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Liquid Crystal Reorientation with Ultra-Low Driving Voltage Between Strong and Weak Anchoring Surfaces

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ABSTRACT

Hybrid aligned cells were designed using strong and weak polar anchoring surfaces. When the weak anchoring strength was less than critical one, the liquid crystal director distribution changed to usual homogeneous and 90° twisted nematic orientations, which LC cells had no threshold voltage and very low driving voltage.

1 Introduction

A conventional nematic liquid crystal display (LCD) is fabricated using a strong anchoring alignment surface on both sides of the substrate to maintain a specific uniform LC orientation in a bulk of the LC layer. Such an LC cell shows a Fréedericksz transition and a typical threshold voltage is about 1 – 2 V. 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 bulk is already tilted to an electric field. Moreover, a "twisted hybrid aligned (THA) [1]" or a "hybrid twisted nematic (HTN) [2]" cell has been proposed. The LC cell has both a hybrid alignment and a twisted director configuration. A faster response and a lower driving voltage were obtained in comparison with a conventional TN mode.

It has been reported that the hybrid orientation changes to a homogeneous and homeotropic orientation when a thickness of the LC layer decreases to "a critical thickness" [3-5], when a polar anchoring strength is finite. Almost the same phenomena can be obtained when the anchoring strength decreases to "a critical anchoring". These homogeneously and homeotropically aligned LC cells have been respectively called a quasi homogeneous (Q-Homo) and a quasi homeotropic (Q-Home) cells, which have no threshold voltages [6].

The HTN cell has also been designed using weak polar anchoring of the homeotropic surface. Without the voltage, the LC director distribution is exactly the same as that in a conventional 90° TN cell. Therefore, we call this LC cell as a quasi-twisted nematic (Q-TN) cell. The LC director distribution and an electro-optical property were calculated and electro-optical curves with low driving voltages less than 0.5 V can be numerically demonstrated.

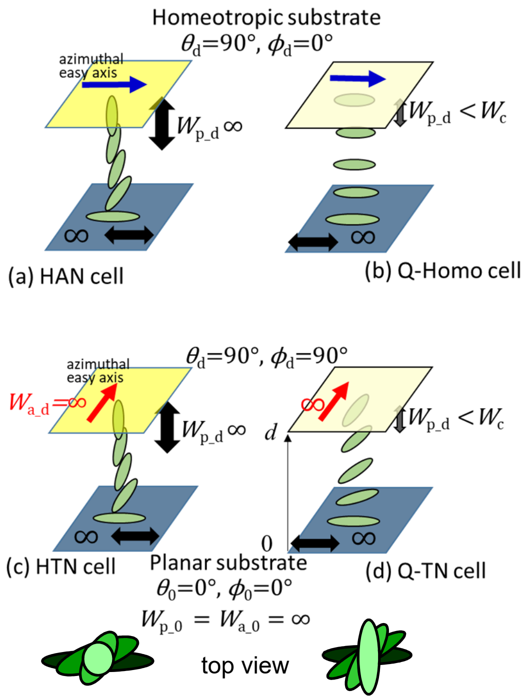

Fig. 1 Schematic model of (a) HAN, (b) Q-Homo and (c) Q-TN cells.

2 Principle

2.1 Free Energy of LC Cells

Figure 1 shows schematic LC orientation models of HAN, Q-Homo, HTN and Q-TN cells. The planar alignment surface has infinite polar and azimuthal anchoring strengths ($W_{p\_0} = W_{a\_0} = \infty$). Azimuthal easy axes of a pair of substrates are parallel and perpendicular in the Q-Homo and Q-TN cells, respectively. The HTN cell shown in Fig. 1(c) has infinite azimuthal anchoring substrates. When only the polar anchoring strength of the homeotropic surface is finite and becomes lower than critical one, a tilt angle on the surface becomes 0° to reduce splay and bend distortion energies, as shown in Fig. 1(b) and 1(d).

A total free energy per unit area F in the LC cell is represented,

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

$$F_{\mathrm{surface}} = \frac{1}{2} W_{\mathrm{p\_d}} \sin^2(\theta_{\mathrm{d}} - \theta(d))$$

$$F_{\mathrm{bulk}} + F_{\mathrm{electric}}$$
$$= \int_0^d \frac{1}{2} \left\{ (K_{11}\cos^2\theta + K_{33}\sin^2\theta)\left(\frac{d\theta}{dz}\right)^2 \right.$$
$$+ (K_{22}\cos^2\theta + K_{33}\sin^2\theta)\cdot\cos^2\theta\left(\frac{d\phi}{dz}\right)^2$$
$$\left. -2K_{22}\frac{2\pi}{P_0}\cos^2\theta\left(\frac{d\phi}{dz}\right) + K_{22}\left(\frac{2\pi}{P_0}\right)^2 - \varepsilon_0(\varepsilon_\perp + \Delta\varepsilon \sin^2\theta)\left(\frac{dV}{dz}\right)^2 \right\} \quad (1)$$

where K_{11}, K_{22} and K_{33} are splay, twist and bend elastic constants, P_0 is a helical pitch of the LC, θ is the tilt angle, ϕ is the twist angle, d is the thickness of the LC layer, and $W_{\mathrm{p\_d}}$ is the polar anchoring strength. The LC director distribution is estimated by minimizing a total free energy F by a finite difference method.

2.2 Critical Anchoring

In the HAN cell shown in Fig. 1(a), $\theta(d)$ is estimated as a function of the homeotropic polar anchoring $W_{\mathrm{p\_d}}$ and results are shown 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 "a critical anchoring W_{c}" which is equal to K_{11}/d and is independent of K_{33}.

Figure 3 shows $\theta(d)$ as a function of $W_{\mathrm{p\_d}}$ in the HTN cell. d and K_{11} are respectively 10 μm and 10 pN as well as in the HAN cell, and P_0 is infinite. W_{c} depends on not only K_{11} but also K_{22} and K_{33}. When K_{11}, K_{22} and K_{33} are 10 pN, W_{c} is is 1×10^{-9} N/m and is three orders of magnitude weaker than that in the HAN cell. Moreover it was found that W_{c} is 1×10^{-6} N/m ($= K_{11}/d$), when K_{33}/K_{22} is 2, as shown dashed lines in Fig. 3. If K_{33}/K_{22} is larger than 2, W_{c} is larger than K_{11}/d, as shown red solid line in Fig. 3. Figure 4 shows $W_{\mathrm{p\_d}}$ vs. tilt angle $\theta(d)$ in the HTN cell with the parameter of P_0. K_{11}, K_{22} and K_{33} are 10 pN. W_{c} increases from 1×10^{-9} N/m to 2.4×10^{-7} N/m by using P_0 of 400 μm (d/P_0 =1/40) and to 1.7×10^{-6} N/m by using P_0 of 40 μm (d/P_0 =1/4).

3 Electro-Optical Properties

From a practical point of view, LC director distributions and electro-optical properties are calculated with common nematic physical properties of K_{11}=10, K_{22}=7, K_{33}=14 pN, $\varepsilon_{//}$=15 and $\varepsilon_\perp$=5. The cell thickness d is 5 μm.

3.1 Q-HOMO cell

Figure 5 shows LC director distributions of θ in the Q-HOMO cell with $W_{\mathrm{p\_d}}=W_{\mathrm{c}}$ (=2×10^{-6} N/m). The tilte angle on the weak anchoring surface $\theta(d$=5) increases with applied voltage without threshold voltage and reaches to 90° by 3 V higher. An effective extraordinary refractive index is represented

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

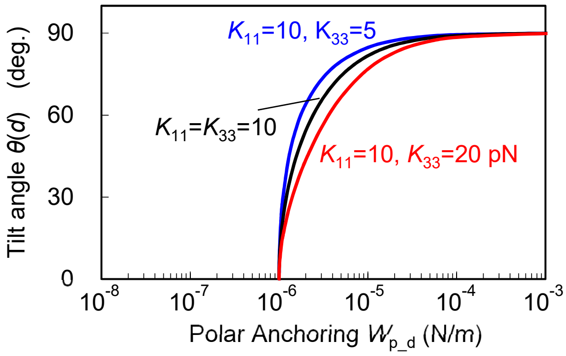

Fig. 2 Anchoring strength of $W_{\mathrm{p\_d}}$ vs. tilt angle $\theta(d)$ in HAN cell. d=10 μm.

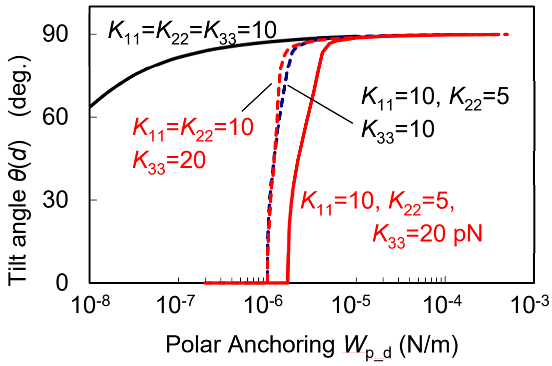

Fig. 3 Anchoring strength of $W_{\mathrm{p\_d}}$ vs. tilt angle $\theta(d)$ in HTN cell. P_0=∞, d=10 μm.

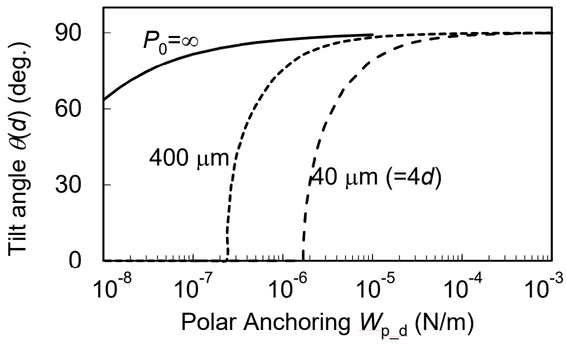

Fig.4 Anchoring strength of $W_{\mathrm{p\_d}}$ vs. tilt angle $\theta(d)$ in HTN cell with the parameter of P_0. K_{11}=K_{22}=K_{33}=10 pN, d=10 μm.

where n_{o} and n_{e} are ordinary and extraordinary indices, respectively. Figure 6 shows $<n_{\mathrm{e}}>$ vs. applied voltage in the homogeneous, HAN and Q-Homo cells, using n_{o} of 1.5 and n_{e} of 1.7. The conventional homogeneous cell (Homo) with infinite anchoring on both substrates shows the threshold voltage V_{th} of 1.06 V. The HAN cell has no threshold voltage and the index variation is about half of that in the Homo cell. The Q-Homo with $W_{\mathrm{p\_d}}=W_{\mathrm{c}}$ (=2×10^{-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. 6. When the anchoring is less than W_c in the Q-Homo cell, the threshold voltage appears, for example V_{th} of 0.51 V with W_{p_d} of 2×10^{-7} N/m. The driving voltage V_{10} at which $<n_e>$ decreases to 1.520 ($=n_o$ $+0.1\Delta n$) is about 5.50 V in the homogeneous cell with infinite anchoring on both substrates. In contrast, V_{10} is 2.60 V in the Q-Home cell with W_{p_d} of 2×10^{-6} N/m.

If in the homogeneous cell using weak anchoring planar substrate on both sides, the threshold voltage decreases with decreasing the anchoring but still exists. In the HAN cell using weak anchoring substrates on both sides, Q-Home orientation can be obtained using suitable anchoring condition and the driving voltage can also be lower [6]. However, the LC orientation is not stable in these cells due to the weak anchoring on both side of substrates and not suitable for the practical application devices.

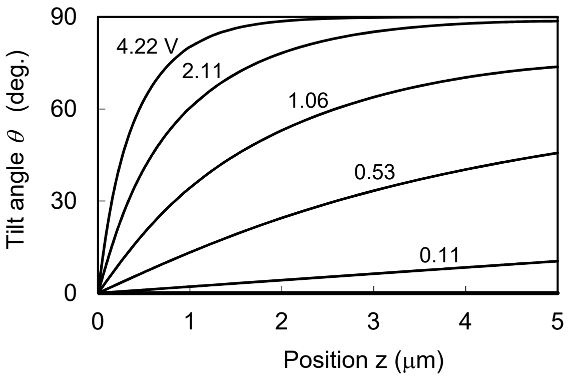

Fig. 5 LC director distributions of *θ* in the Q-HOMO cell with $W_{p\_d}=W_c$.

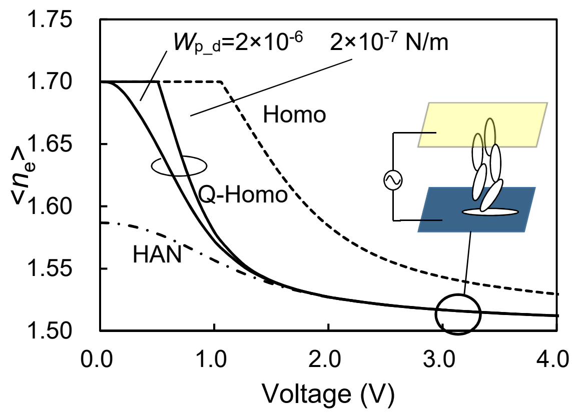

Fig. 6 Effective extraordinary refractive index vs. applied voltage in Q-Homo, HAN and Homo cells.

3.2 Q-TN cell

LC director distributions of θ and ϕ in the Q-TN cell are shown in Fig. 7(a) and 7(b) under the voltage application. P_0 is infinite and W_{p_d} is 2×10^{-6} N/m. The tilt angle on the weak anchoring surface immediately increases by the

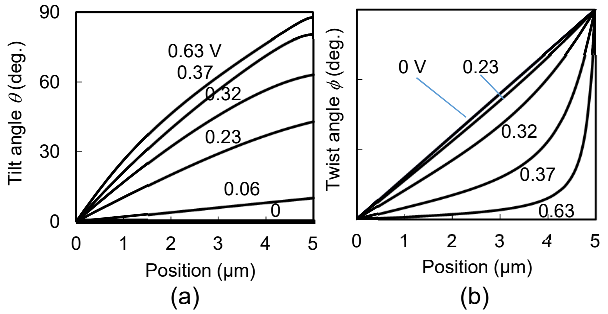

Fig.7 Director distribution of (a)θ and (b)ϕ in the Q-TN cell with $W_{p\_d}=W_c$.

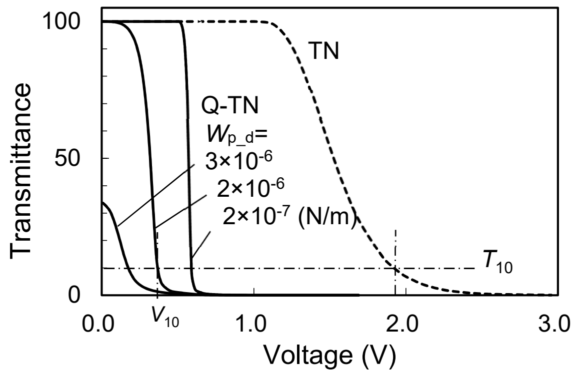

Fig. 8 VT curves of TN and Q-TN cells. $P_0=\infty$.

voltage. When the applied voltage is higher than 1 V, the tilt angle on the weak anchoring surface is 90°, which is almost the same director distribution under the higher applied voltage in the HTN cell using strong anchoring surfaces. A transmittance of the cell is estimated using a Jones matrix between crossed polarizers. Figure 8 shows electro-optical properties in the Q-TN and a conventional 90° TN cell in a normally white mode. Δn is 0.095 which gives the 1st minimum condition at 550 nm. The driving voltage V_{10} is only 0.37 V in the Q-TN with W_{p_d} of 2×10^{-6} N/m, comparing to 1.9 V in the TN cell. If W_{p_d} decreases to 2×10^{-7} N/m, the driving voltage increases to 0.59 V and the steepness also increases.

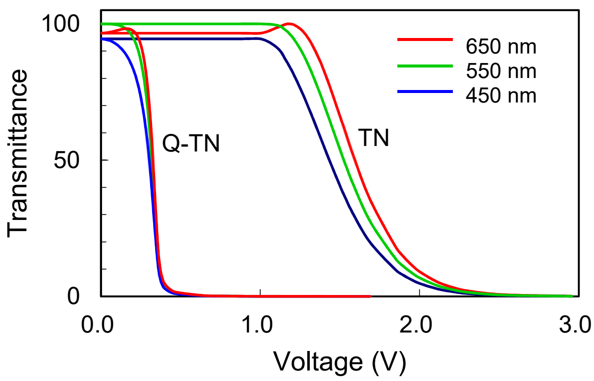

Fig. 9 VT curves of RGB in Q-TN and TN cells. $P_0=\infty$.

VT curves with red (650 nm), green (550 nm) and blue (450nm) light are also shown in Fig. 9. The wavelength dependence is very small as well as a conventional TN cell. This result indicates that the transmission light is colorless in gray scale.

Next, the effect of the helical pitch length P_0 is estimated. A small amount of a chiral dopant is usually added to the LC to prevent from a reverse twist disclination generation. Moreover, in the practical case for the homeotropic alignment surface, the coexistence of weak polar and strong azimuthal anchorings might be difficult. Therefore, the chiral dopant should be adjusted for the Q-TN mode. Figure 10 shows the tilt angle $\theta(d)$ as a function of W_{p_d} in HTN cell with the parameter of P_0. When K_{11}=10, K_{22}=7 and K_{33} =14 pN, W_c slightly increases with shorter P_0, comparing to the drastically increase shown in Fig. 4 (K_{11}=K_{22}=K_{33}=10 pN). Figure 11 shows electro-optical properties in Q-TN and TN cells with the parameter of P_0. It is also well known that the driving voltage becomes higher with shorter pitch length in the TN cell. The driving voltage with P_0 of 200 μm (=40*d*) is only 0.07V higher than that with $P_0 = \infty$. However, the driving voltage in the Q-TN cell with P_0 of 200 μm increases to 0.59 V which is 1.6 times higher than that with $P_0 = \infty$. When P_0 is 20 μm (=4*d*), the twist angle is 90° with any azimuthal anchoring strength and the driving voltage increases to 1.37 V.

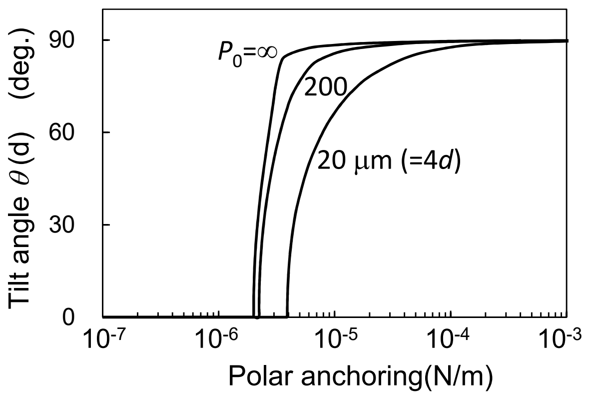

Fig.10 Anchoring strength of W_{p_d} vs. tilt angle $\theta(d)$ in HTN cell with the parameter of P_0. K_{11}=10 pN, K_{22}=7 pN, K_{33}=14 pN, *d*=5 μm.

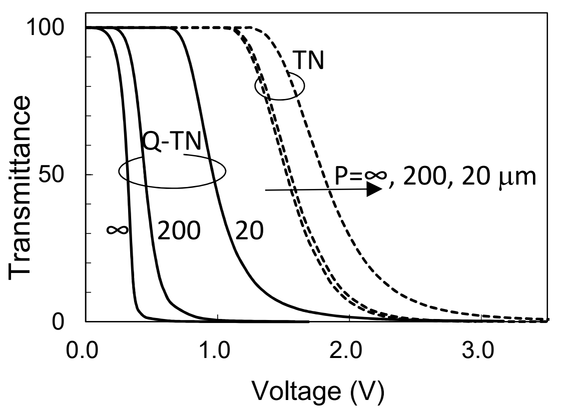

Fig. 11 VT curves in Q-TN with parameter of P_0. W_{p_d} in the Q-TN is 2×10^{-6} N/m.

4 Coclusions

Q-Homo and Q-TN cells which have the HAN configuration of easy axes has been proposed by using strong polar anchoring of the planar surface and weak polar anchoring of the homeotropic surface. These LC cell have no threshold voltage in the LC reorientation and very low driving voltage of electro-optical properties. V_{10} in the Q-TN cell is less than 1/5 of that in a conventional 90° TN cell and the transmittance is colorless in gray scale. Such LC devices have high compatibility with ultra-low-voltage operation C-MOS devices using an ambient energy harvesting.

REFERENCES

[1] Y. J. Kim and S.-D. Lee, "Reflective mode of a nematic liquid crystal with chirality in a hybrid aligned configuration", Appl. Phys. Lett. **72**, pp. 1978-1980 (1998).

[2] A. Kubono, Y. Kyokane, R. Akiyama and K. Tanaka, "Effects of cell parameters on the properties of hybrid twisted nematic displays", J. Appl. Phys. **90**, pp.5859-5865 (2001).

[3] G. Barbero and R. Barberi, "Critical thickness of a hybrid aligned nematic liquid crystal cell," J. Physique, **44**, pp. 609-616 (1983).

[4] G. Barbero and R. Bartolino, "Remarks on critical thickness of a hybrid aligned nematic cell with large elastic anisotropy," Mol. Cryst. Liq. Cryst., **99**, pp. 89-97 (1983).

[5] A. Strigazzi, "Second order elasticity and critical thickness of hybrid aligned nematics strongly anchored on the planar side," Mol. Cryst. Liquid Cryst., **179**, pp. 425-433 (1990).

[6] R. Yamaguchi, "Thresholdless electro-optical property in quasi homogeneous and homeotropic liquid crystal cells using weak anchoring surfaces," IEICE TRANS. ELECTRON., **E102–C**, pp.810-812 (2020).