The Effect of Surface Alignment on Analog Control of Director Rotation in Polarization Stiffened Smc* Devices

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I. INTRODUCTION

Typical surface stabilized ferroelectric liquid crystal cells (SSFLC’s) show a steep threshold that is very useful for bistable display devices, but undesirable in cases where analog switching is needed. A threshold-less ‘V-shaped’ switching mode has been reported\(^1\) in which certain FLC materials demonstrate analog switching in cells having a bookshelf or near-bookshelf smectic structure. Besides displays, FLCs can be used to provide high speed phase modulation for beam steering\(^2\) and wave front control applications. To phase modulate circularly polarized light, the FLC cell is configured as a half wave optical retarder whose optic axis can be rotated in the plane of the cell.\(^3\) Ideally, the director field would be uniform and free of twist throughout its thickness so that the projection of the director field onto the plane of the cell would provide a well defined effective optic axis orientation without introducing unwanted optical rotation.

An electrostatic model of threshold-less switching FLCs that assumes a uniform director distribution throughout the cell thickness has been developed to explain their analog switching properties.\(^4\) The model predicts that large spontaneous polarization leads to the director structure of the FLC being spatially uniform, or ‘stiffened’. If the polarization is sufficiently large, bulk electrostatic energy overwhelms surface influences (which typically favor bistability) to produce threshold-less switching.\(^5,6\) However, in cases of practical interest, electrostatic energies may be low enough for surface forces to play an important role even when the director structure is stiffened by a large spontaneous polarization. An analytical approach that considered a totally stiffened FLC with the inclusion of surface forces led to obtaining clear analytical expressions that describe dynamical response of the FLC.\(^5,7\) An overview of the mechanisms that explain V-shaped switching can be found in Refs 8 and 9.

Our goal is to study in more detail the effect of alignment layers on the character of threshold-less switching. For practical applications, we want surfaces that promote hysteresis-free continuously variable rotation of a cell’s optic axis in response to voltage or charge\(^5,10\) drive. It is known that electrostatic energy more strongly favors threshold-less switching as alignment layer thickness increases,\(^5,11\) with low voltage charge drive using vanishingly thin alignment layers being equivalent to high voltage drive with very thick alignment layers.\(^5\) The focus here, however, is not the capacitive effects of the alignment layer, but instead the more direct effects of the FLC-surface interaction; e.g., azimuthal and zenithal anchoring energy and the pretilt.

Besides the pretilt and anchoring energy, there are other surface effects related to the alignment layer that can be considered, for example, reduction in the smectic order near the surface (surface melting), movement of the easy axis on the surface (gliding), and deformation of the smectic layer spacing during switching. The following paragraphs introduce these other effects.
A. Surface melting

It has been shown that surface melting of the smectic phase can occur.12–14 Theoretical and experimental studies of the smectic phase in confined geometries allow us to suggest that it is likely that the smectic phase in the close vicinity of the rough surface has lowered order. This can be modeled by introducing a thin nematic layer between the aligning surface and the smectic bulk of the cell.

B. Gliding

Another effect often discussed in the relation to surface effects in LC cells is gliding of the surface easy axis,17 which is usually observed for nematic liquid crystals as slow drift of the easy axis under the action of the external torque applied to the bulk of the liquid crystal. Surface gliding has not been considered to our knowledge as an effect that can play a role in the switching behavior of a V-shaped FLC device. But the high surface torques expected in these devices might be considered to cause the easy axis to glide during switching.

C. Deformation of smectic layer spacing and easy axis gliding

The surface alignment layer may also affect spacing of the smectic layers near the surface. Strong zenithal surface anchoring could promote director sliding along the surface rather than director rotation in the smectic cones. However this would lead to layer thickness change and possible appearance of undulations of the smectic layers. We investigate the trade-off of the energies involved with these two scenarios.

To study these possible effects we have utilized an alignment method for the smectic layers that is independent of the effect of the surface condition. Normally, the alignment layer must serve both to align the smectic layers of the liquid crystal as it is cooled through the nematic and smectic A phases, and to provide boundary conditions which promote the desired switching mode in the SmC phase. There is no certainty that these separate goals are mutually compatible. Here we exploit a novel alignment method that orients the smectic layers without requiring the surface to be azimuthally anisotropic,18 allowing us to test surfaces that would otherwise be impractical as they do not promote the desired smectic layer alignment.

It is well known that many ferroelectric devices experience change of the layer thickness under the action of electric field or when going through structural transitions.19–21 We, however, use a high tilt, high polarization FLC with reduced layer shrinkage thought to be well suited for analog phase modulation.22 High polarization combined with a relatively small chevron angle may allow this FLC to approximate the behavior of a fully bookshelf FLC (no layer shrinkage). The phase sequence of this FLC is I-A-C so the smectic layers cannot be aligned as I-N-A-C materials can by using conventional alignment layers (e.g., rubbed polymers). However, the novel alignment method used here offers a promising alternative for obtaining good alignment with FLCs having the I-A-C phase sequence.

In this work, we experimentally and numerically evaluate the effect of zenithal and azimuthal surface anchoring energy, pretilt, a nematic sub-layer, expansion of the smectic layers and the surface gliding on the characteristic of V-shaped switching. The paper is structured as follows. In the experimental section, we demonstrate the V-shaped response that we obtained for various alignment layers and compare their switching uniformity and hysteresis behavior. In the modeling section, we describe results of a computer simulation that help better understand the effect of the surface alignment layer parameters on the experimental results. After that, based on experimental and modeling results, we propose an explanation of the surface parameters’ effect on the V-shaped electro-optical response.

II. EXPERIMENT

We chose a set of alignment layer materials spanning a wide range of FLC-surface interaction characteristics. The choice of alignment layers was dictated by their parameters (anchoring energy, pretilt, tendency for creation of the nematic sub-layer, etc.) that, as we initially assumed, could affect the properties of the V-shaped response. Although, to our knowledge, there are no works that systematically study effect of the smectic ordering decrease near the aligning surface as a function of alignment layer, we expected alignment layers with rough geometries (such as SiOx deposited at the angle of 5°) to have tendency for nematic sub-layer creation.

We used conventional PI 2555 that induces low-pretilt alignment of liquid crystals (~20 nm thickness, zenithal anchoring energy \(W_z \sim 1 \text{ mJ/m}^2\), azimuthal anchoring energy \(W_a \sim 10^{-2} \text{ mJ/m}^2\)).23 SiOx deposited at the angle of 5° (high pretilt alignment, ~20 nm thick, \(W_z \sim 10^{-2} \text{ mJ/m}^2\), \(W_a \sim 10^{-3} \text{ mJ/m}^2\) leads to reduction of the smectic ordering in the vicinity of the surface).23,24 SiOx deposited at the angle of 30° (low pretilt alignment, ~20 nm thick, \(W_z \sim 10^{-2} \text{ mJ/m}^2\), \(W_a \sim 10^{-3} \text{ mJ/m}^2\)), Glymo (3-Glycidoxpropyl trimethoxysilane, ~20 nm thick, \(W_z \sim 10^{-1} \sim 1 \text{ mJ/}

m^2\), \(W_a < 10^{-3} \text{ mJ/m}^3\)),25 and bare ITO. For homeotropic-inducing alignment layers (PI Nissan 7511 and its analog PI Nissan 1211, layer thickness ~20 nm),26,27 azimuthal and zenithal contributions to the anchoring energy effectively become equal from the symmetry considerations, and can be estimated for our purposes as \(W_a \sim W_z \sim 10^{-1} \text{ mJ/m}^2\). (We use the same definition of the anchoring energy coefficients used as by Palto28 that are discussed in the numerical simulation section). Anchoring energy measurements reported in references were made for nematic liquid crystals. The relative strengths of surface characteristics for all the alignment layers are shown in Table I. Filled circles mean strong contribution, half-filled circles - partial contribution, blank circles - small/zero contribution. For example, homeotropic PI 7511/1211 promotes maximum pretilt (filled circle), 5° SiOx - medium pretilt (half-filled circle), PI 2555 - very low pretilt (blank circle).

We used the Displaytech ferroelectric liquid crystal material MX10498, which has large spontaneous polarization \((P_s \sim 200 \text{ nC/cm}^2\) and tilt angle ~45°. This FLC was chosen for three reasons. First, its high tilt angle makes it of special interest for use in optical beam steering and other wavefront manipulation applications. Second, its high polarization is expected to promote thresholdless switching.5–7 And third, it...
exhibits a significant degree of deVries behavior - with its less-than-typical SmC* layer shrinkage, which will result in a reduced chevron angle, making the chevron less of a barrier to obtaining thresholdless switching.29

It is sometimes considered a disadvantage of MX10498 and most other deVries type materials, that they possess an I-A-C phase sequence that cannot be aligned well by the conventional means used to align the smectic layers in I-N-A-C materials. However, this phase sequence is suitable for the alignment method used in this work.

A cell’s surfaces are usually called upon to perform two functions: determine the smectic layer orientation (alignment), and establish surface anchoring energies compatible with the desired switching mechanism. Here we use an alignment technique that de-couples these requirements, and which offers a potentially superior method for aligning I-A-C FLCs. The main idea of our alignment method is using a temperature-gradient when cooling from isotropic to the SmA phase, starting from a smooth edge of the liquid crystal slab created by molecularly smooth LC-air interface that allows growing of smectic layers from this interface without defects. As quality and geometry of the smectic layer structure virtually does not depend on properties of the surface alignment layer, we were able to use surface materials that induce high pretilt and homeotropic alignment. For every surface material used we obtained a uniform bookshelf structure in the SmA phase (please refer to the Ref.18 for the details of the alignment process and the texture photographs). Schematic drawing of the bookshelf geometry is shown in Fig. 1. Electric field is applied in the perpendicular direction to the layer normal, and during switching molecules are revolving around the layer normal direction (y-axis), staying the surface on the cone.

The obtained smectic layer structure in the SmA phase is approximately preserved when the FLC is cooled down to the SmC*. Since material that we used has reduced layer shrinkage, we obtained a structure in the SmC* phase that we assume is nearly bookshelf. We used specially designed cells with channels that were etched into an indium tin oxide (ITO)-coated glass using a photo-patterned resist and hydrofluoric acid (Fig. 2). Both surface interfaces of the cells were identical. The cell gap of 4 μm was defined by powder spacers that were mixed in the UV-sensitive glue, which held two substrates together. In the aligned cell, normal to the smectic layers was in the plane of the cell and directed along the temperature gradient. More details of the cell preparation and the alignment technique are described in another paper.18

A. Experimental set-up and data acquisition

To assess the analog response of FLC cells they were driven with low frequency triangle voltage waveforms, with frequencies ranging from 0.1 to 60 Hz. Thick dielectric layers, an external series capacitance, or charge control can be used to enhance an FLC cell’s analog response.5,10 However, here we are interested in observing the effect of the surface with as little interference as possible, so we used voltage drive and relatively thin dielectric layers (about 20 nm).

The choice of drive frequency is important for at least two reasons. First, at low frequencies, ionic charge within the FLC has time during each half cycle of drive to accumulate at cell surfaces and generate an electric field that affects switching dynamics.7 At higher frequencies the phase of the optic axis response lags the phase of the drive waveform.9 Due to the FLC’s nonlinear response the inversion frequency in general depends also on drive amplitude. Other

![FIG. 1. Bookshelf structure of FLC smectic layers. P is orientation of the FLC dipoles, electric field E is applied across the cell.](image1)

![FIG. 2. (Color online) Design of liquid crystal cell (not drawn to scale). Channel substrates were made by photolithographic etching of standard ITO-coated glass with hydrofluoric acid.](image2)
factors affecting the inversion frequency include FLC cell properties such as alignment layer capacitance, and any external circuitry used with the cell (e.g., series or parallel resistors and capacitors). Second, if a cell contains UP and DOWN domains, their participation in switching can be frequency dependent. Despite the static presence of UP/DOWN domains in a cell, optic axis switching can become spatially uniform throughout the cell aperture at sufficiently high drive frequencies. Thus a bistable cell can appear to be threshold-less under high frequency drive. Since our goal is to assess the influence of surfaces in producing threshold-less switching, measurements are performed at low frequencies to avoid mischaracterizing a cell as threshold-less due to dynamic effects. We also assume that ionic charge accumulation, while affecting details of optic axis dynamics (e.g., hysteresis, phase lag/lead), does not play an important role in determining whether or not test cells exhibit threshold-less switching. To measure the optical response, we used either photodiode or video camera mounted on the top of the polarizing microscope (with crossed polarizers). For frequencies higher than 1 Hz, we used a photodiode connected to the oscilloscope. For lower frequencies we used video camera connected to the computer in order to observe and record FLC texture behavior during switching.

B. Experimental data

FLC switching was assessed by measuring transmitted light intensity versus time while the cell was being driven by a triangle wave, and by video images taken through the microscope during switching. Individual video frames corresponding to labeled points of the intensity vs. time curves are shown in the figures. Solid line corresponds to the voltage increasing from its minimal value to the maximum; dash line corresponds to the decreasing voltage. Light transmission on the plots is in relative units; 0% and 100% correspond to the transmission of light through our system with crossed and parallel polarizers, respectively. The acquired data is shown in Figs. 3–8 was taken with one of the crossed polarizers oriented along the direction of the projection of the smectic layer normal onto the plane of the cell (note that Figs. 7 and 8 show data from two different cells with the homeotropic alignment layer). We would like to note that despite ‘homeotropic’ alignment layers, these cells still have the bookshelf structure with the director lying in the plane of the cell because of the utilized aligning technique. The defects that are seen on the photographs are the alignment disruptions of the bookshelf structure and the switching domains.

Note that in some of the figures, the base of the V does not go to zero. This indicates that the director is not uniformly oriented, as will be discussed later. In some cases, for example, as in Figs. 7 and 8, the base of the V does go close to zero indicating that the director, at the time with the zero point occurs, is uniformly aligned with its projection onto the plane of the cell being along the layer normal. To investigate how the director’s uniformity varies as it rotates in the smectic cones as a function of voltage, we have measured dependence of electro-optical response for different directions of the polarizer’s transmission plane for the PI 7511 cell (Fig. 9). The basic idea of this experiment is the following. The photodiode integrates light from a region of a cell rather than from a point. So, if the optic axis does not switch uniformly throughout the viewed region then the photodetector signal can never drop to zero. Also, if the director field is twisted, the output polarization state will not be linear, and the transmitted light intensity cannot become zero between crossed polarizers. Uniformity is tested by rotating the cell (while being driven) through a range of orientations between crossed polarizers and verifying whether or not there is always a point along the photosignal vs. voltage curve where the signal drops to zero (meaning that the optic axis throughout the viewed region is parallel or perpendicular to the polarizer at that point of the drive cycle).

One can see that transmission goes down to zero for the case of 45°, which implies uniform director configuration when the director is rotated to be at 45° from the layer normal. This configuration corresponds to the maximum value of applied electric field. The higher value of the minimum light transmission in the case of 20° polarizer rotation implies a greater degree of nonuniformity of the director field when the projection of the director on the plane of the cell is rotated at 20° to the layer normal.

One can see that for two cells with the same alignment layers (Figs. 7 and 8) separations between Vs are different, although widths of Vs and the minimal transmissions are close for both cells. Separation of Vs is defined by electric properties of the cell, such as capacitance of alignment layers, concentration of free charges in the liquid crystal, cell gap, etc., which can vary from cell to cell. On the other
hand, shape of V (which characterizes analog electro-optical response of the device), and the base of V (which characterizes uniformity of the director rotation in the cell) is approximately reproducible from cell to cell. The reproducibility of the electric properties of the cell was beyond the scope of this work; however we suggest that careful preparation of the cells with accurately defined cell gap and alignment layer thickness will ensure reproducibility of separation of the Vs in the electro-optical response curves.

As mentioned above, the frequency dependent phase of the FLC cell’s optic axis response relative to the drive signal can be altered by inserting passive circuits in series or parallel with the cell. In Fig. 10 we demonstrate thresholdless, hysteresis-free, V-shaped switching at a standard display working frequency of 60 Hz for cells containing PI 1211 and 30/C14 surfaces. To bring the FLC response in-phase with the drive signal a 10 nF capacitor is connected in series with each of these cells; in addition a 300 kOhm resistor is placed in parallel with the PI 1211 cell, and a 150 kOhm resistor is placed in parallel with the 30/C14SiOx cell.

III. COMPUTER SIMULATION

To augment our experimental observations, we have performed numerical simulations of the effect of the pretilt, anchoring energy, smectic order near the surface, gliding of the easy axis, and layer deformations. The simplest continuum theory models assume bookshelf smectic layers, where the director motion is confined to a cone, and there is a single elastic constant; whereas more general models allow for layer spacing variations, chevron formation, layer curvature, varying tilt angle, multiple elastic constants, etc. As well as being influenced by surfaces, whether or not an FLC cell exhibits threshold-less switching depends on details of the director structure at the tip of the chevron as well as on elastic constants and the magnitude of the FLC’s spontaneous polarization.

Considering that we expect our deVries–like material to have an approximate bookshelf layer structure, and that our interest is in the effect of the surfaces, our model assumes a chevron-free bookshelf smectic layer structure. Also, since we want to explore the possible effect of a nematic–like region where the smectic order is reduced near the surfaces, we’ve chosen to include a free energy term relating smectic layer compression and director tilt (relative to the smectic layer normal) following the treatment by Palto. Our implementation included some simplifications along with inclusion of the effects that were not considered in the original simulation, which we discuss below.

In the method of Palto, surface stabilized FLC cell is considered with the aligning surfaces located in the XY-plane. Smectic layers with a fixed layer normal \( \mathbf{k} = (k_x, k_y, k_z) \) form an arbitrary angle with the XY-plane, and the molecules are tilted at angle \( \Theta \) (cone angle) with respect to the smectic normal \( \mathbf{k} \). FLC molecules at the surfaces are defined by the surface boundaries conditions with variable zenithal and azimuthal anchoring energies. Aligning layers have finite capacitance which plays an important role in the electro-optical switching.
Elastic energy of the chiral smectic phase is written as

$$F_1 = \frac{1}{2} \left( K_{11} (\nabla \cdot \vec{n})^2 + K_{22} (\vec{n} \cdot \nabla \vec{n} + q_0)^2 \right) + K_{33} (\vec{n} \times \nabla \vec{n} - b)^2 + K_4 \left( \cos \Theta - \vec{n} \cdot \vec{k} \right)^2. \quad (1)$$

Here, $K_{ii}$ are Frank elastic constants, $K_4$ (also frequently denoted as $B$ in other papers) describes compressibility of smectic layers related to a change in the cone angle $\Theta$, $q_0$ and $b$ describe spontaneous twist and bend of the director $\vec{n}$. For our simplified case, we set $q_0$ and $b$ equal to zero.

If the charge is fixed at the boundaries of a FLC, the electric contribution to the free energy density is $F_2 = \vec{D} \cdot \vec{E} / 2$, where $\vec{D}$ is a field-induced contribution to the total displacement $\vec{D} = \vec{D}_0 + \vec{D}_i \equiv \vec{D}_I + \epsilon \vec{E}$, $\epsilon$ is the dielectric permittivity tensor which, for a uniaxial medium, defines dielectric anisotropy $\Delta \varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$. $\vec{P}$ is spontaneous polarization. For $\vec{E} = (0, 0, E_z)$, $\vec{D}_i = (D_{xI}, D_{yI}, D_{zI})$ and $d$ is cell gap, one obtains for electric free energy density and voltage on the FLC:

$$F_2 = \frac{D_z E_z}{2} = \frac{(D_z - P_{xz})^2}{2 \varepsilon_{\perp} \left( 1 + \frac{\Delta \varepsilon}{\varepsilon_{\perp}} n_z^2 \right)}, \quad U_{LC} = \int_0^d \frac{D_z - P_{xz}}{2 \varepsilon_{\perp} \left( 1 + \frac{\Delta \varepsilon}{\varepsilon_{\perp}} n_z^2 \right)} dz, \quad (2)$$

where $P_{xz} = P_0 (k \cdot n)(k \times n)$, $P_0 = P \cos \Theta \sin \Theta$. We ignore dielectric effects, setting $\Delta \varepsilon = 0$.

Surface anchoring is determined by the balance of two torques - the elastic torque of a FLC and the surface torque due to anchoring. Equation of the torque balance is

$$\pm \frac{\partial F}{\partial \vec{n}} - \frac{\partial W}{\partial \vec{n}} = 0, \quad (3)$$

where sign depends on the surface ($z = 0$ or $z = d$). Surface anchoring energy is written in the Papoular-Rapini form, which in the problem’s geometry becomes

$$W = W_\psi + W_\zeta = \frac{1}{2} W_\psi n_\psi^2 + \frac{1}{2} W_\zeta n_\zeta^2$$

$$= \frac{1}{2} W_\psi \left( n_\psi \sin \phi_\psi - n_z \cos \phi_\psi \right)^2 + \frac{1}{2} W_\zeta \left( n_\zeta \sin \phi_\zeta - n_z \cos \phi_\zeta \right)^2 + \frac{1}{2} W_\zeta \left( n_\zeta \sin \phi_\zeta - n_z \cos \phi_\zeta \right)^2 \cos \phi_\zeta \cos \phi_\psi \sin \phi_\zeta \sin \phi_\psi \sin \zeta.$$ \quad (4)
the balance of elastic, electric and viscous torques
boundary conditions and general vector-form expression for
axis (the director components in the frame connected to the easy
pretilt. Results of the simulation are shown in Fig. 13.
Considering equivalent electric circuit of the cell, we
ignore resistance of electrodes and conductivity of the align-
ing layers. Resulting system of equations that describe cur-
rent layers. Resulting system of equations that describe cur-
rent and voltage in the equivalent circuit (shown in Fig. 12) i s
ignore resistance of electrodes and conductivity of the align-
ing layers. Resulting system of equations that describe cur-
rent and voltage in the equivalent circuit (shown in Fig. 12) i s
Here \( W_a \) and \( W_z \) are the amplitudes of the azimuthal and zenithal components of the anchoring energy, \( n_x \) and \( n_z \) are the director components in the frame connected to the easy axis (the \( x' \)-axis is the axis about which the easy axis is rotated from the cell normal, and the \( y' \)-axis is along the easy axis. The \( z' \)-axis is then in the plane of the easy axis rotation and perpendicular to the easy axis), \( \theta_a \) and \( \theta_z \) are angles that define direction of the easy axis with respect to the \( z \)- and \( x \)-axis in the lab frame (Fig. 11).

Effect of pretilt angle on the modeled characteristics of
pretilt on the switching characteristics of the V-shaped de-
vice, we simulate electro-optical response of three cells with
different alignment layers that we measured experimentally:
PI 2555, 30° SiOx and PI 7511/1211. These surfaces provide
different anchoring energies (both azimuthal and zenithal) and
pretilt. Results of the simulation are shown in Fig. 13.

B. Pretilt angle
Effect of pretilt angle on the modeled characteristics of
PI 7511/1211 cell is included in Fig. 13.

C. Surface melting
Decrease of smectic ordering near the surface can be mod-
eled by a thin nematic layer exists between aligning surface and
the smectic bulk of the cell. Here we repeat simulations for the case A, but include thin (100 nm) nematic layer at the surfaces. This is realized by eliminating compressibility
interdependence has been addressed in more details in previ-
ous papers (for example 21 and 23).

We have used parameters for the cell and the FLC mate-
rial that were similar to that used in experiment: cell thick-
ness \( d = 4 \mu m \), FLC spontaneous polarization \( P_s = 200 \) nC/cm\(^2\),
elastic constant of the FLC \( K_{11} = K_{12} = K_{33} = 5 \) pN FLC vis-
cosity \( \gamma = 0.5 \) Pa·s, cone angle of the material \( \Psi = 45^\circ \),
dielectric constants of the FLC \( \varepsilon_1 = \varepsilon_2 = 3 \), electrode area
\( A = 0.3 \) cm\(^2\), electric resistance of electrodes \( R_0 = 0 \), orienta-
tion of the smectic layer normal \( (k_x, k_y, k_z) = (1, 0, 0) \). Other
parameters, such as waveform frequency, compressibility module \( K_{ld} \), surface zenithal and azimuthal anchoring ener-
gies \( W_z \) and \( W_a \), capacitance of alignment layers \( C \) and elec-
tric resistance of the FLC \( R_{LC} \) were varied according to conditions of experiment and simulation.

Optical transmission through the FLC cell is calculated
assuming that director is homogeneous throughout the cell
(we can make this assumption due to the polarization stiffen-
ing of the smectic FLC) using well-known expression for the uni-
axial media (see, for example, formula 31 in Ref. 5). The
results of the numerical modeling considering the parameters
of the surface alignment layers are presented below. More
detailed description of the numerical solution of the equa-
tions for the director dynamics can be found in Ref. 32.

A. Zenithal and azimuthal anchoring
To investigate effect of surface anchoring energy and
pretilt on the switching characteristics of the V-shaped de-
vice, we simulate electro-optical response of three cells with
different alignment layers that we measured experimentally:
PI 2555, 30° SiOx and PI 7511/1211. These surfaces provide
different anchoring energies (both azimuthal and zenithal) and
pretilt. Results of the simulation are shown in Fig. 13.

Here \( \Lambda \) is the electrode overlapping area, \( C \) is capacitance
of alignment layers, \( U_C \) and \( U_{LC} \) are voltages across the align-
ing layers and FLC; \( D_z \) is the \( z \)-component of electric dis-
placement in a FLC with constant ohmic resistance \( R_{LC} \).

The last system of equations together with the surface
boundary conditions and general vector-form expression for the balance of elastic, electric and viscous torques

\[
\dot{\hat{n}} = -\hat{n} + \frac{d \hat{F}}{dt} + \lambda \hat{n}, \\
\hat{F} = \hat{F}_1 + \hat{F}_2,
\]

where \( \lambda \) is Lagrange multiplier (introduced for satisfying condition \( n_1^2 + n_2^2 + n_3^2 = 1 \)), presents the full set of equa-
tions which allows the calculations of time and spatial
dependencies of the director components at any voltage.

One can notice that dynamical response of the optic axis
depends on both physical parameters of the FLC and elec-
trical circuitry of the cell which are interconnected (in this
approach through \( D_z \) and \( U_{LC} \)) which may lead to the confu-
sion of what primarily affects the switching of the cell. This

FIG. 12. Equivalent electric circuit of the FLC cell.
module $K_4$ (which is responsible for maintaining of the smectic ordering) for the layers next to the surfaces. Obtained results do not significantly change from the case A for 30° SiOx and PI 7511, but a noticeable effect on the shape of V is observed for the case of PI 2555 (Fig. 14). We assumed that nematic layer near the surface only affects visco-elastic properties of the liquid crystal, but does not affect electric properties of the cell, such as capacitance.

D. Effect of layer expansion

Observation of characteristic undulations of the smectic layers for some cells during switching may suggest change in layer spacing that occurs during rotation of the director. Variation of the smectic layer thickness requires additional work, amount of which is proportional to the compressibility module $K_4$ (or $B$, as it more frequently denoted). In smectic materials this elastic module is typically quite large, $\sim 10^6 - 10^7$ J/m$^3$, therefore considerable smectic layer thickness change does not occur in the conventional smectic devices. Very strong zenithal surface anchoring may overcome condition for the constant smectic layer thickness which would lead to layer thickness change and appearance of undulations of the smectic phase. Here we try to simulate this scenario and see if it can occur given the reasonable values of the $K_4$ and $W_z$ (zenithal anchoring energy). We start by setting reasonably high zenithal anchoring energy ($W_z = 1$ mJ/cm$^2$) and watch the motion of the director. Figure 15 shows angle of the director with respect to the vertical axis $z$ (director tilt from the plane of the cell) during switching cycle depending on the value of $K_4$. It is clear that behavior of the director has threshold character and is sensitive to the value of $K_4$. Critical value of compressibility module for the set of used parameters which makes director slide on the surface instead of moving on the cone is $\sim 2 \times 10^3$ J/m$^3$, which is at least three orders of magnitude smaller than typically observed values.

E. Easy axis gliding

In this case we take into account gliding of the surface’s azimuthal easy axis. It has been shown that for the nematic phase that easy axis can ‘glide’ along the surface following bulk director due to effective ‘surface viscosity’ $\gamma_s$ of the easy axis. Different mechanisms of the surface viscosity has been reported; most frequently easy gliding is related to the anisotropic adsorption/desorption of the liquid crystal molecules on the surface. Characteristic times of this gliding are usually very high - from minutes to days. Not considering the nature of the surface viscosity, we incorporate it as a simple way to model easy axis gliding.

We assume that the easy axis will move to lower the surface energy $W=W_s \sin^2 \Delta \phi$, where $\Delta \phi$ is the difference between the azimuthal director at the surface and the azimuthal easy axis. It has been shown that for the nematic $\Delta \phi = \sin \theta$ and $\Delta \phi = \theta$. We may say that the torque on the easy axis due to the anchoring energy ($2W_s \sin \Delta \phi \cos \Delta \phi$) is balanced by a viscous torque $\gamma_s \frac{d\phi}{dt}$:

$$2W_s \sin \Delta \phi \cos \Delta \phi = \gamma_s \frac{d\phi}{dt}.$$  

Change of the easy axis position $d\phi$ is calculated from this torque balance, and the speed of the gliding is related to the value of surface viscosity $\gamma_s$. Simulation of the effect of $\gamma_s$ on V-shaped switching is presented in Fig. 16.
Additionally, we simulated the effect of the FLC conductivity (or, equivalently, effect of the resistance connected parallel to the FLC cell) and the capacitance of the alignment layers (or the capacitance connected in series to the FLC cell) on the frequency dependence of the V-shaped response. We attempted to simulate the experimental results for the 30° SiOₓ cell (Fig. 10 top) and were able to obtain simulated V-shaped response for the waveform frequency of 60 Hz with external capacitor of 10 nF and external resistance of 200 kOhms (Fig. 17).

IV. DISCUSSION

Generally, as previously shown by O’Callaghan, the shape of V response depends on both the capacitance of the cell with wiring around it and on the surface anchoring if the FLC. In comparing Fig. 3, the data for a PI2555 cell, with Fig. 5 or 7 that are from a 30° SiOₓ cell and one that uses homeotropic alignment layer, we can see that in Fig. 3 that the V-shape is narrower, and that in Fig. 7 it is the widest. These characteristics are reproduced in Fig. 13 using our modeling algorithm with the input parameters shown in the figure caption. However there are two issues that we feel are related.

One is that to obtain the difference between the widths of the V’s in Figs. 13(a) and 13(b), we find the main parameter that needs to be changed is the capacitance of the alignment layer that was changed by a factor of 1.54 in this case. In Ref. 5 it is shown that if the anchoring energy is neglected the width of the V should be \[ \frac{2}{\kappa C_A} \text{,} \] where \( C_A \) is the capacitance of the alignment layer. The ratio of the capacitances used to obtain the desired width of the Vs, turns out to be nearly identical to the ratio of the width of the Vs. This indicates that the effect of the anchoring energy, while significant, cannot explain the large ratio of the width of the Vs seen in the data. So this analysis points toward a change in the capacitance of the alignment layer. The ratio of the capacitances used to obtain the desired width of the Vs, turns out to be nearly identical to the ratio of the width of the Vs. This indicates that the effect of the anchoring energy, while significant, cannot explain the large ratio of the width of the Vs seen in the data. However there are two issues that we feel are related.

However, another point is that while the modeled results of Fig. 13 show that the base of the V goes to zero intensity, this is most noticeably not the case for the data from the PI2555 cell (Fig. 3). Further, the pictures shown in Fig. 3 of the microscope image taken when the transmission is minimized do not show a uniform dark texture, but rather a granular gray texture.

This observation and the inability of our model to predict the narrow width of the V seen in Fig. 3 by increasing the anchoring energy alone, both point to the need to consider domain formation in the PI 2555 cell.

As the focus of this paper was domain-less uniform switching, rather than V-shaped switching in general, we have used a one-dimensional model, which cannot directly explain results related to domain formation; however, we can qualitatively provide an explanation. In one dimension, for the polarization to balance the effect of a small amount of applied charge, the director needs to rotate away from being in the plane of the cell (where the anchoring energy is minimized) to the extent where the projection of the polarization normal to the cell causes the electric field produced by the applied charge to be reduced to zero. So for the polarization to reduce the
electric field, the energy associated the polar anchoring energy is increased. However, in a 2D model, or where domains are allowed, the relative area of “up” or “down” domains can vary to allow for the net polarization to balance the effect of the applied charge, while at the same time having the director everywhere in the plane of the cell and thereby minimizing the anchoring energy contribution to the total energy. So, when considering a cell with domains, the energy associated with the anchoring may not be important in determining the width of the V. Generally, our 1D model correctly reproduces director dynamics only for the devices with the uniform director rotation and the absence of the domains; quantitative modeling of the V-shaped switching with the domains requires implementation of more complicated 2D model.

About the optical transmission, it may be clear that if there is no domain formation, and if the director is uniform in the cell, then when the net polarization is zero the director will be substantially tipped away from the plane of the cell and will be in a plane that contains the cell normal and the layer normal. With this director orientation, the optical transmission of the cell will be zero if it is between crossed polarizers aligned parallel and perpendicular to the projection of the layer normal onto the plane of the cell. However, if there is domain formation, when the net polarization can be zero by having the directors in half of the area of the cell oriented so that the z-component of the polarization is pointing “up” and the other half oriented so it is pointing “down”. In this case the optical transmission would not be zero, as we observe.

So, while our model predicts V-shaped switching for alignment layers that have a strong polar anchoring energy [Fig. 13(a)], the V-shaped switching observed for an alignment layer with strong polar anchoring (Fig. 3) apparently is not due to uniform director rotation in the cone. In this case, even though we optically observe a V-shaped switching, the device may not be useful for applications where a uniform optic axis orientation is needed.

In Table II, we summarize properties of some of the alignment surfaces along with the tendencies of domain switching. $W_a$ is the zenithal anchoring energy for the case of in-plane director configuration, $\theta$ is the pretilt angle (measured for the nematic LC).

We can expect to have the smallest tendency for domain switching for the case of homeotropic anchoring [simulated PI 7511 cell, Fig. 13(c)], where simulations have shown that such anchoring conditions lead to the widest “V” and smooth, analog switching. Experimentally, cells with the homeotropic aligning surface PI 7511 showed the best analog switching among all tested surfaces (Fig. 7).

Considering the effect of a nematic layer, strong deformations of the smectic director field suggest substantial lowering of smectic ordering in the close vicinity of the surface, effectively leading to appearance of the nematic layer, the thickness of which according to different estimates, can vary from few nanometers to hundreds of nanometers.13,14 Results of the simulations may suggest that having a melted layer next to the surface affects switching of the cells, with strong surface anchoring, by ‘softening’ this anchoring and effectively lowering the surface energy. For lower anchoring energies, this effect is weaker. The simulated response of ‘PI 7511/1211’ and ‘30° SiO₂,’ cells were not substantially affected by the inclusion of a 100 nm nematic layer. However it may not be accurate to infer from this result that there is no nematic layer present, as the effect of reduced order at the surface may have been taken into account by the lower value of the anchoring energy parameter used. Another effect caused by a nematic layer can be adjustment of the surface alignment layer capacitance value, as some part of the liquid crystal close to the surface does not take part in switching and therefore can be considered as dielectric surface layer. It is difficult to estimate the thickness of such layer accurately, but if it decreases capacitance of the alignment layer by 25%, this can lead to considerable widening of the V (≈40%). Additional experiments with variation of surface roughness and its effect on V width can be the subject of future work and clarify this question.

Considering the case of smectic layer expansion (presumably leading to appearance of the surface undulations), the simulation has shown that values of compressibility module $K_1$ that allow surface anchoring to compete with smectic elasticity are at least three orders of magnitude lower than typical measured values. It may mean that this scenario is unlikely to take place, unless we assume a very strong decrease of $K_1$ due to reduced smectic ordering near the surface.

Considering the case of easy axis gliding, we have found that values of surface viscosity that considerably affect switching start at $10^{-4}$ Js/m$^2$, which is at least three orders of magnitude lower than typical measured values. However, one may speculate that in the case of smectic

<table>
<thead>
<tr>
<th>Aligning surface</th>
<th>$W_a$, mJ/m$^2$</th>
<th>Pretilt $\theta$</th>
<th>Domain switching tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI 2555</td>
<td>1</td>
<td>~1°</td>
<td>Strong</td>
</tr>
<tr>
<td>Glymo</td>
<td>$10^{-1}$–1</td>
<td>0°</td>
<td>Moderate</td>
</tr>
<tr>
<td>30° SiO₂</td>
<td>$10^{-2}$</td>
<td>0°</td>
<td>Weak</td>
</tr>
<tr>
<td>PI 7511/1211</td>
<td>$10^{-1}$</td>
<td>~90°</td>
<td>Very Weak</td>
</tr>
</tbody>
</table>
distortion of the director field near the surface is very high and the torque transferred from the bulk to the surface layer is much stronger than in nematic, which may explain higher easy axis gliding rates for smectic liquid crystals.

Finally, considering the effect of waveform frequency on V shaped response, results of the simulation of the effect of the waveform frequency on the optical response (Fig. 17) agree with the results of experiment (Fig. 10 top) except for the value of resistance connected to the cell (150 kOhms vs 200 kOhms). This discrepancy can be explained by the fact that the conductivity of FLC is strongly temperature dependent and also is affected by the mobility and concentration of the ions in the cell. However, while the hysteresis-free V-shaped switching with voltage drive at a particular frequency is an interesting effect, the important point about threshold-less analog switching is that there is a predictable relationship between the drive level (voltage or charge) and the response.

Throughout the paper we assumed bookshelf structure of the SmC phase. Although the used material has some layer shrinkage (~7% as shown by x-ray diffraction measurements in Ref. 20), the obtained results allow us to suggest the validity of the assumption. However, including effect of the chevron in the simulation can be a subject of the future work, as chevron structure leads to the switching bistability.

We would also like to note that numerical approach taken in this paper has a good agreement not only with the observed experimental data, but also with the other approaches to the V-shaped switching problem, such as analytical approach of O’Callaghan.5 For a check, we looked at the analytical expression for the saturation voltage, which corresponds to the full rotation of the FLC molecules (maximum transmission in the case of the cell between crossed polarizers).

V. SUMMARY

In this work we investigated effect of the alignment layer on characteristics of director rotation and analog switching of a ferroelectric liquid crystal that exhibits an I-A-C phase sequence and reduced layer shrinkage. We found that alignment layers that do not provide a strong tendency to hold the director in the plane of the cell are the most appropriate. Homeotropic alignment layers lead to the best analog switching with most uniform director configuration and good contrast ratio, while alignment layers that provide low pretilt alignment and stronger anchoring, lead to domain switching. The reasons for the best analog response of the cells with homeotropic alignment layers are low tendency for domain formation, weak polar anchoring and also the lower capacity of the alignment layer.

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29For this material, R_0 = 0.57 (coefficient describing ‘deVries-ness’ of a smectic liquid crystal that depends on layer spacing and tilt angle), and its ratio of chevron angle to tilt angle is R_0 = 0.66. Definitions of these measures can be found in the Ref. 20.
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