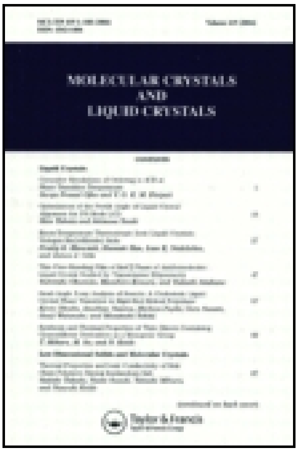

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

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Version of record first published: 23 Sep 2006.

Mol. Cryst. Liq. Cryst. 1995, Vol. 263, pp. 437–444
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ELECTRO-OPTICAL PROPERTIES OF THE ANTIPARALLEL LIQUID CRYSTAL CELL

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Abstract The normal incident light to the cell in which liquid crystal has an angle with the surface of cell, have a phase retardation by the refractive anisotropy of liquid crystal and the other cell parameters. At a field off-state, the transmission is easily calculated from the various methods, but at a field on-state the variation of tilt angles from the surface anchoring angle to maximum angle at z=d/2 across thickness makes the calculation difficult. Considering the distribution of director in the liquid crystal cell under the field with the folded anisotropic layers, to calculate the light propagating through these layers the Jones matrix was expanded sequentially and the transmitted intensity was accurately evaluated consistent with the experiment.

INTRODUCTION

For the improvement of electro-optical performance of liquid crystal display, the liquid crystals in the cell are forced to have some tilted angle on the surface, the pretilt angle, due to the interaction of the liquid crystal and the surface of cell. This angle is propagated to the bulk region of the cell through the interaction between liquid crystals and, then, the director of liquid crystal is aligned homogeneously with an angle in the liquid crystal cell. But this alignment has not been completely identified because of the complications arising from the intrinsic characteristics of various liquid crystal materials and surface materials. This makes it difficult the prediction of tilt angles in the cell theoretically. The accurate prediction or measurement is required to explain the alignment state of liquid crystals. But hardly achieved is the prediction of tilt angle by the most of optical methods in which the measurement is carried out with bulk states and measured with averaged value.

Optical transmissions of liquid crystal cells have been calaculated using the 4x4 method or the Jones matrix by many authors[1,2,3] with an assumption of the constant tilt angle at the field off-state. On the application of field to the cell, however, liquid crystals have undergone the deformation, the direction of director begins to align parallelly with the field direction beyond the threshold field strength(Fredericks transition). Except that the fields are very high and low, the directors are not aligned with the constant angle, but are widely distributed varying from the surface anchoring angle to the maximum angle at the specified field. Therefore, the distribution of director must be considered to obtain the more accurate transmission curve under the field on-state.

THEORETICAL CONSIDERATION

Let's consider the antiparallel liquid crystal cell, the opposite rubbing direction cell, in Figure 1(a), where liquid crystals are homogeneously aligned to the surface of cell. Assuming the z-axis to be the normal to the cell surface with thickness(d) and the x,y-axis to be in-plane of the surface, the free energy of liquid crystal per unit area in the xy plane can be written as[4]

$$F = \frac{1}{2}\int_0^d \left[\left(K_{11}\cos^2\theta + K_{33}\sin^2\theta\right)\left(\frac{\partial\theta}{\partial z}\right)^2 - \varepsilon_a E^2 \sin^2\theta \right] dz \tag{1}$$

where θ is the tilt angle of the liquid crystal, ε_a is the dielectric anisotropy and K_{11} and K_{33} are the splay and bend elastic constants. Following the solution for the equation (1), the most stable state of liquid crystals in the cell can be deduced. After mathematical manipulations, the equation (1) becomes

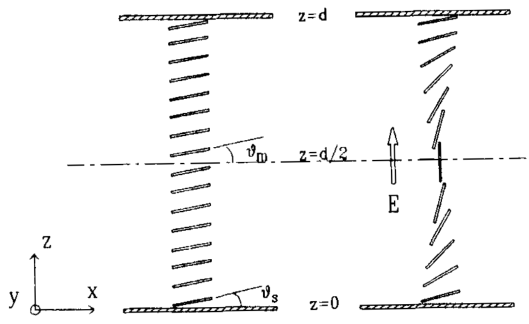
$$d = \frac{2}{E}\sqrt{\frac{K_{11}}{\varepsilon_a}} \int_{\theta_0}^{\theta_m} \left\{ \frac{1 + \gamma \sin^2\theta}{\sin^2\theta_m - \sin^2\theta} \right\}^{1/2} d\theta \tag{2}$$

where $\gamma = \frac{K_{33} - K_{11}}{K_{11}}$.

Further the threshold electric field is defined by $E_c = \pi/d\left(K_{11}/\varepsilon_a\right)^{1/2}$. θ_m is the maximum angle at z=d/2, and θ_0 is the tilt angle at the surface(d=0). The director profiles of liquid crystals can be computed to the equation (3)[4].

$$\frac{z}{d} = \frac{1}{\pi}\frac{E_C}{E} \int_{\theta_0}^{\theta_m} \left\{ \frac{1 + \gamma \sin^2\theta}{\sin^2\theta_m - \sin^2\theta} \right\}^{1/2} d\theta \tag{3}$$

When the electric field is applied to the antiparallel cell, the directors of liquid crystal have a wide distribution from the surface angle to the maximum angle(θ_m) at the z=d/2 in Figure 1(b). To obtain the maximum angle under the field, the equation(2) must be solved at $E>E_c$ and $E<E_c$ respectively. At $E<E_c$, the maximum angle is assumed the equivalent angle with the pretilt angle(θ_0) or calculated accurately by the substitution of $\cosh\lambda = \sin\theta/\sin\theta_m$, and at $E>E_c$, the maximum angle can be also obtained by the substitution of the $\sin\lambda = \sin\theta/\sin\theta_m$[5]. In Figure 2 under the threshold field the maximum angles are shown in the cases of having the same value with the pretilt angle and having the lower value than the pretilt angle with the varying field. Figure 3 shows that the director profile along the z-direction of the cell at the specified electric field is easily obtained from the equation (3) by the given maximum angle in Figure 2. It can be shown in Figure 3 that at the slightly low value of the threshold electric field the liquid crystal with the lower maximum angle than the pretilt angle has already begun to align with the field direction and has had the director profile. Because of this director profile, the distance which the incident light really passes through the cell is differently felt with that of the field off-state, and then the transmission is affected. Therfore the director profile in the cell is important to predict the electro-optic performances at the transient or higher values of the threshold field.



(a) field-off state (b) field-on state

FIGURE 1 The director profiles of liquid crystal.

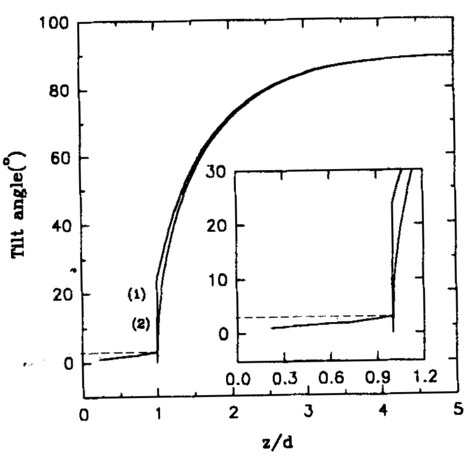


FIGURE 2 The maximum tilt angle(θ_m) at z=d/2 under the electric field with roius pretilt angle (1) 3^o (2) 0^o. Under the threshold the dashed line is the same value with the pretilt angle and the solid line is obtained by the equation (2) by the assumption of the lower value than the pretilt. E7 is used for calculation, $K_{11}=10.7\times10^{-12}$, $K_{33}=20.7\times10^{-12}$, $\varepsilon_a=13.5$.

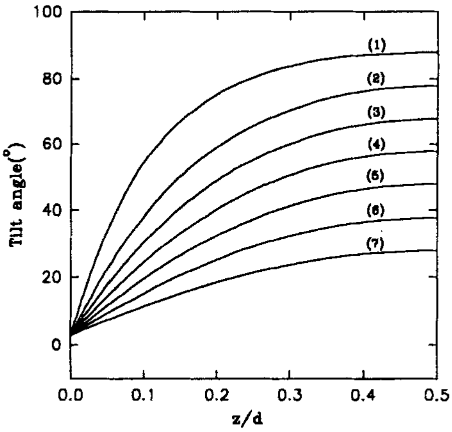


FIGURE 3 The director profile of liquid crystal(E7) across the thickness under various reduced electric field(E/E_c)with pretilt angle 3^o, (1) 3.89 (2) 2.35 (3) 1.83 (4) 1.53 (5) 1.32 (6) 1.17 (7) 1.05

Since the nematic liquid crystal are classified into the uniaxial in the stratified anisotropic media, the transmission of incident light normal to the cell on the field off-state is easily computed by using the Jones matrix[3] incorporating the geometry of numerous stratified layers.

$$\hat{J} = \begin{pmatrix} e^{-i\Gamma/2N} & 0 \\ 0 & e^{i\Gamma/2N} \end{pmatrix} \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \tag{4}$$

where $\Gamma = \frac{2\pi d}{\lambda}\Delta n$, in which $\Delta n = n_e - n_o$ is the optical anisotropy[2], λ is the wavelength of the incident light, d is the total thickness of cell and ϕ is the twist angle. Here, in antiparallel cell the twist angle do not exist, i.e. $\phi=0$. Here the light is normally irradiated to the antiparallel cell. The entrance(Θ) and exit angle(γ) are the angles between the x-direction of director and the plane of incident polarized light at inlet and outlet. Using equation (4), the normalized transmitted intensity is written to the equation (5).

$$T = \cos(\gamma - \Theta)\cos^2\frac{\Gamma}{2} + \cos(\gamma + \Theta)\sin^2\frac{\Gamma}{2} \tag{5}$$

CALCULATIONS

In Figure 3, the tilt angle of director can be known to be distributed from the surface to the maximum at $z = d/2$ according to the electric field, which is schematically depicted as Figure 4. So it is assumed that the light going through each layer, experiences the different refractive indices continuously which is changed from the layer to the layer because of the director orientation given in Figure 4. Therefore, the Jones matrix can be modified to an expanded form,

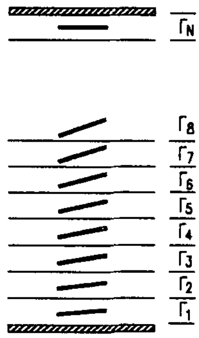


FIGURE 4 The distribution of director across the thickness in hyphothetical stratified cell under the field on-state

$$\hat{J}=\begin{pmatrix} e^{-i\Gamma_1/2} & 0 \\ 0 & e^{i\Gamma_1/2}\end{pmatrix}\begin{pmatrix} e^{-i\Gamma_2/2} & 0 \\ 0 & e^{i\Gamma_2/2}\end{pmatrix}\begin{pmatrix} e^{-i\Gamma_3/2} & 0 \\ 0 & e^{i\Gamma_3/2}\end{pmatrix}\cdots\begin{pmatrix} e^{-i\Gamma_N/2} & 0 \\ 0 & e^{i\Gamma_N/2}\end{pmatrix}$$

$$=\begin{pmatrix} e^{-i(\Gamma_1+\Gamma_2+\Gamma_3+\cdots+\Gamma_N)/2} & 0 \\ 0 & e^{i(\Gamma_1+\Gamma_2+\Gamma_3+\cdots+\Gamma_N)/2}\end{pmatrix}$$

$$=\begin{pmatrix} e^{-ik/2} & 0 \\ 0 & e^{ik/2}\end{pmatrix} \tag{6}$$

where $k=\Gamma_1+\Gamma_2+\Gamma_3+\cdots+\Gamma_N$, (7)

$$\Gamma_i=\frac{2\pi}{\lambda}\ell_i\Delta n=\frac{2\pi}{\lambda}\left(\frac{n_e}{\sqrt{1+\varpi\sin^2\theta_s}}-n_o\right)\ell_i \tag{8}$$

and $\varpi=\left(\frac{n_e}{n_o}\right)^2-1$

where Γ_i is the phase retardation, θ_s is the tilt angle through the layers, ℓi is the thickness of each layer and λ is the wavelength of the incident light. With the equations (6) to (8), the normalized transmitted intensity of the stratified media as above mentioned is written as the equation(9).

$$T = \cos(\gamma - \Theta)\cos^2\frac{k}{2} + \cos(\gamma + \Theta)\sin^2\frac{k}{2} \tag{9}$$

In this transformation, there are no difference in appearence between the equation (9) and the equation(5), in which the tilt angle is regarded as the same to the pretilt angle through the cell, but two equatons are only different in the point whether the phase retardation term is corrected or not. The phase retardation in the equation (9), k, is the sum of that of the individual layers, while that in the equation (5), Γ, is one constant determined by the tilt angle through the cell.

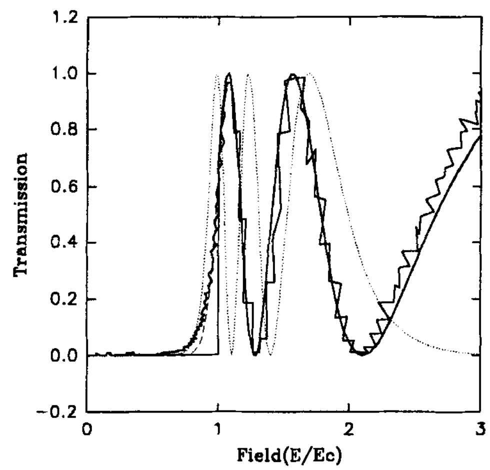


FIGURE 5 The comparision of measurement with the transmission curves resulted from the equation(9) and the equation(5) under the electric field(100Hz) with the pretilt angle 3^0. E7 is used for calculation. $K_{11}=10.7\times10^{-12}$ N, $K_{33}=20.7\times10^{-12}$ N, $\varepsilon a=13.5$. The wavelength of incident light is 632.8 nm and the cell is located 45^0 with entrance angle in the crossed polarizer. Thickness of cell is 8.5 μm[6].

Figure 5 shows the results of the calculation using the equation (9) and the equation (5) and the experiment of the transmission of the antiparallel cell at the varying field strength. The solid line represented the results of measurement, while the smooth solid line is calculated with the pretilt angle, 2^0, by the equation (9) using the result of the director profile in Figure 3, in which the transmission is not largely deviated in the both cases of the same and the low maximum angle, and the dotted line is calculated by the equation(5) assuming the tilt angle is the same as the maximum angle at the specified field across the cell. But in Figure 5 the deviation between the calculation and the experiment is shown in the slightly lower regoin of E_C. In this region the dashed line shown in Figure 5 is well matched with the experiment, which, assuming the the liquid crystal is taken the action even though the applied field is lower than the threshold, is obtained by the extension of the result of $E>E_c$ to the lower region of Ec. Therefore the liquid crystal may be really thought to be aligned and the maximum tilt angle(θ_m) steadily increases before the threshold but the degree of the increase is small. The calculation by the equation (5) shows the large deviation from the measurement, but the measurements and the calculations by the equation (9) in the upper region of the threshold field are well agreed with each other. This result indicates that it is important to consider the director profile for the electro-optical behavior of liquid crystal cell especially at the higher or lower thredshold.

And at the field-off state, the liquid crystal parallelly aligns with the surface but at the distance far from the surface, the effect of surface force is weaken. Therefore the liquid crystal may have some slightly loosed alignmnet state. In Figure 6. the experiment is compared with the three cases of the constant tilt angle (the equation (5)), the extension of the result of $E>E_c$ (the equation(9)) to the lower region of the threshold and the use of the director profile at $E<E_c$ (the equation (9)) in which the maximum angle(θ_m) is lower than the pretilt angle(θ_0). The second case in which the maximum tilt angle is steadily increased shows the large deviation just below region of the threshold but the last case in which the maximum angle is slightly increased is best fitted with the experiment. In fact, the liquid crystal is thought to be aligned with the field direction at E<Ec but the degree is small.

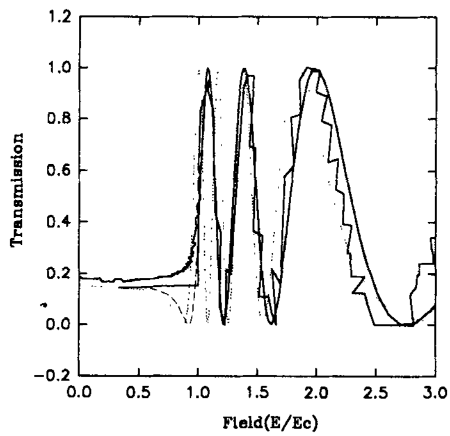


FIGURE 6 The comparision of measurement with the transmission curves resulted from the equation(9) and the equation(5) under the electric field(100Hz) with the pretilt angle 3^o. E7 is used for calculation. $K_{11}=10.7x10^{-12}$ N, $K_{33}=20.7x10^{-12}$ N, $\varepsilon a=13.5$. The wavelength of incident light is 632.8 nm and the cell is located 45^o with entrance angle in the crossed polarizer. Thickness of cell is 11.6 μm.

CONCLUSION

Under the field the liquid crystal is aligned with the field direction and the liquid crystal has a wide distribution from the pretilt to the maximum angle of the director direction through the cell. The transmission due to this wide distribution is consistent with the calculated using the expanded Jones matrix method, and can be used to the objective for the optimal design.

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