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Temperature Dependence of the Electro-optic Characteristics in the Liquid Crystal Display Switching Modes

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Abstract

As the physical properties of nematic liquid crystals vary with respect to temperature, the performances of liquid crystal displays (LCDs) are highly dependent on temperature. Additionally, it is well known that the electro-optic characteristics of LCDs, such as transmittance and threshold voltage, also rely on the LCD switching modes. The temperature dependence of the electro-optic characteristics of the wide-viewing-angle LCD modes, such as in-plane switching (IPS), multidomain vertical alignment by patterned electrode (PVA), and fringe-field switching (FFS), have been studied, and the results showed that the FFS mode has lower temperature dependence compared to the IPS and PVA modes. Since the liquid crystal (LC) reorients in different ways in each mode, this result is associated with the temperature dependence of LC's bend and twist elastic constants, and also with the position of the main reorientation, either in the middle or on the surface of the LC layer.

Keywords: Liquid crystal, temperature dependence, electro-optic, liquid crystal display

1. Introduction

Due to its principal attractions, such as its low power consumption, high resolution, thinness, lightness, and flatness, liquid crystal display (LCD) has become a ubiquitous electro-optical device, widely used in various application fields, such as telecommunication devices, cars, computers, and TVs, and its state-of-the-art technical evolution continually expands its territory. To expand its usage in various environments, many engineers have devoted their efforts to trying to understand the physical properties of liquid crystal (LC) at different temperatures and pressures. Additionally, as LCDs are nonemissive displays, they always require a light source. Owing to the significant amount of light absorptions from several optical films, however, such as polarizers and color filters, the light efficiency of LCD does not reach 10%. Therefore, a strong light should be illuminated from the light source, This strong light, however, will generate much heat, in addition to the heat generated by the integrated circuit drivers of the LCD. As a result, LCDs are often exposed to high temperatures, such as -40°C, in LCD TVs, which greatly affects the physical properties of the LCs compared to when they are exposed only to room temperature.[1]

For the application of LCDs in TVs, several wide-viewing-angle LCD modes have been adopted, including in-plane switching (IPS), multidomain vertical alignment associated with a patterned electrode (PVA), and fringe-field switching (FFS). When LCD-TVs are fabricated, two types of LC alignment at the initial state are generally introduced: (1) a homogenous alignment of the LCs at the initial state, which is driven by the in-plane and fringe-electric fields in the IPS[2],[3] and FFS[4],[5] modes, respectively; and (2) a vertical alignment of the LCs at the initial state in the PVA mode.[6]-[8] The LCDs for homogenous alignment at the initial state use LC molecules with a positive dielectric anisotropy, while the LCDs using vertical alignment at the initial state use LC molecules with a negative dielectric anisotropy. The driving electrical fields for reorienting LC differ from one LC device to another,

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and the physical properties, such as the elastic constants and dielectric anisotropy, together with the electro-optic characteristics, such as threshold voltage, driving voltage, and transmittance, which are highly dependent on temperature, will change according to the changes in temperature.[9]-[11] Therefore, the temperature dependence of the electro-optical and physical properties of different LCD modes must be understood.

In this study, the temperature-dependent electro-optic characteristics of three different wide-viewing-angle LCD modes (IPS, FFS, and PVA) were investigated. The comparison of the electro-optic properties measured in these three LCD modes revealed that the PVA mode has higher dependence on temperature compared to the IPS and FFS modes, possibly due to the different reorientation of the LC molecules during switching.

2. Cell Structure and Experiment

The schematic diagram in Fig. 1 shows the operation principle of the three LCD modes included in this study. In the PVA mode [Fig. 1(a)], transparent indium-tin-oxide-(ITO)-coated pixels and common electrodes were alternately patterned on the bottom and top substrates, with a patterned slit width of 5 ㎛, and an oblique electric field with vertical and horizontal components was thus generated with the biased voltage. This oblique field tilts the LC downward in four different diagonal directions.[12] To tilt the LC downward, in an exactly diagonal direction, the field direction of the horizontal component of an oblique field should be in a diagonal direction. The cell gap was found to be 4 ㎛, and an LC with a negative dielectric anisotropy from Merck Co. ($\Delta\varepsilon$=-4; Δn=0.077 at λ=589 nm; T_{ni}=75℃) was used. During switching, bend deformation occurred mostly in the middle of the LC layer, as shown in Fig. 1(a).

For the IPS cells, the signal and common electrodes existed only on the bottom glass substrate, which had an electrode width of 5 ㎛ and a distance (*l*) of 10 ㎛ between the electrodes [see Fig. 1(b)], while the FFS cells had a signal electrode width of 4 ㎛ and a distance (l) of 5 ㎛ between the electrodes. A 0.69-㎛ passivation layer was introduced between the signal and common electrodes [see Fig. 1(c)]. In both devices, coated indium-tin-oxide(ITO) was applied as an electrode. For the alignment layer, an 80-nm-thick homogenous-alignment layer was spin-coated on the patterned electrode at both the bottom and top glass substrates. Rubbing was done on both substrates, in anti-parallel directions, to align the nematic LC with 80 and 83o angles with respects to the horizontal field in the IPS and FFS cells, respectively. As spacers, plastic balls with a diameter of 3.5 and 3.8 ㎛ in the IPS and FFS cells, respectively, were used to keep the *d*-spacing constant between the bottom and top substrates. In both cells, an LC with a positive dielectric anisotropy from Merck Co. (dielectric anisotropy $\Delta\varepsilon$=7.4; birefringence Δn=0.088 at λ=589 nm; clearing temperature T_{ni}=87℃) was used. As a result, the homogenously aligned LC was rotated mainly by the in-plane field in the IPS cell[2], and by the fringe-electric field in the FFS cell.13,14 In addition, the LCs were twisted mostly in the middle of the LC layer in the IPS mode, where the LC-to-LC interaction was dominant, while in the FFS mode, the LCs were twisted mostly near the bottom substrate,[15],[16] where the LC-to-alignment-layer interaction was stronger than the LC-to-LC interaction.

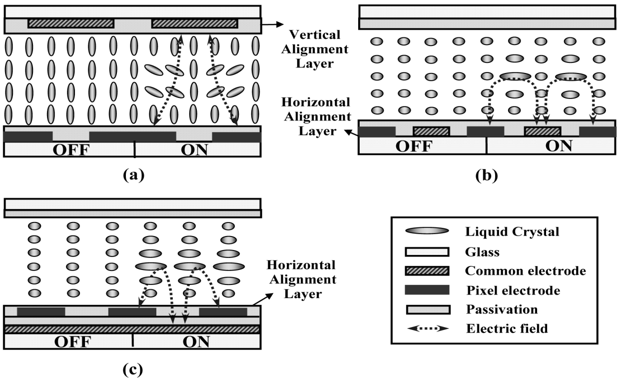

Fig. 1. Schematic structure of the LC device with the orientation of the LC molecules for switching to the off and on states in three different LC devices: (a) PVA; (b) IPS; and (c) FFS

3. Results and Discussion

During heating from T_{ni}-50 to T_{ni}-10°C, the voltage-dependent transmittances of light in the PVA, IPS, and FFS cells were monitored at every 10°C temperature interval, as shown in Fig. 2. The rate of change in the threshold voltage (V_{10}) with respect to the temperature depends on the mode. Here, V_{10} is defined as the voltage that shows a 10% transmittance change from a dark state. The rate of change of V_{10} with temperature in the IPS and FFS modes, mainly driven by the horizontal field, is smaller compared to that in the PVA mode, driven by the vertical field, as shown in Fig. 3.

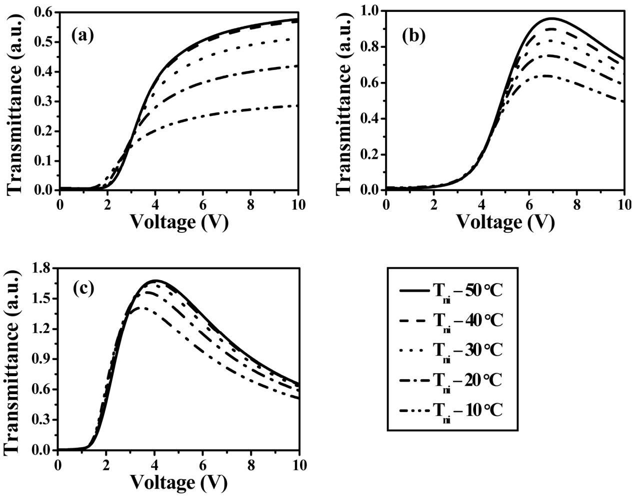

Fig. 2. Measured transmittance with respect to the voltage at different temperatures: (a) PVA; (b) IPS; and (c) FFS

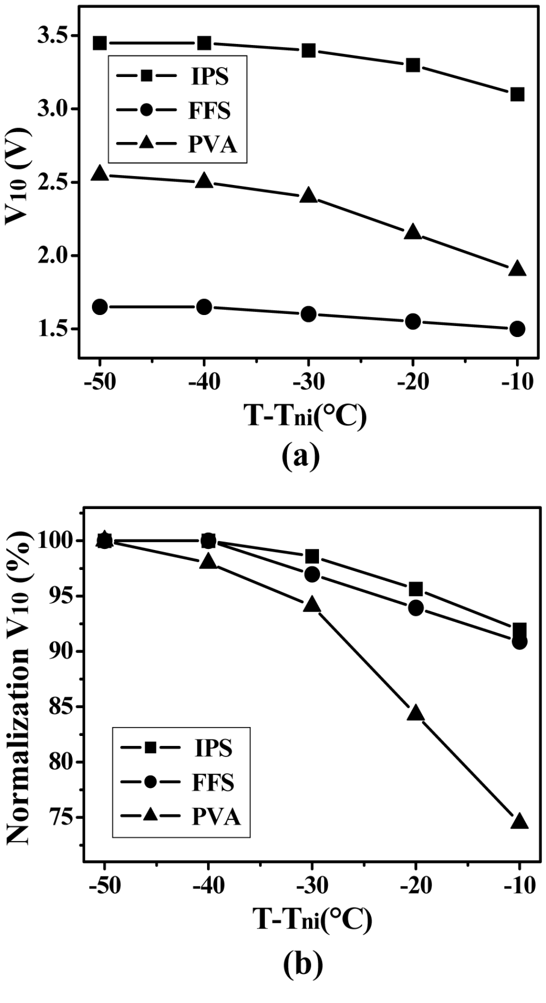

Fig. 3. (a) Temperature dependence of the threshold voltage (V_{10}). (b) Normalized V_{10} in the PVA, IPS, and FFS devices

The Freederickz transition voltage V_F of the LC cells is mathematically described as

$$V_F \propto \sqrt{\left(K_{ii} / \varepsilon_0 |\Delta\varepsilon|\right)}, \qquad (1)$$

where K_{ii} is the effective elastic constant and K_{11}, K_{22}, and K_{33} are the splay, twist, and bend elastic constants, respectively. In most LC devices, V_F is proportional to V_{10}.[17] The K_{ii} of the IPS and FFS modes is mainly equal to K_{22}, whereas K_{ii} is mainly equal to K_{33} for the PVA mode. According to equation (1), V_F is proportional to $\sqrt{\left(K_{ii} / |\Delta\varepsilon|\right)}$ and generally decreases if the elastic constants are in the order of $K_{33}>K_{11}>K_{22}$.[18]-[20] K_{ii} in equation (1) is a function of the reduced elastic constant (C_{ii}), molar volume (V), and order parameter (S) with the relationship[20]

$$K_{ii} = C_{ii} V^{-7/3} S^2, \qquad (2)$$

where S depends on the temperature and can be given by

$$S = [1 - T / T_{ni}]^{\beta}, \qquad (3)$$

where β is a material parameter and T_{ni} the clearing temperature. From equations (2) and (3), it is evident that K_{ii} decreases with increasing temperature. Among the three elastic constants, K_{33} is the most sensitive to temperature. The temperature-dependent elastic constants for +LC ($\Delta\varepsilon$=7.4) were measured using ALCT 4 (Instec Inc.) and are shown in Fig. 4. It is evident in Fig. 4 that K_{33} decreases more rapidly than K_{11} and K_{22} with increasing temperature. Another physical parameter that is responsible for the change in V_{10} is the dielectric anisotropy of the LC. The dielectric-anisotropy behavior with the change in temperature can be explained based on the Maier and Meier theory.[21],[22] According to this theory, the temperature dependence of $\Delta\varepsilon$ is directly proportional to S, and hence, according to equation (3), $\Delta\varepsilon$ will be inversely proportional to the temperature. Further, dielectric anisotropy is a purely materialistic property and is independent of the cell structure. Thus, the rapid reduction in threshold voltage in the PVA cell was due to the fact that the elastic constant (K_{33}) of the LCs in the PVA cell is highly dependent on

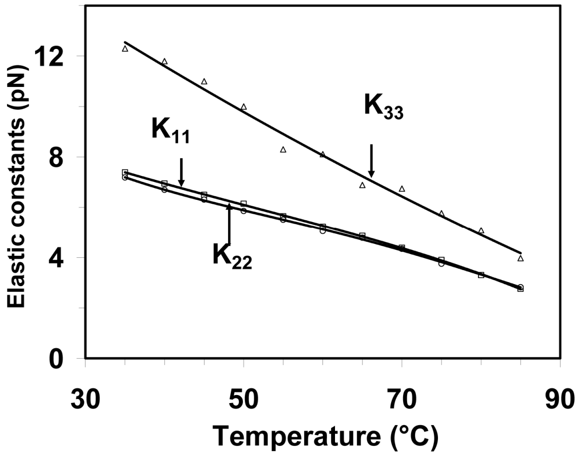

Fig. 4. Variation of the splay (K_{11}), twist (K_{22}), and bend (K_{33}) elastic constants with temperature

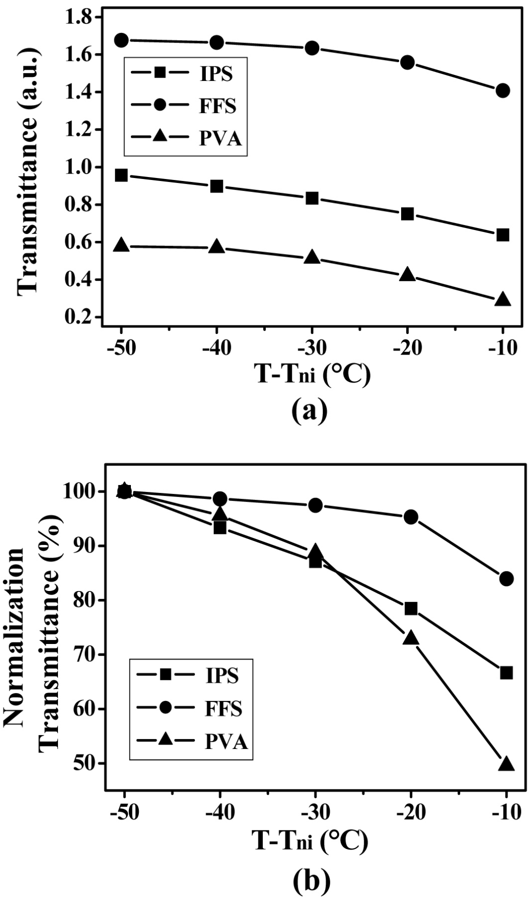

Fig. 5. (a) Variations of transmittance and (b) normalized transmittance with respect to temperature in the PVA, IPS, and FFS devices

temperature, compared with those in the IPS and FFS cells, in which the main deformation was related to K_{22}. Therefore, it can be concluded that V_{10} in the PVA mode is much more sensitive to temperature than those in the IPS and FFS modes, while the IPS and FFS modes showed similar trends.

The maximum transmittances of light in the different LCD switching modes were measured and plotted with respect to temperature, and are shown in Fig. 5. These results also confirm that the FFS cell is less affected by changing temperatures than the PVA and IPS cells are. The normalized transmittance, T/T_o, for these three devices, in which a uniaxial LC medium exists under crossed polarizers, is given by

$$T/To = \sin^2 2\,\psi(V)\,\sin^2(\pi\, d\, \Delta neff(V) / \lambda), \qquad (4)$$

where ψ is a voltage-dependent angle between the transmission axes of the crossed polarizers and the LC director, Δn_{eff} the effective birefringence of the LC layer, and λ the wavelength of the incident light. Through the examination of equation (4), it was found that the transmittance of light in LCD is also highly dependent on temperature because Δn_{eff} is so temperature-dependent that it decreases with increasing temperature due to the decrease in the order parameter of the LC.[23] A question thus arises as to why the FFS cell shows less dependence on temperature compared to the two other devices. As mentioned earlier, the deformation of the LC during switching by bias voltage occurs mostly in the middle of the LC layer, where the LC-to-LC interaction is dominant in the IPS and PVA modes, whereas in the FFS mode, it occurs mostly near the bottom-electrode surface, at the edge of the signal electrode, where the LC-to-alignment-layer interaction is stronger than the LC-to-LC interaction. In addition, the LC orientation is held by the much stronger electric field in the FFS cell than that in the IPS and PVA cells. In other words, the transmittance in the IPS and PVA modes is mainly dependent on the LC orientation in the bulk, but it is less affected in the FFS mode. Consequently, the temperature dependence of transmittance shows similar trends in both the IPS and the PVA cells but is much higher in such cells than in the FFS cell.

Finally, the capacitance at different temperatures was also monitored with respect to the applied voltages, and the results are presented in Fig. 6. The experimental observations shown in Fig. 6 reveal that the capacitance at 10 V decreased with the increasing temperature in all the LC

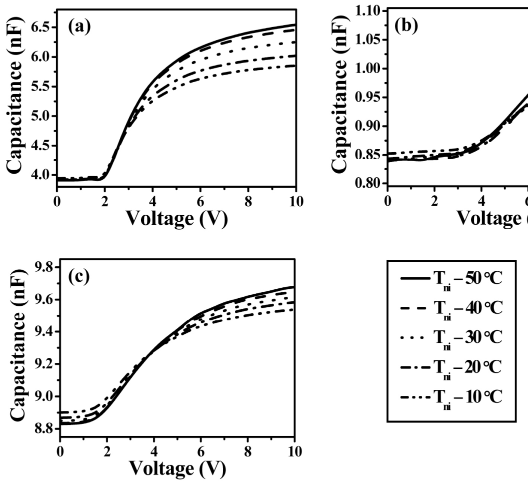

Fig. 6. Measured voltage-dependent capacitances in the (a) PVA, (b) IPS, and (c) FFS devices at different temperatures

cells due to the decrease in the parallel component of the dielectric constant ($\varepsilon_{\|}$) in the IPS and FFS cells and in the perpendicular component of the dielectric constant ($\varepsilon_{\perp}$) in the PVA cell. On the contrary, the capacitance at 0 V increased along with the temperature in all the LC cells due to the increase in the effective dielectric constant. Its decrease rate with the temperature at 10 V, however, is most severe in the PVA cell. As such, the dropping ratios of the capacitance from T_{ni}-50 to T_{ni}-10°C in the PVA, IPS, and FFS cells were 10.6, 6.5, and 1.4%, respectively. The dropping ratio of the capacitance with the increasing temperature is indirectly correlated with the dropping ratio of Δn_{eff}. This result coincides with the result that the transmittance change with increasing temperature was least in the FFS cell and most severe in the PVA cell.

4. Conclusions

In this study, the electro-optic characteristics of the IPS, FFS, and PVA modes were investigated in varied temperatures, and threshold voltage showed higher temperature dependence in the PVA cell than in the IPS and FFS cells. This result can be attributed to the fact that K_{33} decreases more rapidly than K_{22} with increasing temperature. When the maximum transmittance was measured in the different LCD modes, it was found that the PVA and IPS cells are more sensitive to temperature changes than the FFS cell is. Overall, with regard to the electro-optic properties of the different LCD modes in relation to temperature, the FFS mode showed the least dependence on temperature owing to the LC reorientation associated with K_{22} near the electrode surface.

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