Real-condition optical reorientation in liquid crystalline photonic cell

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Abstract— In the present work the mechanism of optical orientational nonlinearity in liquid-crystalline nematic structure is examined. The results obtained in the frame of the classical Oseen-Frank-Leslie model of the effect are considered in real conditions. The paper addresses physical aspects of the mechanism, which are really met but not taken into account in the theory. Some selected aspects are discussed, which are essential in expected applications.

Mutual interaction between light and matter results in a number of nonlinear optical effects. Many of them are expected to find applications shortly in photonic devices like all-optical modulators, switches, routers, displays, light sources and amplifiers, controllable filters and gratings, etc., mainly for use in communication systems, but they are also explored for image processing, adaptive optics, medicine, optical computing, and other application areas. Among various photosensitive media explored, liquid crystals (LC) are materials with the largest optical nonlinearity. The major mechanism of nonlinear optical phenomena observed in liquid-crystalline phase is orientational nonlinearity. It is caused by the distortion of the initial molecular arrangement of an anisotropic medium that is induced by optical field. Deformation of the anisotropic structure means spatial changes of the refractive index of the medium, resulting in several optical phenomena such as self-diffraction of the propagating beam, nonlinear wave-guiding (solitons), etc. Optical phenomena in liquid crystals are also utilized in microstructured elements like photonic fibers, enabling optical or electro-optical control of light propagation properties.

The Oseen-Frank-Leslie theory of orientational nonlinearity in liquid crystals is borrowed from fluid mechanics. Originally, the theory was developed in LC to describe electro-optical effects and was next adapted for light-induced phenomena. It is based on minimization of free Gibss energy density in an LC structure subjected to action of the electric field of a light wave [1,2]. This approach is equivalent to equalization of optical torque produced by light, with elastic torque arising as a reaction of an LC-structure to light-induced distortion. In equilibrium, a certain deformation of the structure is established, the magnitude of which is light-intensity dependent. Optical deformation of an anisotropic structure provokes light-intensity dependent refractive-index changes, resulting in Kerr-like optical nonlinearity. The theory introduces the following simplifying assumptions [3]:

- deformation is locally small and continuous (smoothly distributed in an LC structure),
- LC order-parameter remains constant and is not taken into account (thermal fluctuations are omitted),
- structure elastic reaction is linear, i.e. elastic torque can be written as: $\tau_{el} = K\,\Delta$, where Δ is the induced local deformation and K is a constant.

Each of the above assumptions is more or less distinct from real conditions. Despite that, the theory predicts fairly good experimental results. However, in applications the effects omitted in the theory may play an important role by improving and optimizing device operation. The subject of the present work is verification of the 3rd assumed statement – i.e. linearity of structure elastic response. It may be done by examining the deformation of an LC structure in the simplest homeotropic-nematic geometry [4]. Theoretical solution in this case can be found by solving the constitutive equation of optically introduced deformation:

$$\tau_{opt} = \tau_{el} \tag{1}$$

The optical torque τ_{opt} in the considered case can be written as [3]:

$$\tau_{opt} = V_m \varepsilon_o \Delta\varepsilon E_{opt}^2 \sin\varphi \cos\varphi$$

so that (1) takes the form:

$$V_m \varepsilon_o \Delta\varepsilon E_{opt}^2 \sin\varphi \cos\varphi = K\Delta(\delta) \tag{2}$$

with V_m being the volume of an integral structural element, $\Delta\varepsilon$- dielectric anisotropy of the structure, and K- effective elastic constant of the induced deformation; the angles φ, δ are defined in Fig.1.

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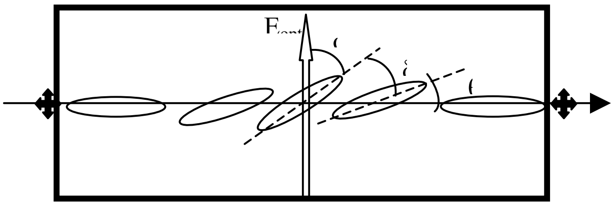

Fig.1. Deformation introduced by optical field E_{opt} in homeotropic nematic structure, initially aligned along z-axis

The solution of eq. (2) delivers the distribution of optical deformation inside the analyzed structure $\delta(z, E_{opt})$, which appears to be a threshold process. It means that no deformation occurs until optical field intensity reaches some critical "threshold" value, I_{th}. In the considered geometry, for an LC-layer of thickness *d* the threshold has the minimal possible value [5],

$$I_{th} \cong \frac{4\pi K}{\Delta\varepsilon}\left(\frac{\pi}{d}\right)^2 \qquad (3)$$

From a physical point of view, the effect of a threshold results from nonlinearity of optical torque $\tau_{opt}(\varphi)$. The effect is illustrated in Fig.2.

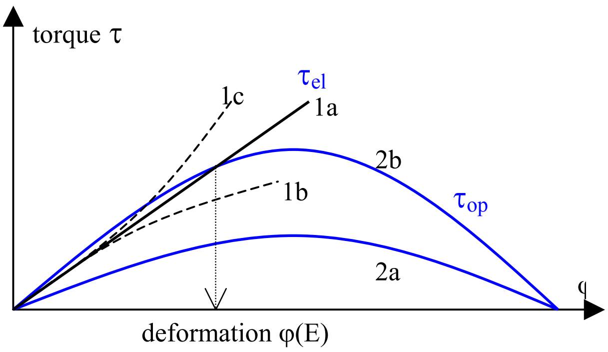

Fig.2. The balance between optical and elastic torques $\tau_{opt,}$ τ_{el} below threshold (2a) and above threshold intensity (2b) by assumed linear elasticity (1a)

The slope of the function $\tau_{opt}(\varphi)$ depends on light intensity $(E_{opt})^2$

$$\frac{d\tau_{opt}}{d\varphi} = V_m \varepsilon_o \Delta\varepsilon E_{opt}{}^2 (\cos^2\varphi - \sin^2\varphi)$$

being maximal at φ=0. For small light intensities, until $d\tau_{opt}/d\varphi < d\tau_{el}/d\varphi$, the both curves $\tau_{opt}(\varphi)$, $\tau_{el}(\varphi)$ intersect only at φ=0, then no deformation occurs. Critical intensity I_{th}~$(E_{opt}{}^{th})^2$ is reached if both curves are tangential at φ=0, while for higher light intensities they intersect for φ>0 and a certain deformation is established obeying eq. (1).

The threshold value is crucial for applications - in most cases it should be as low as possible; since it depends on elastic coefficient K (eq.3), elastic response of the LC structure directly influences the threshold. However, elastic characteristics influences not only the threshold, but also affects the whole reorientation process above the threshold as well, including LC-structure sensitivity to light, as it can be inferred from Fig.2 – curves 1b, 1c.

To check whether elastic reaction of an LC-structure is linear or is not, one can induce its deformation of various magnitudes and then observe the structure response. We did it by studying the dynamics of a reorientation process. We induced optically augmenting deformation in a homeotropic nematic layer by applying pulses of a laser beam with consecutively increased intensity. Then we examined the free relaxation process from induced initial deformation θ_{max} after the laser was shut off.

Structural response was detected by recording far-field self-diffraction images [6]. The magnitude of deformation in a given place of the LC-sample (let say in the layer center) is associated with the number of diffraction fringes that appear in the diffraction plane.

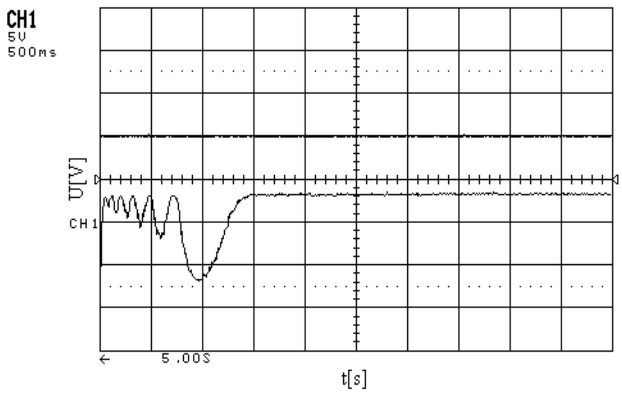

Fig.3. The record of time evolution of diffraction fringes (minima and maxima) showing the dynamics of the relaxation process in an initially deformed LC-layer

During the relaxation process we measured the time $t(\theta)$ needed for deformation to come back to a chosen fixed value θ from a different initial distortion $\theta_{max.}$ Orientational free relaxation is governed by a simple exponential law [1,3]:

$$\theta(t) = \theta_{max} e^{-\frac{t}{\tau_r}} \qquad (4)$$

with characteristic relaxation time inversely proportional to elastic coefficient K:

$$\tau_r = \frac{\gamma d^2}{K\pi^2} \qquad (5)$$

By re-writing eq. (4) one obtains the measured time t_n that has passed until relaxing deformation reaches selected value θ_n attributed to n fringes in diffraction image:

$$t_n = \tau_r \ln\theta_{\max} - \tau_r \ln\theta_n \qquad (6)$$

Since we neither knew the θ_n value nor the exact relation between θ_n and the number of fringes n, we couldn't directly evaluate τ_r; therefore we examined the slope of the function $t_n(\theta_{max})$. From eq. (6) the slope is:

$$\frac{dt_n}{d\theta_{\max}} = \frac{\tau_r}{\theta_{\max}} + \frac{d\tau_r}{d\theta_{\max}}(\ln\theta_{\max} - \ln\theta_n) \qquad (7)$$

The measured experimental data shown in Fig. 4 indicate that this slope is a decreasing function of the θ_n-value (associated with n-fringes) chosen in the relaxation process, i.e. decreases for t_1, t_2, etc.

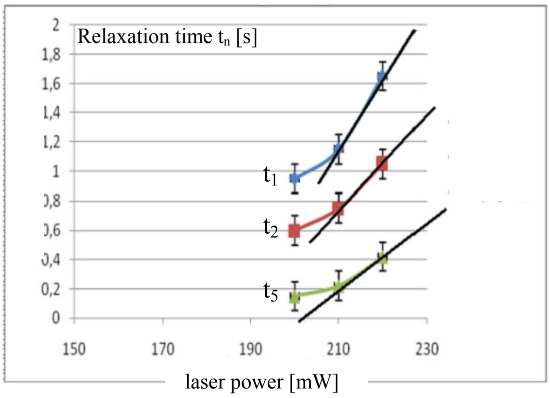

Fig.4. The time t_n passing till the relaxing deformation reaches some fixed value θ_n (defined by the number of diffraction fringes n) versus increasing initial value θ_{max} attributed to laser power, for n= 1, 2 and 5 fringes

According to eq. (7) it is possible if

$$\frac{d\tau_r}{d\theta_{\max}} > 0$$

which, in turn, with regard to (5), indicates a decrease in elastic constant K with increasing deformation θ_{max}. It then means nonlinearity of elastic reaction of an LC-structure in spite of theoretical assumption.

It follows from the above considerations that elasticity of a liquid crystal structure is nonlinear for large deformations; this fact, not taken into account in the present theory, can substantially influence the threshold value, sensitivity, and speed of operation of liquid crystalline photonic devices.

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