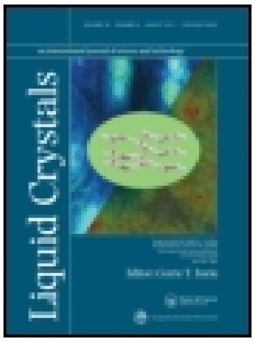

Liquid Crystals

ISSN: 0267-8292 (Print) 1366-5855 (Online) Journal homepage: http://www.tandfonline.com/loi/tlct20

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To cite this article: Lee Tae Rim, Jin Ho Kim, Myung Chul Jun, Seung Hee Lee & Hong Koo Baik (2016): Optimisation of alignment materials for minimising residual retardation in in-plane switching liquid crystal display, Liquid Crystals, DOI: 10.1080/02678292.2016.1221152

To link to this article: http://dx.doi.org/10.1080/02678292.2016.1221152

Published online: 07 Nov 2016.

LIQUID CRYSTALS, 2016
http://dx.doi.org/10.1080/02678292.2016.1221152

Optimisation of alignment materials for minimising residual retardation in in-plane switching liquid crystal display

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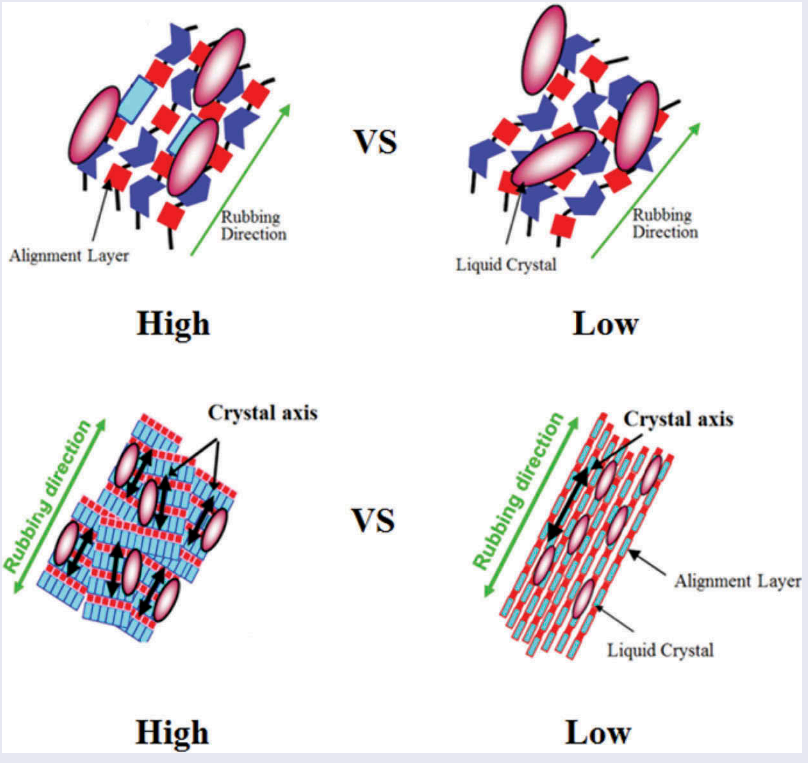
ABSTRACT
The light leakage in a black state of in-plane switching (IPS) liquid crystal display (LCD) associated with rubbing process has been investigated. The mechanical rubbing process with a cloth caused orientation disorders in the liquid crystal directors and these partial orientation disorders result in residual retardations of the IPS LCD, causing the light leakages at the black state. In this study, we theoretically estimated how the light leakage is associated with the rubbing uniformity using 2 × 2 Jones matrix equation and also experimentally confirmed how it is associated with structural properties of the alignment layer. The light leakage was clearly reduced in the alignment layer with reduced crystallinity and flexibility.



ARTICLE HISTORY
Received 29 June 2016
Accepted 2 August 2016

KEYWORDS
In-plane field switching; alignment layer; rubbing; contrast ratio

1. Introduction

Nowadays, liquid crystal displays (LCDs) are dominating flat panel display market owing to its great improvements in image quality and product cost although the standing level of LCDs is challenged by organic light emitting diodes.[1] Many new liquid crystal (LC) modes, such as multidomain vertical alignment (MVA),[2–4] in-plane switching (IPS),[5–7] and fringe-field switching (FFS) [8–16] contribute to the development of high image quality in LCDs. In IPS

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and FFS mode, LC molecules are homogeneously aligned by either rubbing or photoalignment process, and the first is still popular because mechanical rubbing process is still effective process for mass production and reliable LC alignment with low cost. However, the rubbing process yields poor black image quality because of its unique light leakage property at the black level, resulting in a low contrast ratio at a normal direction.[17]

The light leakage in a black state of IPS and FFS mode can be mainly classified by three factors [18]; the depolarisation effects by the light scattering of the thin film transistor layer (TFT), colour filter layer (CF), and liquid crystal (LC); the residual retardation of alignment layer, which is caused by the uniformity problem in the mechanical rubbing process; and the degree of polarisation effect of the polariser and analyser. A scattering and depolarisation effect in IPS and FFS-LCD causes light leakages at black level, and several approaches to reduce the light leakage were already reported.[19–24] However, until now there has been no theoretical analysis and improved method of the light leakage caused by residual retardation of alignment layer with mechanical rubbing process. In the rubbing process, it is not so easy to achieve uniform LC alignment, especially in large-sized glass substrates because of non-uniform cloth-filament shapes and non-uniform directions of rubbing cloths. This non-uniformity of LC alignment results in minute residual retardations in homogeneously aligned LCD cell, causing light leakage in the black state of IPS and FFS LCDs.[25,26]

In this work, the dependence of crystallinity and flexibility of alignment layer on light leakages in a black state of IPS and FFS LCDs has been investigated.

2. Understating relationships between rubbing uniformity and dark state in IPS LCD

In the IPS mode, the LCs are homogenously aligned, and thus its optic axis lies in plane. The normalised transmittance of the cell is given by the following equation:

$$T/T_o = \frac{1}{2}\sin^2 2\alpha_{\mathrm{eff}}\ \sin^2\left(\frac{\pi d\Delta n_{\mathrm{eff}}}{\lambda}\right), \qquad (1)$$

where α_{eff} is a voltage-dependent effective angle between LC director and transmittance axes of the crossed polarisers, d is the cell gap, Δn_{eff} is a voltage-dependent effective birefringence of LC layer, and λ is the wavelength of an incident light. As easily understood from Equation (1), a perfect dark state can be achieved as long as is α_{eff} equal to 0° in a voltage-off state. However, any deviation of LC director from crossed polarisers would render α not equal to 0° and $d\Delta n_{\mathrm{eff}}$ not equal to zero, simultaneously, resulting in a light leakage in a dark state.

In a black state of the real IPS LCD with homogenous alignment under crossed polarisers, a light leakage is easily observed unlike an ideal case and its leakage level varies from position to position. In order to interpret the variation in the light leakage, a simple modelling associated with arrays of LC directors is adopted, as shown in Figure 1. In this modelling, the IPS LCD is divided by thousands of macro cells in which all macro cells (called 'block A') have the same average rubbing angle of 0° and each one macro cell is also divided by thousands of micro cells (called 'block B'), as shown in Figure 1(a). Therefore, although the α_{eff} is 0° in macro cells, the light leakage can be generated only if there is any deviation of LC directors from 0° in micro cells. In an ideal case in which the rubbing process is perfectly performed such that α_{eff} = 0° in all micro as well as macro cells, no light leakage is caused by LC director distribution at all, as shown in Figure 1(b). However, in a real practical case, α is not equal to 0° in each small region of the rubbed area (block B) although the rubbing axis is the same as the polarising axis so that average α equals to 0° in all block As. Consequently, partial residual retardations due to non-uniform rubbing process exist as shown in Figure 1(c). All LC directors in block Bs have a kind of Gaussian distribution with respect to the rubbing angle, that is, each director angle of the LC in block B is not exactly aligned with polariser axis. Polarising optical microscopic images of black states for two IPS cells made with two different commercialised alignment layers (PI-1, PI-2) show such examples in which α is not equal to 0° in small regions of the rubbed area, as shown in Figure 1(d). In addition, it is also noticeable that two IPS LC cells show a large difference in the level of the light leakage and its shapes, despite of being made in the same rubbing condition. The LC cell with PI-1 alignment layer exhibits higher light intensity than that of the LC cell with PI-2 alignment layer in the black state, indicating that there is more residual retardation in the LC cell with PI-1 than the LC cell with PI-2.

In order to calculate the light leakage in IPS LCDs for a cell retardation of $d\Delta n$ (350 nm at 589 nm), angles of each optical layer, such as polariser (Φ_p), analyser (Φ_a), entrance (Φ_0), and exit (θ) LC direction are defined with respect to X-axis, as shown in Figure 2. The theoretical light leakage intensity in a black state of IPS LCD due to partial residual retardations caused by non-uniform rubbing is calculated. The

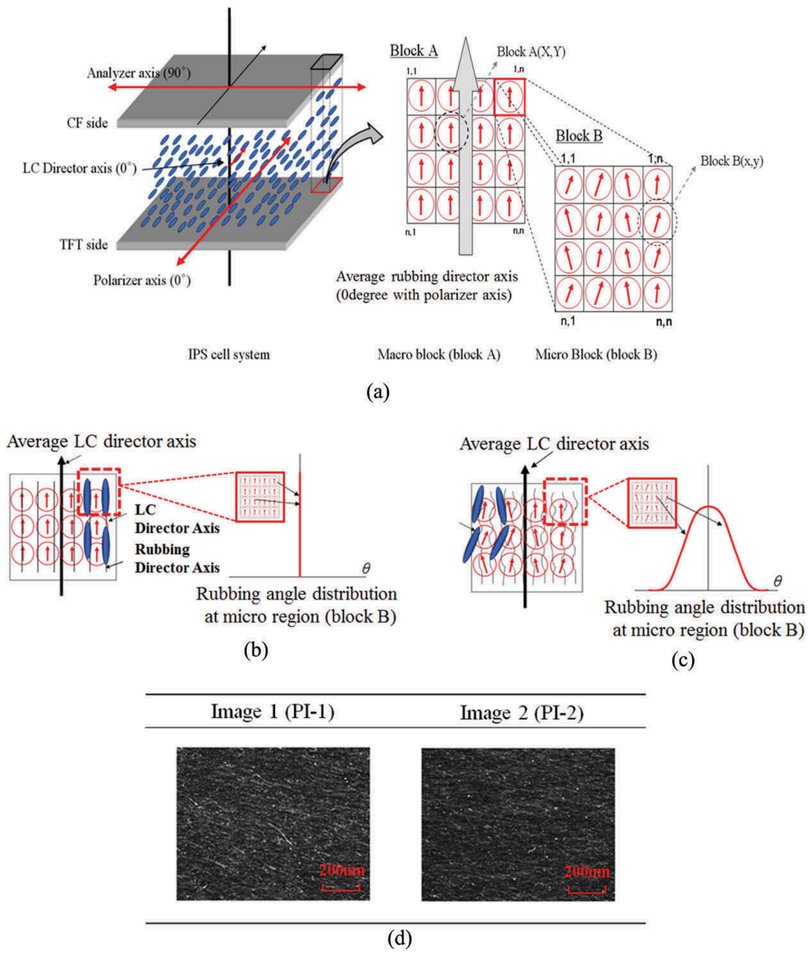

Figure 1. (colour online) (a) Modelling of LC alignment distributions in macro (LC directors inside circles) and micro (LC directors inside squares) blocks by the mechanical rubbing process in voltage-off dark state. (b) An ideal case with $\alpha = 0°$ in all areas, in which light leakage is not observed and (c) a practical case with $\alpha \neq 0°$, in which light leakage is observed. (d) Polarising optical microscopic images of black states for two IPS cells made with two different commercialised alignment layers (PI-1, PI-2).

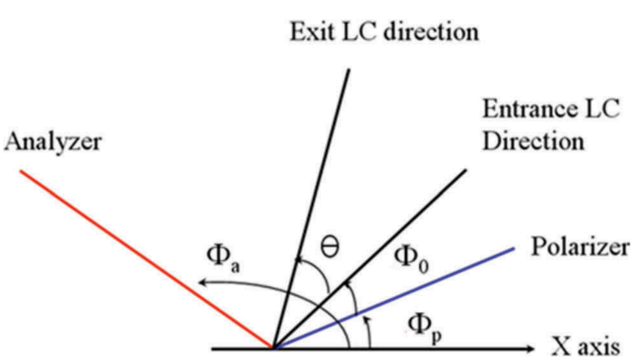

Figure 2. (colour online) Definition of angles for polariser, analyser, and, entrance and exit LC direction with respect to X-axis.

average light leakage intensity at block A(X,Y) for $n \times n$ blocks, $I_A(X,Y)$ is given by the following equation:

$$I_A(X,Y) = \sum_{x=1,y=1}^{n,n} I_B(x,y)/(n \times n), \qquad (2)$$

where $I_B(x,y)$ is the average light leakage intensity at block $B(x,y)$ area. $I_B(x,y)$ can be calculated with 2×2 Jones matrix theory and also utilising the transmittance equation of conventional twisted nematic mode,[27] given by

$$T = \left[\frac{1}{x\sin(\theta)\sin(\theta - \Phi_a + \Phi_p)} + \cos(\theta - \Phi_a + \Phi_p)\right]^2 + \frac{x^2 - 1}{x^2\sin^2(\theta)\cos^2(\theta + 2\Phi_o - \Phi_a + \Phi_p)}, \qquad (3)$$

where $x^2 = 1 + u^2$ and $u = \dfrac{\pi \Delta n_{\mathrm{eff}}}{\lambda\theta}$.

In this modelling case, the crossed polariser is considered such that Φ_p is 0° and Φ_a is 90°. The LC director angles at the entrance side (Φ_0) can be transformed into $\Phi_{0(x,y)}$ and the deviated angle (θ) of LC director between bottom and top substrates coming from rubbing process (θ) can be described as $\theta_{(x,y)}$. Then, from Equation (3), I_B (x,y) can be given as

$$I_{\mathrm{B}}(x,y) = \left[\frac{1}{x\sin^2(\theta_{(x,y)})\cos^2(\theta_{(x,y)} + 2\Phi_{0(x,y)} - \pi/2)} + \cos(\theta_{(X,Y)} - \pi/2)\right]^2 + \frac{x^2 - 1}{x^2\sin^2(\theta_{(x,y)})\cos^2(\theta_{(x,y)} + 2\Phi_{o(x,y)} - \pi/2)}. \tag{4}$$

Using Equations (2) and (4), we calculated $I_A(X,Y)$, which represents the light leakage intensity in a black state of the IPS cell depending on the degree of residual retardations at certain rubbing angle deviations.

3. Experimental conditions

In order to find out a correlation between molecular structures of polyimide (PI) and light leakages in the black state of the IPS LCD, the cell with a simple electrode structure is prepared, as shown in Figure 3. The test cell size is 4.5 cm × 3.0 cm with its active area 1.0 cm^2. Come-like electrodes in the active area have wedge shape for two domains with 20° with respect to the vertical axis. All common electrodes are connected to common (V_{com}) signal pads and all data electrodes are connected to data signal pads. Both electrodes made of indium-tin-oxide (ITO) exist on bottom glass substrates and an additional ITO layer is prepared on the upper layer of the top glass to prevent static electricity damage. To maintain the cell gap of the LC cell, ball spacers are used on the whole area of the test cell.

In order to find an optimal PI which gives a least level of light leakage, four different PIs (PI-A, PI-B, PI-C and PI-D), were tested for homogeneous alignment of the LCs, and the same rubbing process on each bottom glass and top glass layers were performed in anti-parallel direction each other. A LC (MAT-09–190 Merck Advanced Technology, Korea) with physical properties (birefringence Δn = 0.1030 at 589 nm, dielectric anisotropy $\Delta\varepsilon$ = 7.6 at 1 kHz, 20°C) is used and the cell gap is 3.4 μm. For measurement of light leakage in a black state, a brief schematic system for measuring transmittance is shown in Figure 4. A general LCD backlight system with a proper spectrum was irradiated to the LC while the best dark state was

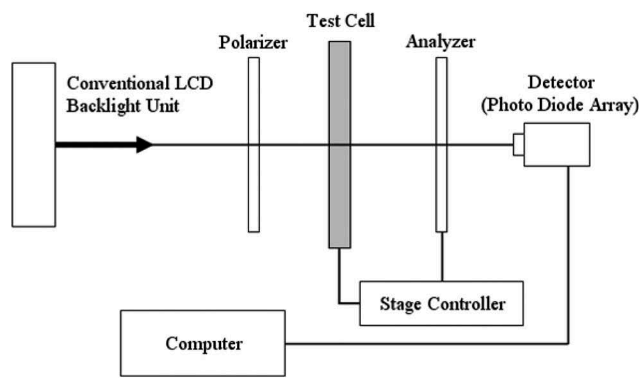

Figure 4. A brief schematic system for measuring transmittance in black state of IPS cells.

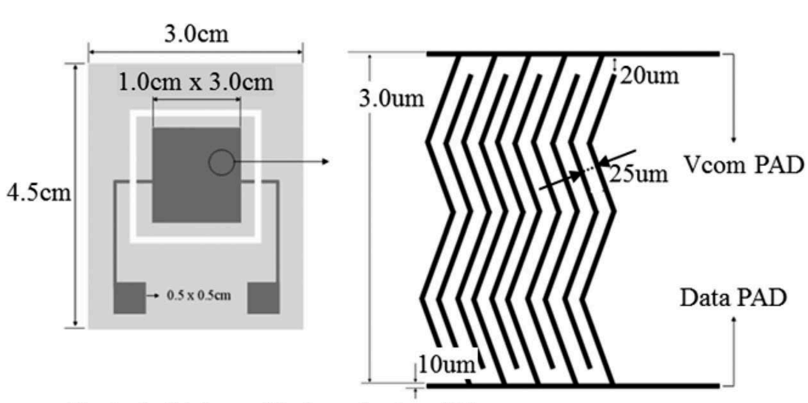

Figure 3. Schematic cell structure of the IPS test cell used for measuring light leakage.

achieved by rotating the LC cell and the analyser once the polariser axis and LC's optic axis was fixed to be coincident each other at first. The outgaining light intensity in the normal direction of the test cell was measured using a luminance detector.

4. Results and discussion

At first, we calculated the intensity of light leakage in the black level by rubbing angle deviations caused by the non-uniform LC orientation using Equations (2) and (4). Once the leakage was calculated, the intensity in the white state was also calculated in a condition with α_{eff} = 45° under crossed polarisers. Finally, the estimated contrast ratio values of the IPS cell were calculated. In these calculations, the light leakage intensity was calculated by assuming a condition that the average rubbing axis is 0° with the Gaussian distribution, as shown in Table 1. And then, as the distribution of LC optic axis (rubbing angle axis) in upper and down substrate increases from 0° to 2° in the micro cell areas, the intensity of light leakage in black level also increases exponentially from 0% to 0.40%. As the result, the contrast ratio drops from 1875:1 (ideal case) to 220:1. As can be seen from the above calculations, the light leakage in the black state of IPS cell decreases with the reduction of deviations in the rubbing axis variations, confirming that residual retardation significantly affects the contrast ratio of the IPS LCD.

In general, the causes of light leakage in IPS LCD can be classified mainly by three factors: the degree of polarisation of polariser; the depolarisation effects by the light scattering of the thin film transistor layer, colour filter layer and liquid crystals; the residual retardation effect from the alignment layer. It has been reported that the residual retardation effect from the alignment layer takes up a proportion of about 20% in the light leakage intensity at black state.[28] In consideration of the display with full white luminance 500 nit and contrast ratio of 1500:1, the black luminance of this display is about 0.33 nit. In addition, if the occurrence of the black luminance due to rubbing angle deviations by uneven rubbing process is assumed to be 20%, the black luminance occurred due to the non-uniform rubbing is calculated to be 0.066 nit (= 0.33 nit × 0.2). Therefore, if we have a perfect rubbing process without any rubbing angle deviations, the black luminance in such an ideal case will be 0.267 nit (= 0.333 nit − 0.066 nit). At present, the contrast ratio of a commercialised IPS LCD is 1500:1 so that if we remove the rubbing non-uniformity up to the ideal case, the contrast ratio will be increased up to 1875:1.

Now, how the molecular structures of PI alignment layer affect a dark state of IPS cell is investigated. As already shown in Figure 1(d), two different IPS cells made with two different alignment layers gave rise to different level of the light leakage such that it was 0.341 and 0.297 nit for PI-1 and PI-2, respectively. Furthermore, more detail observation of two cells with micro image analysis showed the difference in light leakage locally and also dispersion level of the light leakage, clearly indicating that different PI structures can affect the black state of the IPS/FFS LC cells strongly, even though they are made by the same cell process conditions. We believed that this result was caused by the difference in the PI material structures contacted with the rubbing cloth. In other words, the chemical structure of PI alignment material can be a critical factor in reducing the deviation of the rubbing axis in the micro area (block B) under the same rubbing process conditions, and thus an optimisation of molecular structure of PI can give rise to minimal light leakage.

We have attempted to clarify the correlation between chemical structure of PI alignment layer and light leakage in the black state of IPS cell. In general, a clear black state can be achieved in well-oriented surface molecules of an alignment layer during rubbing process. In general, it is estimated that the flexibility of PI structure and surface crystallinity of PI can affect such an orientation strongly, that is, the PI with higher flexibility and lower crystallinity gives rise to better LC orientation along the rubbing direction, as shown in Figure 5. To confirm the estimation, structural changes of PI alignment layer were carried out based on viewpoints of controlling the level of

Table 1. Summary of the light leakage variations in a black state of IPS cell according to specific deviations of LC optic axis from polariser in the micro cell area.

Polariser axis (°)	Analyser axis (°)	Average axis of LC at TFT side (°)	LC axis distribution range at TFT side (°)	Average axis of LC at CF side (°)	LC axis distribution range at CF side (°)	Average transmittance at black state (%)	Calculated contrast ratio
90	0	0	0	0	0	0.0000	1875:1 (Ref.)
90	0	0	0.1	0	0.1	0.0010	1839:1
90	0	0	0.2	0	0.2	0.0042	1737:1
90	0	0	0.3	0	0.3	0.0098	1583:1
90	0	0	0.5	0	0.5	0.0268	1248:1
90	0	0	1.0	0	1.0	0.0944	676:1
90	0	0	2.0	0	2.0	0.4011	220:1

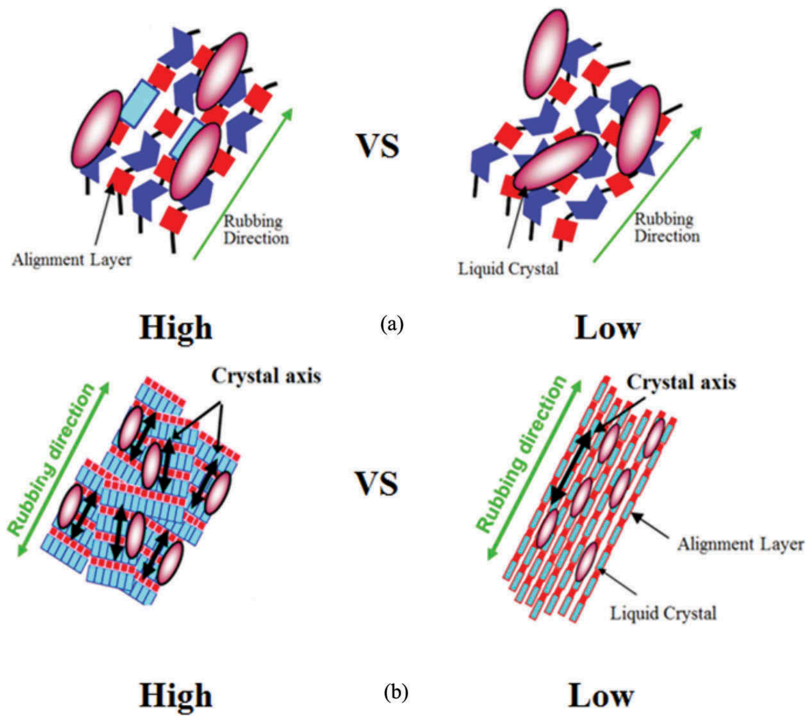

Figure 5. (colour online) Schematic concepts of LC director alignment depending on structures of the alignment layers: (a) the polymer flexibility with high and low degree and (b) the polymer crystallinity with high and low degree. The layer with structures of high flexibility and low crystallinity exhibits better LC alignment along the rubbing direction.

crystallinity and flexibility. Four different PIs with different main diamine structures were prepared, as shown in Figure 6. PI-A has a high crystallinity with linear three-aromatic ring structure, PI-B has a proper crystallinity and proper flexibility with two-aromatic ring which are connected with short aliphatic molecules, PI-C has a lower crystallinity and higher flexibility with its two-aromatic ring which is connected with long aliphatic structure, and PI-D has very low crystallinity and very high flexibility with long

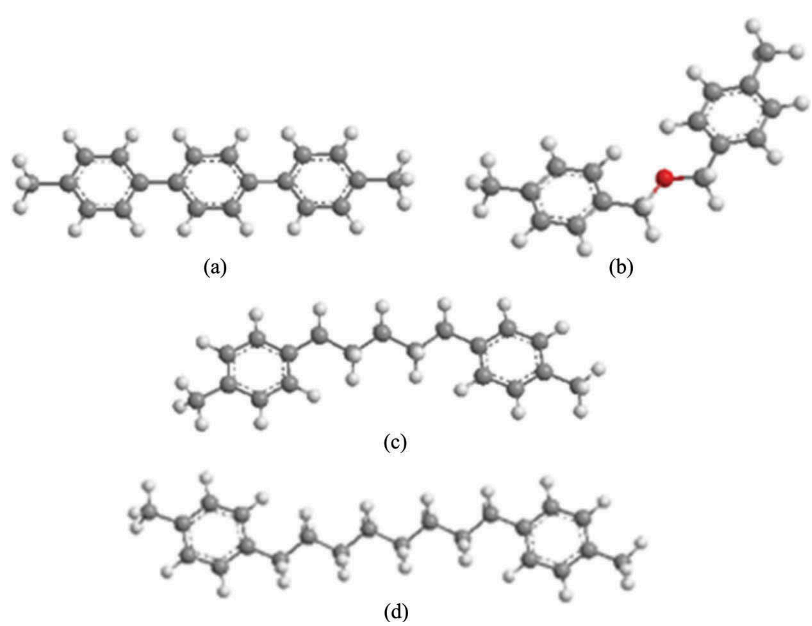

Figure 6. (colour online) Diamine structures of each polyimide alignment materials (white balls: hydrogen, grey balls: carbon, red ball: oxide). (a) PI-A, (b) PI-B, (c) PI-C, (d) PI-D.

aliphatic structure. In summary, the order of bulk crystallinity in a polymer is PI-A > PI-B > PI-C > PI-D, and the order of polymer flexibility is PI-D > PI-C > PI-B > PI-A. For detail interpretation of the light leakage differences between PIs in the black state, we analysed the light leakage distributions with micro image analysis for each PI case. At first, light leakage images of each PI materials were captured by a polarising optical microscope with appropriate scales. All images were captured at the lowest transmittance with controlling polariser and analyser angles. The distributions of light leakage intensity were analysed digitally using a mathematic tool (MAT-LAB 7.0). Figure 7 shows the captured images and converted digital distribution graph for all PIs. Condition 1 shows captured images for the analysis of the light leakage in a wide area of the IPS cell (300 μm × 450 μm). Condition 2 shows its analysis in a smaller area of the test cell (70 μm × 200 μm). Images of condition 2 were captured three times at random positions in the same IPS cell. A converted digital distribution graph extraction was performed using the condition two images. Black light leakage distributions were fitted vertically and horizontally in the distribution graph and the summation of the leakage in both directions is described in Figure 8 and Table 2. The average light leakage intensity in the black level in arbitrary scale is as follows: PI-A is 37.05, PI-B is 28.98, PI-C is 26.68 and PI-D is 20.22. And the standard deviation value for PI-A, PI-B, PI-C and PI-D is 35.88, 25.53, 22.96 and 17.34, respectively. In particular, the cell with PI-D exhibited much less light leakage and the associated standard deviation value than the cell with PI-A by 45.4% and 51.6%, respectively, indicating that the PI with lower light leakage intensity resulted in a narrower distribution in the leakage. As previously explained, the light leakage intensity in IPS cell is decreased when the residual retardations are lowered by decreasing the rubbing angle deviation. These results also explain that the orientational-ordering level of PI film along the rubbing direction by the rubbing process and also the amorphous macro structure of PI film itself are strongly related to the rubbing uniformity in homogeneous alignment layer.

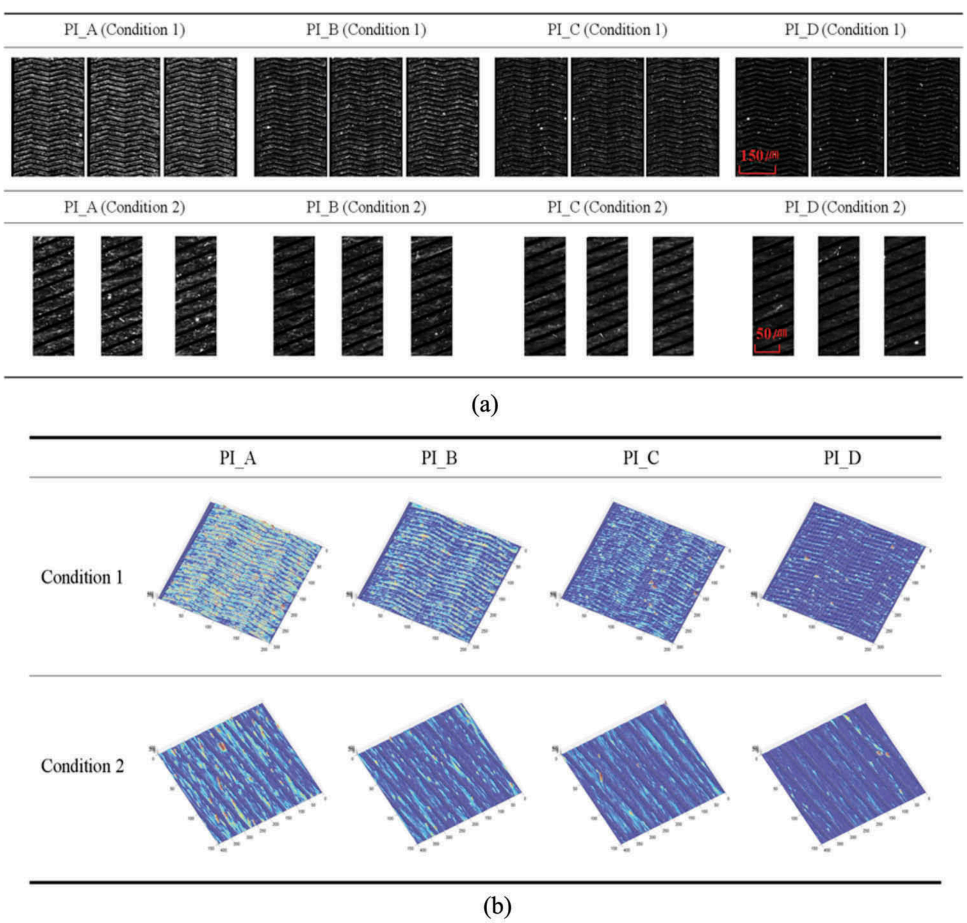

Figure 7. (colour online) (a) Captured images of the light leakage and (b) converted digital three-dimensional distribution images of the rubbed textures in each PI. The measured sizes for condition I and II are 300 μm × 450 μm and 70 μm × 200 μm, respectively.

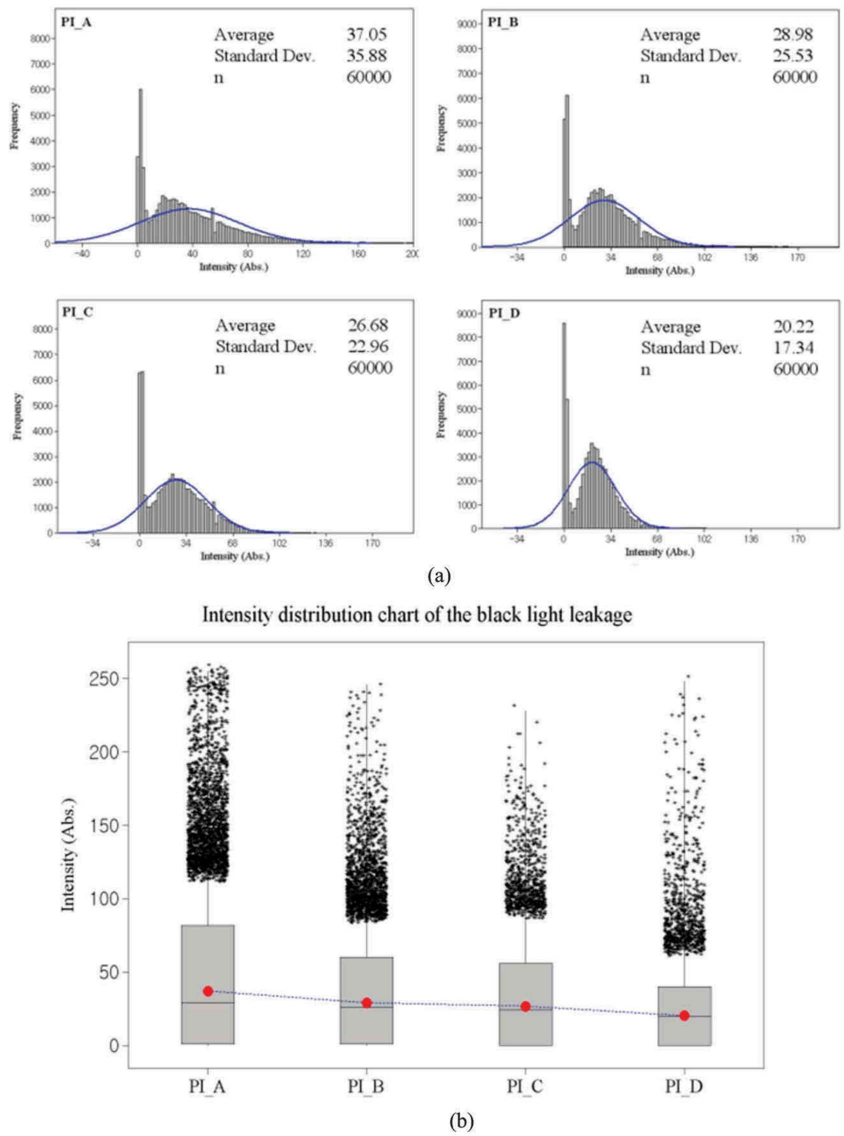

Figure 8. (colour online) Histogram chart (a) and intensity distribution chart (b) of the light leakage in the black state of IPS cell with four different PIs.

Table 2. Leakage intensity and its standard deviation in black states of IPS LCDs for four different PIs.

		PI-A	PI-B	PI-C	PI-D
Leakage intensity (abs.)	Average intensity	37.1	29.0	26.7	20.2
	Standard deviation	35.9	25.6	23.0	17.3
Decrement (%)	Average intensity	Ref.	22%	28%	45%
	Standard deviation	Ref.	29%	36%	52%

The decrement ratio of the leakage for other three PIs is calculated with respect to PI-A.

In particular, increased polymer linearity along the rubbing direction owing to very high flexibility with long aliphatic structure and reduced crystallinity in PI-D structures is a very effective concept for the improvement of rubbing uniformity and the reduction of average black intensity.

In summary, the results clearly show that the PI structure was strongly related to the light leakage intensity in the black state of IPS LCD, which was caused by non-uniform rubbing in the micro cell area (block B) under the same process conditions. In addition, we could confirm that the flexibility and crystallinity of alignment layer affects degree of residual retardation occurrence during rubbing process, and the introduction of high flexible and low crystalline diamine structure in the alignment layer can reduce the light leakage intensity in the black state of IPS cell. With this approach, we successfully developed the PI with low residual retardations and adopted PI-D material to a conventional real 17 in. WXGA IPS panel with process optimisation, and successfully achieved a reduction of over 15% in black light leakage.

5. Conclusion

We confirmed that residual retardation caused by rubbing non-uniformity significantly affects light leakage in a black state of IPS LCDs. In order to reduce such residual retardations, we attempted the structural modification of the alignment materials. Our experimental results showed that the alignment layer with the structure having reduced crystallinity, increased alignment ability, polymer flexibility, and polymer linearity associated with the rubbing process could result in improvement of rubbing uniformity and better alignment of LC director, and thus highly enhance the black state of the real IPS panel.

Acknowledgements

We deeply appreciate the LCD Materials Laboratory of Nissan Chemical and JSR Corporation for their kind support of the research.

Disclosure statement

No potential conflict of interest was reported by the authors.

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