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Viewing Angle Characteristics of Transflective Display in a Homogeneously Aligned Liquid Crystal Cell Driven by Fringe-Field

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We have studied the optimal cell configuration for a fringe-field driven transflective liquid crystal display that exhibits high image quality. The cell is composed of two half-plate compensation films, liquid crystal, and two parallel polarizers in the transmissive region. Viewing angle characteristics of the device mainly depends on the orientation of the polarizer axis. The measured contrast ratio in an optimized configuration is greater than 5 in polar angles of over 50° in all directions and in those over 80° in certain azimuthal cross-sectional planes. [DOI: 10.1143/JJAP.43.L1211]

KEYWORDS: transflective liquid crystal display, fringe-field, contrast ratio

Transflective liquid-crystal displays (LCDs) are strong candidates for portable display devices because they show good visibility under any lighting conditions.[1)] At present, the transflective displays using twisted nematic (TN) and homogenous cells (named ECB) with compensation film,[2)] as well as those with a dual color filter structure[3–5)] exist. However, in both TN and ECB modes, the LC director tilts up in one direction along the vertical field direction so that the viewing angle is narrower in the transmissive region.

Recently, to improve viewing angle characteristics in the transmissive region, several other modes such as vertical alignment[6)] and fringe-field driven homogeneously aligned LC (named FFS mode)[7)] cells have been proposed for use in transflective displays. Displays using the FFS mode show especially the high image quality since the LC director rotate in plane.

For transflective displays using the FFS mode, several possible cell configurations with a combination of compensation films are possible. Research shows that in the reflective region, when the slow axis (θ_F) of the compensation film and LC's axis (θ_{LC}) makes an angle of 15° and 75° with the transmission axis (θ_P) of the polarizer, the device shows the best image quality.[7,8)] In addition, in the transmissive region, the θ_F and θ_P in bottom substrate are designed to be parallel to the film and polarizer on top of the LC cell, respectively. However, according to our study, such a configuration of the transflective cell does not yield the best image quality in the transmissive region.

The transflective FFS device reported previously also had such cell structures that the θ_F and θ_{LC} had angles of 15° and 75° with the θ_P, respectively, however, the actual results were for the cell in which the angles were defined with respect to the absorption axis of the polarizer. In this study, viewing angle characteristics of a transflective display using the FFS mode in the transmissive region with different cell configurations have been calculated in detail by computer simulation. Cells have also been fabricated to compare with theoretical results.

Figure 1 shows the schematic cell structure of the transflective display using the FFS mode. In this device, electrodes exist on the bottom substrate. A common electrode exists as a plane with transparent and reflective areas in proper ratio; a pixel electrode exists in a slit form with measurable distance. The passivation layer is positioned between the common and the pixel electrodes. The LCs are homogeneously aligned at initial state with different cell gaps (d) to maximize light efficiency. With this electrode structure, a fringe electric field is generated when a voltage is applied and thus the LCs rotate almost in plane above the whole electrode surface with bias voltage, giving rise to high transmittance over the entire surface area.[9–11)]

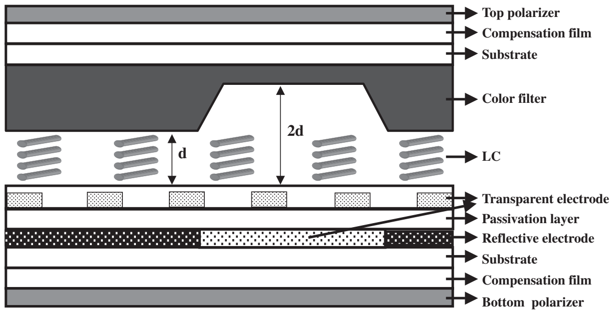

Fig. 1. Schematic cell structure of the fringe-field driven transflective display.

Considering only the transmissive region, the cell is composed of two half-plate compensation films, LC with a half-plate and two polarizers. First of all, the transmittance of the device has been calculated by changing the polarizer axis of the top and bottom substrates as shown in Fig. 2. The simulation conditions for cell and LC physical parameters are the same as in the previous report,[7)] the rubbing direction (θ_{LC}) of the LC with negative dielectric anisotropy is 12° against the horizontal axis and two half-plate compensation films on top and bottom substrate exist with $\theta_F = 75°$. Hereafter, the angle indicates the anticlockwise value against the horizontal axis. As shown in Fig. 2, there are regions in which the transmittance is less than 1%, which could be one of cell configurations for a dark state. Among those, a previous solution with $\theta_P = 87°$ for the top and bottom polarizer yields a good dark state, however, one can notice that a good dark state can also be achieved when the θ_P is 177°. Consequently, the θ_F and the θ_{LC} make angles of 75° and 15° with θ_P, respectively, unlike those in previous results. In the transmittance region, the transmittance of the

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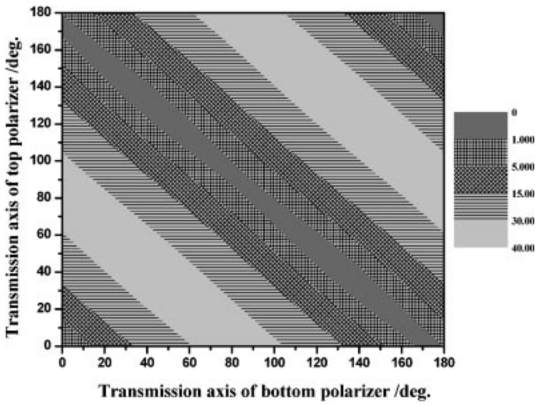

Fig. 2. Parameter space representing transmittance as a function of angle of two polarizers.

cell with two parallel polarizers, two parallel films and the LC is proportional to $\cos^2(\delta_{\text{total}}/2)$ where δ_{total} is the total phase difference defined as $\delta_{\text{total}} = \delta_F + \delta_{LC} + \delta_F$. Therefore, to obtain a dark state, δ_{total} should be π such that the linearly polarized light should be rotated by 90° after passing through the two films and the LC. Both solutions with $\theta_P =$ 87° and 177° at a normal direction satisfy this requirement because the difference between the two solutions is only that the linearly polarized light after passing through the polarizer propagates along the slow axis or fast axis of the compensation film. Nevertheless, the viewing angle characteristics of both configurations are quite different from each other.

To investigate viewing angle characteristics, we consider two possible cell structures, as shown in Fig. 3, and all electrooptic characteristics are compared with each other in detail. Figure 4(a) shows calculated voltage-dependent transmittance (*V*-*T*) curves with the aforementioned cell structures. The *V*-*T* curves for both cases coincide with each other, indicating that the paths of light propagation are the same for each other at a normal direction. Figure 4(b) shows wavelength-dependent transmittance in the dark and white states. The results indicate that even the degree of wavelength dispersion is exactly the same for each other at a normal direction. Next, the contrast ratio (CR) and viewing angle dependence of transmittance in dark and white states have been calculated. Interestingly, the iso-luminance curves

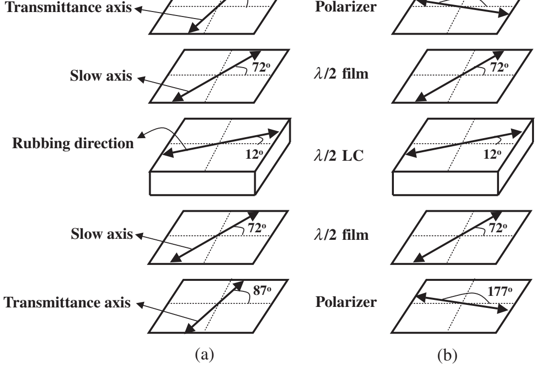

Fig. 3. Two possible cell configurations in the device: (a) $\theta_P = 87°$ and (b) $\theta_P = 177°$.

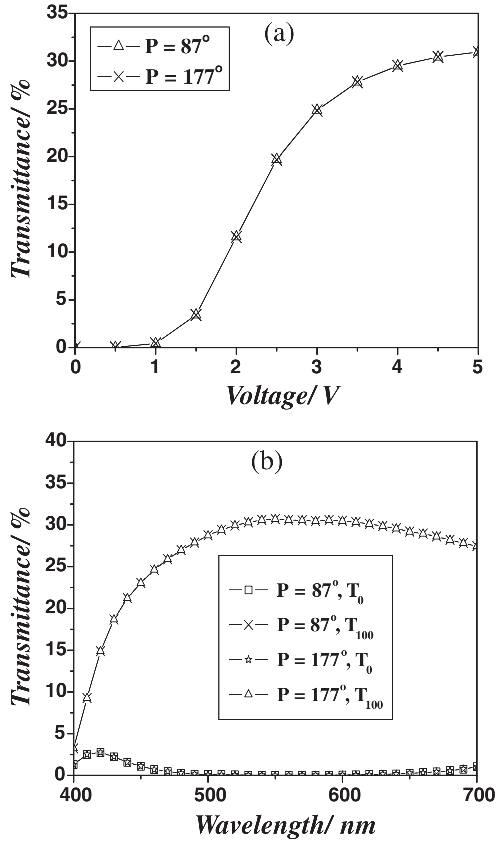

Fig. 4. Calculated voltage-dependent transmittance curves (a) and wavelength dispersion of the dark and white state (b) in two devices.

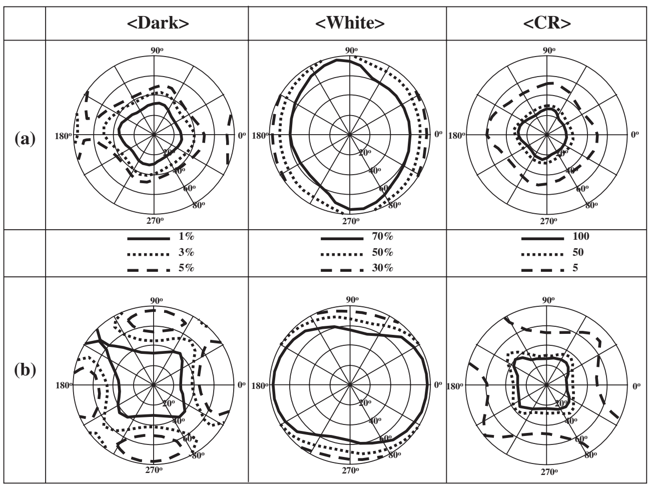

Fig. 5. Calculated iso-transmittance curves in the dark and white state, and iso-contrast curves at a wavelength of 550 nm: (a) $\theta_P = 87°$ and (b) $\theta_P = 177°$.

in the white and dark states for both cases are quite different from each other, as shown in Fig. 5. Most notably, in the dark state, light leakage of less than 5% exists within 80° of the polar angle in all azimuthal directions for the cell with $\theta_P = 177°$; whereas, for the cell with $\theta_P = 87°$, it exists within 50° of the polar angle in most azimuthal directions. This indicates that the cell with $\theta_P = 177°$ shows much better dark state performance than that of the cell with $\theta_P = 87°$. For luminance uniformity in the white states, 70%

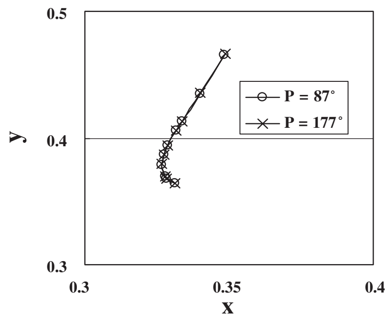

Fig. 6. Calculated color chromaticity of the devices as a function of grey level.

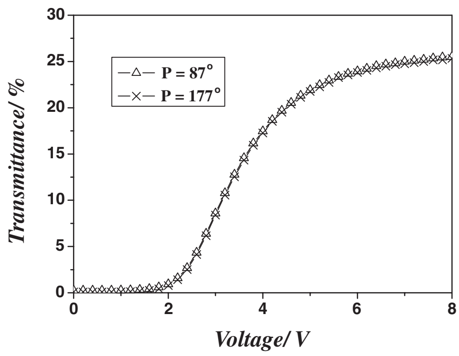

Fig. 7. Measured voltage-dependent transmittance curves for two devices.

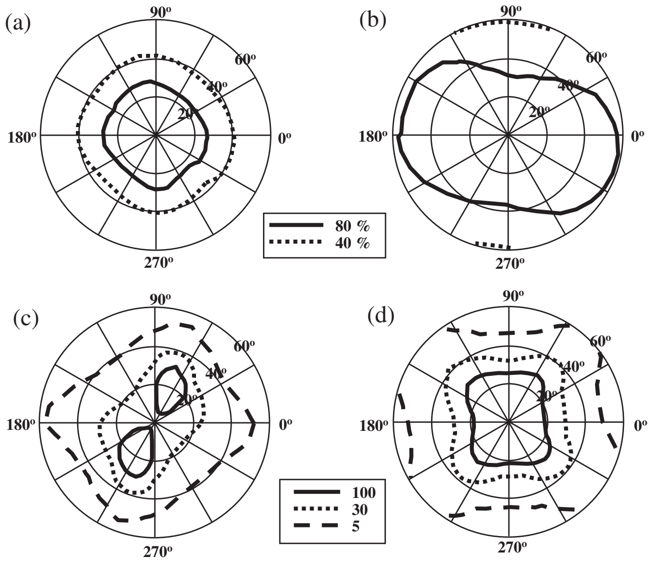

Fig. 8. Measured luminance uniformity in the white state: (a) $\theta_P = 87°$ and (b) $\theta_P = 177°$ and iso-contrast curves: (c) $\theta_P = 87°$ and (d) $\theta_P = 177°$ for two devices.

luminance of the maximum luminance at normal directions exists at over 60° of the polar angle in most azimuthal directions in both cases. Consequently, the region in which the CR is greater than 5 exists at about 50° of the polar angle in all azimuthal directions for the cell with $\theta_P = 87°$ but is much narrower than the cell with $\theta_P = 177°$ in two diagonal azimuthal directions, i.e., it exists at over 70° of the polar angle. Further, the degree of shift in color chromaticity while changing luminance from a white to dark state has been calculated, as shown in Fig. 6. As shown, both results are the same, indicating that wavelength dispersion and color characteristics of both cells are the same each other.

To confirm the theoretical results, a test cell has been fabricated, where LC with a birefringence of $\Delta n = 0.076$ at 550 nm and dielectric anisotropy $\Delta\varepsilon = -4$ was used; the d was 3.8 μm. Here, the light source was a halogen lamp and the 60 Hz square wave was applied to the cell. Figure 7 shows measured *V-T* curves for both cells. The results show that the cell with $\theta_P = 177°$ shows slightly less leakage in the dark state and less transmittance in white state than the cell with $\theta_P = 87°$. This indicates that the cell with $\theta_P = 177°$ shows a better CR value than that of the cell with $\theta_P = 87°$, although we admit that there might be some misalignment between layers. Figures 8(a) and 8(b) show iso-luminance curves of the white state for both cells. The region in which the relative transmittance is 80% of maximal transmittance at a normal direction is wider for the cell with $\theta_P = 177°$ than that of the cell with $\theta_P = 87°$. Figures 8(c) and 8(d) show measured iso-contrast curves. As expected, the region in which CR value is greater than 5 is at about 50° of the polar angle, horizontally and vertically for both cells; however, the cell with $\theta_P = 177°$ has a much wider region than that of the cell with $\theta_P = 87°$ in two diagonal azimuthal directions.

The optimal optical cell configuration for a transflective display using the FFS mode has been studied. Notably, the transmissive region shows the best image quality with a cell configuration of two parallel polarizer axis that makes angles of 15° with the LC axis and 75° with the slow axes of two parallel compensation films, respectively. The optimized transflective display shows wide viewing angle such that the region in which the contrast ratio is greater than five exists at 50° of the polar angle, horizontally and vertically, and at more than 60° of polar angle in two diagonal azimuthal directions.

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