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Thermally induced light leakage in in-plane-switching liquid crystal displays

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In this paper, we report the thermally induced light leakage in in-plane-switching liquid crystal displays (IPS LCDs) that have a built-in small-angle deviation (<4 deg) between the polarization axis of a polarizer and the rubbing directions for liquid crystal (LC) alignment. We have found that the thermally induced light leakage depends strongly on the phase retardation which is a function of cell gap, wavelength, and birefringence of LCs used in the IPS LC cells. In addition, we have measured the light leakage of vertically aligned LC cells, which is independent of temperature and the deviation angle. A temperature-scanning method is proposed to reduce the light leakage of the IPS LCDs. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3073882]

I. INTRODUCTION

In-plane-switching liquid crystal displays (IPS LCDs) have a wide viewing angle, low color shift, and good color performance.[1–4] However, the contrast ratio (CR), defined as the transmittance ratio of a full bright state to a quiescent dark state, is not as good as that of multidomain vertical alignment LCDs (MVA LCDs). The CR of LCDs depends on several important factors such as liquid crystal (LC) modes,[1,5] light scattering of the LCs,[6–8] color filters,[4,8] polarizers,[9] inclined light due to the backlight,[4] surface morphology of thin-film transistor (TFT),[4] nonuniform alignment of alignment layer,[4] and rubbing angles.[10] In fact, CR of IPS LCDs decreases when the temperature of LC cell increases due to the heat from the backlights of the display. In this paper, we have investigated the thermally induced light leakage in the quiescent dark state of an IPS LC cell that has a built-in small-angle deviations (<4°) between the polarization axis of a polarizer and the rubbing direction for LC alignment. The small-angle deviation (generally 2°–3°) was used to represent the error caused by the attachment of polarizers onto LC cells during panel fabrication process. We have found that thermally induced light leakage strongly depends on the phase retardation of the IPS LC cell, where the phase retardation is proportional to the cell gap multiplied by the birefringence of LC mixture and divided by the wavelength of the incident light. In other words, the phase retardation is caused by the different propagation speeds between extraordinary and ordinary rays through the LC medium. Light leakage of vertically aligned (VA) LC cells between crossed polarizers is independent of temperature. However, for IPS LC cells, light leakage is not only sensitive to temperature of the LC medium but also magnified by the built-in small-angle deviation between the polarization axis of a polarizer and the rubbing directions for LC alignment. We have found a method to minimize the deviation angle (DA) in order to reduce the light leakage and increase the CR of IPS LC mode.

II. EXPERIMENTAL SCHEMES AND RESULTS

In order to study the thermally induced light leakage, we have prepared two kinds of LC cells: VA cell and homogeneous cell, and the latter is used to simulate a single-pixel IPS cell with different cell gaps of 4, 7, and 12 μm to represent different phase retardations at same temperature. The pretilt angles were 89° in the VA cell and 2° in the homogeneous cells. The LC mixtures were MLC-2042 (Merck, $\Delta n=0.0743$) for the homogeneous LC cells and MLC-6608 (Merck, $\Delta n=0.0822$) for the VA cells. The nematic-to-isotropic transition temperatures of MLC-2042 and MLC-6608 are 80 and 90 °C, respectively. The experimental scheme is depicted in Fig. 1. A He–Ne laser at wavelength of 632.8 nm (Melles Griot model: 05-LHP-991) was used as an incident light source. The homogeneous or VA LC cell was located inside a temperature-regulated hot stage (Mettler Toledo FP82HT), which was placed between two crossed polarizers (Newport's Glan-Laser Calcite Polarizers). The

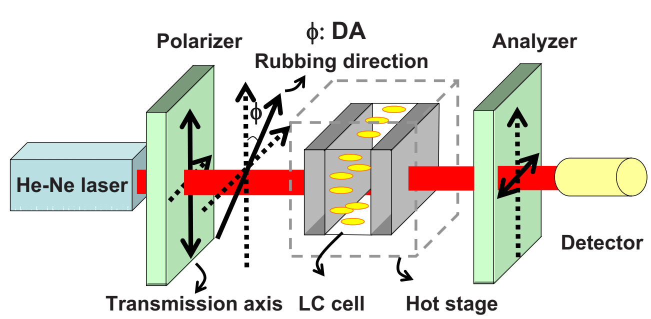

FIG. 1. (Color online) Scheme of the experimental setup for the measurement of transmittance.

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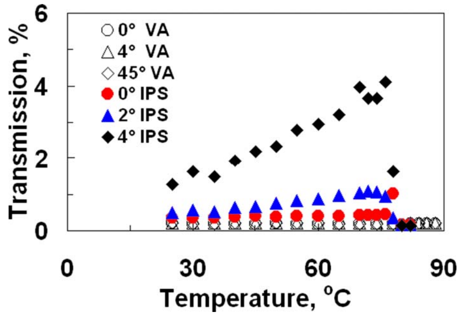

FIG. 2. (Color online) The transmittance as a function of temperature at various DAs in IPS cell (solid points) and VA cell (hollow points). The cell gaps were 7 μm.

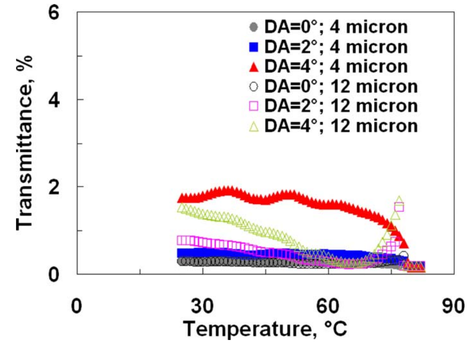

FIG. 3. (Color online) The transmittance as a function of temperature at DA=0°, 2°, and 4° in two IPS cells. The cell gaps were 4 μm (solid points) and 12 μm (hollow points).

transmittance or light leakage at the quiescent state of the LC cell as a function of temperature was measured in the e-mode configuration,[2,3] in which the transmission axis of the linear polarizer was parallel to the rubbing directions of the LC cells. The transmission axis of the analyzer was 90° with respect to the polarizer. In order to measure the thermally induced light leakage at small-angle deviations, we rotated the LC cells to change the angle between the rubbing direction and the polarization axis of a polarizer at different temperatures. This angle is called the DA. Without applying voltage, the transmitted light (or light leakage) was then detected by a photodiode (New Focus Model 2031). We defined the maximum transmittance as 100% when the rubbing directions of the LC cell were 45° with respect to one of the crossed polarizers, and the phase retardation of LC cells was π. The minimum transmittance was around 0.2% when the phase retardation of LC cells was 2π. This minimum transmittance is due to the distribution of the LC directors around the rubbing direction.

Figure 2 shows the experimental results of the temperature-dependent transmittance at the different DAs in the IPS cell and the VA cell without applying any voltage. The cell gaps were 7 μm in Fig. 2. In the IPS cell, the transmittance increased with the temperature and then dropped dramatically after the clearing point at a fixed DA. The transmittance difference between 20 and 80 °C increased as the DA increased because of the larger phase retardation at larger DAs. On the contrary, the transmittance remained the same at different temperatures and is independent of DA for the VA cell. The measured transmittance was within the range of 0.2%–0.4% even at 45° DA. In the experimental results, we have shown that the light leakage in the IPS cell was more sensitive to the temperature and the DA. Our experimental results showed that the light leakage at the quiescent state of the IPS cell at 2° DA increased twofold (from around 0.5%–1%) when the temperature varied from room temperature to near isotropic-to-nematic transition temperature. Therefore, the CR of IPS LCDs at a normal incidence is generally lower than that of MVA LCDs. Without a sensitive way to measure such a small DA, it is difficult to avoid or correct its occurrence. However, by measuring the thermally induced light leakage at the quiescent state of an IPS cell, the value of a small DA can be determined.

In order to further study the thermally induced light leakage of an IPS cell at small DAs, we have prepared two more homogeneous cells filled with same LC mixture, MLC-2042, but different cell gaps of 4 and 12 μm. The LC mixture has a positive dielectric anisotropy. The measured transmittances as a function of temperature at different DAs are shown in Fig. 3. At a fixed temperature, the light leakage increased as the DA increased as expected. At a fixed DA, the transmittance in the 4 μm cell decreased with temperature. The transmittance in the 12 μm cell decreased first with temperature (T) at a fixed DA and then increased after $T > 67$ °C. However, the transmittance of the 7 μm cell increased with the temperature at a fixed DA, as shown in Fig. 2. The different trends of temperature-dependent transmittance are caused by different phase retardations due to different cell gaps and birefringence of thermotropic LCs[2,3] decreasing at different temperatures.

III. DISCUSSION

The DA (ϕ) causes the light leakage at the quiescent state of LC cells because the polarization of the incident light entering the LC cell is not parallel to the rubbing direction of the LC medium. Assuming that light enters a homogeneous LC layer with a tilt angle of α oriented at a DA of ϕ from the transmission axis of the polarizer, the detected light transmittance (t) at normal incidence can be expressed as[1–3,11]

$$t = \frac{1}{2}\sin^2(2\phi) \times \sin^2\left(\frac{\Gamma}{2}\right), \quad (1)$$

where Γ is the phase retardation of the LC layer. The phase retardation Γ can also be expressed as

$$\Gamma = \frac{2\pi d}{\lambda}(n_{\text{eff}} - n_o) = \frac{2\pi d}{\lambda}\left(\frac{n_e n_o}{\sqrt{n_e^2 \sin^2 \alpha + n_o^2 \cos^2 \alpha}} - n_o\right), \quad (2)$$

where n_e and n_o stand for the extraordinary and ordinary refractive indices of LC mixture, respectively, n_{eff} is the effective extraordinary refractive index, d is the cell gap, and λ is the wavelength of incident light.

The DA (ϕ) is generally small ($<4°$) and difficult to be measured or corrected during fabrication process of polarizer attachment, but it can be detected by measuring the phase retardation (Γ) of IPS LCDs. Among the parameters of phase retardation (Γ) in Eq. (2), λ and d are fixed, and α is the voltage-dependent tilt angle; however, n_e and n_o are temperature dependent.[12] When the temperature is less than the clearing-point temperature, n_e decreases and n_o increases. The temperature-dependent birefringence $(n_e - n_o)$ of thermotropic LC materials can be expressed as[2,3,13]

$$\Delta n(T) = n_e - n_o = \Delta n_o \times (1 - T/T_C)^{\beta}, \tag{3}$$

where Δn_o is the birefringence of the LC mixture at the crystalline state, β is a material parameter ($\beta \sim 0.25$ in most of LC materials), and T_c is the clearing temperature of the LC materials. In Eq. (2), $(n_{\text{eff}} - n_o)$ is close to $(n_e - n_o)$ in IPS LCDs without an applied voltage because the tilt angle in IPS LCDs is around 2°. Hence, Eq. (1) turns out to be

$$t = 2\phi^2 \sin^2\left\{\frac{\pi d}{\lambda}[n_e(T) - n_o(T)]\right\}. \tag{4}$$

When the ambient temperature (T) changes, total transmittance changes as well. The trends of the temperature-dependent transmittance in Figs. 2 and 3 depend on the value of $\{\pi d[n_e(T) - n_o(T)]/\lambda\}$. On the contrary, $\Gamma \sim 0$ in VA cell because the large tilt angle (~89°) at voltage-off state results in $(n_{\text{eff}} - n_o) \sim (n_o - n_o) \sim 0$. Thus, the total transmittance of the VA cell is approximately equals to zero and independent of temperature. However, the light leakage in IPS cell is sensitive to temperature at the same DA. Therefore, thermally-induced light leakage of the IPS cell was caused by both DA and Γ that varied with temperatures. The transmittance or light leakage at voltage-off state increases or decreases with temperature depending on Γ which is a function of cell gap, wavelength, and birefringence of LCs.

The different trends of temperature-dependent transmittances of IPS LCDs at the voltage-off state for the cases of 4, 7, and 12 μm cell gaps were caused by different initial phase retardations of $\Gamma \sim 0.939\pi$, $\Gamma \sim 1.64\pi$, and $\Gamma \sim 2.81\pi$, respectively, at room temperature. Plugging those values into Eq. (4) results in $\sin^2(\Gamma/2)$ equal to 0.991, 0.287, and 0.914 at 4, 7, and 12 μm cell gaps, respectively. The birefringence of LCs decreasing with temperature results in the reduction in the phase retardation. For example, as temperature increases, $\Gamma \sim 0.939\pi$ starts to decrease at 4 μm cell gap, causing $\sin^2(\Gamma/2)$ to decrease as well. Similarly, $\sin^2(\Gamma/2)$ increases with temperature at 7 μm cell gap. At 12 μm cell gap, $\sin^2(\Gamma/2)$ first decreases then increases after $\Gamma < 2\pi$. Hence, the experimental results agree with our simple calculations.

In order to improve the light leakage and thus the CR of IPS LCDs, we can correct the small DA by keeping $[n_e(T) - n_o(T)]$ in Eq. (4) at a finite value. This can be done by the thermally scanning method at the voltage-off state. The method is to monitor the transmittance by rotating the IPS cell between two crossed polarizers until the light leakage is minimized at all temperatures. After correcting the angle between the polarizers and the rubbing directions of the LC cell, we then attached the polarizers to the IPS cell. The major impact is to detect the DA between the rubbing direction of the laminated IPS panel and one polarization axis of crossed polarizers. We can feedback such an angle to correct the polarizer-lamination process during the fabrication of IPS LCDs. Therefore, the CR of IPS-LCDs can be improved.

IV. CONCLUSION

We have investigated the thermally induced light leakage at the quiescent state of IPS LCDs. The light leakage between a pair of crossed polarizers was dependent on temperature because of the existences of DA and nonzero phase retardation. The thermally induced light leakage of IPS LC cells is substantially larger than that of the VA cells under the same DA and temperature. In VA cells, the light leakage is independent of temperature even though DA is nonzero. We have analyzed the mechanism of light leakage that agrees well with our experimental results. We have also provided a thermally scanning method to reduce the light leakage of the IPS cell. The light leakage of the IPS cells should remain low and constant with temperature after we minimize the DA. We believe that this paper points out an important method to improve the CR and image quality of IPS LCDs.

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