V. On-time for the LC cells was tenth parts of a second and off-time was about a second.

To verify the experimental results, we simulated the orientational structure of hybrid-aligned cholesteric and the change of linearly polarised light after passing the LC layer. A situation when the polarisation of incident light coincides with the director at the planar anchoring substrate was considered. The calculations show that the light passing through the hybrid-aligned cholesteric layer becomes elliptically polarised, and the semi-major axis of ellipse turns relative to the initial polarisation. The simulated rotation angle is in a good agreement with the experimental value. This confirms the formation of the twisted hybrid director configuration under the DC electric field applied to the LC cell.

Thus, the ionic modification of surface anchoring initiates the nematic-cholesteric transition similar to the transition induced by the Frederiks effect inside the LC cell filled with a cholesteric with negative dielectric anisotropy.[38]

ORCID

Ivan Vladimirovich Timofeev http://orcid.org/0000-0002-6558-5607

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