The concept of biaxial surface potential and polymer aligning layers in electro-optical cells based on helical nanostructures of ferroelectric liquid crystal

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Abstract. The paper considers the possibility of controlling the alignment quality of helical nanostructures of ferroelectric liquid crystals (FLCs) within the concept of biaxial surface potential due to variation the FLCs helical pitch $p_0$ and polymer aligning layers structures.

1. Introduction

The anchoring energy of liquid crystals (LCs) with bounding surfaces plays an important role in the analysis of the LCs orientational structure including the FLCs ones. At the moment, the anchoring energy coefficient $W_n$ is the parameter of well-known uniaxial Rapini potential $\Phi_n$ [1], which can be written also for FLCs as [2]:

$$\Phi_n = -\frac{W_n}{2} \sin^2 \psi$$  (1)

where $W_n$ – is the anchoring energy between the director $n$ of the liquid crystal and the easy alignment axis $R$, and $\psi$-angle is illustrated in Figure 1.

Commonly, the potential (1) corresponds to a monodomain LC structure. However, within this approach, it is hardly possible to obtain an exhaustive description of multi-domain over-molecular helical nanostructures of FLCs that arise most often in reality [3]. To solve this problem, the Rapini potential was extended to a more general case of a biaxial object [2], which is any FLC. It was proposed for this purpose to characterize a spatial position of the biaxial FLC structure not only by the director $n$, as is done for uniaxial molecular structures of liquid crystals, which are equivalent in symmetry to cylinders of rotation but also by a molecular core plane (MCP) that allows introducing additionally to the ordinary $n$-director a second component of the FLC director, so-called $m$-director, which is perpendicular to the MCP (Figure 1).
Figure 1. The designation of the structure of the helix-free (HF) FLC layers in the concept of biaxial surface potential, where \( \mathbf{N} \) is the normal to the smectic layers, \( \delta \) is the angle between the normal to the plane of the smectic layer \( \mathbf{N} \) and the \( \mathbf{R} \), \( \varphi \) is the azimuthal angle of the position of the director \( \mathbf{n} \) in the plane of the smectic layer, \( \theta \) is the angle of inclination of the molecules in the smectic layers, \( \psi \) is the angle between \( \mathbf{n} \) and the easy alignment axis \( \mathbf{R} \), the unit \( \mathbf{K} \) shows the direction of easy alignment of the \( \mathbf{m} \) (normal to the MCP). The direction of the \( \mathbf{K} \) can be, in general, tilted by an angle \( \beta \) relative to the normal to the solid boundary surface, \( \chi \) the angle between \( \mathbf{K} \) and \( \mathbf{m} \) [2].

Given this addition, the biaxial surface potential \( \Phi \) is written in the following form [2]:

\[
\Phi_s = -\frac{W_n}{2} \left( \sin \delta \cos \varphi \sin \theta + \cos \delta \cos \theta \right)^2 + \tilde{W}_1 \sin^2 \varphi \cos^2(\delta - \beta) \pm \tilde{W}_2 \sin \varphi \cos(\delta - \beta)
\]

(2)

where \( \tilde{W}_1 = W_m/W_n \), \( \tilde{W}_2 = W_p/W_n \) - are dimensionless anchoring energies, and the signs + or − correspond to the upper and lower boundaries of the HF FLC cell, respectively, \( W_m \) - is the anchoring energy coefficient of the \( \mathbf{m} \) director with respect to the easy alignment axis \( \mathbf{K} \), \( W_p \) - is the polar part of the anchoring energy of vector \( \mathbf{p}_1 \) (collinear to vector \( \mathbf{m} \)) with the direction of easy orientation \( \mathbf{K} \).

By solving equation (2), for certain values \( \tilde{W}_1 \) and \( \tilde{W}_2 \), it is possible to have several energy minima (Fig. 2.). One minimum (Fig. 2. a) corresponds to the ordinary uniaxial Rapini potential that provides a monodomain texture (Fig. 2. c). The presence of three energy minima (Fig. 2. b) indicates the three-domain texture of the FLC (Fig. 2. d), which often observed in FLC cells.

In this paper, we consider the possibility of controlling the alignment quality of FLC helical nanostructures by transforming the biaxial potential of the FLC to an effectively uniaxial potential due to the diminishing of the FLC helix pitch.
2. Experiment

Continuous films and films with an island structure (Fig.3) made of PMDA-ODA polyimide layers were used as aligning layers. Liquid crystal mixtures of FLC-661/7 series with different helix pitch $p_0$ [4] were used to check the proposed concept of controlling the alignment quality of FLCs helical nanostructures. Images of the FLCs textures were taken using the Olympus BX 53 polarizing microscope, and the optical contrast ratio ($CR$) of electro-optical cells placed between crossed polarizers was measured in white light according to equation (3):

$$CR = \frac{T_{\text{max}}}{T_{\text{min}}}$$

where $T_{\text{min}}$ – minimum light transmittance of the FLC cell, when the helix axis is oriented along the polarizer plane, $T_{\text{max}}$ – maximum light transmittance of the FLC cell, when the helix axis is oriented at an angle of 45 degrees to the polarizer plane.

Figure 3. AFM 2.5 µm × 2.5 µm surface images [3]: a) ITO without PMDA-ODA, b) ITO with an island structure of PMDA layer, c) ITO with a continuous film of PMDA-ODA.
Figure 4. The FLC-661/7 series textures of electrooptical cells with continuous aligning layers at FLC layer thickness of about 3.0 µm. Textures a), b), c) are observed when the helix axis is oriented along the polarizer plane, and textures are d), e), f) when the helix axis is perpendicular to the polarizer plane; a), d) the FLC helix pitch $p_0 = 143$ nm, $CR = 4$; b), e) $p_0 = 112$ nm, $CR = 10$; c), f) $p_0 = 70$ nm, $CR = 28$. Size of images is 250 µm × 200 µm.

In Fig.4. The FLC-661/7 series textures of electrooptical cells with continuous aligning layers and with different helix pitch are shown. A decrease in the helix pitch allows one to achieve a significant decrease in the dislocations density or, in other words, a significant increase in the texture homogeneity. The presence of several colors of birefringence (Fig. 4 a, d) indicates the presence of several types of domains, which appear, probably, due to several potential minima of the biaxial surface potential, which it could be true also for FLCs with a sufficiently large helix pitch ($p_0 = 143$ nm) the same manner as it is valid for the HF FLC. As the helix pitch decreases down to 70 nm (Fig. 4 c, f), the dislocations density sharply decreases, the texture becomes more uniform and with alone birefringence color, which may indicate a gradual transformation of the biaxial surface potential into a uniaxial one. The improvement in optical quality of FLC cells due to diminishing of the $p_0$ magnitude is confirmed by the measured contrast ratio values.

Figure 5. The FLC-661/7 series textures of electrooptical cells with an island structure of aligning layers at FLC layer thickness of about 3.0 µm. Textures a), b), c) are observed when the helix axis is oriented along the polarizer plane, and textures are d), e), f) when the helix axis is perpendicular to the polarizer plane; a), d) $p_0 = 112$ nm, $CR = 7$; b), e) $p_0 = 70$ nm, $CR = 14$; c), f) $p_0 = 50$ nm, $CR = 22$; in the dark and light state, respectively. Size of images is 250 µm × 200 µm.
In Fig.5. The FLC-661/7 series textures of electrooptical cells with an island structure of aligning layers are shown. The deterioration of the optical quality of the FLC with $p_0 = 70$ nm when replacing the continuous aligning layer with the island one is quite obvious when comparing Figs 4 c, f and 5 b, e. However, a further decrease in $p_0$ to 50 nm makes it possible to diminish significantly the dislocation density and improve the optical quality of FLC layers even with the island structure of aligning layers, see Figs. 5 c, f.

Thus, an improvement in the optical quality of FLC layers with a decrease in the helix pitch is observed both for continuous and island structures of aligning layers. A decrease in the helix pitch obviously leads to a more isotropic distribution of vectors $\mathbf{m}$ in space that means a transition to an effectively uniaxial surface potential, which provides a monodomain FLC structure.

3. Conclusion

It is shown experimentally that a decrease in the helix pitch contributes to the FLC monodomain structure formation, in other words to the optical quality of FLC cells improvement independently on aligning layer’s structure. At the qualitative level, the observed phenomenon can be interpreted in terms of the transition from a biaxial to an effectively uniaxial surface potential as the helix pitch decreases.

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