Linear electro-optic effect in a cholesteric liquid crystal

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J. Patel and R. B. Meyer [Phys. Rev. Lett. **58**, 1538 (1987)] found an electro-optic effect in a cholesteric layer with a unidirectionally aligned helix axis, when an electric field was applied normal to it. The effect is flexoelectric in origin and exhibits a linear behavior in the electric field, at least for low fields, where the dielectric coupling between the liquid crystal molecules and the applied field can be neglected. At high fields, however, the electro-optic response might considerably deviate from the linear character due to the field-induced helix unwinding. We have extended the study, both experimentally and theoretically, to take the dielectric phenomena into account. We do this by investigating the electro-optic response in the case of a field-dependent helix profile, making not only the optic axis direction but also the basic optical parameters strongly field dependent. Computer simulations of the electro-optic response, performed on the basis of this model, show an excellent agreement with the experimental results. This means that the combination of flexoelectric and dielectric coupling is sufficient to describe satisfactorily the physics of this electro-optic effect up to reasonably high fields. We finally address the question: How may the region of linear response be extended further by the design of new materials?

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INTRODUCTION

The chiral nematic phase, as known, is characterized by a helical order of molecules, which can be described by two parameters: the spatial period (pitch) and the sense of the helix handedness. In general, in geometries such as the conventional sandwich cells, depending on the surface–liquid crystal interactions, the chiral nematic layer can adopt *Grandjean* or *fingerprint* texture, with the helix axis oriented perpendicular or parallel, respectively, to the confining substrates. The irregular fingerprint texture can be transformed by unidirectional mechanical shearing of the cell substrates into a uniformly aligned stripelike texture, with the helix axis lying everywhere along a unique direction parallel to the substrates. The stripes are then oriented along the direction of shear with the unique helix axis perpendicular to the shear. The optical properties of such a texture are discussed in [2]. A short pitch cholesteric layer with homogeneous stripe texture behaves macroscopically as a uniaxial birefringent crystal plate with its optic axis along the helix. Indeed, on rotating the sample between crossed polarizers, a full extinction of the transmitted light will be achieved when the helix axis coincides with the transmission direction of one of the polarizers. If an electric field is applied across the layer, an in-plane deviation of the effective optic axis may occur, an effect described by Patel and Meyer [1]. The deviation was found to be linear in the applied field. Moreover, a relation between the sense of the field-induced deviation of the optic axis and the helix handedness was found [3]. Increasing the field, however, involves a quadratic effect due to the dielectric coupling. The helix then deforms at the same time as the pitch increases. Finally, when the field exceeds a certain value E_c, the helix is completely unwound.

In this work we investigate both theoretically and experimentally the influence of this field-induced helix unwinding on the character of the electro-optic response.

THEORY

Consider a uniformly aligned chiral nematic layer with the helix axis oriented parallel to the sample substrates (so-called stripe texture) in a right-handed coordinate system, as shown in Fig. 1. The helical ordering of the molecules in the layer is expressed by

$$\begin{aligned} n_x &= 0 , \\ n_y &= \cos\theta(x) , \\ n_z &= \sin\theta(x) , \end{aligned} \tag{1}$$

where θ is the angle between the director **n** and the y axis and is a periodic function of x. The position $x=0$ is defined to be any point where $\theta=0°$ or 180°. Thus, the

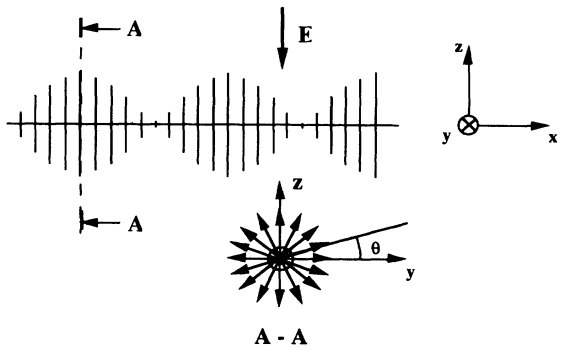

FIG. 1. Reference system used in the calculations of the helical pitch. The lower figure shows successive planes (parallel to *A-A*) along x.

helical pitch p_0 is considered to be the distance corresponding to a rotation of the director by 180°. An electric field is applied across the layer in a direction normal to the helix and along the z axis. The free energy density of the layer is

$$f = f_{\text{el}} + f_{\text{flex}} + f_{\text{diel}} , \tag{2}$$

where

$$\begin{aligned} f_{\text{el}} &= \frac{1}{2}\left\{K_{11}[\nabla\cdot\mathbf{n}]^2 + K_{22}\left[|\mathbf{n}\cdot\nabla\times\mathbf{n}| - \frac{\pi}{p_0}\right]^2 \right. \\ &\quad \left. + K_{33}[\mathbf{n}\times\nabla\times\mathbf{n}]^2\right\} , \\ f_{\text{flex}} &= -\{e_s\mathbf{E}\cdot\mathbf{n}(\nabla\cdot\mathbf{n}) - e_b\mathbf{E}\cdot(\mathbf{n}\times\nabla\times\mathbf{n})\} , \\ f_{\text{diel}} &= -\frac{\Delta\varepsilon}{8\pi}[\mathbf{E}\cdot\mathbf{n}]^2 \end{aligned} \tag{3}$$

are the elastic, flexoelectric, and dielectric parts, respectively. Let us first, for simplicity, discuss separately the cases where either flexoelectric or dielectric coupling is dominating.

Flexoelectric coupling

If the molecules possess, in addition to a permanent dipole moment, a shape asymmetry, then splay or bend deformations will polarize the nematic liquid crystal since the deformation favors a polar ordering of the molecules corresponding to the molecular shape. This effect works also in the opposite direction. An applied electric field may induce splay and/or bend deformations in the nematic liquid crystal by orienting the permanent dipoles. The effect was first described by Meyer [4] and later named the flexoelectric effect [5].

The most general form of the flexoelectric polarization density in nematics is given by [5]

$$\mathbf{P}_{\text{flex}} = e_s\mathbf{n}(\nabla\cdot\mathbf{n}) - e_b(\mathbf{n}\times\nabla\times\mathbf{n}) , \tag{4}$$

where e_s and e_b are the splay and bend flexoelectric coefficients, respectively. The flexoelectric part of the free energy density is then

$$f_{\text{flex}} = -\mathbf{E}\cdot\mathbf{P}_{\text{flex}} , \tag{5}$$

and we get for the free energy density in the absence of dielectric coupling ($\Delta\varepsilon = 0$),

$$f = \frac{1}{2}\left\{K_{11}[\mathbf{n}(\nabla\cdot\mathbf{n})]^2 + K_{22}\left[|\mathbf{n}\cdot\nabla\times\mathbf{n}| - \frac{\pi}{p_0}\right]^2 + K_{33}[\mathbf{n}\times\nabla\times\mathbf{n}]^2\right\} - \{e_s\mathbf{E}\cdot\mathbf{n}(\nabla\cdot\mathbf{n}) - e_b\mathbf{E}\cdot(\mathbf{n}\times\nabla\times\mathbf{n})\} . \tag{6}$$

If e_s and e_b have opposite signs or have very different magnitudes, a domain texture with alternating splay and bend regions may occur. Such a periodic pattern of stripes of splay and bend deformations is easily achieved in a chiral nematic liquid crystal just by rotating each molecule along a certain direction perpendicular to the helix axis. When all molecules turn around an axis collinear with the electric field, this corresponds to the same rotation of the effective optic axis of a short-pitch cholesteric. Patel and Meyer calculated the field-induced deviation $\phi(E)$ of the optic axis, due to flexoelectric effect, to be

$$\phi(E) = \arctan\left[\frac{e_f E p}{\pi K}\right] . \tag{7}$$

Here e_f is the average flexoelectric coefficient, E is the applied electric field, p is the pitch, and K is the elastic constant for splay and bend deformations in the one-constant approximation ($K_{11} = K_{33} = K$). The arctan function is sufficiently linear for all ϕ values ($0 < \phi < 22°$) to be of practical interest, an issue to be further discussed later. Consequently, the electro-optic effect seems to be linear for low fields where the dielectric coupling between the field and the molecules can be neglected. However, in reality, it is very difficult to find a material with $\Delta\varepsilon = 0$. Therefore, one has to take into account the dielectric effects at high fields. The dielectric contribution may become quite pronounced and the linear response strongly distorted when $\Delta\varepsilon \neq 0$, as we shall see later.

Dielectric coupling

The free energy of the chiral nematic layer over one period of the pitch, taking into account only the dielectric coupling ($e_s = e_b = 0$), is given by [6]

$$\frac{F(p)}{A} = \frac{K_{22}}{2}\int_0^p dx\left\{\left[\left|\frac{d\theta}{dx}\right| - \frac{\pi}{p_0}\right]^2 - \frac{1}{4\pi}\frac{\Delta\varepsilon}{K_{22}}E^2\sin^2\theta\right\} , \tag{8}$$

where A is the area of the sample in the y-z plane, assumed to be a constant, p_0 is the pitch at $E = 0$, K_{22} is the twist elastic constant, and $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$ is the dielectric anisotropy of the liquid crystal material. The applied electric field tends to align the liquid crystal molecules unidirectionally (which will deform the helix profile, changing it from a pure sinusoidal to a more square-wave-like form [6,7]), and at the same time lengthen the pitch. Thus, the pitch p becomes a field-dependent quantity and is given by

$$\frac{p}{p_0} = \frac{4}{\pi^2}E_1(k)E_2(k) , \tag{9}$$

where E_1 and E_2 are the complete elliptic integrals of the first and second kind, respectively. For electric fields approaching a certain value E_c, the pitch diverges and at E_c the helix is totally unwound. This "critical field" for total unwinding is found to be [6]

$$E_c = \left[\frac{4\pi K_{22}}{\Delta\varepsilon}\right]^{1/2} \frac{\pi^2}{2p_0} , \tag{10}$$

where K_{22} is the elastic constant for twist deformations. The helix profile can be estimated, cf. Fig. 2, as a function of the applied field [7] from

$$x = \frac{2p_0}{\pi^2} k \frac{E_c}{E} \int_0^{\theta_x} \frac{d\theta}{\sqrt{1-k^2\sin^2\theta}} , \tag{11}$$

where θ_x is the angle for a certain value of x, and k is an integration constant which can be calculated numerically [6] as a function of E/E_c from

$$k = \frac{E}{E_c} \int_0^{\pi/2} d\theta \sqrt{1-k^2\sin^2\theta} . \tag{12}$$

The field-induced deformation of the helix will, of course, change the birefringence of the sample. In order to avoid any complications arising from the light diffraction by the periodic stripe texture, let us consider a short-pitch material in the limit where the pitch is less than the wavelength of the light. Such a layer behaves macroscopically as a uniaxial birefringent crystal plate with its optic axis along the helix axis, and the layer birefringence is defined as

$$\Delta n = n_{\parallel}^{\mathrm{OA}} - n_{\perp}^{\mathrm{OA}} . \tag{13}$$

$n_{\parallel}^{\mathrm{OA}}$ and $n_{\perp}^{\mathrm{OA}}$ are the *macroscopic* refractive indices for the waves with their planes of vibration parallel and perpendicular to the *macroscopic optic axis,* i.e., *helix axis,* respectively. $n_{\perp}^{\mathrm{OA}} = (\varepsilon_{\perp}^{\mathrm{OA}})^{1/2}$ is a function of the helix profile and can be estimated by calculating the θ-dependent *microscopic* effective dielectric component $\varepsilon_{\mathrm{eff}}$, which is varying along the helix as

$$\varepsilon_{\mathrm{eff}}(x) = n_{\mathrm{eff}}^2(x) = \frac{n_e^2 n_o^2}{n_e^2\sin^2\theta(x) + n_o^2\cos^2\theta(x)} , \tag{14}$$

and then taking the average over one period of the pitch to get

$$n_{\perp}^{\mathrm{OA}} = \left[\frac{1}{p}\int_0^p \varepsilon_{\mathrm{eff}}(x)\,dx\right]^{1/2} . \tag{15}$$

n_o and n_e are the *microscopic* refractive indices with respect to the *director,* corresponding, respectively, to the ordinary and extraordinary refractive indices. But, $n_{\parallel}^{\mathrm{OA}}$ is equal to n_o. Hence, the layer birefringence reads as

$$\Delta n = n_o - n_{\perp}^{\mathrm{OA}} . \tag{16}$$

The relative change in Δn as a function of E/E_c is shown in Fig. 3. Consequently, at strong dielectric coupling (large $\Delta\varepsilon$ and/or high fields) the pitch p and the birefringence Δn cannot be considered anymore as constant quantities.

Flexoelectric and dielectric coupling

At high enough electric field, the dielectric moment might become of the same order as the flexoelectric one. However, according to Patel and Meyer, the flexoelectric deformation tends to maintain the helical order in the layer, while the dielectric coupling tends to unwind the helix. Therefore, the critical field for total unwinding is modified by the flexoelectric effect and is calculated to be [1]

$$E_c = \frac{\pi^2}{2p_0}\left[\frac{4\pi K_{22}}{\Delta\varepsilon - \pi^3 e_f^2 K_{11}^{-1}}\right]^{1/2} . \tag{17}$$

Notice that, due to flexoelectric coupling, the critical field increases.

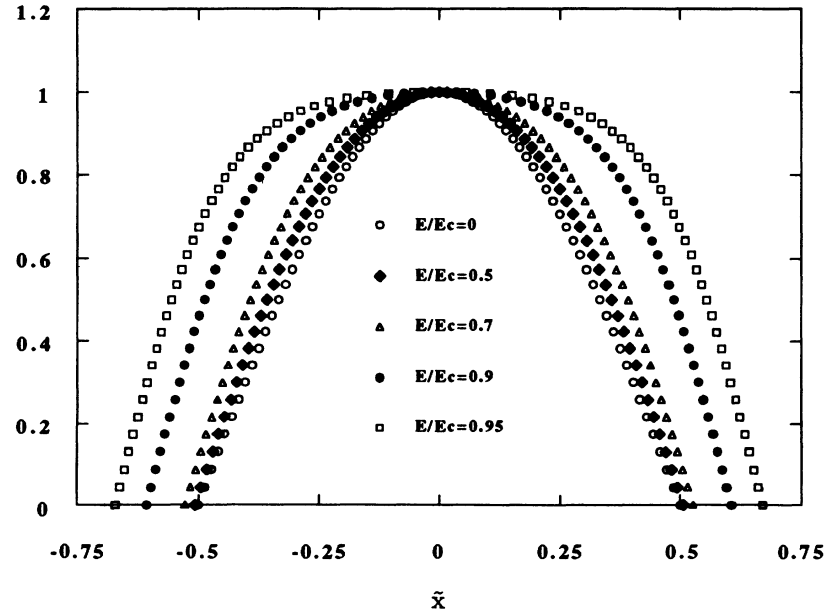

FIG. 2. Distortion of the helical pitch under the applied electric field E/E_c. $\tilde{x}$ is equal to $[x - 0.5p(E/E_c)]p_o^{-1}$.

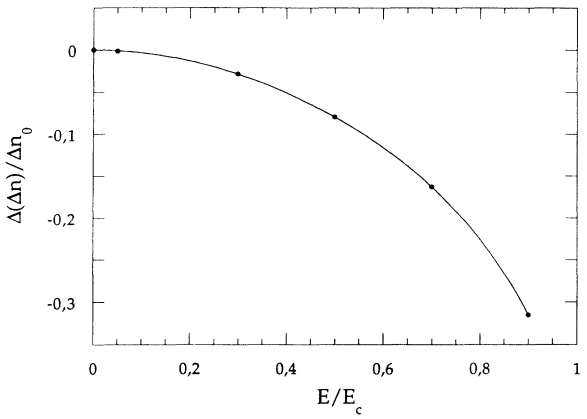

FIG. 3. Field dependence of $\Delta(\Delta n(E))/\Delta n(E=0)$, given by (24). The points are taken from the theoretical dependence given by (16).

Electro-optic response

Let us consider a short-pitch cholesteric layer, with a uniformly aligned helix axis, inserted between two crossed polarizers. The helix axis, being the optic axis of the layer, lies in the polarizer's plane. In general, the transmitted light intensity through such a sample is [8]

$$I=I_0 \sin^2(2\Psi)\sin^2\left[\frac{\pi d}{\lambda}\Delta n\right], \tag{18}$$

where I_0 is a constant, depending on the incident light intensity and polarizer quality, Ψ is the angle between the direction of the first polarizer and the optic axis of the sample, λ is the wavelength of the incident light in vacuum, d is the thickness of the sample, and Δn is the birefringence defined in (13). With Ψ set to any fixed value Ψ_0, a deviation of the optic axis in the layer plane will now cause a modulation of the transmitted light intensity given by

$$I=I_0 \sin^2\{2[\Psi_0+\phi(E)]\}\sin^2\left[\frac{\pi d}{\lambda}\Delta n\right], \tag{19}$$

where $\phi(E)$ is the field-induced deviation of the optic axis.

If $\phi(E)$ is linear in the field, Ψ_0 is set to be 22.5° and the factor $\sin^2(\pi d\Delta n/\lambda)$ is field independent; then the electro-optic response is also linear with the field [9]. But, as mentioned before, due to field-induced helix unwinding, p and Δn are field-dependent quantities. Moreover, the experiment shows that $\phi(E)$ has a linear character only in the low field region. At high fields, however, the dependence $\phi(E)$ saturates, and in order to make simulations of the electro-optic response the relation (7) has to be modified, adding, for example, a correction term

$$\phi(E)\Longrightarrow\phi^*(E)=\arctan\left[\frac{e_f E p_0}{\pi K}\right]+\phi_{\text{corr}}(E,\dots). \tag{20}$$

$\phi_{\text{corr}}(E,\dots)$ should account for the simplifications in the model ($K_1=K_3$ and $e_s=e_b$) on the field-induced deviation of the optic axis. The analytical form of this correction will be discussed elsewhere. However, we have to stress the fact that $\phi_{\text{corr}}(E,\dots)$ seems to be small and will not have any substantial influence on the transmitted light intensity compared to the field-induced change of layer birefringence.

In general, the electro-optic response, setting Ψ_0 at 22.5°, will be given by

$$I=I_0 \sin^2\left[2\left[\frac{\pi}{8}+\phi^*(E)\right]\right]\sin^2\left[\frac{\pi d\Delta n(E)}{\lambda}\right], \tag{21}$$

or

$$I=I_0 \sin^2\left[2\left[\frac{\pi}{8}+\phi^*(E)\right]\right]\sin^2\left[\frac{\pi d\Delta n_{(E=0)}}{\lambda}\left[1+\frac{\Delta(\Delta n(E))}{\Delta n_{(E=0)}}\right]\right]. \tag{22}$$

Simplifications in the Patel and Meyer model as well as in our considerations obviously limit the degree of agreement between theory and experimental results at high fields. We are using a model for the elastic distortion that can only be approximately correct, at least at high induced deviations of the helix axis. Considering this, there is no reason to expect the diverging pitch in our model to give a divergence in the induced deviation near the critical field. Moreover, we have ignored the influence from the surfaces, an effect which will be treated elsewhere.

EXPERIMENT

In our experiments we used cells of the conventional sandwich type, consisting of two glass plates, separated at a constant distance (2 μm) by evaporated SiO spacers. The glass substrates were prepared from indium tin oxide (ITO) coated glass sheets (Balzers Balcatron Z20) on which the electrode pattern was etched. The electrode sides of the glass plates were coated with a protection layer of SiO of about 1000 Å thickness, evaporated at normal incidence. This coating gives degenerate planar alignment of the molecules with a strong in-plane anchoring. The thickness of the empty cell was estimated by capacitance measurements. The liquid crystal material was introduced into the cell in the isotropic phase by means of capillary forces. The material used was a very special cholesteric mixture, 6415L (Hoffmann-LaRoche, Basel), which has a broad temperature interval, from 0 to 50 °C, with positive dielectric anisotropy and with a left-handed helix [10]. The unique feature of this material is that the short pitch (0.3 μm) is temperature independent in the whole nematic range.

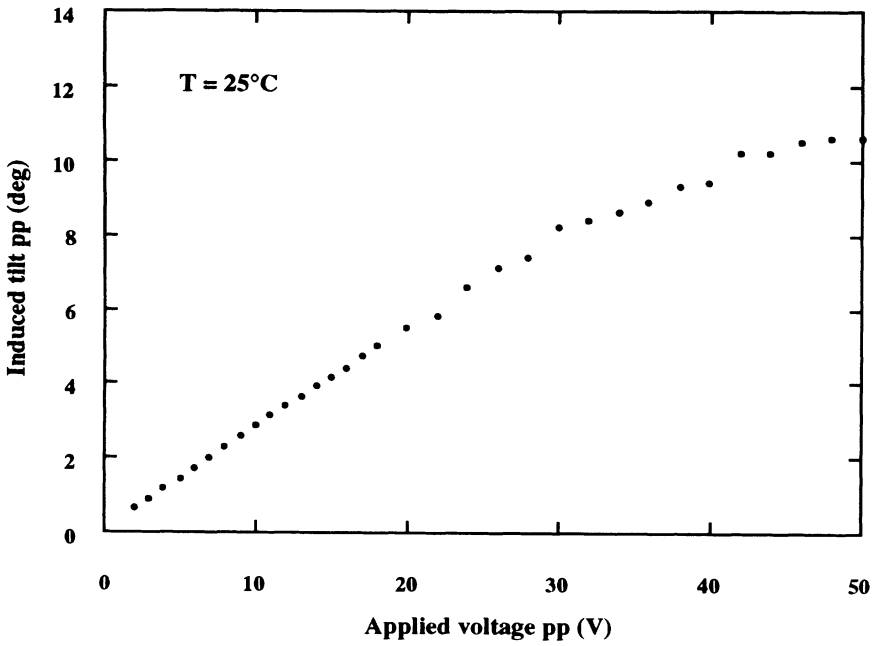

FIG. 4. The induced peak-to-peak deviation of the optic axis as a function of the applied peak-to-peak voltage for Roche 6415L in a cell with thickness $d=2\ \mu$m.

The alignment was obtained by a gentle shearing of the cell while applying an electric field across it. The applied field, approximately $0.5E_c$, reorients the helix from orthogonal (Grandjean texture) to degenerate planar alignment with respect to the surfaces. The shearing flow then aligns the helix perpendicular to the direction of shearing. It is important to keep the applied field during the shearing procedure; otherwise the alignment will turnback into the initial Grandjean texture. When the samples were aligned in such a way, after removing the voltage, the uniform alignment remained for many days without any substantial change. The cell was placed in a Mettler FP 52 hot stage with temperature controlled within 0.1 °C accuracy. The investigation of the electro-optical characteristics was carried out using a Zeiss Photo microscope II Pol, and the response was detected and monitored by a photodiode and an oscilloscope, respectively.

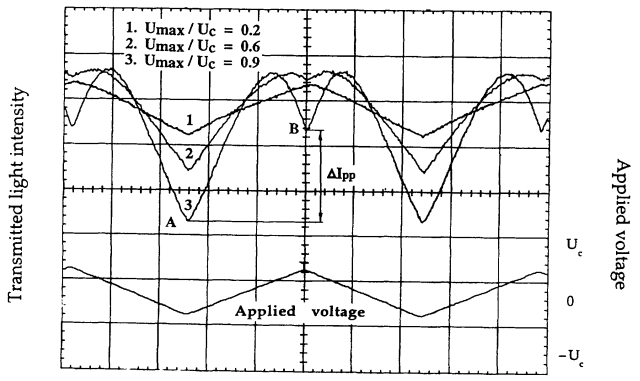

FIG. 5. Light intensity modulation (curves 1, 2, and 3) for three different applied voltages of the shape shown by the lower curve. The dips in the response increase with the applied field.

First we measured the induced deviation of the optic axis as a function of the applied ac electric field, cf. Fig. 4. The applied ac voltage and the induced deviation are expressed by their peak-to-peak values (pp). One can see that the angle of deviation is linear for low fields, tending to saturate at high fields. The critical voltage for total unwinding of the helix was about 54 V_{pp} for a liquid crystal layer thickness of 2 μm. The measured response times were about 50 μs.

However, we would like to stress the fact that, while the induced deviation of the optic axis is almost linear with the field, the light intensity modulation is not. This can be seen in Fig. 5, where the electro-optic response is shown for three applied triangular voltages ($f=200$ Hz). For $U_{max}/U_c=0.2$ the response is still linear, but for higher voltages the linear response is strongly distorted, and dips in the transmitted light intensity appear. Thus, it must be some other change of the layer optical properties than the field-induced deviation that has such an influence on the optic response at high fields. As it turns out, the effect is due to the decrease in the birefringence Δn due to the field-induced unwinding of the helix. From (21) one can see that the decrease in Δn lowers the transmitted light intensity for the case when $|\pi d\Delta n/\lambda|<\pi/2$. The field-induced modulation of Δn is probably also the reason for the quite similar results reported by Wako and Nakamura [11], using a 1:1 mixture of cholesteryl erucate (CE) and cholesteryl 2-(2-methoxy, ethoxy)-ethyl carbonate (CMC).

MODELING OF THE ELECTRO-OPTIC RESPONSE

Based on the general expression of the electro-optic response (22) and the experimental data taken, we were able to perform a computer simulation of the response (see Fig. 6), which in quite some detail describes all observed phenomena (see Fig. 7).

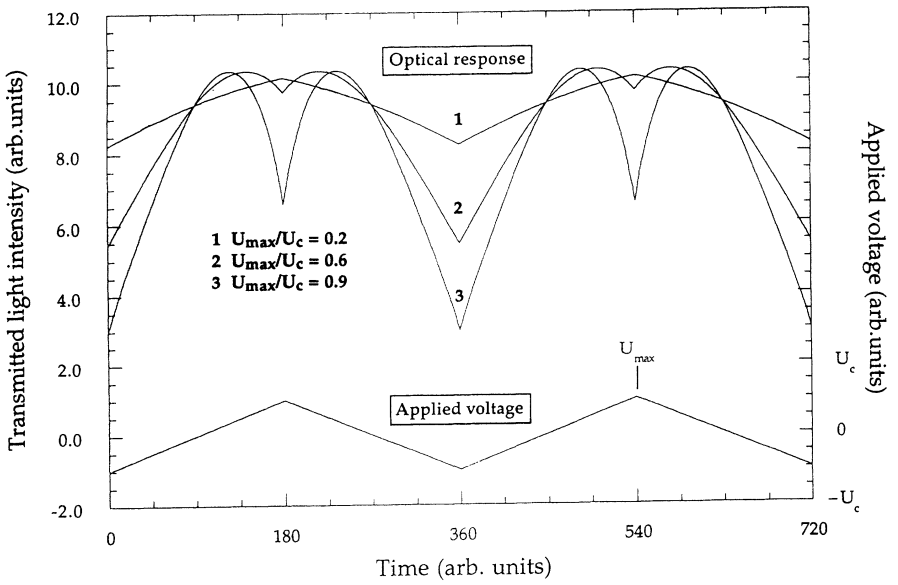

FIG. 6. Computer-simulated electro-optic response for different values of U_{max} [using (23)].

The data used for the simulations and the fittings are $d=2\ \mu m$, $\lambda=0.56\ \mu m$, $n_o=1.498$, and $n_e=1.618$ for the liquid crystal mixture 6415L. The expression used in the simulation has the form

$$I=I_0 \sin^2\left[2\left[\frac{\pi}{8}+\phi^*(E)\right]\right] \times \sin^2\left[-0.66\left[1+\frac{\Delta(\Delta n)}{\Delta n_0}\right]\right] . \quad (23)$$

The amplitude of the applied voltage is normalized with respect to the critical voltage of unwinding U_c. From (16) the relative change in the birefringence (Fig. 3) for the liquid crystal mixture 6415L was approximated with

$$\frac{\Delta(\Delta n)}{\Delta n_0}=-0.314\left[\frac{U}{U_c}\right]^2-0.002\left[\frac{U}{U_c}\right]^4 -0.013\left[\frac{U}{U_c}\right]^6-0.122\left[\frac{U}{U_c}\right]^8 , \quad (24)$$

and $\phi^*(E)$ was estimated from the experimental data to be

$$\phi^*(E)\approx 4.84\times10^{-3}\times U-1.5\times10^{-6}\times U^3 . \quad (25)$$

As one can see from Fig. 6, the simulations and the experimentally detected response (Fig. 5) have a similar shape and exhibit quite the same behavior, with pronounced dips in the transmitted light intensity at high fields. To check the validity of our model we fitted the experimental data to (23) (Fig. 7). In the fitting pro-

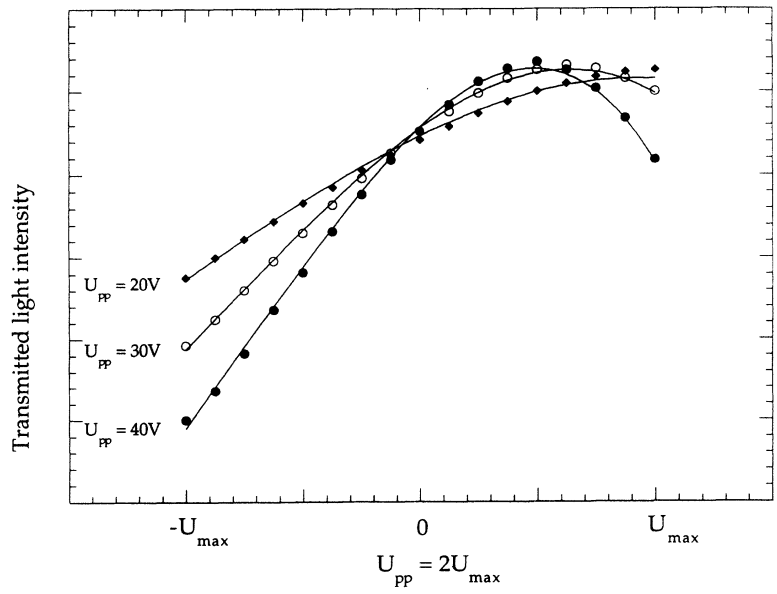

FIG. 7. Experimentally detected electro-optic response in the cholesteric 6415L for three different values of U_{max}. The solid lines are fitted curves using (23), with critical voltage $U_c=54\ V_{pp}$.

cedure, only two parameters were used, I_0 and an offset, corresponding to the incident light intensity and the quality of the layer alignment, respectively. As can be seen, the fitting of the experimental results is rather good.

DISCUSSION

The short-pitch cholesteric with a unidirectional helix axis exhibits a field-induced deviation of this axis when an electric field is applied normal to the helix. In a microscopic view, each molecule rotates along an axis parallel to the field. Important characteristics of the effect are short response times of about 50–100 μs, and the linearity in the electric field, at least for low fields. This study was performed with the aim of identifying the factors affecting the linearity of the optical response, as well as of finding a way to control their influence.

Expanding the linear regime of the electro-optic response

Linear electro-optic effects are relatively rare in liquid crystals. Therefore, the linear regime is of specific interest for a large number of useful applications. As we have shown, the unwinding of the helix due to dielectric torques must be suppressed as much as possible to keep the response linear. This means that one should use a liquid crystal material with $\Delta\varepsilon \approx 0$ in order to increase the critical field for unwinding the helix and thus both enlarging the linear regime and achieving a larger induced deviation of the optic axis. One possible way is to choose a material that possesses a sign reversal of the dielectric anisotropy and to work in the frequency range in which $\Delta\varepsilon$ is substantially small. In order to minimize the influence of the dielectric effects on the linearity of the electro-optic response, we also have to know how changes in the quantities $p(E)$ and $\Delta n(E)$ affect the intensity of the transmitted light.

With the unwinding voltage found to be $U_c = 54$ V_{pp} we calculate $p/p_0 = 1.07$ corresponding to $U = 40$ V_{pp} ($U/U_c = 0.74$). Taking e_f and K as constants and differentiating the expression

$$\phi = \arctan\left[\frac{e_f E p}{\pi K}\right], \tag{26}$$

we get

$$\Delta\phi = \frac{a}{1+a^2p^2}\Delta p , \tag{27}$$

where we have $a \equiv e_f E/\pi K \approx 0.07E$ from experiments. This gives a value of $\Delta\phi$ equal to 0.006 rad $\approx 0.4°$ as compared with the field-induced deviation ϕ of about 0.5°. The corresponding relative change in modulated intensity $[I(p)-I(p_0)]/I(p_0)$ due to the deviation in pitch is found from (23) to be about 3%. For the same value of the electric field, $\Delta(\Delta n)/\Delta n_0$ is found from (24) to be -0.2, giving a value $[I(\Delta n)-I(\Delta n_0)]/I(\Delta n_0)$ of -0.36. Consequently, the change in Δn due to the field-induced helix distortion causes a change in the transmitted light intensity of about 35%, i.e., the contribution from $\Delta(\Delta n)$ is approximately 10 times larger than the contribution from the field-induced helix lengthening Δp. Obviously, to minimize the influence of changes in Δn on the transmitted light intensity is of great importance (confirming the need for a small $\Delta\varepsilon$ in general). The effect of the macroscopic birefringence $\Delta n(E)$ on the light intensity modulation is represented by the factor $\sin^2[(\pi d/\lambda)\Delta n(E)]$ in (21). In our case, with $|(\pi d/\lambda)\Delta n_0| \approx 0.66$ and $\Delta\varepsilon > 0$, Δn decreases and the transmitted light intensity is reduced when increasing the applied electric field. On the contrary, if the liquid crystal material has $\Delta\varepsilon < 0$, the transmitted light intensity should increase under the same conditions. By choosing $(\pi d/\lambda)\Delta n_0$ to fulfill the $\lambda/2$-wave plate condition, i.e., ($|(\pi d/\lambda)\Delta n_0| \approx \pi/2$), the influence of $\Delta(\Delta n)$ on the transmitted light intensity will be reduced to a minimum and thus the influence of helix unwinding on the electro-optic response will be minimized. For instance, with the liquid crystal material 6415L we need a cell with thickness $d \approx 5$ μm in order to attain the $\lambda/2$ condition. However, with increasing thickness of the cell, it becomes more difficult to achieve a homogeneously aligned sample. Therefore, another surface treatment different from the one used in this work might be needed. Instead of increasing the thickness of the cell, in order to obtain the $\lambda/2$-wave condition, we can choose a liquid crystal material with larger Δn and/or decrease the wavelength of the light. A larger value of Δn is not automatically in conflict with a small $\Delta\varepsilon$ since the frequency regions are completely different.

Increasing the induced tilt of the optic axis

Consider the expression for the induced tilt of the optic axis [1]:

$$\phi = \arctan[(e_f E p)/(\pi K)] . \tag{28}$$

Obviously, for low fields, the induced tilt increases linearly with the applied field E. However, there is a saturation in ϕ because of the arctan dependence, and this also sets a limit for the linear regime. The induced deviation should be linear with the field as long as $\tan\phi \approx \phi$. The theoretical linear region is found to be within the interval $0 \le \phi \le 22°$ allowing a deviation of 5% from linearity. To achieve a large induced tilt one has to apply a high electric field. In our case, if we assume that $\Delta\varepsilon = 0$ and thus no unwinding of the helix takes place, an induced deviation of about 20° requires $U \approx 75$ V ($E = 380$ kV/cm). Such voltage might damage the cell. The remaining parameters to play with are material parameters like e_f, p, and K. A material with a large flexoelectric coefficient e_f and/or large pitch p and/or small elastic constant K might be found. Very little if anything can be predicted for e_f, whereas p and K are relatively easy to change. A longer pitch means a lower critical field for unwinding of the helix, and a low K value might effect the dynamics of the response, which has to be investigated theoretically and experimentally. Another possibility is to use a double cell package as in [9] to achieve a higher degree of light intensity modulation.

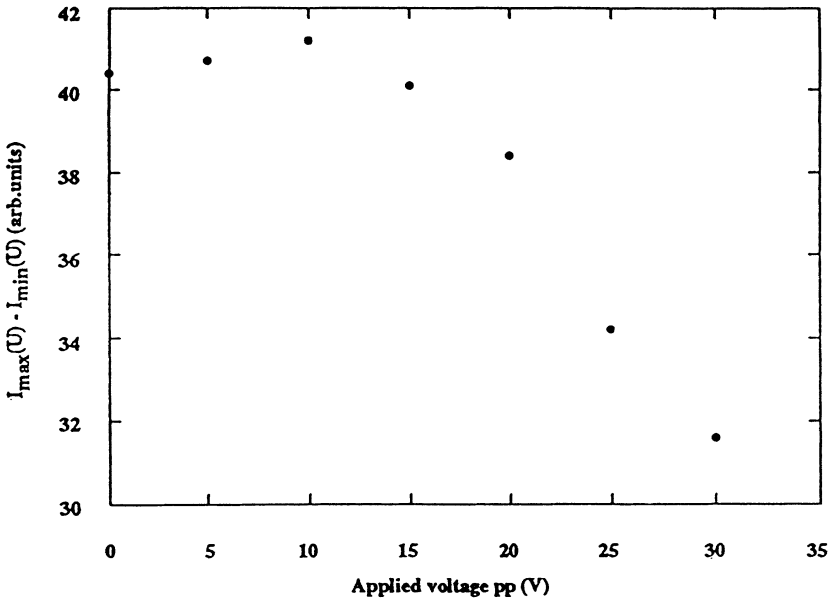

FIG. 8. $I_{max}(U)-I_{min}(U)$ as a function of the applied voltage. The maximum value is reached for 10 V_{pp} indicating some improvement of the uniformity of the stripe texture at low fields.

Possible effect of the alignment relaxation

As mentioned in the experimental part of this work, the achieved alignment with unidirectionally aligned helix remained at field off condition for several days. However, there is a slow relaxation to the Grandjean texture with time. This relaxation process has an influence on the transmitted light intensity. Since the applied electric field keeps the uniform alignment of the helix parallel to the surface, the maximum of the difference between the maximum and minimum transmitted light intensities, $I(\Psi=45°)-I(\Psi=0°)$, could be found for a nonzero field. If we plot $I_{max}(U)-I_{min}(U)$ (Fig. 8), then the maximum value of $I_{max}(U)-I_{min}(U)$ is for $U\approx 10$ V_{pp}, which agrees with the assumption of some relaxation of the alignment when the field is switched off. Notice that $\phi(E)$ is included in Ψ. Consequently, a method assuring stable uniform alignment of the chiral nematic layer might be necessary to develop.

CONCLUSIONS

The physics of the linear electro-optic effect in a short-pitch cholesteric, due to the flexoelectric torques, is described in the extended case where the helix profile is field dependent and found to be strongly influenced by the dielectric torques. It should be stressed that while the induced tilt in the optic axis is almost linear in the field, the light intensity modulation is not, due to the strong field dependence on the cell birefringence, $\Delta n(E)$. This generally leads to a distortion of the response, which appears as a dip in the transmitted light intensity. As we were able to show, this could be fully taken into account by including the dielectric effects alongside of the flexoelectric effect. Taking into account the field-induced unwinding of the helix, all essential features of the electro-optic response could be well accounted for, qualitatively as well as quantitatively. Moreover, the analysis shows that by suppressing the dielectric torque with a low $\Delta\varepsilon$ value and choosing the liquid crystal and the cell parameters in a proper way, one may optimize the conditions for obtaining a linear electro-optic response with an induced deviation approaching 20°. This would lead to new powerful devices in the field of linear electro-optic modulators similar to the ones based on the deformed helix mode in short-pitch Sm-C^* [12] or the electroclinic effect in the Sm-A^* phase [9].

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