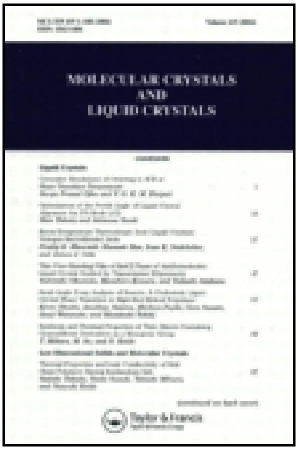

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Orientational Oscillations in Homeotropic Layers of Liquid Crystals Induced by Low Frequency Pressure Gradient in the Presence of Stabilizing and Destabilizing Electric Field

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ORIENTATIONAL OSCILLATIONS IN HOMEOTROPIC LAYERS OF LIQUID CRYSTALS INDUCED BY LOW FREQUENCY PRESSURE GRADIENT IN THE PRESENCE OF STABILIZING AND DESTABILIZING ELECTRIC FIELD

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The results of optical investigations of periodical orientational changes in homeotropic layers of nematic liquid crystals distorted by low frequency (<1 Hz) pressure gradient are presented. The experiments were carried out using the liquid crystal cells with space inhomogeneities induced by electric field, or by the variation of the local thickness of the layer. The LC MBBA with a negative sign of a dielectric permittivity anisotropy ($\Delta\varepsilon$) and two nematic mixtures with positive sign of $\Delta\varepsilon$ were used to investigate the electric field influence on the mechanic-optical response. It is established, that maximal value δ_m of phase difference between an extraordinary ray and an ordinary one is proportional to the square of amplitude of a pressure gradient for all LCs both in the absence and in the presence of electric field. It is in accordance with linear theory predictions and can be used for an elaboration of high sensitivity liquid crystal sensors. In quasi-stationary limit when the director motion is in a phase with pressure gradient oscillations the universal functions describing the relative phase difference were obtained and compared with the experimental results.

Keywords: electric field; nematic liquid crystals; pressure gradient

INTRODUCTION

One of the fundamental properties of nematic liquid crystals is the connection between the velocity gradients and the orientational structure of this media. There is a whole class of the phenomena (formation of instabilities, back-flow effects etc.) caused by the connection mentioned above.

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Moreover, the influence of shear flows on LC orientation can be used at an elaboration of high-sensitivity sensors of mechanical disturbances [1]. In the latter case a control of the technical parameters of the given devices is possible with the help of an electric field [2]. In particular, one can realize LC sensors with a linear mode of a director motion in a wide diapason of amplitudes of mechanical oscillations using stabilizing electric fields. Such fields also provide the improvement of the inertial properties of LC sensors. In this connection it is of interest to get an adequate theoretical description of orientation changes induced by flows in layers of nematic liquid crystals at additional influence of controlling electric fields. The theory of linear response of LC on influence of the oscillating pressure gradient causing the Poiseulle flow , is developed rather well for a case of absence of electric fields [3]. Earlier we have shown [2,4], that in the presence of the stabilizing electric field one can use the simplified theoretical model for a qualitative description of experimental data. Such situation takes place when electric field is applied to a LC layer with positive value of anisotropy of dielectric permittivity to realize a quasi-stationary regime of a director motion. It can be explained by the electric field induced displacement of the spectrum of orientational fluctuations to the high frequency region. Thus at high enough values of controlling voltage and low values of frequency of oscillations the orientation of LC layer changes in phase with the variable gradient of pressure applied to the layer. The same result can be achieved by decreasing of the layer thickness due to the dependence of the relaxation frequency of a director on this parameter. This work is devoted to the quantitative comparison of the experimental results obtained at low frequencies of pressure oscillations with universal dependencies following from the linear hydrodynamic theory of nematic liquid crystals. The measurements, which were performed using different types of LC cells and three nematic liquid crystals have shown that such dependencies indeed can be realized at a proper choice of experimental parameters.

EXPERIMENTAL

Experimental set-up is shown on Figure 1. It consists of the optical part and the hydrodynamic system. The optical part includes: the He-Ne laser (1); the diaphragm (2); the long-focus lens (3); the polarizer (4) and the analyzer (5), which were crossed and oriented under 45° relatively to the flow direction; the liquid crystal cell (6), which can be moved relatively to the laser beam; the lens (7); the photo-diode (8), which transforms the optical intensity changes into the electric voltage, so the dependencies I(t) could be obtained and served using a personal

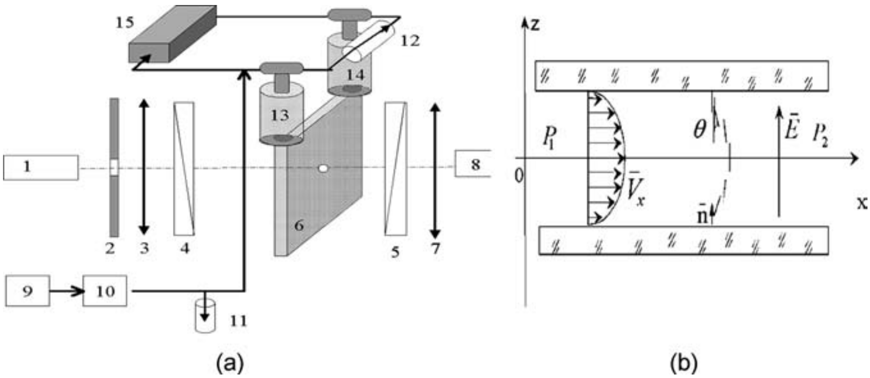

FIGURE 1 Set-up (a) and experimental geometry (b).

computer and a proper interface. The lenses (3) and (7) were used to obtain an information from a relatively small area ($< 1\,\mathrm{mm}^2$). So the thickness variations in the scanning region can be neglected for the cell of a variable thickness.

The hydrodynamic system includes: the special mechanical set-up (9), which provides a harmonic motion of the piston moving into the tube and a regulated time dependent compression of the air; the vessel (10) (the changes of it's volume provides a regulation of a pressure difference amplitude); the capillaries (11) and (12), which are used to compensate very slow irregular pressure variations (induced by thermal fluctuations, for example) and to provide an additional regulation of the pressure difference $\Delta P(t) = \Delta P \sin(2\pi ft)$ applied to the cell; the tubes (13) and (14) of a relatively large diameter (it is necessary to exclude the influence of possible changes of LC levels in the tubes in the case of low-frequency pressure difference) filled partly by LC and connected with the cell; the pressure difference sensor (15) used to control the time dependent pressure difference (ΔP) (as the described LC cells had a very high sensitivity, the pressure difference lower than 10 Pa was calculated using the known values of the degree of an air compression).

The sandwich-like liquid crystal cells with the open edges were used in the described experiments (Fig. 2). The rectangular channel of a constant thickness ($d = 105\,\mu\mathrm{m}$) was formed in the LC cell of the first type [2] to study electric field influence on the optical response of liquid crystal layer acted by a low-frequency pressure gradient. Different electric voltages were applied to the different parts of the cell (Fig. 2a) to induce a step-like inhomogeneity in the direction of the flow. In the liquid crystal cells of the second type [1] the channel of a variable thickness (the diapason of local thickness variation – 30…210 μm) was used to provide an inhomogeneity

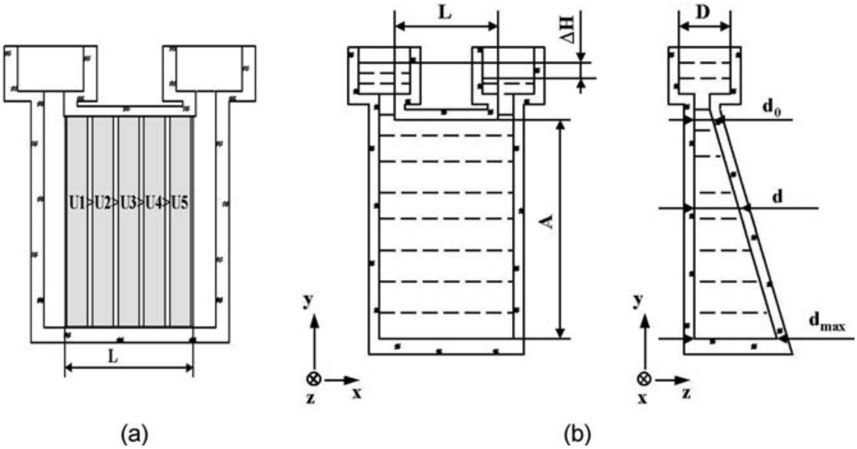

FIGURE 2 Experimental cells: (a) the sandwich-like liquid crystal cell L = 2, 5 cm, d = 105 μm, (b) the wedge-shape LC cell, front-view (left) and side-view (right). A = 10 cm, L = 1 cm, D = 1.5 cm, d_{max} = 210 μm, d_0 = 33 μm.

in the direction normal to the flow (Fig. 2b). This cell can be approximated by a number of channels of a different thickness acted by the same pressure gradient $G(t) = \Delta P(t)/L, = G \sin(2\pi ft)$, where L – the length of the channel (this parameter was equal to 2.5 cm and 1.0 cm for the cells of the first and of the second type respectively). The general geometry of the experiments is presented in Figure 1b. The applied pressure gradient G induces the oscillating Poiseuille flow with a quasi-parabolic velocity profile and distortions of an initial homeotropic structure described by the angle θ (z,t). Electric voltage applied to the cell can stabilize ($\Delta\varepsilon > 0$) or destabilize ($\Delta\varepsilon < 0$) the initial orientation.

In the described experiments we have studied the well known liquid crystal (MBBA) with a negative sign of a dielectric permittivity anisotropy ($\Delta\varepsilon = -0.59$, $k_{33} = 8.6^* 10^{-12}$ N) and two liquid crystal mixtures LC-616 and LC-654 produced by NIOPiK on the base of well studied binary nematic mixture LC-440 [5] doped by a polar substance (cyanophenyl ether of heptylbenzoic acid) of a different concentration (12% and 40% for LC-616 and LC-654 respectively). Thus two mixtures had values of the elastic constant $k_{33} = 10.5^*\ 10^{-12}$ N and different positive values of $\Delta\varepsilon$ (3.4 for LC-616 and 10.5 for LC-654) which provides the stabilizing action of an electric field on the initial homeotropic orientation used in these experiments. All measurements were carried out in a dielectric regime of electric field influence to avoid the possible EHD instabilities (for example in the case of MBBA the electric field frequency was equal to 5 kHz).

RESULTS AND DISCUSSION

The typical time dependence of the intensity of a polarized light passing through the LC cell of the second type under an action of low frequency pressure variations $\Delta P(t)$ at the presence of electric field is shown in Figure 3.

The non-linear character of I(t) dependencies is connected with an interference between an extraordinary and an ordinary rays and can be excluded [4] by transforming I(t) into $\delta(t)$ dependencies (in the geometry under consideration the phase difference δ is connected with the light intensity by the next relation: $I = I_0 \sin^2(\delta/2)$, I_0–the input intensity). So it is reasonable to use $\delta(t)$ dependencies to compare the experimental results with the linear theory predictions. The example of such transformation is presented in Fig. 3. Contrary to the I(t) dependence the time dependence of the phase difference $\delta(t)$ has a linear character, which reflects the linear regime of motion of a director. Indeed, our experiments have shown that the general result of a linear theory, namely $\delta_m \sim (\Delta P)^2$ is in an accordance with experimental dependencies obtained at variations of a pressure an amplitude and a frequency both in the absence and in the presence of electric field and at layer thickness variations. The example of such dependence is shown in Figure 4.

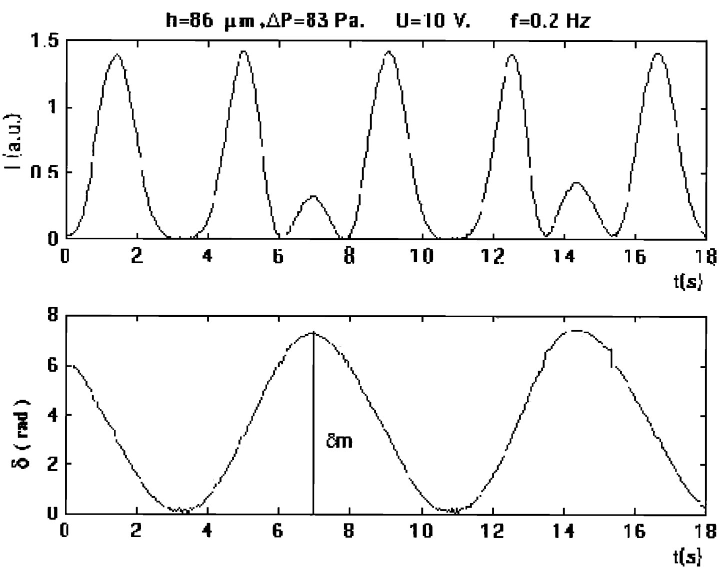

FIGURE 3 Time dependencies of light intensity I(t) and phase difference $\delta(t)$; LC-616, LC cell of the second type.

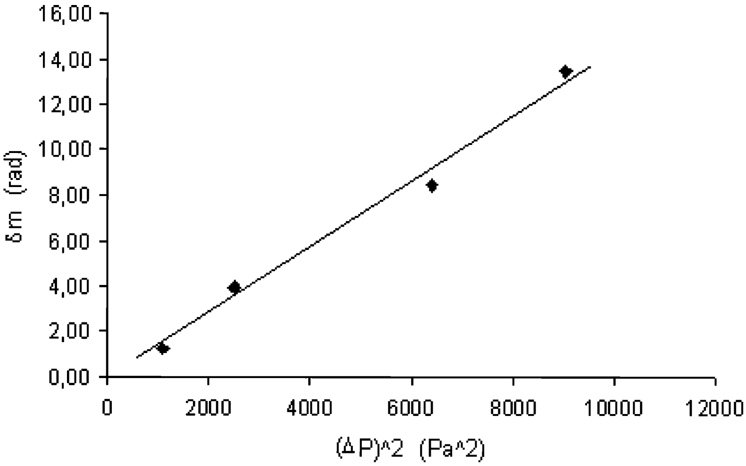

FIGURE 4 The dependence of the maximal phase difference δ_{m} on the square of pressure difference amplitude ΔP; LC-654, LC cell of the first type, U = 6.9 V, f = 0.29 Hz; solid curve – the theoretical dependence $\delta_{\mathrm{m}} \sim (\Delta \mathrm{P})^2$.

This general result is the main one from the point of view of an elaboration of liquid crystal sensors of mechanical vibrations. Earlier we have shown [2] that in the case of a quasi-stationary linear oscillating flow, the dependence of the phase difference δ on the electric voltage U can be described by the universal function F(ph):

$$\delta \sim \langle \theta^2 \rangle \sim F(ph), \tag{1}$$

where $\langle \theta^2 \rangle$ the average value of θ^2(z,t) and the universal function F(ph) for the case $\Delta\varepsilon > 0$ can be written as:

$$F(ph) = \frac{1}{(ph^6)} \cdot \left\{ \begin{array}{c} \frac{ph}{4sh^2(ph)}[sh2ph - 2ph] + \\ +2\left[1 - ph \cdot \frac{ch(ph)}{sh(ph)}\right] + \frac{(ph)^2}{2} \end{array} \right\}$$

$$\text{where } ph = \frac{U}{4} \cdot \sqrt{\frac{\Delta\varepsilon}{\pi \cdot k_{33}}} \qquad h = d/2 \tag{2}$$

From the point of view of possible practical applications of LC cells as sensors of mechanical vibrations controlled by electric field it is of importance that the function F(ph) does not depend on the viscosity coefficients. It gives an opportunity to calculate the degree of field influence on mechanic-optic response of LC layer in a very simple way (one has to know only the $k_{33}/\Delta\varepsilon$ value for such calculation). The analysis of the obtained experimental results has shown that this universal behavior really takes

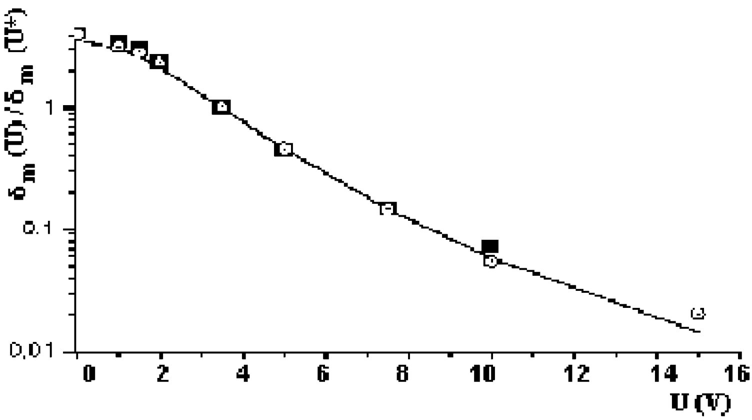

FIGURE 5 Universal function F(ph)/F(ph* = 2.94) and experimental values of δ_m(U)/δ_m(U* = 3.5 V) for LC-616 Θ-G = 2230 Pa/m; ■-G = 1170 Pa/m; f = 0.04 Hz.

place for low frequency oscillations. The comparison between the theory predictions and the experimental results, obtained for LC-616 (LC cell of the second type) and LC-654(LC cell of the first type) at varying experimental parameters is shown in Figures 5 and 6. One can see that δ_m(U) dependencies are satisfactory described by the universal function mentioned above.

In the case of MBBA the influence of electric field on δ_m is not so essential as previously described due to the existing of the Freederiksz

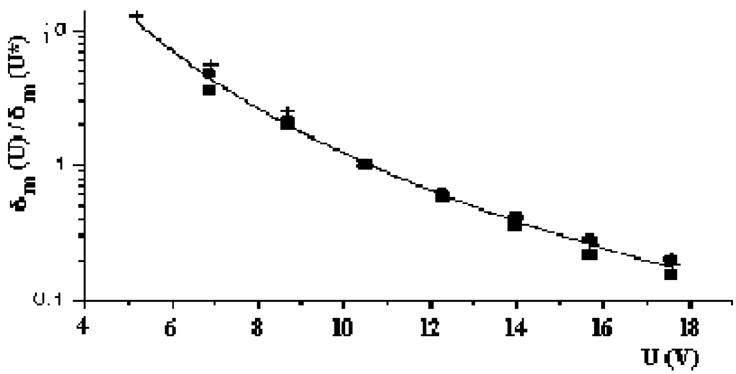

FIGURE 6 Universal function F(ph)/F(ph* = 15.9) and experimental values of δ_m(U)/δ_m(U* = 10.5 V) for LC-654 •-G = 2000 Pa/m, f = 0.29 Hz; ■-G = 3200 Pa/m; f = 0.29 Hz; + - G = 3200 Pa/m, f = 0.092 Hz.

TABLE Dependence of Phase Difference δ_m on Electric Voltage U: MBBA G = 3000 Pa/m, f = 0.170 Hz, d = 61 μm; $\delta_{m0} = \delta_m$ at U = 0 V, F_0 = F at ph = 0.

U, V	0,5	1,1	2,0	2,4	2,6	2,8	3,1	3,3	3,4
δ_m, rad	16,5	16,5	17,5	17,9	18,2	19,2	19,8	20,2	21,0
δ_m/δ_{m0}	1,0	1,0	1,1	1,1	1,1	1,2	1,2	1,2	1,3
ph	0,2	0,5	0,8	1,0	1,1	1,2	1,3	1,4	1,5
F/F_0	1,0	1,0	1,2	1,2	1,3	1,4	1,5	1,6	1,6

transition. Nevertheless the universal function F(ph) can be obtained for this case too and written as:

$$F(ph) = \frac{1}{(ph)^4}\left[\frac{1}{3} - \frac{2}{(ph)^2} + \frac{1}{2\sin^2(ph)} + \frac{3}{2ph}ctg(ph)\right] \tag{3}$$

The comparison between the theoretical predictions and the experimental values of δ_m, obtained for MBBA (the LC cell of the second type) is shown in the Table.

The theory gives a correct estimate of a destabilizing influence of electric field on the optical response. Some difference between theoretical and experimental results can be explained taking into account an increasing of the director relaxation time at approaching to the Freederiksz transition (critical voltage is about 4 V). In this case the quasi-stationary regime is realized rather approximately and additional experiments have to be done to establish the universal behavior of an optical response.

CONCLUSION

The experimental investigations of an optical response of LC layers on low frequency oscillating pressure gradient have shown that an influence of electric field on the phenomena under consideration can be described by the universal way in the case of quasi-stationary director motion (low frequency limit). The universal functions obtained in the framework of the linear hydrodynamic theory do not include the viscosity coefficients and depend only on the ratio $k_{33}/\Delta\varepsilon$.

These functions satisfactory describe the dependence of the pressure induced phase difference between an extraordinary ray and the ordinary one on the applied electric voltage for nematic mixtures with a positive sign of $\Delta\varepsilon$. The qualitative agreement between the theory and the experimental results also takes place for the liquid crystal with a negative sign of $\Delta\varepsilon$(MBBA), but in this case the universal behavior can be broken due to slowing down of an orientation motion at the Freederiksz transition.

The obtained results can be used for an elaboration of liquid crystal sensors controlled by electric field.

REFERENCES

[1] Pasechnik, S. V. *et al.* (1991). The device for measuring of pressure difference. *Patent of RF №* 1719944.
[2] Pasechnik, S. V. & Torchinskaya, A. V. (1999). *Mol. Cryst. Liq. Cryst.*, *341*, 331.
[3] Tarasov, O. S. & Krekhov, A. P. (1998). Crytallography Reports, *43*, 476.
[4] Pasechnik, S. V., Torchinskaya, A. V., Shustrov, B. A., & Yurmanova, T. N. (2001). *Mol. Cryst. Liq. Cryst.*, *727*, 367.
[5] Barnik, M. I., Belyaev, V. V., & Grebenkin, M. F. (1978). Elektricheskie, Opticheskie i vyzko-uprugie svo'istva LC smesi azoksisoedineni'i, Krisstallografiy, *805*, 23.