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Minimization of halo mura in homogenous alignment liquid crystal displays via a dichroic light absorber [Invited]

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Abstract: Local dimming technology enables high dynamic range liquid crystal displays (LCDs). However, when displaying a bright image in a dark background, so-called halo mura (halation caused by local light leakage in oblique viewing directions) appears and degrades image quality owing to reduction in contrast ratio (CR). Here light-absorbing vertically aligned dichroic dye film cells are demonstrated to enhance the CR in a homogenously aligned LC mode. The light leakage in normal and oblique viewing directions is reduced greatly in both simulated and experimental results. Positioning such a functional film above the conventional polarizer can greatly improve the CR of all LCDs while reducing surface reflection.

1. Introduction

Liquid crystal displays (LCDs) have widely been dominant in flat panel display markets, including televisions (TVs), monitors, laptops, tablets, and displays in vehicles. Though, emissive displays like organic light-emitting diodes (OLEDs) and quantum-dots OLEDs are emerging owing to its free form factor and high image qualities such as high contrast ratio (CR) and wide color gamut, dominating high-end displays for mobiles [1–5]. Nevertheless, LCD markets are expected to be growing further because their industrial infra, matureness in technology, long lifetime with high reliability are unique characters among many displays. Recently, high-end LCD televisions with adoption of local dimming mini-LEDs and quantum dot film still dominate premium TV market. Applying local dimming LEDs greatly improve CR of LCDs over 3,000,000:1 at normal direction [6–8]. However, when a bright image in a dark background like stars in the dark sky is displayed, light leakage in oblique viewing directions, so-called halo mura, is inevitable. This may relatively be a weak point compared to OLEDs [9–11]. On the other hand, touch panel displays are ubiquitous, and homogeneously aligned LC modes are mostly preferable because their molecular alignment stands well under the finger pressure. In homogeneously aligned LC mode, LCDs with in-plane switching (IPS) [12–14] and fringe-field switching (FFS) [15–17] are mainly used but the CR at normal direction is relatively lower than that of vertically aligned LC modes. This highly encourages the improvement in CR for the homogeneously aligned LC mode. For example, the highest CR for gaming displays in homogeneous alignment LC mode is about 2,000:1 [18], which is yet less than that in vertically aligned LC mode (about 5,000:1). This requires improving the CR at least higher than 2,000:1 in the homogeneously aligned LC mode. As above-mentioned, the local-dimming technology was applied to high-end LCDs to

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improve CR greatly at normal direction, but the halation occurs as an issue when bright images are displayed on a dark background [6–8]. The halation arises because the backlight unit is divided into less than the actual number of pixels in the active matrix when locally dimming. Thus, the light leakage occurs in a turned-off region of the active matrix, which comes obliquely from the nearby turned-on region of the backlight. This degrades the dark level, which is the most important factor for the CR. Incident light from an oblique direction causes light leakage mainly because the crossed polarizers are no longer 90°. For this, compensation films such as positive C-plate ($n_x = n_y < n_z$) and negative ($n_x < n_y = n_z$) or positive ($n_x > n_y = n_z$) A-plate have been applied to reduce the light leakage in oblique viewing angles [19–21]. However, even with the compensation films, the light leakage still exists, and CR still needs to be improved to minimize halo mura. The well-known, useful formula of transmittance in homogeneously aligned LCDs is given as, , where ϕ is the angle between the transmitting axis of the polarizer and the LC director, d is the cell gap, Δn is birefringence of LC, and λ is the wavelength of light [22,23]. For an ideal dark state, ϕ must be zero mathematically. However, the order parameter of LC molecules cannot perfectly be unity and there is always error in manufacturing process so that ϕ cannot be zero, which results in light leakage in a dark state even at normal direction [22,23]. Here, we propose a novel optical design to improve CR greatly in both normal and oblique viewing directions by adopting vertically aligned dichroic dyes either as a thin film cell on top of the second polarizer or doping the dyes into a positive C-plate that exists for the viewing angle compensation. We firstly optimized cell and film parameters of placing the vertically aligned dichroic dye layer via simulations and fabricated vertically aligned dichroic dye cells with dichroic dyes of 1 and 2 wt% to verify the CR compensation performance on a real uncompensated display panel of a TV set.

2. Simulations and experiments

To compare the reduction of light leakage in the homogeneously aligned LC mode when applying the vertically aligned dichroic dyes, we used a one-dimensional simulation program (TechWiz LCD, SANAYI System Co.) to simulate the optical properties of our proposed structures: a homogeneous alignment LC cell with no compensation (S1), the S1 cell compensated by positive A- and positive C-plates inserted between LC and the second (top) polarizer (S2), the S2 cell replacing the positive C-plate by a 1 wt% dye-doped positive C-plate (S3) and by a 2 wt% dye-doped positive C-plate (S4), a 1 wt% vertically aligned dichroic dye layer on top of the S2 (S5), and a 2 wt% dichroic dye layer on top of S2 (S6). In all cases, the angle between the transmission axes of the two polarizers is 90°, the rubbing angle of LC cell is 0°, and the optical axis of the A-plate is 90°. The thickness of positive C-plate ($n_x = n_y = 1.4780$, $n_z = 1.4802$ at 550 nm) and positive A-plate ($n_x = 1.4804$, $n_y = n_z = 1.4787$ at 550 nm) are both 40 µm and dichroic dye layer thickness is 10 µm. The dichroic ratio in the database is 10.77 at 550 nm. We determined the appropriate concentration of the dichroic dye through simulation, followed by experiments. The fabricated dichroic thin films contain a mixture of Black X12 dye (dichroic ratio = 11.1 at 550 nm, BASF Korea) and RMS-03-013C ($n_e = 1.680$, $n_o = 1.543$, $\Delta n = 0.137$, Merck Performance Materials, Ltd.). The RMS-03-013C was mixed with propylene glycol methyl ether acetate solvent for mixing and evaporated at last. The final mixture was injected into cells with indium tin oxide (ITO)-deposited glass substates by capillary action in a dark room at room temperature. The cell cap d was 10 µm. A voltage of 40 V was applied to the cell to align the dichroic dyes vertically, and then cured by UV at 20 mW/cm^2 for 2 minutes. To confirm the vertical alignment, conoscopic images of the sample were measured by CCD camera (DXM 1200, Nikon) equipped on a polarizing optical microscope (Eclipse E600, Nikon). Finally, the prepared dichroic thin film was placed on the 42” IPS-TV (CR = 1000:1, LG-Philips LCD) to confirm the decrease of light leakage and the CR enhancement.

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3. Results and discussion

Figure 1 shows the possible structures we proposed. The first structure is a homogeneously aligned LC cell with no compensation (Fig. 1(a)). The second structure is to compensate the light leakage from the diagonal directions at oblique viewing angles by positive A- and positive C-plates, inserted between LC and the second (top) polarizer (Fig. 1(b)). The third and fourth structures include the vertically aligned dichroic dyes based on the second structure. In the third structure, we have the dichroic dyes as a light absorber, embedded into the positive C-plate (Fig. 1(c)). In the fourth structure, the dichroic dyes are placed in between polyvinyl alcohol (PVA) and triacetyl cellulose (TAC) in the second polarizer (Fig. 1(d)). In this way, the polarizer contains vertically aligned dichroic dye molecules in addition to uniaxially aligned iodine molecules in plane in the PVA layer.

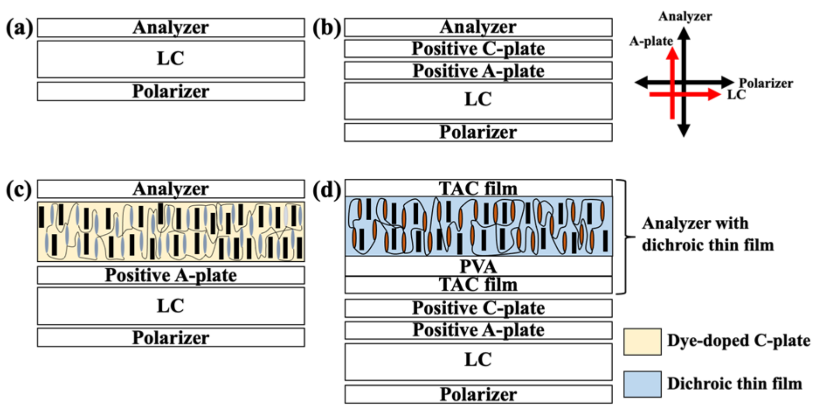

Fig. 1. The schematic diagrams of proposed structures: (a) a homogeneous alignment LC cell with no compensation (S1), (b) the cell compensated by positive A- and positive C-plates (S2), (c) the cell with a positive A-plate and dye-doped C-plates (S3 and S4), and (d) the cell with a thin film of dichroic dyes on top of the conventional polarizing layer (S5 and S6).

Figure 2 shows iso-luminance contours in dark states to confirm the degree of light leakage in each sample. The maximum value in the iso-luminance contour in Fig. 2(a) is higher than that in Fig. 2(b-f) for suitable representation because the maximum light leakage is 1.270, 0.050, 0.038, 0.029, and 0.023% for the samples S1-S6, respectively. It is obvious that the case with the higher doping concentration of dichroic dye more effectively reduces the light leakage. However, the optimum concentration should also be considered by the bright state, which contributes to the maximum CR. Thus, we plotted the dark, bright states and CR in the normal and oblique viewing directions as shown in Fig. 3. As the concentration of the dichroic dye increased, the transmittance of both the dark and bright states decreased, as shown in Fig. 3(a,b). The light leakage in the oblique viewing direction is greatly reduced as shown in the inset of Fig. 3(a). The CR of S3 and S4 is improved up to about 6000:1, and the CR of S5 and S6 is improved up to about 1850:1 at the azimuthal angle $\phi = 45°$ and polar angle $\theta = 70°$ whereas the CR of S1 and S2 is about 14:1 and 1450:1. This shows the CR of S6 is enhanced up to 13160% and 127%, compared to the S1 and S2, respectively.

Figure 4 shows iso-CR contours of each sample. The CR in the normal direction with no compensation (Fig. 4(a)) seems too high, calculated by about 9900:1 because the manufacturing error or the LC order parameter are not considered. It is dramatically reduced even at $\phi = 45°$ and $\theta = 20°$ as shown in Fig. 4(a). The samples S3-S6 with vertically aligned dichroic dye exhibit about 2000:1 up to $\theta = 60°$ in most of the azimuthal angles as shown in Fig. 4(c-f). If the

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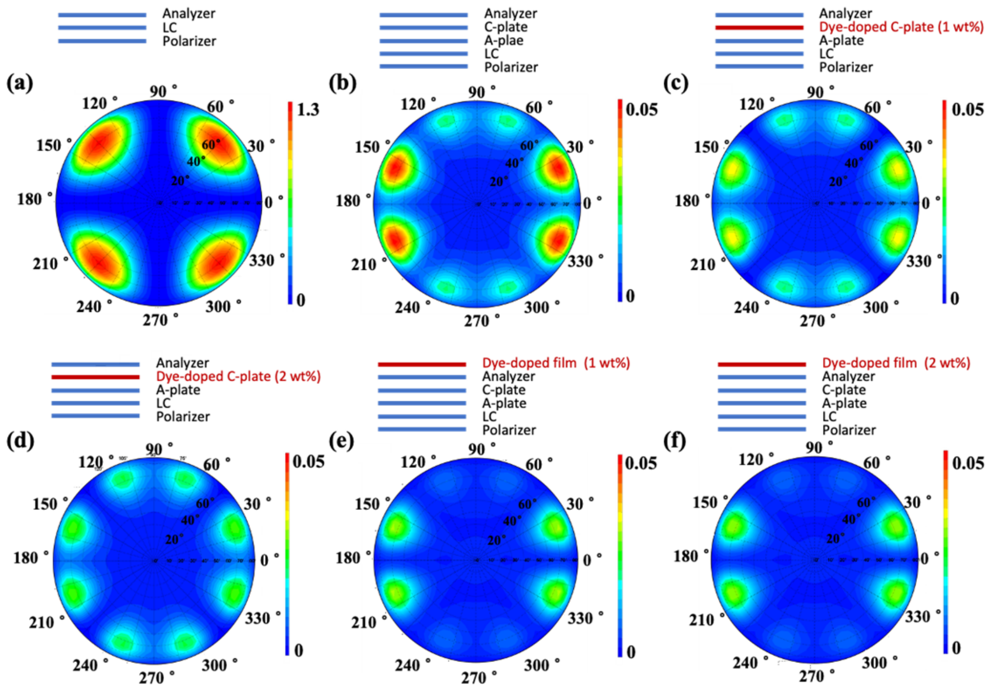

Fig. 2. Simulated iso-contours of luminescence in dark states of each sample: (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6.

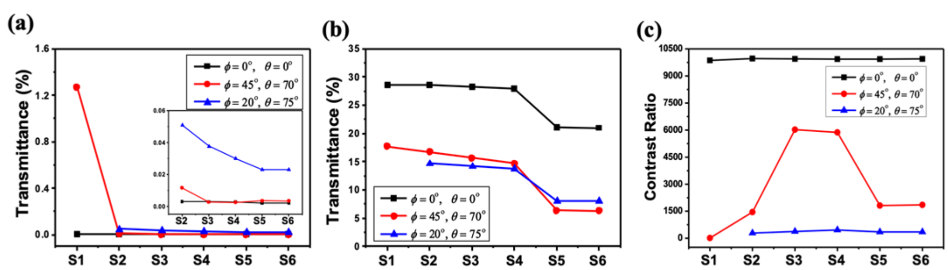

Fig. 3. Simulated transmittance in (a) dark, (b) bright states, and (c) CR of the normal and oblique viewing directions in each sample.

vertically aligned dye layer can be made into positive C film, the overall display thickness and cost can be reduced compared to the dye layer existing above the polarizing layer.

Based on the simulated results, we fabricated dichroic dye films in ITO-glass cells as shown in Fig. 5. The dichroic dye and reactive mesogen (RM) mixture filled in the cell was vertically aligned by a vertically applied electric field and cured by UV as shown in Fig. 5(a). The cells were given under pressure by a pencil stick and no optical change exists, which means the RM is fully cured and the vertically aligned dichroic dye molecules are well maintained as shown in the inset of Fig. 5(a). Photographs were taken when a single conventional polarizer (Fig. 5(b)), the fabricated cells with the dichroic dye of 1 wt% (Fig. 5(c)) and 2 wt% (Fig. 5(d)) are placed on a printed image on a backlight unit. Here, the conoscopic images (the insets in Fig. 5(c,d)) show the vertical alignment of the dichroic dye is well maintained. At this time, the orientational ordering of dye in the film doped with 2 wt% is lower than the one with 1wt% as shown in conoscopic

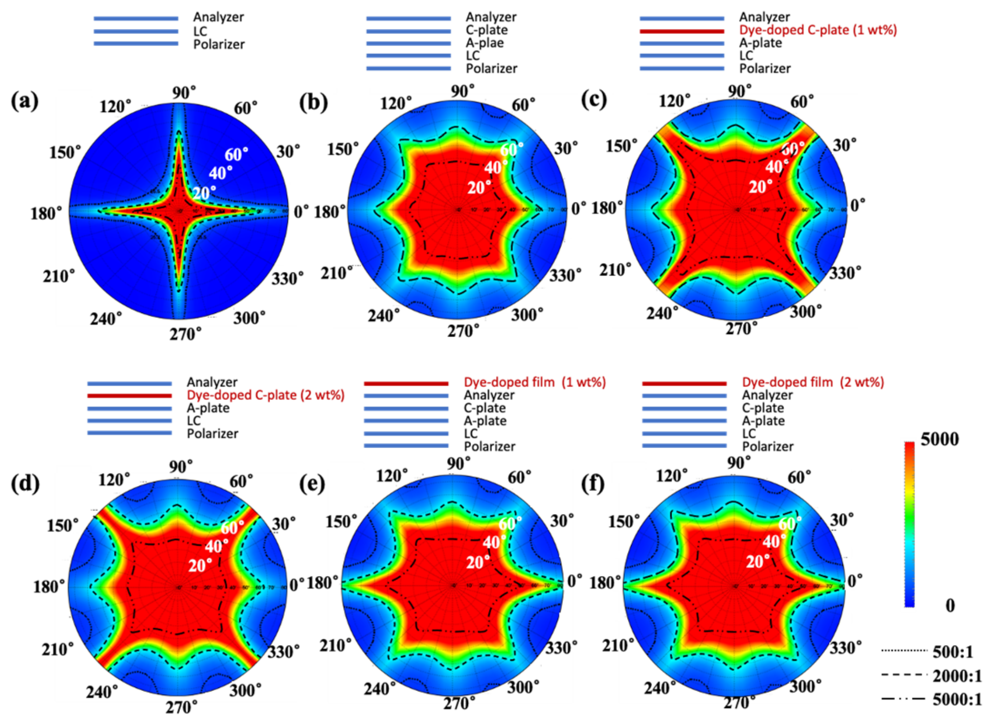

Fig. 4. Simulated iso-contours of CR in each sample: (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6.

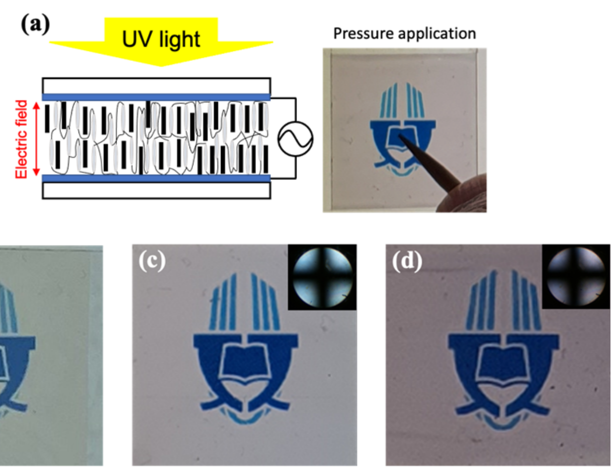

Fig. 5. Schematic and investigation of the fabricated dichroic thin films. (a) Schematics of electric field application and photo-polymerization. Inset shows the cell under pressure. (b) Photographs of a conventional dye polarizer, (c,d) fabricated dichroic films with dye-doping of (c) 1 wt% and (d) 2 wt%, placed on a backlight unit. The insets in (c,d) are conoscopic images.

images of the Fig. 5 resulting in a difference in the transmittance at the normal direction. The dark cross with the dye-doped layer is relatively thicker than that without dichroic dyes, indicating that more light is absorbed in viewing directions when the vertically aligned dye-doped layer exists.

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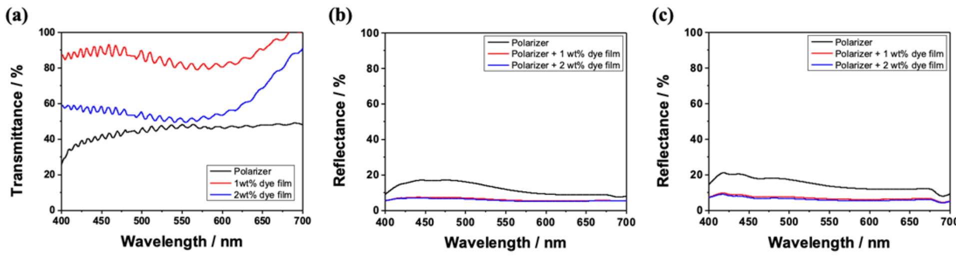

Fig. 6. Spectral (a) transmittance and (b,c) reflectance of a polarizer, 1, 2wt% dichroic dye cells from the (b) normal and (c) oblique (45°) views.

The transmittance and reflectance of the fabricated vertically aligned dye doped cells were compared with that of a conventional polarizer. We measured spectral transmittance and reflectance for comparison of a polarizer and dichroic dye cells of 1 and 2 wt% as shown in Fig. 6. The transmittance of each polarizer and the fabricated 1wt% and 2wt% dichroic cells is 48%, 82%, and 52% at 550 nm, respectively as shown in Fig. 6(a). The transmittance of the dichroic thin films is higher than that of the polarizer, and the transmittance of the dichroic film of 1 wt% is over 80%, which is about two times higher than that of the conventional polarizer as shown in Fig. 6(a). From this result, we can conclude that the optimum concentration of the dichroic dye is less than 2 wt%. Although the well-reduced dark level leads to high CR, the transmittance becomes too low to maintain the high CR. The polarizer is placed underneath of the dichroic thin films with both 1 and 2 wt% dyes when measuring the reflectance as shown in Fig. 6(b,c). The reflectance of the polarizer is 11.5%, and it decreases to 6.2% and 5.9% with the 1 and 2 wt% dichroic dye cells, respectively, in the normal direction (at 550 nm). In the oblique

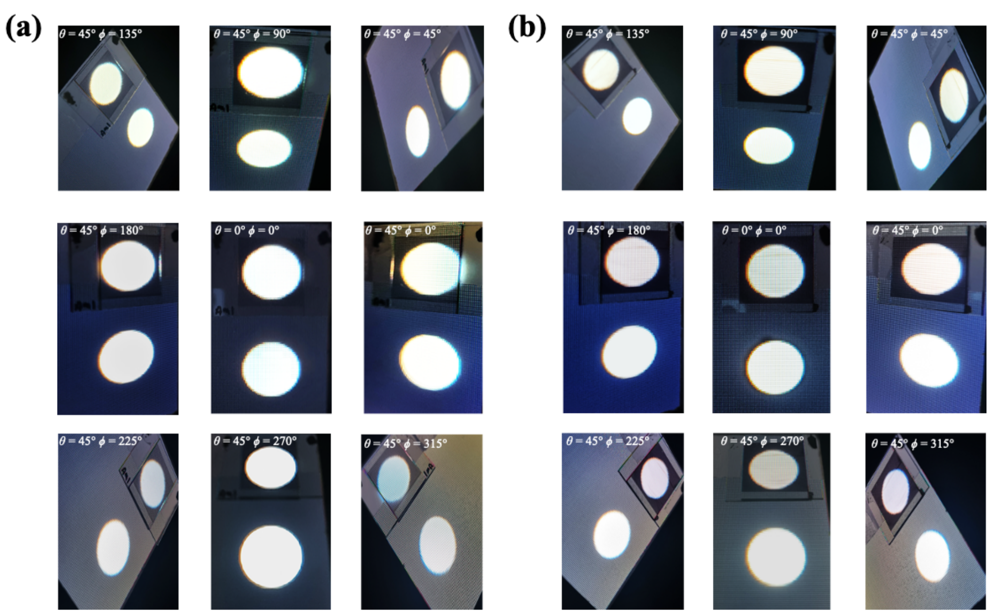

Fig. 7. Photographs showing comparison of dark states around bright circles between an uncompensated TV panel and the fabricated cells on it in various viewing directions. The fabricated dye-doped cells show superior dark state around the bright circles, observed in the normal and oblique when (a) 1wt% and (b) 2wt% dichroic dye concentration.

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direction (45°, at 550 nm), the reflectance is 14.7% for the polarizer, and it decreases to 7.0% and 6.3% with the 1 and 2 wt% dichroic dye cells, respectively. This shows the proposed and fabricated dichroic film cells can improve the ambient CR with low reflectance in both normal and oblique viewing directions.

We tested the reduction of halation near a bright image in dark background. Two bright circles were displayed in dark background by an IPS mode TV panel, and the fabricated cells were placed on one of the bright images with 1 and 2 wt% dichroic dyes as shown in Fig. 7(a) and (b), respectively. Without the sample cells, the dark area appears either bluish or yellowish depending on viewing directions, which comes from the wavelength-dependent phase retardation in oblique views in the uncompensated IPS panel. We may consider this bright light leakages as the halation from the local dimming. We note that the light leakages from oblique views around the bright circles become clearly dark because of the vertically aligned dichroic dye molecules. Also, it shows that the much clearer dark states around the bright circle images are achieved with 2 wt% dichroic dyes as shown in Fig. 7(b). This clear dark state near the bright images implies not only the overall value of the CR is greatly improved but also the image quality becomes much clear without the halo mura when assuming the adoption of this method to the high dynamic range LCDs.

4. Conclusion

We have demonstrated vertically aligned dichroic dye cells, which can compensate the light leakage coming from the oblique direction. The dichroic dye plays a role of anisotropic light absorber to increase the contrast ratio (CR) in homogeneously aligned LCDs. The dark state is improved by reducing the light leakage while absorption of light in normal direction is minimized to maintain the bright state to increasing the CR greatly. The simulated results show the CR of the mode with no optical compensation in the oblique viewing direction was as low as about 14:1, but with the proposed dichroic thin film cells, the CR in the oblique viewing direction is enhanced to about 2000:1 up to the polar angle of 60°. The experimental results show great possibility to compensate dark state around the bright image, which can be used to minimize the halation, so-called halo mura. The dichroic dye concentration in our experiment is less than 2 wt% for an optimum CR because the transmittance becomes too low at the higher concentration. We believe that this approach can greatly improve the CR in all LCDs, including the high dynamic range LCDs with the local dimming technology.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper may be obtained from the authors upon reasonable request.

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