Continuous Viewing Angle Distribution Control of Liquid Crystal Displays Using Polarization-Dependent Prism Array Film Stacked on Directional Backlight Unit

Min-Kyu Park, Heewon Park, Kyung-Il Joo, Hee-Dong Jeong, Jun-Chan Choi, and Hak-Rin Kim*

School of Electronics Engineering, Kyungpook National University, Daegu 41566, Korea

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We present a polarization-dependent prism array film for controlling the viewing angle distribution of liquid crystal (LC) display panels without loss of light efficiency. On a directional backlight unit, our polarization-dependent prism array film, made into a stacked bilayer with a well-aligned liquid crystalline reactive mesogen (RM) layer on the UV-imprinted prism structure, can continuously control the light refraction function of the prism array by electrically switching incident polarization states of a polarization-controlling layer prepared by a twisted nematic LC mode. The viewing angle control properties of the polarization-dependent prism array film are analyzed under different prism angle and refractive index conditions of the RM layer. A simple analytic model is also presented to describe the intermediate viewing angle distributions with continuously varying applied voltages and incident polarization states.

Keywords: Polarization-dependent prism array, Viewing angle distribution control, Reactive mesogen, Liquid crystal display
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I. INTRODUCTION

Compared to organic light-emitting diodes, liquid crystal displays (LCDs) exhibit higher viewing-angle-dependent visibility because of viewing-angle-dependent retardation of the liquid crystal (LC) layer, which has been considered a problem to be solved. Over decades, many efforts have been devoted to obtain wide viewing angle (WVA) LCDs and significant improvement has been achieved, especially for large-area panels, with the development of several WVA LC modes such as multi-domain vertical alignment (MVA) [1-3], patterned vertical alignment (PVA) [4, 5], optically compensated bend (OCB) [6-8], and in-plane switching (IPS) LC modes [9-12]. Improvement on optical compensation films also helped in realizing WVA LCDs [13, 14].

Recently, with the tremendous increase in portable electronic devices such as mobile phones, tablet personal computers, personal digital assistants, and notebook computers, privacy protection has become a new issue as an additional display function. For solving this privacy issue especially in public places, a narrower viewing angle for LCDs would be suitable for a single user. However, for these personal display applications, WVA technology should also be adopted so that the displayed image can be seen by a single user under oblique viewing conditions or even by multiple users under different viewing conditions. Practically, although displays can provide privacy protection, a display that can be switched between the conventional WVA and privacy-protecting narrow viewing angle (NWA) states needs to be developed.

For achieving the viewing angle distribution control properties between the WVA and NVA in LCDs, several approaches have been introduced [15-22]. In most cases, a stacked structure using multiple LC panels has been proposed, where one panel is used for the conventional pixelized gray level control with WVA LC modes, such as IPS, MVA, PVA, and fringe-field switching (FFS) modes, and the other stacked panel is used just for the viewing angle distribution control with NVA LC modes, without a pixel pattern, such
as electrically controlled birefringence (ECB), hybrid-aligned nematic (HAN), and vertical alignment (VA) modes [17-22]. Depending on the electrically switched states of this viewing angle switching (VAS) panel, the viewing angle property of the stacked LC panel structure can also exhibit WVA and NVA conditions. However, in principle, these approaches utilize viewing-angle-dependent light absorption in polarizers for the NVA state without changing the incident beam distribution. That implies that much optical loss inevitably occurs in the NVA state considering the beam distribution of the BLU, which is not designed to be narrow because the WVA state is more frequently used in general. In addition, the viewing distributions of the NVA state of the stacked structure become highly asymmetric owing to the asymmetric viewing angle properties of the VAS LC layer.

Other approaches are to realize the viewing angle control function without additional panel by using the pixel division method, in which one pixel is divided into two sub pixels for displaying the main image and controlling viewing angle [23-28], or by using three-terminal electrodes to control the gray scale together with viewing angle [29-32]. However, these methods need additional electronic circuits and electrodes within a pixel, which reduce the aperture ratio and light efficiency.

In this paper, we propose a novel method for controlling the viewing angle distribution of the LCD panel without loss of light efficiency by using a polarization-dependent prism array film stacked on a directional BLU. The polarization-dependent prism array film is made by preparing a well-aligned liquid crystalline reactive mesogen (RM) layer on an optically isotropic prism structure, where the ordinary refractive index \( n_o \) of the RM meets the index match condition with the refractive index \( n_p \) of the isotropic polymer material used for the prism-shaped structure, and the extraordinary refractive index \( n_e \) of the RM is larger than \( n_p \) [33]. When the polarization state of the incident light is parallel to the ordinary axis of the prism-shaped RM, the incident beams pass through the stacked prism structure without refraction, which corresponds to the NVA mode owing to the narrow beam distribution of the underlying directional BLU. When the polarization direction of the incident light is changed to be along the extraordinary axis of the prism-shaped RM, the incident beams experience refraction at the slanted interface between the RM and the isotropic polymer layers, which provides the WVA mode. By controlling the polarization angle of the incident light with a twisted nematic (TN) LC layer, the viewing angle distribution can be continuously switched from the NVA state to the WVA LC layer, without loss of light efficiency while preserving symmetric viewing angle characteristics.

II. FABRICATION OF POLARIZATION-DEPENDENT PRISM ARRAY

Figure 1 shows the fabrication process of the polarization-dependent prism array film: (a) spin-coating the UV curable resin on a film and imprinting process with a prism-shaped template, (b) UV curing the resin, (c) detaching the prism-shaped template from the solidified resin structure, (d) UV ozone treatment for surface energy control, (e) coating the surface of the imprinted prism structure with PVA and then curing it, (f) rubbing process on the PVA-coated prism structure along the prism structure direction, (g) coating liquid crystalline reactive mesogen (RM) on the prism structure and then laminating the rubbed PVA layer for the top-down RM alignment together with the bottom-up alignment, (h) UV curing for the crosslinked RM film, and (i) peeling-off the top PVA film from the RM-aligned prism film.
dependent prism array film. We used a prism array template with pitch, height, and angle of 18.5 µm, 11 µm, and θ_{prism} = 50°, respectively. The original prism array structure was replicated on a film substrate by using an imprinting process with a UV-curable resin (NOA89, n_p = 1.51, Norland Products Inc.) that is transparent in the visible region and optically isotropic, as shown in Figs. 1(a)–1(c). The UV-cured resin surface replicated with the prism structure was treated by a UV ozone process for 30 min to increase the surface wettability, as shown in Fig. 1(d). After the UV ozone treatment, polyvinyl alcohol (PVA) diluted into a 2 wt% aqueous solution was spin-coated on the prism array structure to promote RM alignment on the prism-shaped slanted surface. Then, a thermal curing process was conducted at 100°C for 20 min; the crosslinked resin layer was preserved well without detaching from the plastic film owing to our low-temperature annealing process. The PVA layer was unidirectionally rubbed along the prism structure to provide the bottom-up alignment effect for the RM layer to be coated on the isotropic prism structure, as shown in Fig. 1(f). In our experiment, to enhance the alignment property of the RM layer on the prism structure exhibiting sharp prism edges, the top-down alignment effect was also provided by the rubbed PVA layer of the top film covering on the RM layer, as shown in Fig. 1(g). To make the polarization-dependent prism array film, an RM (RMM727, Δn = 0.17, Merck) was coated on the isotropic prism array. Then, it was covered with the top PVA-coated film. To obtain a well-aligned RM film, the stacked film was thermally annealed at 50°C for 30 min. Then, UV light was irradiated on it for 90 s at 50 mW/cm² to obtain the crosslinked RM layer, as shown in Fig. 1(h). Finally, the top film was detached, as shown in Fig. 1(i) and the polarization-dependent prism array film was obtained with the stacked prism-shaped bilayers of the optically anisotropic RM and isotropic polymer layers.

In our polarization-dependent prism array film, the optically anisotropic RM layer prepared on the optically isotropic polymer layer has birefringence with n_e and n_o like LC molecules; we matched the n_o value of the RM with the n_p value of the isotropic polymer material. When the polarization state of an incident light is parallel with the ordinary axis of the RM layer, the incident beams pass through the stacked prism film without refraction, as shown in Fig. 2(a). When the polarization state of the incident light is switched by the underlying polarization control layer, the incident beams parallel with the extraordinary axis of the RM layer experience optical refraction at the slanted interface owing to the refractive index mismatch between the RM and isotropic polymer layers, as shown in Fig. 2(b). The TN LC mode was adopted as the polarization switching layer to minimize the chromatic effects in polarization changes; the E7 LC (Δn = 0.22, Merck) was used for the TN LC cell.

Figure 3 shows the scanning electron microscope (SEM) images of the polarization-dependent prism array film. Figure 3(a) shows the replicated prism array structure made by the UV curable resin with the imprinting process on the film substrate. Figure 3(b) shows the cross-sectional image of the RM-coated polarization-dependent prism array film. In our structure, the UV-cured RM layer was formed on the replicated prism array structure, where the RM surface was planarized after the lamination process and the successive peel-off process of the PVA-coated top film used for the top-down alignment effect. The total thickness of the polarization-dependent prism array prepared on the bottom film (thickness ~ 100 µm) was about 50 µm; the thickness of the residual layers was about 20 µm for both the RM and isotropic polymer layers.

Figure 4 shows the polarizing optical microscope (POM) images of the polarization-dependent prism array that were observed between the crossed polarizers. When the rubbing direction of the LC alignment PVA layer was parallel to one of the crossed polarizers, the POM image exhibited a clearly dark texture, as shown in Fig. 4(a). Although there were very sharp prism edges under the RM layer, the RM molecules were aligned well on the prism array structure by utilization of the bottom-up and top-down alignment methods and the annealing process. When the RM-coated
FIG. 4. Polarizing optical microscope images of the RM-coated polarization-dependent prism array through crossed polarizers when the rubbing direction is (a) parallel and (b) rotated by 45° with respect to one of the polarizers.

prism sheet was rotated by 45° with respect to the polarizers, a bright image was obtained, as shown in Fig. 4(b), owing to the retardation of the RM layer. On the prism array structure, the thickness of the RM layer was linearly changed within one period of the prism structure. The periodic colored line images in Fig. 4(b) were visible because of the thickness-dependent retardation effect of the prism-shaped RM layer.

III. VIEWING ANGLE DISTRIBUTION CONTROL USING POLARIZATION-DEPENDENT PRISM ARRAY

With our approach, by utilizing the switchable refractive behavior of the polarization-dependent RM-coated prism film, the viewing angle distribution was changed from the initial NVA state to the WVA state. Therefore, a directional BLU with a narrower viewing angle was needed. This was realized by attaching microlouver films (3M) to a conventional Lambertian BLU [34].

Figure 5 shows the polar viewing charts of the luminance distribution for the RM-coated polarization-dependent prism array that were measured on the directional BLU. All of the results for characterizing the viewing angle properties were obtained with the equipment of DMS 803 (Autronic-Melchers GmbH). In Fig. 5, the prism direction or the RM alignment direction is along the y-axis (φ = 90° in the presented polar chart). In the field-off state (V_a = 0 V) of the TN LC layer under the RM-coated prism film, the incident polarization state became parallel with the ordinary axis of the RM (n_o = n_p). Consequently the prism function was turned-off while exhibiting the NVA property, as shown in Fig. 5(a). In contrast, when the TN LC layer was electrically switched to the c-plate with the applied voltage of V_a = 5 V, the incident beams from the directional BLU were refracted at the slanted interface owing to the index mismatching condition (n_e ≠ n_p), as explained in Fig. 2(b). Compared to Fig. 5(a), the front viewing intensity shown in Fig. 5(b) decreased, whereas the oblique viewing intensity increased. In our experiment, the RM was aligned along the direction of φ = 90° in the presented polar chart. Thus, the beam refraction in the field-on state occurred along the φ = 0° direction, as shown in Fig. 5(b).

In contrast with conventional approaches using VAS LC layers, which have highly asymmetric viewing angle properties, the viewing angle chart in Fig. 5(a) for the NVA state is highly symmetric. In addition, the viewing angle chart in Fig. 5(b) for the WVA state is also symmetric for each azimuthal direction along the φ = 0° and 90° directions, although the viewing angle distributions became wider only along the φ = 0° direction because the beam refraction occurred only along the φ = 0° direction in our single-layer polarization-dependent prism structure. The WVA property can also be easily obtained along the φ = 90° direction with the same operation principle, by orthogonally stacking an additional RM-coated prism film on the structure used in this experiment.

Figure 6(a) plots the angular luminance distributions according to the polar angle of the RM-coated polarization-dependent prism array film stacked with the polarization switching layer and directional BLU. When V_a = 0 V, the angular
luminance distributions along the horizontal ($\phi = 0^\circ$) and vertical ($\phi = 90^\circ$) directions were almost the same. When $V_a = 5$ V, the angular luminance distribution along the horizontal direction became broader compared to that along the vertical direction. Under the front viewing condition ($\theta = 0^\circ$), the luminance for $V_a = 5$ V ($L_{V_a=5V, \theta=0^\circ}$) was decreased by about 13% compared to that for $V_a = 0$ V ($L_{V_a=0V, \theta=0^\circ}$), whereas at the oblique angle of $\theta = 28^\circ$ and $\phi = 0^\circ$, the luminance for $V_a = 5$ V ($L_{V_a=5V, \phi=28^\circ}$) increased by approximately 44% compared to that for $V_a = 0$ V ($L_{V_a=0V, \phi=28^\circ}$) because of the optical refraction effect at the slanted interface between the well-aligned RM and isotropic polymer layer.

Figure 6(b) shows the angular luminance distributions according to the polar angle at the fixed azimuthal viewing condition ($\phi = 0^\circ$) and under different voltage conditions ($V_a = 0, 1.5, 1.8, 2.15,$ and 5 V) applied to the polarization switching layer placed between the RM-coated polarization-dependent prism array film and directional BLU. As the applied voltage to the TN LC layer was increased, the luminance for the normal viewing condition gradually decreased, whereas the luminance for the oblique viewing condition gradually increased. At all applied voltage conditions, the luminance distributions were symmetric along the polar viewing angle variation. In addition, when we calculated the total luminance by integrating the angular luminance distribution obtained from the experimental results, the total amounts of luminance measured under different applied voltage conditions were almost the same within a variation of 1.5%. These results imply that the angular luminance distribution can be controlled continuously without optical loss by using the stacked structure of the RM-coated polarization-dependent prism array film, polarization switching layer, and directional BLU.

In our polarization switching layer, the TN LC cell provided two orthogonal incident polarization states needed for the index matching and mismatching conditions of the RM-coated polarization-dependent prism array film under the applied voltage conditions of $V_a = 0$ V and $V_a = 5$ V, respectively. For the intermediate voltage conditions, the angular luminance distributions according to the polar angle can be estimated by superposing $L_{V_a=0V}$ and $L_{V_a=5V}$ with relative weighting factors. A weighting factor is determined by the relative ratio of the polarized intensities for $\phi = 0^\circ$ and $\phi = 90^\circ$, and is varied according to the applied voltage condition of the polarization switching layer. Figure 7(a) shows the normalized transmittance of the TN LC cell used as the polarization switching layer between the crossed polarizers under different applied voltages. The normalized transmittances became 75%, 50%, and 25% when the applied voltages were $V_a = 1.50, 1.80,$ and 2.15 V, respectively. This can be analyzed with the following example. Under the applied voltage condition of $V_a = 1.50$ V showing 75% transmittance, 75% of the incident beams from the directional BLU did not refract upon meeting the index matching condition at the slanted interface between the RM and isotropic polymer layers and the 25% of the incident beams were refracted because of the index mismatching condition at the interface. Therefore, the luminance distributions - $L_{V_a=1.50V}$, $L_{V_a=1.80V}$, and $L_{V_a=2.15V}$ - depending on the polar angle for the intermediate voltage conditions can be simply expressed by $0.75L_{V_a=0V} + 0.25L_{V_a=5V}$, $0.5L_{V_a=0V} + 0.5L_{V_a=5V}$, and $0.25L_{V_a=0V} + 0.75L_{V_a=5V}$, respectively, based on the two angular luminance distributions that can be obtained at the two orthogonal states of incident polarizations as determined by the polarization switching layer. Figures 7(b)-7(d) plot the calculated results for the angular luminance distributions obtained with $0.75L_{V_a=0V} + 0.25L_{V_a=5V}$, $0.5L_{V_a=0V} + 0.5L_{V_a=5V}$, and $0.25L_{V_a=0V} + 0.75L_{V_a=5V}$ with the measurement results. The analytic results for the intermediate voltage conditions matched well with the experimental results. This implies that the continuously changing behavior of the angular luminance distribution can be predicted by simple linear superposition using only the information on the two angular luminance distributions obtained at two orthogonal incident polarization conditions providing complete index matching and mismatching conditions at the slanted interface of the RM and isotropic polymer layers in our RM-coated polarization-dependent prism array film.

The refraction angle of the incident light is related to the angle of the prism structure and the difference between the refractive indices of the RM and isotropic polymer layer. To analyze the viewing angle distribution change while considering these factors, we performed optical simulations by using the optical modeling software of Advanced System Analysis Program (ASAP) at Breault Research Organization, Inc.). First, we reproduced the angular luminance distribution...
of the directional BLU light used in our experiment, as shown in Fig. 8, which was similar to the measured data of Fig. 6.

Figure 8(a) shows the simulated results of the angular luminance distribution according to the polar angle under different prism angle conditions of \( \theta_{\text{prism}} = 40^\circ, 50^\circ, \) and \( 60^\circ \), where the refractive index conditions of the RM and isotropic polymer layers were fixed to \( n_o = 1.51 \) and \( n_e = 1.65 \) for the RM layer and \( n_o = 1.51 \) for the isotropic polymer. As \( \theta_{\text{prism}} \) increased, the viewing angle distribution became broader and the luminance of the front viewing condition decreased. Compared to the experimental condition of \( L_{\theta=50^\circ} \), the result of \( L_{\theta=50^\circ} \) was so broad that the WVA condition could be provided. Figure 8(a’) shows the normalized angular luminance distribution of Fig. 8(a) scaled by \( L_{\theta=0^\circ} \). Under the oblique viewing condition, as \( \theta_{\text{prism}} \) increased, the normalized luminance increased nonlinearly, where the normalized luminance of the directional BLU at \( \theta = 32^\circ \) was almost 0, whereas the normalized luminance for the prism angle condition of \( \theta_{\text{prism}} = 60^\circ \) was 24% under the same viewing condition of \( \theta = 32^\circ \).

Figure 8(b) shows the simulated results of the angular luminance distribution according to the polar angle under different refractive index conditions \( (n_e = 1.55, 1.65, \text{ and } 1.75, \text{ and } n_o = 1.51) \) for the RM layer. The prism angle condition was fixed at \( \theta_{\text{prism}} = 50^\circ \). As the \( n_e \) value of the RM layer was increased, the viewing angle also became broader because of the increased index mismatching and the increased refraction effect at the RM/polymer interface. The normalized luminance for the oblique viewing condition of \( \theta = 32^\circ \) increased to almost 35% under the RM condition of \( n_e = 1.75 \), as shown in Fig. 8(b’).

Based on the results in Figs. 8(a) and 8(b), we simulated the angular luminance distribution according to the polar angle for the high extraordinary refractive index condition of \( n_e = 1.75 \) for the RM layer compared to our experimental condition while varying the prism angle conditions to \( \theta_{\text{prism}} = 40^\circ, 50^\circ, \) and \( 60^\circ \), as shown in Fig. 8(c). Compared to Fig. 8(a), owing to the increased \( n_e \) value of the RM layer, the angular luminance distributions became broader at the same prism angle conditions. Under the condition of \( \theta_{\text{prism}} = 60^\circ \), the luminance at the front viewing condition was even weaker than that under the oblique viewing condition. The normalized luminances for the oblique viewing conditions of \( \theta = 20^\circ \) and \( \theta = 32^\circ \) became almost 165% and 98%, respectively, as shown in Fig. 8(c’).

Considering the RM-coated prism conditions \( (\theta_{\text{prism}} = 60^\circ \) for the prism angle and \( n_o = n_p = 1.51 \) and \( n_e = 1.75 \) for the refractive indices of the RM and isotropic polymer layer), we simulated a continuously changing angular luminance distribution depending on the applied voltage condition of the polarization switching layer. In this analysis, we applied the voltage-dependent polarization changing properties of the experimentally measured TN cell shown in Fig. 7(a). It shows that the RM-coated polarization-dependent prism array film and the stacked structure of the polarization switching layer and directional BLU could provide a high NVA condition to a high WVA condition. The properties could be continuously changed and predicted while the symmetric viewing angle distribution behavior was maintained.

Compared to the simulated results, the experimental results shown in Figs. 5 and 6 were narrower for the WVA state because of the limited refractive index available for our experiment. However, the simulated results in Fig. 8(a) that were obtained with the increased prism angle condition showed that the viewing angle property of the WVA state can be effectively improved even with currently commercially available RM materials. In addition, Figs. 8(b) and 9 show that the viewing angle property of the WVA state can be

![Image](Image 50x235 to 283x320)

![Image](Image 50x335 to 283x421)

![Image](Image 50x436 to 283x523)

![Image](Image 50x648 to 283x748)

**FIG. 8.** (a) Simulated results of the angular luminance distribution according to the polar angle at different prism angle conditions of \( \theta_{\text{prism}} = 40^\circ, 50^\circ, \) and \( 60^\circ \) and at the fixed refractive index condition \( (n_e = 1.51, n_e = 1.65) \) of the RM layer. (b) Simulated results of the angular luminance distribution according to the polar angle at different refractive index conditions \( (n_e = 1.55, 1.65, \text{ and } 1.75, \text{ and } n_o = 1.51) \) and at the fixed prism angle of \( \theta_{\text{prism}} = 50^\circ \). (c) Simulated results of the angular luminance distribution according to the polar angle at different prism angle conditions of \( \theta_{\text{prism}} = 40^\circ, 50^\circ, \) and \( 60^\circ \) and at the higher refractive index condition of \( n_e = 1.75 \). (a’), (b’), and (c’) are the angular luminance distributions according to the polar angle normalized by \( L_{\theta=0^\circ} \) and obtained from the results in (a), (b), and (c), respectively.
the increased extraordinary refractive index of the RM layer.

IV. CONCLUSION

We presented a polarization-dependent prism array that controls the viewing angle properties of LCD panels without loss of light efficiency. By stacking the polarization switching layer and directional BLU under the RM-coated polarization-dependent prism array film, the proposed BLU structure can provide both the NVA and the WVA conditions, and the luminance distribution can be electrically controlled between two viewing conditions continuously depending on the user’s situation and purpose. The intermediate viewing distribution states can be easily predicted using a simple analytic model based on the polarization behavior of the polarization switching layer. By optimizing the angle of the prism structure and the difference of the refractive indices between the RM and the isotropic polymer layers, large variations in the viewing angle distribution can be achieved. These properties can also be obtained by the directional BLU with a narrower luminance distribution is developed.

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