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Theoretical study of reorientation and torque of liquid crystal molecules under influence of external electric field and experimentally generation of spatial optical soliton beam and getting a sharp switching in chiral nematic liquid crystal

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ABSTRACT

Liquid crystals (LC) are anisotropic materials which experience a torque if an electric field is present. This field can be due to an external voltage or to the presence of a light beam. Reorientation due to light leads to non-linear behavior in the optical behavior. Due to this kind of nonlinearity therefore it is possible to generate optical spatial soliton beam in LC by bias voltage or without it and interestingly chiral nematic liquid crystals has a opportunity to generate spatial optical solitons without the need for a bias voltage. In this paper we also demonstrate that a sharp switching of the helix structure occurs when the spatial soliton is launched in the middle of two regions where soliton generation is favorable. Due to the optical nonlinearity, the helical structure becomes asymmetric and a sharp switching in one direction can be obtained. Moreover, in this paper, the torque and reorientation of the liquid crystal and the change in angular momentum of the light are discussed.

1. Introduction

The positive point of liquid crystals [3,5] is to a large extent related to the extremely low amounts of energy that are required to affect and manipulate the optical properties. In electrically driven liquid crystal displays, the low operation voltage and current enable battery operation of large area high quality displays. For the same reason, liquid crystals are as compared to other materials also very susceptible to light, leading to non-linear effects [1,4] for relatively low light power. This makes liquid crystal very interesting and fascinating material for use in devices based on all-optical signal handling.

In nematic liquid crystals several different kinds of non-linearities can be distinguished. Increasing the intensity of a light beam may increase the temperature and change the optical properties, but this is only important if there is some absorbing species present (ITO electrodes or dye molecules). Typically a temperature increase leads to a reduction of the order parameter and the birefringence of the liquid crystal or the transition to the isotropic state. The geometry of the heat source and heat flow is very important in this case. The light beam may generate electrical charges in the (doped) liquid crystal or in the alignment layers, and these may have an important influence on the electric field and the director orientation in the liquid crystal.

The electrical field of a light beam just like the electric field that is applied over a liquid crystal device exerts a torque on the liquid crystal molecules and can reorient the director. It turns out that the torque, director reorientation and light propagation can be described rather accurately, based on a simple set of equations.

2. Electrical and optical torque

2.1. Definitions

Consider a layer of liquid crystal between two glass plates, covered with ITO with a voltage V_a applied and light entering from the left side, as shown in Fig. 1.

The tilt angle $\theta(z)$ of the liquid crystal director lies in the *xz*-plane. The dielectric constant (low frequency range) perpendicular to the long axis is $\varepsilon_\perp$ and the dielectric anisotropy is $\Delta\varepsilon$. The liquid crystal only shows splay and bend, with elastic constants K_{11} and

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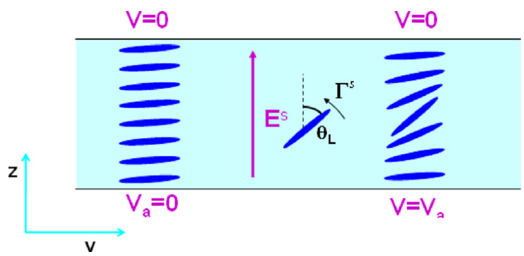

Fig. 1. LC crystal between two glass plates, covered with ITO with and without a voltage.

K_{33}. The low frequency dielectric tensor has the following relevant components:

$$\begin{cases} \varepsilon_{xx}^s = \varepsilon_\perp^s + \Delta\varepsilon^s \cos^2\theta \\ \varepsilon_{xx}^s = \varepsilon_\perp^s + \Delta\varepsilon^s \cos^2\theta \\ \varepsilon_{xz}^s = \varepsilon_{xz}^s = \Delta\varepsilon^s \sin\theta \cos\theta \end{cases} . \tag{1}$$

The light in air is linearly polarized along the x-axis and the ordinary and extra-ordinary indices (optical frequency range) are n_o and n_e. The dielectric tensor in the optical range has components:

$$\begin{cases} \varepsilon_{xx} = \varepsilon_0(n_e^2\cos^2\theta + n_o^2\sin^2\theta) \\ \varepsilon_{zz} = \varepsilon_0(n_e^2\sin^2\theta + n_o^2\cos^2\theta) \\ \varepsilon_{xz} = \varepsilon_{zx} = \varepsilon_0(n_e^2 - n_o^2)\cos\theta \sin\theta \end{cases} . \tag{2}$$

2.2. Electrical torque

If a voltage V_a is applied over the electrodes, the liquid crystal will show a certain tilt $\theta(z)$ and static electric and displacement fields appear in the liquid crystal. In a one-dimensional approximation (all variables depend only on z), the field will only have a component perpendicular to the substrates and the displacement field will have both x and z components:

$$\begin{aligned} D_x^s &= \varepsilon_{xz}^s E_z^s \\ D_z^s &= \varepsilon_{zz}^s E_z^s \end{aligned} . \tag{3}$$

with D_z equal to the surface charge density on the left electrode (and thus independent of z) and:

$$\int_0^d E_z^s dz = V_a. \tag{4}$$

The torque per volume unit on the liquid crystal follows from the derivation of the electrical energy density under the application of a constant voltage: $F^s = -(1/2)\mathbf{D}^s \cdot \mathbf{E}^s$ and is given by:

$$\begin{aligned} \mathbf{\Gamma}^s &= \Delta\varepsilon^s(\mathbf{L}\cdot\mathbf{E}^s)(\mathbf{L}\times\mathbf{E}^s) \\ \Gamma_y^s &= -E_z^s D_x^s = -\Delta\varepsilon^s \sin\theta \cos\theta |E_z^s|^2 \end{aligned} . \tag{5}$$

The clockwise torque on the liquid crystals is compensated by an equal counter-clockwise torque on the electrode charges. This torque arises from the fact that charges at both sides of a flux tube, formed by displacement field lines, are shifted along the x-axis. Fig. 2 is shown that how to apply electric field to a LC molecule.

2.3. Optical torque

If an electromagnetic plane wave enters from the left perpendicularly to the substrate (wave vector along the z-axis), the wave vector in the liquid crystal will also be along z and the corresponding D vector only has a component along x. The effective refractive index is given by:

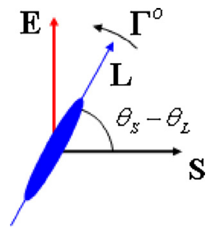

Fig. 2. LC molecule experience an electric torque.

$$n_{\text{eff}} = \frac{n_e n_o}{\sqrt{n_e^2\cos^2\theta + n_o^2\sin^2\theta}}. \tag{6}$$

Because of the anisotropy, the Poynting vector makes an angle θ with the z axis and the electric field makes the same angle θ with the D-field:

$$\tan\beta = \frac{\varepsilon_{zx}}{\varepsilon_{xx}} = \frac{(n_e^2 - n_o^2)\cos\theta \sin\theta}{n_e^2\cos^2\theta + n_o^2\sin^2\theta}. \tag{7}$$

For simplicity, we assume that there are no reflections at the interfaces (using perfect anti-reflection coatings). The energy density in the liquid crystal is higher than the energy density in air by a factor equal to the effective refractive index. Using complex notation for the electric field components, we find:

$$F = -\frac{1}{2}\mathbf{D}^* \cdot \mathbf{E} = -\frac{1}{2}\varepsilon_0 n_{\text{eff}} |E_0|^2, \tag{8}$$

with E_0 the amplitude of the electric field in air. The torque is found by taking the derivative with respect to the angle θ:

$$\Gamma_y = -\frac{\partial F}{\partial\theta} = \frac{1}{2}\varepsilon_0 \frac{\partial n_{\text{eff}}}{\partial\theta}|E_0|^2. \tag{9}$$

Alternatively, we can use the formula for the torque by light on an anisotropic medium (the factor ½ is due to the harmonic oscillation of the field):

$$\begin{aligned} \mathbf{\Gamma} &= \frac{1}{2}\varepsilon_0(n_e^2 - n_o^2)(\mathbf{L}\cdot\mathbf{E}^*)(\mathbf{L}\times\mathbf{E}) \\ \Gamma_y &= \varepsilon_0(n_e^2 - n_o^2)\cos(\theta+\beta)\sin(\theta+\beta)|E_{LC}|^2 \end{aligned} . \tag{10}$$

Both formulas lead to the same result for the torque per unit volume:

$$\begin{aligned} \Gamma_y &= \frac{1}{2}\varepsilon_0(n_e^2 - n_o^2)\frac{n_{\text{eff}}^3}{n_e^2 n_o^2}\cos\theta \sin\theta |E_0|^2 \\ &= \frac{1}{2}\varepsilon_0 n_{\text{eff}} \tan\beta |E_0|^2 \end{aligned} . \tag{11}$$

Due to the anisotropy, the light that passes the liquid crystal layers is shifted laterally over a distance Δx:

$$\Delta x = \int_0^d \tan\beta dz. \tag{12}$$

Due to this shift, the two oppositely directed forces that act on the surfaces of the substrates will yield a clockwise torque:

$$-\frac{1}{2}\varepsilon_0|E_0|^2(n_{\text{eff}} - 1)\Delta x. \tag{13}$$

The angular momentum with respect to the y axis increases when photons travel through the substrate. The change in angular momentum is $\hbar k \Delta x$ per photon. The rate of change in angular momentum per unit area is given by:

$$-\frac{1}{2}\varepsilon_0|E_0|^2\Delta x. \tag{14}$$