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Study of High Tolerant Pixel Structure Due to Mispatterning of Electrodes for the Fringe-Field Switching Liquid Crystal Display

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A homogenously aligned liquid crystal device driven by fringe-electric field named as fringe-field switching mode, are being widely used for all kinds of liquid crystal displays due to its excellent wide viewing angle and high transmittance characteristics. One of the characteristics is the voltage-dependent transmittance (V–T), which strongly depends upon the pixel electrode width and distance between them. As a result, if pattern size of the pixel electrode at different positions is not the perfectly matched, the non-uniformity in transmittance does occur because field intensity to rotate liquid crystal would not be same at each and every pixel electrode. In this work, correlation between the size of electrode pattern and V–T characteristic has been carried out to get an optimized size of the electrode pattern in order to minimize the non-uniformity in the transmittance.

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1. Introduction

Recently, thin film transistor-liquid crystal displays (LCDs) are becoming popular, even in television market, owing to several wide-viewing angle technologies such as multi-domain vertical alignment (MVA),[1,2] in-plane switching (IPS),[3–5] and fringe-field switching (FFS)[6–9] modes. Among these technologies, the FFS device exhibits wide viewing angle and high transmittance at the same time, while other technologies generally have relatively low transmittance. Consequently, the FFS device is being adopted in most of the LCD applications, from small size mobile to large size television.[10]

Until now, there are many efforts to understand switching principle of the device and subsequently improvement in the electro-optical characteristics of the FFS device has been carried out. For example, light efficiency of the device depending on rubbing direction,[11] electrode structure,[12,13] cell's retardation,[14,15] cell gap[16,17] and dielectric anisotropy,[18] and image quality depending on dual domain[19] and configuration of polarizer with respect to optic axis of the liquid crystal (LC)[20] were reported. In addition to these, electrode structure associated with rubbing mura,[21] and reverse twist domain[22–24] were also reported.

In general, there are two transparent electrode layers in the FFS device. One is playing a role of common electrode with plane shape so called first indium–tin-oxide (ITO) and another slit shaped electrode is playing role of pixel electrode, so called second ITO. Therefore, the width (w) of slit and distance (l') between slits strongly affect electro-optic characteristics of the device and thus having uniform pattern of slit over whole display area is a key requirement in order to get homogeneous transmittance over whole display area. However, the electrode structures could be different from position to position in a real panel because of imperfect manufacturing process, and this causes transmittance to be different at different electrode's positions although the same voltage is applied.

In this paper, we investigate on the structure of pixel electrode through calculation and experiment, which causes the least non-uniformity in electro-optic characteristics although some change in w exists due to manufacturing imperfection. This work is highly important in a real mass production.

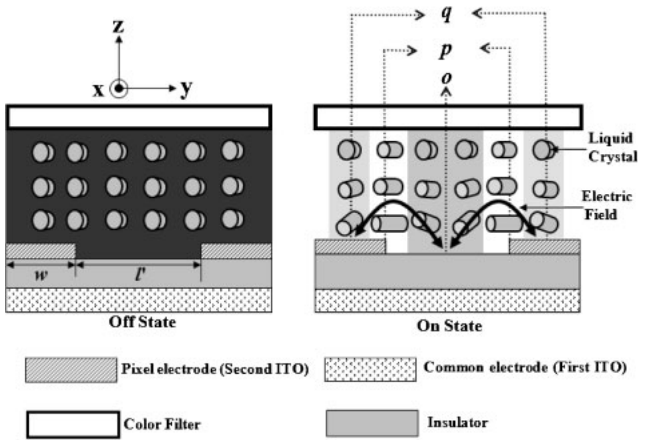

Fig. 1. Schematic of cell structure and configuration of the LC molecules in the off and on state of the FFS mode.

2. Switching Principle and Cell Structure of the FFS Mode

Figure 1 shows schematic of cell structure and configuration of the LC molecules in the off and on states of the FFS mode. In the off state, an optical axis of LCs is coincident with one of the transmission axis of the crossed polarizers and thus the device appears to be black at normal direction. When a voltage is applied, the LC directors tilt up and rotate almost in plane, giving rise to transmittance. This is quite different behavior from that of the IPS device in which mainly twist deformation occurs. The main difference comes from electrode structure. In FFS mode, both pixel and common electrodes exist on the bottom substrate with passivation layer between them and then the pixel electrode is patterned in the form of the slit. With this electrode structure, a fringe electric field of both horizontal (E_y) and vertical (E_z) components is generated when a bias voltage is applied. The interesting feature of FFS mode is that both

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field components E_y and E_z generate dielectric torque proportional to $|\Delta\varepsilon|E^2$, which in turn orients the LC in twist and tilt directions respectively. In addition, the field intensity and thus the dielectric torque changes periodically along the electrodes and hence, the LC molecular orientation in on state is strongly dependent on electrode-position as shown in on state of Fig. 1. As a result, the LC at position p has higher twist angle than those at o and q positions. In other words the LC orientation at different positions of pixel electrode is not same due to the different corresponding electric field intensity. Also the electric field intensity is much larger near bottom substrate and keeps on decreasing towards the top substrate. Therefore the LC orientation also varies in vertical direction such that the LC closer to bottom signal substrate has larger tilt and twist angles than that near top substrate.

In general, when the uniaxial medium exists under crossed polarizer, the normalized transmittance of a device can be described by

$$T/T_0 = \sin^2 2\varphi(V) \sin^2[\pi \Delta n(V) d/\lambda], \quad (1)$$

where φ is voltage-dependent rotational angle of the LC from polarizer axis, Δn is voltage-dependent effective birefringence of the LC layer, d is cell gap, and λ is wavelength of incident light. In the FFS device, φ is mainly determined by competition between elastic free energy of the LC and E_y while effective Δn is determined by competition between elastic free energy of the LC and E_z. However, the field intensities E_y and E_z in each electrode position are strongly influenced by w and l' between them, i.e., if the w and l' are not uniform over whole displayed area, the LC orientation in on state will be different from position to position, causing non-uniformity in transmittance.

3. Simulated and Measured Results and Discussion

For the calculation, a computer simulation was performed using commercially available software 2Dimos (Autronic Melchers). Here, the thickness of first and second ITO is 400 Å, and passivation thickness with dielectric constant of 5.6 is 0.6 μm. The physical properties of LC are as follows: dielectric anisotropy $\Delta\varepsilon = 8.2$, $\Delta n = 0.0987$, elastic constants $K_{11} = 9.6$ pN, $K_{22} = 5.8$ pN, $K_{33} = 11.6$ pN, rotational viscosity $\gamma = 84$ mPa·s. The cell has boundary conditions such that the pretilt angle is 2°, initial rubbing angle is 83° with respect to E_y, and the cell gap is 3.8 μm.

Figure 2 shows variation of the transmittance in each structure with changing w, in which w varies from 0.5 μm to $w + l' - 0.5$ μm while keeping $w + l'$ equal to 6, 7, 8, 9, 10, 11, 12, and 13 μm. For instance of $w + l'$ equal to 6, w is changed from 0.5 to 5.5 μm and the transmittance change is calculated. As the non-uniformity in luminance from position to position can be well detected by human eyes at low gray levels, hence the low voltage of 2 V was employed for a computer simulation. As indicated, the electrode condition showing maximal transmittance only at a certain w (hereafter it will be referred as peak w) and value of peak w changes with change in the value of $w + l'$. Also the full width at half maximum (FWHM) is strongly dependent on $w + l'$, that is, when the $w + l'$ is larger, it becomes larger

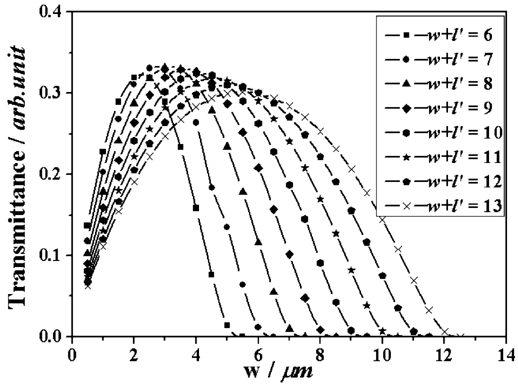

Fig. 2. Calculated transmittances variation of each electrode structure with changing w at 2 V.

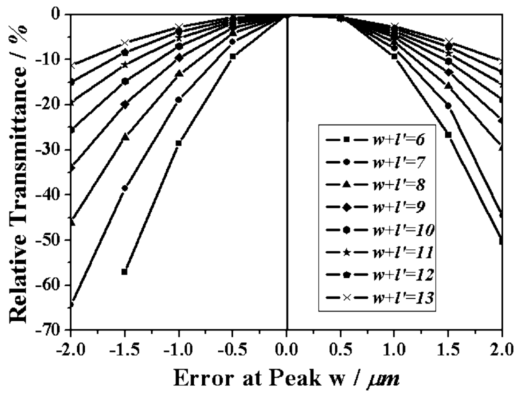

Fig. 3. Relative transmittances according to error at peak w of Fig. 2.

and the transmittance change is observed to be less for large value of $w + l'$. This implies that the change in transmittance is very much sensitive to the manufacturing process or patterning of the electrodes, especially when the low value of $w + l'$ is used.

In order to find out the sensitivity of transmittance change according to the mis-patterning of the w, relative transmittance change $\Delta T/T_{max}$ according to error at peak w is calculated from Fig. 2. Here, ΔT is defined as maximum transmittance (T_{max}) in peak w minus transmittance at each $w + l'$. As presented by Figs. 2 and 3, one can notice that once we target electrode structure showing maximal transmittance at peak w, the transmittance change from position to position could occur from mis-patterning of w. However, the data clearly shows that, if $w + l'$ is larger, the FWHM becomes larger, which indicates that the transmittance change is lower for $w + l' = 13$ μm than that for $w + l' = 6$ μm, for example, when error at peak w is 2 μm, it is 10 and 50% for $w + l'$ equal to 13 and 6 μm, respectively. Conclusively speaking, in order to minimize non-uniformity resulted from mismatching of w in the LCD panel, electrode structure with large $w + l'$ and w close to the maximal transmittance is favorable.

In order to confirm the validity of the calculated results, 10.4″ XGA thin-film-transistor FFS LCD was made. Figure 4 shows schematic of the device with different sets of $w - l'$, in each area for the device. Here, 2−3 means that w is 2 μm and l' is 3 μm. Two pairs of the $w - l'$ mean that

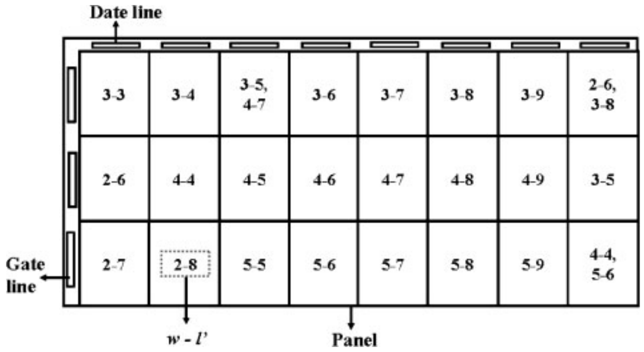

Fig. 4. Schematic of the 10.4″ XGA LCD with different $w + l'$ sets in each area.

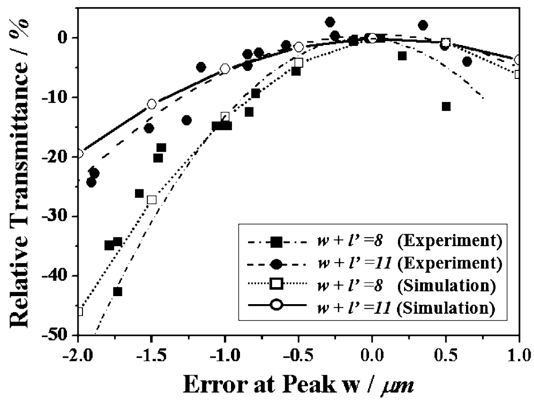

Fig. 5. Measured and calculated relative transmittances according to error of the peak w in two electrode structures ($w + l' = 8$ and 11 μm) at 2 V. The solid and dotted lines are polynomial fitted lines.

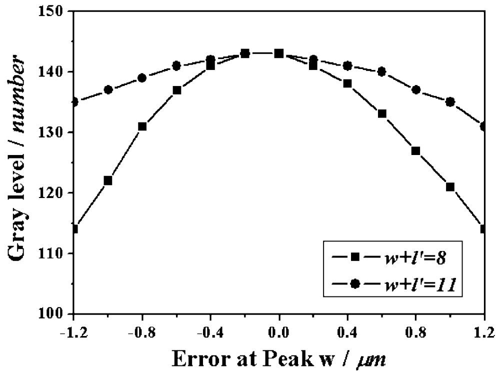

Fig. 6. Change in gray level according to error of the peak w for two different electrode structures ($w + l' = 8$ and 11 μm) at 2 V.

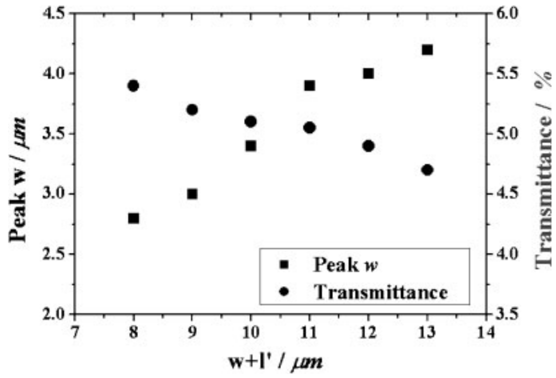

Fig. 7. Measured peak w and transmittance in each $w + l'$ structure.

two different structures are designed in the particular designated area. After fabricating panel, we measured real w of each site in seven panels using microscope. We also measured voltage dependent transmittance (V–T) curves and response time of these panels, using LCD 7000 (Otsuka).

Figure 5 shows measured and calculated relative transmittances according to error of the peak w for two electrode structures ($w + l' = 8$ and 11 μm) at the applied voltage of 2 V. As indicated, each case has maximal transmittance at a particular w and shows relative transmittance variation with changing w in both simulation and experiment results. Both calculated and experimental results confirm that when $w + l' = 11$ μm, the relative transmittance variation is less than that in case of $w + l' = 8$ μm, supporting our arguments.

In order to visualize the transmittance change according to the w variation, gray level according to the change of w for two different electrode structures at 2 V is calculated, which is defined as

$$\text{Gray level} = \text{integer}\ [256 \times (T/T_{\max})^{1/2.2}], \qquad (2)$$

where T is transmittance in each w and $T_{\max}$ is maximum transmittance at the peak w. Through Fig. 6, we can realize that the electrode structure with large $w + l'$ has a less variation in grey levels compared to that with small $w + l'$. It means that larger $w + l'$ has more advantageous than smaller $w + l'$ to achieve a better uniformity in gray level when mis-patterning is considered in a real panel.

The physical explanations of why one structure shows less transmittance variation than other structures near peak w are as follows. When the length of w and l' change, the distribution of electric field lines also change, and thus the reorientation of the LC changes according to the electrode position, resulting in the transmittance change. The intensity of E_y which rotates the LC is strongest at the edge of electrodes position p in Fig. 1 and the transmittance is the highest at position p compared to other electrode positions. In addition, the rotating angle of the LC director at electrode position o and q is determined by twist angle of the neighboring molecules. Therefore, for a structure with smaller $w + l'$ the transmittance portion for position o and q will be larger compared to the electrode structure with larger $w + l'$ and also the transmittance at electrode position o and q is more influenced by rotating angle of the LC director at position p in the structure with small $w + l'$ than in that of large $w + l'$. Consequently, the small change in w from the original target w will cause stronger transmittance change in the structure with smaller $w + l'$ than that of the structure with larger $w + l'$, causing more sensitivity in the transmittance change according to the electrode w change in the electrode structure with smaller $w + l'$.

Figure 7 shows measured transmittances at operating voltage and the optimal peak w at each $w + l'$. As $w + l'$ increases, the value of peak w increases but the transmittance decreases, though the operating voltage remains almost constant ~4 V. Based on the data, one can understand that the higher transmittance can be achieved with the

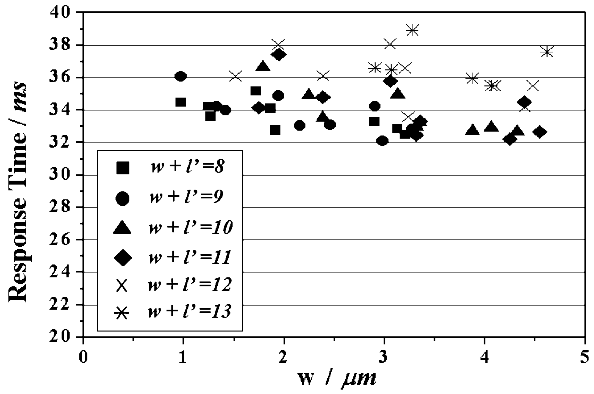

Fig. 8. Measured response time (80% change rate) according to w in each $w + l'$ structure.

electrode structure of smaller $w + l'$, but better uniformity in displayed image can be obtained with the electrode structure of larger $w + l'$, resulting in better production yield possibly.

Finally, the response times (80% change rate) according to w for each $w + l'$ structure was measured as shown in Fig. 8. The response times was not strongly dependent on the change of electrode structure, which indicates that the electrode structure can be chosen in terms of high transmittance or better uniformity from position to position in one displayed image of LCD.

4. Conclusions

We have studied on pixel structure of the FFS-LCD having high tolerant electrode structure which shows less non-uniformity in V–T curve from position to position although there is difference in electrode width and electrode distance depending on panel positions. Our research shows that the V–T curves of the electrode structure with large value of $w + l'$ exhibits better uniformity in gray level. However the low value of $w + l'$ shows higher transmittance. This work is of interest for LCDs' research in order to get better uniformity in transmittance in tune with high transmittance at particular value of $w + l'$. The design rule is still valid even though other cell parameters such as cell thickness, LC, and driving conditions are changed.

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