Dielectric Relaxation in Electrooptical Switching of Nematics

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Abstract

We describe how the phenomenon of dielectric dispersion in nematic liquid crystals influences the director dynamics and thus the switching speed of nematic-based displays.

1. Introduction

Liquid crystals (LCs) are anisotropic fluid dielectrics. When an electric field $\mathbf{E}(t)$ is applied, the LC director reorients and thus causes optical effects that are at the heart of modern display technologies. In the physics of LCs, dielectric response is described as instantaneous: It is assumed that the electric displacement at the moment of time t is determined by the electric field at the very same moment t. The approach is valid when the LC experiences no dielectric relaxation and the tensor of dielectric permittivity ε is frequency-independent. In reality, LCs are dielectrically dispersive. The characteristic relaxation time τ vary in a broad range from millisecond to nanosecond, depending on the material. When the characteristic time with which $\mathbf{E}(t)$ varies becomes shorter or comparable to τ, the dielectric torque depends not only on the current value of the field but also on its past values [1]. The corresponding theories are well known for isotropic fluids and solid crystals; in both cases, the dielectric properties of medium do not change with time. In LCs, the situation is more complex as the electric field $\mathbf{E}$ causes director reorientation which in turn changes the dielectric coupling with the field. Thus the electric displacement should also depend on the current and past director orientations [1,2].

Our goal is to develop physical understanding of the time-dependent dielectric response of nematic LCs. The research focuses on dielectric phenomena in the nematic LCs that occur at the time scale comparable to τ (or shorter); the issue is of relevance for the fast switching nematic devices.

2. Theory

Dielectric relaxation is responsible for the dependence of the electric displacement **D**(t) and the torque not only on the present electric field **E**(t) but also on its past value **E**(t′). For materials with a single relaxation process we can use the Debye model for the frequency dependent components of the dielectric tensor. We evaluate the director dynamics using the Ericksen-Leslie equation which balances the dielectric, viscous, and elastic torques. If we choose a coordinate system such that the glass plates of the cell lie in the *x-y* plane then the electric field and the director vary in the *x-z* plane and depend on *z* only. In this configuration the only non zero torques lie on the y axis. When only the parallel component $\varepsilon_{\|}$ is dispersive, the dielectric torque is given by [1]

$$
\begin{aligned}
&M_d(t) = \varepsilon_0 E(t)\sin\theta(t)\times \\
&\Big[\Delta\varepsilon_h E(t)\cos\theta(t) + \\
&\frac{\varepsilon_{l\|}-\varepsilon_{h\|}}{\tau}\int_{-\infty}^{t}\exp\left(-\frac{t-\hat{t}}{\tau}\right)E(\hat{t})\cos\theta(t)\,dt\Big]
\end{aligned}
\qquad (1)
$$

where θ is the angle between the director and the field, $\Delta\varepsilon_h = \varepsilon_{h\|} - \varepsilon_{h\perp}$, "h" and "l" refer to the high and low frequency values of the components of the dielectric tensor ε and τ is the dielectric relaxation time. For $\varepsilon_{l\|} = \varepsilon_{h\|}$, Eq.(1) reduces to the classic "instantaneous" dielectric response theory. Note that M_d contains a term that is linear in the current value of the applied field. It means that in the dielectric coupling, there is a term that is sensitive to polarity of the electric field. This leads to a spectacular effect [2]: The switching off stage of the nematic can be accelerated if, instead of switching the display abruptly, one uses an electric pulse of a duration $\sim\tau$ and of a proper polarity, to couple with the residual polarization in the nematic cell in such a way that the director relaxation is accelerated.

The effect can be qualitatively explained as follows. Consider first a NLC with $\Delta\varepsilon > 0$ in a planar cell. A positive dc field $E_z > 0$ reorients the director $\hat{\mathbf{n}}$ towards the z-axis. E_z also induces a dipole moment density $\mathbf{p}$ with the components $p_\perp = \varepsilon_\perp E_z \sin\theta$ and $p_\parallel = \varepsilon_{h\parallel} E_z \cos\theta + p_{mem}$, perpendicular and parallel to $\hat{\mathbf{n}}$, respectively. Here p_{mem} is the "memory" contribution that saturates to the value $p_{mem} = \left(\varepsilon_{l\parallel} - \varepsilon_{h\parallel}\right) E_z \cos\theta$ after the dc field E_z acted for a sufficiently long time $> \tau$. Note that $p_{mem} > 0$ and $E_z > 0$ are of the same sign. When the field is switched off at $t = 0$, $p_{mem} > 0$ does not disappear instantaneously, but decays with a characteristic time τ. If within the interval $0 < t \le \tau$, one applies a new electric pulse of *the opposite polarity*, $E_z < 0$, then this field would interact with the decaying $p_{mem} > 0$ to assist the reorientation towards the planar state, $\theta \to \pi/2$.

In a similar fashion, in a homeotropic cell (such as the one used in patterned vertical alignment displays) with a negative LC, the field $E_z > 0$ at $t < 0$ also induces $p_{mem} > 0$ (of the same polarity). If within the interval $0 \le t \le \tau$ one applies a new voltage pulse of *the same* polarity, $E_z > 0$, then this field will couple to $p_{mem} > 0$ to assist the director reorientation into the homeotropic state. This latter effect is illustrated experimentally in the next section.

3. Experimental

We used homeotropic cells (EHC Ltd.) comprised of glass substrates with indium tin oxide electrodes. The field-induced director dynamics was monitored by measuring the He-Ne laser ($\lambda = 633\,\text{nm}$) light transmission through the cells placed between two polarizers that depends on θ (through the phase retardation dependence). The driving pulses were produced by WFG500 wave-form generator (FLC Electronics); the maximum rate was 240 V/μs. To test the switch-off dynamics, we used two different profiles for the pulse's back edge: (i) an instantaneous back edge (in practice $\sim 1\,\mu$s in duration because of the finite voltage change rate); (e) an exponentially decaying back edge $u(t) = a\,\mathrm{Exp}\left(-\Gamma t/\tau\right)$, where a and Γ are the two optimization parameters.

4. Results and discussion

To drive the homeotropic cell with a negative LC, we first apply a square 100 V dc pulse of duration $225\,\mu$s, much longer than $\tau = 33\,\mu$s for this material, to produce the saturated "memory" dipole moment. This pulse is switched off by an instantaneous back edge (i) or by three different exponential edges with $\Gamma = 0.45$ and: (e1) positive polarity, $a = 50$ V; (e2) $a = 87$ V; (e3) negative polarity, $a = -50$ V; Fig. 1. The optical response is different in all four cases. In the case (i), $\hat{\mathbf{n}}$ reorients slowly toward the homeotropic state $\theta \to 0$, as evidenced by the decrease in $I\left(t\right)$ in Fig. 1 inset.

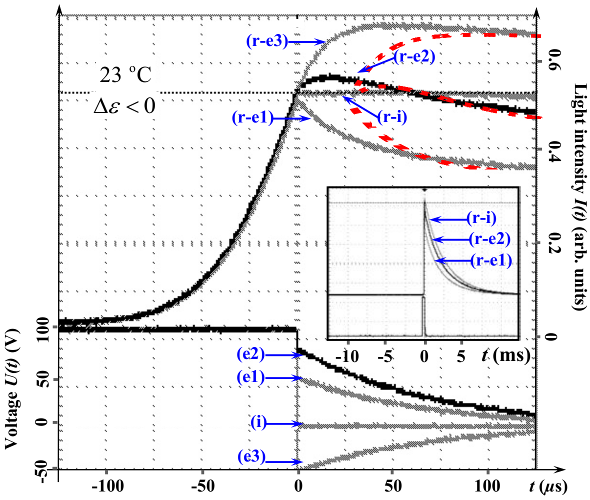

Fig.1. Switching the dielectrically negative nematic with an abrupt (i) and exponentially decaing back edges of the voltage pulse (e1, e2, e3).

The pulse (e1) produces much faster reorientation (r-e1), despite the fact that U decreases less abruptly as in case (i). The shape of the pulse (e1) is close to the optimum, as any departure from the pre-selected $a = 50\,\mathrm{V}$ and $\Gamma = 0.45$ causes a slower or even a non-monotonous response, as in (e2) case. The linear $\mathbf{E}$-dependence of the "memory" torque is well illustrated by the response to pulses (e1) and (e3) that differ only in polarity: (e1) drives $\hat{\mathbf{n}}$ toward $\theta = 0$ while (e3) continues to drive $\hat{\mathbf{n}}$ toward $\theta = \pi/2$. After a sufficiently long time, the NLC relaxes to the same homeotropic state with $I = 0$ for all pulses, Fig. 1. The different scenarios can be fitted by the model above, using the model with Eq. (1). The model (1) reproduces the response curves (r-e2) and (r-e3) very well, Fig. 1.

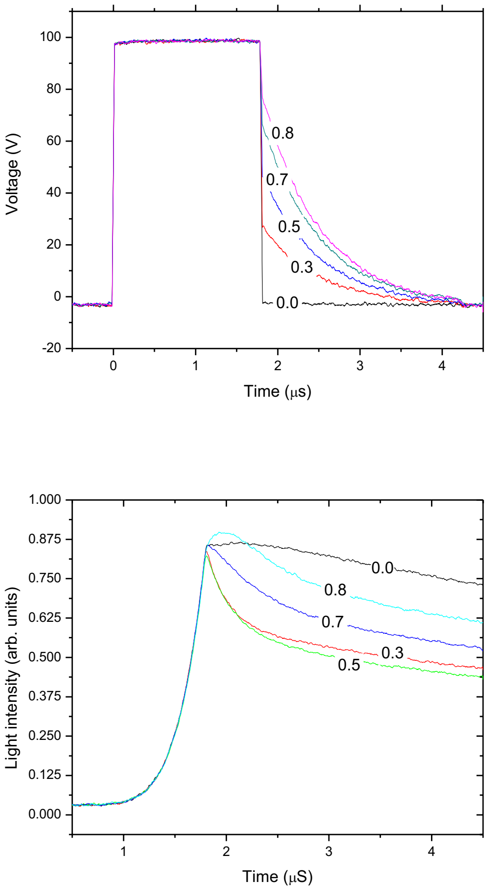

Fig. 2. Electrooptic response of the negative nematic in a homeotropic cell to different amplitudes of the back edge pulse; the number indicate the amplitude as a fraction of 100 V. The fastest result is for $a = 50\,\mathrm{V}$ (bottom).

In order to check the model for the correct shape of the back edge pulses we looked at the response as a function of the amplitude a of the pulse, Fig 2. The amplitude of the pulse varied from 0 to 0.8 multiplied by the 100 V initial pulses. As can be seen from Fig.2, the responses were very different for the varying amplitudes, with the best (fastest) response resulting from 50 V amplitude. The 80 V pulse resulted in a non monotonic decay which may be due to backflow coupling to the dielectric dispersion effect.

5. Summary

The theory and experiments demonstrate that the dielectric response in a nematic material with dielectric dispersion is sensitive to the polarity of the applied voltage. The effect is caused by a "memory" term in the dielectric torque $\mathbf{M}_d(t)$ that is linear in the present field $\mathbf{E}$(t). This is in contrast to the "classic" contribution which is quadratic in $\mathbf{E}(t)$. This feature opens new possibilities for optimization of electrooptical effects in nematic-based displays. For example, we demonstrated that the "switch off" phase of the director reorientation can be accelerated by exponentially decaying short pulses of a proper polarity with the duration determined by the relaxation time τ.

The linear in $\mathbf{E}(t)$ nature of the "memory" dielectric torque in a dispersive nematics offers the possibility of interaction with other field effects, such as flexoelectricity, order electricity, surface polarization, etc. Fig.2 suggests that the hydrodynamic processes (back-flow) are also coupled to the dielectric memory effect. It would be also of great interest to explore the similar effects in the biaxial nematic liquid crystals. Therefore the observed polarization sensitive dielectric response of the dispersive nematics opens opportunities for both basic and applied research.

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6. References

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