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Hysteresis upon light-induced hydrodynamic reorientation of the director of a nematic liquid crystal

R S Akopyan, R B Alaverdyan, A S Vardanyan, Yu S Chilingaryan

Abstract. Oscillations and hysteresis in the behaviour of the director of a nematic liquid crystal were observed upon its light-induced hydrodynamic reorientation caused by direct volume expansion. The light propagated through the liquid crystal placed between crossed polarisers provides the feedback. This light falls back on the liquid crystal and is absorbed by producing the volume expansion. A theory is suggested that describes the observed behaviour of the director of the nematic liquid crystal.

The fact that a quite moderate absorbed power is sufficient for a substantial reorientation of the director of a nematic liquid crystal (NLC) has long been known (see, e.g., [1]). Two mechanisms of a transformation of the absorbed energy to the energy of elastic orientation (theromocapillary and gravitational) were proposed in Refs. [2, 3].

Recently [4], the third, light-induced hydrodynamic (LIH) mechanism of the reorientation of the director of an NLC by a light wave with power of the order of 10^{-5} W was suggested. The essence of this mechanism is as follows. The light energy absorbed in the NLC volume heats it, resulting in the volume expansion. Under the action of pressure produced by the expanding liquid, a Poiseuille's flow of the NLC appears in a capillary connected with the liquid absorbing light, resulting in the director reorientation.

In this paper, we found and studied experimentally oscillations and hysteresis in the reorientation of the director of an NLC upon varying the light field intensity, which are caused by a competition between the direct reorientation of the director produced by the light wave electric field and the LIH reorientation. An important feature of the LIH effect under study is that the reorientation angle of the NLC director is proportional not simply to the temperature change but to the rate of this change. In this respect, the LIH effect is analogous to a pyroelectric effect in crystals, where the current produced is proportional to the time derivative of the temperature.

In our experiments, a 0.51-μm beam from an argon laser that passed through a polariser was incident on a cell containing a homotropous NLC of thickness 35 μm, producing the light-induced Freedericksz transition (see, for example, [5]). Then, the light, having passed through an analyser crossed with the polariser, was reflected from a mirror (with the reflectivity $R = 1$) back to the NLC, where it was absorbed, producing the LIH reorientation of the director.

Fig. 1 shows a schematic of the experimental setup. To increase absorption, we added a rhodamine 6G dye to the NLC at a concentration of 10^{-3} mol litre^{-1}. The absorption coefficient of this mixture at 0.51 μm was ~ 0.2 cm^{-1}. To reduce the influence of the ambient temperature, we placed the cell inside a Dewar flask. The rate of temperature variation in the flask did not exceed 10^{-5} K c^{-1}.

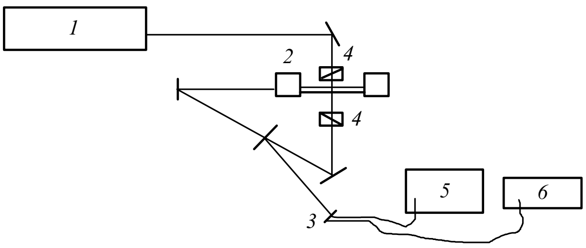

Figure 1. Experimental setup: (*1*) argon laser; (*2*) homotropous NLC cell; (*3*) FEK-1 photoelement; (*4*) crossed polarisers; (*5*) C1-77 oscillograph; (*6*) recorder.

The low-intensity laser radiation is not transmitted through the polariser-NLC-analyser system. Above the Freedericksz transition threshold $P_1 = 2.2$ kW cm^{-2}, the light passes through the system, is reflected from a mirror and falls on the NLC, producing the LIH flow (Poiseuille's flow caused by the liquid volume expansion upon absorption of light). The LIH flow further increases the reorientation of the NLC director, so that above the Freedericksz transition threshold the system transmission $T = P_2/P$ (where P_2 and P are intensities of the transmitted and incident waves, respectively) abruptly increases (Fig. 2). When the incident light intensity is $P = P_3$, the intensity of transmitted light exhibits oscillations and a jump (Fig. 3).

At higher intensities, from $P = P_3 = P_1$ to $P = P_4 = 2.95$ kW cm^{-2}, the system stabilises the intensity of the transmitted wave. For the incident wave intensity above $P_5 = 3.2$ kW cm^{-2}, the reorientation of molecules in the NLC volume equals $\pi/2$ and the uniformity of the director distribution is destroyed only near the cell boundary. For this reason, the cell only weakly changes polarisation of the incident light,

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R S Akopyan, R B Alaverdyan, A S Vardanyan, Yu S Chilingaryan
Department of Physics, Erevan State University, ul. Alek Manukyan 1, 375025
Erevan, Armenia

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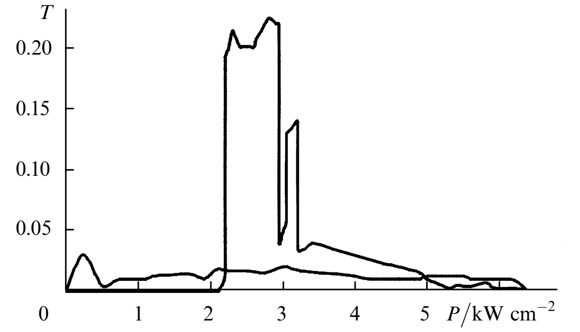

Figure 2. Hysteresis of the system transmission as a function of the incident radiation intensity.

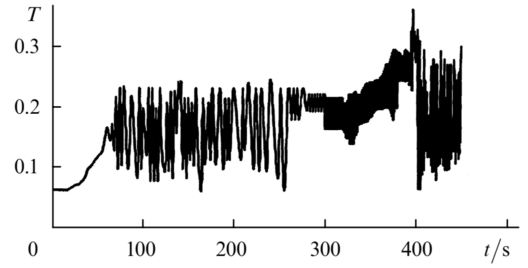

Figure 3. Time oscillations of the system transmission at points of its abrupt changes.

and the polariser–NLC–analyser system weakly transmits the light. Therefore, for $P > P_5$, the transmission of the system drastically decreases. This situation also takes place at the lower intensity of the incident light because even at such a weak transmission the intensity of the transmitted wave is sufficient for producing a strong LIH reorientation. This means that the LIH effect is observed virtually to the zero intensity of the incident light.

Thus, the transmission of the system under study exhibits a very unusual hysteresis. Note also that upon the abrupt change in the transmission of the system, oscillations of the transmission are observed at all points (Fig. 3).

We will use the stationary equation of the LIH reorientation [4]

$$\frac{d^2\varphi}{dz^2} + \frac{\pi^2}{2L^2}\frac{\alpha\beta V\chi P_{\rm lhd}}{l\rho C_p K}\cos\frac{\pi z}{L} = 0 \qquad (1)$$

for the description of the hysteresis effect. In Eqn (1), φ is the director reorientation angle; the z axis is directed perpendicular to the NLC capillary; $P_{\rm lhd}$ is the intensity of light absorbed by the NLC; L and l are the thickness and width of the capillary, respectively; α is the Lesly coefficient; β is the volume expansion coefficient; V is the light absorbing volume; χ is the absorption coefficient; ρ is the NLC density; C_p is the heat capacity at constant pressure; and K is the Franck elastic coefficient. The intensity of light transmitted by the polariser–NLC–analyser system in the case of normal incidence is described by the expression [6]

$$P_2 = P\sin^2\frac{\Delta\Phi}{2}, \quad \Delta\Phi = \Phi_{\rm a}\frac{\varepsilon_\perp^{1/2}}{L}\int_0^L \varphi^2(z)\,dz, \quad \Phi_{\rm a} = \frac{\omega}{2c}L\frac{\varepsilon_{\rm a}}{\varepsilon_\parallel}. \qquad (2)$$

Here, $\Delta\Phi$ is the phase difference of the ordinary and extraordinary waves at the capillary exit; $\varepsilon_{\rm a} = \varepsilon_\parallel - \varepsilon_\perp$ is the anisotropy of the NLC permittivity at the frequency ω; and c is the speed of light in vacuum. The intensity of light absorbed by the NLC is $P_{\rm lhd} = RP_2$.

Simultaneous numerical solution of equations (1) and (2) gives a hysteresis loop corresponding to this shown in Fig. 2. For low intensities P, the reorientation is absent ($\varphi = 0$), so that $\Delta\Phi = 0$ and light does not pass through the system ($P_2 = 0$). Above the threshold of the light-induced Freedericksz transition ($P \geqslant P_1$, $P_1 = P_{\rm Fr} = \pi^2 c\varepsilon_\parallel K_3\varepsilon_{\rm a}^{-1}\varepsilon_\perp^{-1/2}L^{-2}$, where K_3 is the elastic modulus), the NLC director is reoriented by the electric field of the light wave ($\Delta\Phi \neq 0$). In this case, the light passes through crossed polarisers and is reflected back to the NLC by a mirror.

The NLC volume expansion caused by absorption of light results in the additional LIH reorientation of the director. As the laser intensity P decreases, the reorientation angle becomes zero at the intensities P_6 that are much lower than P_1. This is explained by the fact that the intensities required for reorientation are very low ($\sim 10^{-5}$ W), and the polariser-NLC-analyser system remains open for a long time during the reverse passage.

The system suggested above can be used in a compact bistable device. In addition, it can stabilise the transmitted radiation power in a broad range of intensities of the incident radiation. The effect studied in this paper can also be used for analysis of viscosity and elasticity of liquid crystals.

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