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Optimized electro-optical properties of polymer-stabilized vertical-aligned liquid crystal displays driven by an in-plane field

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ABSTRACT

Polymer networks are employed in vertical-aligned liquid crystal (LC) cells to stabilize the LC molecular configuration under the in-plane field driving. Two different polymer morphologies, respectively produced by the monofunctional and bifunctional acrylate monomers, are assembled on the glass-substrate surface. The enhanced electro-optical performance is observed on the LC cell with bifunctional acrylate polymer networks, and the appropriate display cell is developed at an optimum concentration of 2 wt%. This type of polymer-LC cell shows the fast turn-off and turn-on responses at the low driving voltage, which are attributed to the strong anchoring and the stable LC reorientations, respectively. Furthermore, around 30% improvement in the gray-level response on the 2-wt%-TA-9164-polymer-LC cell is successfully achieved, as compared to the pure LC cells.

1. Introduction

Liquid crystal displays (LCDs) have been widely used since they possess many attractive properties such as their low operating voltage, low power consumption, and thinness. However, the slow response of liquid crystal (LC) molecules is regarded as the major drawback of LCDs in dynamic display applications [1,2]. In the various advanced display modes, in-plane switching (IPS) [3,4], multi-domain vertical alignment (MVA) [5], and patterned vertical alignment (PVA) [6] display modes are dominant technologies in the current LCD industry because they provide a superior wide viewing angle. The conventional IPS display mode usually involves the rubbing process to effectively govern the arrangement of the LC molecules during cell fabrication [7]. After long-term driving in the IPS mode, an irreversible director deviation of LC molecules from surface polyimide alignment causes a reduction in the quality of the contrast ratio (CR) [8]. The VA-type LCDs without the rubbing process exhibit a high CR because the LC molecules are vertically aligned against the substrates with an excellent dark state, but such an alignment of negative dielectric anisotropy LC (negative LC) leads to a longer response time [9]. The turn-on time (τ_r) can be reduced by applying high voltage via the overdriving method [10], but sophisticated driving schemes must be employed. The turn-off time (τ_d) is only related to the cell gap thickness and material parameters of the negative LC, such as rotational viscosity and the bend elastic constant [9] (although the gray-level τ_d responses can be improved by an under-shooting driving method). The negative LC, which usually has higher viscosity, is disadvantageous to the τ_d and more expensive than the positive LC. To eliminate the drawbacks of VA-type LCDs, the VA-IPS display mode using the positive LC has been proposed in order to realize good electro-optical properties and fast response times [11–13].

Polymers have been employed in forming the surface pretilt direction of LCs to improve the turn-on time τ_r in the MVA, PVA, and VA-IPS modes [14–18]. However, the polymer stabilized pretilt angle may deteriorate the turn-off response time τ_d and cause light leakage in the dark state, which will sacrifice the high CR. Recently, Lee et al. produced a 3D polymer network in a VA cell during the process of polymerization [19]. The volume polymer anchoring reduced τ_d, but a very high driving voltage (~80 V) is required to obtain a fast τ_r. Generally, the in-cell polymer networks form the anchoring with respect to the substrate surface in order to improve the switching process of the LC cell, while the adverse effect on the electro-optical properties such as the transmittance, threshold voltage (V_{th}), and on-state voltage may be revealed [20]. This indicates that the electro-optical properties of the LC cell with polymers require optimizing.

In this paper, to realize superior electro-optical characteristics for information display devices, VA-IPS LC cells with polymer

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networks are fabricated. The polymer networks used here enhance the anchoring effect on the LC molecular reorientation, and thus provide satisfactory electro-optical performance for this display mode due to the well-controlled concentration of the selected monomer. The higher concentration doping can significantly enhance the response time, but it also gives rise to the sacrificed transmittance and increased on-state voltage. Thus trade-offs between the monomer concentration and electro-optical properties are needed to improve the performance of VA-IPS LCDs.

2. Material and device fabrication

In this study, VA-IPS LC cells were driven by indium-tin-oxide (ITO) interdigital electrodes, which were processed on the bottom glass-substrate surface. The electrode width (w) was 4 μm and the period was 12 μm. Both the top and bottom glass substrates were coated with the VA polyimide (AL60101L) and heated at 200 °C for 1 h. After that, 4-μm glass spacers were used to control the cell gap (d) of the assembled substrates. The LC E7 ($\Delta n = 0.2179$, and $\Delta\varepsilon = +14.5$, from Merck) and monomers (UCL002 with monofunctional acrylate from DIC Corp. and TA-9164 with bifunctional acrylate from Tatung University) were mixed and then injected into the assembled cell by capillary action. The mixed concentration, which is defined as the ratio of monomer weight to the sum of monomer and LC weight, is approximately 2 wt%. In addition, higher mixed concentrations of 4 wt% and 5 wt% were only produced using the TA-9164 monomer in order to further investigate the electro-optical properties of cell. These cells were illuminated with ultraviolet (UV) light (365 nm, 16 mW/cm^2) for 30 min to form the polymers on the substrate surface. The cell structures before and after the UV illumination are respectively illustrated in Fig. 1(a) and (b). In the electro-optical measurement, the laser light with a 650-nm wavelength and ac voltage with 1 kHz square waveform were applied to the cells, sandwiched at 45^o (strip-electrode direction) between two crossed polarizers.

3. Results and discussion

Fig. 2 shows the field-emission scanning electron microscope top-view images of the bifunctional acrylate (TA-9164) and monofunctional acrylate (UCL002) polymers on the ITO-patterned substrate surface. In Fig. 2(a), the TA-9164 polymers exhibit cross-linking morphology and connect with their neighbors. This cross-linking ability will generate high-density polymers and have a strong anchoring effect on the surrounding LC molecules. An enlarged image of the TA-9164 polymers on the local area is shown in Fig. 2(b) to clearly observe the linking morphology which is more remarkable on the cell with high polymer concentration. In contrast, the linear-linking UCL002 polymers are clustered and prone to having a spherical formation, as shown in Fig. 2(c). This structure could not strongly interact with the LC molecules, as compared with the TA-9164 polymers. The effect of the polymer structure on the electro-optical characteristics of VA-IPS cells will be demonstrated and described in detail later.

Before inspecting the polymer-LC device performance, we firstly show the LC molecular alignments of the conventional VA-IPS cell subject to the in-plane electric field in Fig. 3. When the cell is driven by a small electric field, the LC molecules near the IPS-electrode edge start tilting toward the substrate surface, whereas the LC molecules, located in the center of the spacing area (*s* area) between the IPS electrodes, are still perpendicular to the substrate surface, as shown in Fig. 3(a). Such a discontinuous LC molecular configuration observed under the crossed polarizers shows a central “dark line” in the *s* area due to no phase retardation being created. In contrast, when a large electric field is applied to the cell, as illustrated in Fig. 3(b), the LC molecules near the IPS-electrode edge will more closely tilt to the substrate surface. Those in the center of the *s* area will be reoriented to form a parallel alignment, attributed to the minimized total free energy of the LC system with the elastic free energy and electrical free energy. This leads to the “dark line” vanishing and a continuous LC molecular configuration, formed in the *s* area.

Fig. 4(a)–(o) shows the voltage-dependent images observed by polarized optical microscopy (POM) for the pure E7 LC, UCL002 polymer, and the TA-9164 polymer cells, respectively. The driven voltage, labeled as V_{IPS}, was applied to these three kinds of cells. At the initial state, when the V_{IPS} is equal to 2 V ($<V_{\mathrm{th}}$), the three kinds of cells are all dark due to the LC molecular director normal to the substrate surface, as shown in Fig. 4(a), (f), and (k). The E7 LC cell with TA-9164 cross-linking polymers has better vertical alignment than the pure E7 LC cell [21], leading to the improvement in light leakage in the dark state and CR. Such results can be confirmed and proved from the POM image. When the polymer concentration is increased (>2 wt%), the quality of the vertical alignment of the LCs, due to the stronger cross-linking ability and stronger anchoring effect on the LC molecules, will be much better, indicating that the CR of the cell can be further enhanced.

With the V_{IPS} increased to less than 10 V, the IPS-electrode edge becomes bright and the central “dark line” is observed on these three types of cells. The brightness of the pure E7 LC cell in Fig. 4(b) and (c) is superior to that of the others (Fig. 4(g) and (h) for the UCL002 polymer cell, and Fig. 4(l) and (m) for the TA-9164 polymer cell), which is attributed to the fact that polymer networks, introducing the additional anchoring effect, can affect the LC molecular reorientation. The average brightness of the TA-9164 polymer

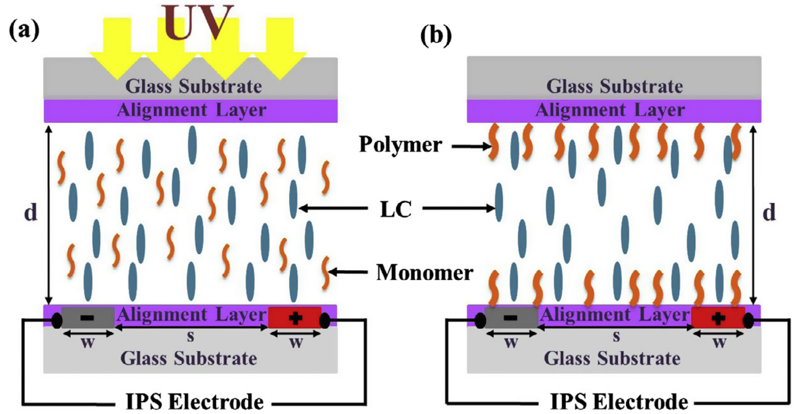

Fig. 1. Schematic illustration of the fabricated process for the VA-IPS LC cell with polymers: (a) well mixed monomer in the LC cell and UV-light exposure, and (b) polymers assembling on the top- and down-substrate surfaces after UV curing.