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Measurements of the maximum transmittance of an in-plane switching liquid crystal display showed that it increases as rubbing angle is increased from 10 to 20°. This dependence was analysed in terms of the local variation of electric field intensity between electrodes, which in turn makes liquid crystal at various positions between the electrodes rotate to different angles. The local variation of electric field becomes prominent, especially in the case that the distance between the electrodes is much larger than the cell gap or electrode width.

Keywords: liquid crystal display; in-plane switching; rubbing angle

1. Introduction

Liquid crystal displays (LCDs) are now used in many different applications (*1*). The in-plane switching (IPS) mode is widely used because of the wide viewing angle characteristics that it facilitates (*2–4*). In the IPS mode, the liquid crystal (LC) rotates in-plane, driven by horizontal electric fields produced by arrays of electrodes that are made on the side of the same substrate. Light efficiency is an important characteristic related to power consumption. One factor determining light efficiency is transmittance characteristic of the LC cell. In IPS, an increase of electrodes distance provides an improvement in transmittance, since the area ratio of the electrodes in each pixel is reduced. Although the maximum transmittance of LC cell is simply assumed to be proportional to aperture ratio, local LC motion inside an LC cell determines the actual transmittance. Rubbing angles of currently mass-produced IPS-mode LCDs are 15–20°. Although the effects of rubbing angle on response time and driving voltage have been reported a few times, relatively little attention has been paid to the effect of rubbing angle on maximum transmittance (*5–7*). An increase of maximum transmittance for larger rubbing angle has been reported under simulation, but the mechanism involved remains unclear (*8*).

In this paper, the effect of rubbing angle on maximum transmittance is analysed using both experimental and simulated results. The dependence of maximum transmittance on rubbing angle is experimentally verified for IPS test cells of various electrode structures. The cause of this depedence is analysed by simulating LC configurations under driving electric fields.

2. Experiments

To understand the relationship between LC motion and maximum transmittance, test samples of IPS cells were made, as illustrated in Figure 1. Metal electrodes of width of 5 μm and electrode distances of 6, 11.5, 15, 20 and 28 μm (see Table 1) were made on one side of the substrates and commercial alignment layers were coated on the surface of both substrates. The initial LC alignment direction was determined by a rubbing angle with respect to the direction of the electrodes. Rubbing angles of 10, 15 and 20° were used for the experiment and pretilt was kept below 2°. Ball spacers of diameter of 4 μm were spread, the two substrates were sealed together by a sealant and the gap between the two substrates was filled by LC. The LC material used was such that elastic constants K_{11}, K_{22} and K_{33} were 9.4, 5.4 and 13.9×10^{-12} N, respectively, the dielectric anisotropy was 9.5 and refractive anisotropy 0.08 at 550 nm. Voltages V and V' were applied to each electrode and the LC rotated in-plane by this horizontal electric field.

Figure 2 shows measurements of the voltage–luminance curve for test samples of different electrode distances and rubbing angles, illuminated by the same backlight. Transmittance is proportional to measured luminance. Figures 3a and 3b illustrate the measured maximum luminance and maximum luminance divided by aperture ratio for various conditions. Aperture ratio is defined as ratio of electrode distance divided by summation of electrode distance and electrode width. At the same electrode distances, the maximum luminance is observed to be larger at the largest rubbing angle. This dependence of maximum luminance on rubbing angle becomes

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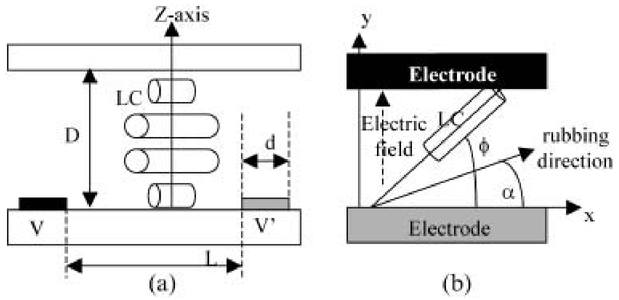

Figure 1. Configuration of IPS test cell for (a) side-view (b) top view. Cell gap, electrode width and electrode distance are represented by D, d and L, respectively. The rubbing angle and angle of optical axis of LC with respect to the electrodes are represented by α and ϕ.

Table 1. IPS test cell conditions.

Cell gap (μm)			4		
Rubbing angle (°)		10	15	20	
Electrode distance (μm)	6	11.5	15	20	28

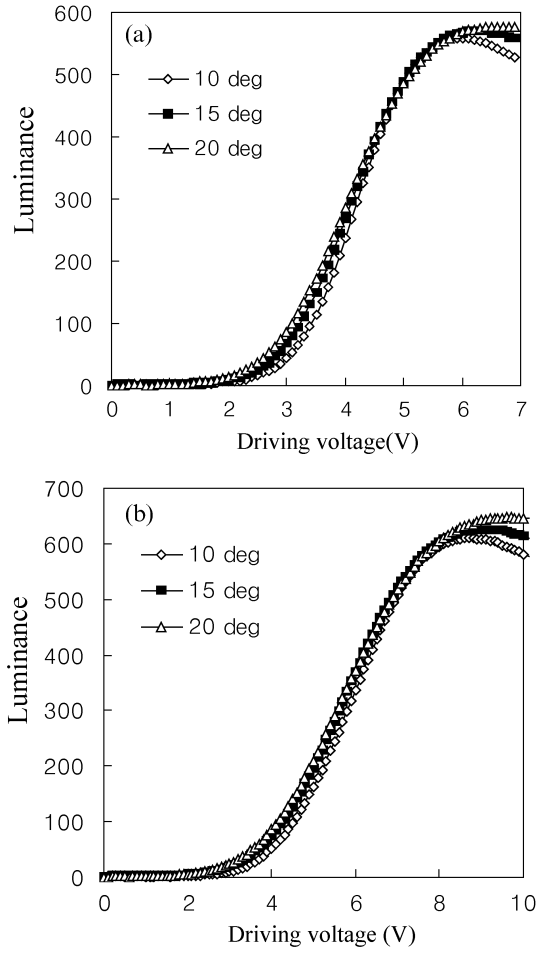

Figure 2. Measured luminance as functions of driving voltage for various rubbing angles with electrodes distances of (a) 11.5 μm and (b) 20 μm. Numbers on the upper left side represent rubbing angles.

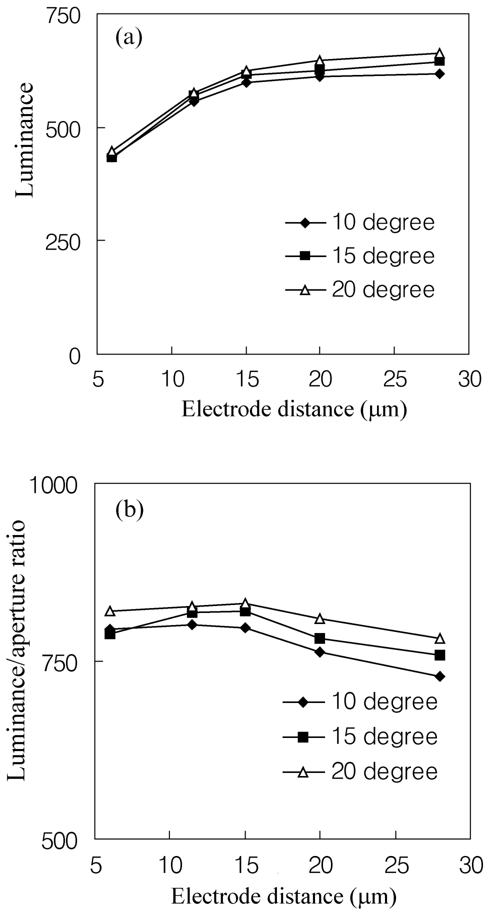

Figure 3. (a) Measured maximum luminance and (b) measured maximum luminance divided by aperture ratio for various rubbing angles and electrode distances. Numbers on the lower right side represent rubbing angles.

larger when electrode distance increases, as shown in Figure 3a. Maximum transmittance divided by aperture ratio shows decreasing trends as electrode distance increases, as shown in Figure 3b.

Figure 4 shows microphotographs of the IPS test sample for the condition of near low, medium and maximum transmittance when a driving voltage is applied. For the test sample with an electrode distance of 6 μm, the transmittance between electrodes is observed to change uniformly. For a test cell with electrode distance of 28 μm, transmittances are observed to increase more at the edge region than at the centre region between electrodes for voltage levels far from maximum transmittance.

3. Analysis

Field-induced LC movement was simulated by using commercial software (2dimMOS^{TM}, Autronic-Melchers GmbH), which uses the finite element method (*9*). Calculations were performed for the

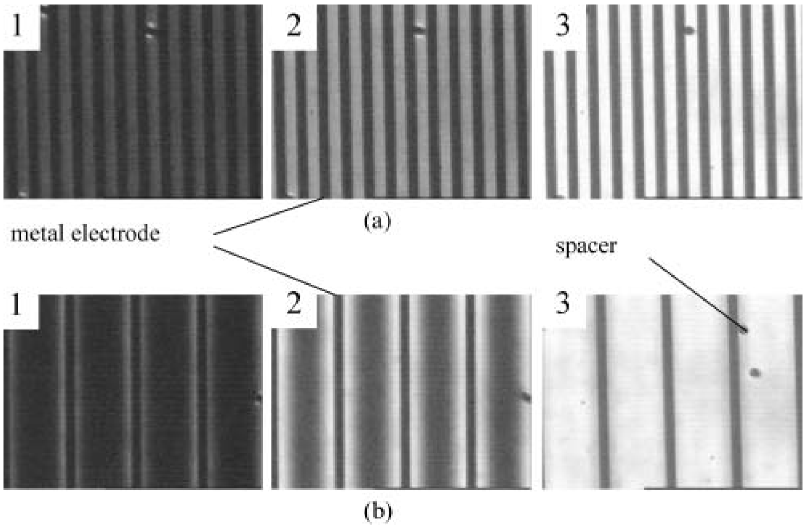

Figure 4. Microphotographs of LC test cell under applied voltages, where electrode distances are (a) 6 μm and (b) 28 μm. From left to right, the pictures show transmittance distribution change of test samples at (1) low grey level near voltage threshold, (2) middle grey, (3) white level. Dark lines and black dots represent metal electrodes and ball spacers.

two-dimensional cross-section of the *yz*-plane of Figure 1a, assuming infinite electrode length along the *x*-direction. Cell gap , electrode configuration and the material parameters for simulation were the same as those of the experiment. Calculated transmittance distributions along horizontal directions between electrodes are illustrated in Figure 5. LC directly on the top of the electrodes is little affected by a horizontal electric field. So regions of low transmittance exist on the top of electrodes. In the case of an electrode distance of 6 μm, transmittance increases until it reaches a maximum and then decreases uniformly. In the case of structure of an electrode distance of 28 μm, at low voltage, V1, LC near the electrodes starts to move first, whereas LC near centre positions between electrodes does not move. As voltage increases, different regions inside the LC cell do not reach maximum transmittance at the same time. These trends in the calculated results agree with the observations of Figure 4.

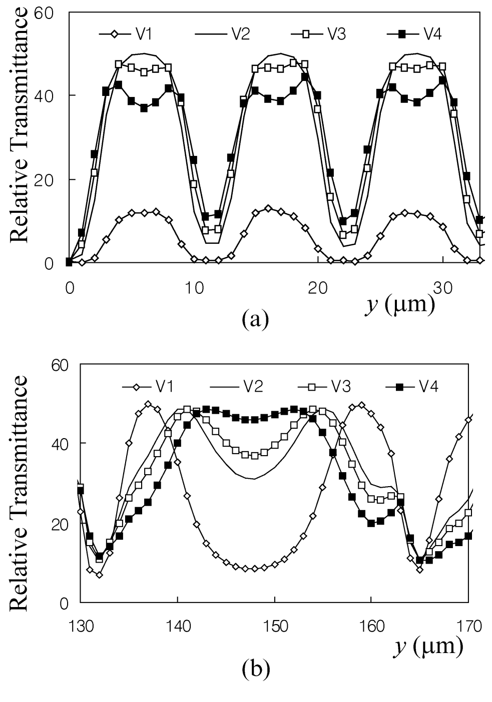

Figure 5. Simulated transmittance distribution as function of horizontal direction *y* for electrode distances of (a) 6 μm and (b) 28 μm for rubbing angle of 10°. Transmittance for four different voltage levels are represented, where V1<V2<V3<V4 and these voltage values are different for (a) and (b).

To understand the dependence of non-uniform transmittance on electrodes distance, the electric field distribution caused by the electrodes was derived and averaged along the *z*-direction normal to cell gap. The average electric field at three positions is shown in Figure 6b as a function of electrode distances. Position 1, 2 and 3 were selected as the position at the edge of the electrodes, 2.5 μm distance from the edge of the electrodes and the centre position between electrodes (see Figure 6a). Figure 6b reveals the trend that differences between local electric fields increase as the electrode distance increases. This local non-uniformity of electric field seems to cause the LC to rotate by different angles, especially for the case of the larger electrode distances.

The range of LC rotations driven by the electric field is confined between the electric field direction and the initial rubbing direction such that the sum of rubbing angle and LC rotation is less than 90°, where

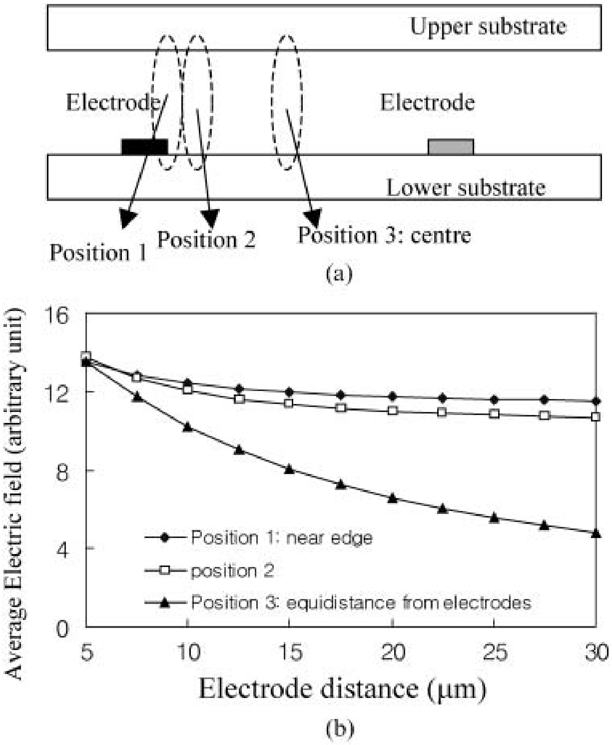

Figure 6. (a) Positions for average horizontal electric field inside LC cell and (b) the average horizontal electric field at these positions as a function of electrode distance.

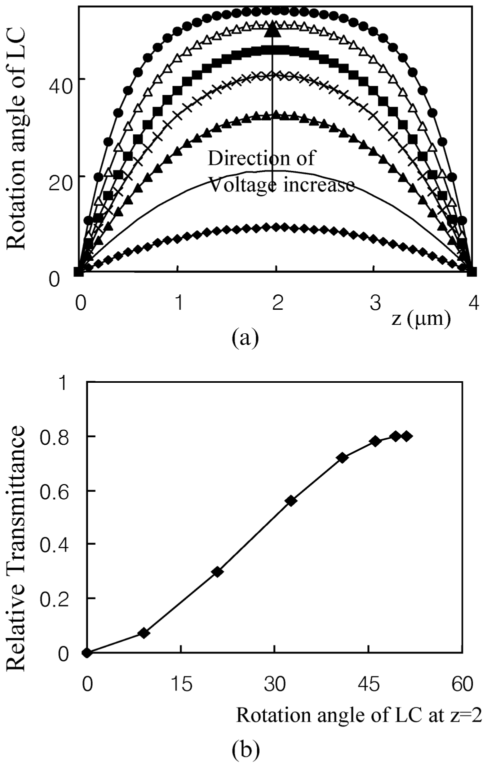

Figure 7. Simulated relation (a) between rotation angle of LC director and z under various driving voltage and (b) between relative transmittance and rotation angle of LC at $z=2\,\mu\text{m}$. Simulated condition is electrode distances of 28 μm, rubbing angle of 35° and steady step increase of driving voltage. The z-axis is defined as normal to the substrates, as illustrated in Figure 1.

rubbing angle is defined as the angle with respect to the direction of the electrode. LC does not rotate at the same angle along the z-direction as the strong anchoring at boundary layers causes twisting of LC alignment inside LC cell under a driving voltage. So, in a one-dimensional model of an IPS cell, maximum transmittance is known to occur when LC of the equal distance to the upper and lower boundaries rotates not 45°, but 50–55° from the initial alignment (*10*). If the rotation angle becomes larger than this angular range, the maximum transmittance decreases. The uniformity of electric field distribution between electrodes deteriorates as the electrode distance increases. Non-uniformity of the electric field distribution makes it difficult to control the local LC distribution for local maximum transmittance at the same driving voltage, as shown by Figures 4–5. So this implies that rotation angles of LC at localized positions should be kept to the range 50–55° beyond a specific voltage to obtain an improvement of maximum transmittance.

Figure 7 illustrates simulated LC rotation under various driving voltage and transmittance, for the configuration of electrodes distances of 28 μm and rubbing angle of 35°. As driving voltage steadily increases, the rotation angle of LC exhibits a saturating trend toward rotating angle of 55° where LC aligns parallel to the electric field. In this case, local LC distribution can be confined to approximately 55° by just applying the strong electric field and this matches the condition of maximum transmittance.

Figure 8 shows the simulated transmittance distribution for the same configuration as that for

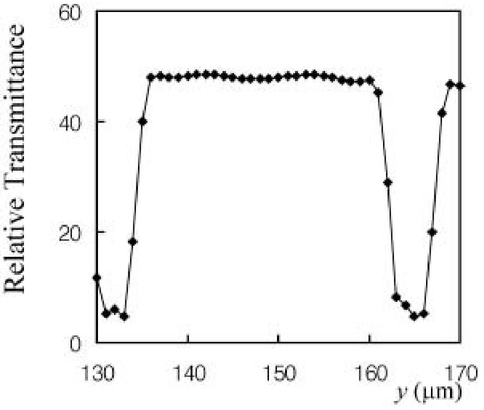

Figure 8. Simulated transmittance distribution near white level as function of horizontal direction y for electrode distance of 28 μm and rubbing angle of 35°.

Figure 7. A uniform improvement of transmittance distribution is observed compared with the condition of the same electrode distance and 10° rubbing, as illustrated in Figure 5b.

Maximum transmittance can be obtained by keeping the local transmittance distributions between electrodes at their maximum values. To obtain a uniform transmittance distribution under non-uniform electric field distribution, the rubbing angle should be larger. On the other hand, local maximum transmittance would decrease if rubbing angle is larger than 30–35° since the range of LC rotations cannot reach the 50–55° range no matter how strong the electric field is. Thus, rubbing angles in the range 30–35° seem preferable for electrode distances much larger than 15 μm for the purpose of maximizing transmittance.

4. Conclusion

The dependence of maximum transmittance on rubbing angle has been observed for IPS test cells; the dependence is related to the electrode distance. Non-uniformity of electric field distribution becomes noticeable for the case where electrode distance is much larger than the cell gap and electrode width. The dependency of maximum transmittance is explained in terms of LC rotation under a non-uniform electric field distribtuion.

To improve transmittance per unit area, configuraton for LC rotation are preferred to be made insensitive to local electric field variations. For this purpose, rubbing angles in the range 30–35° seem preferable for an electrode distance much larger than 15 μm.

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