Viewing angle control mode using nematic bistability

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Abstract: As an approach using bistable nematic liquid crystals, we present a liquid crystal display with viewing angle control using two stable states, splay and 180˚-twist at π cell, with three terminal electrode structures. The splay state is controlled by in-plane switching for a wide viewing angle (WVA), while the 180˚-twist state is operated by vertical switching for a narrow viewing angle (NVA). With this bistable mode, we fabricated viewing angle-controlled LCDs without additional optical components.

OCIS codes: (230.0230) Optical devices; (230.3720) Liquid-crystal devices.

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1. Introduction and links

In the past, various liquid crystal display (LCD) modes such as patterned vertical alignment (PVA) [1], mutidomain VA (MVA) [2], in-plane switching (IPS) [3], fringe field switching (FFS) [4], and optically-compensated bend (OCB) [5] have been extensively developed for wide viewing angle characteristics, particularly in TV applications. Due to an explosive increase of mobile electronic devices such as the PDA, mobile phone, and notebook computer, privacy protection has recently become a crucial factor in display functions. Users want to decide whether to disclose or share various information with others in public places. In order to do that, the displays with controllable viewing angles are required in such devices: a narrow viewing angle is required for personal security, while a wide viewing angle is necessary for sharing information. To control the viewing angle, various methods have been proposed by adopting multiple LC layers or a dual backlight system [6-11]. Since such approaches increase the display thickness, power consumption, and production cost, those methods are not optimal for mobile display applications. Recently, Baek *et al*. presented dual-mode switching using both vertical and horizontal fields and a three-terminal electrode structure to control the viewing angle without additional optical components [10]. However, this can lead to a gray inversion in NVA mode that uses vertical and horizontal fields simultaneously.

The simplest way to control viewing angle is the fabrication of the LCD to prepare two different modes in a single LC layer (i.e. each mode realizes NVA or WVA). For the best performance of the viewing angle control, horizontal and vertical switching is required for WVA and NVA, respectively. To accomplish that, we need a bistable LC mode satisfying the above conditions. Until now, however, research concerning the bistable LC mode has focused on reducing the power consumption of the memory use in the bistable mode [12], and attempts to create a dual mode system for dynamic memory capabilities using each stable mode [13].

In this paper, as an approach to bistable nematic displays, we present a viewing angle-controlled LCD using two stable states, splay and 180˚-twist at π cell, with three-terminal electrodes. The splay state with interdigitated electrodes under crossed polarizers shows WVA by horizontal switching as the IPS or FFS modes, and the twisted state with vertical electrode shows NVA characteristics using vertical switching. Using this bistable mode, we can control the viewing angle using a single LC layer and backlight.

2. Principle of viewing angle control

As illustrated in Fig. 1(a), we used three terminal electrodes for horizontal and vertical switching. The bistable mode, splay and 180˚-twist at π cell, can be achieved by the same method used in a previous study for the dual mode [13]. In that study, the bistable characteristics were realized by blending an appropriate concentration of a chiral dopant in the LCs, and thus can be changed by a horizontal or vertical field.

Figures 1(b) and 1(c) show the operating of WVA and NVA modes for viewing angle control with three terminal electrodes, respectively. The dark state of the WVA mode can be obtained using the splay mode, in which the LCs are aligned parallel to the transmissive axis of the light-input polarizer as shown in Fig. 1(b). When voltage is not applied, the input light of 0˚ linear polarization, which passes through LC layer without changing the polarization, is blocked perfectly by the output polarizer with a 90˚ transmissive axis. The bright state can be achieved when the LC director is rotated by 45˚ by the horizontal field. In this case, the input light of 0˚ linear polarization is rotated about

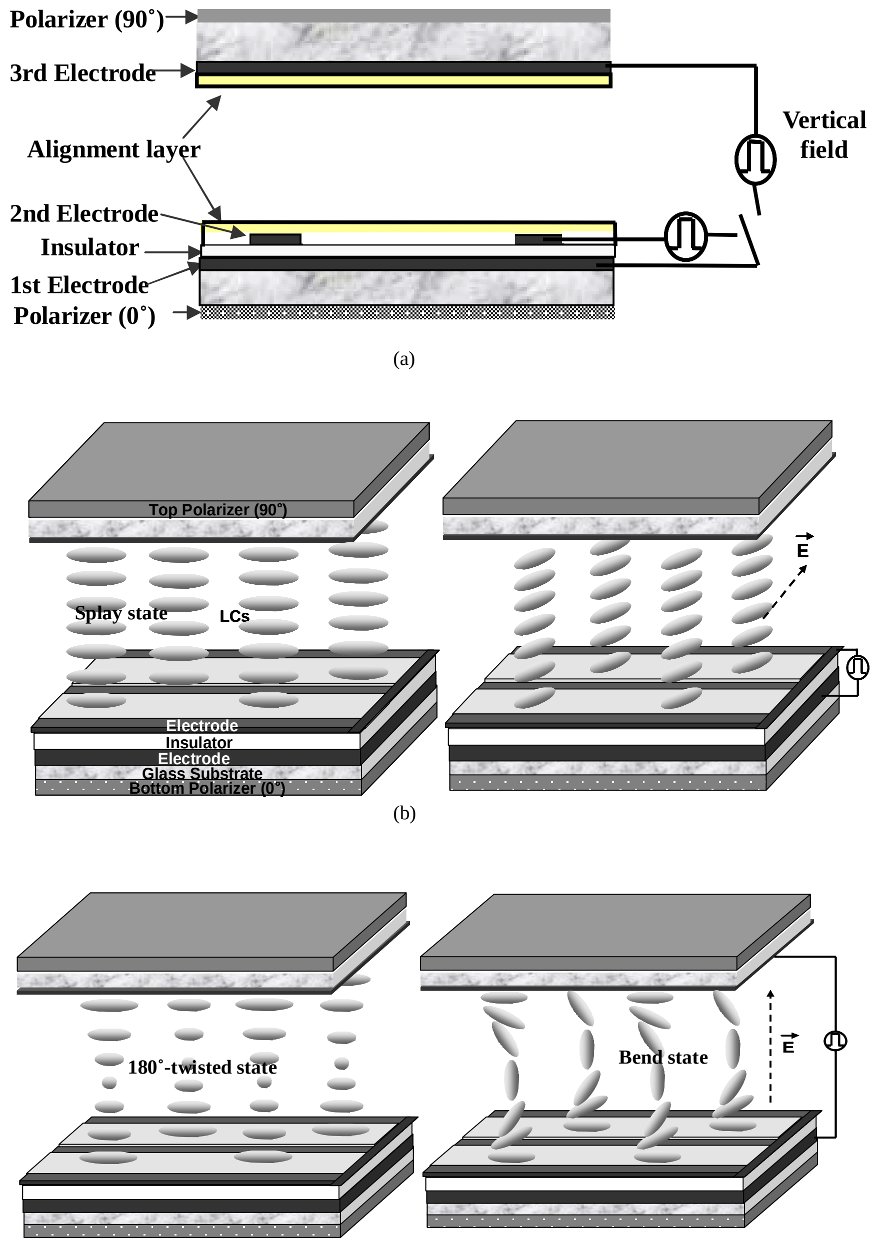

Fig. 1. Switching structure at two modes of π cell with bistable state to control viewing angle: a) cross section of the used LC cell; b) horizontal switching in splay state for wide viewing angle; c) vertical switching in 180˚-twisted state for narrow viewing angle.

90˚ at the LC layer. Such horizontal movement of the LC exhibits an optically high contrast ratio for all viewing directions due to the absence of polarization changes in the light while in the dark state, even when light is obliquely incident. We used the 180˚-twist state as an NVA mode. In this case, when the input LC director coincides with the transmissive axis of the input polarizer under the crossed polarizer, the optical transmittance can be expressed as

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$$T=\frac{1}{1+u^2}\sin^2(\sqrt{1+u^2}\phi \qquad (1)$$

where the twisted angle, ϕ, is 180˚, and

$$u=\frac{\pi d}{\lambda\phi}(n_e-n_o) \qquad (2)$$

where $n_e-n_o=\Delta n$ is the birefringence of LC, d is the cell thickness, and λ is the wavelength of the incident light. The condition of $\sqrt{1+u^2}\approx 3/2$ in Eq. (1) produces $T\approx 0.45$ which is a bright state. When the LC layer becomes a bend state by the application of appropriate vertical fields with the top and bottom electrodes, ϕ becomes 0 and $T=0$, yielding a dark state. In this case, the front view is nearly perfectly dark, because the LC directors coincide azimuthally with the transmissive axis of the input polarizer. However, light leakage inherently occurs at the side view, because LCs for oblique incident light results in optical retardation due to the LCs tilted by vertical field. This is the reason why the π-twist state leads to NVA. The transition from splay to 180˚-twist state is achieved via high and low bend states produced by the vertical field generated from the first (1st) and the third (3rd) electrodes, [14] while transition from π-twist to splay can be obtained by a horizontal field generated by 2nd electrode like IPS or 1st electrode and 2nd electrode like FFS mode [13]. We can therefore realize a viewing angle-controlled LCD in the π-cell with the three-terminal electrode structure.

3. Simulation and experimental results

In order to confirm the optical characteristics of the proposed two LC structures, we used DIMOS (Autronic Melchers) to compute their properties numerically. Figure 2(a) shows the calculated viewing angle of the WVA mode by horizontal switching. We can achieve a contrast ration (CR) greater than 10:1 from almost all viewing areas in the contours having polar angle limits of 80˚. In the case of the 180˚-twisted mode, CR values greater than 10:1 are limited to 40˚ along the diagonal, as shown in Fig. 2(b). In the case of WVA mode, this result is due to the absence of changes in the state of polarization, because the LC director and transmission axis of the input polarizer are on the same plane at oblique incidences along the diagonal direction. Alternatively, in the case of the 180˚ twisted mode, the result is due to changes in the state of polarization, because the LC director and transmission axis of the input polarizer are not in the same plane by the polar directionally-tilted LC directors at oblique incidence along the diagonal. In order to confirm the simulated results, we prepared a cell by adding chiral additive (S-811) in LC to achieve the stable 180˚ twisted state. The cell thickness (*d*) and cell thickness-to-pitch (*p*) ratio, *d/p*, of the fabricated LC cell were 3.85 um and 0.15, respectively. If the *d/p* ratio is in the vicinity of 0.25, a more careful treatment is required, since the initial state may be the 180˚ twisted state. The LC used in our experiment was ZLI-3950 of Δn=0.1374. SE-3140 (Nissan Chemicals), which yields a pretilt angle of 5˚ after general rubbing, was spin-coated on glass substrate as the LC alignment layer. The width and gap of the interdigitated electrode (2nd electrode) were 4 and 5 um, respectively. The bottom electrode was separated from the interdigitated electrode by a 200 nm thick layer of SiNx functioning as an insulator. The electrode material used here was indium-tin oxide. Figure 3 shows transmittance as a function of applied voltages of 180˚-twisted mode with the vertical switching and IPS mode with the horizontal switching. Halogen lamp and signal function generator (DS345 of stanford research systems) were used as the light source and the voltage source. The bright state at IPS mode with a splay state for WVA was achieved at 5 V, while the dark state at 180-twisted mode for NVA was achieved at 3 V.

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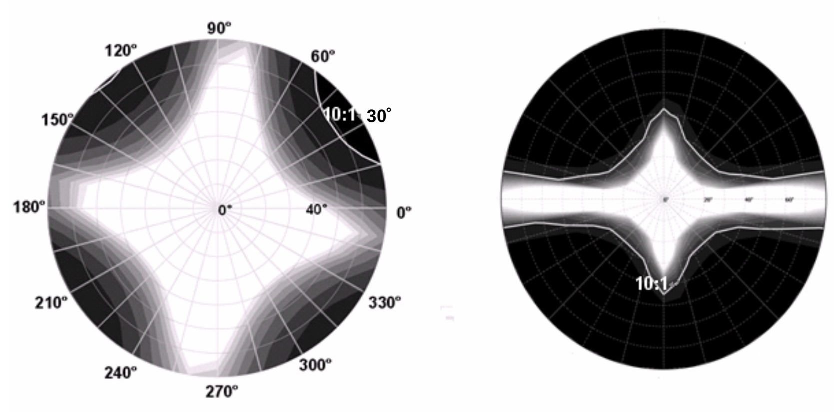

(b)

(a)

Fig. 2. Numerically-calculated viewing angle characteristics: (a) viewing angle characteristics of splay state with horizontal switching, which shows wide viewing angle characteristics; (b) viewing angle characteristics of 180˚-twisted state with vertical switching, which shows narrow viewing angle characteristics.

The voltage for maximum transmittance increases about 1V with comparing to general IPS cell without top electrode. This increasing may due to the disturbance by 3rd electrodes on top substrate. Even with the disturbance we can get maximum transmittance at 5 V which is comparable to normal LCDs. A voltage of 10 V with a square wave of 1 kHz was applied to the electrode for vertical and horizontal switching to convert a splay state into an 180˚-twisted state and an 180˚-twisted state into a splay state.

Figure 4 shows the viewing angle characteristics of an LC cell fabricated under the above conditions. It was measured by DMS-900 (Autronic Melchers Co.) As estimated in the numerical calculation, we can achieve wide viewing angle characteristics in a splay

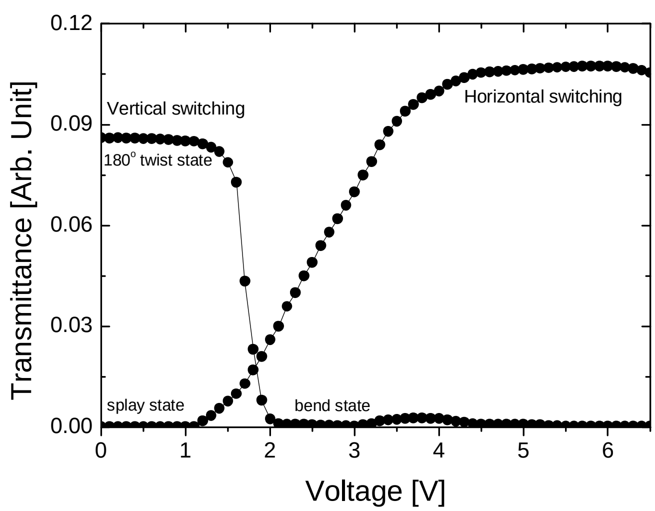

Fig. 3. V-T curves of NVA mode by the vertical switching and WVA mode by the horizontal switching.

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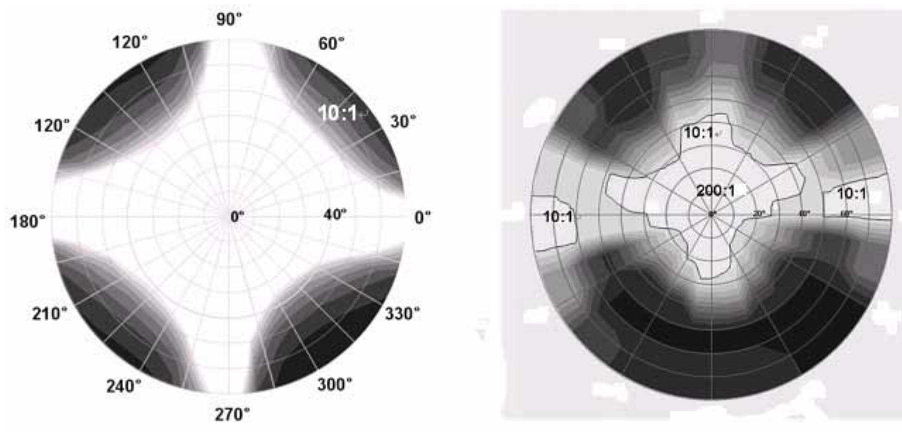

(a)

(b)

Fig. 4. Measured viewing angle characteristics: (a) viewing angle characteristics of splay state with horizontal switching. As expected by optical calculation, horizontal switching shows wide viewing angle characteristics; (b) viewing angle characteristics of 180˚-twisted state with vertical switching, which shows narrow viewing angle characteristics as estimated by optical calculations.

state (over 175˚ in terms of CR=10:1 with azimuthally 0˚ and 90˚ directions and 110˚ at both diagonal directions), as shown in Fig. 4(a). The 180˚-twisted mode shows NVA characteristics in all directions except a direction parallel to the rubbing direction (under 45˚ in terms of CR=10:1 in all directions), as shown in Fig. 4(b). Such distinction of viewing angles occurs naturally because of the bistability of π cell with both vertical and horizontal switching. As a result, we can control viewing angle using the bistability of π cell. We also can expect that more obvious viewing angle distinctions can be obtained through using compensation films with positive C- and A-plates to extend the viewing angle of the IPS mode [15]. This would increase the viewing angle at horizontal switching but decrease it at vertical switching. This approach for viewing angle control may also be available at other bistable devices, such as zenithal bistable devices [16] and bistable nematic displays [17], as well as in dual in-plane switching mode [18].

4. Discussion

In order to minimize the disturbance, we made the 3rd electrode floated when the electrode for in-plane switching is operated. In our measurement, the saturation voltage for maximum transmittance increases about 1V with comparing to general IPS cell without 3rd electrode as shown in Fig. 3. This increasing may due to the disturbance by 3rd electrodes on top substrate. Even with the disturbance we can get maximum transmittance at 5 V which is comparable to normal LCDs. we did simulation using commercial LCD simulator supported from TechWiz LCD which has developed multi-dimensional simulation software for TFT-LCD. The simulated result agrees to our experimental result. Figure 5 shows LC director profiles from side in the cell structure with top floating electrode. From the results we found that the LC directors in the bulk are rotated by average 45˚ when we apply in-plane field as same as a general IPS without 3rd electrode.

The transition time from splay to pi-twist orientation was about 12 sec at 2 cm x 2 cm unit LC cell under vertical field of 10 V. If it is applied to pixel size (about 200 um x 100 um), the transition time will be within 500 ms. If we increased the strength of electric field, we can have faster transition speed. Retention time of pi-state was over six hours.

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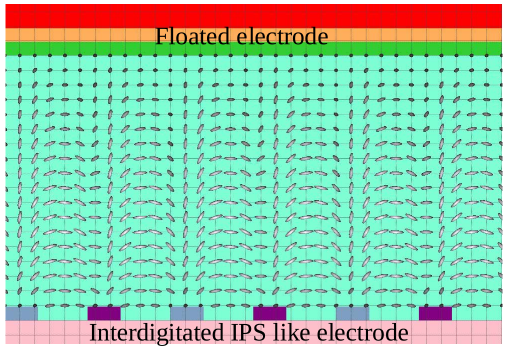

Fig. 5. LC director profiles from side in the cell structure with top floating electrode.

Theoretically, if the cell is refreshed by once every six hours using vertical field for bend transition, the cell will keep pi-state constantly without returning to splay state. The time can be controlled by chiral dopant. Increasing chiral dopant (over d/p>0.25) may increase the retention time during more than a month. In such a case, however, pi-twist to splay transition time will increase. Since the main purpose of this paper is not the achievement of low power consumption with memory state but viewing angle control at dynamic operation, we believe that the six hours is enough time for our purpose.

In this study, the 180˚ twisted state has lower brightness, comparing with other LC modes. It can be compensated by increasing slightly power consumption of back light system. Commonly, amount of light of the back light lamp used in conventional LCDs is about 70% of its maximum emitting light. Therefore, if the emitting light is increased by 15% at NVA, the less light efficiency will be compensated even though it requires more power consumption. However, we believe that the viewing angle control has the worth even if it were so. Almost LCDs with vertical switching has dispersion (wavelength dependency). NVW has also obvious dispersion characteristics. However, as a best solution, if some different bias voltage is applied to blue and green pixels to induce different LC bulk tilt angle at each pixel, letting which have same optical retardation in all pixels, we think that it could be solved.

In order to drive a device with conventional driving system, TFT should be located at the 1st electrode. For WVA, the first TFT electrode and the 2nd electrode (interdigitated electrode which acts as a common electrode) can be used as same as FFS mode. If we switch from WVA to NVA for floating the second electrode, the electric field is applied between the first TFT electrode and the 3rd electrode (3rd electrode which acts as a common electrode). In order to realize this operation, the 2nd and the 3rd electrodes can be switched between common and floated state which will be possible with simple electronic circuit.

5. Conclusion

Viewing angle control liquid crystal display using two stable states, splay and 180˚-twist at π cell was proposed. The states are obtained by parallel rubbing in three terminal electrode structures. The splay state is operated by a horizontal field for WVA, the while 180˚-twist state is operated by vertical switching for NVA. As a result, we can easily control the viewing angle of the LC cell. We expect that this distinct viewing angle difference between the two modes will open up further intriguing opportunities for applications of liquid crystal displays.

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