Current Applied Physics 11 (2011) 725–730

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

Film compensation of twisted nematic liquid crystal display using a rod-like reactive mesogen

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ARTICLE INFO

Article history:
Received 14 April 2010
Received in revised form
5 October 2010
Accepted 15 November 2010
Available online 22 November 2010

Keywords:
Twisted nematic
Hybrid aligned compensation film
UV curable rod-like mesogen

ABSTRACT

A hybrid aligned nematic liquid crystal compensation film using UV curable rod-like mesogen has been made to compensate the residual birefringence of a twisted nematic (TN) device at oblique viewing directions in the dark state. Effective retardation value of the fabricated film was characterized by experiment and calculation using simulation. The results showed that the film has a hybrid alignment with a tilt angle variation from 3° to 19°. The optical compensation effects are evaluated in terms of light leakage in the dark state and contrast ratio (CR). The measured results showed that the light leakage is greatly suppressed with the compensation film and the viewing angle characteristics of TN device are greatly improved, most particularly in the up direction.

1. Introduction

Twisted nematic liquid crystal displays (TN-LCDs) [1] which were proposed several decades ago are still popular in small portable displays because of the characteristics of low power consumption, high light efficiency and low cost caused by high process margin in spite of their narrow viewing angle characteristics.

The residual birefringence effect is the cause of limited viewing angles in TN-LCDs, since when light passes through the medium, the strong light leakage occurs at oblique viewing directions in the dark state, which decreases the contrast ratio (CR) and is the basic reason of gray scale inversion in the displayed image. To eliminate the residual birefringence effect of the LCDs in dark state is the serious issue and has a great attention of current research.

In order to overcome the narrow viewing angle problems, several wide viewing angle liquid crystal (LC) devices such as in-plane switching (IPS) [2], multi-domain vertical alignment (MVA) [3], patterned vertical alignment (PVA) [4], and fringe-field switching (FFS) [5–7] have been developed and commercialized. Nevertheless, TN-LCDs with adoption of film compensation are emerging as an important area in the method for wide viewing angle due to relatively low production cost and easy fabrication. The compensation films such as a polymerized discotic LC film called as wide-view (WV) film [8–10] and hybrid aligned LC film [11,12] using a rod-like liquid crystalline polymer were developed and showed wide viewing angle characteristic compared with conventional TN-LCD. However, WV film with discotic LC has high production cost and gray scale inversion still persists.

In this paper, we have developed a compensation film using a rod-like reactive mesogen (RM) based on thiol-ene polymerization as an alternative to acrylate photopolymerizations [13]. In this system, step-growth free-radical polymerization between diene-type RMs and dithiol compounds, initiated by photoinitiator, proceeds rapidly under an ambient environment as compared to the conventional acrylate-type RMs of which polymerization has to be performed under nitrogen atmosphere to avoid an inhibition by oxygen [14]. In addition, the photosensitive resin formulated from the novel RM gave a uniformly aligned polymeric film having a hybrid LC alignment after photocuring, which enabled us to explore a new type of nematic liquid crystal compensation film. Since the new compensation film is based on a rod-like RM, it is cheaper than those obtained from discotic LC, and is very useful to remove viewing angle dependent light leakage in the dark state of conventional TN-LCD. Through the experiment, simulation and analysis of results, we confirm the configuration and tilt angle of

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1567-1739/$ – see front matter
doi:10.1016/j.cap.2010.11.039

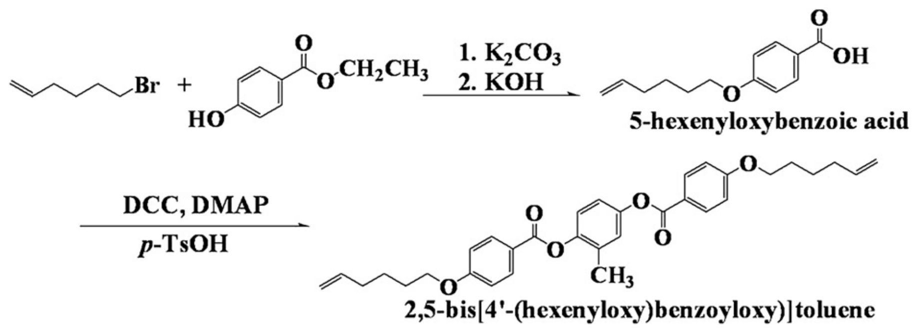

Fig. 1. Synthetic route and chemical structure of UV curable RM.

RM on substrate and compensation effect on TN cell where the viewing angle and CR are important perspectives.

2. Film fabrication and analysis

Firstly, a diene-type reactive mesogen (DERM), 2,5-bis[4′-(hexenyloxy)benzoyloxy]toluene, was synthesized as shown in Fig. 1 by condensation reaction between methyl hydroquinone and 4′-(5-hexenyloxy)benzoic acid [13], and mixed with 1 eq 1,6-hexanedithiol and 2 wt% of diphenyl(2,4,6-trimethylbenzonyl)-phosphineoxide (TPO, Ciba Darocure™) in xylene to obtain a photo-curable RM resin. Then, homogeneous alignment layer (Polyimide, AL 16157) was coated on the glass substrate and rubbed to be aligned in one direction. After rubbing, the synthesized photo-curable RM resin was spin-coated, solvent was removed, and UV light (365 nm, 90 mW/cm^2) was irradiated for 120 s to give a uniformly aligned polymeric film by step-growth free-radical polymerization between DERM and dithiol.

Fig. 2 shows retardation value depending on viewing angle and microscopic images of hybrid film in the left, front, and right directions. The difference in the effective phase retardation values according to viewing angle is clear from Fig. 2(a). The retardation value in the front direction was 138 nm, smaller than the retardation value of 149 nm in the left direction but larger than that of 103 nm in the right direction at polar angles of −40° and 40° respectively, at an incident light of 589 nm. Fig. 2(b) shows that the left direction image of the film is brighter than the front one, however the right direction image of film is darker, comparatively. These results indicate that the effective phase retardation value according to viewing angle of fabricated film gradually decreases from left to light, which is responsible for the darker and darker images in the same direction. The optical properties of the hybrid compensation film were measured by using REMS-150 in Sesim Photonics Technology.

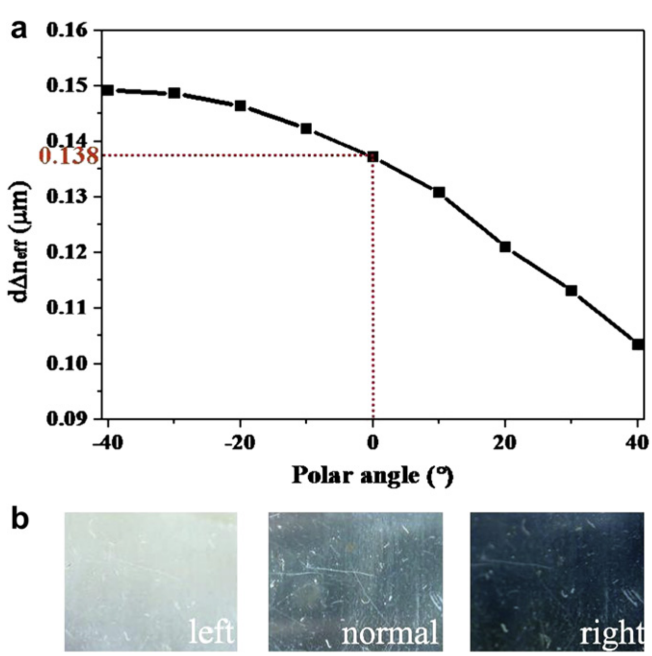

Fig. 2. (a) Retardation values depending on viewing angle and (b) microscopic images of fabricated film according to the left, normal, and right viewing direction.

Fig. 3(a) shows a simple modeling of the tilt and distribution of RM from bottom to top direction on the fabricated film, as based on the results we expected here that fabricated film has hybrid alignment. At the bottom, the RM is aligned homogeneously due to the interfacial interaction between RM molecules and homogeneous alignment layer rubbed. However, to minimize the surface tension difference between the RM and the surface in contact with air, RM at the surface should be aligned homeotropically, so the RM is aligned from horizontally to perpendicularly on the substrate from the bottom to top. The angle formed by the RM on the top is a maximum tilt angle, whereas the angle of RM on the substrate is minimum tilt angle, as shown in Fig. 3(a). From the scanning electron microscopic (SEM) image of fabricated film, we confirmed that photo-curable resin formed polymer layer of a thickness of 815.5 nm, which can be seen in Fig. 3(b).

3. Principle of film compensation

Although molecules of the both TN cell and fabricated film have rod-like shape and positive birefringence ($n_x = n_y < n_z$), compensation effects in the dark state of the TN cell can be improved effectively as the rubbing direction of TN cell is perpendicular against rubbing direction of hybrid aligned film as shown in Fig. 4(a). In the TN mode, effective birefringence (Δn_{eff}) is not zero at off-normal axes in the dark state because mid-director of LC molecules tilts up close to 90°, whereas LC molecules in the vicinity of surfaces are hard to tilt up due to surface anchoring energy, which causes the tilt angle distribution of LC into a symmetric LC orientation from the middle to either top or bottom surfaces of the TN cell. In addition, the tilt angle variations have hybrid alignment from the surfaces to middle of the TN cell along the z-axis. To compensate the residual birefringence generated by hybrid configuration of TN cell in the dark state, the molecules pattern of the compensation film should also be in hybrid structure similar to half of the dark state in TN cell. The normalized transmittance (T) of TN cell under the crossed polarizer is given as follows:

$$T \propto \sin^2(\delta(\theta, \Phi, \lambda)/2),$$

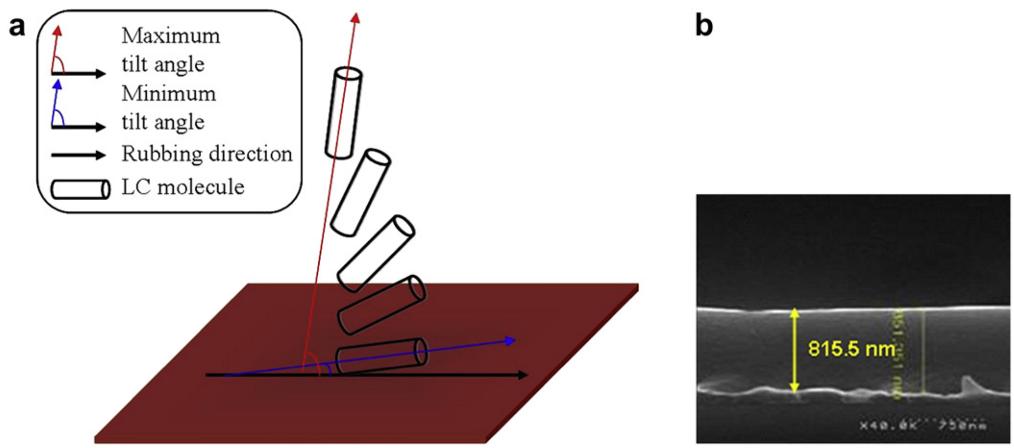

Fig. 3. (a) The configuration of the molecules of the RM on the film and (b) scanning electron microscopic image of the film.

where δ is the phase difference, θ and Φ are the polar and azimuthal angles in spherical coordinates, respectively, and λ is the wavelength of the incident light [10]. To perfectly compensate the light leakage with fabricated film in all viewing directions of the proposed cell, it should be satisfied with following condition:

$$d\Delta n_{\mathrm{LC}}(\theta,\Phi,\lambda) + d'\Delta n_{\mathrm{film}} = 0,$$

where d, d', Δn_{LC}, and Δn_{film} are cell gap, film thickness, LC birefringence, and film birefringence, respectively. In other words, the value of phase retardation of the film should be the same as that of the TN cells, but the sign should be opposite to each other. Consequently, to compensate the angular dependent phase difference in LC molecules with hybrid distributions of the dark state in TN cells, the compensation films need to be aligned in hybrid orientations that change from parallel to vertical alignment, as shown in Fig. 4(b).

4. Results and discussion

To check the compensation effect of fabricated film on the TN cell, we fabricated normally white state TN cell with 90° twist from top to bottom substrate and O-mode. It has phase retardation value of 0.40 μm which is relatively lower than the typical value of the normal TN cell, considering the color characteristics when the compensation film was used. Physical properties such as a dielectric anisotropy ($\Delta\varepsilon$) and birefringence (Δn) of the LC were 8.1 (20 °C, 1 kHz) and 0.10 (20 °C, 589.3 nm), respectively.

Fig. 5 shows the microscopic images in different (up, normal, and down) viewing angle directions taken at polar angle of ±30° in the dark state of normal TN and film compensated TN cell. In conventional TN cell, light leakage in the dark state was generated strongly at upper direction but weakly at lower direction, which results in very low contrast ratio in the upper direction, as shown in Fig. 5(a). On the other hand, in compensated TN cell using hybrid aligned compensation film, light leakage in the dark state was reduced greatly in the upper direction, however, the light leakage was found approximately the same as compared to conventional TN cell in normal and lower directions as shown in Fig. 5(b). Therefore, these results show that the viewing direction dependent residual birefringence in TN cell is compensated effectively by hybrid aligned film, most particularly in the upper direction.

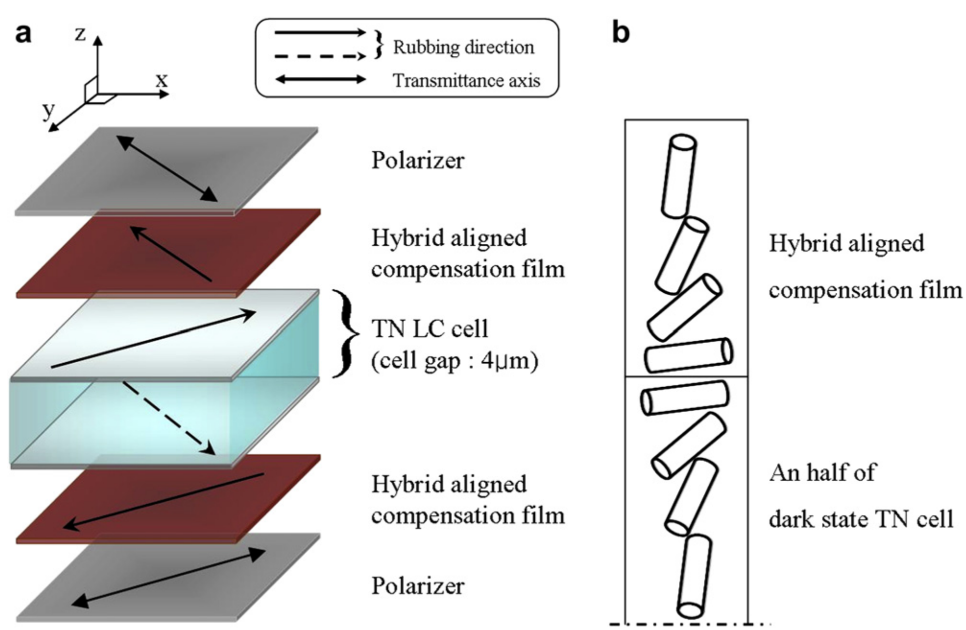

Fig. 4. (a) Arrangement of the compensated TN LC cell and (b) concept of compensation based on hybrid aligned film.

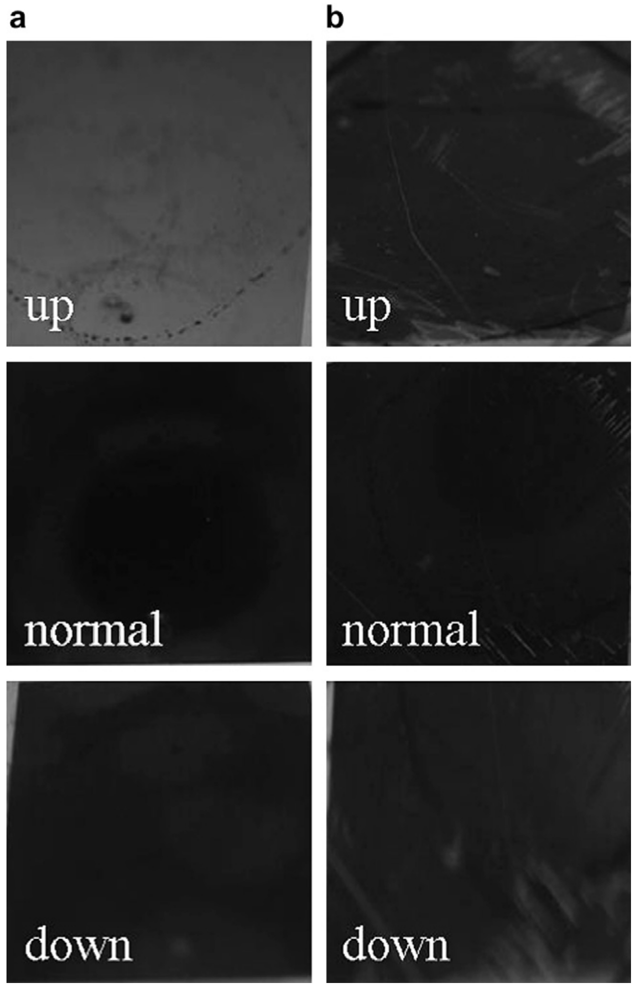

Fig. 5. Microscopic images according to viewing angle directions in the dark state: (a) normal and (b) film compensated TN, cells.

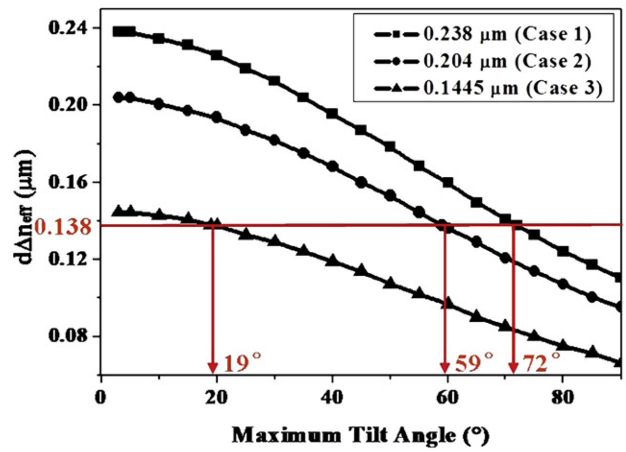

Fig. 7. Calculated effective phase retardation, $d\Delta n_{eff}$, as a function of the maximum tilt angle of compensation film with the different phase retardation values at 0.238 μm (Case 1), 0.204 μm (Case 2), and 0.1445 μm (Case 3).

In order to understand more clearly the reason of film compensation effect, we estimated the tilt angle at the top of the hybrid aligned film from the simulation tool (LCD Master, Shintech). Fig. 6 shows iso-luminance curves of normal TN mode without compensation film and compensated TN mode using hybrid aligned film to compare their results in dark state. The simulation conditions for the TN cell were the same as those of fabricated TN cell and pretilt angle assumed here was 3°. As shown in Fig. 6(a), the normal TN viewing angle characteristics have the strong light leakage at the upper direction in dark state. We expected maximum tilt angle of the hybrid aligned film was 90°, and therefore the maximum tilt angle of 90° and minimum tilt angle of 3° were taken for simulation of compensated TN mode. Fig. 6(b) shows iso-luminance curve of compensated TN mode in dark state and found that this has similar problem of strong light leakage at oblique viewing directions in dark state like normal TN mode. Hence the tilt angle of 90° at the top of the

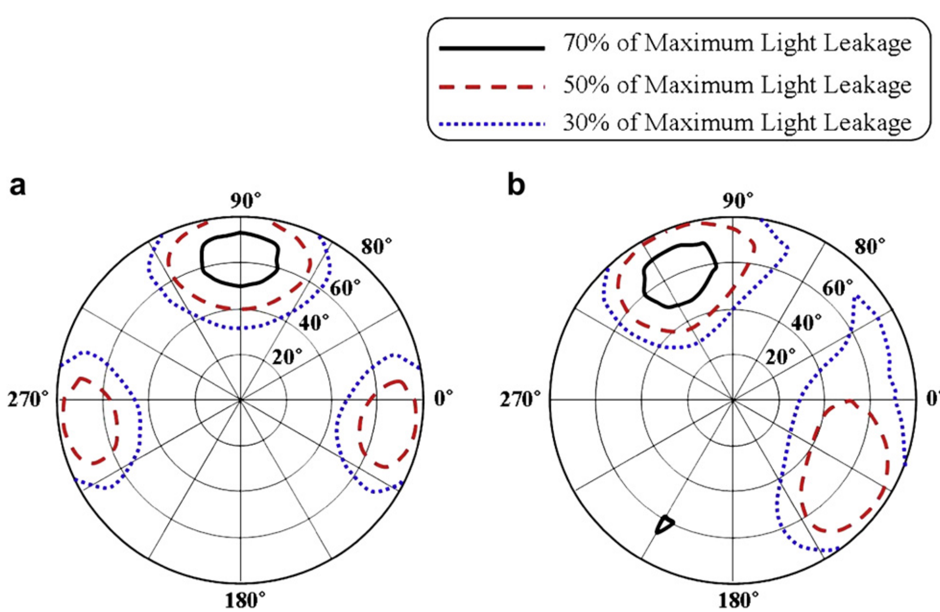

Fig. 6. Iso-luminance curves of (a) normal TN mode and (b) compensated TN mode, in dark state.

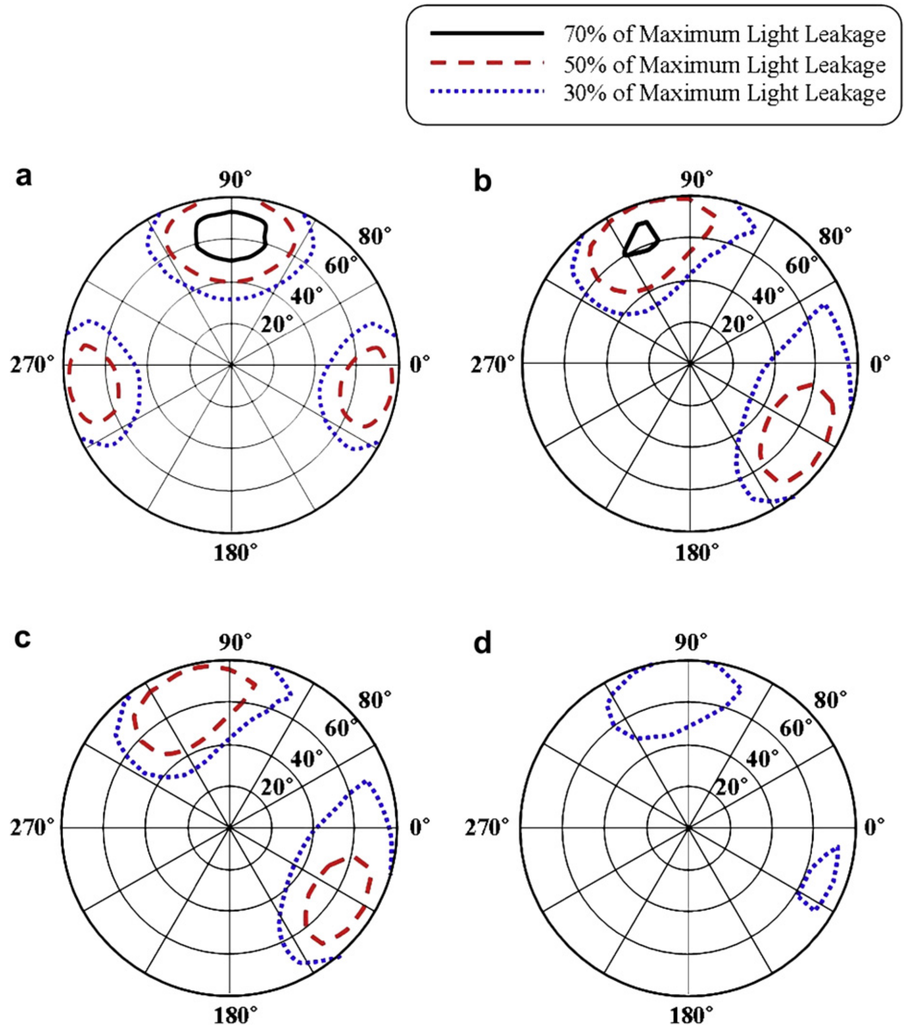

Fig. 8. Iso-luminance curves state of (a) normal TN and compensated TN with various phase retardation values at (b) 0.238 μm, (c) 0.204 μm, and (d) 0.1445 μm, of the compensation film in dark state.

hybrid aligned film did not show the compensated dark state as observed in the experimental observation of Fig. 5.

To find out the maximum tilt angle of compensation film according to our experimental result, we calculated effective phase retardation ($d\Delta n_{eff}$) as a function of tilt angle at the top of compensation film with different phase retardation values of 0.238 μm (Case 1), 0.204 μm (Case 2), and 0.1445 μm (Case 3), using simulation tool as shown in Fig. 7. Effective phase retardation of simulation data was observed at experimental value of 0.138 μm as given in Fig. 2. Thus the maximum tilt angle of the compensation film at $d\Delta n_{eff}$ equal to 0.138 μm was found to be 72° (Case 1), 59° (Case 2), and 19° (Case 3) respectively as given in Fig. 7.

As shown in Fig. 8, we compared the light leakage of normal TN without compensation film and compensated TN using hybrid aligned film with various phase retardation such as 0.238 μm, 0.204 μm, and 0.1445 μm through the iso-luminance curve. It is clear from Fig. 8(d) that when the phase retardation value of the compensation film was 0.1445 μm, the light leakage was found lowest as a function of viewing angle in dark state.

In order to compare the experimental result and the simulation result, we also calculated $d\Delta n_{eff}$ as a function of polar angle at the phase retardation value of 0.1445 μm. As shown in Fig. 9, the experimental data coincides with the simulation data at a maximum tilt angle 19° for the retardation value of 0.1445 μm. This provides further evidence that the maximum tilt angle of hybrid aligned compensation film in our experimental data was 19°.

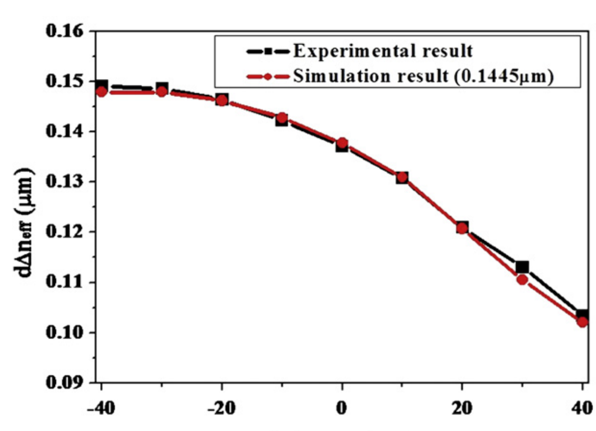

Fig. 9. Calculated effective phase retardation, $d\Delta n_{eff}$, with respect to the polar angle for experimental and simulated data at a retardation value of 0.1445 μm.

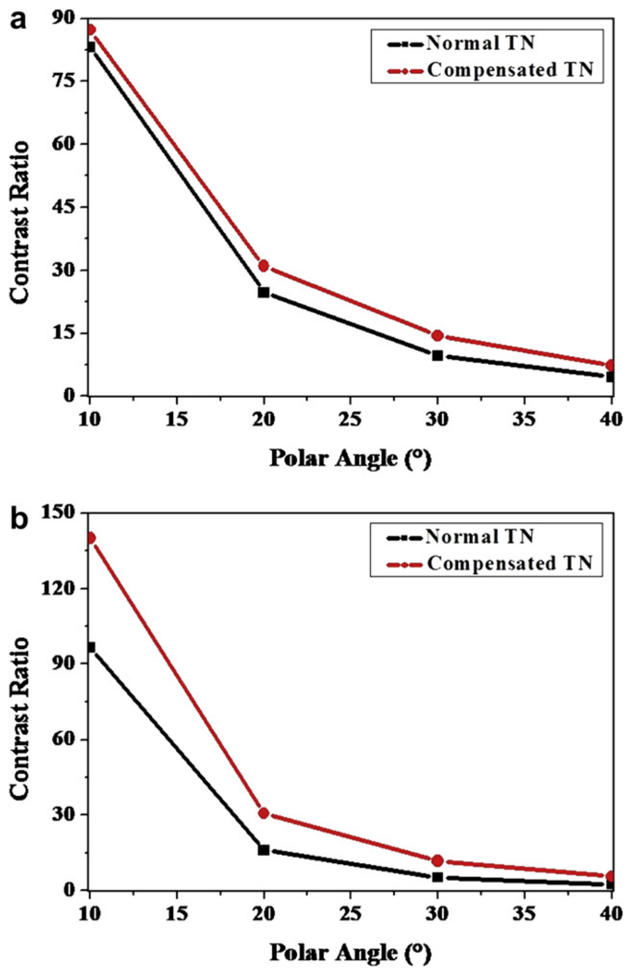

Fig. 10. Contrast ratio as a function of polar angle for (a) experimental and (b) simulation results of normal TN and compensated TN.

Fig. 10 shows contrast ratio according to polar angle in experimental case and simulated case of normal TN mode and compensated TN mode with hybrid aligned compensation film having retardation value of 0.1445 μm. In the upper direction, the compensated TN mode has better contrast ratio than normal TN mode, which is in the good agreement with the obtained experimental results.

5. Conclusions

In conclusion, we have developed a compensation film with hybrid structure for TN mode using a rod-like LC, which can do UV-curing process under ambient condition. The hybrid structure of mesogenic units in the cured polymeric film was confirmed by measuring the effective phase retardation values with respect to the viewing angle as well as the photographic images of hybrid film in the left, front, and right directions. We also have studied optical compensation effect of compensation film to reduce the light leakage in the dark state for TN-LCD using the results of experiment and simulation. Hybrid aligned compensation film affected greatly the performance of the TN cell and reduced the light leakage in the dark state. The compensated TN cell with hybrid aligned film shows good viewing angle performance in terms of light leakage in the dark state and contrast ratio, especially in the upper direction.

Acknowledgments

This research was financially supported by the Ministry of Commerce, Industry and Energy (MOCIE) and Korea Industrial Technology through the Human Resource Training Project for Regional Innovation and WCU program through MEST (R31-2008-000-200029-0).

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