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## Electrically induced anchoring transition in cholesteric liquid crystal cells with different confinement ratios

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### ABSTRACT

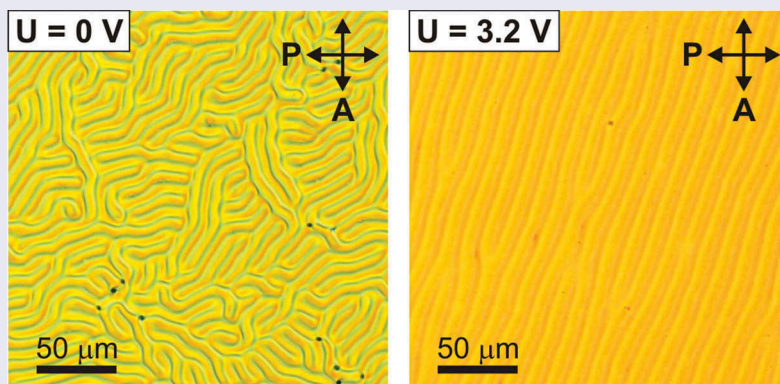
Reorientation of cholesteric liquid crystal induced by the electrically controlled ionic modification of surface anchoring within the cell with confinement ratio exceeding 1 has been studied. The change of homeotropic surface anchoring to the planar one on the electrode-anode substrate under the action of DC voltage causes the formation of the modulated hybrid-aligned cholesteric layer in the cell. Optical texture of the liquid crystal layer with such an orientation structure is the linear periodic stripes. Homogeneity of emerging optical texture depending on the confinement ratio as well as on the prehistory of voltage application has been considered. It has been found that the ionic modification of surface anchoring results in total transformation of the diffraction pattern observed after the laser beam passing through the sample.

### ARTICLE HISTORY

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### KEYWORDS

Cholesteric; ionic surfactant; anchoring transition; modulated hybrid-aligned cholesteric layer; diffraction grating



## 1. Introduction

The cholesteric liquid crystals (CLCs) have a helical ordering characterised by the equilibrium helix pitch  $p$ . In most experiments and practical application, the cholesteric is placed between two parallel substrates. The key parameter here is the confinement ratio  $\rho$  which is the ratio of LC layer thickness  $d$  to the helix pitch  $p$ . The confinement ratio specifies the initial orientation structure of cholesteric. If the cell substrates assign the rigid homeotropic anchoring for LC, varying this parameter allows achieving both the twisted orientation structure and the homeotropic director configuration. The latter is generally observed at  $\rho < 1$  [1]. Besides, the confinement ratio affects the response of CLC to an electric field applied. For example, the threshold value of electric field strength is inversely to  $p$  for the cholesteric-nematic transition [2,3].

Consequently, the threshold voltage for such a transition is linearly proportional to  $\rho$ .

The resulting LC orientation structure specifies the macroscopic optical properties of the cell. The structure can be transformed under the action of electric (magnetic) field on the LC bulk due to the Frederiks effect [4]. In addition, the director reorientation can be initiated by modifying the LC surface anchoring under the influence of external factors (anchoring transition) [5–15]. One of these effects is the electrically induced ionic modification of surface anchoring, which is based on the change of the surface-active ions concentration on the substrate under the action of DC voltage [16–20]. Previously this effect has been studied within the cholesteric LC layer with confinement ratio  $\rho < 1$  in [21]. In the initial state, the cholesteric helix in the LC cell is completely untwisted and the homeotropic

director configuration is formed. The application of DC voltage causes the transition to the twisted hybrid orientation structure. This resulted from the fact that one of the substrates gets free from the layer of surface-active ions and the planar anchoring proper to the polymer orienting coating is formed at this substrate. The aim of this article was to study the anchoring transitions caused by electrically induced modification of boundary conditions in the cholesteric layer doped with ionic surfactant for the confinement ratios exceeding 1.

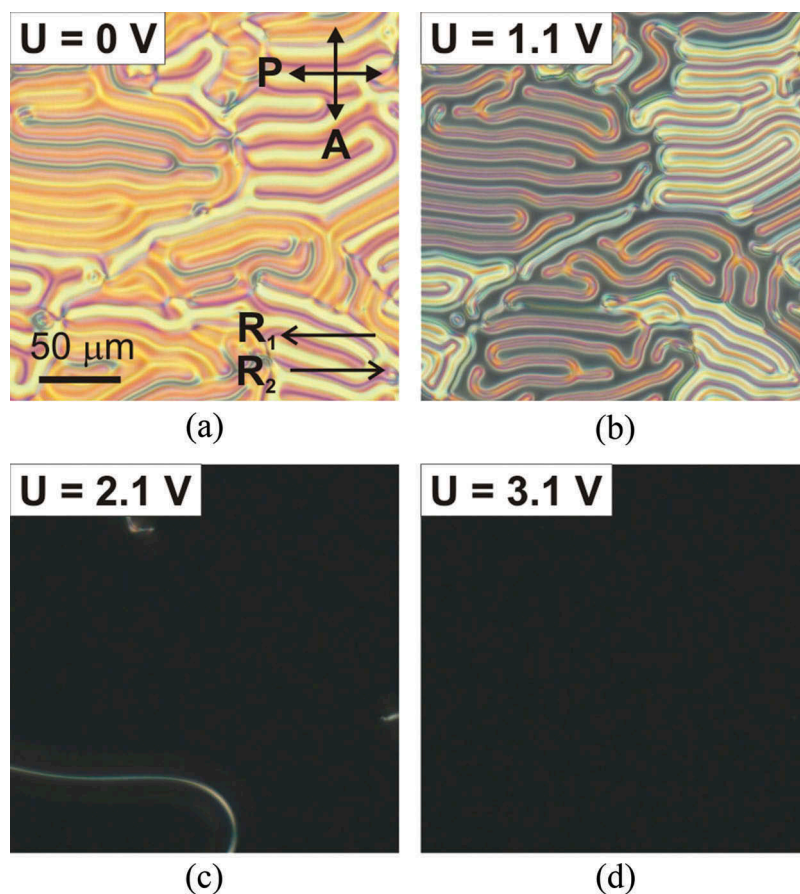
## 2. Experiment

The experiment was carried out with sandwich-like cells consisting of two glass substrates with transparent indium tin oxide electrodes coated with polymer films and the cholesteric layer between them. The polymer films of polyvinyl alcohol (PVA) with additive of glycerine compound (Gl) in the weight ratio PVA : Gl = 1 : 0.479 were used as the orienting coating. The polymer

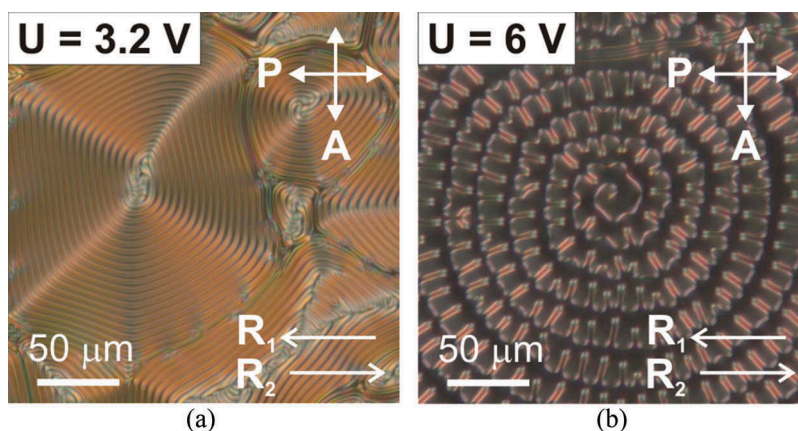
films were deposited on the substrates by spin coating and then were uniaxially rubbed. The teflon spacers set the LC layer thickness  $d$  in the cell. The nematic 4-pentyl-4'-cyanobiphenyl (5CB) doped with the chiral additive cholesterylacetate in the weight ratio varying from 1 : 0.0233 to 1 : 0.0658 was used as CLC. The cationic surfactant cetyltrimethylammonium bromide (CTAB) was preliminarily added to the nematic in the weight ratio 5CB : CTAB = 1 : 0.0041. The helix pitch  $p$  in the utilised mixtures changed from 2.6 to 7.1  $\mu\text{m}$ , and  $d/p$  ratio in the cells under study was within 1.2–8. The cells were filled with the liquid crystal by the capillary method in the isotropic phase. The samples were examined by means of the polarising optical microscope. The diffraction patterns were obtained using He-Ne laser ( $\lambda = 632.8 \text{ nm}$ ).

## 3. Results and discussion

The LC cells response to the 1 kHz AC voltage was foremost investigated. Figure 1 demonstrates the optical



**Figure 1.** (Colour online) Polarising optical microscope (POM) images of the optical textures of the cholesteric layer doped with the ionic surfactant made under AC voltages  $U = 0 \text{ V}$  (a),  $1.1 \text{ V}$  (b),  $2.1 \text{ V}$  (c) and  $3.1 \text{ V}$  (d). The thickness of liquid crystal (LC) layer is  $d = 8.2 \mu\text{m}$ . Confinement ratio is  $\rho = 1.2$ . Here and below, **P** and **A** are the directions of polariser and analyser, respectively;  $R_1$  and  $R_2$  are the rubbing directions of the bottom and top substrates, correspondingly.



**Figure 2.** (Colour online) POM images of the optical textures of the cholesteric layer doped with the ionic surfactant. (a) Confinement ratio is  $\rho = 1.9$  and 1 kHz AC voltage is  $U = 3.2$  V; (b) Confinement ratio is  $\rho = 3.2$  and 1 kHz AC voltage is  $U = 6$  V.

textures of the LC cell filled with cholesteric doped by the ionic surfactant under AC voltage of different values. The LC thickness  $d$  in the cell under study is  $8.2 \mu\text{m}$  and the equilibrium helix pitch is  $p = 7.1 \mu\text{m}$ ; therefore, the confinement ratio is  $\rho = 1.2$ . Originally, the fingerprint texture is realised in the cell (Figure 1(a)). Application of AC electric field perpendicularly to the cell substrates transforms the fingerprint texture into a homogeneous dark area (Figure 1(b–d)) which does not change while the sample is being rotated relative to the crossed polarisers.

The surfactant CTAB dissolving in LC dissociates into the positive surface-active ions  $\text{CTA}^+$  and negative ions  $\text{Br}^-$ .  $\text{CTA}^+$  ions are adsorbed on the cell substrates and specify the homeotropic anchoring for cholesteric. As was mentioned earlier, the formation of the homeotropic or twisted director configuration at the rigid perpendicular anchoring depends on the confinement ratio  $\rho$ . The critical value  $\rho_c$  corresponding to the transition between these structures is specified by the ratio of the LC elastic modulus [22] and it is about 1 for typical materials [1]. The confinement ratio exceeds 1 for the cell presented in Figure 1; and consequently, the twisted cholesteric structure with the proper fingerprint texture is initially formed (Figure 1(a)).

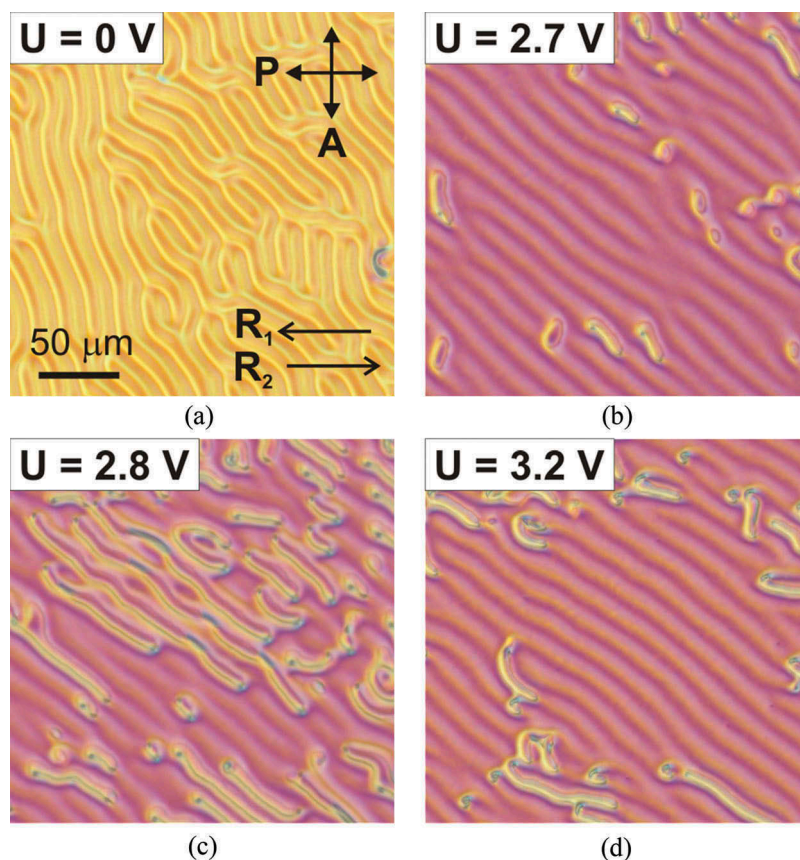
The action of AC voltage gets the cholesteric twisted structure transformed into the homeotropic director configuration due to the positive LC dielectric anisotropy. The optical texture of LC layer shown in Figure 1(d) corresponds to the homeotropic configuration. The analogous transition from the twisted structure to the homeotropic one was also observed in other LC cells with the 1.2–8 confinement ratios. The more  $\rho$  value, the more voltage required for the formation of homeotropic director configuration. In addition, at

certain values of AC voltage, the hydrodynamic flows of LC form specific patterns (Figure 2) similar to the ones shown earlier [23].

The DC voltage application causes totally different transformations of the cholesteric optical texture (Figure 3). The LC cell being unpowered reveals the fingerprint texture (Figure 3(a)) which remains invariable up to  $U = 2.7$  V. The optical texture of LC layer begins transforming at  $U = 2.7$  V, and it turns into the linear periodic stripes with the various number of defects (Figure 3(b–d)) in the range of control voltages  $2.7 \text{ V} \leq U \leq 3.3$  V. Further increase of the control voltage results in the appearance of the domains related to the hydrodynamic instability in LC. It has been found that a number of structure defects for the considered sample depend on the prehistory of voltage application to the cell. For example, if the cell is preliminarily exposed to a pulse of AC voltage, the linear periodic texture formed under the action of DC voltage contains fewer defects. The optical texture of LC layer with numerous defects formed under DC voltage  $U = 3$  V is presented in Figure 4(a). Another pattern is formed under the same DC voltage if the cell is preliminarily influenced by 1 kHz AC voltage of 10.3 V value (Figure 4(b)). As a result, a number of defects decreased dramatically.

The observed changes of cholesteric optical texture under the action of DC voltage (Figure 3) are caused by the modification of LC molecule anchoring at one of the substrates. Originally, the adsorbed  $\text{CTA}^+$  cations assign a homeotropic anchoring of LC molecules on the top and bottom cell substrates. Applying the DC electric field makes the surface-active cations leave the anode-substrate and the ion surface density decreases at a certain voltage, so that the planar anchoring proper to the polymer coating



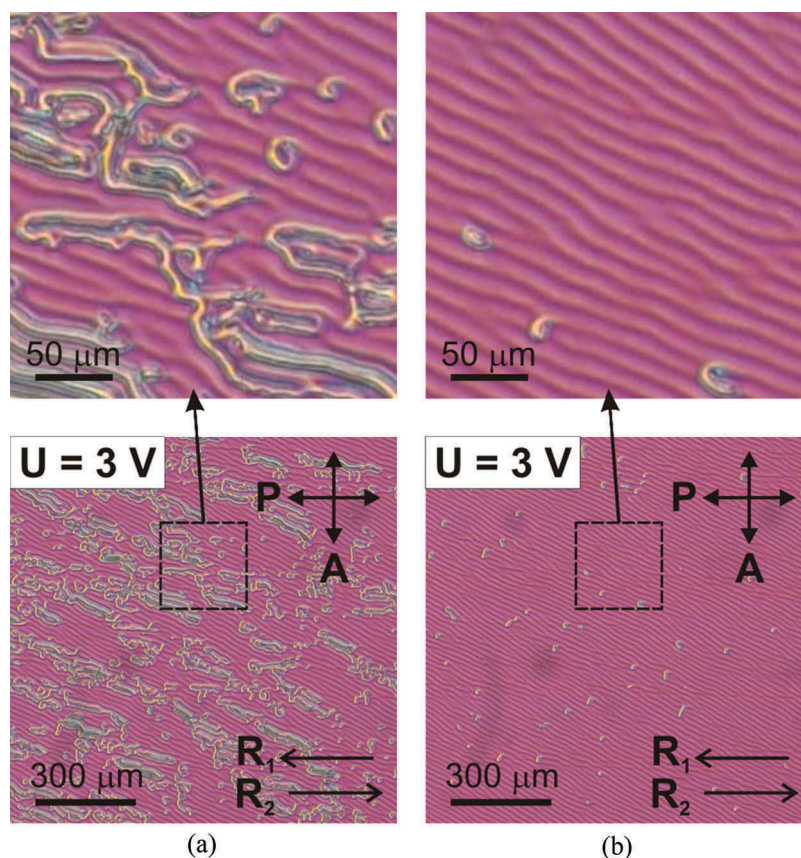


**Figure 3.** (Colour online) POM images of the optical textures of the cholesteric layer doped with the ionic surfactant made under DC voltages  $U = 0\text{ V}$  (a),  $2.7\text{ V}$  (b),  $2.8\text{ V}$  (c) and  $3.2\text{ V}$  (d). LC layer thickness is  $d = 8.2\ \mu\text{m}$ . Confinement ratio is  $\rho = 1.2$ .

is formed here. Such a modification of the surface anchoring at one of the substrates results in the formation of hybrid-aligned cholesteric (HAC) orientation structure within the LC cell. It is known that the structure of uniform HAC (UHAC) or modulated HAC (MHAC) can be formed depending on the confinement ratio in LC cell with different boundary conditions, if one of the substrates assigns a homeotropic LC molecule anchoring and another substrate specifies the planar one [24]. In HAC structure, the tilt and twist of the director occur simultaneously along the normal to the LC layer. At that the director orientation in the layer plane is homogeneous in the UHAC structure while in the MHAC one there is a surface layer near the homeotropic substrate where a periodic bend of the cholesteric helix axis takes place [24,25]. Optical textures of the LC layer with UHAC and MHAC structures are rather different. The optical texture of the CLC with UHAC structure is a homogeneous area while the pattern of periodic stripes is observed in the LC layer with MHAC structure, where the stripes orientation depends on the confinement ratio [24–29].

The transition from UHAC to MHAC structure at the confinement ratio is about 1 was demonstrated experimentally in [26], and that is in a good agreement with our results. Thus, a formation of the UHAC structure owing to the ionic modification of the surface anchoring was observed at  $\rho < 1$  in the LC cells, and its optical texture was a homogeneous bright area [21]. In this work, the MHAC structure is realised in the LC cell with  $\rho = 1.2$  under the action of DC voltage (Figure 3, 4) that is confirmed by the periodic stripes pattern of the cholesteric layer.

Figure 5 shows the optical texture transformation of the LC cell filled with cholesteric doped with ionic surfactant at  $\rho = 1.9$ . The main features of optical texture transformation caused by DC voltage are seen to be the same as in the LC cell with  $\rho = 1.2$ . The optical texture of cholesteric layer remains invariable up to  $U = 2.6\text{ V}$ . The optical texture in the form of the periodic stripes pattern with defects is observed in the range of control voltages  $2.7\text{ V} \leq U \leq 3.4\text{ V}$ . However, in contrast to the cell with  $\rho = 1.2$ , this sample had more defects and we failed to obtain the homogeneous stripes on a



**Figure 4.** (Colour online) POM images of the optical textures of the cholesteric layer doped with the ionic surfactant made under DC voltage  $U = 3$  V without the preliminary AC voltage influence (a) and with preliminary action of 1 kHz AC voltage of 10.3 V value (b). The scaled-up area of  $250 \times 250 \mu\text{m}$  size is presented in the top row. LC layer thickness is  $d = 8.2 \mu\text{m}$ . Confinement ratio is  $\rho = 1.2$ .

sufficiently large area using preliminary action of AC voltage. The periodic stripes formed under the DC voltage have another rotation angle relative to the rubbing direction of the substrates in comparison with the cell at  $\rho = 1.2$ . The dependence of the rotation angle on the confinement ratio was mentioned earlier.

For the cell with  $\rho = 3.2$  (Figure 6) the threshold voltage of LC reorientation caused by the ionic-modified surface anchoring is 2.7 V which is close to the values for previous samples. However, the periodic stripes pattern appears only on a small sample area (Figure 6(c)). Applying the DC voltage to the CLC cell with  $\rho = 8$ , a visible change of optical texture was not observed at all.

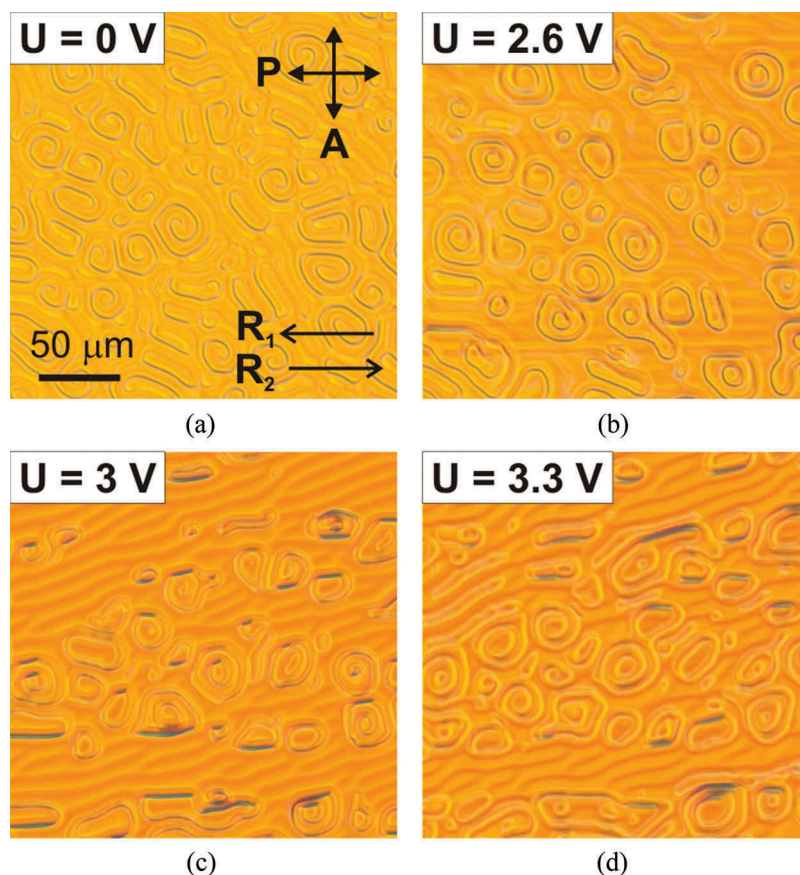
As was experimentally demonstrated in [28] for HAC structure, the optical texture with periodic stripes pattern of high quality can be obtained only in a certain range of the confinement ratios. Exceeding the range, the stripes texture with numerous defects is formed. It is explained that the forces of planar surface anchoring become too weak to

form defect-free structure [28]. It is probably due to this reason the MHAC structure with variable number of defects was formed within studied cells with various confinement ratios. At that, the higher  $\rho$ , the more number of defects.

The reorientation time of a director in LC cell operated by ionic-surfactant method is determined by the complex of several processes such as the leaving of  $\text{CTA}^+$  cations from the electrode-anode substrate, the change of surface anchoring of LC molecules and reorientation of LC in the bulk [18]. The response time of optical texture transformations of cholesteric layer under the action of DC voltage and relaxation time after switching off electric field was of the order of a one second for LC cells under study. These values are in a good agreement with dynamic characteristics measured in nematic cells with ionic-surfactant operation [18,19].

The MHAC structure ordered is known to be applied as a controllable phase grating [27–29]. Changing the helix pitch caused by an electric field, temperature or light radiation leads to the rotation of





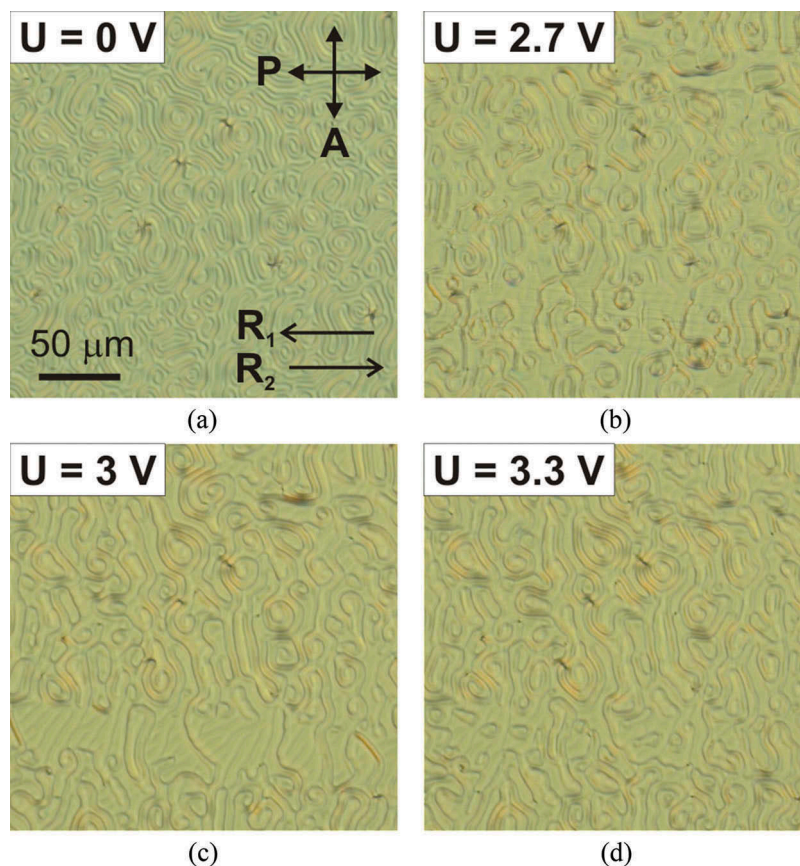
**Figure 5.** (Colour online) POM images of the optical textures of the cholesteric layer doped with the ionic surfactant made under DC voltages  $U = 0$  V (a), 2.6 V (b), 3 V (c) and 3.3 V (d). The LC layer thickness is  $d = 7.9$   $\mu\text{m}$ . Confinement ratio is  $\rho = 1.9$ .

linear stripes. We have also studied the changes of the diffraction pattern observed on the screen after a linearly polarised laser beam passed through the sample. The LC cell with confinement ratio 1.2 was considered. To improve homogeneity of the domain structure (Figure 4(b)) the cell was previously exposed to the pulse of 1 kHz AC voltage of 10.3 V. Figure 7 demonstrates the diffraction pattern observed when the electric field is switched off and under the DC voltage of 3 V applied to the cell. Initially, the fingerprint texture was realised in the LC cell (Figure 3(a)). The latter did not show a preferred orientation, which made the diffraction pattern look as concentric rings (Figure 7 (a)). Applying the DC voltage makes a texture with periodic stripes formed (Figure 4(b)). The diffraction pattern appears as a set of three light spots (Figure 7 (b)). The diffraction pattern is practically invariable in the range of control voltage 2.7–3.2 V. It means that the rotation angle of linear domains in the MHAC structure relative to the rubbing direction of the substrates does not change. Thus, modifying the surface anchoring allows switching only between two diffraction patterns (Figure 7).

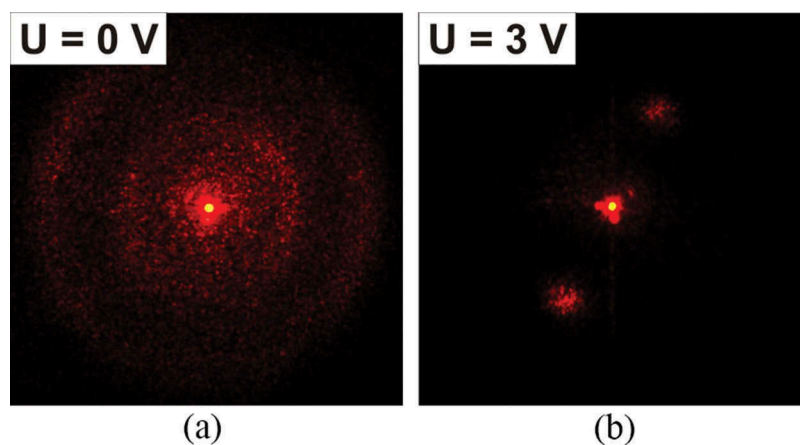
#### 4. Conclusions

In this article, the reorientation of CLC caused by the electrically controlled ionic modification of surface anchoring in the LC cells with various confinement ratios exceeding 1 has been studied. Initially, the fingerprint texture is realised owing to the homeotropic anchoring of LC with the cell substrates. Applying DC voltage, the modification of surface anchoring from homeotropic to planar on the electrode-anode substrate is occurred. As a result, a modulated hybrid-aligned cholesteric structure is formed and its optical texture appears as periodic stripes. Besides the linear stripes, there are defects which number increases as the confinement ratio grows. The fewest defects are observed in the cells with  $\rho$  close to 1. In addition, it is shown that an optical texture quality can be improved by a preliminary influence of AC voltage on the cell.

The electrically controlled ionic modification of surface anchoring allows changing the diffraction pattern obtained after the laser beam passed through the sample. Thus, the diffraction pattern is concentric rings in the unpowered state. The DC voltage transforms it into three light spots because the MHAC structure acts as a phase grating.



**Figure 6.** (Colour online) POM images of the optical textures of the cholesteric layer doped with the ionic surfactant made under DC voltages  $U = 0\text{ V}$  (a),  $2.7\text{ V}$  (b),  $3\text{ V}$  (c) and  $3.3\text{ V}$  (d). The LC layer thickness is  $d = 8.2\ \mu\text{m}$ . Confinement ratio is  $\rho = 3.2$ .



**Figure 7.** (Colour online) Diffraction patterns behind the cholesteric layer doped with the ionic surfactant in the initial state (a) and under DC voltages  $U = 3\text{ V}$  (b). The LC layer thickness is  $d = 8.2\ \mu\text{m}$ . Confinement ratio is  $\rho = 1.2$ .

### Disclosure statement

No potential conflict of interest was reported by the authors.

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