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The influence of longitudinal voltage, applied along semiconductor substrate of planar-oriented liquid-crystal cell, on the birefringence of nematic liquid crystal (NLC) has been studied. It is shown that with the fixed value of transverse voltage the application of longitudinal voltage creates an additional possibility to control the electro-optically induced phase shift of light passing through NLC. The dependence of phase shift vs. control voltages is obtained. The results of simulation of the longitudinal voltage influence on the process of NLC reorientation are given. The obtained results can be used for development and fabrication of liquid-crystal phase modulators.

Keywords Liquid crystal cell; nematic liquid crystal; phase shift; semiconductor substrate

Introduction

One of the highly important characteristics of liquid crystal (LC) based optoelectronic devices is the switch time, caused mainly by LC molecules reorientation. The problem of reorientation time improvement is extremely urgent, particularly in adaptive optics and spatial filtration using electrically controlled LC transparency. There are specific methods for improvement of LC cells time characteristics by increasing the control voltage, decreasing of LC layer thickness, changing of the pretilt angle of LC director, as well as by synthesizing of new types of fast-response LCs [1–3]. Today the spatial light modulators, based on semiconductor – nematic liquid crystal (NLC) structure, are widely used.

In this work the results of theoretical and experimental investigation of the voltage influence, applied to the semiconductor substrate of LC cell, on birefringence are presented.

It is shown that by a change of the voltage amplitude, applied to the semiconductor substrate of planar-oriented liquid-crystal cell, it is possible to realize the

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control of induced birefringence. It is also shown, that the application of voltage to the semiconductor leads to improvement in NLC relaxation time.

Problem

To reveal the possibility for additional control of induced birefringence the planar-oriented LC cell, one of substrates of which is semiconductor, is investigated. For control of electro-optically induced birefringence, in addition to the transverse voltage, causing Freedericksz transition, control voltage is applied along the semiconductor substrate (longitudinal voltage). To avoid LC heating the short bipolar electric pulses were applied to the semiconductor. The pulse duration is chosen enough long to ensure the process of NLC reorientation, and the selection of the pulse period is chosen necessary for total relaxation of LC until the next pulse.

To deal with the problem it is necessary to take into account the influence of transverse and longitudinal control voltages on birefringence. For this purpose the phase shift dynamics, caused by Freedericksz transition, under the influence of longitudinal voltage, applied to the semiconductor, should be investigated.

Simulation of the Process of Director Reorientation of Nematic Liquid Crystal in the Longitudinal and Transverse Electric Fields

Let us analyze the behavior of NLC director in AC electric field formed by superposition of two mutually perpendicular components with equal frequencies and phases. The planar-oriented NLC is considered: the x axis coinciding with the director initial direction. The longitudinal field component is directed along the conducting substrate, i.e., along the x axis, and the transverse is perpendicular to the initial direction of director, along the z axis. Effect of disorientation, caused by the fluid motion, is neglected. Let us choose plane geometry of interaction in Cartesian coordinate system $r=(x,\ z)$ for obtaining of dynamic equations. Let's introduce notation: $E=E(t,\ r)$ – real vector of electric field in crystal; $n=n(t,\ r)$ – unit vector (director); θ – angle between director and z axis, connected with n by the following expression

$$n = (n_x, 0, n_z) = (\sin\theta, 0, \cos\theta) \tag{1}$$

For further statement it is convenient to introduce additional unit vector, orthogonal to n:

$$\begin{aligned} m = (m_x, 0, m_z) &= \frac{\partial n}{\partial \theta} = (\cos\theta, 0, -\sin\theta) \\ (nm) &= 0 \end{aligned} \tag{2}$$

The free energy density F for NLC is written as follows [4]

$$F = \frac{1}{2}\left[K_{11}(div\ n)^2 + K_{22}(nrotn)^2 + K_{33}(n \times rotn)^2\right] - \frac{\varepsilon_0\varepsilon_a}{8\pi}(nE)^2 \tag{3}$$

In the functional (3) K_{11}, K_{22}, K_{33} – elastic coefficients of Frank; $\tilde{\varepsilon}_0$ vacuum dielectric constant, $\varepsilon_a = \varepsilon_{\|} - \varepsilon_{\perp}$ parameters of permittivity tensor, which are expressed by Cartesian components of n_i director as

$$\varepsilon_{ij} = \varepsilon_{\perp}\delta_{ij} + \varepsilon_a n_i n_j, \quad i,\ j = x, y, z \tag{4}$$

where δ_{ij} – Kronecker symbol.

For simplification let us suppose, that the values of material parameters K_{11}, K_{22}, K_{33}, $\varepsilon_{\|}$, $\varepsilon_{\perp}$ are constant in the observed frequency range of electric field E. In the one-dimensional case, when all unknown values depend only on one coordinate z and on time t, the expression (3) can be expressed as

$$F = \frac{1}{2}\left[f\left(\frac{\partial\theta}{\partial z}\right)^2 - \frac{\varepsilon_0\varepsilon_a}{4\pi}(nE)^2\right] \tag{5}$$

$$f = f(\theta) = K_{11}\sin^2\theta + K_{33}\cos^2\theta \tag{6}$$

Variation of the functional (6) taking into account the relaxation terms gives the following nonlinear equation for θ

$$\gamma\frac{\partial\theta}{\partial t} = f\frac{\partial^2\theta}{\partial z^2} + \frac{1}{2}\left[f_\theta\left(\frac{\partial\theta}{\partial z}\right)^2\right] + \frac{\varepsilon_0\varepsilon_a}{4\pi}(nE)(mE) \tag{7}$$

where $f_\theta = \partial f/\partial\theta$, γ – NLC viscosity coefficient.

In accordance with the (7) the flexoelectric terms were not considered and the hydrodynamic flows appearance was neglected.

The material Eq. (7) must be supplemented with boundary conditions at $z = 0, L$ (L – the thickness of crystal). Following [5], these conditions were selected as

$$\left[K\frac{\partial\theta}{\partial 3} \pm a_\theta\theta\right]\Bigg|_{z=0,L} = b_\theta \tag{8}$$

where the signs $+/-$ are related respectively to $z = 0$ and $z = L$, K – the averaged constant of Frank, the parameters a_θ, b_θ in general depend on the surface energy density of molecules coupling with the substrates, flexoelectric coefficients and electric fields. For obtaining the closed system it is necessary to add to (7) the Maxwell's equations, which take into account electric fields variation in LC. For the electric fields frequency range 1000–2000 Hz, the medium conductivity can be neglected and subsequently the electric field in LC can be presented as

$$div\ (\tilde{\varepsilon}E) = 0, \quad rotE = 0, \tag{9}$$

where $\tilde{\varepsilon}$ – the permittivity tensor (4). Particularly in the one-dimensional case the Eq. (9), with taking into account (4), takes the form

$$\frac{\partial}{\partial z}[\varepsilon_{\perp}E_z + \varepsilon_a n_z(nE)] = 0, \quad \frac{\partial E_x}{\partial z} = 0 \tag{10}$$

The Eq. (10) are easily integrated and the electric fields in the crystal are determined exceptionally through the values of given fields. Taking into account the corresponding initial condition for the orientation angle $\theta(0, z) = \theta_0(z)$, boundary condition (8) and (10) Eq. (7) becomes closed for description of NLC interaction with arbitrary directed electric field in the one-dimensional case. Generally it is not possible to solve the system (7) analytically, it will be done numerically. Let us consider the case, when the field $E(t)$ is in the plane (x, z), and the field components have the shape of repetitive rectangular pulse sequence of equal frequency – ω_0 and phase – ψ_0

$$E_z(t) = a_z \prod(t) sign\left\{\cos\left(\frac{2\pi}{T_0}t + \psi_z\right)\right\}, \quad E_x(t) = a_x \prod(t) sign\left\{\cos\left(\frac{2\pi}{T_0}t + \psi_x\right)\right\}, \tag{11}$$

where a_z, a_x – initial values of fields amplitudes, T_0 – oscillation period of electric fields, ψ_z, ψ_x – initial phases of electric fields oscillation, $sign(x)$ – sign function,

$$\prod(t) = \prod(t + kT) = \begin{cases} 1, kT < t < kT + 10T_0 \\ 0, kT + 10T_0 < t < kT + 40T_0 \end{cases}, \tag{12}$$

where $k = 0, 1, 2, \ldots, N$, T – rectangular pulses sequence repetition period. The boundary conditions (8) for planar orientation are expressed as follows

$$\theta|_{0,L} = \frac{\pi}{2}.$$

The initial conditions were selected equal to $\theta(0, z) = \pi/2$.

The system of Eqs. (7) and (10), describing the NLC interaction with arbitrary directed electric field in the one-dimensional case, with taking into account the boundary and initial conditions, was solved by the method of finite differences.

The numerical calculation of time dependence of intensity and phase shift of the light, passed through NLC, placed in the crossed polarizers, was carried out. In the calculations 5CB NLC with the 7 μm thickness is observed. The case, when the rectangular bipolar pulses of transverse (V_z) and longitudinal (V_x) voltages are applied to the cell is considered. Duration of bipolar pulses is 1 ms and the repetition period is 15 ms. Numerical solutions have been received for different relations of longitudinal and transverse voltages. As an example some time dependencies of intensity and phase shift of light passing through the NLC are given bellow (Fig. 1a–d).

In the Figure 1a the time dependences of intensity and phase shift are presented for the case when the voltage amplitude of transverse component $V_z = 20$ V and the voltage amplitude of longitudinal component $V_x = 0$ V. Figure 1b–d represent the time dependences of light intensity and phase shift for the case when $V_z = 20$ V, $V_x = 40$ V; $V_z = 20$ V, $V_x = 60$ V and $V_z = 20$ V, $V_x = 84$ V correspondingly.

According to the results on simulation, at $V_x \geq 4.2\,V_z$ the relaxation process exponentially damp and phase shift is 2π. At the same time by increasing V_x the relaxation time decrease is observed. In the Figure 2 the dependence of relaxation time vs. the amplitude V_x obtained by numerical solution for fixed value $V_z = 20$ V, V, is presented.

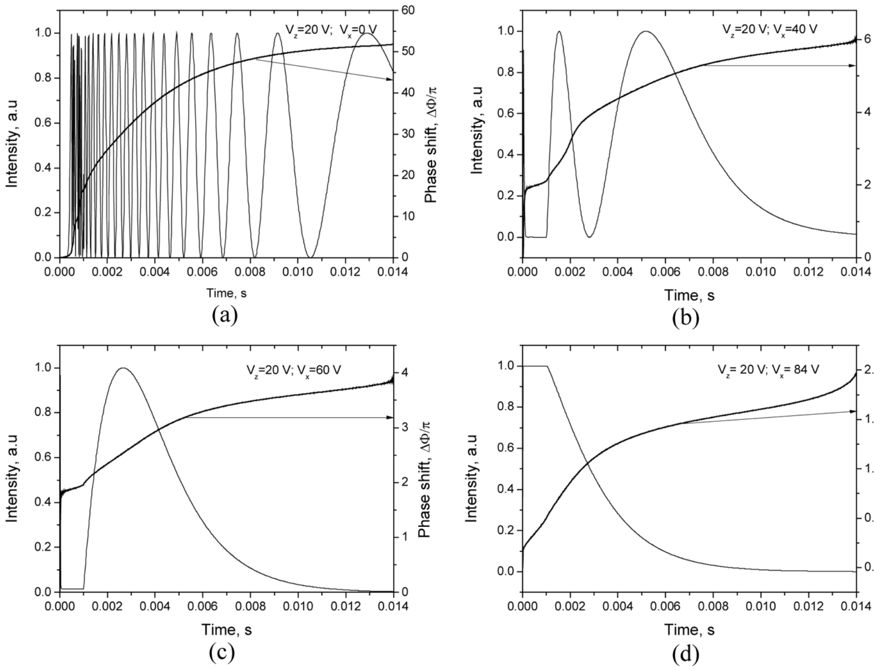

Figure 1. The time dependences of light intensity and phase shift for different V_x.

Thus, for identical frequencies and phases of longitudinal ($V_x = V_{\|}$) and transverse ($V_z = V_{\perp}$) components of variable electric field the director orientation depends on the ratio of amplitudes of these components. In other words, an additional option is accessible to control the phase shift of the light, passed through NLC, and to reach decrease in relaxation time by changing the longitudinal voltage at the fixed transverse voltage.

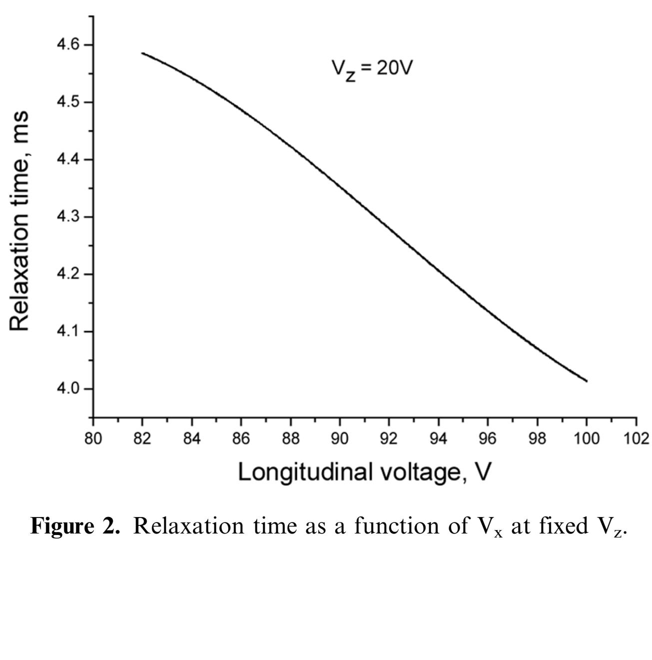

Figure 2. Relaxation time as a function of V_x at fixed V_z.

Experiment

A planar-oriented cell, filled with 5CB NLC (Merck) of 7 μm thickness was prepared. Both substrates of LC cell are 1 mm thick BK7 optical glass covered with transparent conducting layer (ITO), and one of them is covered with an additional thin layer of amorphous silicon by chemical vapor deposition. The orientation of NLC molecules on the substrate was conducted by machine rubbing of alignment layer (polyvinyl alcohol).

In Figure 3 the optical scheme of experimental setup is presented.

The radiation of *He-Ne* laser 1 ($\lambda = 0.63$ μm) through the neutral filter 2 and Glan prism 3 is directed to LC cell 4, positioned perpendicular to the direction of laser beam propagation. Thus, the beam, reflected from the semiconductor substrate, falls on Glan prism. The alteration in polarization of the beam reflected from LC cell is caused by electro-optically induced birefringence of NLC. Reflected from the Glan prism the beam with polarization plane perpendicular to polarization of the beam, falling to LC, was recorded by photodetector 5. The electric signal from photodetector was recorded by PC via NI DAQ 6025E. This optical scheme presented in the Figure 3 is similar to the case, when the cell under investigation is placed between the crossed polarizers.

A LabView based special program for control of parameters of external longitudinal and transverse voltages was designed. The program allows forming bipolar pulses with different frequency, duration and amplitude, which after amplification are applied to the investigated cell through two channels. By one channel longitudinal voltage was applied along the semiconductor substrate, and by the second – the transverse voltage was applied to the cell. The control voltages and photodetector signal were recorded simultaneously. The NLC cell view is given in the Figure 4.

Due to bipolar pulses applied to NLC cell, the Freedericksz transition takes place. At the same time with the transverse voltage the second channel bipolar pulses were applied to silicon substrate (longitudinal voltage). The duration of both pulses was maintained to be 1–2 ms with repetition rate 0.25–1 Hz. To study the influence of control voltages on NLC birefringence two series of the experiments were carried out:

1. Influence of transverse voltage ($V_{\perp}$) on phase shift at the fixed longitudinal voltage ($V_{\|}$).

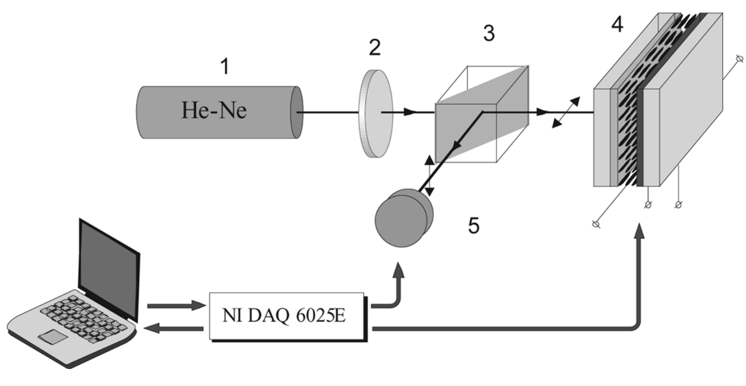

Figure 3. The optical scheme of experimental setup.

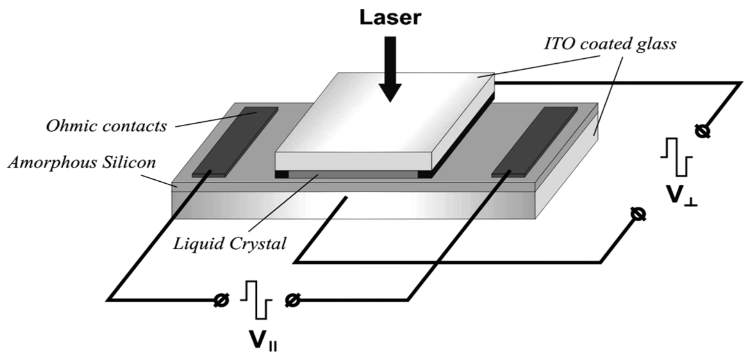

Figure 4. The view of investigated NLC cell.

2. Influence of longitudinal voltage ($V_{||}$) on phase shift at the fixed transverse voltage ($V_{\perp}$).

Results of processed experimental data were visualized on the interface, representing the reorientation and relaxation processes (Fig. 5a,b).

The dynamics of phase shift was restored from the time dependence of relaxation process intensity by applying the Hilbert transformation (Fig. 5c).

For each pair of the values $V_{\perp}$ and $V_{||}$ the corresponding time dependence of phase shift was determined. The dependence of phase shift vs. variable control voltage was determined from the set of such curves. The value of phase shift was determined for the fixed moment of time, at which the relaxation process can be considered finished.

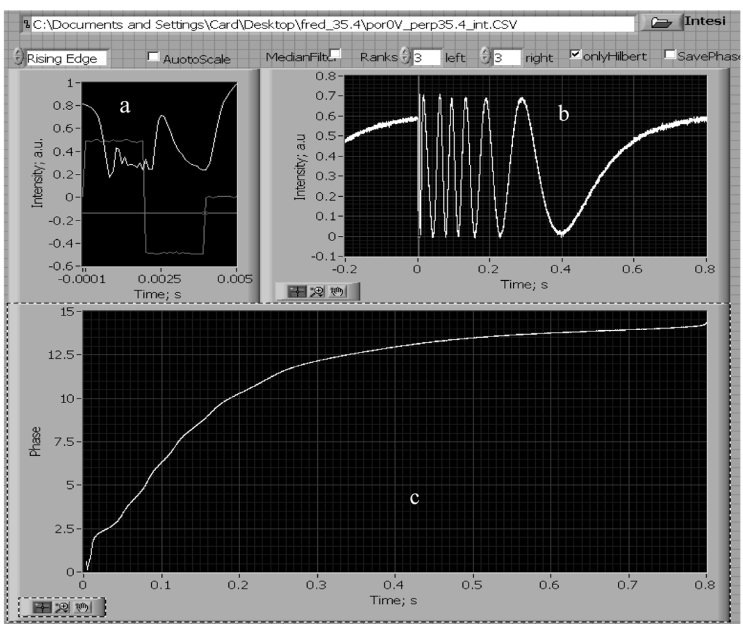

Figure 5. Interface for visualization of experimental data processing.

Results and Discussion

1. *The Phase Shift Control by Varying $V_\perp$ at the Fixed Value of $V_\parallel$*

In Figure 6 the time dependences of the reflected light phase shift for different values $V_\perp$ at fixed $V_\parallel = 0\,V$ (a) and $V_\parallel = 57.6\,V$ (b) are presented.

It should be noted that when no transverse voltage is applied, the application of longitudinal voltage does not induce birefringence.

From the obtained family of curves the dependences of phase shift vs. transverse voltage amplitude at the fixed moment of time (in this case 0.7 s) for different values of longitudinal voltage are determined (Fig. 7). As it is seen from the figure, for different values of longitudinal voltage the nature of dependences is the same: phase shift sharply grows with increase of $V_\perp$, and then saturation is observed. However, increase in $V_\parallel$ leads to the shifting of Freedericksz threshold to greater values.

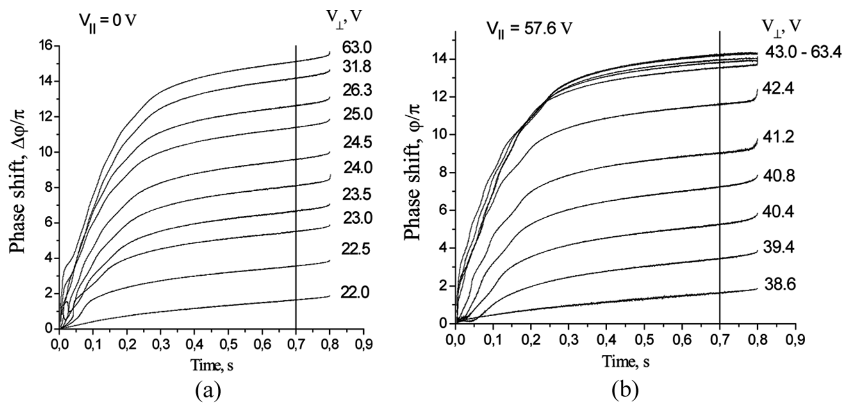

Figure 6. Time dependence of phase shift for various $V_\perp$ at fixed $V_\parallel = 0\,V$ (a) and $V_\parallel = 57.6\,V$ (b).

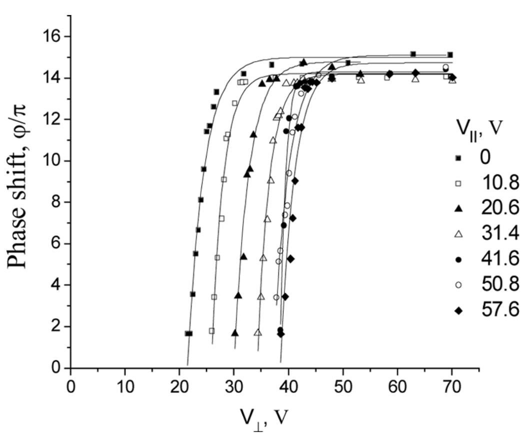

Figure 7. Phase shift vs. transverse voltage at different values of longitudinal voltage.

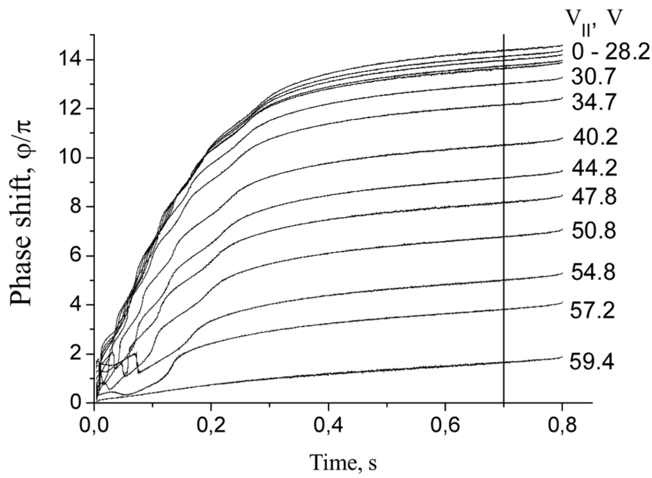

Figure 8. Time dependence of phase shift for different values of $V_{||}$ at fixed $V_{\perp} = 38$ V.

2. *The Phase Shift Control by Varying $V_{||}$ at the Fixed Value of $V_{\perp}$*

The transverse voltage (higher than Freedericksz threshold) was applied to LC cell, as a result of which the radiation passing through LC accumulates appropriate phase shift. Then, transverse pulses of fixed-step increased amplitude synchronously to the longitudinal pulses were applied to the cell. From Figure 8 one can see that increasing of $V_{||}$ causes decrease in phase shift, induced by transverse field.

From the obtained set of curves in accordance with the described procedure the dependence of phase shift vs. longitudinal voltage at different values of transverse voltage was determined (Fig. 9).

As it is seen from the figure, varying the $V_{||}$ at each fixed $V_{\perp}$ it is possible to realize fine tuning of phase shift. Thus the range of longitudinal voltage variation is wider for more initial phase shift. In this case, in contrast to previous, any small

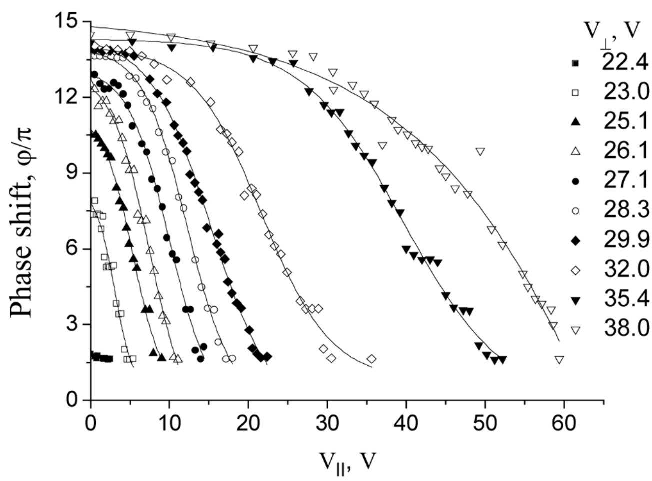

Figure 9. Phase shift as a function of $V_{||}$ at different values of $V_{\perp}$.

change in the amplitude of longitudinal voltage leads to a small change in the passed radiation phase.

Conclusions

An option of a fine control of phase shift of light passing through NLC is found by applying the longitudinal voltage along the semiconductor substrate of the planar-oriented liquid-crystal cell. It allows one to realize an additional control of the induced birefringence in NLC. It is also found that an increase of longitudinal voltage amplitude leads to an increase of Freedericksz threshold. The results of the numerical simulation of longitudinal voltage influence on NLC reorientation process agree with the experimental data. Particularly, it is shown, that for identical frequencies and phases of longitudinal ($V_x = V_{II}$) and transverse ($V_z = V_{\perp}$) components of variable electric field the director orientation depends on the ratio of amplitudes of these components. The obtained results can be used for development of liquid crystal phase retarders, in particular, for improvement of time characteristics and control of modulation process.

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