Short pitch cholesteric electro-optical device based on periodic polymer structures

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The helical flexoelectro-optic effect produces a submillisecond, temperature-independent in-plane rotation of the optical axis and is potentially interesting for the display industry. The main drawback is that it relies on a texture, the uniform lying helix (ULH), which is intrinsically unstable. We present a method based on the use of periodic polymeric microchannels to create highly ordered and stable ULH structures. Electro-optic measurements performed on a test device show a large contrast ratio between bright and dark states (better then 100:1), fast switching (200 μs), and large optical rotation (>30°). © *2009 American Institute of Physics*. [DOI: 10.1063/1.3159624]

The flexoelectro-optic effect in chiral nematic liquid crystals, first described by Patel and Meyer[1] in 1987, is the macroscopic tilt of the optic axis of a uniform lying helix (ULH) cholesteric (i.e., a cholesteric with the helix axis uniformly parallel to the device substrates) in the plane of the cell under the action of an electric field applied normal to the cell glass plates. The tilt ϕ of the optic axis is predicted[1,2] and experimentally found[1,3] to vary linearly with the applied field E. If the tilt ϕ is assumed constant throughout the cell, it can be shown that

$$\tan \phi = \frac{ep}{2\pi k} E, \tag{1}$$

where p is the cholesteric pitch, e is the mean flexoelectric coefficient,[1] and k is an average elastic constant associated to the deformation of the nematic director.

The linear regime of the flexoelectro-optic effect in a chiral nematic is in general limited by the distortion induced in the cholesteric texture by the dielectric coupling with the electric field.[4] An appropriate design of the liquid crystal (LC) molecules can substantially increase the range of linearity.[2,5] In the past 10 years, a considerable improvement has been made in this direction and new LC mixtures have been synthesized based on the use of bimesogenic molecules.[6–8] The use of such materials has extended the linear range of the flexoelectric effect to angles as large as 30°,[9] allowing within the linear regime, full modulation between dark and bright states, which is achieved with a rotation ϕ such that 2ϕ=45°.

Linear effects in LCs are quite rare and potentially very interesting since they allow fast changes in the optical state.[10] The case of the chiral flexoelectro-optic effect is particularly interesting since it is also temperature-independent.[11] This makes the flexoelectro-optic effect in chiral nematics potentially useful for applications such as wide viewing angle displays with gray-scale possibility or submillisecond light shutters.

On the other hand, a severe problem for the exploitation of the flexoelectro-optic effect in chiral nematics is that it relies on the use of an unstable texture, the ULH. Not only is the ULH nontrivial to create since it is compatible with neither the planar nor homeotropic surface conditions but even when an ordered ULH is created, it can be irreversibly damaged by factors such as dielectric coupling, phase transitions, and mechanical stress. Several methods have been proposed to overcome this problem but a viable solution has still to be found.

In order to stabilize the ULH texture, the use of reactive mesogens has been proposed to create a polymeric structure that locks the cholesteric into the ULH texture.[12–14] The use of an appropriate concentration of reactive mesogens leads to stability of the ULH without having deterioration in the tilt magnitude or the switching speed. Nevertheless, this method relies on the good quality of a pre-existing ULH texture. This is usually done by mechanical shearing of the substrates in order to induce a flow while applying a moderate electric field through the cell to uniformly align the helix axis in the plane of the device but this can only be done to align chiral nematics with positive dielectric anisotropy. Moreover, it is not viable to align devices in this way for industrial applications. The use of a surface showing periodic (horizontal/vertical) anchoring conditions has also been used to produce ULH alignment.[15] Even though the idea is very interesting and allows the creation of a ULH without complex procedures such as mechanical shearing, the resulting ULH structure does not show good stability during thermal cycling, which is essential for practical applications. Moreover, since an electric field needs to be used to favor the ULH over other less ordered textures (such as focal conic textures), it can only be used for positive dielectric anisotropy materials.

In this paper, we present an alternative approach to solve the problem: rather than preventing the ULH to relax to a lower energy texture, we impose confining conditions, which allow the ULH as the lowest energy texture. This is obtained by using periodic polymer walls to break the in-plane translational symmetry while imposing perpendicular alignment of the LC molecules on all the confining surfaces. In this geometry, the cholesteric helix can only orient along the polymer channels. The creation of the polymer microchannel is based on the polymer liquid crystal polymer slides

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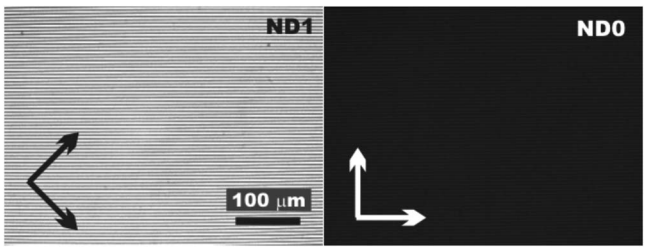

FIG. 1. Cholesteric filled periodic polymeric microchannel observed with a polarizing microcope. The optical axis is oriented (a) 45° and (b) 0° with respect to the polarizer.

(POLICRYPS)[16] method and involves a physical-chemistry multistep process, which will be reported elsewhere. This process results in a series of side-by-side microchannels with a very sharp morphology and within each channel the cholesteric orients along the microchannels.

Based on the latter approach, we engineered a device using a chiral nematic LC, which consists of a bimesogenic mixture (Merck) doped with ~2% of R5011 (Merck), a chiral dopant with large helical twist power. The mixture resulted in a chiral nematic with a pitch $p \approx 330$ nm.

The choice for the value of the pitch is the trade-off between large rotation of optical axis and fast switching speed. In fact, as predicted by Eq. (1), larger tilt angles ϕ are promoted by using long pitch.[1] On the other hand, faster switching speeds are achieved using short pitch

$$\tau = \frac{\gamma p^2}{4\pi^2 k}, \tag{2}$$

where τ is the switching time and γ is the effective viscosity associated with the tilt of the director within the helix and is approximately equal to the twist viscosity γ_1.[17]

Due to the small index contrast between polymer and LC, the device is expected to produce diffraction of the incident light. In the past, a theoretical model[18] based on Kogelnik's idea[19] has been implemented to predict the diffraction efficiency (η) of the POLICRYPS gratings. The approach yields the expression $\eta = \sin^2[\Phi(T,L,\lambda)]$, where the phase Φ is a function of the grating thickness L, the probe wavelength λ, and temperature T. η is therefore a periodic function of the phase Φ. The value of L has been chosen to obtain a very low efficiency grating since for this application, the grating should ideally transmit all the impinging light. The evaluation has been carried out by means of the commercially available GSOLVER software,[20] which exploits a rigorous coupled wave analysis.[21] Experimentally, we observe a diffraction efficiency smaller than a few percent.

Using a polarizing microscope, we verified that once realized, the cell acts as a uniaxial retardation plate with its optical axis parallel to the direction of the microchannels. The optical contrast between dark and bright is quite large (see Fig. 1), better than 100:1 for white noncollimated light, thanks to the very good quality of the dark state, which reflects the good ULH alignment. The stability of the texture was tested by applying large electric fields as well as performing temperature cycles across the nematic-isotropic phase transition. The quality of the ULH alignment was not affected by either of these.

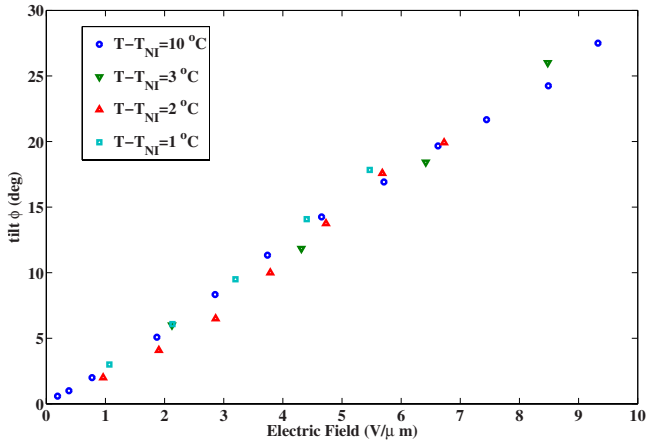

FIG. 2. (Color online) The tilt ϕ of the optical axis as a function of the applied voltage for four shifted temperatures. The tilts show linear increase with the applied field without temperature dependence.

In order to perform electro-optic characterization, the sample was placed in a micro-oven (instec HCS412W, which allowed temperature control within 0.01 °C) and then mounted on the rotating stage of an optical setup where the light of a He–Ne laser ($\lambda = 632.8$ nm) passes through a polarizer A, the sample, a polarizer B, whose optical axis is crossed with respect to A, and is finally detected by a photodiode. A function generator (Wavetek 395) and a 10x power amplifier (FLC Electronic) were used to apply an ac voltage across the device. Both the voltage applied to the cell and the signal coming out from the photodiode were monitored on a digital oscilloscope used to both visualize and record the signal.

A measurement of the maximum tilt ϕ of the optical axis as a function of the applied voltage V_{in} was performed. For each temperature T and each value of the applied voltage V_{in}, the mean intensity $\bar{I}$, measured by the photodiode, was recorded for $\theta = 22.5°$, where θ is the angle between the polarizer and optical axis of the device at zero field. Because of the ac electric field applied to the device, the optical axis oscillates around its direction at zero field and the intensity measured by the photodiode is an ac signal oscillating between I_{max} and I_{min}. If θ is rotated, I_{max} and I_{min} change. In order to measure ϕ, θ was first rotated so that the I_{max} reaches the value measured for $\bar{I}$ at some value of $\theta = \theta_{max}$ and then in the opposite direction so that the I_{min} reaches the value measured for $\bar{I}$ at some value of $\theta = \theta_{min}$. The tilt ϕ of the optical axis was then evaluated as $2\phi = \theta_{max} - \theta_{min}$. Figure 2 shows the tilt ϕ as a function of the applied voltage for several shifted temperatures. As expected from Eq. (1), the tilt increases linearly with the applied field and no temperature dependence is observed, which reflects a temperature independence of the helical pitch. The values of the tilt are smaller than expected for this material.[22] This is probably due to the constrained geometry caused by the microchannels. Even for a regular cell, it is well known that anchoring and confinement effects tend to decrease the flexoelectric tilt.[9,23] A detailed study of the effect of confinement in these systems will be carried out elsewhere.

The switching times τ as a function of the applied field for different shifted temperatures are shown in Fig. 3. τ was measured as the time required for the transmitted intensity to change from 10% to 90% of the peak to peak amplitude after

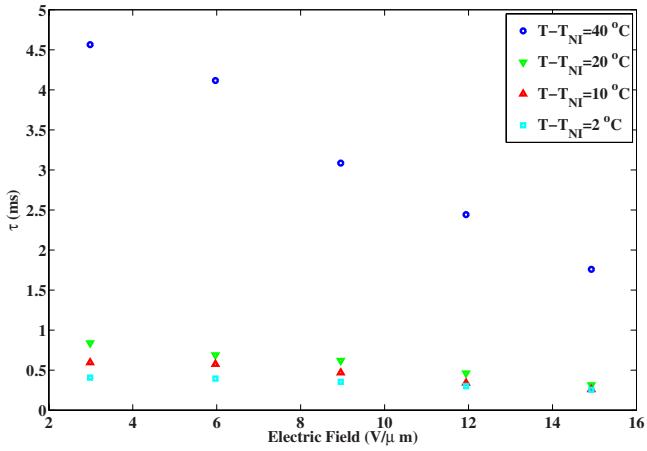

FIG. 3. (Color online) Switching time as a function of the applied field for different shifted temperatures.

field polarity reversal of a square wave with $\theta=22.5°$. The values of τ show a strong dependence on temperature, mainly due to the temperature dependence of γ. From Fig. 3 it is clear that τ also depends on the electric field. Even though this is not predicted by the theory,[1] it is often observed in experiments.[6,14,23]

To conclude, we have presented a method based on the use of periodic polymeric microchannels, which allows the creation of highly ordered and stable ULH structures. The ULH is shown to be stable under the application of large electric fields and temperature cycling through phase transitions. A unique characteristic of this method is that it has the potential to be applicable to any cholesteric material regardless of the dielectric anisotropy since the creation of the ULH structure does not rely on dielectric properties but rather on surface coupling. The electro-optic characterization of a device constructed using this method shows tilts of the optical axis that are large enough to produce full modulation between dark and bright states, switching times on the order of ~ 100 μs, and a large contrast ratio between dark and bright states.

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