

Surface effects in the model of polymer-stabilized ferroelectric liquid crystal cells

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Abstract: The interplay between volume and surface interactions in polymer-stabilized ferroelectric liquid crystals often results in the so-called quasi-bookshelf or tilted layer structure. Unambiguous description of the most probable orientation of the long molecular axes within a ferroelectric liquid crystal cell (director profile) stabilized by polymer network implies the consideration of the confined volume effects. The model of polymer-stabilized ferroelectric liquid crystal cell with a quasi-bookshelf layer structure was investigated by using the liquid crystal continuum theory. Promising applications of the biaxial surface potential for preparation of ferroelectric liquid crystal cells with the desired surface parameters has motivated us to embark upon the proposed model. To fully consider the surface effects, the proposed model accounts splay deformation of the spontaneous polarization. This enables us to estimate the effective applied voltage across the cell. The effect of polymer stabilization on the director orientation profiles across the cell was examined. We have found that the director-polymer network interaction coefficient induces insignificant difference between the director orientation profiles. We believe that this theoretical model can be useful for fabrication of experimental ferroelectric liquid crystal cells.

Keywords: Polymer-stabilized ferroelectric liquid crystal; Thin films; Bistability; Euler's equation

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1. Introduction

Surface-stabilized ferroelectric liquid crystal (SSFLC) cells possess exceptional electro-optic properties with microsecond response time. However, application of ferroelectric liquid crystals in smectic C* (SmC*) phase for display and photonic devices has not yet been realized in full due to the inherent mechanical sensitivity, hysteresis effects and temperature dependence of liquid crystal material parameters [1]. This situation is not optimal for applications and requires a novel research intended to stabilize the desired ordering of SmC* molecules.

Recent advances in liquid crystalline materials applications are developing in two directions: synthesis of new materials [2] and tailoring the existing liquid crystalline materials by dispersing/doping dyes, nanoparticles [3, 4]

and polymers [5, 6]. The latter is the promising remedy to solve the stability problems.

The addition of polymer network in ferroelectric liquid crystal (FLC) structure results in the interaction between the polymer and SmC* molecules, which adds new constraints on its dynamics [5]. Typical experimental concentration values of polymer are about 2–10 wt% [6, 7], but the interaction coefficient between the director and the polymer network better fits for the continuum model. As the result, mechanical stability of SmC* molecules in thin films can be improved. Therefore, the study of the confined volume effects in polymer-stabilized ferroelectric liquid crystals (PSFLCs) represents a practical value for applications.

A number of studies show that the dispersed in FLC polymer network not only enhances mechanical properties without the loss of the favorable electro-optic properties, but also opens up new ways of device fabrication (e.g., [8, 9]). In other words, the dispersed polymer network

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behaves as the template for the liquid crystal ordering, aiding to align the long molecular axes [6].

A thorough understanding of the interaction between the long molecular axes of SmC* phase stabilizing polymer network and the bounding surfaces is of a paramount importance for any application of such materials [10]. While the theoretical work has laid a fairly firm foundation for the interpretation of the experimental material, there is still no experimentally significant theory, which is capable to forecast the director orientation profile within the cell. For example, in Refs. [5, 11] it was taken for granted that the applied electric field is equal to the external electric field. Disregarding the spatial inhomogeneities of the spontaneous polarization in PSFLCs cells, one can get inaccurate estimates of the associated cell characteristics. Surface effects in PSFLC cells have not yet been considered as well.

The above-mentioned thermodynamically steady effects are accounted in this study.

Pioneering theoretical studies on the biaxiality of smectic C phase were published in Ref. [12]. Soon after this publication, the biaxiality was experimentally confirmed, and study [13] was published. After the discovery of ferroelectricity in chiral SmC* phase [14], its optical biaxiality was measured [15, 16]. The reported value of the optical biaxiality in SmC* phase typically ranges within 0.001 and 0.005. Such a small biaxiality can lead to the difficulties for its direct optical applications. However, recently introduced the biaxial surface potential allows adequate description of the hysteresis loop and qualitatively explains types of the domain structures and methods for its control [17]. Experimental evidence for transformation chevron layer structure into quasi-bookshelf layer structure [7] have motivated us to elaborate the proposed model in terms of the inherent biaxial structure of FLCs.

In this study, we refer to the biaxial surface potential for the investigation of the interplay between the layer tilt angle and the molecular orientation angle at the surface. Consideration of this coupling enabled us to obtain the reasonable boundary conditions for the time-dependent torque balance equation. With the aim to develop the model of PSFLC cell with all commonly observed surface and volume effects, we expand the earlier studies [11, 18–20]. Thus, our model accounts smectic layer tilt and spatial inhomogeneities of the spontaneous polarization. By varying the electric field, we determine how the boundary effects shift the director orientation angle at the surfaces. The interaction between the polymer network and the director field is also discussed. Consideration of these factors in PSFLC cell represents the novelty of our study.

2. Electrostatic model

2.1. Geometry

Figure 1 is the illustration of SmC* layer, confined between the bounding surfaces, which are spaced by distance d . We denote the yz -plane parallel to the bounding surfaces, while the x -axis is perpendicular to the bounding surfaces located at $x = 0$ and $x = d$.

The most probable orientation of the long molecular axes is characterized by the director $\mathbf{n}$, which also represents the optical axis. The unit orthogonal projection of $\mathbf{n}$ onto the smectic plane is conventionally described in terms of vector $\mathbf{c}$ (often called the c -director). Due to the anchoring effects at the substrate, smectic layers are usually tilted from the substrate normal by an δ angle [21].

In order to achieve bistability in the FLC cell, uniaxially anisotropic boundary surfaces must be obtained. Consequently, the director $\mathbf{n}$ preferably aligns along the rubbing direction, which is characterized by the unit vector $\mathbf{R} = (0, 0, 1)$. By analyzing the geometrical configuration of Fig. 1, one can conclude that the layer tilt angle δ is also the angle between the z -axis and the smectic layer normal, which is given by $\mathbf{a} = (\sin \delta, 0, \cos \delta)$. The SmC* molecules are confined to rotate within the smectic planes, while the director field is constrained to tilt away from the layer normal by some angle θ , which depends on the FLC chemical structure and temperature. Meanwhile, recent investigations have disclosed that polymer stabilization preserves angle θ fairly constant within a large temperature range [6].

Throughout this article, we will refer to the director geometry introduced in Ref. [22], which has the form

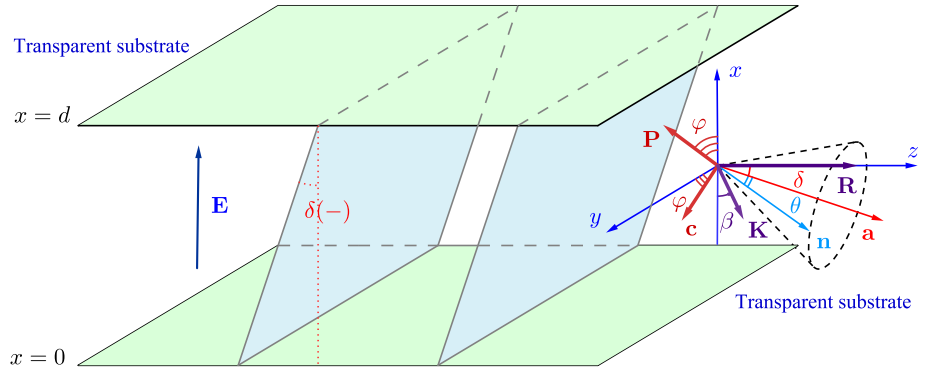
$$\mathbf{n} = (-\sin \theta \cos \delta \sin \varphi + \sin \delta \cos \theta) \mathbf{e}_x + \sin \theta \cos \varphi \mathbf{e}_y + (\sin \delta \sin \theta \sin \varphi + \cos \delta \cos \theta) \mathbf{e}_z, \quad (1)$$

where $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$ are the bases of the Cartesian coordinate system, and φ is the director's azimuthal angle around the layer normal. It is worth being noted that we consider a defect-free layered structure because of the smallness of the cell thickness d [17]. Another restriction that this geometry meets is severe restrictions to the optimum layer thickness [23].

We can see immediately from Fig. 1 that the angle φ ranges within the interval $-\pi/2 \leq \varphi \leq \pi/2$. Regarding the signs of angles δ and φ , we will use the sign convention such that the angle is considered negative or positive if it is measured in a clockwise or counterclockwise direction from the particular axis, respectively.

Fig. 1 (Color online)

Geometry, specifying the coordinates needed to discuss the FLC cell with tilted layers. The FLC director $\mathbf{n}$ lies on the smectic cone, depicted by the dashed lines with the smectic tilt angle θ . Electric field E is applied across the cell. Here, the x -axis is perpendicular to the substrate plates, and the yz -plane is parallel to the substrates



2.2. Free energy density

The bulk free energy density f_b includes the elastic free energy density f_{elas} , contributions from the electric energy density f_{elec} and the polymer network stabilization f_{stab} , i.e., $f_b = f_{\text{elas}} + f_{\text{elec}} + f_{\text{stab}}$. The total free energy of the FLC system can be obtained from the following expression:

$$F = \int_0^d (f_{\text{elas}} + f_{\text{elec}} + f_{\text{stab}}) dx + f_s(\varphi)|_{x=0} + f_s(\varphi)|_{x=d}, \quad (2)$$

where $f_s(\varphi)$ is the surface anchoring energy. We stress that our model assumes no interaction between the adjoining layers.

A commonly used expression to describe the f_{elas} -term for the one-constant approximation is given by

$$f_{\text{elas}} = \frac{K}{2} \sin^2 \theta \left(\frac{d\varphi}{dx} \right)^2, \quad (3)$$

where K is the Oseen elastic constant, which is often reduced to $B = K \sin^2 \theta$ [19, 24].

Many studies take for granted that the applied electric field E is equal to the external field, which is applied across the sample (e.g., [20, 25, 26]). But this will not in general be true due to non-homogeneous P -field. To account this effect, we assume that there is no y -dependence for the P -field. Then, $\mathbf{P} = P_0 \mathbf{b}$, where $\mathbf{b} = [\mathbf{n} \times \mathbf{a}] / |\mathbf{n} \times \mathbf{a}|$ is the unit vector [25]. The splay of the P -field induced by the electric field gives rise to the polarization charge density $\rho = -\nabla \cdot \mathbf{P}$ [19], which has the form $\rho = P_0 \sin \varphi \cos \delta \frac{d\varphi}{dx}$. After we apply the Gauss theorem, the equation governing the polarization field becomes

$$E_p(x) = \frac{P_0}{\varepsilon} \cos \delta \cos \theta (1 - \cos \varphi),$$

where ε is the absolute dielectric permittivity [19, 24]. Consequently, the total electric field in the ion-free sample

can be defined as $E_{\text{tot}} = E + E_p(x)$. The electric contribution into the free energy density becomes

$$f_{\text{elec}} = -\mathbf{P} \cdot \mathbf{E}_{\text{tot}}, \quad (4)$$

where we assumed that the contribution from the anisotropy of the dielectric constants is negligibly small in comparison with the spontaneous polarization term (see parameters in Table 1). If the φ -dependence is known, the effective voltage V across the FLC cell can be computed by the following relation

$$V = Ed + \frac{P_0}{\varepsilon} \cos \delta \sin \theta \int_0^d (1 - \cos \varphi) dx. \quad (5)$$

The free energy contribution from the polymer network is our next consideration. Referring to the model by Li et al. [5], the interaction between the polymer network and the liquid crystal director can be considered as a field-like effect, which is imposed to restore the local liquid crystal director field to the φ_{stab} —the mean azimuthal angle of polymer stabilization. This approach assumes that the network is elastic, i.e., exerting only the bulk anchoring force on the liquid crystal director. The well-known form of the f_{stab} -term reads as

Table 1 Model parameters of the polymer-stabilized FLC cell

Tilt angle	$\theta = 35^\circ$
Angle of polymer stabilization	$\varphi_{\text{stab}} = 90^\circ$
Angle between the x -axis and vector $\mathbf{K}$	$\beta = 0$
Cell thickness	$d = 1.6 \mu\text{m}$
Spontaneous polarization	$P_0 = 75 \text{ nC cm}^{-2}$
Electric constant	$\varepsilon_0 = 8.85 \cdot 10^{-12} \text{ F m}^{-1}$
Absolute dielectric permittivity	$\varepsilon = 4 \varepsilon_0$
Elastic constant	$B = 10^{-11} \text{ N}$
Rotational viscosity	$\gamma_\varphi = 50 \text{ mPa s}$
Prime anchoring energy coefficient	$w_n = 38 \cdot 10^{-3} \text{ J m}^{-2}$
Polar dimensionless anchoring energy	$\tilde{w}_2 = 0$

$$f_{\text{stab}} = \frac{\gamma_s}{2} \sin^2 \theta \sin^2 \left(\frac{\varphi - \varphi_{\text{stab}}}{2} \right), \quad (6)$$

where γ_s is the interaction coefficient the between the director $\mathbf{n}$ and the polymer network [5].

A further consideration of the remaining interaction between the SmC* molecules and the surfaces will enable us to set the boundary conditions. To achieve this goal, we refer to the biaxial surface potential [17], which has the form

$$f_s(\varphi) = -\frac{w_n}{2} [(\sin \delta \cos \varphi \sin \theta + \cos \delta \cos \theta)^2 + \tilde{w}_1 \sin^2 \varphi \cos^2 (\delta - \beta) \pm \tilde{w}_2 \sin \varphi \cos (\delta - \beta)], \quad (7)$$

where $\tilde{w}_1 = w_m/w_n$ and $\tilde{w}_2 = w_p/w_n$ are the dimensionless anchoring energies; the $(-)$ sign applies to the bottom boundary, while the $(+)$ sign corresponds to the top boundary. The parameters w_n , w_m , w_p have the following meanings: anchoring energy coefficient for the director with respect to the easy alignment axis $\mathbf{R}$; anchoring energy coefficient, related to the inherent FLC biaxiality and the polar contribution associated with the presence of the polar axis, respectively.

It is clear that the surface potential predetermines the layer tilt and the director orientation angles at the surfaces. So, it is instructive to consider the torques $N_\varphi = -\partial f_s / \partial \varphi$ and $N_\delta = -\partial f_s / \partial \delta$. Equating N_φ and N_δ to its maxima [18], we obtained the system of coupled equations. Substituting the typical model parameters (Table 1) into the system, numerical solution can be obtained. So, we get that the layer tilt angle depends on the surface potential coefficients, which is totally consistent with experimental tests. Recalling the range of feasible values for δ and φ , we can determine the layer tilt angle and the director orientation angle at the surface, which we denote as φ_s .

To visualize the simulation results, the torque field N_φ is plotted in Fig. 2(a). The torque density field φ -dependencies for a series of $\tilde{w}_1$ values and the computed layer tilt angles are depicted in Fig. 2(b). The obtained value pairs (δ, φ_s) are given in the caption of Fig. 2(b).

We can now write the time-dependent torque balance equation [24]

$$\gamma_\varphi \frac{\partial \varphi}{\partial t} = \frac{d}{dx} \frac{\partial f_b}{\partial \varphi_x} - \frac{\partial f_b}{\partial \varphi},$$

where φ_x denotes $\partial \varphi / \partial x$, and γ_φ is the rotational viscosity coefficient. Substituting free energy contributions (3), (4) and (6) into the expression for f_b , the torque balance equation becomes

$$\begin{aligned} \gamma_\varphi \frac{\partial \varphi}{\partial t} = & - \left(\frac{P_0 E}{\sin \theta \cos \delta} + \frac{P_0^2}{\varepsilon} \right) \sin^2 \theta \cos^2 \delta \sin \varphi \\ & + \frac{1}{2} \frac{P_0^2}{\varepsilon} \sin^2 \theta \cos^2 \delta \sin 2\varphi \\ & - \frac{\gamma_s}{4} \sin^2 \theta \sin(\varphi - \varphi_{\text{stab}}) + B \frac{\partial^2 \varphi}{\partial x^2}. \end{aligned} \quad (8)$$

The boundary conditions for Eq. (8) can be obtained from the following identities:

$$B \frac{\partial \varphi}{\partial x} - \frac{\partial f_s}{\partial \varphi} \Big|_{x=0} = 0, \quad B \frac{\partial \varphi}{\partial x} + \frac{\partial f_s}{\partial \varphi} \Big|_{x=d} = 0. \quad (9)$$

The surface torque maximum can be found from the surface potential derivative $\pm df_s / d\varphi$, which is balanced by the elastic torque $B \varphi_{xx}$.

The solution of Eq. (8) with boundary conditions (9) will enable to obtain the φ -dependence versus the coordinate and analyze it for different coefficients γ_s . At this point, it is convenient to introduce the quantities

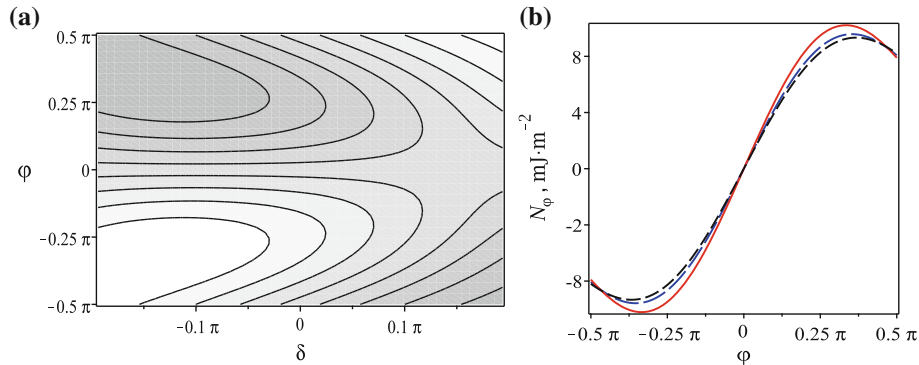


Fig. 2 (Color online) (a) Model torque density field in $\delta\varphi$ -coordinates, where $\tilde{w}_1 = 0.33$. (b) Model surface torque density $N_\varphi = -df_s/d\varphi$ for $\tilde{w}_1 = 0.4$ (solid curve), $\tilde{w}_1 = 0.35$ (long-dashed curve), $\tilde{w}_1 = 0.33$ (dashed curve). The calculated value pairs δ and φ_s for the

listed dimensionless anchoring energies are $(-0.544, \pm 1.05)$; $(-0.566, \pm 1.11)$; $(-0.584, \pm 1.15)$, respectively. Other model parameters are given in Table 1

$$\xi_P = \frac{\sqrt{\varepsilon B}}{P_0}, \quad \xi_{PE} = \sqrt{\frac{B \sin \theta \cos \delta}{P_0 E}},$$

$$\eta^2 = \frac{\gamma_s \sin^2 \theta}{4B}, \quad \tilde{\sigma} = \frac{\xi_P^2}{\xi_{PE}^2}$$

and dimensionless variables $\tilde{x} = \frac{x}{\xi_P}, \tilde{t} = \frac{t}{\tau}$, where $\tau = \frac{\gamma_\phi}{P_0 E} \cos \delta \sin \theta$ is the characteristic time. This form of the characteristic time is convenient for representation of the final equation. After simple mathematical manipulations, Eq. (8) reads as follows:

$$\tilde{\sigma} \frac{\partial \varphi}{\partial \tilde{t}} = \frac{1}{\tilde{d}^2} \frac{\partial^2 \varphi}{\partial \tilde{x}^2} - (1 + \tilde{\sigma}) \sin^2 \theta \cos^2 \delta \sin \varphi - \frac{1}{2} \sin^2 \theta \cos^2 \delta \sin 2\varphi - \chi \sin(\varphi - \varphi_{\text{stab}}), \quad (10)$$

where the thickness is normalized to the unit length, i.e., the new x -coordinate in Eq. (10) ranges within the interval $[0; 1]$, and $\chi = \xi_P^2 \eta^2$. Accordingly, the normalized boundary conditions take the form

$$\left. \frac{d\varphi}{dx} \right|_{x=0} = \frac{d}{B} \frac{df_s}{d\varphi}, \quad \left. \frac{d\varphi}{dx} \right|_{x=1} = -\frac{d}{B} \frac{df_s}{d\varphi}. \quad (11)$$

It is also practically instructive to represent expression (5) in terms of the normalized coordinate. The effective voltage across the PSFLC cell is related with the azimuthal angle profile as follows:

$$V = d \left[E + \frac{P_0}{\varepsilon} \cos \delta \sin \theta \int_0^1 (1 - \cos \varphi) dx \right]. \quad (12)$$

We can now assume that if no external field is applied ($1/\xi_{PE}^2 = 0$) to the cell with the smectic layers normal to the substrates, i.e., $\delta = 0$, and $\gamma_s = 0$, then Eq. (8) becomes

$$\xi_P \frac{dx^2 \varphi}{dx^2} = \sin^2 \theta \cos^2 \delta \left(\sin \varphi - \frac{1}{2} \sin 2\varphi \right),$$

which is identical with the governing equation for electrostatic self-interaction in SSFLC cell [19].

Families of plots are given in the subsequent section to examine the c -director behavior.

3. Modeling

To consider a certain example, we must set the value pair (δ, φ_s) . The two calculated value pairs (see caption to Fig. 2(b)) for each $\tilde{w}_1$ indicate two possible directions of the director field, i.e., either preferably along or opposite the x -axis. Let $\tilde{w}_1 = 0.33$, then $\delta = -0.544$ rad, $\varphi_s = -1.05$ rad (i.e., the electric field is applied along the

positive x -axis). From the analysis of the surface potential, it is clear that the biaxial parameter $\tilde{w}_1$ predetermines the angles δ and φ_s . Accordingly, the director orientation along the x -axis can be obtained.

Once the boundary conditions are specified, the model, represented by Eqs. (10) and (11), can be handled if we choose a trial solution in the form $\varphi(x) = \varphi_s + 0.01 \sin(\pi x)$. Inspection of the model shows that for $\tilde{t} \gg 1$, its solution becomes stationary. Common material parameters (see Table 1) were used for our further computations.

The effective voltage can be calculated from the obtained φ -dependence. To do this, we used the following approach: each φ -dependence can be represented as a polynomial function. So, the cell width was divided into equally spaced points, and we obtained the corresponding (x_i, φ_i) pair values, $i = 1, \dots, 20$. This set of points was interpolated by the Lagrange polynomial, which was substituted into Eq. (12). The obtained polynomial φ -dependencies have the error of order 10^{-4} .

Although the relaxation method has proven to be adequate for the model cell, it can show the convergence difficulties. To avoid it, the input data should not yield high derivative values in the vicinity of the boundaries.

4. Results and discussion

The surface potential form presumes that (7) can have one, two or three minima, which correspond to one, two or three types of domains [17], i.e., different director profiles. Recall that our example allows two director orientation angles at the surface φ_s .

Further, we investigated the electric field effect on the azimuthal angle director profiles for different director-polymer network interaction coefficients. Figure 3(a) shows numerical solutions over a range of the applied voltages for the constant level of polymer stabilization. As a starting point for the discussion of thermodynamically stable effects in PSFLC cell, we turn our attention to the director orientation at the surface φ_s . If the applied voltage increases, φ_s will be driven further from its 0 V equilibrium position. This gives rise to the formation of zones with length ξ_{PE} nearby the surfaces and characterized by strong gradients in the P -field, exerting the conflict between electric and elastic torques via the boundary conditions. Elastic torque, applied by the electric field, is the largest as φ approaches to φ_s , and drops to zero when the c -director aligns perpendicular to the electric field and parallel to the yz -plane.

The results provide that the director field configuration is twofold: first, the twist state is near the bounding surfaces and second, it is rather homogeneous over the bulk.

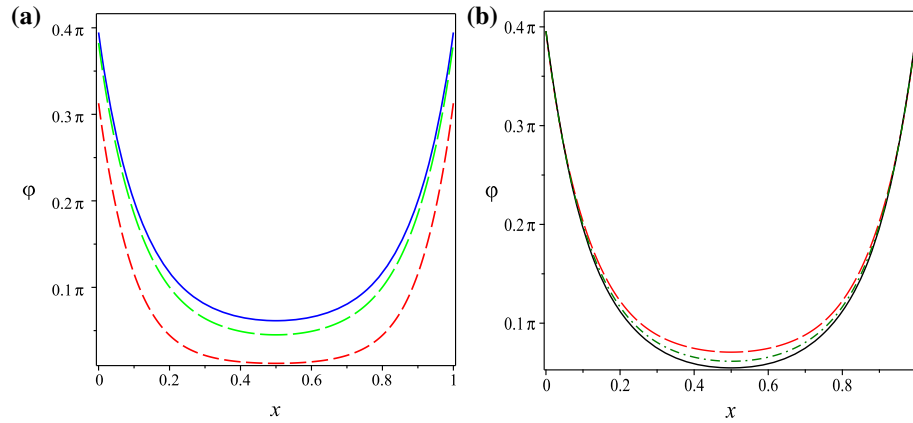


Fig. 3 Azimuthal angle profiles of polymer-stabilized FLC cell. (a) For varying electric fields: $E = 1 \text{ MV m}^{-1}$ (solid curve), $E = 1.5 \text{ MV m}^{-1}$ (long-dashed curve), $E = 5 \text{ MV m}^{-1}$ (dashed curve) at $\gamma_s d = 4.8 \cdot 10^{-4} \text{ J m}^{-2}$. The computed effective voltages for the input electric fields: 3.57 V, 4.07 V, 8.8 V, correspondingly. (b) For varying

director-polymer network interaction coefficients at $E = 10^6 \text{ V m}^{-1}$: $\gamma_s d = 1.6 \cdot 10^{-4} \text{ J m}^{-2}$ (solid curve), $4.8 \cdot 10^{-4} \text{ J m}^{-2}$ (dash-dotted curve), $9.6 \cdot 10^{-4} \text{ J m}^{-2}$ (long-dashed curve). The effective voltages for the input parameters: 3.48 V, 3.57 V, 3.67 V, correspondingly

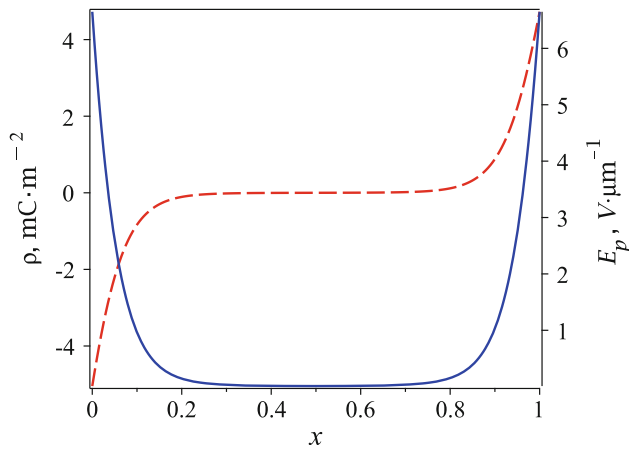


Fig. 4 (Color online) Profiles of the polarization charge density (red dashed curve) and the polarization field (blue solid curve) for $\delta = -0.544$, $E = 5 \text{ MV m}^{-1}$ and $\gamma_s d = 4.8 \cdot 10^{-4} \text{ J m}^{-2}$. The computed normalized characteristic lengths: $\xi_{PE} = 0.023$ and $\xi_P = 0.016$

When the absolute voltage increases (see Fig. 3(a)), the c -director tends to align perpendicular to the electric field, so the azimuthal angle profile asymptotically approaches zero. Consequently, the f_{stab} -term rapidly changes only within the zones with length ξ_{PE} .

If no polymer is added to the FLC structure, the concavity of the c -director orientation profile insignificantly increases (not shown here) due to the absence of the polymer stabilization energy density. Furthermore, Fig. 3(b) shows that the increase in the polymer density yields less concavity of the azimuthal angle profile. It means that the same light transmission will be obtained with slightly higher voltages. The reason is that the amount of bulk polymer present in PSFLC system leads to the decrease in the dipole moment contribution. The

subsequent increase in the polymer density in the cell yields the viscosity to play the role of a dominating factor.

We may now pass to consider the plots of $\rho(x)$ and $E_p(x)$, depicted in Fig. 4. The dipole field orientation organizes itself to increase the electric field due to the polarization charge in the regions of width ξ_P —approximate thickness of the twist regions. The homogeneity degree strongly depends on the boundary conditions. This issue can be interpreted as the balance between the bulk anchoring strength of the polymer network and the surface anchoring strength.

The obtained φ -dependence enables us to compute the total free energy per unit area F by using Eq. (2). Estimates of the total free energy do not exhibit its pronounced dependence versus the director-polymer network interaction coefficient due to the interplay between the bulk free energy density terms.

5. Conclusions

In this article, we have developed the physically based approach for studying the interplay effect between the director orientation angle at the surface and the layer tilt angle. By means of a simple theoretical investigation, the value pairs (δ, φ_s) were calculated. The obtained boundary conditions enabled us to elaborate the mathematical model of steady-state effects in PSFLC cell. The computations we carried out suggest that the electrostatic energy can be low enough for the surface forces to play an important role even when the director orientation profile is strongly stiffened within the ξ_{PE} zones. Estimates of the total free energy do not show its pronounced dependence versus the director-

polymer network interaction coefficient due to the interplay between the bulk free energy density terms.

The elaborated model of PSFLC cell can be viewed as relatively realistic because it does not consider several aspects. The alignment uniformity can be imperfect due to the general difficulty of achieving good results. So, the zero value of angle β is originated due to perfectly treated surface. Another concern, which is not considered here, is the presence of ions, which can arise in such cells. Nevertheless, we believe that the degree to which the model and the actual cell behavior match because we captured much of the essential effects. This approach also provides a new way for understanding the surface effects in PSFLC cells.

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