



Field-induced non-uniform director reorientation for a low molar mass nematic imposed by a strong orthogonal electric field

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ABSTRACT

The director dynamics for a low molar mass nematic liquid crystal (LC) has been investigated theoretically based on the hydrodynamic theory including the director motion. Analysis of the numerical results for the turn-on process provides an evidence for the appearance of the spatially periodic patterns in 4-n-pentyl-4'-cyanobiphenyl LC film, only in response to the suddenly applied strong electric field orthogonal to the magnetic field. It has been shown that at the values of the voltage in 200 V across the 194.7 μm LC film and the magnetic field of 7.05 T directed at the angle $\alpha = 1.57$ ($\sim 89.99^\circ$) between two fields there is the threshold value of the amplitude of the thermal fluctuations of the director over the LC sample which provide the nonuniform rotation mode rather than the uniform one, whereas the lower values both of the amplitude and the angle α (< 1.565 ($\sim 88.81^\circ$)) dominate the uniform mode. During the turn-off process, the reorientation of the director to its equilibrium orientation is characterized by the complex destroying of the initially periodic structure to a monodomain state.

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1. Introduction

It is important, both from an academic and a technological point of view, to investigate the dynamic director reorientation in a thin nematic liquid crystal (LC) film confined between two transparent electrodes and subject to competing constraints. In the presence of external electric and magnetic fields, and surface anchoring in a nematic film, the motion of the director, $\hat{n}(r, t)$, to its equilibrium orientation, $\hat{n}_{eq}(r)$, across the LC film is governed by elastic, electric, magnetic, and viscous torques. Nuclear magnetic resonance (NMR) spectroscopy is by now a well-established method for investigating orientational order and dynamic properties in thermotropic liquid crystalline phases [1]. Recently, the time-resolved deuterium NMR spectroscopic measurements of field-induced director reorientations have been performed [2–6]. Taking into account that the quadrupolar splitting is related to the angle θ made by the director $\mathbf{n}$ with the magnetic field $\mathbf{B}$ (see Fig. 1), deuterium NMR spectroscopy is found to be a powerful method, with which to investigate the dynamic director reorientation in nematic films. When the deuterated 4- α , α - d_2 -pentyl-4'-cyanobiphenyl (5CB- d_2) subject to the strong electric field $\mathbf{E}$ applied at the angle α to the magnetic field $\mathbf{B}$, the director moves from being parallel to the magnetic field to being parallel to the electric field (the turn-on process), with the relaxation

time τ_{ON} , because both dielectric and magnetic anisotropies are positive for 5CB. After the electric field is switched off, the director relaxes back to being parallel to the magnetic field (the turn-off process), with the relaxation time τ_{OFF} . Deuterium NMR spectra were recorded during the turn-on and turn-off alignment processes as a function of time [7]. Analysis of these results shows that $\tau_{ON}(\alpha)$ monotonically grows with increasing of the angle α , up to the maximum value, $\tau_{ON}(\max)$. With further growth of α , up to the right angle ($\alpha \sim \frac{\pi}{2}$), $\tau_{ON}(\alpha \sim \frac{\pi}{2})$ rapidly decreases with a few milliseconds, with respect to $\tau_{ON}(\max)$ [7]. Analysis of the experimental results, based on the predictions of hydrodynamic theory including both the director motion and fluid flow, provides an evidence for the appearance of the spatially periodic patterns, at the angles $\alpha > 60^\circ$, in response to the suddenly applied $\mathbf{E}$. These periodic distortions produce a lower effective rotational viscosity, and give a faster response of the director rotation than for a uniform mode, as observed in NMR experiment [7].

In this work we focus on the geometry where the electric and magnetic fields are orthogonal (or approximately orthogonal) to each other. In this configuration the state of the system, immediately becomes unstable after applying orthogonal electric field. When the misalignment of the director with respect to the direction imposed by the aligning magnetic field is due to the thermal fluctuations with small amplitudes, the reorientation following the sudden application of a sufficiently strong and orthogonal electric field manifests itself by the growing of one particular Fourier mode. In this case, the spectral line shape characterizing the initially aligned sample broadens with time-dependent splitting while the initial steady doublet with constant splitting progressively vanishes [2–4], and the application

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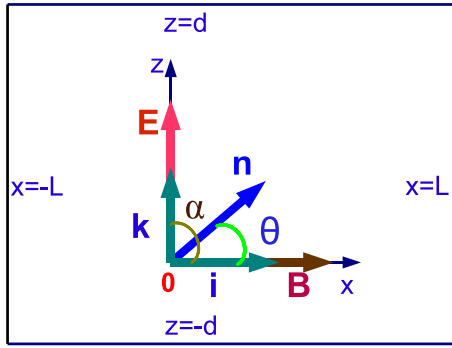


Fig. 1. The geometry used for the calculations. The z-axis is normal to the electrodes. The magnetic field $\mathbf{B}$, electric field $\mathbf{E}$, and director, $\mathbf{n}$, are in the xz-plane. The director makes an angle θ both with the x-axis and the magnetic field $\mathbf{B}$, and the electric field makes a right angle with the magnetic field.

of the strong orthogonal electric field gives rise to the appearance of new doublet with vanishing amplitude that progressively grows with constant splitting so that the total spectral intensity is transferred from the initial doublet to the new one, with half the quadrupolar splitting. These results strongly suggest that the initial state is not homogeneous and perturbed by thermal fluctuations. It is, therefore, necessary to analyse the nematic response to an initial state exhibiting some thermal fluctuations of the director under the influence of the strong electric field. Since anomalous changes of the spectral line shapes do not give any information about the average director orientation, the additional numerical investigations of the system that include both director reorientation and fluid flow should be done. So, the aim of this paper is to investigate the response of a strongly aligned LC phase confined between two surfaces and subject to suddenly applied orthogonal electric field to the magnetic one. However, this raises a question: how much does the initial perturbing of the director with respect to the direction imposed by the aligning magnetic field, and caused by the thermal fluctuations with small amplitudes, influence on the character of the further evolution of the director field to its equilibrium orientation? Physically, this means that for certain values of the electric and magnetic fields there is the threshold value of the amplitude which provides the nonuniform rotation mode rather than the uniform one. The outline of this paper is as follows. In the next section we describe the theoretical treatment including the director motion in the nematic film and the numerical results for a number of hydrodynamical regimes. The discussion of these results are summarized in Section 3.

2. Theoretical treatment and numerical results

The coordinate system defined by our experiment assumes that the electric field $\mathbf{E}$ is applied normal both to the electrodes and the magnetic field $\mathbf{B}$ (see Fig. 1). We consider a nematic system such as cyanobiphenyl, which is delimited by two horizontal and two lateral surfaces at mutual distances $2d$ and $2L$ on a scale in the order of tens micrometers. According to this geometry the system may be seen as the two-dimensional, since the director is maintained within the xz-plane (or in the yz plane) defined by the two fields, where $\hat{\mathbf{i}}$ is the unit vector directed parallel to the horizontal surfaces, which coincides with the direction of the magnetic field $\mathbf{B}$, $\hat{\mathbf{k}}$ is a unit normal vector, which coincides with the direction of the electric field $\mathbf{E}$, and $\hat{\mathbf{j}} = \hat{\mathbf{k}} \times \hat{\mathbf{i}}$. We can suppose that the components of the director, $\mathbf{n} = \cos\theta(x, z, t)\hat{\mathbf{i}} + \sin\theta(x, z, t)\hat{\mathbf{k}}$ (see Fig. 1) depend only x , z -components and time t . Here θ denotes the angle between the director and the magnetic field. Our recent investigation of the field-

induced relaxation of the director field under the influence of a strong electric field suggests that in order to describe the dynamical reorientation of the director correctly, we do not need to include a proper treatment of backflow [8]. This means that the role of the viscous forces becomes negligible in comparison to the electric, magnetic and elastic contributions. In that case the torque balance equation composed of the electric $\mathbf{T}_{el} = \frac{\partial \psi_{el}}{\partial \mathbf{n}} \times \mathbf{n}$, magnetic $\mathbf{T}_{mg} = \frac{\partial \psi_{mg}}{\partial \mathbf{n}} \times \mathbf{n}$, elastic $\mathbf{T}_{elast} = \frac{\partial \psi_{elast}}{\partial \mathbf{n}} \times \mathbf{n}$, and viscous $\mathbf{T}_{vis} = \frac{\partial \mathcal{R}_{vis}}{\partial \mathbf{n}_t} \times \mathbf{n}$ torques exerted on the director takes the form [8]

$$\begin{aligned} \gamma_1 \theta_{,t} = & (K_1 \sin^2 \theta + K_3 \cos^2 \theta) \theta_{,xx} + (K_1 \cos^2 \theta + K_3 \sin^2 \theta) \theta_{,zz} \\ & + (K_3 - K_1) \sin 2\theta \theta_{,xz} + \frac{1}{2} (K_1 - K_3) \sin 2\theta (\theta_{,x}^2 - \theta_{,z}^2) \\ & + (K_3 - K_1) \cos 2\theta \theta_{,x} \theta_{,z} + \frac{1}{2} \epsilon_0 \epsilon_a E^2 \sin 2(\alpha - \theta) - \frac{1}{2} \frac{\chi_a}{\mu_0} \sin 2\theta B^2. \end{aligned} \quad (1)$$

In our case the elastic energy density is equal to $\psi_{elast} = \frac{1}{2} [K_1 (\nabla \cdot \mathbf{n})^2 + K_3 (\mathbf{n} \times \nabla \times \mathbf{n})^2] = \frac{1}{2} [K_1 (n_{x,x} + n_{z,z})^2 + K_3 (n_{z,x} - n_{x,z})^2]$, where K_1 and K_3 are the splay and bend elastic constants, whereas the viscous dissipation function is equal to $\mathcal{R}_{vis} = \gamma_1 \mathbf{N}^2 = \gamma_1 (n_{x,t}^2 + n_{z,t}^2)$. Here only rotations of the director field have been accounted for. So, the vector $\mathbf{N}$ is equal to $\frac{\partial \mathbf{n}}{\partial t} = \dot{\mathbf{n}}$, where γ_1 is the rotational viscosity coefficient. The electric energy density is equal to $\psi_{el} = -\frac{1}{2} \epsilon_0 \epsilon_a (\mathbf{n} \cdot \mathbf{E})^2 = -\frac{1}{2} \epsilon_0 \epsilon_a (n_x E_x + n_z E_z)^2$, where ϵ_0 is the dielectric permittivity and ϵ_a is the dielectric anisotropy of the nematic sample, while the magnetic energy density is equal to $\psi_{mg} = -\frac{1}{2} \frac{\chi_a}{\mu_0} (\mathbf{n} \cdot \mathbf{B})^2 = -\frac{1}{2} \frac{\chi_a}{\mu_0} (n_x B)^2$, where μ_0 is the magnetic constant and χ_a is the magnetic anisotropy of the nematic sample. It allows us to rewrite the torque contributions as $\mathbf{T}_{elast} = \{n_z [K_1 n_{x,xx} + K_3 n_{z,zz} + (K_1 - K_3) n_{z,xz}] - n_x [K_1 n_{z,zz} + K_3 n_{x,xx} + (K_1 - K_3) n_{x,xz}]\} \hat{\mathbf{j}}$, $\mathbf{T}_{vis} = \gamma_1 [n_x n_{z,t} - n_z n_{x,t}] \hat{\mathbf{j}}$, $\mathbf{T}_{el} = \epsilon_0 \epsilon_a (n_x E_x + n_z E_z) \times (n_z E_x - n_x E_z) \hat{\mathbf{j}}$, and $\mathbf{T}_{mg} = \frac{\chi_a}{\mu_0} n_x n_z B^2 \hat{\mathbf{j}}$, where $n_{x,xx} = \frac{\partial^2 n_x}{\partial x^2}$. The appropriate angle's forms for the torques are given below as $-T_{elast}^y = (K_1 \sin^2 \theta + K_3 \cos^2 \theta) \theta_{,xx} + (K_1 \cos^2 \theta + K_3 \sin^2 \theta) \theta_{,zz} + (K_3 - K_1) \sin 2\theta \theta_{,xz} + \frac{1}{2} (K_1 - K_3) \sin 2\theta (\theta_{,x}^2 - \theta_{,z}^2) + (K_1 - K_3) \cos 2\theta \theta_{,x} \theta_{,z}$, $T_{vis}^y = \gamma_1 \theta_{,t}$, $T_{el}^y = -\frac{1}{2} \epsilon_0 \epsilon_a (E_z)^2 \times \sin 2(\alpha - \theta)$, and $T_{mg}^y = \frac{1}{2} \frac{\chi_a}{\mu_0} B^2 \sin 2\theta$. Here the electric field $\mathbf{E}$ makes the angle α with the magnetic field $\mathbf{B}$, and the values of which is varied in the vicinity of $\frac{\pi}{2}$. In the case of the two-dimensional LC system the dimensionless torque balance equation describing the reorientation of $\mathbf{n}$ to its equilibrium orientation $\mathbf{n}_{eq}$ can be written as

$$\begin{aligned} \theta_{,\tau} = & \delta_1 \left[\left(\frac{d}{L} \right)^2 (\sin^2 \theta + K_{31} \cos^2 \theta) \theta_{,xx} + (\cos^2 \theta + K_{31} \sin^2 \theta) \theta_{,zz} \right] \\ & + \delta_1 \left[\frac{d}{L} (K_{31} - 1) \sin 2\theta \theta_{,xz} + \frac{1}{2} (1 - K_{31}) \sin 2\theta \left(\left(\frac{d}{L} \right)^2 \theta_{,x}^2 - \theta_{,z}^2 \right) \right] \\ & + \delta_1 \frac{d}{L} (K_{31} - 1) \cos 2\theta \theta_{,x} \theta_{,z} + \frac{1}{2} [\sin 2(\alpha - \theta) - \delta_2 \sin 2\theta]. \end{aligned} \quad (2)$$

Here $\bar{x} = x/L$ and $\bar{z} = z/d$ are the dimensionless space variables (the bar is omitted), $\tau = \frac{\epsilon_0 \epsilon_a}{\gamma_1} \left(\frac{U}{2d} \right)^2 t$ is the dimensionless time, and $\delta_1 = \frac{4K_1}{\epsilon_0 \epsilon_a U^2}$, $\delta_2 = \frac{4\chi_a B^2 d^2}{\mu_0 \epsilon_0 U^2}$ and $K_{31} = \frac{K_3}{K_1}$ are three parameters of the system.

2.1. Turn-on process

When a strong electric field $\mathbf{E}$ is applied at the angle α close to the right angle to the magnetic field $\mathbf{B}$, the director moves from being parallel to the magnetic field to being parallel to the electric field (the turn-on process), because both dielectric and magnetic anisotropies are positive for 5CB. Now the reorientation of the director in the nematic film under the influence of the external forces can be obtained by solving the nonlinear differential Eq. (2) with appropriate boundary and initial conditions. In order to elucidate the role of the thermal fluctuations in maintaining of the spatially periodic patterns in the LC sample under the influence of the strong orthogonal electric

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