A high transmittance and fast response in-plane switching liquid crystal display with the zero-azimuth anchoring layers on the electrodes

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Abstract

An in-plane switching (IPS) liquid crystal display (LCD) containing the zero-azimuth anchoring layers formed only on the electrodes and rubbed polyimide (PI) covered on the other areas was successfully developed. This configuration was realized using photoreactive PI with photo-radical generation units and the mask exposure technique. The maximum transmittance ($T_{\text{max}}$) of this LCD was 1.12 times higher than that of a conventional IPS LCD. This was attributed to a large aperture in the voltage-on state because the nematic liquid crystals (NLCs) on the electrodes were barely anchored to the surface, such that the NLCs could be rotated by applying a small in-plane electric field above the electrodes, and by an elastic torque caused by the twisted NLCs between the electrodes. Furthermore, the response times of this LCD were equivalent to those of a conventional IPS LCD because the NLCs between the electrodes quickly recovered to their initial orientation after removing the electric field, and the NLCs on the electrodes followed this movement. This novel LCD is termed a ‘partially zero-azimuth anchoring IPS (PZ-IPS) LCD’, which is the first practical LCD utilizing these weak anchoring characteristics in the history of LCDs.

Keywords: liquid crystal display, in-plane switching, zero-azimuth anchoring, photoreactive polyimide, response time

(Some figures may appear in colour only in the online journal)
1. Introduction

The liquid crystal display (LCD) industry is maturing, and organic light-emitting diode (OLED) displays are now practically used as television and smartphone displays [1]. LCDs and OLED displays are in a fierce competition to dominate the flat panel display market. Therefore, the LCD industry must develop new and innovative LCDs for practical applications to maintain a competitive edge in the flat panel display market.

Anchoring between the nematic liquid crystals (NLCs) and the interface is indispensable in all the LCDs that are currently employed in practical applications. A uniform orientation of the NLCs in their initial orientation and recovery to the initial NLC orientation after the removal of an applied electric field are achieved by strong anchoring between the NLCs and interface. However, no anchoring between the NLCs and interface can enable realizing LCDs that possess unique characteristics, such as ultra-low-voltage driven and memory-type LCDs [2–4].

We have previously succeeded in producing a stable zero-azimuth anchoring interface using a high-density, concentrated brush of poly(n-hexyl methacrylate) (PHMA) and application-type PHMA bottlebrush polymers over a broad temperature range that spanned from room temperature to the nematic-isotropic transition temperature (≃20 °C–110 °C) [5–7]. An anchoring force in the direction of an azimuthal angle does not exist in the zero-azimuth anchoring state, although a force exists in the angular direction [4]. The zero-azimuth anchoring state is realized when the twist anchoring coefficient $A_2$ is less than approximately $10^{-6}$ J m$^{-2}$ [5–7].

We developed a one-side zero-azimuth anchoring in-plane switching (OZ-IPS) LCD based on the above-mentioned results by placing the zero-azimuth anchoring material and a strong anchoring material (rubbed polyimide: RPI) on the electrode substrate and counter substrate, respectively [7, 8]. The OZ-IPS LCD which was enhanced the optical design and utilized negative NLCs exhibited 1.3 times or more higher maximum transmittance ($T_{\text{max}}$) than a conventional IPS LCD [9–11], as well as a high contrast ratio that was equivalent to a vertical alignment LCD (VA LCD) [12, 13]. An optical simulation demonstrated that the OZ-IPS LCD exhibited the highest transmittance in the history of LCDs. Furthermore, the higher transmittance of OZ-IPS LCDs was also confirmed for practical TFT LCD (19.5 inch, 1280 × 720 pixels), which exhibited 30% higher luminance than a conventional IPS TFT LCD [7]. However, a considerable drawback of OZ-IPS LCDs is their longer response time in the voltage-off state ($\tau_{\text{off}}$) compared to that of conventional IPS LCDs, which caused by the higher transmittance of OZ-IPS LCDs [7, 8]. Such a configuration enables the following functions: (1) homogeneous orientation of the NLCs parallel to the rubbing direction in the electric field off state; (2) guaranteed high transmittance characteristics because the NLCs on the comb-shaped electrodes, as well as between the electrodes, rotate when applying an electric field; and (3) rapid recovery of the NLCs to their initial orientation after removing the electric field due to the effect of the strong anchoring material formed on the counter substrate and between the comb-shaped electrodes. The improved OZ-IPS LCDs are termed ‘partially zero-azimuth anchoring IPS (PZ-IPS) LCDs’. Figure 1 illustrates the conceptual diagram of the PZ-IPS LCDs.

The $\tau_{\text{off}}$ and transmission efficiency (TE) of the PZ-IPS, OZ-IPS, and conventional IPS LCDs were compared via simulations (LCD Master 2D; Shintech. Inc., Japan). TE is defined as the ratio of $T_{\text{max}}$ to the transmittance measured by setting two polarizers parallel to each other. The lines and spaces of the comb-shaped electrodes, and the cell gap were set to 4 and 10 µm, and 2.9 µm, respectively, in the simulations. MLC-3019, Merck, (refractive index anisotropy: $\Delta n = 0.1037$; dielectric anisotropy: $\Delta \varepsilon = 9.9$; elastic constants: $K_{11} = 11.9$ pN, $K_{22} = 6.8$ pN, $K_{33} = 13.6$ pN; rotational viscosity: $\gamma_1 = 71$ mPa s) was used as the NLC. The simulation results yielded $\tau_{\text{off}}$ values of 13.0, 37.4, and 11.6 ms for the PZ-IPS, OZ-IPS, and conventional IPS LCDs, respectively. The $\tau_{\text{off}}$ of the PZ-IPS LCD was much shorter than that of the OZ-IPS LCD, and similar to that of the conventional IPS LCD. The TE values of the PZ-IPS and OZ-IPS LCDs were 1.12 and 1.24 times higher than that of the conventional IPS LCD, respectively. Continually, to validate our concept, we tried to form the zero-azimuth anchoring material only on comb-shaped electrodes by using an inkjet printer. Though the PZ-IPS panel fabricated by this method was confirmed a significant reduction in $\tau_{\text{off}}$ compared with the OZ-IPS panel, it took very long time to form the zero-azimuth anchoring material only on the comb-shaped electrodes in millions of pixels using the inkjet printer. It was impossible to apply this method to mass production process.

We selected the production method where the zero-azimuth anchoring material monomers dissolved in NLCs were only polymerized onto the comb-shaped electrodes as the PZ-IPS production method that is applicable to the LCD mass-production process. This process can be realized in the following way. Photoreactive PI with photo-radical generating units and conventional RPI are formed on the electrode substrate and counter substrate, respectively. Only the photoreactive PI between the comb-shaped electrodes is exposed to ultraviolet light and polymerized by ultraviolet (UV) light.
configuration, respectively. In PZ-IPS LCDs, the NLCs are homogeneously aligned, parallel to the rubbing direction in the voltage-off state. In the voltage-on state, the NLCs on and between the comb-shaped electrodes transit to a continuous twisted configuration and a double twisted configuration, respectively.

Figure 1. Conceptual diagram of PZ-IPS LCDs. The left and right figures show the alignment of NLCs at the voltage-off and -on states, respectively. In PZ-IPS LCDs, the NLCs are homogeneously aligned, parallel to the rubbing direction in the voltage-off state. In the voltage-on state, the NLCs on and between the comb-shaped electrodes transit to a continuous twisted configuration and a double twisted configuration, respectively.

3. Experimental procedure

The PZ-IPS, OZ-IPS, and conventional IPS panels were fabricated for comparison to demonstrate the above-mentioned concept, with the schematics of the PZ-IPS, OZ-IPS, and conventional IPS panels shown in figures 2(a)–(c), respectively. These panels comprised electrode and counter substrates on which were formed the indium-tin oxide (ITO) comb-shaped electrodes (55 nm thick; lines and spaces were 4 and 10 μm, respectively) and 2.9 μm photo spacers, respectively. The electrode substrate was coated with photoreactive PI (RN-4101; Nissan Chemical) in the PZ-IPS panel, which had photo-radical generating units and was designed to lose the photo-radical generating function when UV rays over a certain integrated light quantity irradiated its surface. RN-4101 was first rubbed in the direction that was tilted 20° with respect to the comb-shaped electrodes. UV light (peak wavelength: 365 nm) with an integrated light quantity of 5 J cm⁻² then irradiated only the RN-4101 between the comb-shaped electrodes using a photomask that shielded UV light from the comb-shaped electrodes. The counter substrate was coated with conventional PI (AL-16301; JSR) rubbed in the direction that was tilted 20° with respect to the comb-shaped electrodes. A positive NLC (MLC-3019; Merck) that was dissolved using 10 wt% hexyl methacrylate (HMA) was injected between the two substrates via capillary action at ambient temperature. An isotropic treatment was performed on the panel at 120 °C for 10 min, followed by UV irradiation (peak wavelength: 365 nm) with the integrated light quantity of 3.9 J cm⁻² onto the entire panel from the rear side of the electrode substrate. Radicals were generated on the RN-4101 surface on the comb-shaped electrode. A chain polymerization of HMA monomers was initially formed from the radical-generating component with the zero-azimuth anchoring material (PHMA) only forming on the comb-shaped electrodes. Figure 2(d) shows the conceptual diagram of PZ-IPS LCD manufacturing process used in this study.

The PHMA bottlebrush polymers [7] and rubbed PI (AL-16301; JSR), with the rubbing direction tilted 20° with respect to the comb-shaped electrodes, were formed on the electrode and counter substrates, respectively, of the OZ-IPS panel. The same NLCs that were used in the PZ-IPS panel (MLC-3019 mixed with 10 wt% HMA) were injected into the OZ-IPS panel. PI (AL-16301; JSR) was coated on the electrode and counter substrates of the conventional IPS panel, with the rubbing direction tilted 20° with respect to the comb-shaped electrodes. NLCs (MLC-3019) were then injected into the conventional IPS panel. Each of the fabricated panels was placed between a linear polarizer (P) and an analyzer (A), which were arranged with crossed Nicols, and the P was placed on the rear side of the electrode substrate, with its axis parallel to the rubbing direction. Melles Griot 03 FPG 003 Dichroic Sheet Polarizers were used for both P and A.

The electro-optical properties of these three types of panels were examined using an Otsuka Electronics LCD-5200 instrument. Polarized optical microscopy (POM) observation was performed using the Olympus BX50P microscope.

4. Results and discussion

Figure 3(a) compares the voltage–transmittance (V–T) curves of the three panels at 25 °C. The transmittance began to increase at the threshold voltage (V_{th}) as the applied voltage (V_{appl}) increased, and it eventually reached the T_{max} at V_{appl} = V_{max}. The V_{max} and T_{max} values of the PZ-IPS, OZ-IPS, and conventional IPS panels were 7.2 V and 8.91%, 5.2 V and 9.93%, and 7.2 V and 7.97%, respectively. The V_{max} value of the PZ-IPS panel increased by approximately 1.4 times compared to that of the OZ-IPS panel and was equivalent to that of the IPS panel owing to the strong anchoring material between the comb-shaped electrodes in the PZ-IPS panel. The T_{max} value of the PZ-IPS panel was 1.12 times higher than that of the conventional IPS panel. This was consistent with the value obtained via simulation and was estimated to be approximately the same as that of fringe-field switching (FFS) LCDs [14].
and slightly lower than that of twisted nematic (TN) LCDs [15]. The higher $T_{\text{max}}$ value of the PZ-IPS panel compared to that of the conventional IPS panel can be attributed to a large aperture in the voltage-on state. Given that the FFS mode only provides superior transmittance for high-resolution LCDs (i.e. in smartphone applications), the PZ-IPS mode is suitable for television displays. Figures 3(b) and (c) show POM images of the PZ-IPS and conventional IPS panels, respectively, with an applied voltage of $V_{\text{max}}$ at room temperature. The PZ-IPS panel transmitted light more than the conventional IPS panel on the comb-shaped electrodes. The electric field in the in-plane direction above the electrodes is too small to rotate the direction of the NLCs that are strongly anchored to the RPI surface in the conventional IPS panel. However, the NLCs on the comb-shaped electrodes in the PZ-IPS panel, which were barely anchored to the PHMA, could be rotated via a small in-plane electric field above the electrodes and the resulting elastic torque caused by the twisted NLCs between the electrodes.

On the other hand, the $T_{\text{max}}$ value of the PZ-IPS panel was 10% lower than that of the OZ-IPS panel. The transmittance distributions in the PZ-IPS and OZ-IPS panels calculated during the simulations (LCD Master 2D; Shintech. Inc., Japan) are shown in figure 4(a). It can be confirmed that the transmittance on the comb-shaped electrodes in the PZ-IPS panel is lower than that in the OZ-IPS panel. A comparison of the rotation angles of the NLCs just above the comb-shaped electrode and at the center of the cell gap on the comb-shaped electrode indicates that those of the PZ-IPS panel were both smaller than those of OZ-IPS panel (figures 4(b) and (c)). The NLCs on the comb-shaped electrodes in the PZ-IPS panel could not rotate the director direction as much as those in the OZ-IPS panel because the NLCs beside the comb-shaped electrodes were strongly anchored to the RPI surface in the
PZ-IPS panel. From the simulation results, the twist angles of the NLCs at the edge and center of the comb-shaped electrodes in the PZ-IPS and the OZ-IPS panels were estimated to be approximately 35° and 31°, and 50° and 34°, respectively. Because the twist angle of the NLCs in the PZ-IPS panel was smaller than that in the OZ-IPS panel, the rotation angle of the polarization plane of incident linearly polarized light in the PZ-IPS panel became smaller than that in the OZ-IPS panel. Consequently, the transmittance on the comb-shaped electrodes of the PZ-IPS panel decreased compared with the OZ-IPS panel. Herein, the optical design that maximized the $T_{\text{max}}$ value of the OZ-IPS panel was applied to the PZ-IPS panel in this study. The $T_{\text{max}}$ value of the PZ-IPS panel is expected to increase if the retardation value $\Delta n d$, and the lines and spaces of the comb-shaped electrodes of the PZ-IPS panel are optimized for the PZ-IPS structure.

The response times of the PZ-IPS panel were greatly shortened compared to those of the OZ-IPS panel, as expected. When $V_{\text{appl}}$ was set to $V_{\text{max}}$ for the PZ-IPS (7.2 V), OZ-IPS (5.2 V), and conventional IPS (7.2 V) panels, the $\tau_{\text{on}}$ and $\tau_{\text{off}}$ values at 25 °C were 5.8 and 9.0 ms, 10.4 and 13.8 ms, and 5.7 and 8.6 ms, respectively. The response characteristics of the three panels are shown in figure 5 with similar $\tau_{\text{on}}$ and $\tau_{\text{off}}$ response behaviors for the PZ-IPS and conventional IPS panels. The $\tau_{\text{on}}$ state of LC panels with a weak anchoring surface is expressed by the following equation [16]:

$$\tau_{\text{on}} = \frac{\gamma_1}{|\varepsilon_0| \Delta \varepsilon |E^2 - 2 W/d|} = \frac{\gamma_1}{|\varepsilon_0| \Delta \varepsilon (V/l)^2 - 2 W/d},$$  

(1)

where, $\varepsilon_0$ is the dielectric constant in a vacuum, $E$ is the electric field intensity, $V$ is the voltage, $l$ is the space between the comb-shaped electrodes and $W$ is the anchoring energy on the LC-alignment layer surface. Shorting $\tau_{\text{on}}$ of the PZ-IPS panel compared to that of the OZ-IPS panel is mainly attributed to the increase of $V_{\text{max}}$ value (7.2 V and 5.2 V for the PZ-IPS and OZ-IPS panels, respectively). On the other hand, the $\tau_{\text{off}}$ of the LC panels with a very weak anchoring surface is inversely proportional to $W$, as expressed by equation (2) [16].

$$\tau_{\text{off}} \propto \frac{\gamma_1 d}{W}.$$  

(2)

Because the PZ-IPS panel had a smaller zero anchoring material application area on the electrode substrate compared with OZ-IPS LCD, the $\tau_{\text{off}}$ value of PZ-IPS panel was significantly reduced compared to that of OZ-IPS panel. In addition, the NLCs between the comb-shaped electrodes quickly recovered to their initial orientation after removing the electric field, as those on the comb-shaped electrodes followed this movement, yielding $\tau_{\text{off}}$ of the PZ-IPS panel that were equivalent to that of the conventional IPS panel. The above-mentioned results show that PHMA layers formed on the comb-shaped electrodes had the same functionality as PHMA.
Figure 4. (a) Calculated transmittance distribution in the PZ-IPS (solid line) and OZ-IPS (broken line) panels from the simulations (LCD Master 2D; Shintech, Inc., Japan). The transmittance of the two polarizers at parallel Nicols was set to 50% in the simulations. The comb-shaped electrode is located at 5–9 µm on the horizontal axis. Calculated distribution of NLC rotation angles in the (b) PZ-IPS and (c) OZ-IPS panels from the simulations (LCD Master 2D; Shintech, Inc., Japan). The circles (●) and triangles (△) indicate the rotation angles with respect to the rubbing direction of the NLCs in the vicinity of the electrode substrate and in the center of the cell thickness, respectively. The comb-shaped electrodes are located at 5–9 µm on the horizontal axis in both figures. In the OZ-IPS panel, the NLCs near the electrode substrate rotate to the electric field direction both on and between the comb-shaped electrodes, whereas, in the PZ-IPS panel, the NLCs near the electrode substrate rotate to the electric field direction only on the comb-shaped electrodes.

Figure 5. Response characteristics of the PZ-IPS (circles), OZ-IPS (triangles), and conventional IPS (squares) panels for the (a) voltage-on and (b) voltage-off states against the applied $V_{\text{max}}$, measured at 25 °C. The transmittance is normalized, with the maximum transmittance of each panel set to 100%. The voltage was applied after 5 ms in (a) and removed after 5 ms in (b).
brushes and the application-type PHMA bottlebrushes, as expected. Though further systematic investigations on PHMA layers are necessary, the PHMA layers are assumed to offer the zero-azimuth anchoring surface to NLCs by the same mechanism as PHMA brushes and the application-type PHMA bottlebrushes [6–8].

5. Conclusions

In summary, we successfully shortened the response times of the OZ-IPS LCDs by only forming the zero-azimuth anchoring layers on the comb-shaped electrodes. We termed the improved OZ-IPS LCDs ‘partially zero-azimuth anchoring IPS (PZ-IPS) LCDs’. The $T_{\text{max}}$ value of the PZ-IPS panel was 1.12 times higher than that of the conventional IPS panel and equivalent to that of the FFS panel. The response times of the resultant PZ-IPS panel were greatly shortened compared to those of the OZ-IPS panel, as expected, and similar to those of the conventional IPS panels. Conversely, the response times of the PZ-IPS panel were greatly shortened compared to those of the OZ-IPS panel, as expected, and similar to those of the conventional IPS panels because the NLCs between the comb-shaped electrodes quickly recovered to the initial direction after removing the electric field and the NLCs on the comb-shaped electrodes followed this movement.

This PZ-IPS LCD is the first practical LCD that utilizes these weak anchoring characteristics in the history of LCDs, and is suitable in television displays where high transmission, superior moving image quality, and wide viewing-angle characteristics are required. The PZ-IPS LCD greatly contributes to reducing the power consumption of the display and becomes a powerful tool for the LCD industry to compete with the OLED industry. Future research directions include increasing the mass productivity and improving the reliability of the PZ-IPS LCDs, such as reducing the accumulated light amount of UV light and residual monomers, toward the commercialization of PZ-IPS LCDs.

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Conflicts of interest

The authors declare no conflicts of interest.

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