Жидкие кристаллы и их практическое использование. 2023. Т. 23, № 3. С. 46–53
Liquid Crystals and their Application. 2023. Vol. 23, № 3. P. 46–53
ISSN 1991–3966 (print), 2499–9644 (online), Journal homepage: http://nano.ivanovo.ac.ru/journal/ru/

Physics

Research Article

ELECTRICALLY DRIVEN KINK-LIKE DISTORTION WAVES IN LIQUID CRYSTALS

Semen S. Kharlamov[1]*, Dina V. Shmeliova[1], Sergey V. Pasechnik[1], A. V. Zakharov[2]

[1]*MIREA – Russian technological university, Problem laboratory of molecular acoustics, Moscow, Russia*
[2]*Saint-Petersburg institute for machine sciences, Russian Academy of Sciences, V.O., Saint-Petersburg, Russia*

A R T I C L E I N F O:

Article history:
Received 25 May 2023
Approved 22 June 2023
Accepted 26 June 2023

Key words:
nematic liquid crystal,
kink-like wave,
electric field

A B S T R A C T

Electrically driven kink-like distortion regimes in micro sized liquid crystal channel have been investigated both experimentally and analytically. Kink-like distortion waves were excited by interaction between electric field **E** and the gradient $\nabla\hat{\mathbf{n}}$ of the director field in a homogeneously aligned liquid crystal (HALC) channel. Calculations, based upon the nonlinear extension of the classical Ericksen-Leslie theory, show that due to the coupling between $\nabla\hat{\mathbf{n}}$ and **E** in the HALC channel, the horizontal flow $\mathbf{v} = \mathrm{u}\hat{\mathbf{i}}$ may be excited. The results of calculations revealed that the dependence of the maximum value of stationary velocity distribution $|\,\mathrm{u}_{\max}(E/E_{th})|$ across the LC channel vs electric field E/E_{th} is characterized by maximum value at $E/E_{th} = 2.0$. When the electric field $E \gg E_{th}$, the horizontal flow of the LC material completely stops and a novel mechanism of converting of electric field in the form of kink-like wave reorientation of the director field $\hat{\mathbf{n}}$ can be excited in the LC channel. The experimental part of the work presents the observation results of a kink-like wave in a plane capillary.

DOI: 10.18083/LCAppl.2023.3.46

For citation:
Kharlamov S. S., Shmeliova D. V., Pasechnik S. V., Zakharov A. V. Electrically driven kink-like distortion waves in liquid crystals. *Liq. Cryst. and their Appl*., 2023, **23** (3), 46–53.

*Corresponding author: semen.kharlamov.95@mail.ru

Физика

Научная статья
УДК 532.5:53.05:532.783

ВЫЗВАННЫЕ ЭЛЕКТРИЧЕСКИМ ПОЛЕМ КИНК-ОБРАЗНЫЕ ВОЛНЫ В ЖИДКИХ КРИСТАЛЛАХ

Семен Сергеевич Харламов[1]*, Дина Владимировна Шмелева[1], Сергей Вениаминович. Пасечник[1], Александр Васильевич Захаров[2]

[1]*МИРЭА – Российский технологический университет, Проблемная лаборатория молекулярной акустики, Москва, Россия*
[2]*Институт проблем машиноведения Российской академии наук, В.О., Санкт-Петербург, Россия*

И Н Ф О Р М А Ц И Я

История статьи:
Поступила 25.05.2023
Одобрена 22.05.2023
Принята 26.06.2023

Ключевые слова:
нематический жидкий кристалл,
кинк-образная волна,
электрическое поле

А Н Н О Т А Ц И Я

В представленной работе экспериментально и аналитически исследованы режимы кинк-образных возмущений, вызванных электрическим полем в жидкокристаллическом канале микроразмеров. Кинк-образные волны искажения возбуждались взаимодействием электрического поля $\mathbf{E}$ и градиента $\nabla\hat{\mathbf{n}}$ поля директора в однородно ориентированном жидкокристаллическом (ООЖК) канале. Расчеты, основанные на нелинейном расширении классической теории Эриксена–Лесли, показывают, что из-за связи между $\nabla\hat{\mathbf{n}}$ и $\mathbf{E}$ в ООЖК канале может возбуждаться горизонтальный поток $\mathbf{v} = \mathrm{u}\hat{\mathbf{i}}$. Результаты расчетов демонстрируют, что зависимость максимального значения стационарного распределения скорости $|\, \mathrm{u}_{\max}(E/E_{th})|$ по ЖК-каналу в зависимости от электрического поля E/E_{th} характеризуется максимальным значением при $E/E_{th} = 2.0$. В случае, когда электрическое поле $E \gg E_{th}$, горизонтальное течение ЖК-материала полностью прекращается и может возникать новый механизм преобразования электрического поля в виде кинк-образной волновой переориентации поля директора $\hat{\mathbf{n}}$ в ЖК-канале. В экспериментальной части работы представлены результаты по наблюдению кинк-образной волны плоском капилляре.

DOI:
10.18083/LCAppl.2023.3.46

Для цитирования:
Харламов С. С., Шмелева Д. В., Пасечник С. В., Захаров А. В. Вызванные электрическим полем кинк-образные волны в жидких кристаллах // *Жидк. крист. и их практич. использ.* 2023. Т. 23, № 3. С. 46–53.

*Адрес для переписки: semen.kharlamov.95@mail.ru

Introduction

The current trend toward further miniaturization in drug delivery devices, manipulation of biomolecules and biosensing has brought an increasing number of integrated microdevices for chemical and biological applications [1]. Such manipulation (for instance, by flow) can be achieved either by forces applied macroscopically, e.g., at appropriate inlets or outlets, or can be generated locally within microfluidic channel or liquid crystal (LC) cell [2–4]. Electro-osmosis, dielectrophoresis and electrowetting have been explored for controlling microflows [1–4]. Nematic liquid crystal (NLC) cells of appropriate size are microdevices, whose molecular orientations can be manipulated by the presence of electric field **E** and the temperature gradient ∇T [5, 6]. A challenging problem in such systems is the precise handling of LC or anisotropic liquid microvolume, which in turn requires self-contained micropumps of small package size exhibiting either a very small displacement volume (displacement pumps) or a continuous volume flow (dynamic pumps). One of the liquid crystal pumping principle is based on the coupling between the electric **E** and director $\hat{\mathbf{n}}$ fields [5, 7]. In this case, the uniform textures of nematic LCs are produced by orienting a drop of bulk material between two conveniently treated bounding surfaces, which usually define a fixed orientation for the boundary molecules. By applying the electric field **E** perpendicular to an uniformly (homogeneously) oriented NLC, the initial molecular orientation can be distorted at $E > E_{th}$, where a critical threshold field E_{th} is given by:

$$E_{th} = \frac{\pi}{d}\sqrt{\frac{K_1}{\varepsilon_0 \varepsilon_a}}, \tag{1}$$

where d is the thickness of the microsized LC layer, K_1 is the splay elastic constant, ε_0 is the absolute dielectric permittivity of free space, ε_a is the dielectric anisotropy of the NLC [8]. This form for the critical field is based upon assumption that the director remains strongly anchored (in our case, homogeneously) at two horizontal bounding surfaces and that the physical properties of the LC are uniform over the entire sample for $E < E_{th}$. When the electric field is switched on with a magnitude E greater than E_{th}, the director $\hat{\mathbf{n}}$, in the "splay" geometry, reorients as a simple monodomain [5], and exciting of the electrically driven nematic flow in microfluidic channel is a question of great fundamental interest, as well as the essential piece of knowledge in soft material science [1].

Based on the nonlinear extension of the classical Ericksen-Leslie theory, the coupling effect among $\nabla\hat{\mathbf{n}}$ and **E** on electrically driven nematic flow in microfluidic LC channel will be investigated.

Formulation of the balance of linear momentum and torque equations for microsized nematic fluids

We are primarily concerned with the description of a physical mechanism responsible for the electrically driven nematic flow in microfluidic homogeneously aligned liquid crystal (HALC) channels. This description corresponds to the case of NLC confined by two parallel horizontal surfaces with symmetrical boundary conditions (planar in our case). As a result, we consider the picture, where there is a balance between the applied electric, viscous, elastic and anchoring forces, and, in general, the LC fluid settles down to a stationary flow regime in the plane of surfaces [7]. Upon assuming an incompressible fluid, the hydrodynamic equations describing the orientational dynamics induced by electric field $\mathbf{E} = E\hat{\mathbf{k}}$ can be derived from the torque and linear momentum equations for such LC system. Here $\hat{\mathbf{k}}$ is a unit vector directed normal to the horizontal surfaces, while a unit vector $\hat{\mathbf{i}}$ directed parallel to the horizontal surfaces.

We consider a homogeneously aligned nematic liquid crystal with the $\varepsilon_a > 0$, which is delimited by two horizontal bounding surfaces at distance d on a scale in the order of tens micrometers. According to this geometry, the director $\hat{\mathbf{n}} = n_x\hat{\mathbf{i}} + n_z\hat{\mathbf{k}} = \sin\theta(z,t)\hat{\mathbf{i}} + \cos\theta(z,t)\hat{\mathbf{k}}$ is maintained within xz-plane defined by the electric field and the unit vector $\hat{\mathbf{i}}$. Taking into account that the length of the channel l is much bigger than the thickness d, we suppose that the component of the director $\hat{\mathbf{n}}$ as well as the rest of the physical quantities depend only on z-coordinate and time t. Here, θ denotes the angle between the director and the unit vector $\hat{\mathbf{k}}$.

Our main aim was to investigate the influence the external electric field **E** on the process of director $\hat{\mathbf{n}}$ reorientation and electrically driven nematic flow **v** in the microfluidic HALC channel. We consider a regime, when the director $\hat{\mathbf{n}}$ is strongly anchored to both solid surfaces with planar boundary orientations, where

$$\theta(z)_{z=0} = \frac{\pi}{2}, \qquad \theta(z)_{z=1} = \frac{\pi}{2}\ . \qquad (2)$$

Here, $\bar{z} = z/d$ is the dimensionless distance away from the lower solid surface. The incompressibility condition $\boldsymbol{\nabla} \cdot \mathbf{v} = 0$ assumes that only one nonzero component of the vector $\mathbf{v}$ exists, *vis.* $\mathbf{v}(z,\tau) = u(z,\tau)\hat{\mathbf{i}}$, where, $\tau = (\varepsilon_0\varepsilon_a E^2/\gamma_1)t$ is the dimensionless time, $\bar{u} = (\frac{\gamma_1}{d\varepsilon_0\varepsilon_a E^2})u$ is the dimensionless velocity.

Notice that the overbars in the space variable and velocity have been eliminated.

To be able to observe the evolution of the director field $\hat{\mathbf{n}}$ (or the polar angle $\theta(z,\tau)$) to its stationary orientation $\hat{\mathbf{n}}_{st}(z)$, and exciting the velocity field $u(z,\tau)$ caused by the external electric field, we consider the dimensionless analog of the torque and linear momentum balance equations [5, 7].

The dimensionless torque balance equation describing the reorientation of the LC phase can be written as:

$$\theta_{,\tau} = A(\theta)u_{,z} + \Delta\left[(G(\theta)\theta_{z})_{,z} - \frac{1}{2}G_{,\theta}(\theta)\theta_{,z}^2\right] - \frac{E^2(z)}{2}\sin 2\theta, \qquad (3)$$

where: $A(\theta) = \frac{1}{2}(1 - \gamma_{21}\cos 2\theta)$,
$G(\theta) = \sin^2\theta + K_{31}\cos^2\theta$,
$G_{,\theta}(\theta)$ is the derivative of $G(\theta)$
with respect to θ,
$\theta_{,z} = \partial\theta(z,\tau)/\partial z$, $\Delta = \left(\frac{E_{th}}{\pi E}\right)^2$,
$\gamma_{21} = \gamma_2/\gamma_1$, γ_2 and γ_1 are the rotational viscosity coefficients (RVCs),
$K_{31} = K_3/K_1$, and K_1 and K_3 are the splay and bend elastic constants of the LC phase.

In the case of incompressible fluid, the dimensionless Navier-Stokes equation reduces to:

$$\frac{1}{\Delta}\delta_1 u_{,\tau}(z,\tau) = \left[\bar{h}(\theta)u_{,z} - \bar{A}(\theta)\theta_{,\tau}\right]_{,z}, \qquad (4)$$

where

$$h(\theta) = \alpha_1\sin^2\theta\cos^2\theta - \bar{A}(\theta) + \frac{1}{2}\alpha_4 + g(\theta),$$
$$\bar{A}(\theta) = \gamma_1 A(\theta),$$
$$g(\theta) = \frac{1}{2}(\alpha_6\sin^2\theta + \alpha_5\cos^2\theta),\ u_{,z} = \partial u(z,t)/\partial z,$$
$$\theta_{,z} = \partial\theta(z,t)/\partial z,$$

and $\delta_1 = \rho K_1/\gamma_1^2$ is a parameter of the system, while α_i (i = 1,..., 6) are six Leslie coefficients [5, 7].

We consider a regime when the velocity on the bounding surfaces has to satisfy the no-slip boundary condition:

$$u(z)_{z=0} = 0, \qquad u(z)_{z=1} = 0, \qquad (5)$$

while the initial director orientation is perturbed parallel to the bounding surfaces with

$$\theta(z,\tau = 0) = \frac{\pi}{2}, \qquad (6)$$

and then allowed to relax to its stationary distribution $\theta_{st}(z)$ across the microsized HALC channel.

Numerical results for the relaxation regimes in HALC channel

In our case, the electric field $\mathbf{E} = E\hat{\mathbf{k}}$, applied normally to the initial director orientation, tends to reorient the director field $\hat{\mathbf{n}}$, parallel to $\mathbf{E}$. Thus, in the initially homogeneously aligned LC volume, the hybrid-aligned microsized domain with nonzero gradient of the director field $\nabla\ \hat{\mathbf{n}}$ may arise.

Case $E > E_{th}$

In the case when the electric field is equal to $E/E_{th} = 2.0$, the evolution of the director field $\hat{\mathbf{n}}$ to its stationary orientation $\hat{\mathbf{n}}_{st}$ in the microsized HALC channel is shown in Fig. 1, *a*. It was described by the polar angle $\theta(z,\tau_k)$, at different times $\tau_k = \Delta\tau(k-1)$ ($k = 1, \dots, 11$). Here, $\Delta\tau = 0.05$ and $\tau_{11}\left(\frac{E}{E_{th}} = 2.0\right) = 0.5$ ($\sim 2.25\ ms$).

The evolution of the dimensionless velocity field $u(z,\tau) = \left(\frac{\gamma_1}{d\varepsilon_0\varepsilon_a E^2}\right)v_x(z,\tau)$ to its stationary distribution $u(z,\tau_{11})$ across the microsized HALC channel, at different times τ_k $(k = 1, ..., 11)$ under the effect of the electric field $E/E_{th} = 2.0$ is shown in Fig. 1, *b*. The highest velocity value $|u_{\max}(E/E_{th} = 2.0)| \sim 2.92$ ($\sim 3.24 \times 10^{-3} m/s$) is reached near the upper (*z* = 0.8) restricted surface.

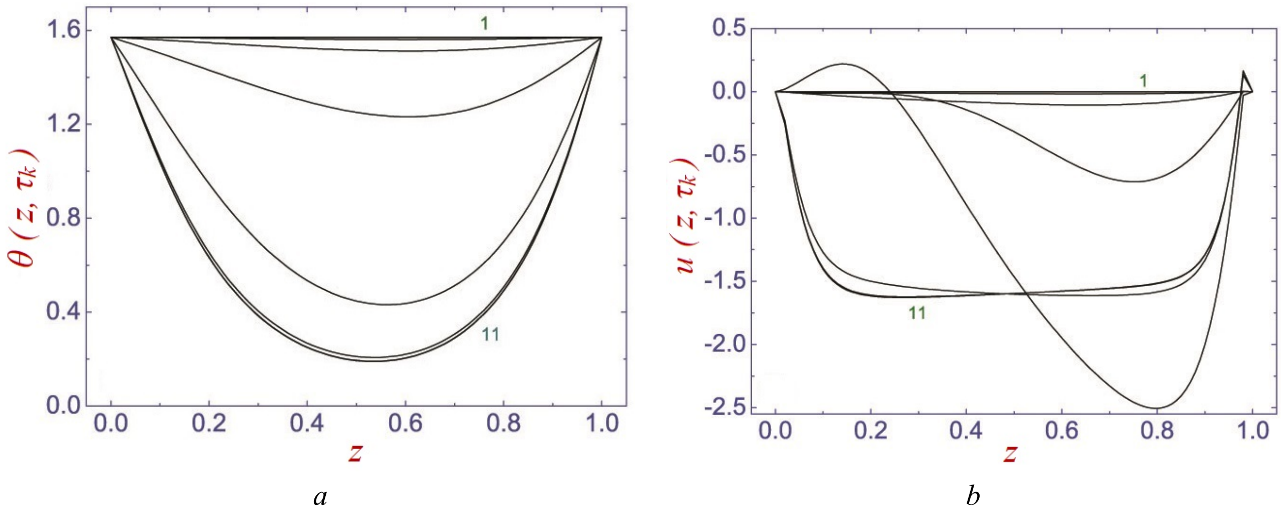

Fig. 1: a – Plot of evolution of the polar angle $\theta(z,\tau_k)$ to its stationary distribution across the HALC microfluidic channel, under the effect of the electric field $E/E_{th} = 2.0$, at different times $\tau_k = \Delta\tau(k-1)$ $(k = 1, ..., 11)$, respectively; *b* – The same as in (*a*), but for the evolution of the dimensionless velocity $u(z,\tau_k)$ to its stationary distribution across the HALC channel

Case E >> E_{th}

In the case when the electric field E is much greater than E_{th}, the evolution of the velocity field $u(z,\tau)$ in the microsized HALC channel is described by the reduced dimensionless Navier-Stokes equation (4), which can be written as:

$$\lim_{E\to\infty} \frac{1}{\Delta} \delta_2 u_{,\tau}(z,\tau) \to \infty \,, \tag{7}$$

where $1/\Delta = (\frac{\pi E}{E_{th}})^2$. In this case, when $\lim_{E\to\infty} \frac{1}{\Delta} \to \infty$, one can get $u(z,\tau) = 0$, taking into accounting the no-slip boundary condition (see Eq. (5)). As a result, when $E \to \infty$, the dimensionless torque balance equation (3) is reduced to equation:

$$\theta_{,\tau}(z,\tau) = -\frac{E^2(z)}{2} \sin 2\theta(z,\tau). \tag{8}$$

There is exact solution of Eq. (8):

$$\bar{\theta}(z,\beta) = \tan^{-1}[\sinh^{-1}(w\beta - z + z_0)], \tag{9}$$

where $\beta = E^2\tau$, z_0 is a constant, and *w* is the solitary wave velocity along the *z* axis, which can be written in dimensional form as:

$$w(z,t) = \frac{E^2 \bar{E}(z) d \varepsilon_a \varepsilon_0}{\gamma_1} = \frac{1}{\Delta} \frac{K_1}{d\gamma_1} \bar{E}(z), \tag{10}$$

where $\bar{E}(z) = E(z)/E$, $E = U/d$, and *U* is the voltage applied across the LC channel.

Physically, it means that the director disturbance, induced by electric field $E \gg E_{th}$, in the vicinity of one of the bounding surfaces must propagate in the form of the solitary wave along the *z* axis with the velocity *w*.

Experimental

The experimental setup used for investigation of kink-like waves included the polarizing microscope (OLYMPUS BX53F2) with the high-speed camera (Photron FASTCAM Mini UX50 a frame rate of 20,000 frames per second was used) and high voltage AC generator.

Fig. 2 shows a schematic representation of the cell. The upper and lower substrates were made of display glasses 1.1 mm thick. They were covered by a layer of chromium stearyl chloride (chromolane, 0.5 % isopropanole solution) using spin-coating technique. After applying chromolane, the glasses were dried at 90 ^{0}C for 1 hour. Such preparation provides a homeotropic boundary orientation.

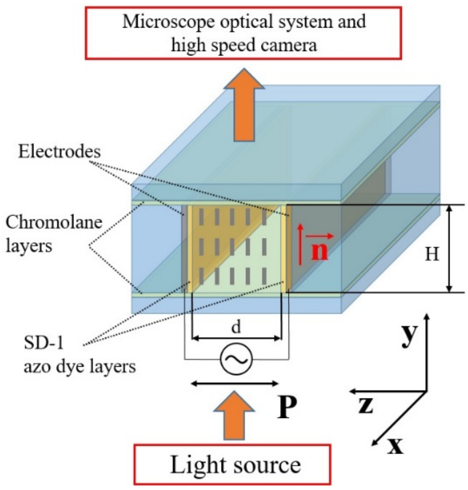

Fig. 2. Schematic representation of the cell and the experimental geometry

The spacers acting as electrodes were made of glass plates of thickness H = 350 μ*m* with polished edges, coated by conductive layers. To get the planar boundary orientation on the electrodes, they were spin-coated with 0,1 % solution of azo dye (SD-1) in dimethyl formamide (DMF) with further annealing at 90 ^{0}C for a 1 hour and then were treated by ultraviolet (UV) linear polarized irradiation (λ = 345 *nm*) of exposure dose $D = 0.45$ *W/cm*^{2}. The distance between spacers (*d* in Fig. 2) was 270 µm.

Thus, an uniform orientation of the liquid crystal director in the direction along the *Y* axis was realized in the sample. The direction of light propagation coincides with the orientation of the LC director. The experimental cell was filled with nematic liquid crystal 5CB (4-cyano-4'-pentylbiphenyl) in isotropic phase and then cooled. The experiments were carried out at room temperature ($T = 26 \pm 0.5$ ^{0}C).

In order to induce the initial reorientation of the liquid crystal director, an alternating voltage with an amplitude value of 250 *V* and a frequency of 50 *kHz* were applied along the *Z* direction.

The sample was illuminated with polarized white light. It should be noted that the analyzer was not used in the experiment to avoid the interference pictures induced by birefringence. The transmission plane of the polarizer was co-directed with the *Z* axis, i.e. with the direction of the electric field.

The distributions of light intensity in the near-wall region obtained by processing of the digital images taken at different times are shown in Fig. 3.

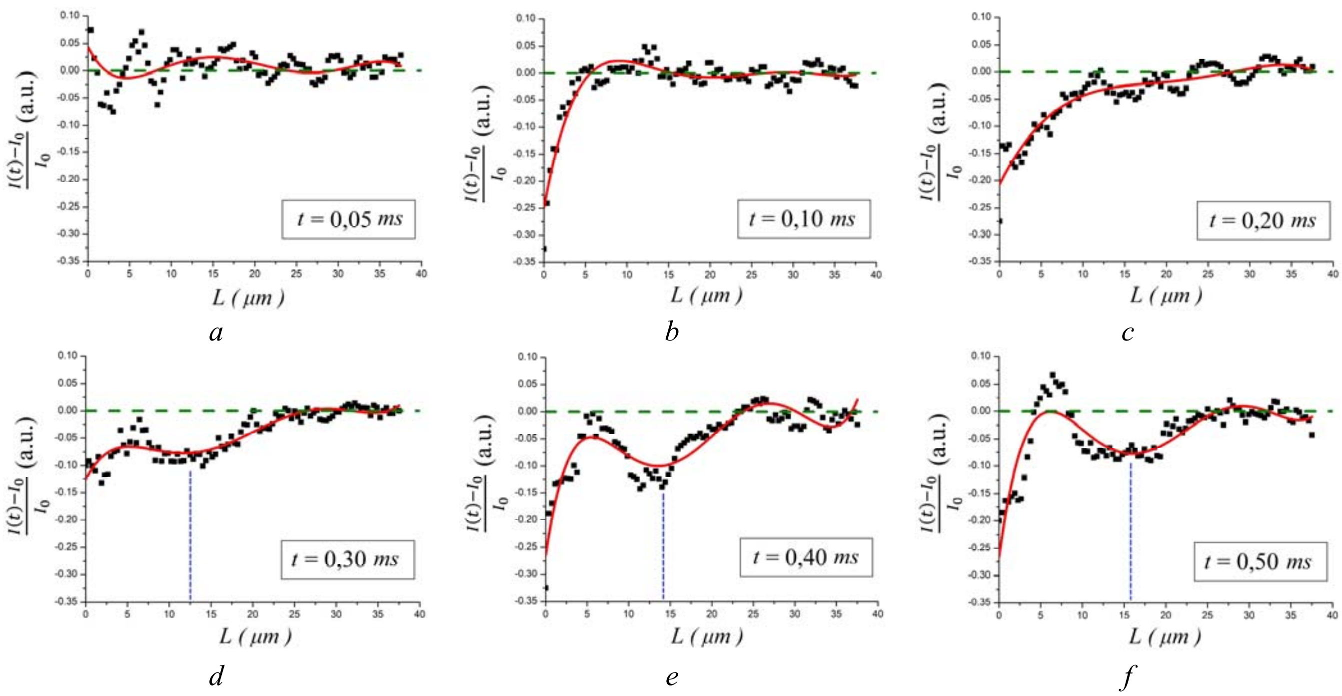

Fig. 3. Dependences of the normalized intensity on the coordinate at various times. Solid lines show the trend

As seen in Fig. 3, after turning on the electric field, there is a strong decrease in the light intensity in the near-boundary region. At the time of 0.3 ms, a separation of the region with sharp intensity change is observed, which subsequently moves to the center of the channel. The processing of the obtained data makes it possible to determine the dynamics of velocity change in that region, which can be treated as the motion of kink-like wave (Fig. 4).

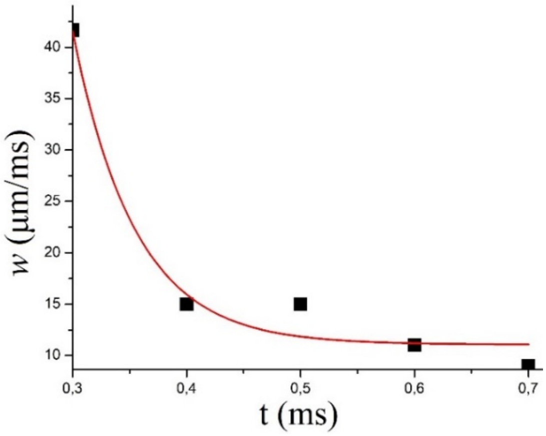

Fig. 4. Time dependence of kink-like wave velocity. The solid line shows the approximation by a simple exponential dependence

To compare the obtained results with the theoretical predictions, we considered that the total cell gap $d = L_{\parallel} + L_{\perp}$, where $L_{\parallel}$ is the distance at which the LC molecules have already reoriented in the direction of the electric field, and $L_{\perp}$ is the distance, on which the LC molecules have not yet reoriented.

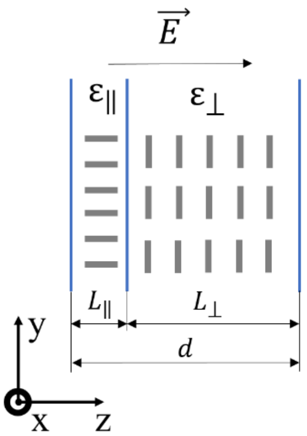

Fig. 5. Model of series-connected dielectrics

Using this model (Fig. 5), one can write the simple expressions for the total voltage drop on the cell, as well as for the field strength distribution:

$$U = E_{\parallel} * L_{\parallel} + E_{\perp} * L_{\perp}, \tag{11}$$

$$E_{\parallel} * \varepsilon_{\parallel} = E_{\perp} * \varepsilon_{\perp}. \tag{12}$$

Taking into account that at the initial moments of time the reorientation of the director occurs in a small near-wall region, it can be assumed that $L_{\parallel} << L_{\perp}$ and therefore:

$$E = E_{\perp} \approx \frac{U}{d}, \tag{13}$$

$$E(z) = E_{\parallel} \approx E * \frac{\varepsilon_{\perp}}{\varepsilon_{\parallel}}. \tag{14}$$

Using the material parameters of 5CB NLC, the geometric dimensions of the cell (Table 1), as well as inserting Eq. (13) and (14) in (10), we calculated the value of wave velocity *w* at the initial moments of time (it was equal to 0.056 *m/s*). The maximum experimentally obtained value of *w* was equal to 0.042 *m/s*.

Table 1. **Characteristics of the experimental cell and physical parameters of 5CB LC**

Peak value of voltage (*U, V*)	250
Distance between electrodes (L, μ*m*)	270
Anisotropy of dielectric constant (ε_a)	11,5
The dielectric constant $\varepsilon_{\parallel}$	18,5
The dielectric constant $\varepsilon_{\perp}$	7
Rotational viscosity (γ_1, *Pa*s*)	0,077

The experimentally obtained value of the velocity of the kink-shaped wave is close to that calculated theoretically within the framework of the model used.

Conclusion

The non-mechanical method for producing flow in a microfluidic homogeneously aligned liquid crystal (HALC) channel under the effect of the external electric field **E** has been proposed. Fluid pumping principle is based on the coupling between the electric and director fields.

Calculations, based upon the nonlinear extension of the classical Ericksen-Leslie theory, show that due to the coupling between $\nabla\hat{\mathbf{n}}$ and $\mathbf{E}$ in the HALC microfluidic channel, the horizontal flow $\mathbf{v} = v_x\hat{\mathbf{i}} = u\hat{\mathbf{i}}$ may be excited. The calculation results showed that the dependence of maximum value of stationary velocity distribution $|u_{\max}(E/E_{th})|$ across the LC channel vs electric field E/E_{th} is characterized by maximum value at $E/E_{th} = 2.0$. In the case when the electric field $E >> E_{th}$, the horizontal flow of the LC material completely stops and a novel mechanism of converting the electric field in the form of kink-like wave reorientation of the director field $\hat{\mathbf{n}}$ can be excited in LC channel.

Physically, this means that in the case $E >> E_{th}$, directed across the HALC channel, the director field $\hat{\mathbf{n}}$ has initially been disturbed, for instance, at the bottom of the LC channel, and the disturbance must propagate in the form of kink-like wave across LC channel.

It should be noted that the relaxation behavior of the director field $\hat{\mathbf{n}}$ in the form of a kink-like wave $\bar{\theta}(z,\tau)$, which is spreading along the *z* axis with the velocity *w*, probably can be observed in polarized white light. Under the influence of the electric field $E = 100E_{th}$, the estimation of king-like wave velocity gives the value of $w \sim 2.87\ m/s$ for NLC 5CB in 5 μm channel.

The performed investigation shows that the macroscopic description of the nature of hydrodynamic flow of anisotropic liquid subtly senses the microscopic structure of LC material.

The experimental values of the kink-like wave velocity were found to be close to those calculated by the theory using simple two-layer approximation.

Acknowledgements: *the reported study was funded by the Russian Science Foundation, project No. 22-22-00736.*

References

1. Schoch R.B., Han J., Renaud P. Transport phenomena in nanofluidics. *Rev. Mod. Phys*., 2008, **80**, 839–883.
2. Ajdari A. Pumping liquids using asymmetric electrode arrays. *Phys. Rev. E*, 2000, **61** (1), 45-48.
3. Long D., Ajdari A. A note on the screening of hydrodynamic interactions, in electrophoresis, and in porous media. *Eur. Phys. J. E,* 2001, **4**, 29–32.
4. Bazant M. Z., Ben Y. Theoretical prediction of fast 3D AC electro-osmotic pumps. *Lab. on a Chip.,* 2006, **6**, 1455–1461.
5. Zakharov A.V., Vakulenko A.A. Field-induced director dynamics in confined nematic liquid crystals imposed by a strong orthogonal electric field. *Phys. Rev. E,* 2013, **88**, 022505–8.
6. Zakharov A.V., Maslennikov P.V. Laser-excited motion of liquid crystals confined in a microsized volume with a free surface. *Phys. Rev. E.* 2017, **96**, 052705–10.
7. Zakharov A.V., Vakulenko A.A. Influence of the flow on the orientational dynamics induced by temperature gradient in nematic hybrid-oriented cells. *Chem. Phys*., 2007, **127**, 084907–7.
8. de Gennes P.G., Prost J. The physics of liquid crystals, 2nd. ed. Oxford University Press, Oxford, 1995, 597 p.
9. Ericksen J.L. Anisotropic fluids. *Arch. Ration. Mech. Anal*., 1959, **4**, 231–237. **DOI:**10.1007/BF00281389
10. Leslie F.M. Some constitutive equations for liquid crystals. *Arch. Ration. Mech. Anal.*, 1968, **28**, 265–283. **DOI**: 10.1007/BF00251810
11. Berezin I.S., Zhidkov N.P. Computing Methods, 4th ed. Pergamon Press, Oxford, 1965, 673 p.

Contribution of the authors:
[1]***Kharlamov S.S.*** – assembled an experimental setup, conducted experiments, and analyzed the obtained optical microscopy images.
[2]***Shmeliova D.V.*** – prepared an experimental sample and characterized it.
[3]***Pasechnik S.V.*** – led the research.
[4]***Zakharov A.V.*** – composed the theoretical part of the work.

All authors participated in writing and revising the text. All authors have read and agreed with the version sent to the journal.

The authors declare no conflict of interests.

[1]Orcid – 0000-0002-6911-3228
[2]Orcid – 0000-0003-3869-8806
[3]Orcid – 0000-0002-6050-2761
[4]Orcid – 0000-0002-8216-9947

Поступила 25.05.2023, одобрена 20.06.2023, принята 26.06.2023
Received 25.05.2023, approved 20.06.2023, accepted 26.06.2023