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Transmittance Improvement with Reversed Fishbone-Shape Electrode in Vertical Alignment Liquid Crystal Display

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A polymer-stabilized vertical alignment (PS-VA) mode with fishbone-shaped pixel electrode structure is mainly used in large-sized liquid crystal displays (LCDs) owing to its advantages such as wide viewing angle, good transmittance and fast response time. One drawback of this mode is a main bone electrode, which crosses in the center of a pixel. It causes the transmittance to decrease badly because LCs cannot be reoriented in this region, and thus, it is particularly unfavorable in an ultra-high-definition LCD. Here, we propose an innovative structure with the main bone electrode relocated to the edge area in a pixel, and investigate how this reverse directed fishbone-shaped pixel electrode structure affects electro-optic characteristics. The proposed structure shows enhanced electro-optic performance, such as the higher transmittance and the faster response time than the conventional VA mode with fishbone-shaped pixel electrode structure.

Keywords : Vertical alignment, Fishbone shape, High transmittance, Fast response time
OCIS codes : (230.2090) Electro-optical devices; (230.3720) Liquid-crystal devices

I. INTRODUCTION

Over the last two decades, owing to their excellent electro-optical performance and low cost, liquid crystal displays (LCDs) have been dominating the markets of information displays. Meanwhile, several LCD modes have also been highly developed for commercialization and they can be distinguished by a ground state of LC and an electrode structure, such as twisted nematic (TN) [1], vertical alignment (VA) [2-9], in-plane switching (IPS) [10,11] and fringe field switching (FFS) modes [12-15]. Among them, advantages of the VA mode are rubbing-free, an excellent dark state at normal view, and wide viewing angle. Herein, due to the wide viewing, the LC reorientation needs to be in multi-directions. The conventional multi-domain VA (MVA) [2-6] and patterned VA (PVA) [7-9] have shortcomings, such as low transmittance and slow rise response time. In order to overcome the slow rise response time of such VA modes, the polymer-stabilized VA (PS-VA) mode [16-20] has recently been proposed, but the low-transmittance issue still persists and furthermore gives rise to a power consumption issue when employed in high resolution LCDs such as ultra-high-definition (UHD) LCDs. In a PS-VA device as shown in Fig. 1 (a), the main-bone electrode is cross-shaped

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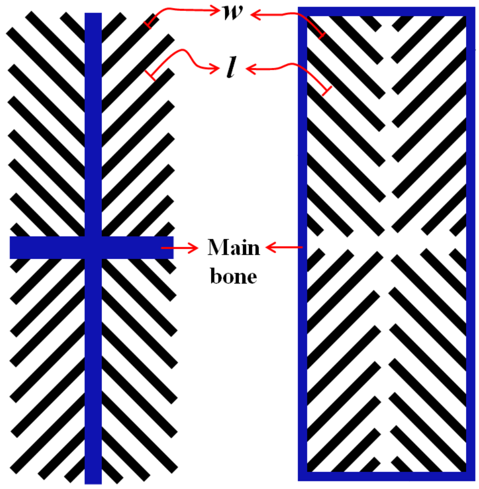


(a) (b)

FIG. 1. Pixel electrode structures of (a) the conventional VA mode with fishbone-shaped electrode structure and (b) the proposed VA mode with reverse fishbone-shaped electrode structure.

because it needs to connect side bone electrodes, which determine the azimuthal direction of the LC director during the reorientation under an applied electric field. Despite the irreplaceability of the main bone electrode, the transmittance above this area is ineffective because the straight vertical direction of an electric field does not direct a uniform azimuthal orientation to LC directors. Consequently, there is local transmittance in this area resulting in low transmittance.

Here we propose a new reverse directed fishbone-shaped pixel electrode structure, that is, the main bone electrode is relocated to the edge area in a pixel as shown in Fig. 1 (b). We expected the proposed device would show highly enhanced electro-optic performance, such as the high transmittance owing to the elimination of the inefficient area and the fast response time from quick relaxation of LC directors in this area.

II. SWITCHING PRINCIPLE OF THE PROPOSED VA MODE AND SIMULATION CONDITIONS

The normalized transmittance in the VA cell with uniaxial LC medium exists between crossed polarizers is given by

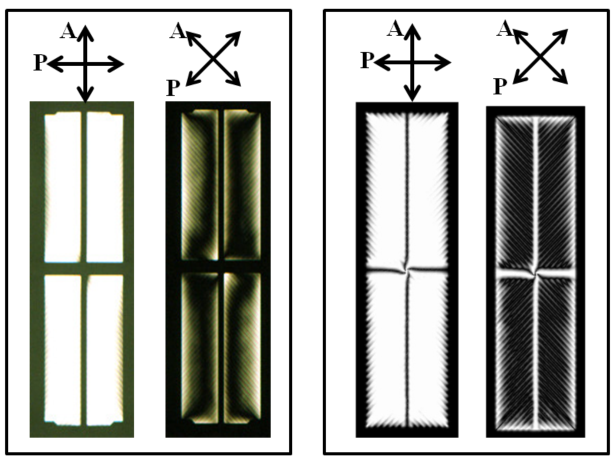
$$T/T_0 = sin^2(2\psi(V))sin^2(\pi d\Delta n_{eff}(V)/\lambda) \quad (1)$$

Where ψ is a voltage-dependent angle between one of the transmittance axes of the crossed polarizers and the LC director, d is the cell gap, Δn_{eff} is the voltage-dependent effective birefringence of the LC medium, and λ is the wavelength of incident light. In the PS-VA mode, the LC director is initially aligned in a pretilt angle of about 89° so that an excellent dark state is achieved in a voltage-off state and ψ is close to 45° in a voltage-on state. To achieve maximum transmittance at the normal direction in the voltage-on state, ψ (V) should be 45° and $d\Delta n_{eff}$ (V) should be $\lambda/2$. In addition, the LC director should reorient in four azimuthal directions to minimize the viewing-angle dependence on the $d\Delta n_{eff}$.

In order to calculate profiles of LC directors and the transmittance depending on the electrode structure in a pixel, the simulation was performed using a three-dimensional finite element method (FEM) module of TechWiz LCD (Sanayi System, Korea). The optical transmittance was calculated by the 2×2 extended Jones matrix [21]. Except for the shapes of pixel electrode of the conventional PS-VA and the proposed VA modes, all cell conditions were the same, and the LC had the following physical parameters: birefringence Δn = 0.079 at λ = 550 nm, dielectric anisotropy $\Delta\varepsilon$ = -4.2, rotational viscosity γ =136 mPa·s, K_{11} = 13.5 pN, K_{22} = 6.5 pN, K_{33} = 15.1 pN. The size of each pixel was 150 μm × 560 μm, which is comparable to a 42 inch Full HD TV. The electrode width w was 3 μm, and the distance between electrodes l was 5 μm including center of the reverse directed fishbone-shaped pixel electrode on the bottom substrate, and the cell gap d was 4 μm.

III. RESULTS AND DISCUSSION

Figure 2 shows experimental and simulated pixel images when crossed polarizers are rotated from 0° (90°) to 45° (135°) in a voltage-on state of the conventional VA mode with fishbone-shaped pixel electrode structure. Under an applied voltage, assuming the LC directors were tilted downward in four diagonal directions, the transmittance would be maximized where the crossed polarizers are 0° (90°). The LC texture



(a) (b)

FIG. 2. (a) Experimental and (b) simulated pixel images in on-state of the conventional VA modes with fishbone-shaped pixel electrode structure when crossed polarizers are 0°(90°) and 45° (135°).

in a pixel image then should show a complete dark state by rotating the polarizers to 45° (135°). However, the results shown in Fig. 2 are deviated from the expectation, that is, at 45° (135°), strong light leakages near boundaries occur both in simulated and experimental results in Fig. 2 (a) and (b), respectively. From these observations, we confirm that the LC directors near the edge of a pixel and the main bone electrode do not tilt downward to the azimuthal angle of 45°, resulting in a low-transmittance. To improve the transmittance, we relocate the main bone electrode to the edge area in the pixel so that the shape of the main bone changes to a rectangle as shown in Fig. 1(b).

The top- and side-views of the electrode structures and LC directors at a voltage-on state in the proposed VA mode with nonpatterned and patterned common electrodes are shown in Fig. 3(a) and (b), respectively. While the pixel electrode is reverse fishbone-shaped on the bottom substrate, a plane common ITO electrode is on the top substrate as shown in Fig. 3(a). In a voltage-on state with these electrode structures, initially vertically aligned LC directors tilt downward along different directions of applied electric field formed by four different azimuthal directions of the electrodes to form four domains. However, near the edge of the main bone, the LC directors collide, resulting in low transmittance. To eliminate this collision area, the rectangular edge area of the common electrode on the top substrate is patterned while keeping the reverse fishbone-shaped pixel electrode on the bottom substrate as shown in Fig. 3(b). The patterned rectangular area coincides with the edge of the main bone in the pixel electrode.

With these patterned common electrode structures, initially vertically aligned LC directors quickly tilt downward without the collision of LC directors in the voltage-on state so that the desired four domains are successfully formed with less unwanted LC director reorientation. Thus, it gives rise to high transmittance. In addition, it can spontaneously remove the capacitance between data lines and top common electrodes so that the signal-delay can be reduced greatly. This can be beneficial in high-speed driving and low power consumption.

The time-dependent transmittance of the conventional and the proposed devices before the polymer-stabilization is shown in Fig. 4. In the proposed device, the transmission was increased by 13.3% and the settling response time is reduced by about 60% from the conventional VA mode. This result shows that the LC directors are quickly relaxed even without the polymer stabilization due to the reduced amount of the collision between LC directors in the proposed electrode structure.

Figure 5 shows time-resolved LC textures when applying the voltage of 7 V for maximum transmittance to the conventional and the proposed devices. The relaxation of the LC directors in the conventional device takes much

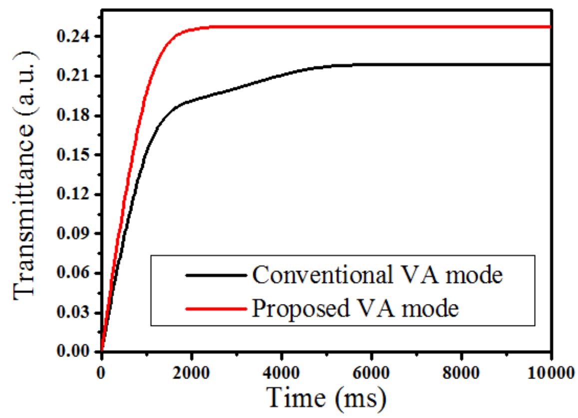


FIG. 4. Time-dependent transmittance curves under an applied voltage of 7 V of the conventional VA mode with fishbone-shaped electrode structure and the proposed VA mode with reverse fishbone-shaped electrode structure.

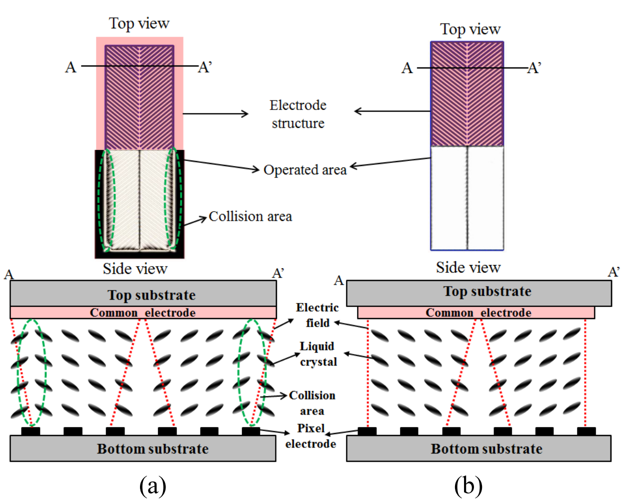


FIG. 3. Side-views of cross-sectional line from A to A' and top-views of single pixel structure in the proposed VA mode with (a) nonpatterned and (b) patterned common electrodes.

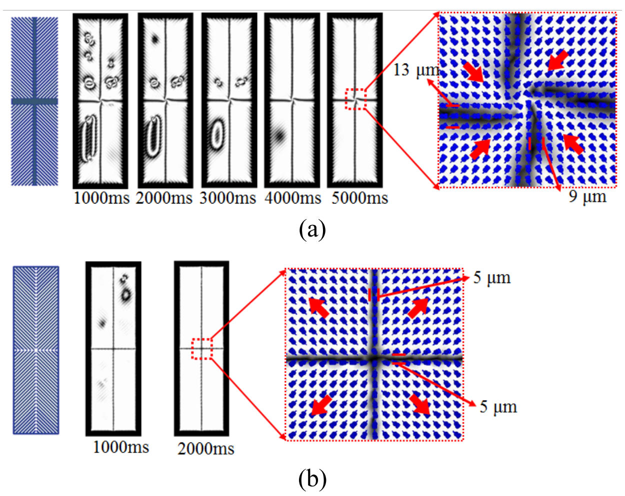


FIG. 5. Time-resolved LC textures under an applied voltage of 7 V in (a) the convectional VA mode with fishbone-shaped electrode structure and (b) the proposed VA mode with reverse fishbone-shaped electrode structure.

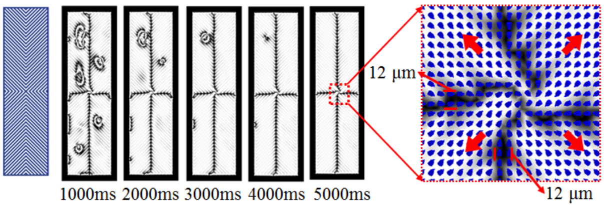


FIG. 6. Time-resolved LC textures under an applied voltage of 7 V when the pixel electrode is connected in the center area of the proposed VA mode.

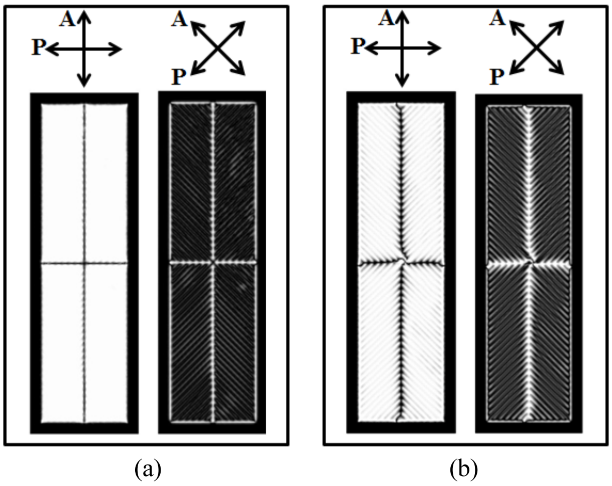


FIG. 7. Simulated pixel images in the proposed VA mode with (a) nonconnected and (b) connected pixel electrode in center area when crossed polarizers are 0° (90°) and 45° (135°).

longer (5000 ms) than for the proposed device (2000 ms), which is in a good agreement with the time-dependent transmittance curves in Fig. 4. Furthermore, when LC directors relaxed in the conventional VA device, the widths of disclinations in the boundary between the domains are measured as 13 μm and 9 μm in horizontal and vertical directions, respectively. These are wider than those in the proposed VA device whose widths of both disclinations at the same location are measured as 5 μm. The transmission calculated from the Fig. 5, confirmed that the transmittance is improved by 7.2%. The increased transmission is due to decreased disclination areas by 54.5% as compared to the convention VA mode.

In Fig. 6, the time-resolved LC textures are simulated with an additional structure of which the all side bone electrodes are connected in the center area. In this structure, however, the relaxation time becomes about 5000 ms and the widths of both disclinations become 12 μm. Consequently, we claim that the pixel electrode should not be connected in the center area of pixel to keep high transmittance and to prevent the collision of LC directors in this region.

In order to investigate the remaining 6.1% of improved total transmittance of 13.3% as shown in Fig. 4, the LC

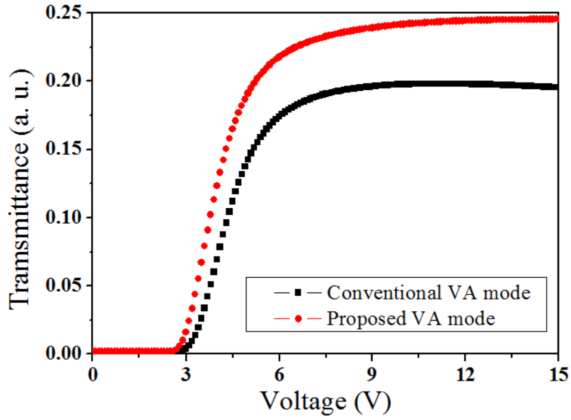


FIG. 8. Voltage-dependent transmittance curves of the convectional VA mode with fishbone-shaped electrode structure and the proposed VA mode with reverse fishbone-shaped electrode structure for UHD TV.

director profile is analyzed by rotating the polarizers from 0° (90°) to 45° (135°) in a voltage-on state as shown in Fig. 7(b). It is clearly observed that the disclinations occupy a huge area when the side bone electrodes are all connected in Fig. 7(b) while the disclinations are optimally suppressed when the side bone electrodes are not connected as shown in Fig. 7(a); consequently, it is an advantage in terms of aperture ratio for the transmittance.

Finally, we apply this structure to a practical display, specifically to a 42 inch UHD TV. The meaning of this application is that we redesign the size of a pixel by 75 μm × 280 μm in which the w including the main bone in the edge is 1.6 μm, and the l including the center area of the fishbone-shaped pixel electrode on the bottom substrate is 4.4 μm. Figure 8 shows the voltage-dependent transmittance curves of the conventional and the proposed devices. The transmittance of the proposed VA mode with reverse fishbone-shaped pixel electrode is higher than that of the conventional VA mode, but the operating voltages of both modes increase to 11 V because of increase in l/w.

IV. CONCLUSION

We demonstrate that a proposed reverse directed fishbone-shaped pixel electrode structure exhibits higher transmittance and faster response time than the conventional VA mode with fishbone-shaped electrode. Relocating the main bone electrode to the edge area in a pixel causes efficient LC reorientation upon the electric field application. From a fabrication perspective, although it needs one more step in fabrication to pattern the electrode on the top substrate, we believe that the highly advanced fabrication technology has been reached with a degree of cost effectiveness sufficient to motivate seeking such advantages of the proposed device.

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