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Novel achromatic polariser for the homogeneously aligned nematic liquid crystal displays

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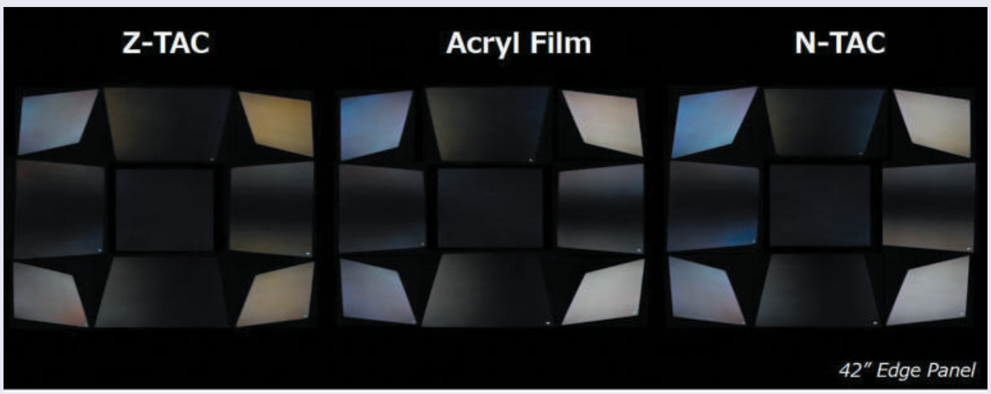
ABSTRACT
Recent development of optical compensation scheme for liquid crystal display (LCD) enables to realise a high quality display by eliminating the unnecessary birefringence at oblique viewing directions. However, the red colour mura in a voltage-off dark state of homogeneously aligned LCD (HA-LCD) needs to be suppressed. In this report, we propose a novel optical compensation scheme for eliminating off-axis red colour mura by utilising a negative retardation tri-acetyl cellulous (TAC) film which results in a uniform spatial deviation of polarisation states for an incident white light. The proposed compensation scheme is demonstrated in detail by performing simulations and experimental studies, and high image quality of HA-LCDs without red colour mura in the dark state is realised.



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Homogeneously aligned LCD; negative retardation; TAC film; high image quality

Introduction

Since the appearance of liquid crystal display (LCD), several LCD modes such as twisted nematic (TN) [1–3], multi-domain vertical alignment (MVA) [4–6], in-plane switching (IPS) [7–9] and fringe field switching (FFS) [10–15] have been successfully demonstrated and commercialised. Every mode has its own specific advantage so that each is applied to different application displays for best utilisation of their own advantages. Among all modes, the homogenously aligned (HA) FFS mode exhibits outstanding electro-optic properties such as high transmittance, wide-viewing angle, low operating voltage and fast response time so that it has been widely used especially in high-image quality LCD products with high resolution. Nevertheless, the light leakage from the crossed polarisers occurs especially in off-axis oblique view, where the two crossed polarisers are no longer orthogonal to each other, and thus it deteriorates the viewing angle property at voltage-off dark state. To overcome this effect, several optical compensation techniques by using a C-plate, A-plate, biaxial films and tri-acetyl cellulous (TAC) films has been proposed [16–19]. The combination of compensation films of C- and A-plates that can made of discotic and rodlike LC (or stretched film) ordered in specific direction compensate unnecessary birefringence of LC cell at oblique viewing direction. The other one, TAC film which exhibits a low birefringent polymer film can be used as protective layers for polarisers [20]. Both HA-LCDs utilising either a single TAC or set of compensation films effectively suppress the off-axis light leakage

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and exhibits a good dark state at voltage-off state, which improves the contrast ratio and wide viewing angle. However, both IPS and FFS modes still exhibit a red or yellow colour mura in large oblique viewing directions in a dark state when using just the conventional TAC film only. In order to suppress the colour mura, a zero-TAC, is developed and commercialised. The optical properties of the compensation film can be characterised with two parameters R_0 and R_{th} that are defined as follows [21]:

$$R_0 = \left(n_x - n_y\right) \times d \tag{1}$$

$$R_{th} = \left(\frac{n_x + n_y}{2} - n_z\right) \times d \tag{2}$$

where n_x, n_y and n_z are the refractive indices in the x, y and z directions and d is a thickness of the film, respectively. In the conventional TAC, R_0 and R_{th} are about 5 nm and 45 nm, respectively. In the zero-TAC, both values are close to zero though R_{th} has a small positive value depending on the stretching ratio of the film. In such a case, more red light than blue light passes through the crossed polariser at off-axis, causing a reddish colour in a dark state.

In this paper, we propose a novel TAC film with negative R_{th} that could effectively eliminates the red colour mura at off-axis viewing direction of HA-LCDs. Utilising a negative retardation TAC film, the incident linearly polarised light with longer wavelengths is blocked more than shorter wavelengths at off-axis, therefore suppress the red colour mura even for off-axis oblique view. The proposed compensation scheme is demonstrated in detail by performing simulations and experimental studies as well and found the TAC film with negative R_{th} greatly improves image quality of HA-LCDs without red colour mura even for large oblique viewing angles.

Colour mura of the TAC film with positive R_{th} in oblique viewing directions

The light leakage ($T_{leakage}$) of the HA-LCD in a dark state is given as

$$T_{leakage} = \sin^2[2\psi_{eff}(\theta, \phi)]\, \sin^2[\pi d \Delta n_{eff}(\theta, \phi, \lambda)/\lambda] \tag{3}$$

where ψ_{eff} is the effective angle between LC director and the absorption axes of the crossed polarisers dependent on the polar (θ) and azimuthal (ϕ) angles, d is a cell gap, Δn_{eff} is the effective birefringence of the LC layer dependent on the θ, ϕ and the wavelength of the incident light (λ) in spherical polar coordinates. In the dark state, the effective angle ψ_{eff} between the absorption axes of the crossed polariser and the analyser increases according to increase the angle (θ, ϕ) of the viewing direction [22,23]. Consequently, the light leakage in the dark state is generated because ψ_{eff} is deviated from 0° as a change in the effective angle between the two polarisers. In addition, Δn_{eff} is non-zero at the off-axis except for the directions coincident with the polariser axis, resulting in light leakage as well as chromatic. The colour mura shows due to the wavelength dependences of LC layer and protective film of polariser with retardation.

Figure 1(a) shows the optical configuration of the HA-LCD with two low-retardation TAC films under crossed polarisers. More specifically, the LC layer is sandwiched between two TAC films at which optic axis of the LC layer parallel to the transmission axis of the top TAC film. Again, the polariser and the analyser are attached to this film in a manner both transmission axis perpendicular to each other and perpendicular to TAC films. The obtained colour contour of optical viewing angle at voltage-off state is shown in Figure 1(b). For optical properties calculations, a commercially available LCD evolution software TechWiz LCD (Sanayi Systems, Korea) is used. The specifications of HA-LCD (retardation = 314 nm at 589 nm) are as follows, the LC is homogeneously aligned to 90° direction and pretilt angle is 2°. Here, R_o and R_{th} of both top and bottom TAC films are 2 nm and 4 nm at 589 nm, respectively. The TAC films are biaxial plate with $n_x > n_y > n_z$ and the thickness of both TAC films are 40 µm. From Figure 1(b), no colour mura was observed along both absorption axis of the polariser and analyser (bisector directions). However, the slight wavelength dependent luminance is manifested which leads to the red colour mura, in oblique viewing angle directions (off-axis directions).

Figure 2 explains how the polarisation state of blue (486 nm), green (589 nm) and red (656 nm) changes on Poincaré sphere when passing through the positive and negative retardation TAC compensation schemes of HA-LCD when the observer views from an oblique direction (ϕ = 45°, θ = 60°). In this test, the positive and negative R_{th} were set to 10 nm and −10 nm, respectively, for extreme comparison.

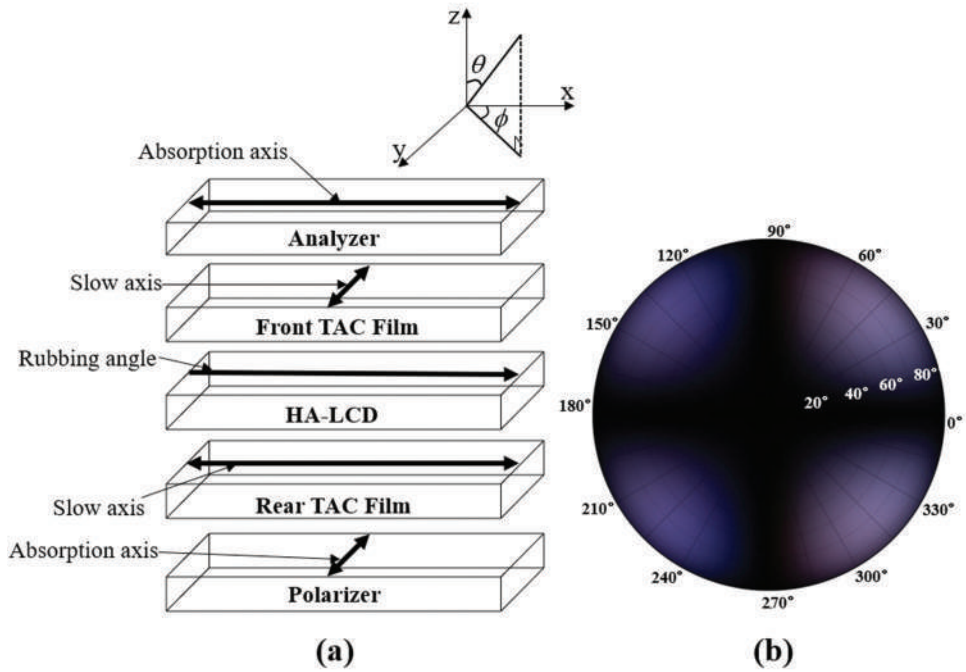

Figure 1. (Colour online) (a) Schematic of optical compensation with TAC films. (b) Colour contour with brightness at dark state of a conventional HA-LCD using TAC film with positive R_{th}.

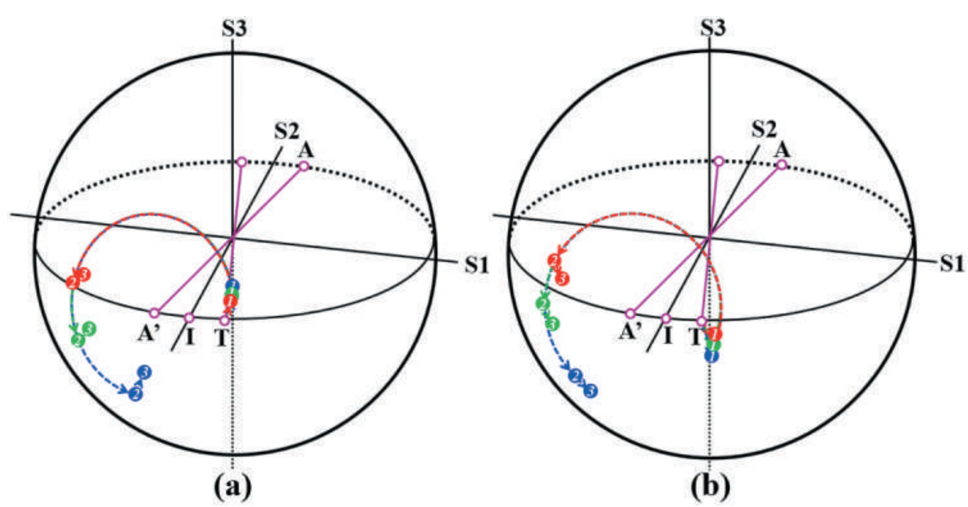

Figure 2. (Colour online) Representation of different polarisation states on Poincaré sphere for each step in optical compensation scheme of HA-LCD by using TAC film with, (a) positive retardation R_{th} and (b) negative retardation R_{th}. The red, green and blue colour lines represents the transformation of polarisation state with red, green and blue colour wavelength incident light under oblique direction (ϕ = 45° and θ = 60°).

The incident light in the oblique viewing angle direction deviates from the polarisation angle of an incident light at normal direction, so that the polarisation direction of the polariser shifts to position **T** from position **I** which is the polarisation state of the polariser in the normal direction, as shown in Figure 2(a) and (b). Then, the light passing through the rear TAC film reaches the polarisation position 1. Next, the light will move to the position 2 after passing through the HA-LCD. Finally, the front TAC film will shift the polarisation state of position 2 to position 3. Here, the point **A** represents the

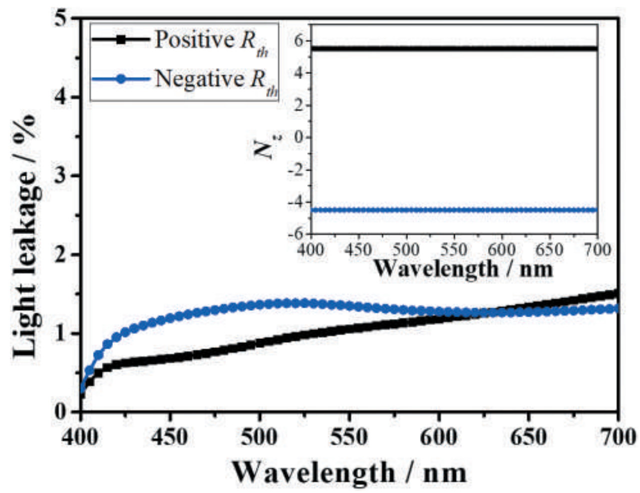

Figure 3. (Colour online) Comparison of the light leakage according to wavelengths in oblique viewing angle (ϕ = 45° and θ = 60°) in the HA-LCD using TAC films with positive and negative R_{th}s. The inset illustrates wavelength-dependent refractive index parameter (N_z) of TAC films.

transmission axis of the analyser in the oblique direction. It is evident that from Figure 2(a), the incident light with blue wavelength closely reaches the point **A'** which is absorption axis of the analyser in oblique direction, whereas the incident light with red and green wavelengths takes positions far away from point **A'**. This means that the light leakage is stronger at the red and green wavelengths compared to the blue wavelength. On the contrary, the final polarisation states of all wavelengths in oblique directions are equally deviated from position **A'** in case of the HA-LC cell using TAC films with negative R_{th}, as shown in Figure 2(b). The equal spatial deviations of the polarisation state effectively suppress the off-axis red colour mura because the leaked light becomes white colour when all wavelengths equally shift the polarisation state of an incident light at the same degree.

Figure 3 compares the light leakage of the HA-LCD in the oblique direction (ϕ = 45°, θ = 60°) when R_{th} = 10 nm and −10 nm. As can be seen from the inset in Figure 3, the refractive index parameter N_z defined as $(n_x - n_z)/(n_x - n_y)$ [24] for TAC films with biaxial optical axis is independent of wavelength regardless of negative and positive retardations. Nevertheless, when R_{th} is positive, the longer the wavelength the light leakage increases such that the light leakage of red wavelength is larger than that of other wavelengths. However, the light leakage is relatively constant over the entire visible spectra when R_{th} is negative.

Colour mura comparison of the TAC films with positive and negative R_{th}s in oblique viewing directions

Figure 4 shows the calculated colour contour for different R_{th} and R_o values of the front and rear TAC films in a dark state of the HA-LC cell. All conditions are the same as those in Figure 1(a), however, refractive indices of the TAC films with positive and negative R_{th} are $n_x > n_y > n_z$ and $n_z > n_x > n_y$, respectively. As indicated in Figure 4, when R_{th} of the TAC film is negative with large value, the red colour mura is minimal in all viewing directions regardless of the R_o. In terms of the viewing angle associated with colour contour with brightness, the colour difference depending on the R_{th} value does not show distinct difference because it is also associated with luminance factor. However, the colour shift in chromaticity diagram could reveal a clear colour difference depending on the R_{th} value. Figure 5 shows the colour or chromaticity coordinates (x, y) in a 1931 colour space [25] according to the R_{th} values of TAC film in an oblique viewing direction (ϕ = 45° and θ = 60°) of the HA-LC cell at voltage-off state. Here, the results are obtained for fixed R_o value of 2 nm, while the R_{th} value varies from 6 nm to −6 nm with a step size of 2 nm. As the R_{th} value changes from 6 nm to −6 nm, the colour in the off-axis has been shifted from red region to blue region, as clearly presented in Figure 5.

To confirm the calculated results, the experimental observations were performed and the red colour mura

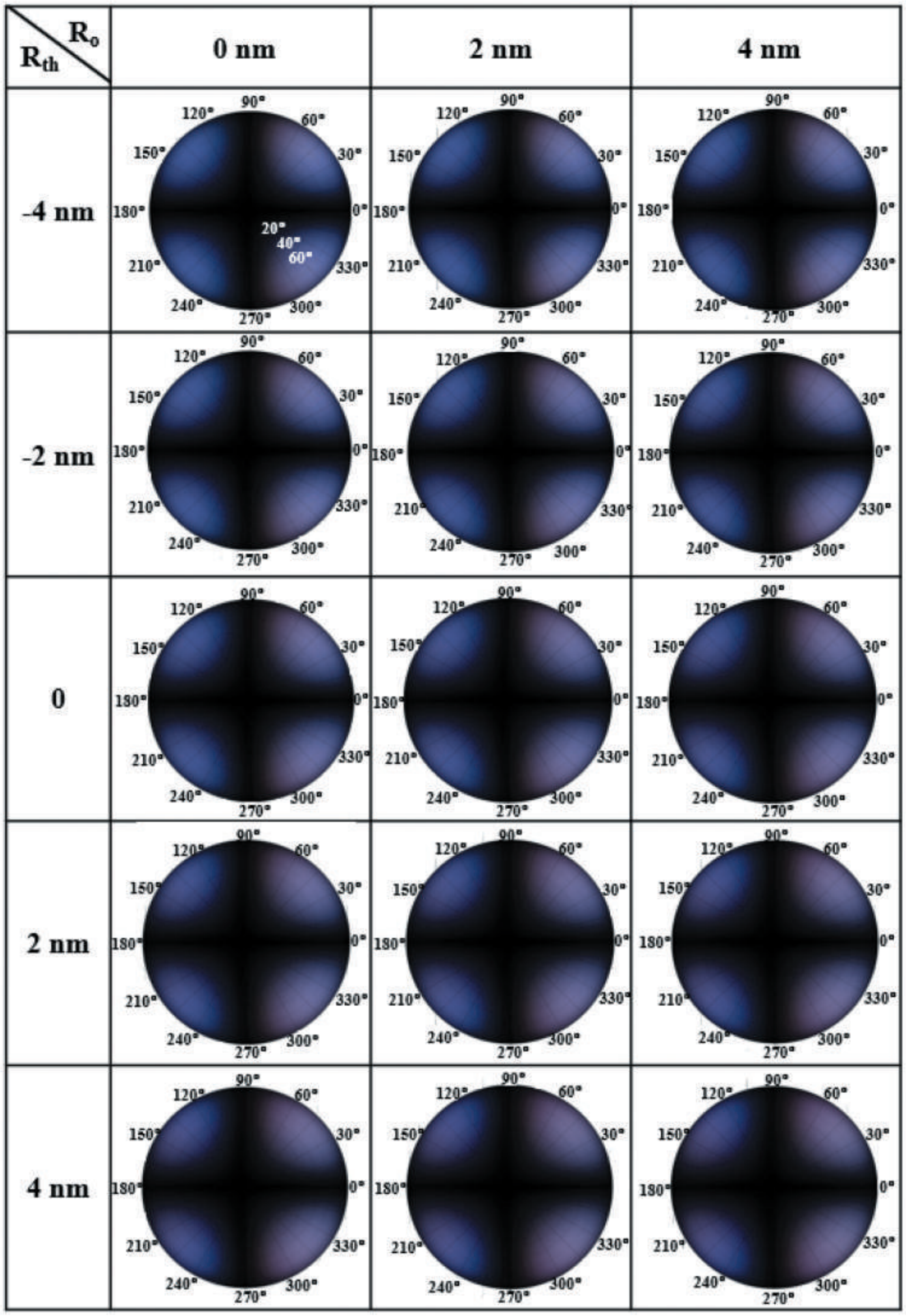

Figure 4. (Colour online) Calculated colour contour with brightness as a function of R_{th} and R_o of the front and rear TAC films in a dark state of the HA-LCD.

in 42” Edge IPS Panel with HA-LCD (LG Display Co.) is measured under different compensation schemes by using the Z-TAC (Fujifilm), Acryl film (Sumitomo) and N-TAC (Konica Minolta). The Z-TAC, Acryl and N-TAC film are attached to both sides of the HA-LCD in the same manner shown in Figure 1(a). The red colour mura images are measured by using Digital Single-Lens Reflex camera (D3500, Nikon Cor.). The measure R_o and R_{th} values of the Z-TAC, Acryl film and N-TAC using AxoScan System (Axometrics Inc)

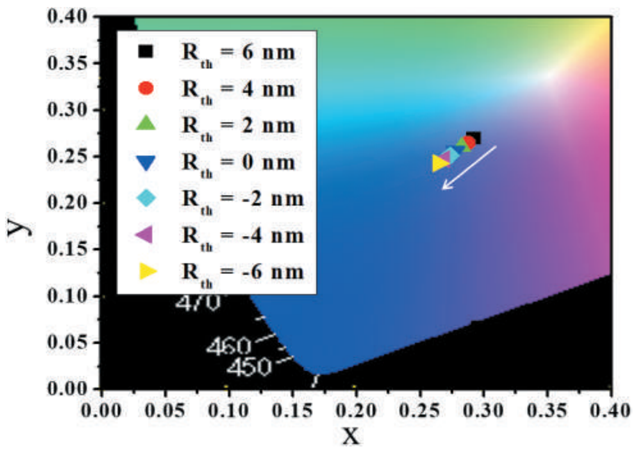

Figure 5. (Colour online) Calculated chromatic coordinates in 1931 colour space for various R_{th} values of TAC film in an oblique viewing direction (ϕ = 45 °, θ = 60 °) of the HA-LCD.

are 3.0 nm and 2.1 nm, 3.4 nm and −1.6 nm, 1.8 nm and −5.2 nm, respectively. As shown in Figure 6, all three films show a good dark state with no colour mura at normal direction. However, a strong red colour mura appears in oblique viewing directions (ϕ = 45 ° or 135° at θ = 60 °) for the Z-TAC with positive value R_{th} of 3 nm. Interestingly, when the Acryl film with negative value R_{th} of −1.6 nm or the N-TAC with negative value R_{th} of −5.2 nm are used, the red colour mura is disappeared. From these results, we could confirm that the experimental results are strongly consistent with the calculated results shown in Figure 4.

Figure 7 shows the measured chromaticity coordinates (x, y) by using SR-3AR (Topcon Technohouse Co.) for Z-TAC, acryl film and N-TAC film in an oblique viewing direction (ϕ = 45 ° and θ = 60 °) of HA-LC cell. The colour characteristic of the Z-TAC with

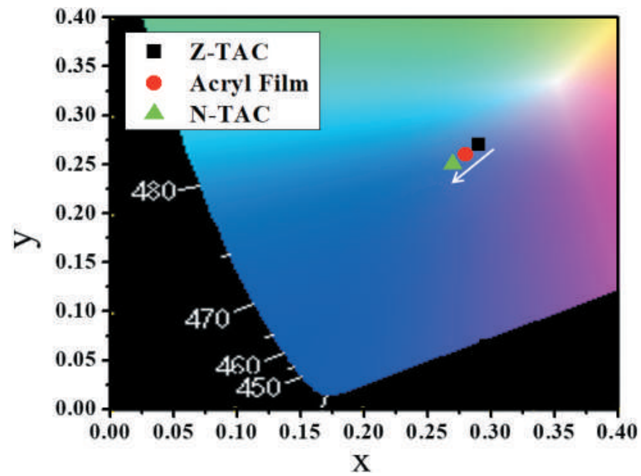

Figure 7. (Colour online) Measured chromatic coordinates of HA-LCD with different optical compensations by using Z-TAC, acryl film and N-TAC observed at oblique viewing direction (ϕ = 45°, θ = 60°).

positive R_{th} is positioned in a red colour region but those of acryl film and N-TAC with negative R_{th} values are positioned in a blue region. Overall, the red colour mura is suppressed for the polariser protection TAC film with adoption of negative R_{th}.

Conclusion

We have demonstrated how in-plane and out-of-plane retardation of a protection TAC film of a polariser affects a dark state of the HA-LCD by simulation and experiment. A minimal wavelength dispersion in polarisation conversion is confirmed by negative out-of-plane retardation TAC film compared to the film with positive retardation, which effectively eliminates the off-axis red colour mura. Our study reveals the negative retardation

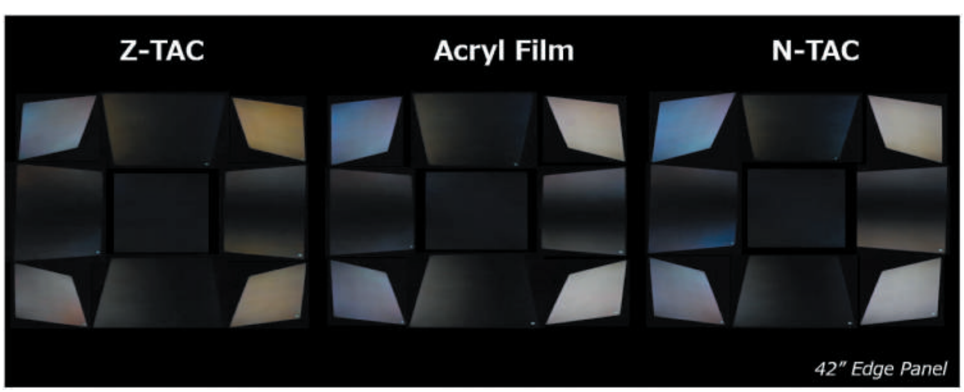

Figure 6. (Colour online) Optical compensation of 42″ Edge IPS panel with Z-TAC, acryl and N-TAC films in the normal and oblique directions.

TAC film is an efficient approach to eliminate the off-axis red colour mura for the HA-LCD.

Disclosure statement

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