Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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D. I. Anikeev[a]; Yu. V. Bocharov[a]; A. D. Vuzhva[a]
[a] N. N. Andreev Institute of Acoustics, Moscow, U.S.S.R.

To cite this Article Anikeev, D. I. , Bocharov, Yu. V. and Vuzhva, A. D.(1989) 'Reduction of threshold of acousto-optic effect in a nematic crystal subject to combined actions', Liquid Crystals, 6: 5, 593 — 596
To link to this Article: DOI: 10.1080/02678298908034178
URL: http://dx.doi.org/10.1080/02678298908034178

LIQUID CRYSTALS, 1989, VOL. 6, NO. 5, 593–596

Reduction of threshold of acousto-optic effect in a nematic crystal subject to combined actions

by D. I. ANIKEEV, YU. V. BOCHAROV and A. D. VUZHVA
N. N. Andreev Institute of Acoustics, 4 Shvernik Street, Moscow 117036, U.S.S.R.

(*Received 9 November 1988; accepted 9 May 1989*)

The acousto-optic effect in a homeotropically aligned layer of a nematic liquid crystal was investigated subject to combined actions: 1, for coherent excitation of ultrasonic and viscous waves, 2, for ultrasonic action in an electric field near the Freedericksz transition. The acousto-optic effect threshold was reduced by two orders of magnitude. The experimental results are discussed using the acoustic streaming model. The theoretical analysis is supported by our experimental results.

The action of ultrasound on the structure and optical properties of homeotropically aligned layers of nematic liquid crystals has been studied by a number of authors, see the references in [1]. The change in the optical properties of the nematic layer is due to the reorientation of the director caused by acoustic streaming which results from the interaction between the eigenmodes of the nematic cell excited by ultrasound [2–4]. The threshold for the acousto-optic effect may be reduced in two ways: first, by increasing the streaming velocity and, secondly by increasing the optic response to acoustic streaming. In order to achieve this reduction the acousto-optic effect in a nematic was investigated subject to combined actions 1, for coherent excitation of ultrasonic and viscous waves and 2, for excitation of ultrasound in an electric field near the Freedericksz transition.

The experimental setup is shown in figure 1. The surface acoustic wave was excited at a *Y*-cut *X*-oriented quartz substrate by means of an interdigital transducer. The nematic layer, 40 μm thick, was placed between the substrate and a glass plate. A *Y*-cut quartz plate was used to generate the viscous wave. The operating frequency was 30 MHz. We have used a mixture of 4-methoxy-benzylidene-4′-n-butylaniline (MBBA) and 4-ethoxybenzylidene-4′-n-butylaniline (EBBA) (approximately 2 : 1) at room temperature. Homeotropic alignment was produced by treating the inner surfaces with lecithin. To achieve uniform optical transmission the laser beam ($\lambda_0 = 0{\cdot}633\,\mu$m) was focused on the nematic layer in a small spot 25 μm in diameter. The light reflected from the mirror coating was analysed. The polarizer and analyser were at an angle of 45° to the propagation direction of the surface acoustic wave. The velocity and amplitude of the nematic cell eigenmodes were measured from the diffraction of light on the mirror coating.

Under the action of the surface acoustic wave two modes were excited with the phase velocities – $c_1 = 3{\cdot}2 \times 10^3\,\mathrm{m\,s^{-1}}$ and $c_2 = 1{\cdot}5 \times 10^3\,\mathrm{m\,s^{-1}}$. The second mode quickly decayed along the layer. The optical pattern arising from the interaction of these modes was a number of stripes located near the feeding edge of the layer. When a viscous wave was excited a regular system of stripes with spatial period $x = (55 \pm 5)\,\mu$m appeared in the region of the viscous wave and the first mode interaction.

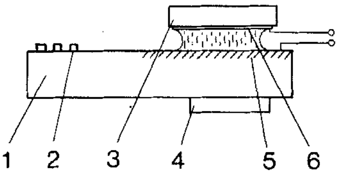

Figure 1. Experimental setup: 1, quartz substrate, 2, interdigital transducer, 3, glass plate, 4, quartz plate, 5, mirror coating, 6, optically transparent electrode.

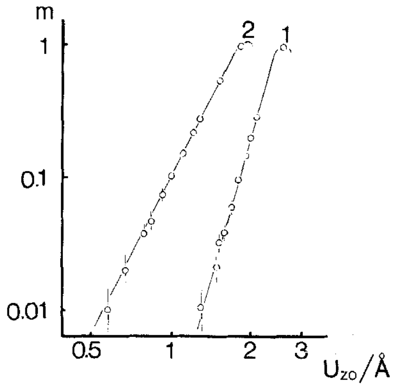

Figure 2. Dependence of the optical transmittance on the amplitude of the surface acoustic wave (viscous wave amplitude: 1, 0 Å, 2, 2 Å).

The dependence of optical transmittance m on the amplitude of the surface acoustic wave, U_{z0}, is shown in figure 2. Under the action of this wave $m \sim U_{z0}^8$ (see line 1) corresponding to results reported in [4]. With a viscous wave $m \sim U_{z0}^4$ (see line 2). The conditional threshold (surface acoustic wave power corresponding to $m = 10^{-2}$) in the second case is an order of magnitude lower.

To investigate the acousto-optic effect in an electric field the surface acoustic wave with a 6 MHz frequency was generated. A nematic layer 40 μm thick was placed between the substrate and the glass plate with an optically transparent electrode. The second was the substrate mirror coating. Figure 3 shows the dependence of the cell transmittance on the amplitude of the surface acoustic wave for various voltages applied to the electrodes. The threshold of the Freedericksz transition was 4·65 V. In the vicinity of the transition the acousto-optic effect threshold diminishes by more than an order of magnitude.

Let us find the optical transmittance of the homeotropically aligned nematic layer resulting from the interaction of the viscous wave with one of the eigenmodes of the nematic cell. The z axis is normal to the layer with boundaries at $z = 0, h$. We are interested in the tilt of the nematic director in the plane (x, z) caused by the flow with a velocity V along the x axis. The equation for the flow is

$$\eta \frac{\partial^3 V}{\partial z^3} = \varrho \frac{\partial^2}{\partial z^2} \langle v_x v_z \rangle, \tag{1}$$

where η is the viscosity coefficient, ϱ is the density and the symbol $\langle\ \rangle$ indicates a time average. The velocity components of the viscous wave and the eigenmode of the layer are

$$v_x = v_{x0} \cos(\omega t - \delta z) \exp(-\delta z), \tag{2}$$

$$v_z = v_{z0}(z) \cos(\omega t - kx + \phi), \tag{3}$$

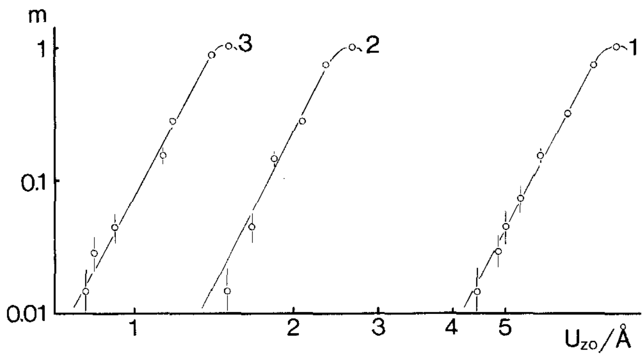

Figure 3. Dependence of the optical transmittance on the amplitude of the surface acoustic wave in electric field (1, no voltage, 2, 4·50 V, 3, 4·60 V).

where ω is the frequency. The wavevectors $\delta = \sqrt{(\varrho\omega/2\eta)}$ and $k = \omega/c$ in the frequency range $(\omega/2\pi) > 10^6\,\mathrm{s}^{-1}$ are such that $\delta \gg k$ and $\delta h \gg 1$. Therefore the solution of equation (1) with the boundary conditions:

$$V(0) = V(h) = 0, \quad \int_0^h V dz = 0 \tag{4}$$

is

$$V = \frac{\varrho v_{x0} v_{z0}(0)}{2\sqrt{2\eta\delta}} \left[\cos\left(kx - \phi + \frac{\pi}{4} - \delta z\right) \exp(-\delta z) - \cos\left(kx - \phi + \frac{\pi}{4}\right)\left(1 - 4\frac{z}{h} + 3\frac{z^2}{h^2}\right)\right]. \tag{5}$$

Using this result we can determine the tilt angle, θ, of the director from

$$K_3 \frac{\partial^2 \theta}{\partial z^2} = \alpha_2 \frac{\partial V}{\partial z}, \quad \theta(0) = \theta(h) = 0 \tag{6}$$

(K_3 is the elastic constant and α_2 is Leslie coefficient) and the transmittance of the nematic layer between crossed polarizers:

$$m = \sin^2\left(\frac{\Delta}{2}\right), \quad \Delta = \frac{2\pi}{\lambda} \Delta n \int_0^h \theta^2 dz, \tag{7}$$

where Δn is the refractive index anisotropy and λ is wavelength of light. Finally

$$\Delta = \frac{\pi \Delta n h^3 \varrho}{210 \lambda \eta \omega} \left[\frac{\alpha_2}{K_3} v_{x0} v_{z0}(0) \sin\left(kx - \phi + \frac{\pi}{4}\right)\right]^2. \tag{8}$$

The spatial period of the clearing pattern equals $x_0 = 53\,\mu\mathrm{m}$ coinciding with the experimental value. The result of the optical transmittance calculations is shown in figure 2 as the full line. The parameters used in the calculations are: $\Delta n = 0{\cdot}2$, $\alpha_2 = 0{\cdot}8p$, $\eta = 0{\cdot}28p$, $K_3 = 7 \times 10^{-7}\,\mathrm{dyn}$.

The equation for the tilt angle in the electric field E directed along the z axis is

$$\alpha_2 \frac{\partial V}{\partial z} = K_3 \frac{\partial^2 \theta}{\partial z^2} - \frac{1}{4\pi} \Delta\varepsilon E^2 \theta, \tag{9}$$

where $\Delta\varepsilon$ is permittivity anisotropy. The first spatial harmonics of V and θ are of interest. For the boundary conditions specified by equations (4) and (6)

$$V = V_0 \sin 2k_0 z, \tag{10}$$

$$\theta = \theta_0 \left(\cos 2k_0 z - \cos k_{\mathrm{E}} z - \mathrm{tg}\,\frac{k_{\mathrm{E}} h}{2} \sin k_{\mathrm{E}} z\right), \tag{11}$$

where

$$k_0 = \frac{\pi}{h}, \quad k_{\mathrm{E}} = \sqrt{\left(\frac{|\Delta\varepsilon|}{4\pi K_3}\right)} E.$$

The quantities V_0 and θ_0 are related by

$$\theta_0 = \frac{2\alpha_2 k_0 V_0}{K_3 (k_E^2 - 4k_0^2)}. \tag{12}$$

Near the threshold of the Freederickz transition ($E \to E_0$)

$$\frac{m(E)}{m(0)} = \frac{1}{\pi^2}\left(1 - \frac{E}{E_0}\right)^{-4}, \tag{13}$$

which is in a good agreement with the experimental results.

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