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BRIEF PAPER *Special Section on Electronic Displays*

Thresholdless Electro-Optical Property in Quasi Homogeneous and Homeotropic Liquid Crystal Cells Using Weak Anchoring Surfaces

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SUMMARY Liquid crystal director distributions between strong and weak polar anchoring surfaces in hybrid aligned cells are numerically analyzed. When the anchoring is a critical one, homogeneously or homeotropicly liquid crystal alignment can be obtained. Such cells have no threshold voltage and a driving voltage can be reduced less than 0.5 volt.

key words: *liquid crystal, hybrid aligned nematic, homogeneous, homeotropic, Fréedericksz transition*

1. Introduction

Nematic Liquid crystals (LC) are sandwiched between two substrates coated with LC alignment layers in conventional LC devices. Conventional LC displays use a strong anchoring surface to maintain a specific uniform LC orientation in bulk. A Fréedericksz transition is one of the most famous electro-optical switching mechanisms for nematic LCs [1] and a typical threshold voltage is about 1–2 volts.

On the other hand, a hybrid aligned nematic (HAN) LC mode in which one substrate alignment is planar and another is homeotropic has no threshold voltage, since the LC director in the middle of the LC layer is already tilted to an electric field. It has been reported that the HAN orientation changes to a homogeneous or homeotropic orientation when a thickness of the LC layer decreases to “a critical thickness” [2]–[4]. Papers have theoretically discussed the tilt angle on the substrate surface as a function of external electric field or magnetic field parallel to the substrate.

In this paper, from a practical point of view, the LC director distribution in the HAN cell is numerically calculated between two substrates using a weak polar anchoring surface as a function of applied voltage. The condition of the polar anchoring to change the HAN orientation to the homogeneous or homeotropic orientation, that is “a critical anchoring”, has been clarified and thresholdless electro-optical properties and very low driving voltages are numerically demonstrated.

2. HAN Cell without Applying Voltage

Let us consider the HAN orientation with strong and weak polar anchoring substrates schematically illustrated in Fig. 1. A total free energy per unit area F in the HAN cell is represented

$$F = F_{bulk} + F_{electric} + F_{surface}$$

$$F_{bulk} + F_{electric} = \int_0^d \left\{ \begin{aligned} &\left(\frac{1}{2}K_{11}\cos^2\theta(z) + \frac{1}{2}K_{33}\sin^2\theta(z)\right)\left(\frac{d\theta(z)}{dz}\right)^2 \\ &-\frac{1}{2}\varepsilon_0(\varepsilon_\perp + \Delta\varepsilon\sin^2\theta(z))\left(\frac{dV(z)}{dz}\right)^2 \end{aligned} \right\} dz$$

$$F_{surface} = \frac{1}{2}W_{p\_0}\sin^2(\theta_0 - \theta(0)) + \frac{1}{2}W_{p\_d}\sin^2(\theta_d - \theta(d)), \quad (1)$$

where K_{11} and K_{33} are splay and bend elastic constants, θ(z) is the tilt angle of the LC, d is the thickness of the LC layer, V(z) is the voltage potential. $W_{\mathrm{p\_0}}$ and $W_{\mathrm{p\_d}}$ are polar anchoring strengths of each substrate. A flexoelectric effect has been known in the HAN cell due to an asymmetry moleculer orientation [5], [6]. In this paper, however, the effect is neglected since homogeneous and homeotropic like orientations are discussed and the applied field is supposed to be an AC voltage. The LC orientation changes to a kind of homogeneous orientation when the LC is anchored weak only at the homeotropic wall, $z = d$, while at the strong anchoring planar substrate, $z = 0$, as shown in Fig. 1 (b). $\theta(d)$ is estimated as a function of the homeotropic polar anchoring $W_{\mathrm{p\_d}}$ and results show in Fig. 2. Here, d is 10 μm and K_{11} is 10 pN. The tilt angle decreases with decreasing the anchoring. The tilt angle is zero, that is, the cell completely turns to the homogeneous orientation, when $W_{\mathrm{p\_d}}$ is less than 1×10^{-6} N/m, it is called as “a critical anchoring W_{c}”. In this case, the W_{c} is equal to K_{11}/d and is independent of K_{33}. On the other hand, between infinite homeotropic and weak planar anchoring surfaces, the LC orientation tends to the homeotropic like orientation, as shown in Fig. 1 (c). The fully homeotropic orientation can be obtained when $W_{\mathrm{p\_0}}$

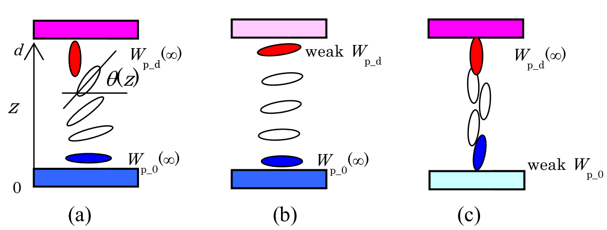

Fig. 1 Schematic model of LC director distribution in (a) HAN, (b) quasi homogenous and (c) quasi homeotropic cells.

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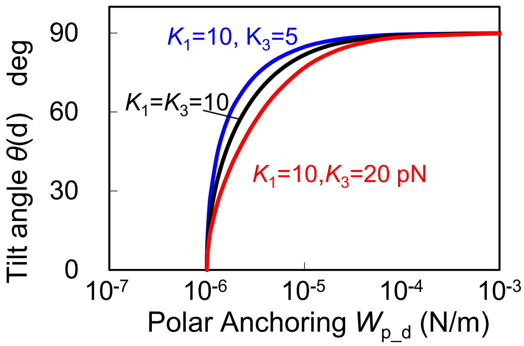

Fig. 2 Anchoring strength of W_{p_d} vs. tilt angle $\theta(d)$. W_{p_0} is infinite.

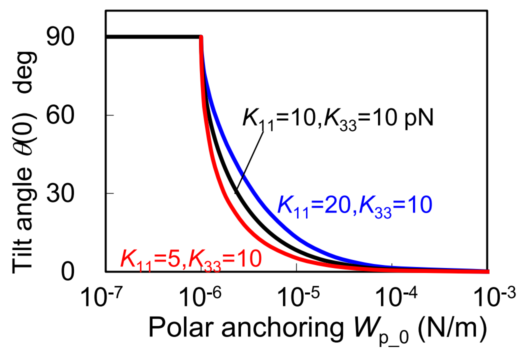

Fig. 3 Anchoring strength of W_{p_0} vs. tilt angle $\theta(d)$. W_{p_d} is infinite.

is lower than K_{33}/d, as shown in Fig. 3. Such HAN cells without splay and bend distortions are respectively called a quasi homogeneous (Q-Homo) and a quasi homeotropic (Q-Home) cells in this paper.

3. HAN Cell with Applying Voltage

Figure 4 shows an effective extraordinary refractive index $<n_e>$ vs. applied voltage in the homogeneous, HAN and Q-Homo cells. $<n_e>$ is represented

$$<n_e> = \frac{1}{d}\int_0^d \frac{n_e n_o}{\sqrt{\cos^2\theta(z){n_o}^2 + \sin^2\theta(z){n_e}^2}}dz, \qquad (2)$$

where n_o and n_e are ordinary and extraordinary indices, respectively. The cell parameters are, $d = 5\,\mu$m, $K_{11} = 7$ pN, $K_{33} = 10$ pN, $\Delta\varepsilon = 5$, $n_o = 1.5$ and $n_e = 1.7$. The conventional homogeneous cell (Homo) using infinite anchoring on both substrates shows the threshold voltage V_{th} of 1.29 volt. The HAN cell has no threshold voltage and the index variation is about half of that in the Homo cell. The Q-Homo with $W_{p\_d} = W_c$ ($= 1.4 \times 10^{-6}$ N/m) also shows no threshold voltage and the index variation is larger than that in the Homo cell, because the LC director distribution under the higher voltage application is almost the same as that in the HAN cell, as shown inserted schematic model in Fig. 4. When the anchoring is less than W_c in the Q-Homo cell, the threshold voltage appears, for example V_{th} of 0.59 volt with W_{p_d} of 1.4×10^{-7} N/m.

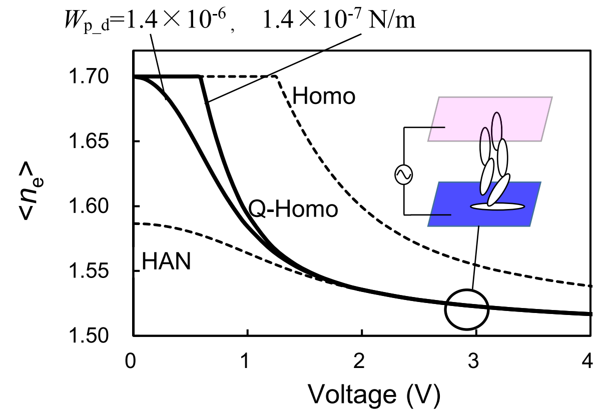

Fig. 4 Effective extraordinary refractive index vs. applied voltage in Q-Homo, HAN and Homo cells.

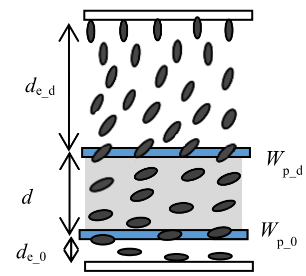

Fig. 5 Schematic model of HAN cell with finite anchoring surfaces in the case of $W_{p\_d} < W_{p\_0}$ ($d_{e\_d} > d_{e\_0}$).

If in the homogeneous cell using weak anchoring planar substrate on both sides, the threshold voltage decreases with decreasing the anchoring but still exists [7]. V_{th} is 0.52 volt when W_{p_0} and W_{p_d} are 1.4×10^{-6} N/m. In this anchoring condition, the homogeneous orientation fully turns to the homeotropic by applying 0.60 volt. In the HAN cell using weak anchoring substrates on both sides, a similar switching to the fully homogeneous reorientation has also been analyzed theoretically under the in-plane electric field of a laser light [8].

Next, let consider electro-optical properties in Q-Homo and Q-Home cells using weak anchoring substrates on both sides, as a function of applied voltage. Figure 5 shows a schematic model of the HAN cell with weak anchoring surfaces in the case of $W_{p\_d} < W_{p\_0}$. An extrapolation length of d_{e_d} or d_{e_0} shown in Fig. 5 is defined as K/W_p [9]. When the cell thickness is equal to a difference between d_{e_d} and d_{e_0}, it is called a critical thickness d_c ($\equiv d_{e\_d} - d_{e\_0}$) [2]. If the cell thickness is smaller than d_c, the HAN orientation turns to the homogeneous orientation in this case. Therefore, the Q-Homo cell can be obtained when anchoring strengths of both substrates satisfy the condition of $d < K_{11}\,(1/W_{p\_d} - 1/W_{p\_0})$. The Q-Home cell can be obtained in the HAN cell with $W_{p\_d} > W_{p\_0}$, if d is smaller than $K_{33}(1/W_{p\_0} - 1/W_{p\_d})$.

Table 1 shows extrapolation lengths and anchoring strengths under the condition of the critical thickness of 5μm. Here, we use same parameters shown in Fig. 4. The ef-

Table 1 Extrapolation length and anchoring strength

d_{e_0} (μm)	d_{e_d} (μm)	W_{p_0} (N/m)	W_{p_d} (N/m)
0	5	∞	1.4×10^{-6}
1	6	7.0×10^{-6}	1.2×10^{-6}
2	7	3.5×10^{-6}	1.0×10^{-6}
4	9	1.8×10^{-6}	7.8×10^{-7}
8	13	8.8×10^{-7}	5.4×10^{-7}

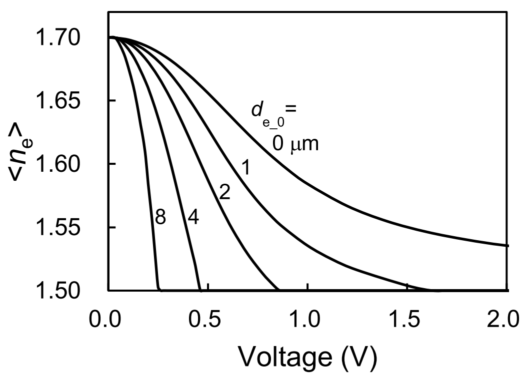

Fig. 6 Electro-optical property in Q-Homo with finite anchoring substrates of $W_{p\_d} < W_{p\_0}$.

fective extraordinary refractive index is estimated as a function of applied voltage with the parameter of d_{e_0}, as shown in Fig. 6. All Q-Homo cells have no threshold voltage. $<n_e>$ decreases to 1.5, that is the ordinary index, in the Q-Homo μ cell with d_{e_0} of 1 μm due to the fully homeotropic orientation switching by applying 1.7 volt. When d_{e_0} increases to 8 μm, the cell turns to the homeotropic orientation only by 0.3 volt.

The Q-Home cell is designed using finite anchoring surfaces of $W_{p\_d} > W_{p\_0}$. The cell parameters are follows; $d = 5\ \mu$m, $K_{11} = 7$ pN, $K_{33} = 10$ pN and $\Delta\varepsilon = -5$. A guest-host (GH) mode electro-optical property in Q-Home cells is estimated in Q-Home cells. Typical absorption coefficients of 0.05 and 0.5 μm^{-1} for short and long axes of a dichroic dye were used [10]. Maximum (homeotropic orientation) and minimum (homogeneous orientation) transmittances are estimated 77.8% and 8.2%, respectively. Figure 7 shows transmittance curves as a function of applied voltage in GH mode Q-Home cells with the parameter of d_{e_d} ($d_{e\_0} = d_{e\_d} + 5$). Anchoring strengths of planar and homeotropic alignment surfaces are estimated as K_{33}/d_{e_0} and K_{33}/d_{e_d}, respectively. When d_{e_d} is 2 μm, for example, W_{p_d} is 5×10^{-6} N/m and W_{p_0} is 1.4×10^{-6} N/m. The transmittance immediately decreases with the voltage and the LC orientation turns to the homogeneous orientation by 1.4 volt, which results in the widest transmission variation. If d_{e_d} is 10 μm, the minimum transmittance can be obtained only by 0.3 volt. In the conventional Home cell, the transmittance cannot reach to the minimum level since the LCs on the strong anchoring surfaces do not reorient. Therefore, the driving voltage V_{10} at which the transmittance decreases to 10% transmittance T_{10} (= 15.2%) is about 3.2 volt. In

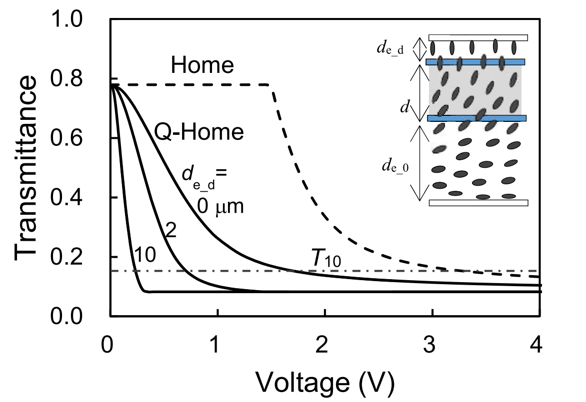

Fig. 7 Transmittance as a function of applied voltage in GH mode Q-Home cells with weak anchoring substrates of $W_{p\_d} > W_{p\_0}$.

contrast, V_{10} is only 0.2 volt in the Q-Home cell of on d_{e_d} of 10 μm.

4. Conclusions

LC director distributions in the HAN cell using weak and strong polar anchoring surface are is numerically analyzed. Optical properties are clarified as a function of applied voltage. Q-Homo and Q-Home cells can be obtained by the critical anchoring strength. Such cells do not have threshold voltage and the LC alignment completely switches from homogeneous to homeotropic (homeotropic to homogeneous) alignment by extremely low driving voltage, for example, less than 0.3 V.

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