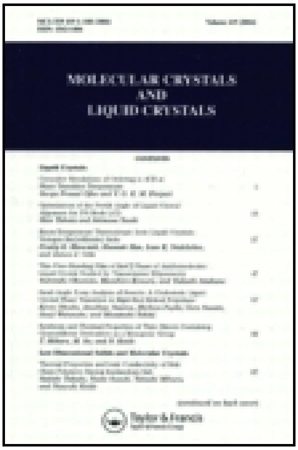

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Director Profile in the In-Plane Switching of Nematic Liquid Crystals Cell

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DIRECTOR PROFILE IN THE IN-PLANE SWITCHING OF NEMATIC LIQUID CRYSTALS CELL

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In this paper we calculated an electric field produced by interdigital electrodes in in-plane switching mode analytically in the quasi linear model in between electrodes space. Using the results for the electric field we calculated numerically the director profile in our model for the nematic cell with the strong director anchoring.

Director profile gave us optic properties of nematic LC cell with in-plane electrodes.

Keywords: director profile; Freedericksz transition; in-plane switching mode; liquid crystal; optic properties; threshold voltage

1. INTRODUCTION

Liquid crystals as a media with the anisotropic properties (birefringence, dielectric and elastic properties) are now widely studied for their promising possibility in display applications. One serious problem of these displays

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lies in the limited viewing-angle characteristics. In particular, it was too difficult to achieve a symmetric high contrast ratio with no gray scale reversal as a function of viewing angles, because the director profile is significantly asymmetrical with respect to the substrate normal when an electric field is applied. The concept of liquid crystal displays employing in-plane switching (IPS) mode i.e., the electro-optical effect with interdigital electrodes at the lower substrate was developed in the 1970's. In 1990's this concept attracted scientific attention again [2–3]. This novel technology provides extremely wide viewing-angle characteristics [2–5].

In the IPS mode, an electric field is applied to the liquid crystals along the direction parallel to the plane of the substrates. The liquid crystals, aligned homogeneously between the substrates in the state without the electric field, are twisted by an in-plane electric field. The initially untwisted homogeneous configuration of the liquid crystals provides excellent light blocking. This behavior contributes to a high contrast ratio without gray scale reversal even for obliquely incident light at wide angles.

The threshold behavior and response characteristics of the liquid crystals in the IPS mode were studied [4–5] assuming uniform electric field and strong director anchoring at the cell boundaries. In this paper we analyze the behavior of nematic liquid crystals in the IPS mode taking into account the inhomogenity of applied electric field.

The structure of the paper is as follows. In the second section we simplified of the general problem with an approximation of the electric field profile for in-plane electrode configuration using Fourier expansion. In the third section we calculated threshold voltage with averaged electric field obtained in the second section for nematic liquid crystal cell; and using the analytical results for electric field we calculated numerically the director profile in our model.

2. ELECTRIC FIELD FOR IN-PLANE ELECTRODE CONFIGURATION

As we know the uniform electric field and strong director anchoring at the cell boundaries assumption gives the acceptable results for the threshold behavior in the in-plane switching (IPS) mode [4–5], the exact electric field distribution is not too inhomogeneous in between electrodes space. This fact gave us the model of the electric field for the comb-shape interdigital electrodes formed on one lower substrate [3] (Fig. 1). These electrodes produce inhomogeneous electric field nonparallel to the substrate, namely an in-plane electric field (Figs. 1–2). Electric field potential Φ satisfies the Laplace equation $\Delta\Phi = 0$ with the boundary

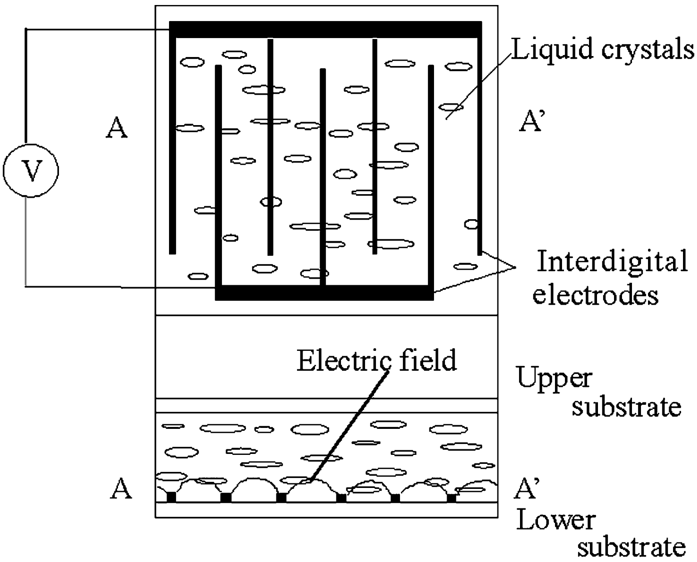


FIGURE 1

conditions (Fig. 2):

$$\Phi(y, z=0) = \Phi_0, \quad \text{if } \frac{d_1}{2} + d_2 + (2n-1)(d_1 + d_2) \le y \le \frac{d_1}{2} + 2n(d_1 + d_2);$$

$$\Phi(y, z=0) = -\Phi_0, \quad \text{if } \frac{d_1}{2} + d_2 + 2n(d_1 + d_2) \le y \le \frac{d_1}{2} + (2n+1)(d_1 + d_2);$$

$$n = 0, \pm 1, \ldots \quad \Phi_0 - \text{is the electrodes potential.}$$

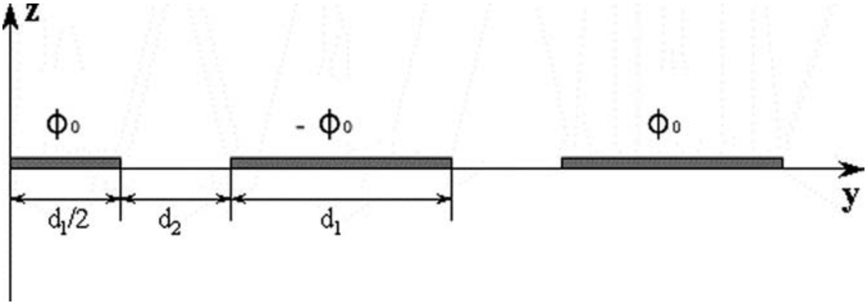


FIGURE 2

This problem was solved [6] for electric field potential Φ. To simplify the problem we hypothesized that potential $\Phi(y, z=0)$ has a linear dependence on y in between the electrode space (the reason for this assumption is the acceptable result in uniform field assumption):

$$\Phi(y, z=0) = \Phi_0\left(\frac{d_1+d_2}{d_2} - \frac{2}{d_2}y\right),$$

where

$$\frac{d_1}{2} + n(d_1+d_2) \leq y \leq \frac{d_2}{2} + \left(n+\frac{1}{2}\right)(d_1+d_2); \quad n = 0, \pm 1, \ldots$$

$$\Phi(u, v, \delta) = \Phi_0 \sum_m A(m, \delta)\cos\left(\frac{m\pi u}{1+\delta}\right)\exp\left(-\frac{m\pi v}{1+\delta}\right);$$

where $A(m, \delta)$ is the Fourier factor; dimensionless coordinates $u = \frac{y}{d_2}$, $v = \frac{z}{d_2}$, $\delta = \frac{d_1}{d_2}$; d_1 – electrode width, d_2 – electrode gap.

$$A(m, \delta) = \frac{4}{m\pi}\sin\left(\frac{m\pi}{2}\right)\left[2\frac{1+\delta}{m\pi}\sin\frac{m\pi}{2(1+\delta)} - \cos\frac{m\pi}{2(1+\delta)}\right]$$

Respectively for electric field $E = -\nabla\Phi$ we got for $z \geq 0$:

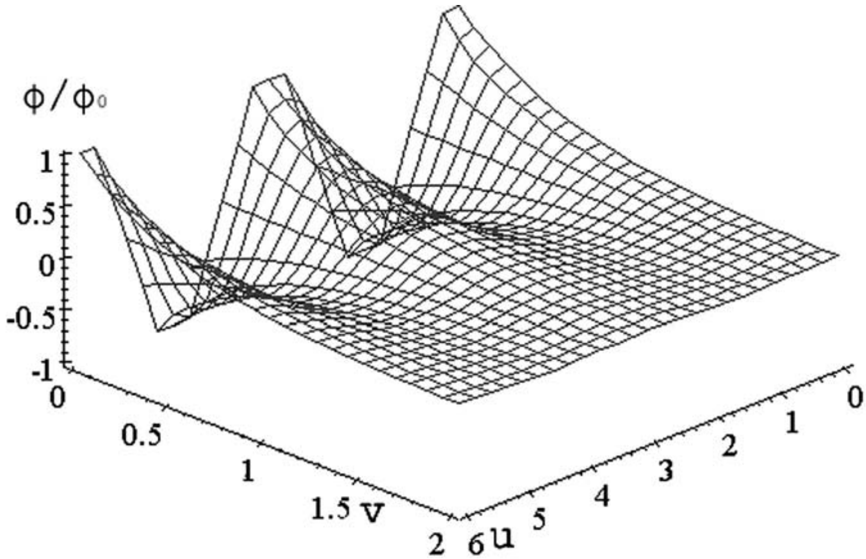
$$\begin{aligned} E_y(u, v, \delta) &= \frac{1}{d_2}\Phi_0 \sum_n A(n, \delta)\frac{n\pi}{1+\delta}\sin\frac{n\pi u}{1+\delta}\exp\left(-\frac{n\pi v}{1+\delta}\right); \\ E_z(u, v, \delta) &= \frac{1}{d_2}\Phi_0 \sum_n A(n, \delta)\frac{n\pi}{1+\delta}\cos\frac{n\pi u}{1+\delta}\exp\left(-\frac{n\pi v}{1+\delta}\right) \end{aligned} \tag{1}$$

The total number of A (m, δ) (4) in the full solution is infinite, in our approximate solution we have truncate the series (however as result we have the oscillation in the Figs 3b and 4b,d). In Figure 3 we show the dimensionless potential Φ/Φ_0 as the function of u and v at $d_1/d_2 = 0.5$ and in Figure 4 we plot the dimensionless electric field components $E_y d_2/\Phi_0$ and $E_z d_2/\Phi_0$ as the function of u and v at $d_1/d_2 = 0.5$.

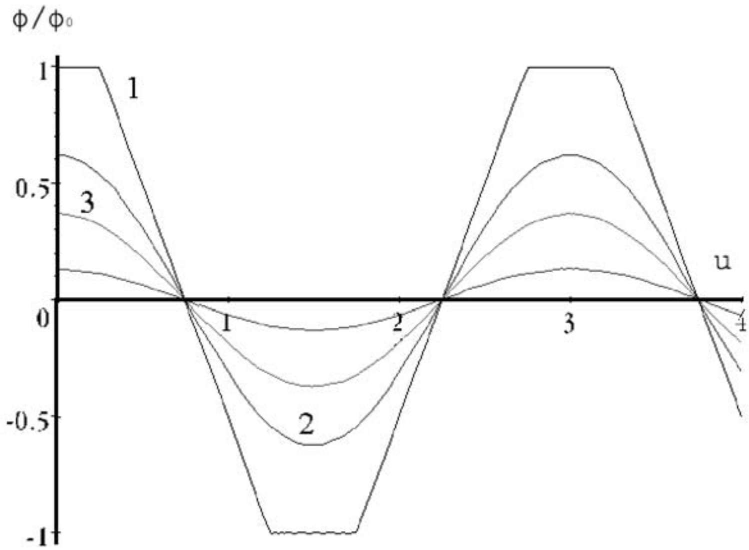
3. DIRECTOR PROFILE

3.1. Total Elastic Free Energy

Detailed switching behavior of liquid crystals following applied electric field in the IPS mode were analyzed by O-he [5] from the viewpoint of the Freedericksz transition, using the continuum elastic theory and supposing the electric field to be homogeneous and to have only E_y component.



(a)



(b)

FIGURE 3

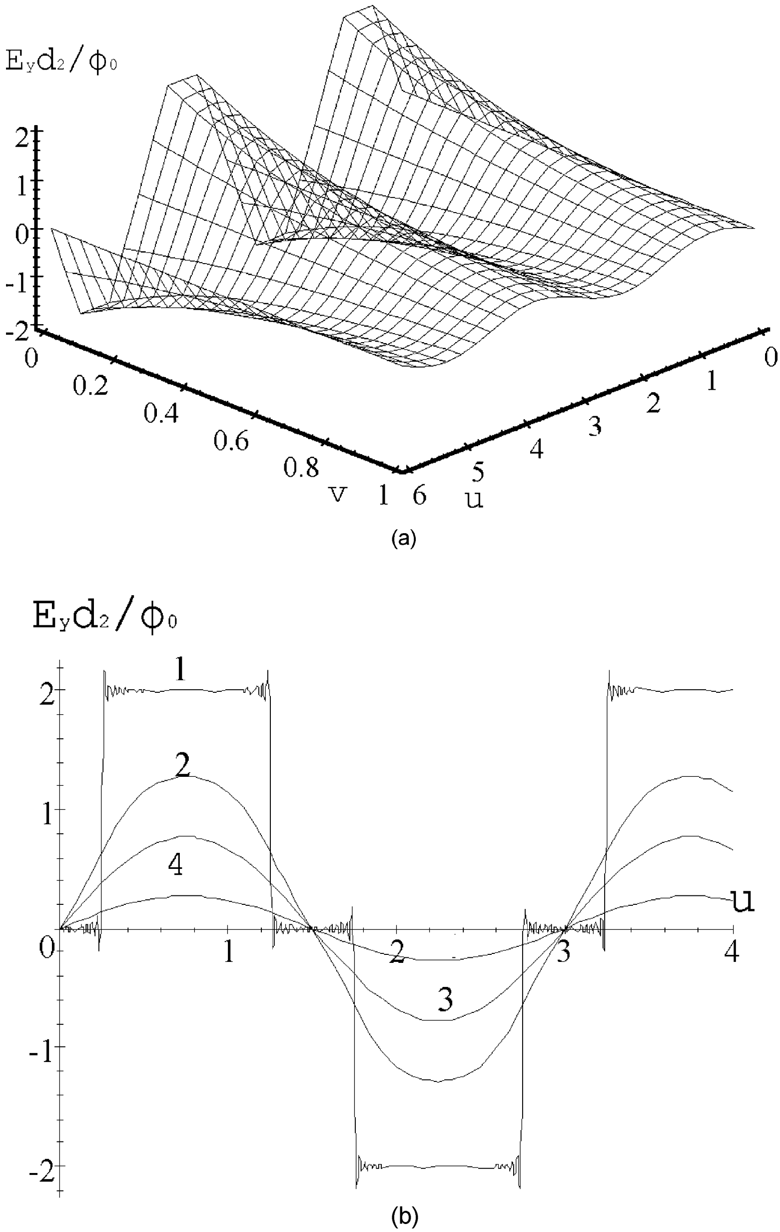
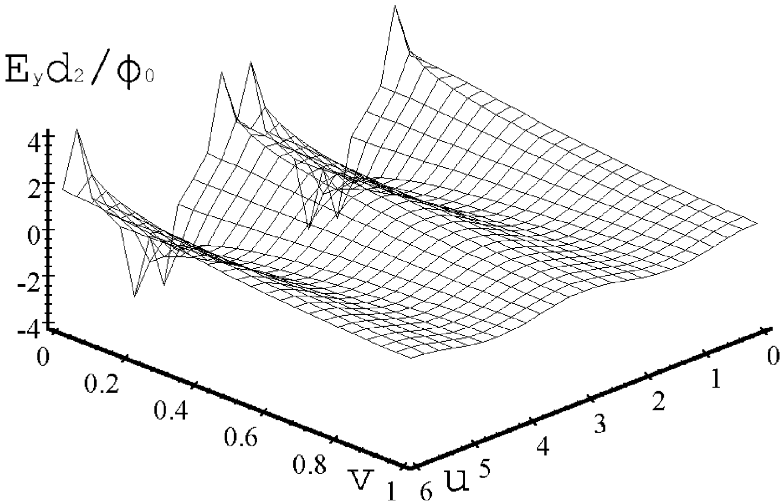
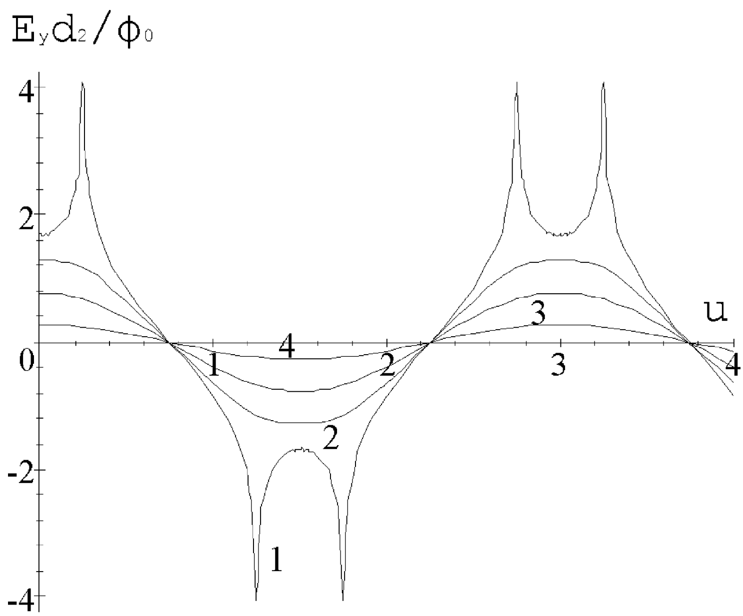


FIGURE 4



(c)



(d)

FIGURE 4 Continued.

Figure 5 shows the real geometry of the director deformation by an in-plane electric field.

In the switched off state the director is given by the unit vector $n = (1, 0, 0)$. On applying the voltage director rotates and it is convenient to describe the director profile by two angles φ and θ.

$$n = (\sin\theta(y,z)\cos\varphi(y,z), \sin\theta(y,z)\sin\varphi(y,z), \cos\theta(y,z) \tag{2}$$

Long-range bulk distortions of liquid crystal director can be described by the continuum theory [7]. According to this theory the bulk elastic energy F_V of a distorted nematic LC has the form

$$\begin{aligned} F_V &= \frac{1}{2}K_{11}\int(\mathrm{div}\mathbf{n})^2 dV + \frac{1}{2}K_{22}\int(\mathbf{n}\cdot\mathrm{curl}\mathbf{n})^2 dV \\ &+ \frac{1}{2}K_{33}\int(\mathbf{n}\times\mathrm{curl}\mathbf{n})^2 dV - \frac{\varepsilon_a}{8\pi}\int(n\vec{E})^2 dV \end{aligned}$$

here K_{11}, K_{22}, K_{33} are the splay, twist and bend elastic constants respecti vely $\varepsilon_a = \varepsilon_{\|} - \varepsilon_{\perp}$ is the anisotropy of the liquid crystal dielectric tensor. We will use the simple model, known as one elastic constant approximation.

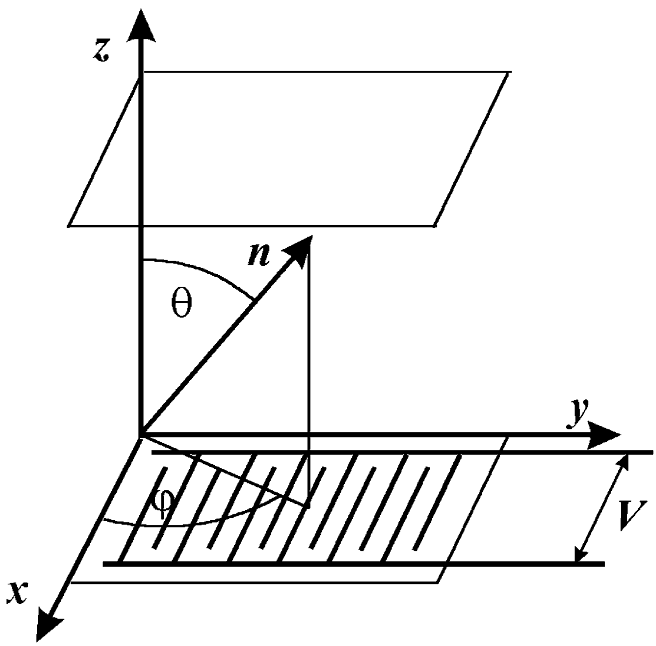


FIGURE 5

The total elastic free energy F of the nematic liquid crystal in one elastic constant approximation and with strong director anchoring one can write [7]:

$$F = \frac{K}{2}\int \left[(\nabla\vec{n})^2 + \left(\vec{\nabla}\times\vec{n}\right)^2\right]dV - \frac{\varepsilon_a}{8\pi}\int \left(n\vec{E}\right)^2 dV;$$

or in terms of φ and θ:

$$F = \frac{K}{2}\int_0^L \int_0^{2(d_1+d_2)} \left\{\left[\left(\frac{\partial\theta}{\partial y}\right)^2 + \left(\frac{\partial\theta}{\partial z}\right)^2 + \left(\left(\frac{\partial\varphi}{\partial y}\right)^2 + \left(\frac{\partial\varphi}{\partial z}\right)^2\right)\sin^2\theta\right] + 2\sin^2\theta\cos\varphi\left(\frac{\partial\theta}{\partial y}\frac{\partial\varphi}{\partial z} - \frac{\partial\varphi}{\partial y}\frac{\partial\theta}{\partial z}\right)\right\}dydz$$
$$- \frac{\varepsilon_a}{8\pi}\int_0^L \int_0^{2(d_1+d_2)} \left(E_y^2\sin^2\theta\sin^2\varphi + E_z^2\cos^2\theta + 2E_yE_z\sin 2\theta\sin\varphi\right)dydz$$

where K is the elastic constant, E_y, E_z are the electric field components, and ε_a denotes the anisotropy of the LC dielectric tensor, L is the cell thickness.

3.2. Ostrogradsky's Equations

The equilibrium director profile have to realize the minimum of total free energy. And we have to solve the following Ostrogradsky's equations [8]:

$$\begin{aligned}
&\frac{K}{2}\left(2\Delta\theta - \sin 2\theta\left(\left(\frac{\partial\varphi}{\partial y}\right)^2 + \left(\frac{\partial\varphi}{\partial z}\right)^2\right)\right) \\
&\quad + \frac{\varepsilon_a}{8\pi}\left(\sin 2\theta\left(E_y^2\sin^2\varphi - E_z^2\right) + 2E_yE_z\cos 2\theta\sin\varphi\right) = 0, \\
&\frac{K}{2}\left(2\sin 2\theta\left(\frac{\partial\theta}{\partial y}\frac{\partial\varphi}{\partial y} + \frac{\partial\theta}{\partial z}\frac{\partial\varphi}{\partial z}\right) + 2\sin^2\theta\Delta\phi\right) \\
&\quad + \frac{\varepsilon_a}{8\pi}\left(E_y^2\sin^2\theta\sin 2\varphi + E_yE_z\sin 2\theta\cos\varphi\right) = 0
\end{aligned} \tag{3}$$

with the boundary conditions:

$$\left.\left(\sin^2\theta\left(\frac{\partial\varphi}{\partial y} - \cos\varphi\frac{\partial\theta}{\partial z}\right)\right)\right|_{y=0;2(d_1+d_2),z} = 0$$

$$\left(\sin^2\theta\left(\frac{\partial\varphi}{\partial z}+\cos\varphi\frac{\partial\theta}{\partial y}\right)\right)\Big|_{y,z=0;L}=0$$
$$\left(\frac{\partial\theta}{\partial z}-\sin^2\theta\cos\varphi\frac{\partial\varphi}{\partial y}\right)\Big|_{y,z=0;L}=0$$
$$\left(\frac{\partial\theta}{\partial y}+\sin^2\theta\cos\varphi\frac{\partial\varphi}{\partial z}\right)\Big|_{y=0;2(d_1+d_2),z}=0$$

These conditions include the conditions that we can write down from the physical reason:

$$\begin{aligned}&\varphi(y,z=0)=\varphi(y,z=H)=0;\\&\varphi(y=0,z)=\varphi(y=d_1+d_2,z)=0;\\&\theta(y,z=0)=\theta(y,z=H)=\pi/2;\\&\theta(y=0,z)=\theta(y=d_1+d_2,z)=\pi/2.\end{aligned}\tag{4}$$

3.3. Threshold Voltage

To study the stability of the initial director profile we linearised those equations with respect to φ and $\psi=\frac{\pi}{2}-\theta$ and got the following system of separated equations for small angles ψ and φ:

$$\begin{aligned}&K\Delta\psi+\frac{\varepsilon_a\psi}{4\pi}E_z^2=0;\\&K\Delta\varphi+\frac{\varepsilon_a\varphi}{4\pi}E_y^2=0\end{aligned}\tag{5}$$

To proceed further we can use the approximation of the electric field components by their averaged value $\langle E_y\rangle$ and $\langle E_z\rangle$ [6]. Now from the Eq. (5) it is easy to find the averaged value of the critical field $\langle E_y\rangle_{th}$ at which the twist angle φ just begins to change:

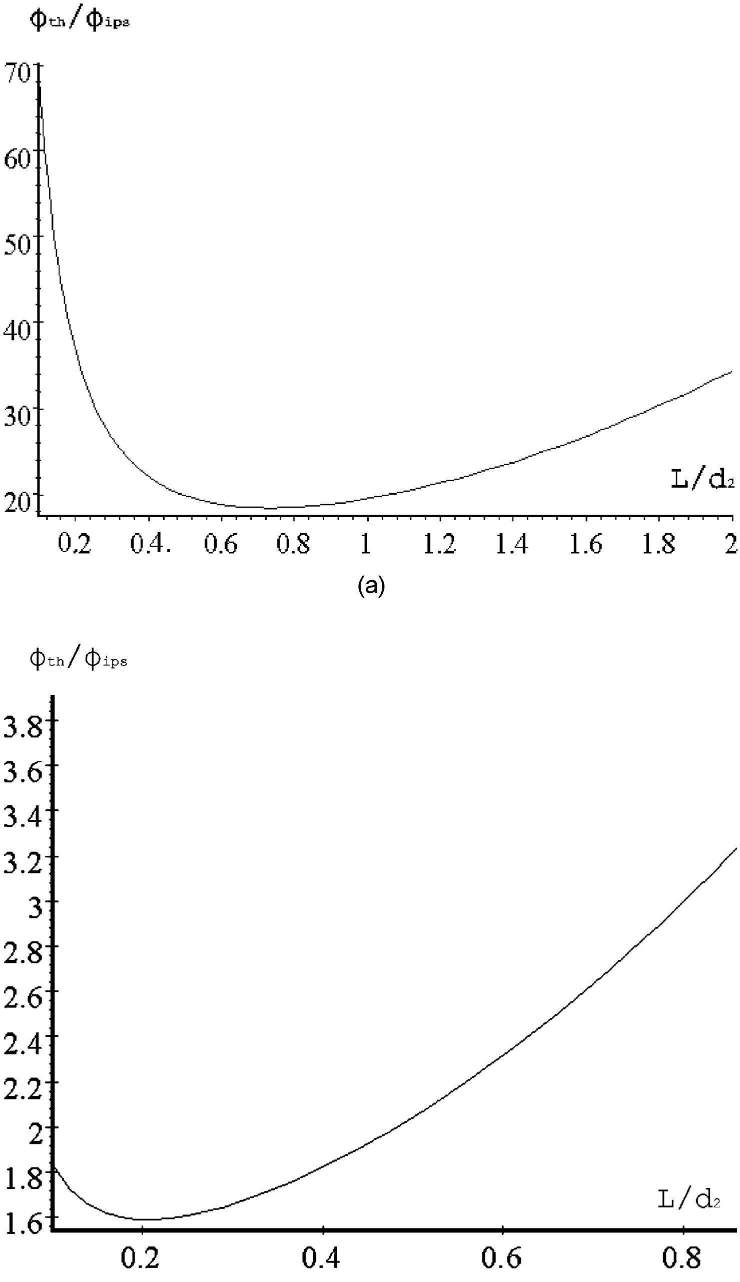
$$\langle E_{y,th}\rangle^2=\left(\frac{4\pi K}{\varepsilon_a}\right)\left(\frac{\pi^2}{H^2}+\frac{\pi^2}{(d_1+d_2)^2}\right),$$

the threshold voltage is given then by (5)

$$\Phi_{0,th}=\langle E_{y,th}\rangle\frac{d_2}{g(\delta,\gamma)},\tag{6}$$

where $g(\delta,\gamma)$ is the ratio [6]:

$$g(\delta,\gamma)=\frac{1}{\gamma}\sum_m A(m,\delta)\frac{2}{m\pi}\sin^2\frac{m\pi}{2}\left(1-\exp\left(-\frac{\gamma m\pi}{1+\delta}\right)\right).$$



ϕth/ϕips
70
60
50
40
30
20
L/d2
0.2
0.4.
0.6
0.8
1
1.2
1.4
1.6
1.8
2

(a)

ϕth/ϕips
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
L/d2
0.2
0.4
0.6
0.8

(b)

FIGURE 6

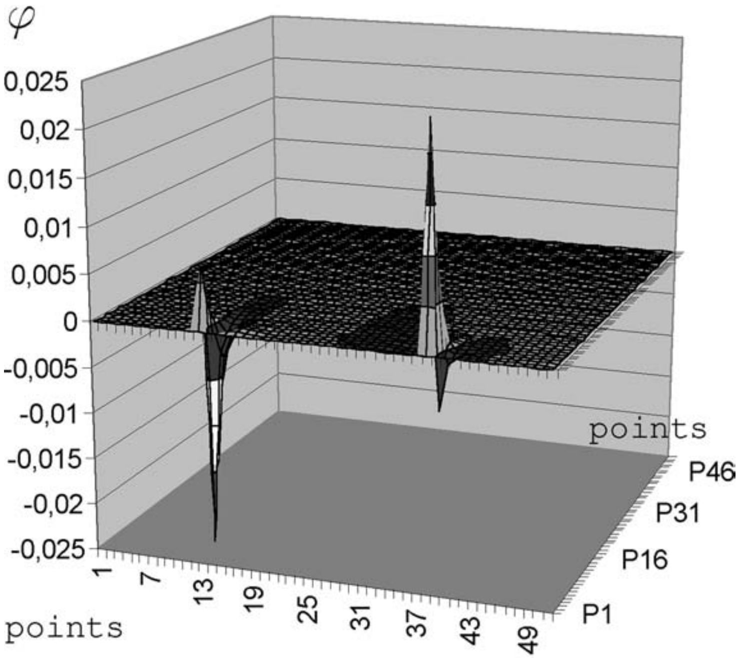


FIGURE 7

The Oh-e's results [5] for threshold electric field and threshold voltage are:

$$E^{IPS} = \frac{\pi}{H}\sqrt{\frac{4\pi K}{\varepsilon_a}}, \qquad \Phi^{IPS} = E^{IPS} d_2.$$

To compare the results of our calculations with Oh-e's one [4,5] we can write down the ratio between them:

$$\frac{\Phi_{th}}{\Phi^{IPS}} = \frac{1}{g(\delta,\gamma)}\sqrt{1 + \frac{\gamma^2}{(1+\delta)^2}}.$$

Figure 6a,b presents the ratio $\frac{\Phi_{th}}{\Phi^{IPS}}$ as the function of $\gamma = \frac{L}{d_2}$ at $\delta = \frac{d_1}{d_2} = 1; 0.1$.

3.4. Director Profile

Using the results for electric field (1) and threshold voltage (6) we can solve numerically the Ostrogradsky's equations (3) with the corresponding boundary conditions (4).

As we can see in Figure 7a,b there is no real threshold behavior because of the inhomogenity of electric field in between electrode space.

4. CONCLUSIONS

Threshold voltage as it is seen from the Figure 6 may be significantly different from that predicted by simple theory of Oh-e [2–6], which doesn't care about the electric field inhomogenity in the liquid crystal cell.

The numerical results for director profile (Fig. 7) will give us the possibility to calculate the optic properties depend on the electrode potential, and shows us that is no real threshold behaviour as in uniform electric field assumption.

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