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Dual Domain Effect on a Rubbing Mura in Liquid Crystal Displays Associated with In-Plane Rotation of LC Director

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The liquid crystal (LC) modes, in-plane switching (IPS) and fringe-field switching (FFS), associated with a transition from a homogenously aligned to twist deformation require rubbing process. In both devices, 1° of misalignment in azimuthal direction could cause voltage–dependent transmittance (V–T) to be different from that in a normal area and consequently results in a rubbing mura. According to our studies, dual domain structure of the FFS and IPS modes could reduce such a V–T difference dependent on the position although 1° of misalignment exists since the LC directors rotate clockwise and anticlockwise. [DOI: 10.1143/JJAP.44.6577]

KEYWORDS: color tracking, fringe-field switching, liquid crystal, authentic color

1. Introduction

Recently, the image quality of the liquid crystal displays (LCDs) has been greatly improved with development of the new LC modes. Among them are both in-plane field switching (IPS)[1–5] and the fringe-field switching (FFS)[6–10] modes. The reason that both devices exhibit a high image quality is that the homogenously aligned LC with an optic axis coincident with one of the crossed polarizer axes shows a good dark state before applying bias voltage and rotates almost in plane with bias voltage, giving rise to transmittance with excellent luminance uniformity. However, both devices require a rubbing process to align the LCs in one direction, which is a demerit compared to multi-domain vertical alignment (MVA)[11] mode which does not require a rubbing process.[12]

In general, the rubbing process is performed by moving a rotating cylinder roll covered with cotton or rayon. Unfortunately, this process sometimes causes non-uniformity in surface tilt angle or azimuthal anchoring direction so that the rotating angle of the LC directors could be different depending on the position, when voltage is applied. This induces non-uniformity in transmittance in a displayed area, and since this is caused by the rubbing process, it is called a rubbing mura.

In the IPS and FFS modes, an in-plane and fringe-electric field rotates the LC almost in-plane, respectively. Although both devices show excellent viewing angle characteristics, if the LC directors rotate in one direction, it causes a yellowish and bluish color shift depending on the viewing direction. To prevent this, a wedge shaped electrode, especially for large size LCDs, is introduced such that in one pixel there are two field directions, forcing the LCs to rotate clockwise and anticlockwise similar to a dual domain.[13–15]

In this paper, we investigated how electrode shapes for single and dual domains can affect the display uniformity when we assume that there is 1° of misalignment in azimuthal direction compared to the normal areas by calculation. The detailed analysis on this study is reported herein.

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2. Theoretical Background on Switching Principle and Cell Structure

In the FFS mode, the LCs are homogeneously aligned with an optic axis coincident with one of the crossed polarizers. Therefore, the normalized light transmission of the cell can be described by:

$$T/T_0 = \sin^2(2\varphi(V))\sin^2(\pi d\Delta n/\lambda) \tag{1}$$

where φ is an angle between one of the transmission axis of the crossed polarizers and the LC director, d is a cell gap, Δn is the effective birefringence of the LC medium, and λ is the wavelength of an incident light. From the equation, one can understand that φ is a voltage dependent value, that is, without a bias voltage (off state), φ is zero and the cell shows a dark state. With bias voltage (on state), the φ starts to deviate from the polarizer axis, showing light transmittance.

Theoretically, the φ must be zero to show a complete black state before applying a voltage. However, in real cell fabrication the φ may not be zero in some parts since the rubbing process is performed to align the LC, in which that case the transmittance on that area looks different compared to the normal areas, causing rubbing mura. Further, this value could be either positive or negative depending on the case. The rubbing process causes non-uniformity in LC alignment such as polar and azimuthal anchoring direction. Here, we only consider misalignment of $\varphi = \pm 1°$ in azimuthal anchoring direction from the defined direction, where + sign indicates a clockwise direction with respect to vertical axis. First, we consider the FFS electrode structures using the LC with negative dielectric anisotropy, where one pixel is for a single domain and the other pixel is for dual domains, as shown in Fig. 1. Here, the field makes an angle of 12° with the LC director in a normal area. When there is no misalignment, the LC director rotates clockwise with increasing voltage so that the transmittance increases continuously from a dark to white state. With the misalignment of +1° in which the field makes an angle of 13° with the LC director, the slight light transmittance already exists before applying any voltage. Also with increasing voltage, the transmittance keeps increasing. With the misalignment of −1° in which the field makes an angle of 11° with the LC director, the slight light leakage also exists at zero voltage but with a slight increase in the applied voltage φ becomes

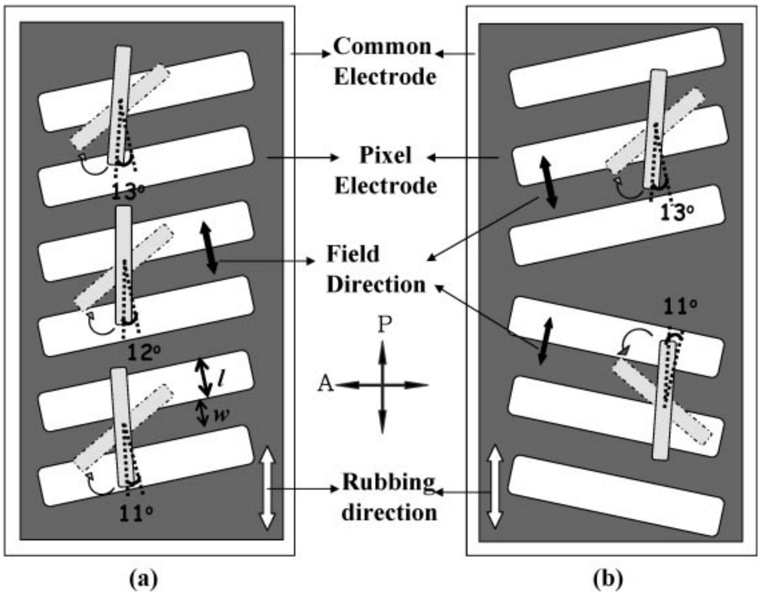

Fig. 1. Schematic drawings describing angles between the field direction and the initial LC alignment in (a) single and (b) dual domains with rotating directions, where P and A indicates the polarizer and analyzer, respectively.

effectively zero, causing the cell to appear to be a dark state. With further increasing voltage, the transmittance starts to occur again. In any case, one can notice that voltage–dependent (V–T) curves at normal and misaligned areas are different from each other, causing the rubbing mura to appear. However, in a dual domain structure, when there is a misalignment of 1°, in one half of a pixel the field makes angle of 13° with the LC director while in the other half the field makes an angle of 11° with the LC director, so that the average transmittance is observed to the observers. Although the V–T curves in each half of a pixel is different from that in the normal area, the difference between the normal and misaligned areas is reduced when the pixel structure is designed with a dual domain, which will be proved hereafter.

3. Result and Discussion

For calculations, we performed a simulation using a "LCD Master" (Shintech, Japan) where the motion of the LC director is calculated based on the Eriksen–Leslie theory and 2×2 Jones Matrix is applied for an optical transmittance calculation. In the FFS device, the electrodes exist only at the bottom substrate, where a common electrode exists as a plane and a pixel electrode in slit form with a gap (l) existing between them. The width of the pixel electrode (w) and the l is assumed to be 3 and 4.5 µm, respectively. The cell gap is 4 µm and the passivation layer with a thickness of 3000 Å is positioned between the common and the pixel electrodes. Here, the LC with physical properties (dielectric anisotropy $\Delta\varepsilon = -4$, $\Delta n = 0.09$, $K_1 = 13.5$ pN, $K_2 = 6.5$ pN, $K_3 = 15.1$ pN) is used and a strong anchoring for the LC to the surface is assumed. The surface pretilt angle for both substrates is 2°.

Figure 2 shows calculated V–T curves when the rubbing direction is 12° ($\varphi = 0°$), and misaligned 11° ($\varphi = -1°$) and 13° ($\varphi = +1°$) in a single domain and also the pixel has a dual domain structure. As expected, in cases of the cells with $\varphi = \pm 1°$, the V–T curves are different from each other from

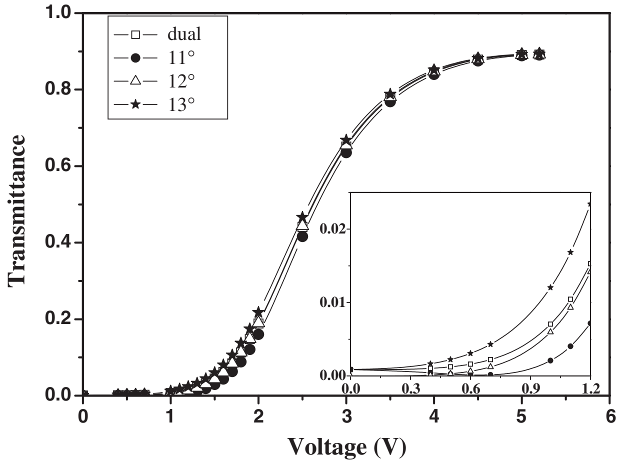

Fig. 2. Calculated voltage–dependent transmittance curves depending an initial LC alignment and electrode structure in the FFS mode.

that of cell with $\varphi = 0°$ because for 11° cell the transmittance keeps increasing with increasing voltage, but for 13° cell the transmittance exists at an initial state and with increasing voltage, it becomes dark and then occurs again. Therefore, for the single domain FFS mode, whenever the LC directors do not direct to a defined direction, the different transmittance although the same voltage is applied occurs, causing rubbing mura. However, for the dual domain FFS mode, although some parts have a misalignment of 1° the LC directors rotate in two opposite directions, clockwise and anticlockwise. Therefore, in the dual domain FFS mode, both V–T curves with $\varphi = \pm 1°$ are combined together. As the result, the transmittance increases with increasing voltage but the increase rate is reduced compared to that in the single domain. Consequently, it shows most similar V–T curve to that in area with $\varphi = 0°$, as shown in an inset of Fig. 2.

Next, we evaluate how many grey scales could be

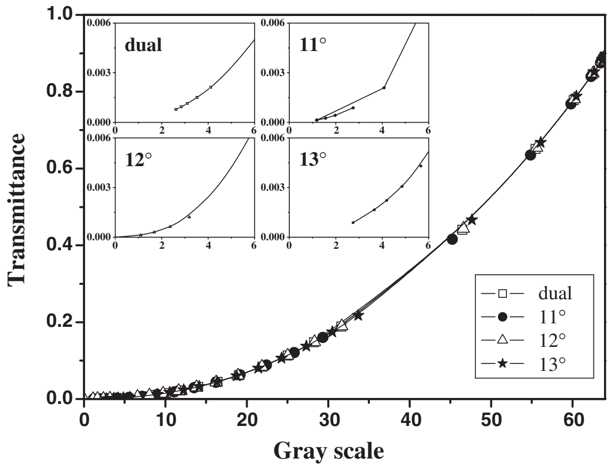

Fig. 3. Calculated gray scale dependent transmittance curves with rubbing-misalignment of $\pm 1^\circ$ in single and dual domains in the FFS mode.

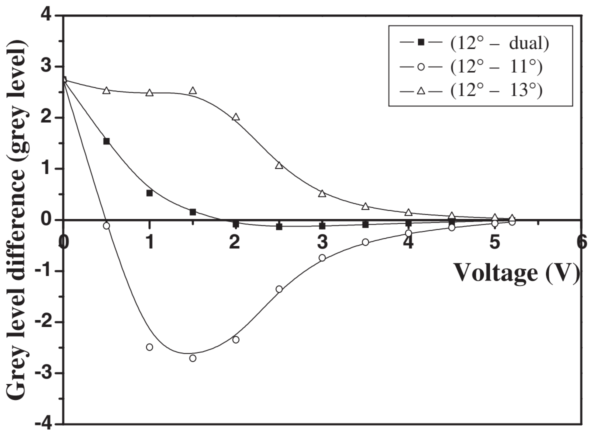

Fig. 4. Calculated voltage–dependent gray scale difference with rubbing-misalignment of $\pm 1^\circ$ in single and dual domains in the FFS mode.

different with the misalignment of $\varphi = \pm 1^\circ$ in the single and dual domains. We have used eq. (2) to calculate the transmittance with gray scale.[16)]

$$T = T_{\max}(\text{Gray}\,\#/\,\text{max.Gray})^{\gamma} \qquad (2)$$

Figure 3 shows the gray scale curve with transmittance for 64 gray scales when γ value is 2.2. As indicated, the gray scale curve is shifted by the V–T curve change because transmittance is in proportion with the gray scale, as appeared in the insets of Fig. 3. Figure 4 shows calculated voltage–dependent gray scale difference with rubbing misalignment in the single and dual domain FFS mode, in which it is defined as the difference between gray scale number in a cell without misalignment and gray scale number in a cell with misalignment at a given voltage. At zero voltage, the misalignment gives rise to the gray scale difference more than 2 grays, irrespective of the single and dual domain. However, the single domain cell shows more than 2 gray scale difference up to 2 V and even at 3 V, about 1 gray difference is noticeable. In fact, for displaying television, 8 bit driving that expresses 256 grey levels is normal, so that 2 grays are equal to 8 grays. However, in the dual domain when an applied voltage is 1.5 V, the difference is already negligible. This results clearly indicates that the dual domain FFS mode has a greater advantage compared to the singe domain FFS in viewpoints of rubbing mura.

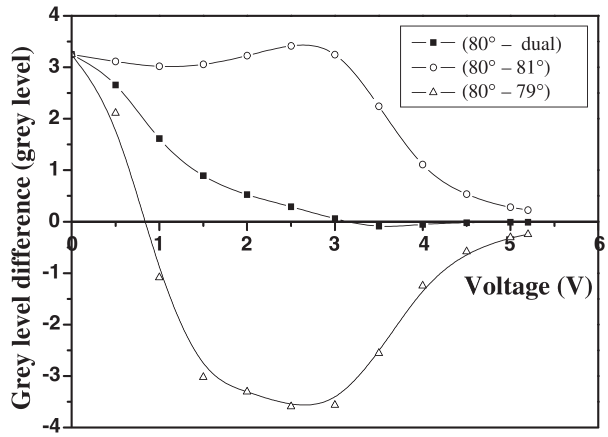

Fig. 5. Calculated voltage–dependent gray scale difference with rubbing-misalignment of $\pm 1^\circ$ in single and dual domains in the IPS mode.

We also evaluated the rubbing mura in the IPS device, where the electrode width and the distance between the pixels and common electrodes is assumed to be 5 and 10 µm. The rest of the cell structures are the same except for the birefringence. Here we used $\Delta n = 0.08$ so that the cell retardation value is 0.32 µm. Figure 5 shows calculated voltage–dependent gray scale difference with rubbing misalignment in the single and dual domain IPS mode. For a single domain cell, the single domain IPS mode is more sensitive to the rubbing mura than the single domain FFS mode. This comes from the difference of two factors such as initial light leakage and threshold voltage. Here, the threshold voltage is defined as the voltage at which the transmittance is 10% with respect to a maximal transmittance. The FFS mode has higher cell retardation value (0.36 µm) than that (0.32 µm) in the IPS mode at initial state, to maximize the light efficiency. Consequently, the intensity of light leakage at a dark state for the FFS and IPS mode is 0.00088 and 0.00104, respectively, with 1° of misalignment. The higher light leakage before applying voltage, the rubbing mura becomes stronger. In addition, the threshold voltage is lower in the FFS mode (1.7 V) than in the IPS mode (2.6 V). As we discussed in the paper, the gray level difference becomes zero as the voltage approaches the operating voltage which generates strong light intensity, that is, the stronger the light transmittance, the transmittance difference between normal and misaligned area becomes smaller. In this view point, the higher the threshold voltage, the rubbing mura exists at a higher voltage. However, for the dual domain IPS mode, the grey level difference is strongly reduced compared to that of the single domain, due to the compensation effect, and disappears around 2 V, which shows similar trends with those in the FFS mode, although the grey level difference in the IPS mode is larger than in the FFS mode at a dark state.

4. Conclusion

In this paper, we have studied how to reduce the rubbing mura on the LC device in which the LC director rotates almost in plane. We found that the single domain IPS and

FFS cells are much more sensitive to the rubbing mura than the dual domain cell. The reason is that in the dual domain the LC director rotates in two opposite directions, compensating for the transmittance difference by the misalignment of the LC director caused by the rubbing process, so that the V–T curve does not deviate much from the normal one.

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