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A Single Gap Transflective Display using In-Plane Switching Mode

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A single gap transflective liquid crystal display (LCD) using an in-plane switching (IPS) mode is being studied. In the IPS mode, the degree of the rotation of the LC director, between and above electrodes is different. When it is 45° between the electrodes, it is only 22.5° above the electrodes for an optimized cell design. Utilizing this mechanism and an in-cell retarder with a quarter-wave plate that is used below the LC layer, the transflective IPS mode is realized as such that the area between the electrodes is used as a transmissive part and the area above the electrodes is used as a reflective part.
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KEYWORDS: single gap transflective LCD, in-plane rotation, in-cell retarder

Recently, transflective liquid-crystal displays (LCDs) are widely used because they show good visibility in any environmental lighting conditions while keeping characteristics such as portability, good legibility and low power consumption.[1)] Recently, many results such as homogenous cells with a compensation film that are driven by a vertical electric field (called ECB)[2–5)] and driven by a fringe-electric field[6,7)] with a dual color filter structure for dual cell gapping, and singe gap transflective display using a multi-driving circuit[8)] have been reported. In the dual gap structure, a cell gap (d) in the transmissive (T) part is twice that of a reflective (R) part and thus compared to reflective LCD the fabrication process is relatively complicated. Furthermore, the ECB cell shows a very narrow viewing angle in the T part. For a transflective display with multi-driving circuit, a single cell gap is used; but the cost of circuit parts increases.

The in-plane switching (IPS) mode[9)] is known to exhibit wide viewing angle since the LC director rotates in plane, though it has a low transmittance problem due to not enough rotation in the LC director above the electrodes. Nevertheless, the IPS has a low transmittance problem and the reflective-IPS mode has been studied.[10–12)] However, in the device, the film exists below substrate, which may cause a parallax problem.

In this paper, we propose a single gap transflective display using the IPS mode with a normally black (NB) mode. In the device, the in-cell retarder with a quarter wave plate ($\lambda/4$)[13)] and an optical compensation film of $\lambda/4$ is used. The optimized cell shows a single gap and a single driving circuit with wide viewing angle in both reflective and transmissive displays.

Figure 1 shows a cell structure of the proposed single gap transflective display. In the device, the pixel and counter electrodes exist only on the bottom substrate and are reflective metals. The in-cell retarder with $\lambda/4$, exists above the electrodes which could be patterned or not (here, only a non-patterned case is reviewed) and a compensation film of $\lambda/4$ film exists below the substrate. Two polarizers are crossed to each other and an optic axis of the LC coincides with one of the polarizer axes.

In order to decide the optic axis of each layer, the degree of the rotation of the LC director should first be calculated. For calculations, the LCD master (Shintech, Japan) is used. An electrode structure with an electrode width of 5 μm, a distance of 10 μm between them is considered, and the d is 4 μm. The thickness of in-cell retarder is 1.8 μm. Here, the LC with physical parameters such as $\Delta\varepsilon = 7.4$, $\Delta n = 0.08$ at 550 nm, $K_1 = 11.7$ pN, $K_2 = 5.1$ pN, $K_3 = 16.1$ pN is used and the surface tilt angle of the LC is 2° with an initial rubbing direction of 78° with respect to its horizontal field. Figure 2 shows the twist angle of distribution at the different positions when an operating voltage is applied. At position

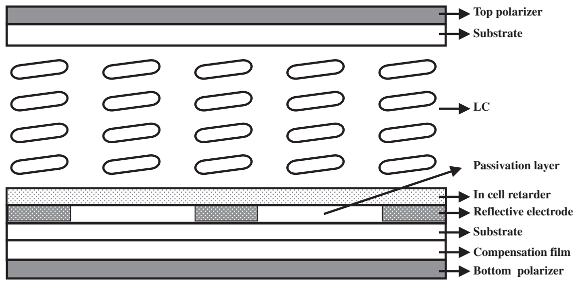

Fig. 1. Schematic cell structures of the in-plane switching driven transflective display.

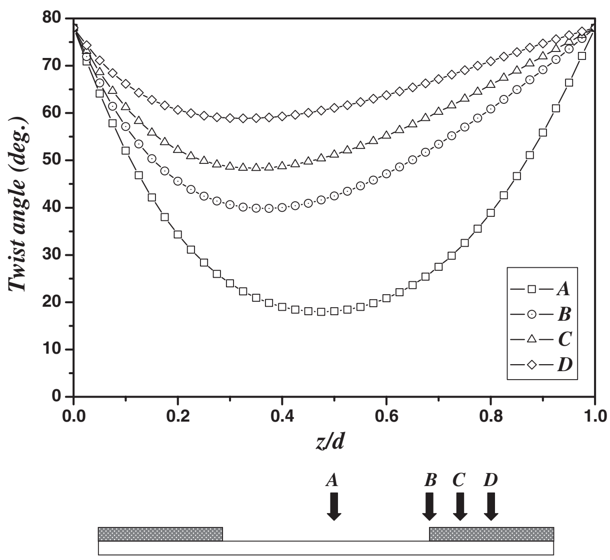

Fig. 2. Twist angle distribution of LC director at four different positions.

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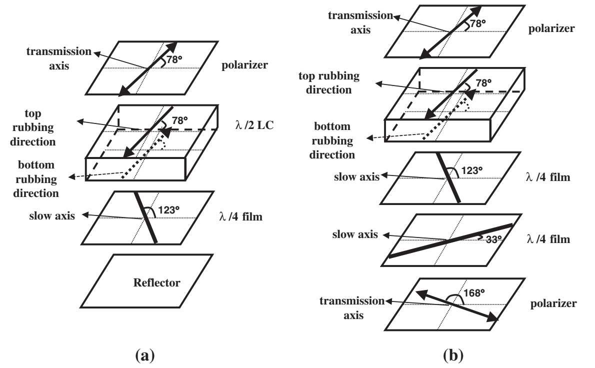


Fig. 3. Cell configurations of (a) *R*-area and (b) *T*-area.

A, the LC is in average twisted by 45° from the initial alignment. However, at position *D* which is at the center of electrode, the LC is twisted in average by 15° while at positions *B* & *C*, it is twisted in average by 23° and 29°, and thus an average twist angle is 22.5°. From this, one can understand that the degree of the LC's twist angle between the electrodes is two times that of the above electrode. Besides the tilt angle of the LC at the operating voltage was very low since most of the in-plane field rotates the LC.

By understanding the LC director in the IPS mode, we suggest a single gap transflective display with an optical cell configuration for both the *R* and *T* areas, as shown in Fig. 3. Here, the area above the electrodes is used as the *R* area, whereas the area between the electrodes is used as the *T* area. In the *R* area, the polarizer axis and the LC axis coincide with each other, and below the LC layer the in-cell retarder with $\lambda/4$ is used. The electrode plays the role of a reflector. In the off state, the linearly polarized light (P1) just passes through the LC layer without a change of polarization, and becomes circularly polarized after the retarder of $\lambda/4$ (P2). After reflection, it propagates along the retarder and the LC layer again, and becomes linearly polarized rotated at 90°, as shown in the Poincare sphere of Fig. 4(a). Then the cell appears to be black. Now, when the LC rotates

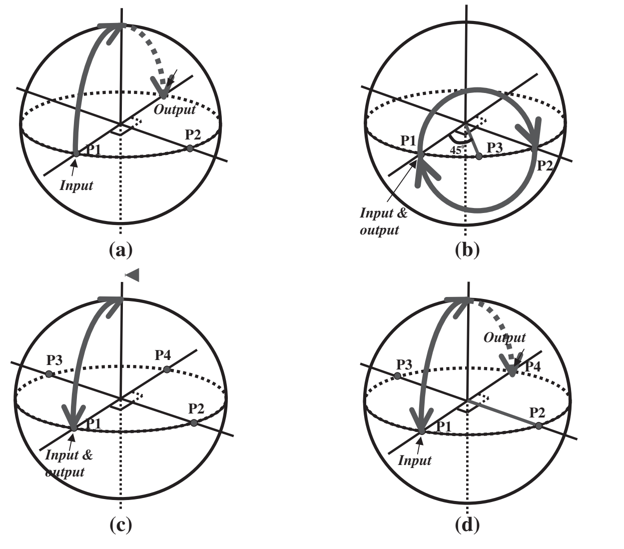


Fig. 4. Poincare sphere representation of the polarization path of the (a) dark and (b) white states in *R*-area and the (c) dark and (d) white states in *T*-area.

22.5° (P3) in the in-plane field, the linearly polarized light (P1) changes to a 45° (P2) direction since the effective cell retardation value is assumed to be $\lambda/2$, and it propagates along a slow axis of the retarder, without changing its polarization state. This light passes the LC cell again and then the vibration direction is the same as the original (P1), resulting in a bright state, as described in Fig. 4(b). In the *T* area with use of a non-patterned retarder under crossed polarizers, a compensation film of $\lambda/4$ with an optic axis of 90° with the slow axis of the retarder is used below the substrate to cancel the phase generated by the retarder. In the off state, the linearly polarized light (P1) passes through the film (P3) so that it becomes circularly polarized. Next, this circularly polarized light passes through the in-cell retarder (P2), and it then becomes a linearly polarized light, returning to its original polarization state. Finally, this light propagates along the LC layer without a change in its polarization state, as shown in Fig. 4(c), and thus it is blocked by the analyzer, resulting in a dark state. With a bias voltage, the LC rotates 45° so that the input light (P1) is rotated 90° (P4) (see Fig. 4(d)), resulting in a bright state.

Since the twist and tilt of the LC depends on the horizontal position, largely between electrodes and above electrodes, the transmittance and reflectance according to the applied voltage is calculated as a function of the cell retardation value (here, d is fixed and Δn is varied), as shown in Fig. 5. Here, to calculate transmittance, a 2×2 extended Jones matrix has been used[14] and the transmittances for the single and parallel polarizers are assumed to be 41%, and 35%, respectively. As indicated, the reflectance is almost the same when $d\Delta n$ is between 0.24 µm and 0.36 µm, while the transmittance is relatively dependent on the $d\Delta n$. The operating voltage (V_{op}) was about the same when it is between 0.32 µm and 0.36 µm. Therefore, in order to realize a single driving circuit, we choose an optimal cell retardation value of 0.32 µm. Figure 6 shows the voltage-dependent reflectance and transmittance in this cell condition. Though the two curves do not perfectly coincide with each other, a display can be generated with a single driving circuit since the threshold and driving voltages are the same. Next, we have calculated the viewing angle characteristics of the cell at 550 nm, as shown in Fig. 7. The uniformity of the white state in both its

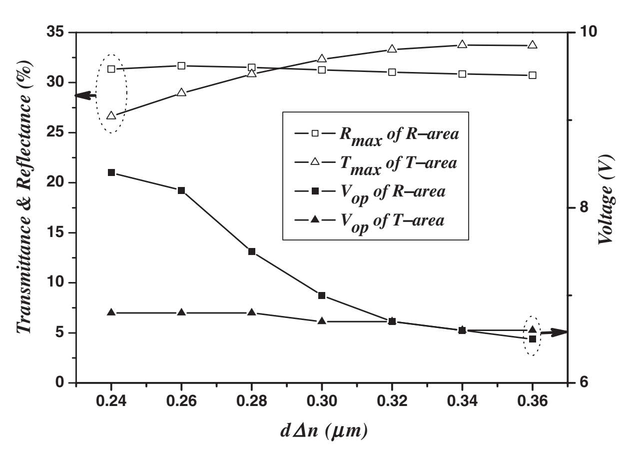


Fig. 5. Maximum reflectance, transmittance and operation voltages of each area as a function of $d\Delta n$.

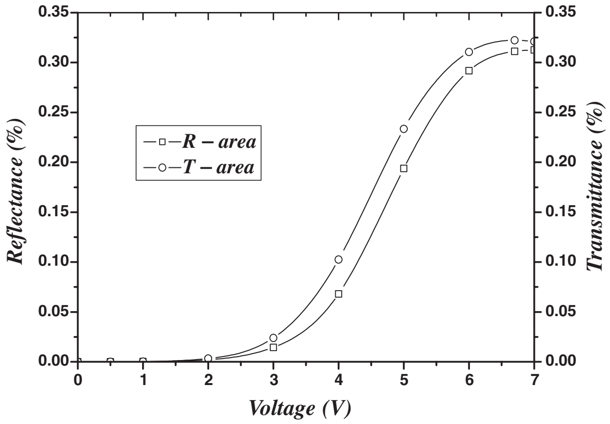


Fig. 6. Calculated voltage-dependent reflectance and transmittance curves.

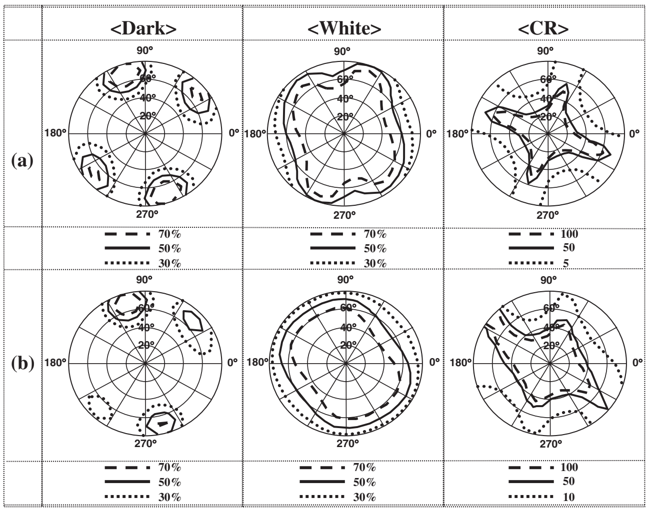
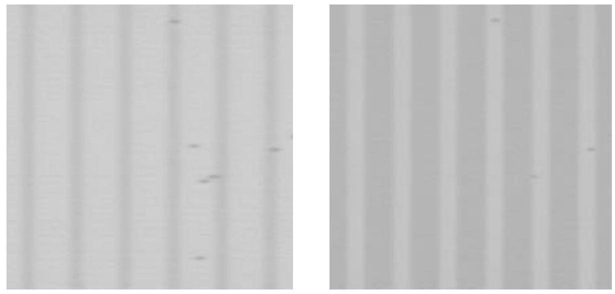


Fig. 7. Calculated isoluminance curves in the dark and white state, and isocontrast curves at a wavelength of 550 nm: (a) R-area and (b) T-area.

reflectance and transmittance is excellent, and also quite a good dark state is obtained, where T_{70}, T_{50}, and T_{30} indicate relative transmittance with respect to maximal transmittance. Consequently, in the R area, the region in which the CR is large than 5 exists to about 50° of the polar angle in all directions and in the T area, the region in which the CR is large than 10, exists over 50° of the polar angle in all directions. Furthermore, the device does not show the grey scale inversion at all at the given viewing angle range since the LC director rotates in plane.

Finally, a test cell is evaluated to confirm feasibility. Here, the electrodes are transparent and the other cell conditions are the same as those in the calculation. The cell with a compensation film and reflector below substrate is observed under a polarizing microscope in a reflective mode. When a voltage of mid-grey, in which the LC director rotates by 22.5° between electrodes, is applied, the reflectance is maximal between electrodes and is much brighter than that above electrode. However, when a voltage of white-grey, in which the LC director rotates by 45° between electrodes, is applied, the reflectance becomes maximal above the electrodes while the reflectance between electrodes decreases,



(a) (b)

Fig. 8. Optical microphotographs of the reflective mode cell in voltages of (a) mid-grey and (b) white-grey states.

indicating the LC director above the electrode rotates by about 22.5°. This is in good agreement with the calculated results and indicates that a single cell gap transflective display, with a single driving circuit, is possible.

In summary, we have proposed the use of a novel single gap transflective display associated with a homogenous alignment to in-plane switching of the LC director, utilizing a different degree of rotation on the reflective and transmissive area. Owing to the in-plane orientation of the LC director, the device exhibits a wide viewing angle without the occurrence of a grey scale inversion in a polar angle of 50° in all directions, in both the reflective and transmissive areas. Furthermore, the device has advantages in cell gap margins since the dark state in the normal direction is irrespective of the cell retardation value, and the optical configuration of the device can be applied to any LC device associated with the in-plane rotation of the LC director.

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