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Quantitative Theory and Experiments on Optical Imaging and Switching Properties of Nematic Liquid Crystals

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Recently, the nonlinear optical properties of nematic liquid crystals under the action of optical and dc-plus-optical fields have received considerable attention [1–3]. The similarity of an optically induced Freedericksz transition to the well-known dc field counterpart has been theoretically and experimentally studied. For nonlinear optical processes, the underlying mechanism is the intensity dependent refractive index change associated with molecular reorientation.

In this paper, we present an analytic and explicit solution of the Euler-Lagrange equation that describes the molecular reorientation under an optical field. We work in the small angle (angle <0.5 radians) limit. The accuracy of the approximation is negligible, in fact, compared to many other more frequently made assumptions (e.g. the one-constant approximation) in some of the so-called exact solutions. Furthermore, the explicit expressions for the molecular reorientation and optical nonlinearities allows one to clearly identify the following: (i) a numerical estimate of the nonlinearity, (ii) the dependence on geometry (i.e. relative orientation of the optical field with the nematic axis, and (iii) the thickness dependence.

These explicit solutions are summarized as follows. First, a solution of the Maxwell equation for the birefringement medium (in which an optical field is incident on a homeotropically aligned nematic film such that the optical wave vector k makes an angle β with the director axis $\hat{n}$) yields an effective dielectric ε_{eff} given by

$$\varepsilon_{eff} = \varepsilon_\perp \varepsilon_\parallel / [\varepsilon_\parallel \cos^2(\beta+\theta) + \varepsilon_\perp \sin^2(\beta+\theta)], \tag{1}$$

where θ is the reorientation of the molecule and $\varepsilon_\perp$ and $\varepsilon_\parallel$ are the dielectric constants for optical field polarized perpendicular and parallel to the nematic axis, respectively. The reorientation angle θ obeys the Euler-Lagrange equation.

$$2\xi^2 \frac{d^2\theta}{dz^2} + \theta(2\cos 2\beta) + \sin 2\beta = 0, \tag{2}$$

where z is the direction of the unperturbed director (optic) axis of the nematic, in the limit of small θ. In (2), $\xi^2 = 4\pi K(\Delta\varepsilon)^{-1} E_{op}^{-2}$ where K is the elastic constant, $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ and E_{op} is the optical electric field. The solution of (3) for θ subject to the hard boundary conditions $\theta = 0$ at $Z = 0$ and at $Z = d$ is a simple sine-cosine function from which the dependence on the thickness d can be simply derived. More specifically, the maximum molecular reorientation θ_{max} is given by $\theta_{max} = \frac{\sin 2\beta}{16\xi^2 d^{-2}}$. From (1) and (2) and θ_{max}, the intensity dependent refractive index $\delta\varepsilon_\theta$ can be simply obtained.

$$\delta\varepsilon_\theta \sim \Delta\varepsilon \varepsilon_\perp \beta \sin 2\beta / 8\varepsilon_\parallel \xi^2. \tag{3}$$

If the finite absorption of the laser by the nematic is also accounted for, a further change in refractive index via the thermal indexing effect is induced and is shown to be of the form

$$\delta\varepsilon_{th} \sim \alpha_{th} I - \alpha_{th}(\gamma+1)\beta \sin 2\beta, \tag{4}$$

where γ is the ratio of $d\varepsilon_\parallel/dT$ (T, the temperature) to $d\varepsilon_\perp/dT$. α_{th} is a constant.

We have verified these theoretical results in degenerate four wave mixing process of two laser beams and in the self focusing effect of a single laser beam. Quantitative agreements between theory and experiments on the thickness, the geometry and on the intensity dependences are obtained. Numerical comparisons between the experimental wave mixing efficiency, the self-focusing power etc. with theory also show good agreement. In our experiments, two kinds of nematic liquid crystals were used, MBBA (p-methoxybenzylidene-p-butylaniline and PCB (4-cyano-4-pentyl-biphenyl), the former absorbs more of the laser light and exhibits a larger thermal indexing effect.

We have also succeeded in using the molecular reorientational and the thermal indexing effect for optical switchings. A nematic film sandwiched between two prism was shown to be able to switch from a total-internal-reflection state to a transmission state; some bistability behaviors were also observed. In conjunction with two crossed polarizes the nematic film was also demonstrated to be an optical polarization switch.

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