Quantum Electronics **30** (7) 653 – 654 (2000)

PACS numbers: 61.30.Gd; 42.50.Vk
DOI: 10.1070/QE2000v030n07ABEH001784

Photoinduced thermomechanical effect in homogeneous nematics

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Abstract. A laser-induced thermomechanical hydrodynamic flow is theoretically predicted and experimentally detected in a horizontal layer of a nematic liquid crystal with a homogeneous distribution of the director in the presence of vertical temperature gradient. This effect is caused by the gradient in the director distribution (which is necessary for the usual thermomechanical effect) produced by the light field due to photoinduced Freedericksz transition.

The thermomechanical effect in nematic liquid crystals (NLCs) with an inhomogeneous distribution of the director is now well studied both theoretically and experimentally [1 – 4]. The effect consists in the appearance of a hydrodynamic flow of matter in a horizontal layer of the NLC in the presence of vertical temperature gradient. It has been shown that this effect is specifically related to the inhomogeneous distribution of the NLC director, being absent in planar or homotropically oriented cells.

In this paper, we observed a photoinduced thermomechanical hydrodynamic flow in a homotropically oriented horizontal layer of the NLC. The effect is caused by the inhomogeneous reorientation of the NLC director that occurs above the threshold of the photoinduced Freedericksz transition, resulting in the appearance of a hydrodynamic flow in the presence of the vertical temperature gradient.

We used in our experiments a cell with the homotropically oriented 5TsB NLC (Fig. 1). At the lower substrate, a homotropic boundary condition was specified, while for the upper substrate no boundary conditions were specified. As a result, in the case of a small thickness of the NLC layer, the NLC molecules possessed a homogeneous homotropic orientation. The thickness of glass substrates was 1 mm.

The vertical temperature gradient was produced by water circulating at two controlled temperatures. The thermal conductivity of the cell substrates was two-three times higher than that of the NLC film. This necessary condition provided constant boundary conditions for the temperature. The hydrodynamic motion was visualised by adding aluminium powder with a weight concentration of the order of $10^{-3}\%$ to the NLC. The difference of temperatures of the substrates was set within 0 – 10°C with an error of 0.1°C.

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Received 4 October 1999
Kvantovaya Elektronika **30** (7) 653 – 654 (2000)
Translated by M N Sapozhnikov

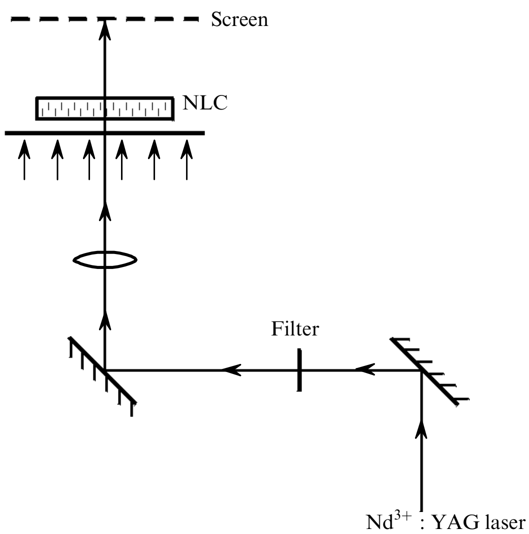

Figure 1. Schematic of the experiment.

Linearly polarised radiation of the second harmonic of a pulsed Nd^{3+} : YAG laser at 0.53 μm was normally incident on an NLC layer. The pulse duration and repetition rate were 20 ps and 50 Hz, respectively. The radiation was focused on the cell with a lens with a focal distance of 25 cm. When the laser radiation intensity was lower than a threshold value, a thermomechanical hydrodynamic flow was absent.

For the cell thickness of 110 μm, the threshold power of the photoinduced Freedericksz transition was approximately 15 mW. Above this threshold, the director changed its orientation. In accordance with the boundary conditions, the reorientation angle near the lower substrate was zero and reached a maximum value near the upper substrate, which was directly proportional to the radiation intensity.

Thus, laser radiation produced a specific hybrid distribution of the director. In this cell, in the presence of the temperature drop $\Delta T = 5.2$°C, a hydrodynamic flow appeared. As the laser radiation power increased, the flow rate also increased and tended to saturation (Fig. 2) (the method for measuring the hydrodynamic velocity was described in Ref. [2]). This increase is caused by the increase in the orientation angle of the NLC director. For the laser power equal to 32 mW, the flow rate achieved a maximum value of ~ 0.62 ms^{-1}. A further increase in the laser power would result in a decrease in the gradient of the orientation angle of the director and a drastic drop in the hydrodynamic flow velocity to zero. However, a strong absorption in the NLC at high radiation intensities causes the bubble cavitation, which prevents the effect under study.

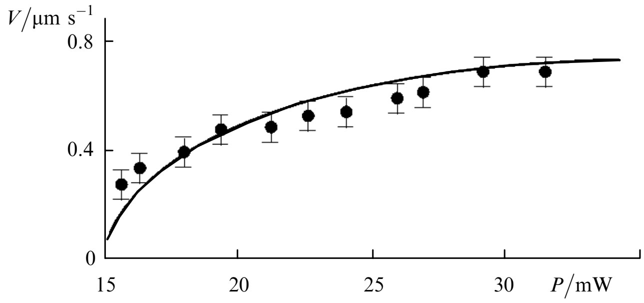

Figure 2. Dependence of the NLC flow velocity V on the laser radiation power P at the temperature drop on the cell walls $\Delta T = 5.2$ °C.

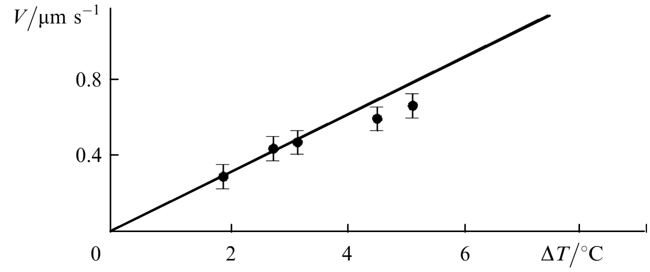

Figure 3. Dependence of the NLC flow velocity V on the temperature drop on the cell walls ΔT for the laser radiation power $P = 21.5$ W.

We also measured the dependence of the maximum velocity of the hydrodynamic flow on the temperature drop on the cell walls at the constant radiation power $P = 21.5$ mW (Fig. 3).

To make theoretical estimates, consider first the thermomechanical effect in a plane-oriented nematic with the director $\boldsymbol{n} = \{n_x = \sin\theta, n_y = 0, n_z = \cos\theta\}$ in the case of hybrid orientation, when $\theta = \pm\pi z/2L$, where L is the cell thickness. Let the condition $T(z=0) > T(z=L)$ be satisfied for the temperatures kept on the NLC cell substrates. Then, in the presence of the gradient of the director orientation angle along the z co-ordinate, a thermomechanical hydrodynamic flow appears which moves along the x-axis at the velocity $\boldsymbol{V}(z) = \boldsymbol{e}_x V_x(z)$. Consider a stationary ($\partial/\partial t = 0$) and homogeneous (in the xy ($\partial/\partial x = \partial/\partial y = 0$) plane) problem. The Navier–Stokes equation in the thermomechanical single-constant approximation ($\xi_1 = \xi_2 = ... = \xi_{12} = \xi$) has the form [1]

$$\left(\eta_1 n_x^2 + \eta_2 n_z^2\right)\frac{\mathrm{d}^2 V_x}{\mathrm{d}z^2} + 2\left(\eta_1 - \eta_2\right) n_x n_z \frac{\mathrm{d}\theta}{\mathrm{d}z}\frac{\mathrm{d}V_x}{\mathrm{d}z}$$

$$= \frac{1}{4}\xi\nabla T\left(\frac{\mathrm{d}\theta}{\mathrm{d}z}\right)^2\left(3 - n_x n_z - 15 n_x^2 + 16 n_x^3 n_z + 12 n_x^4\right) \qquad (1)$$

$$+ \frac{1}{4}\xi\nabla T\frac{\mathrm{d}^2\theta}{\mathrm{d}z^2}\left(3 + 3n_x n_z - n_x^2 - 3n_x^3 n_z + 4n_x^4\right).$$

Here, $\nabla T = \mathrm{d}T/\mathrm{d}z$ is the temperature gradient and η_1, η_2 are the Messovich viscosity coefficients.

For a particular distribution $\theta(z)$, it is necessary to solve numerically Eqn. (1) with boundary conditions $V_x(z=0) = V_x(z=L) = 0$ and to obtain the velocity distribution $Vx(z)$. The latter has the shape that is close to the parabolic one, with a maximum at the cell centre. In the case of hybrid orientation of the cell, this maximum is described by the expression

$$V_{\max} \approx 0.148\frac{\Delta T}{L\xi(\eta_2 - \eta_1)}. \qquad (2)$$

Consider now a NLC with the initially homogeneous distribution of the director. There is no thermomechanical hydrodynamic flow in such a cell in the absence of the director gradient. However, linearly polarised laser radiation incident on the cell induces the Freedericksz transition, which consists in the reorientation of the NLC director by the angle

$$\theta = \theta_m \sin\frac{\pi z}{2L}, \quad \theta_{\mathrm{m}} = 2\left(\frac{P - P_{\mathrm{th}}}{P_{\mathrm{th}}}\right)^{1/2}. \qquad (3)$$

when the radiation power exceeds a threshold value P_{th}. By substituting the distribution (3) into Eqn. (1) and integrating it, we obtain the maximum flow velocity

$$V_{\max} = \frac{\pi\Delta T}{64L\eta_2}\xi\theta_{\mathrm{m}}. \qquad (4)$$

The found dependences of the hydrodynamic flow velocity on the temperature drop ΔT and laser radiation power P well agree with the experimental results (Figs. 2 and 3).

Thus, we demonstrated the photoinduced thermomechanical effect in a homogeneously-homotropically oriented NLC cell. This effect is yet another example of conversion of the light energy to hydrodynamic energy.

Acknowledgements. This work was supported by the INTAS (Grant No. 97-1672).

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