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ELECTRICALLY INDUCED SHEAR FLOWS OF LIQUID CRYSTALS CONFINED TO POROUS POLYMER FILMS FOR THz APPLICATION

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In this paper we consider new possibilities to control the THz irradiation via usage of the previously studied [1] electro-kinetic phenomena in the porous polymer (PET) film filled with a nematic liquid crystal (NLC). It is shown that a sample of the porous film may play the role of electro-hydrodynamic (EHD) pump, which induces a shear Poiseuille flow of NLC through the sandwich-like cell connected with the pump. The shear flow results in changing of the initial orientation of LC, which can be used to control the THz irradiation passing through the sandwich-like cell.

Key words: liquid crystals, electro-hydrodynamic (EHD) pump, electro-kinetic phenomena.

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ЭЛЕКТРИЧЕСКИ ИНДУЦИРОВАННЫЕ СДВИГОВЫЕ ПОТОКИ ЖИДКИХ КРИСТАЛЛОВ, ОГРАНИЧЕННЫЕ ПОРИСТЫМИ ПОЛИМЕРНЫМИ ПЛЕНКАМИ ДЛЯ ТЕРАГЕРЦОВЫХ ПРИМЕНЕНИЙ

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В данной работе рассматриваются новые возможности контроля терагерцового излучения с использованием ранее изученных [1] электрокинетических явлений в пленке пористого полимера (ПЭТ), заполненной нематическим жидким кристаллом (НЖК). Показано, что образец пористой пленки может играть роль электрогидродинамического (ЭГД) насоса, который индуцирует сдвиговое течение Пуазейля НЖК через «сэндвич»-ячейку, связанную с насосом. Сдвиговый поток приводит к изменению начальной ориентации ЖК, что может применяться для контроля ТГц излучения, проходящего через «сэндвич»-подобную ячейку.

Ключевые слова: жидкие кристаллы, электро-гидродинамический насос, электрокинетические явления.

Introduction

Development of THz technique for the last decades resulted in arising of a number of new applications like non-destructive distant control of materials, THz vision and high speed internet [2–5]. It demands elaboration of tunable quasi-optic components (modulators, polarization controllers, filters etc). Usage of liquid crystals (LC) is very attractive for this aim and different LC based THz devices were already proposed [6]. It demands to solve the specific problems, like quality of surface induced orientation and slow operating times, arising due to a relatively thick LC layers needed to manipulate the THz irradiation. Moreover, the electric control of an orientational structure and optical properties of LC, widely used for visible and near red irradiation, is restricted by high losses of THz waves in thin conductive ITO layers of standard LC cells. Recently we proposed [7] shear flows as an alternative tool for a control of LC structure, which makes it possible to overcome some restrictions, mentioned above.

The connection between translation motion and a director field $\mathbf{n}(\mathbf{r}, t)$ in shear flows of NLC is responsible for a number of specific phenomena. Some of them, like various *instabilities* induced by electric fields in thin layers of nematic liquid crystals or back flow effects arising at turning off electric fields are of a great practical importance in a display industry [8]. In this paper, we will focus on shear flows of LC arising at application of DC electric field to the porous PET films filled with LC. The experimental investigations of such flows [1] make it possible to predict technical parameters of terafluidic LC devices of different types.

Experimental

In general, electro-kinetic phenomena (EKP) arise when DC or low frequency electric field is applied to the channels of different shapes and sizes filled with polar liquids [9]. It originates due to absorption of polar molecules by the internal surface of a capillary which results in an appearance of the double electric layer with thickness h_0 (of order some nanometers for typical water solutions) and near surface diffusion layer of characteristic thickness l_D (Debye length), expressed as [9]:

$$l_D = k^{-1} = \left[\frac{(\varepsilon_0 \varepsilon k_B T)}{2e^2 z^2 n} \right]^{\frac{1}{2}}, \quad (1)$$

where ε_0 – permittivity of vacuum, ε – dielectric permittivity, k_B – Boltzmann constant, T – absolute temperature, e – elementary charge, z – ion valence, n_0 – bulk concentration of the ions. The ions in a diffuse layer begin motion after application of static or low frequency electric field E_z . It results in arising of overall steady (or oscillating) flow sensitive to the electric field direction with a velocity profile, dependent on the parameter $\mu = kR$ (for a channel of a circular cross section with a radius R). In particular, for $\mu \ll 1$ a velocity profile is close to the parabolic one, typical for the Poiseuille flow, while for $\mu \gg 1$ a specific “plug” profile takes place. It is characterized by a constant value of the linear velocity v_0 everywhere, except for a thin near surface layer of thickness $l_s \approx l_D$ with a high value of the velocity gradient. $\partial v / \partial r \approx v_0 / l_D$. The corresponding expressions for volumetric flow rate through the capillary Q_i as a function of the axial component E_z of the electric field strength reads as [9]:

$$Q_i = -(\varepsilon_0 \varepsilon \zeta) \left[\frac{\pi R^2}{\eta} \right] E_z, kR \cong 1, \quad (2)$$

where η – the shear viscosity of a liquid, ζ – so called zeta potential which is typically of order 10...100 mV. Previously [1] we performed experiments with electro-osmotic flows of liquid crystal 4-cyano-4'-pentylbiphenyl (5CB) through the porous polymer polyethylene terephthalate (PET) films of thickness $h = 23 \mu\text{m}$, characterized by cylindrical open-end and randomly allocated pores, oriented normally to the film's surface. It turned out, that the predicted by equation (2) linear dependence $Q_i(U)$, in the range of the applied voltage $U = 0...30 \text{ V}$ was valid not only for an isotropic phase but for a nematic phase too (Fig. 1).

It means that such composite material can be used for elaboration of a linear *EHD pump*, controlled by low voltage. The overall volumetric rate Q of the pump is proportional to the total number N of pores and can be expressed as:

$$Q = Q_i N = Q_i N_0 S, \quad (3)$$

where N_0 – pore density, S – surface area of the sample. Equations (2) and (3) can be used for calculation of the dependence $Q(E_z)$, which defines the efficiency of the pump. The values of material parameters needed for such calculations were estimated from the experimental data [1] as $\zeta = -12 \text{ mV}$, $\eta = 0.032 \text{ Pa}\cdot\text{s}$ and $\varepsilon = 7$ (for a nematic phase of 5CB). The values of Q , calculated for the sample ($S = 1 \text{ cm}^2$) of a porous film with the pore density $N_0 = 10^8 \text{ cm}^{-2}$ are presented in Table.

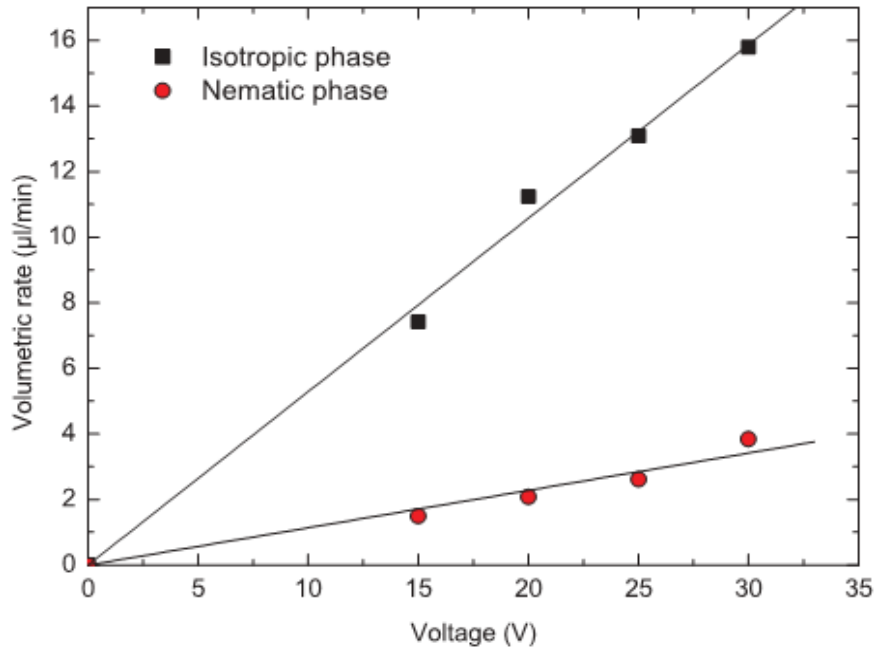


Fig. 1. Volumetric flow rate Q for the sample of porous film with $R = 150$ nm as a function of applied voltage U in isotropic ($T = 60^\circ\text{C}$) and nematic ($T = 25^\circ\text{C}$) phases of 5CB [1]

Results and discussion

One of the ways to use LC EHD pump to control the THz irradiation is to provide circulation of LC through a standard sandwich-like cell (or another external hydrodynamic unit) connected with the pump (Fig. 2). In the case when the hydrodynamic resistance Z_e of the external unit is essentially lower than the internal hydrodynamic resistance Z_i of the pump the values of the flow rate Q , presented in Table are the same for the internal and external units of a hydrodynamic circuit. In our case, the values Z_e and Z_i are defined as:

$$Z_e = \frac{12L}{Ad^3} \eta; \quad Z_i = \frac{8h}{\pi R^4} \eta, \quad (4)$$

where L , A and d are, correspondently a length, a width and a gap of the plane capillary formed inside a sandwich-like cell. For the used above values of the EHD pump's parameters and with dimensions of a plane cell $A = L = 1$ cm, $d = 100$ μm the ratio Z_i/Z_e is about 150 and the approximation of a constant value of Q is valid. The pressure gradient $G = \Delta P/\Delta x$, arising in the plane cell due to viscous losses can be found from well-known expression:

$$Q = \frac{G}{Z_e}. \quad (5)$$

The action of the flow, pumped through the plane cell on the orientation and optical properties of LC drastically depends on the initial orientation, stabilized by surfaces, and the experimental geometry. In particular, the initial homeotropic orientation with LC director normal to the plane substrates shows the maximal sensitivity to the action of the steady Poiseuille flow, realized in this hydrodynamic schema. In the linear regime the flow induced director distortions are confined by a flow plane and can be described by a polar angle $\theta(z)$, which can be expressed as [8]:

$$\theta(z) = -\frac{a_2}{6K_{22}\eta_1} \cdot z(z^2 - \frac{d^2}{4}) \cdot G, \quad (6)$$

where K_{33} and η_1 are the Frank's elastic module and the Miesowicz viscosity coefficient corresponding to the initial configuration. The phase delay δ between the extraordinary (refraction coefficient n_e) and ordinary (n_o) rays, propagating through LC layer, and induced by the orientational distortions can be defined as:

$$\delta \cong \frac{2\pi d}{\lambda} \cdot \frac{n_o(n_e^2 - n_o^2)}{2n_e^2} \cdot \langle \theta^2 \rangle =$$

$$= \frac{1}{15120} \cdot \frac{\pi d}{\lambda} \cdot \frac{n_o(n_e^2 - n_o^2)}{2n_e^2} \cdot \left(\frac{\alpha_2 G d^3}{K_{33}\eta_1} \right)^2, \quad (7)$$

where λ – a wave length, α_2 – the Leslie coefficient. It is worthwhile to notice, that equations (6) and (7) are valid only for a linear regime, when the maximal value θ_m of the angle θ :

$$\theta_m = -\frac{\alpha_2}{18\sqrt{3}K_{33}\eta_1} \cdot d^3 \cdot G \quad (8)$$

is essentially smaller, than π .

Contrary to the case of visible light, THz waves are characterized by essentially larger values of a wavelength ($30 \mu\text{m} < \lambda < 300 \mu\text{m}$ for frequency range $f = 10 \dots 1$ THz). It demands thicker layers (of order 1 mm) to provide the value of δ close to π needed for an effective modulation of the electromagnetic wave's intensity I , defined as:

$$I = I_0 \sin^2 \left(\frac{\delta}{2} \right), \quad (9)$$

where I_0 – the input wave intensity. At the same time, surfaces stabilize the initial structure of liquid crystals only for relatively thin layers ($d < 200 \mu\text{m}$). So, multilayer structures are often used in this case [10]. It can also be simply realized in terafluidic LC modulator described above, due to usage a number m of plane channels, connected in a parallel schema as

an external unit. Obviously, it results in corresponding decreasing of the volumetric flow rate Q_m for each channel ($Q_1 = Q/m$) with simultaneous increasing of the phase delay ($\delta = \delta_1 m$) at the propagating of the wave through the multilayered structure. The results of calculations of the main parameters mentioned above for a wavelength $\lambda = 60 \mu\text{m}$ ($f = 5$ THz) are presented in Table.

The calculations were made using material parameters of 5CB [11]: $K_{33} = 8.2 \cdot 10^{-12} \text{N}$, and $\eta_1 = 0.1052 \text{ Pa}\cdot\text{s}$, $\alpha_2 = -0.0812 \text{ Pa}\cdot\text{s}$. The values $n_e = 1.715$, $n_o = 1.534$ [12] correspond to the visible light. In spite of some wavelength dependence of the refractive indexes, the optical anisotropy $\Delta n = n_e - n_o$ which determines the phase delay is not changed essentially at decreasing of frequency to 1 THz [6].

The data, shown in Table, demonstrate the possibility of elaboration of effective LC modulator of THz irradiation tuned by electroosmotic flow at relatively low (about 50 V) operating voltages. The usage of multilayered external unit provides high efficacy of modulation for a linear regime of a director motion. This regime can be broken at high enough values of the pressure gradient ($> 1000 \text{ Pa/m}$ for $d = 100 \mu\text{m}$ as it was estimated, for a N-(4-methoxybenzylidene)-4-butylaniline [8]). It results in an escape of a director from the flow plane. The further increasing of G may induce the long living (up to some hours) instabilities and break the operation of the terafluidic LC modulator.

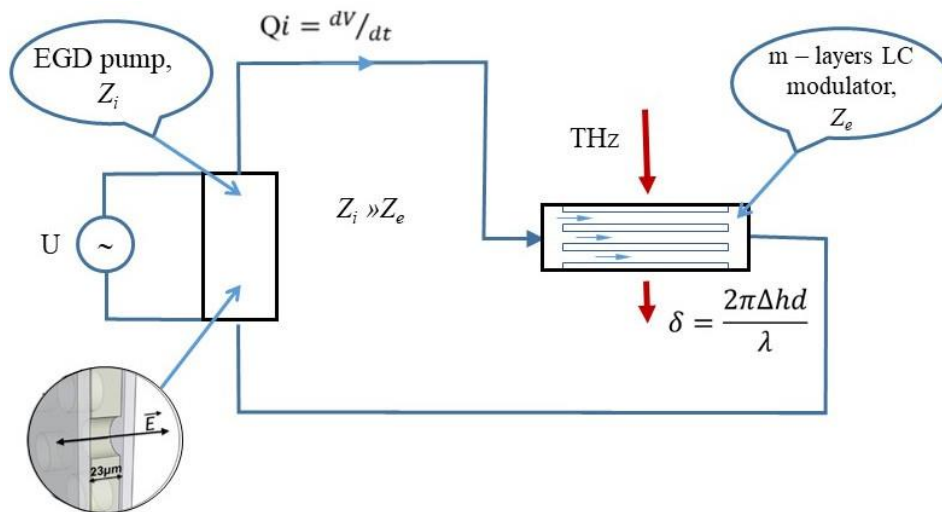


Fig. 2. Terafluidic LC modulator: hydrodynamic schema

Table. Technical parameters of the terafluidic modulator

E_z , V/ μm	Q , 10^{-12} m ³ /s	G , Pa/m for $m = 1/10$	θ_m , rad for $m = 1/10$	δ/π for $m = 10$	$I/I_0 \times 100$ %
0.01	0.233	89/8.9	0.028/0.0028	0.0112	0.0306
0.1	2.33	890/89	0.28/0.028	0.112	3.06
1.0	23.3	8900/890	$> (\pi/2)/0.28$	1.12	≈ 100

Conclusion

The existing information about electroosmotic flows in porous PET films were used to propose a new terafluidic LC modulator, based on integration of the electroosmotic unit, playing the role of LC EHD pump, and external unit, which can include one standard LC cell or multilayer structure. The detailed calculations were made for a linear regime of flow of the initially homeotropic layer (or layers) of a liquid crystal (5CB). It is shown that the multilayer structure provides operation of the terafluidic LC modulator at moderate voltages. The main advantage of such decision is the absence of electrodes in the region of THz wave. Further optimization of the technical characteristics can be achieved due to theoretical calculations and experimental investigations.

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