Influence of an external electric field on structure in surface-stabilized smectic-*C* chevron cells

Nataša Vaupotič,[1,2] Vladimir Grubelnik,[1] and Martin Čopič[1,3]
[1]*Department of Physics, Faculty of Education, University of Maribor, Koroška 160, 2000 Maribor, Slovenia*
[2]*Department of Physics, Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia*
[3]*Institute Jožef Stefan, Jamova 39, 1000 Ljubljana, Slovenia*

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We use a Landau–de Gennes model to study the effect of static external electric fields on the director and layer structure and switching in surface stabilized smectic-*C* cells with uniform chevron structure. We consider uniform switching of the whole cell and find the threshold electric field needed to switch the director from one stable state to the other stable state. The effect of temperature and cell thickness on the value of the threshold electric field is studied. We also find the switching time as a function of the strength of the applied electric field and study the director and layer structure during the switch.

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I. INTRODUCTION

In surface stabilized ferroelectric liquid crystal cells smectic layers usually deform into a characteristic chevron structure [1,2]. The chevron structure (see Fig. 1) is believed to arise due to the mismatch between the natural smectic layer thickness and the periodicity imposed by the layer pinning at the surface in the smectic-*A* phase. This surface memory effect has been confirmed experimentally [3], but recent theoretical considerations [4] also suggest that the conservation of layers, combined with the extremely slow time scale of nonequilibrium layer drift through the smectic fluid, impose the chevron structure.

In the past two decades several theoretical models have been presented to describe the director and layer structure in smectic-C chevron cells. This extensive work has mainly been motivated by a potential use of surface stabilized liquid crystal cells in display devices. The original model was put forward by Clark and co-workers [1,5]. In this model the continuity of the director across the cell is considered. The model, however, includes the discontinuity of smectic layers at the chevron tip. Recently the model of Clark *et al*. has been extended to include continuity of the biaxial ordering at the chevron tip [6].

A number of models of the chevron structure have been reported which take into account layer bending and the director rotation on the cone [7–12]. None of these models, however, decoupled the molecular cone angle from the smectic layer tilt angle. When this constraint was removed [13] an important physical consequence resulted. It was shown that the director at the chevron tip tilts out of the plane defined by the smectic layer normal and the surface normal (xz plane in Fig. 1) even if the equilibrium layer tilt equals the bulk value of the cone angle. Out of plane tilt results due to the competition between the surface and the bulk forces. The surface periodicity requires that the molecular cone angle reduces to zero at the chevron tip, the bulk periodicity, however, prefers the molecular cone angle being equal to its bulk value. As a result solutions were found where the director tilt reduces at the chevron tip, but it does not reduce to zero. This out of plane tilt propagates throughout the cell which leads to the most important characteristic of chevron cells—bistability. This means that chevron cells exhibit two stable director states [see Figs. 1(b), 1(c)] between which the cell can be switched by the application of an external electric field. An important reason to model surface stabilized cells is to describe the switching dynamics between these stable director states.

Molecular director and layer response of chevron surface stabilized ferroelectric liquid crystals in low electric fields have first been studied by Willis *et al.* [14]. They showed experimentally and also presented theoretical arguments that there is no significant change in smectic layer thickness or chevron layer structure under typical director switching conditions. The simple model of Clark *et al.* has also been used to find the director structures in external electric field at different strengths of surface orientational director anchoring [15].

The director profiles in surface stabilized smectic-*C* cells in external electric fields are studied in more detail both ex-

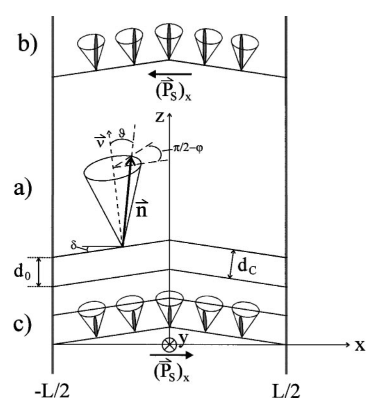

FIG. 1. The chevron structure. d_0 is the smectic layer thickness in the smectic-*A* phase, d_C is the smectic layer thicknes in bulk smectic-*C*. (a) The structure is described by the layer tilt angle δ, the molecular cone angle ϑ and the director position on the cone φ. (b) One bistable state with the director tilted out of the xz plane in the $+y$ direction (the *D* state). The layer polarization has a component along the $-x$ direction, i.e., down the x axis. (c) Another stable state with the director tilted out of the xz plane in the $-y$ direction (the *U* state). The layer polarization has a component along the $+x$ direction, i.e., up the x axis.

perimentally and theoretically by Brown *et al.* [16–18]. They compose a chevron by two layers, tilted uniformly but in the opposite direction. A continuum model of Leslie *et al.* [19] is used to study switching.

An early quantitative investigation which related physical characteristics of tilted layers in surface stabilized ferroelectric liquid crystal cells to devices and electrical addressing was presented by Escher *et al.* [20]. They have presented a simple dynamical model of switching including the effect of biaxiality, ionic effects, and ion diffusion. Switching behavior of surface stabilized ferroelectric liquid crystal cells was studied in more detail by Sako *et al.* [21]. Their simple uniform switching model incorporates the ferroelectric and dielectric energy term and nonpolar surface orientational anchoring. Recently this model was improved by the incorporation of the elastic energy terms as well [22].

In this work we use the Landau–de Gennes model to study the switching dynamics and the director and layer structure in surface stabilized smectic-*C* cells with uniform chevron structure in low external electric fields. The advantages of this model over other continuous models have already been discussed in detail in our previous work [13]. The model is compact but it includes all the significant characteristic of the chevron structure including the detailed structure of the layer and director structure of the chevron tip.

The plan of the paper is as follows. In Sec. II we introduce the model. In Sec. III we present numerical results for the director and layer structure in the cell in an external electric field. In Sec. IV we find the threshold electric field at which the director switches from one stable structure to the other and study its dependence on temperature and cell thickness. In Sec. V we find the switching time as a function of the strength of the electric field applied and study the director and layer structure during the switch. In Sec. VI we discuss the results and make the conclusions.

II. MODEL

We use the Landau–de Gennes model, based on the analogy between superconductors and smectics [23–25]. In the context of this model the smectic-*C* structure is described by the nematic director $\mathbf{n}$ and the complex smectic order parameter $\psi(\mathbf{r})=\eta(\mathbf{r})\exp\{i\phi(\mathbf{r})\}$, where $\eta(\mathbf{r})=|\psi(\mathbf{r})|$ is the magnitude of the smectic order parameter and $\phi(\mathbf{r})$ is the phase factor that determines the position of smectic layers. We assume that $\eta(\mathbf{r})$ is constant and equal to its bulk value η_B. The free energy density consists of the nematic and the smectic contribution [13,25] and the contribution due to the external electric field ($\mathbf{E}$) applied across the cell:

$$f=\frac{1}{2}K([\nabla\cdot\mathbf{n}]^2+(\nabla\times\mathbf{n})^2)+c_\parallel|(\mathbf{n}\cdot\nabla-iq_0)\psi|^2 + c_\perp|\mathbf{n}\times\nabla\psi|^2+D|(\mathbf{n}\times\nabla)^2\psi|^2-\mathbf{P}_\mathrm{S}\cdot\mathbf{E}, \quad (1)$$

where K is the nematic elastic constant, $c_\parallel$, $c_\perp$, and D are related to smectic elastic constants. The de Gennes smectic layer compressibility elastic constant B is related to $c_\parallel$ as $B=c_\parallel q_0^2\eta_\mathrm{B}^2$ [13]. The parameter $c_\perp$ is temperature dependent:

$$c_\perp=c_{\perp 0}(T/T_{AC}-1)=c_{\perp 0}t_\mathrm{r},$$

where T_{AC} is the phase transition temperature from the smectic-*A* to the smectic-*C* in bulk and t_r is a reduced temperature. The periodicity required by the surface is $q_0=2\pi/d_0$, where d_0 is the smectic layer thickness in the smectic-*A* phase. The bulk value of the molecular cone angle that follows from the model is $\tan\vartheta_B=\sqrt{|c_\perp|/(2Dq_0^2)}$.

The chevron cell geometry is shown in Fig. 1. The director and layer structure in chevron cells are usually described by the smectic layer tilt angle δ, the molecular cone angle ϑ, and the director position on the cone φ [see Fig. 1(a)]. The characteristic chevron tip width is $\lambda_\mathrm{ch}=\sqrt{2D/|c_\perp|}$ [26]. The director at the chevron tip (at $x=0$) can tilt either in the $+y$ or $-y$ direction. This out of xz plane tilt then propagates throughout the cell. We shall call the state in which the director tilts in the $+y$ direction the D state [Fig. 1(b)] and the other stable state the U state [Fig. 1(c)].

The numerical calculation are performed in the xyz coordinate system. The director is expressed by its components along the x, y, and z axes. Since we study the case where the electric field is applied in the $\pm x$ direction everywhere in the cell, the director is a function of x coordinate only:

$$\mathbf{n}(x)=\{k(x),l(x),m(x)\}, \quad (2)$$

where $m=(1-k^2-l^2)^{1/2}$, because $|\mathbf{n}(x)|=1$. The smectic order parameter phase factor is

$$\phi(x,z)=q_0[z+u(x)]. \quad (3)$$

The layer displacement field $u(x)$ describes the departure from the planar layer configuration. The variables used in calculations are thus $k(x)$, $l(x)$, and $u(x)$.

The effect of external electric field E on the structure is taken into account by the last term in the free energy density (1). We neglect the effect of free charges and bound charges due to the divergence of spontaneous polarization. We also neglect the effect of the dielectric anisotropy which becomes important at fields much higher than the typical threshold fields. The ferroelectric polarization is perpendicular to the smectic layer normal ($\boldsymbol{\nu}$) and the director:

$$\mathbf{P}_S=P_0\boldsymbol{\nu}\times\mathbf{n}. \quad (4)$$

The two stable director states differ in the direction of the spontaneous polarization. In the D state the x component of the polarization points in the $-x$ direction (down the x axis). In the U state the x component of the polarization points in the $+x$ direction (up the x axis). The smectic layer normal is obtained from the smectic order parameter phase factor as $\boldsymbol{\nu}=\nabla\phi/|\nabla\phi|$. With the use of Eqs. (2) to (4) we find the expression for the electric contribution to the free energy density. For the electric field applied along the $+x$ axis we obtain

$$\frac{P_0El}{\sqrt{1+(du/dx)^2}}.$$

The two bistable structures thus differ in the sign of $l(x)$. If $l(x)$ is positive, the electric field applied along the $+x$ axis can rotate the director to the other stable state. A structure with $l(x)$ negative will be switched by the electric filed applied along the $-x$ axis.

The effect of surface orientational anchoring should be added to the free energy of the cell. Here we assume strong anchoring of the director at the surface along the z axis. The boundary conditions at $x=\pm L/2$ are then $k=0$, $l=0$ and $d^2u/dx^2=0$.

III. DIRECTOR AND LAYER STRUCTURE

In this section we show the numerical results for the director and layer structure in the chevron cell in low external electric fields. The initial structure in the absence of the electric field is the D state in which the director tilts from the xz plane in the $+y$ direction everywhere in the cell [Fig. 1(b)]. If an electric field E, greater than the threshold field $E_{\rm th}$, is applied across the cell in the $+x$ direction the D state can be switched to the U state in which the director tilts from the xz plane in the $-y$ direction everywhere in the cell [Fig. 1(c)].

Due to the additional electric torque on the director in the cell in the external electric field the director and layer profile in the external electric field are different than in the absence of the field. The external field mainly changes the director position on the cone. This effect we discuss first. The variations in the smectic layer profile and the molecular cone angle are much smaller and will be discussed at the end of this section.

To present the director and layer structure in the chevron cell in external electric fields we have chosen the following set of parameters: $L=2.1\ \mu$m, $d_0=3.0$ nm, $K=10^{-11}\ \mathrm{J\,m^{-1}}$, $c_\parallel/c_{\perp 0}=1$, $B=c_\parallel q_0^2\eta_B^2=10^6\ \mathrm{J\,m^{-3}}$, $Dq_0^4\eta_B^2=3.8\times10^5\ \mathrm{J\,m^{-3}}$. This parameters are chosen such that at the reduced temperature $|t_r|=0.1$ the bulk value of the molecular cone angle is $\vartheta_B=20°$ and the characteristic chevron width is $\lambda_{\rm ch}=0.5d_0$. The structure is shown at two values of the reduced temperature: at $|t_r|=0.1$ and at $|t_r|=0.01$, where $\vartheta_B=6.4°$ and $\lambda_{\rm ch}=1.4d_0$.

The spatial dependence of the director position on the cone (φ) at different strengths of the external electric field is shown in Fig. 2. In the absence of an external field the director rotates from $\varphi=0$ at the chevron tip to $\varphi\approx1.1$ over the distance of the order of the chevron tip width $\lambda_{\rm ch}$. Then it rotates uniformly to $\varphi=\pi/2$ at the surface. When the electric field is applied the structure deforms most in the middle between the surface and the chevron tip. There the torque on the director due to the surface anchoring and the ''anchoring'' at the chevron tip is least felt. The director rotates on the cone toward the position in which the component of the spontaneous polarization along the external electric field is maximum. If the field is applied along the $-x$ direction (no switch) then the director rotates toward $\varphi=0$. If it is applied in the $+x$ direction (possible switch) then φ in the middle between the surface and the chevron tip increases. The elastic torque on the director around the chevron tip increases and at the electric field E greater than the threshold field $E_{\rm th}$, the director at the chevron tip flips from the D state to the U state with $\varphi=\pi$ at the chevron tip.

In Fig. 3 we show the spatial variation of the director y component $[l(x)]$ at different strengths of the external electric field. As already mentioned $l(x)$ changes sign during the switch. It also determines the amount of the director tilt out of the xz plane, i.e., the plane determined by the layer and surface normals. It is related to the director ''in plane tilt'' β

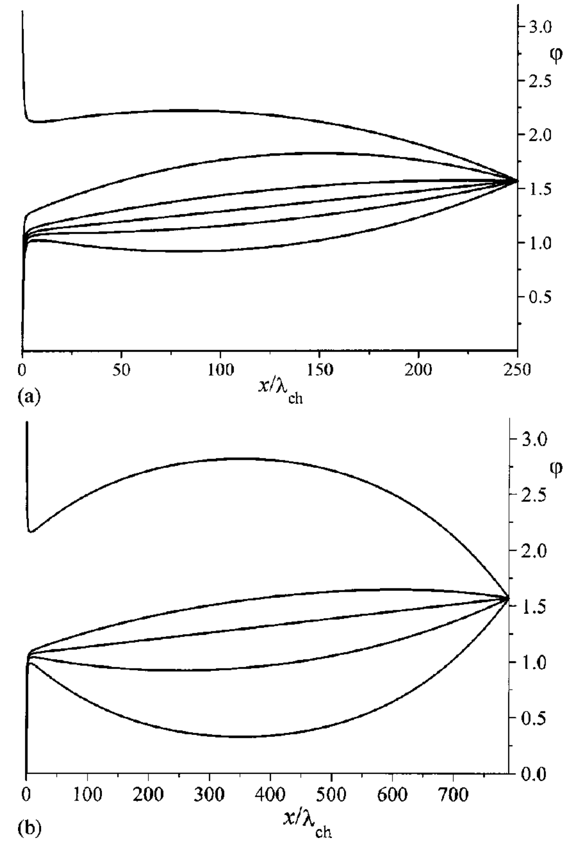

FIG. 2. The director position on the cone φ (in radians) at different ratios $E/E_{\rm th}$, where E is the strength of the electric field applied across the cell and $E_{\rm th}$ is the threshold electric field. (a) $|t_r|=0.01$, $E_{\rm th}=3.0\times10^{-6}B/P_0$, from bottom to top: $E/E_{\rm th}=-1.00$, -0.33, 0, $+0.33$, $+0.97$, $+1.00$; (b) $|t_r|=0.1$, $E_{\rm th}=4.5\times10^{-5}B/P_0$, from bottom to top: $E/E_{\rm th}=-1.04$, -0.22, 0, $+0.22$, $+1.04$. The chevron tip is at $x=0$.

(''in plane'' with respect to the surface plane), defined by Brown *et al.* [17]. The angle β is the angle between the z axis and the director projection to the zy plane and is related to $l(x)$ as $\tan\beta(x)=l(x)/m(x)$. Usually $l(x)\ll1$ and $m(x)\sim1$, so in most cases we have $\beta(x)\sim l(x)$.

We discuss in more detail the structure in the cell in the external electric field which is lower than the threshold field and applied in the $+x$ direction. The elastic free energy of the cell increases as long as $E<E_{\rm th}$. The main contribution to this increase is due to the elastic deformation around the chevron tip. At the chevron tip the director cannot switch form one state to the other by the rotation on the cone. The cone angle can only decrease before the structure flips to the stable state on the other side of the cone. The external field affects the magnitude of the cone angle only around the chevron tip. Everywhere else in the cell the cone angle equals its bulk value and is not affected by the application of the external electric field. This confirms that typical switching fields can cause only director rotation on the cone to the position in which the polarization component along the external field is maximum. Typical switching fields are too low to cause an increase in the equilibrium cone angle which would also increase the spontaneous polarization.

The director at the chevron tip is dragged to the opposite side of the cone by the liquid crystal in the rest of the cell

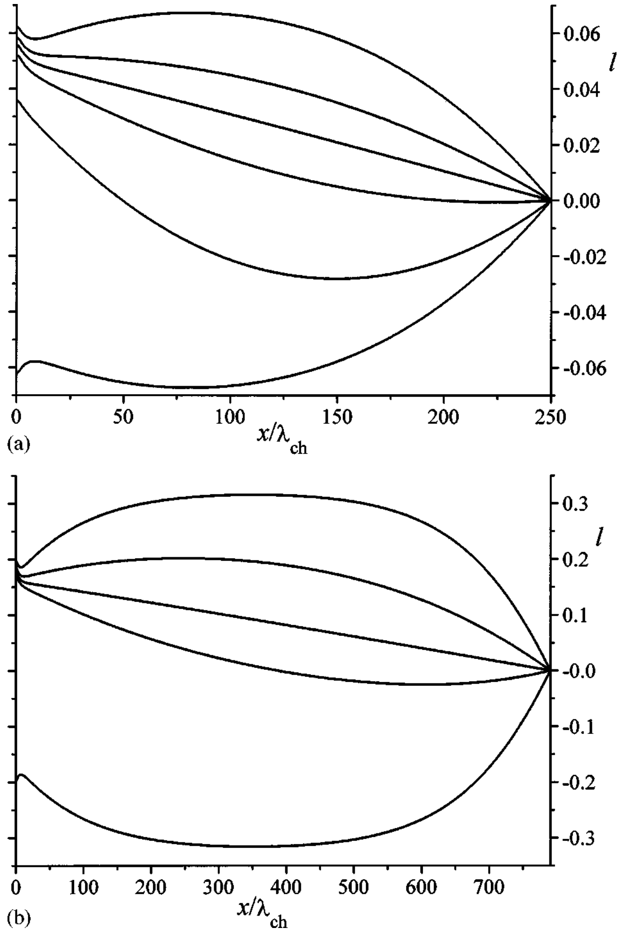

FIG. 3. The director y component (l) at different ratios $E/E_{\rm th}$, where E is the strength of the electric field applied across the cell and $E_{\rm th}$ is the threshold electric field. (a) $|t_r|=0.01$, $E_{\rm th}=3.0\times10^{-6}B/P_0$, from top to bottom: $E/E_{\rm th}=-1.00$, -0.33, 0, $+0.33$, $+0.97$, $+1.00$; (b) $|t_r|=0.1$, $E_{\rm th}=4.5\times10^{-5}B/P_0$, from top to bottom: $E/E_{\rm th}=-1.04$, -0.22, 0, $+0.22$, $+1.04$. The chevron tip is at $x=0$.

where the director has already rotated to the opposite side of the cone at the electric fields lower than the threshold field (see Fig. 2). This effect is much larger than the direct coupling between the external electric field and the spontaneous polarization around the chevron tip, since **P** and **E** are nearly antiparallel there. So if the biaxial ordering and thus the magnitude of spontaneous polarization go to zero around the chevron tip [6] over the width that is comparable to the chevron tip width (as can be reasonably expected), this should have no significant influence on the switching conditions as long as the cell thickness is a lot larger then the chevron tip width. Melting of the biaxial ordering could have a significant effect on switching only in very thin cells or at temperatures close to the phase transition to the smectic-A phase. None of these conditions is in general applicable to the typical cells used in switching devices.

The variations in the smectic layer profile in the chevron cell in low external electric fields are extremely small. If the electric field is applied along the $-x$ direction, i.e., along the nonswitching direction, then the external electric field slightly flattens the chevron tip. This agrees with experimental results [27,28] where bookshelf structure was obtained

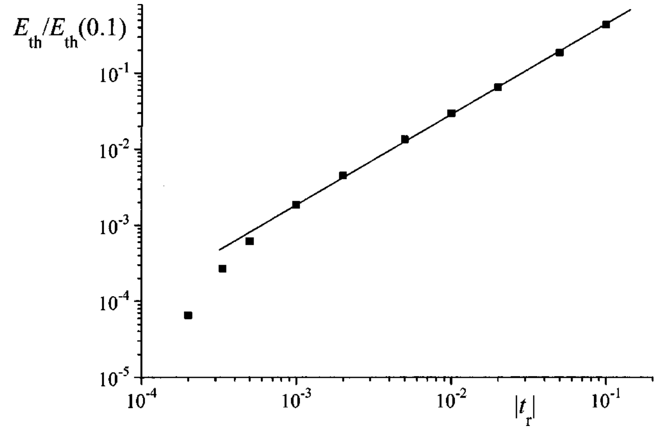

FIG. 4. Threshold electric field $E_{\rm th}$ as a function of temperature. The line presents the best power law fit to the numerical results. $E_{\rm th}(0.1)=4.5\times10^{-5}B/P_0$ is the threshold electric field at the reduced temperature $|t_r|=0.1$.

from the chevron structure with rather high voltages ($\sim$50 V) applied across the cell. In the typical fields that induce switching between the two stable states, however, the effect is rather small. If the electric field is applied along the $-x$ direction, the chevron tip sharpens as long as the electric field is smaller than the threshold value. At $E>E_{\rm th}$ the chevron tip is again slightly less sharp than in the absence of the external field. The numerical results thus confirm the estimates by Willis *et al.* [14], who suggested that the fields typical for switching have no influence on the smectic layer structure and smectic layer thickness. This small variations in the layer profile are, however, important. If they are neglected we find significantly higher threshold fields. Instead at $E>3.0\times10^{-6}B/P_0$ the cell whose director profile is shown in Fig. 2(a) would switch at $E>4.0\times10^{-6}B/P_0$.

IV. THRESHOLD ELECTRIC FIELD

The dependence of the threshold electric field on temperature and cell thickness is shown in Figs. 4 and 5. To find the threshold field E we calculate the equilibrium director and layer structure at different values of E and find the value at which the structure flips from one stable state to the other.

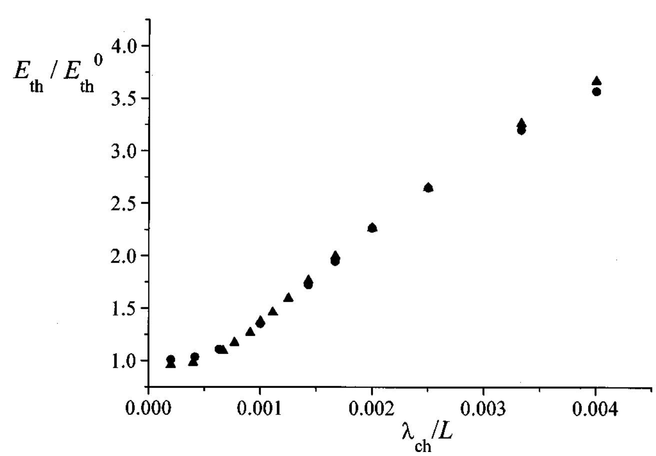

FIG. 5. Threshold electric field $E_{\rm th}$ as a function of the cell thickness L. Triangles: $|t_r|=0.01$; circles: $|t_r|=0.1$. At both temperatures: $E^0_{\rm th}$ is the threshold value at $L=5000\lambda_{\rm ch}$.

We first discuss temperature dependence (see Fig. 4). The dependence obeys a power law with the exponent of 1.25 ± 0.02 as long as the cell thickness is a lot greater than the chevron tip width and the surface anchoring does not significantly influence the structure around the chevron tip. At $|t_r| < 10^{-3}$ the cell thickness is already comparable to the chevron tip width. As a result the layer structure inside the cell looks more sinelike instead of solitonlike [26]. In this region the threshold electric field is lower than predicted by the power law dependence.

Strong director anchoring along the z direction was chosen at the surface. This type of anchoring tries to enforce a planar chevron structure in the cell. The relative strength of surface to bulk forces increases at temperatures close to the phase transition to the smectic-A phase. At $|t_r| \leqslant 10^{-4}$ we thus obtain a planar chevron structure [26] which is monostable.

The dependence of the threshold value E_{th} on the cell thickness L is shown in Fig. 5. In thicker cells the influence of the surface torque and the torque at the chevron tip is becoming smaller in comparison to the electric torque on the bulk between the surface and the chevron tip. As a result the threshold value of E_{th} decreases when thickness increases. The dependence of E_{th} on L is shown at two different temperatures: at $|t_r| = 0.1$ (and $\vartheta_B = 20°$) and at $|t_r| = 0.01$ (and $\vartheta_B = 6.4°$). If $E_{\mathrm{th}}/E_{\mathrm{th}}^0$ (where E_{th}^0 is the threshold value at $L \gg \lambda_{\mathrm{ch}}$) vs $1/L$ is plotted both curves have the same shape. The cell with higher ϑ_B, however, switches at higher fields and also switches faster as will be shown in the following section. In a realistic cell ($L \sim 2\ \mu$m), $\vartheta_B \sim 20°$ the ratio L/λ_{ch} is 1500 and more which is in the region where the curve E_{th} vs $1/L$ flattens out.

Finally we can estimate the value of the critical field in a realistic case where $L = 2\ \mu$m, $\vartheta_B = 20°$, $|t_{\mathrm{r}}| = 0.1$, $P_0 = 10^{-4}\ \mathrm{C\,m^{-2}}$, and $B = 10^6\ \mathrm{J\,m^{-3}}$. The value of E_{th} is $4.5 \times 10^{-5} B/P_0$ (see Fig. 4). We find that the threshold electric field is $4.5 \times 10^5\ \mathrm{V\,m^{-1}}$. In a very rough estimate the threshold voltage across the cell is then of the order of 1 V. This estimate qualitatively agrees with the experimental results [29].

V. SWITCHING TIME

Finally we find the switching time from one stable state to the other after the external field was applied. The initial condition in the numerical calculations presented is the following. In the absence of an external field the whole cell is in the D state. Then an external electric field E is applied. To find the structure at time t after the field was switched on, we use the simplest possible approach, i.e., Landau-Khalatnikov equations

$$\frac{\partial g}{\partial k} - \frac{\partial}{\partial \xi}\frac{\partial g}{\partial k_\xi} + \frac{\partial k}{\partial t'} = 0,$$

$$\frac{\partial g}{\partial l} - \frac{\partial}{\partial \xi}\frac{\partial g}{\partial l_\xi} + \frac{\partial l}{\partial t'} = 0,$$

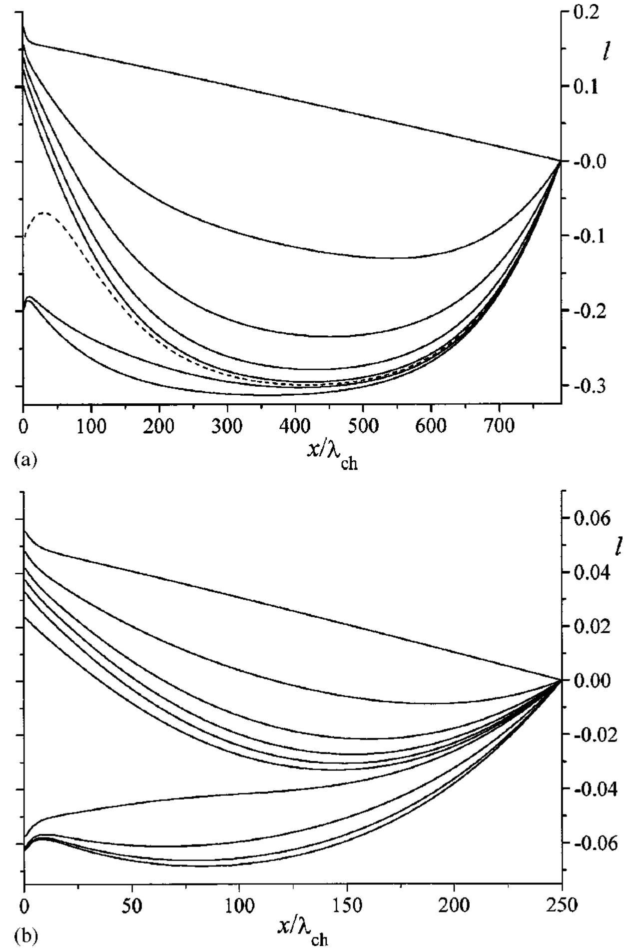

FIG. 6. Spatial dependence of the director y component (l) at different times after the field was switched on. (a) $|t_r| = 0.1$, $E = 5.2 \times 10^{-5} B/P_0$, $E_{\mathrm{th}} = 4.5 \times 10^{-5} B/P_0$, the full line curves are drawn for every 400τ; top curve: $t = 0$, bottom curve: $t = 2400\tau$; dashed line: $t = 1800\tau$; (b) $|t_r| = 0.01$, $E = 3.3 \times 10^{-6} B/P_0$, $E_{\mathrm{th}} = 3.0 \times 10^{-6} B/P_0$, the curves are drawn for every 100τ; top curve: $t = 0$, bottom curve: $t = 900\tau$. τ is the characteristic time at a given reduced temperature.

$$\frac{\partial g}{\partial w} - \frac{\partial}{\partial \xi}\frac{\partial g}{\partial w_\xi} + \frac{\partial w}{\partial t'} = 0.$$

The parameter t' in Landau-Khalatnikov dynamic equations is a dimensionless time: $t' = t/\tau$, where

$$\tau = \frac{\gamma}{|c_\perp| q_0^2 \eta_B^2} = \frac{\gamma}{B|t_{\mathrm{r}}|}.$$

Here γ is the rotational viscosity. With $\gamma \sim 10^{-1}\ \mathrm{kg(ms)^{-1}}$ [21], $B \sim 10^6\ \mathrm{J\,m^{-3}}$ and $|t_{\mathrm{r}}| \sim 0.1$ we obtain $\tau \sim 10^{-6}$ s. We essentially neglect the effect of backflow on switching dynamics. The effect, however, can significantly affect the switching [30,31].

To present the switching from one stable state to the other we show the spatial dependence of the director y component (l) at different times after the field was switched on. In Fig. 6 the time development is shown for a 2.1 μm cell at two temperatures: $|t_r| = 0.1$ ($\vartheta_B = 20°$) and at $|t_r| = 0.01$ ($\vartheta_B = 6.4°$). In both cases $E = 1.1\ E_{\mathrm{th}}$. We see that the director

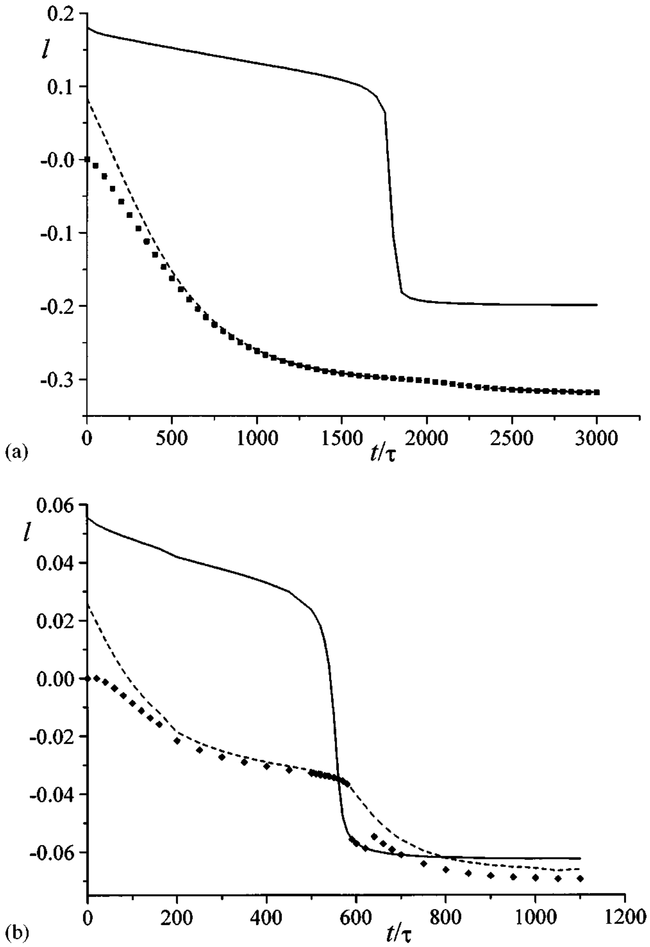

FIG. 7. The time dependence of the director y component at the chevron tip (full line), in the middle between the surface and the chevron tip (at $x=L/4$) (dashed line) and the minimum value of l (squares). (a) $|t_r|=0.1$, $E=5.2\times10^{-5}B/P_0$; (b) $|t_r|=0.01$, $E=3.3\times10^{-6}B/P_0$.

close to the surface rotates first. The rotation then propagates towards the chevron tip. The chevron tip switches last. As the switching time we have chosen the time at which the director at the chevron tip flips to the new stable state.

In Fig. 7 we show the time dependence of l at the chevron tip. In the same figure we also show the time dependence of l in the middle between the surface and the chevron tip (i.e., at $x=L/4$) and the maximum tilt l in the $-y$ direction. The behavior at two different temperatures is significantly different. In typical cells used in display devices we can expect the behavior shown in Fig. 7(a). In this case ($|t_r|=0.1$ and $\vartheta_B=20°$) the bulk liquid crystal between the surface and the chevron tip switches before the chevron tip switches. At higher temperatures ($|t_r|=0.01$ and $\vartheta_B=6.4°$) the director in the bulk starts rotating towards the new bistable state immediately after the field is switched on. The bulk, however, switches completely only after the chevron tip has switched as well [see Fig. 7(b)].

Finally, in Fig. 8 we show the switching time as a function of E. At a given temperature the switching time decreases with increasing field strength. At higher temperatures (lower $|t_r|$) the threshold field strength decreases and as a result the switching time increases. We note that in our case the switching time would always monotonically decrease with increasing field strength because we did not include the effect of dielectric anisotropy. This effect is quadratic in field, it becomes important at higher fields and it eventually causes the switching time to increase with the increasing field strength [21,22].

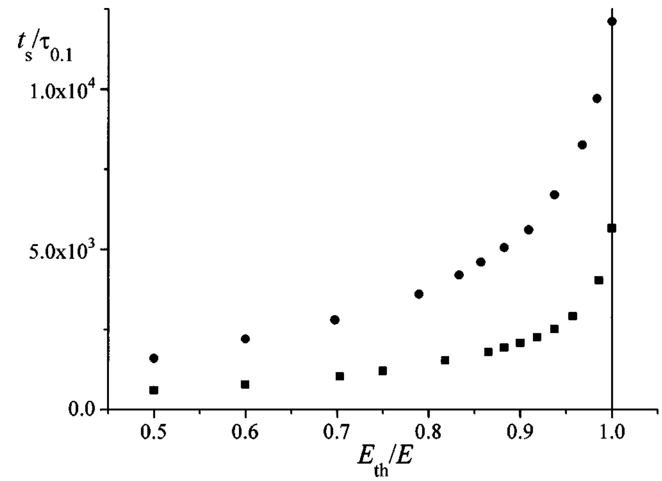

FIG. 8. Switching time (t_s) as a function of strength of the applied electric field. Switching times are expressed in terms of the characteristic time at the reduced temperature $|t_r|=0.1$ ($\tau_{0.1}$). Squares: $|t_r|=0.1$, $E_{\rm th}=4.5\times10^{-5}B/P_0$, $\tau_{0.1}=\gamma/(B|t_{\rm r}|)\sim10^{-6}$ s; circles: $|t_r|=0.01$, $E_{\rm th}=3.0\times10^{-6}B/P_0$, $\tau=10\tau_{0.1}$.

VI. CONCLUSIONS

We have presented a theoretical study of switching between the bistable states in chevron surface stabilized ferroelectric liquid crystal cells. This is the first study of switching that takes into account a detailed director and layer structure of the chevron tip. We showed how the director and layer structure deform in the cell in external electric field. We confirmed the predictions that smectic layer deformation is negligible at the typical switching fields. We found the threshold electric field as a function of temperature and cell thickness. We also studied the time development of the director and layer structure after the field, stronger than the switching field, was applied to the cell. We have shown that the threshold electric field increases with decreasing temperature and that it obeys a power law dependence on temperature. The threshold field increases also if the cell thickness decreases.

When studying the switching dynamics we have found two possible scenarios. At lower temperatures and higher bulk values of the molecular cone angle the director rotation on the cone from one stable state to the other begins at the boundary and propagates toward the chevron tip. The liquid crystal between the surface and the chevron tip switches up to an order of magnitude faster than the chevron tip. At higher temperatures and lower values of the bulk molecular cone angle the director rotation again starts at the surface and propagates toward the chevron tip. However, the chevron tip switches before the rest of the cell. After the tip is switched, the switch propagates from the chevron tip towards the middle between the surface and the chevron tip. We have also shown that as long as the effect of dielectric anisotropy can be neglected the switching time decreases if the electric field strength increases.

The model presented in this work gives all the essential characteristics of switching. However, at this stage we have considered only symmetrical chevron cells with strong nonpolar orientational anchoring at the surfaces. Inclusion of the polar surface anchoring leads to well known splayed states in chevron structures. In our study we have also neglected the effect of the spontaneous polarization self-interaction on the structure and switching in chevron cells. This effect becomes important in materials having sufficiently high polarization. Due to the spontaneous polarization self-interaction the director out of plane tilt decreases which leads to the decrease in the threshold field value. The combination of very strong polar surface anchoring together with the sufficiently high spontaneous polarization can lead to the planar chevron structure in which the director aligns in the xz plane everywhere in the cell except close to the surfaces. Such structure would exhibit continuous reorientation of the director in the external electric field, i.e., it would switch without threshold. In our future work we intend to study the effect in full detail.

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