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Light induced thermomechanical hydrodynamics in homeotropic nematic liquid crystals

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ABSTRACT

A new method of inducing thermomechanical hydrodynamic flow in homeotropic nematic liquid crystals (NLC) is proposed based on using different anchoring conditions on the cell boundaries. Effect of different pairs of boundary conditions including hard, weak and conical on the director orientation, director gradient and NLC flow are studied, theoretically. Absorption of a linearly polarized laser light is considered to induce the need temperature gradient for the thermomechanical effect (TM) in the NLC cell. Coupling of fluidity to the director orientation distorts the director. Consequent optical nonlinearity is calculated and compared with the optical nonlinearity due to other kinds of the TM effect.

1. Introduction

Nematic liquid crystals (NLC) can have hydro dynamical motions else than molecular orientation. Different hydro dynamical mechanisms are investigated theoretically and experimentally in the NLCs [1–16]. A laminar flow between two parallel plates, one in which moving relative to the other is known as the Couette flow [1], and in the presence of a pressure gradient is known as the Poiseuille flow [2]. When a parallel plate NLC cell is heated from below [3] or above [4] Rayleigh–Benard convection can be observed above a threshold. In a NLC doped with ionic impurities, Electro convection occurs when the imposed voltage on the NLC exceeds a threshold voltage [5]. Surface tension-driven in a horizontal NLC cell with a free surface is named Marangoni effect, and when the Marangoni effect is due to the temperature gradient is known as the thermocapillary effect [6]. Backflow can show up in a Freedericksz experiment with a magnetic or electric field above a second threshold exceeding the Freedericksz threshold [7]. The effects of weak anchoring on the static and dynamic behavior of liquid crystals in the presence of an external field are studied theoretically [8] and experimentally [9]. The formation of a hydrodynamic flow in a non-uniformly aligned molecular director in the presence of a temperature gradient is known as the thermomechanical hydrodynamic effect [10]. TM hydro dynamical flow in hybrid [11], cylindrical hybrid aligned NLC [12], and dye doped NLC [13], are studied theoretically and experimentally. Initial director non-uniformity is essential for the thermomechanical hydrodynamic flow and is absent in planar and homeotropically oriented cells. So, for observing the TM hydro dynamical motion in the homogeneously aligned NLC, the director is distorted by an external electric field in a homogenously aligned cylindrical cavity [14], a quasi-static electric field in a planar NLC [15], and by a laser light beam in a homeotropically NLC [16].

Here, another method different from the mentioned methods is proposed to induce a TM flow in a homogenously aligned NLC cell, applying different boundary conditions on the NLC cell without need to external forces used in the previous methods. Proper selection of surface anchoring distorts the director in the NLC bulk, and prepares the needed director non-uniformity for the TM effect occurring. Partial absorption of a linearly polarized plane light wave which propagates perpendicular to a homeotropic NLC cell creates a uniform temperature gradient along the cell thickness (Fig. 1). The cell walls are kept in a constant temperature by contacting them to a thermostat. Different kinds of surface anchoring are considered on the liquid crystal–cell walls interface to find the suitable anchoring pairs. The temperature gradient in the presence of director non-uniformity leads to NLC hydrodynamic owing to the TM effect. The director orientation is coupled to the NLC fluidity. So, the director is reoriented due to this coupling. Ericksen–Leslie coupled equations for the hydrodynamic flow and director reorientation and consequent optical nonlinearity are calculated, numerically.

The paper proceeds as follows: Section 2 deals with governed equations to the problem, and different boundary conditions which can be used. Numerical solutions of the equations with respect to the selected surface anchoring are shown in Section 3. Section 4 devotes a discussion about the earned results. Appendix A briefly discusses the theoretical background of the equations. Finally, in

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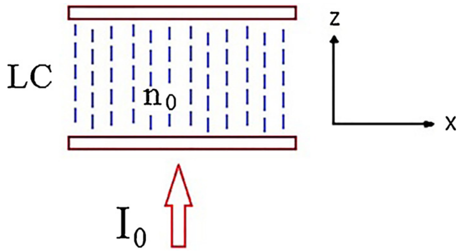

Fig. 1. Schematic representation of a homeotropic nematic liquid crystal cell for light induced TM hydro dynamical flow.

Appendix A, the optical phase shift and optical nonlinearity are calculated.

2. Theory

Considered a set up as Fig. 1. The director is aligned orthogonal to the confining plates and has homeotropic alignment. Partial absorption of a polarized plane laser beam induces a temperature gradient along the z axis. The light beam intensity is considered to be significantly lower than the optical Freedericksz (OFT) transition threshold I_F to discard the effects of the director reorientation due to the OFT. For a homeotropic NLC cell with thickness L, the OFT threshold is $I_F = \frac{\pi^2}{L^2}\frac{c\varepsilon_\parallel K_3}{\varepsilon_a\sqrt{\varepsilon_\perp}}$,where L is the cell thickness, c is the velocity of the light in the vacuum, K_3 is the bend elastic constant, $\varepsilon_\parallel$ and $\varepsilon_\perp$ are the dielectric permittivity at optical frequency parallel and perpendicular to the molecular director $\vec{n}$, and $\varepsilon_a = \varepsilon_\parallel - \varepsilon_\perp$ is the dielectric anisotropy [17]. The director initially is in the z direction $\vec{n_0} = (0, 0, 1)$. The light intensity attenuation crossing the cell $(\exp(-\alpha_\perp L))$ is small, where $\alpha_\perp$ is the perpendicularly polarized light absorption coefficient. The plane light beam propagates in the z direction with a polarization in the y direction. So, the cell can be considered homogeneous in the y direction and the director is distorted in the x–z plane. The perturbed director can be written as $\vec{n} = \vec{n_0} + \vec{\delta n}$ where $\vec{\delta n} = (\delta n_x, 0, \delta n_z)$. Resulted equations are linearized with respect to the director perturbation using $\vec{n_0}\cdot\vec{\delta n} = 0$. So, $\delta n_z = 0$ and the director is only reoriented in the x direction.

The light intensity, light absorption coefficient and cell thickness control the temperature rise in the NLC cell. These parameters are selected in a way that the heat conduction by Rayleigh–Benard convection mechanism can be ignored. The Rayleigh–Benard convection is controlled by the dimensionless Rayleigh number $R_a = g\beta\Delta TL^3/(\nu\kappa)$ where, g is the acceleration due to gravity, β is the thermal expansion coefficient, ΔT is the temperature difference between the plates, κ is the thermal diffusivity, and ν is the kinematic viscosity. Below a critical temperature difference, heat is transported only by the conductivity [3]. Neglecting the heat transport by convection, the heat transport equation in the steady-state is given by

$$\frac{d^2T}{dZ^2} + \eta/L^2 \exp(-\alpha_\perp ZL) = 0, \tag{1}$$

where $\eta = \alpha_\perp I_0/k_\parallel$, I_0 is the incident light intensity, $k_\parallel$ is the heat conduction coefficient parallel to the director, and $Z = z/L$. Keeping the temperature on the cell walls on a constant temperature T_0 by a thermostat, the temperature and temperature gradient in the NLC are easily obtained

$$T = T_0 + \eta[(\exp(-\alpha_\perp L) - 1)Z + (1 - \exp(-\alpha_\perp ZL))], \tag{2}$$

$$\frac{\partial T}{\partial Z} = \eta[(\exp(-\alpha_\perp L) - 1) + \alpha_\perp L \exp(-\alpha_\perp ZL)]. \tag{3}$$

Fig. 2a indicates the temperature rise above the cell temperature T_0 in the NLC cell where T_0 is the cell walls temperature. The light absorption coefficient perpendicular to the director is considered to be $\alpha_\perp = 10\,\text{cm}^{-1}$, which can be tuned by the absorbed light wavelength. The used parameters are assumed to be $L = 100\,\mu\text{m}$, $k_\parallel = 2.4$ mW/cmK, $\varepsilon_\parallel = 3.05$, $\varepsilon_\perp = 2.32$. Light intensity is considered to be $I_0 = 40\,\text{W/cm}^2$, which is small enough to ignore the director distortion by the OFT. The used parameters ensure that I_0 is very smaller than I_F. However, if the director could deviate from the x–z plane, the director could be distorted by the electric field of the light without threshold. But the light polarization perpendicular to the director induces a reorientation only in the x–z plane. Maximum temperature increase with the mentioned parameters is about $2K$ which is at the center of the cell thickness that seems to be reasonable. Because quantities such as boundary conditions and heat transfer in the up or down directions are symmetric with respect to this point. It is acceptable to ignore the temperature dependence of the NLC parameters such as elastic constants, viscose coefficients, density and etc., in this range of temperature rise. The temperature rise is also very smaller than the critical temperature difference which indicates the Rayleigh–Benard convection threshold [3]. The temperature gradient maximum is seen at the entrance interface with a positive magnitude and decreases approximately with a linear slope through the whole cell. It is zero at the center of the cell thickness and finally, at the exhaust interface reaches the minimum value with a negative magnitude (Fig. 2b).

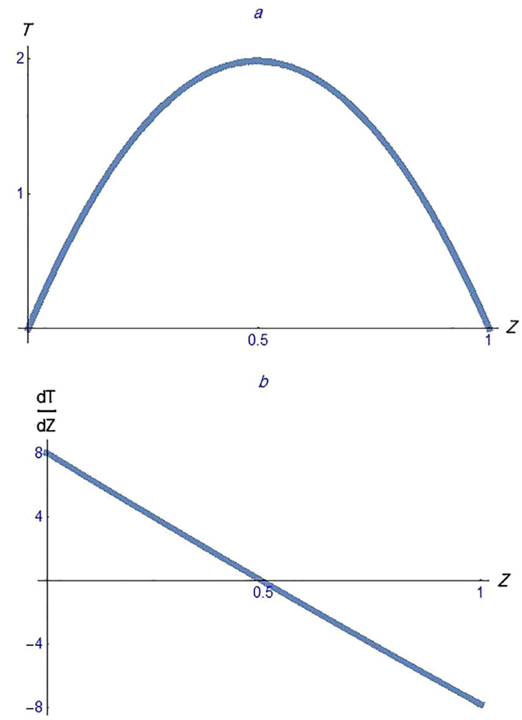

Fig. 2. (a) Temperature increase above the cell walls temperature T_0, and (b) temperature gradient due to a linearly light absorption.

The coupled equations of the NLC hydrodynamic and torque balance can be derived using Ericken–Leslie continuum theory. The NLC hydrodynamic equation (Navier–Stokes) in the steady-state becomes

$$\frac{d^2\delta n_x}{dZ^2}\frac{\partial T}{\partial Z} + \frac{d\delta n_x}{dZ}\frac{d^2T}{dZ^2} + \zeta\frac{d^2v_x}{dZ^2} = 0, \tag{4}$$

where $\zeta = (-\alpha_3 + \alpha_4 + \alpha_6)/(-\xi_4 + \xi_8 - \xi_{11})$, ξ_is (in erg/Kcm) are the TM coefficients, α_i s (in dynes/cm^2) are the Leslie viscosity coefficient [18]. The first and second terms are derived from TM hydrodynamic stress tensor, and the third term comes from viscose stress tensor (Appendix A). The stability loss of the liquid crystals