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Novel wide viewing liquid crystal display with improved off-axis image quality in a twisted nematic configuration

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Abstract. We developed a novel twisted nematic (TN) liquid crystal display (LCD) having wide viewing angle characteristics through the reduction of the residual liquid crystal phase retardation at oblique angles using an embedded diffusing unit. Compared to a conventional TN panel, this embedded approach provides extended isocontrast contours by more than ±10 deg at a contrast ratio of 100:1 along the horizontal direction and a wide region free of grayscale inversion by a factor of 2 along the vertical direction. Moreover, the off-axis image distortions in our novel LCD are improved by 50% compared to those in a film-compensated TN LCD. [DOI: 10.1117/1.3265524]

Subject terms: twisted nematic; embedded diffusing unit; grayscale inversion; off-axis image.

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1 Introduction

Recently, liquid crystal displays (LCDs) have been widely used for applications from mobile terminals to high-definition television sets, where thin-film transistors (TFTs) are driving elements of pixels. For small and medium-size LCDs like cellular phones, personal digital assistants, and notebook computers, a twisted nematic (TN) mode is commonly employed due to several advantages such as high light transmittance, good process margin, and cost effectiveness.[1,2] However, the TN mode shows limited viewing angles due to asymmetric director distortions in gray scales.[3,4] In order to improve the narrow viewing characteristics of the TN mode, several approaches have been proposed. One is to use multidomains, which inevitably complicate fabrication processes.[5–8] Another is based on an optical compensation film that removes the residual phase difference in the dark state.[9–12] Although an optical compensation film (wide-view film), which is based on a polymerized discotic material, significantly improves the contrast ratio (CR) of a TN LCD panel at large oblique angles,[9] problems of grayscale inversion as well as excessive brightness and darkness still exist, particularly along the vertical direction.

In this paper, we developed a novel wide viewing TN LCD with improved off-axis image quality and grayscale inversion along all viewing directions. Our LCD consists of a collimated backlight unit (BLU), a TN LC panel, and a diffusing unit, as shown in Fig. 1(a). By means of collimation of the light distribution from the BLU, viewing direction–dependent variations of the phase difference were significantly reduced. The narrow light distribution through the TN LC layer along the normal direction was enlarged using a polarizer-integrated diffusing unit, and thus wide viewing characteristics were achieved.

2 Design of Collimated BLU

The BLU provides collimated illumination for the TN panel in such a way that the residual phase retardation experienced by the obliquely incident light is reduced. An embedded diffusing unit in the LCD panel was used for enlarging the light distribution through the TN LC layer. We first design a collimated BLU that consists of a light source of light-emitting diodes (LEDs), a lightguide plate (LGP) with two microprism structures, and a light redirection film (a reverse prism sheet)[13,14] as shown in Fig. 1(b). The light emitted from the light source is guided along the LGP by total internal reflection (TIR) and is outcoupled at high polar angles in the presence of the prism structures. This outcoupled light is redirected along the normal direction by a commercially available light redirection film whose apex angle is 68 deg with respect to the normal direction (Mitsubishi Rayon Co., Japan). For designing the two microprism structures, which play a critical role in the collimation of the outcoupled (OC) light on both sides of the LGP, a commercially available Monte Carlo ray tracing simulation and analysis program, Advanced System Analysis Program (ASAP, BRO Inc., Tucson, Arizona), was used.

Two microprism arrays, different in shape and direction, exist on both sides of the LGP, as depicted in Fig. 1(b). One microprism array is to collimate the beam along the light source direction (along the x direction), and the other is for the light propagation direction (along the y direction). It is known that for the collimation purpose along the light

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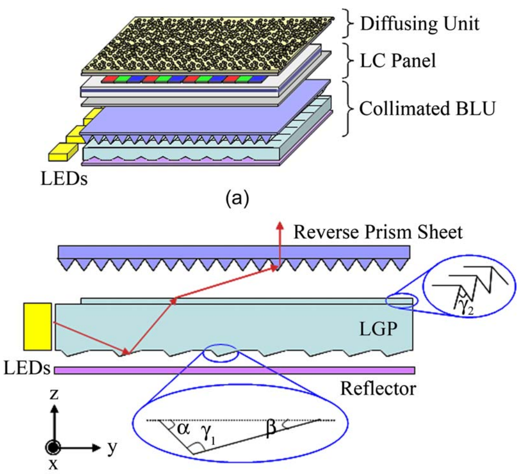


Fig. 1 Schematic diagrams of (a) our novel wide viewing LCD, consisting of a collimated BLU, a TN LC panel, and a diffusing unit embedded on the front polarizer, and (b) a collimated BLU where a light-ray path, represented by a red arrow, is shown. Two microprism arrays are present on the LGP, by which the incident light from the LEDs is collimated and outcoupled toward high polar angles. A reverse prism sheet redirects the outcoupled light toward the normal direction by the TIR. The base angles and the apex angle of the lower microprism are denoted by α, β, and γ_1. The apex angle of the upper microprism is γ_2. (Color online only.)

propagation direction, it is more effective to place a microprism array on the lower surface of the LGP than on the upper surface.[14] Numerical simulations were carried out to determine the optimal values of the base angles, α and β, and the apex angle γ_1 of the first microprism array from the luminous intensity and its angular dependence as a function of the polar angle at the central wavelength of 550 nm. The optimal values for the beam collimation along the light propagation direction and the maximum OC energy were found to be $\alpha=45$ deg, $\beta=2$ deg, and $\gamma_1=133$ deg. The half width at half maximum (HWHM) angle for light propagation along the vertical direction is $V=10$ deg, as shown in the measured polar-angle-dependent isoluminance contour of Fig. 2(a), and the relative OC energy is about 78%. For our LCD panel of 2.3-in in diagonal (34.6 mm $\times$46.2 mm), the width between two successive flat regions in the prism array was gradually varied from 90 μm to 30 μm for effective collimation and uniform distribution of the OC light through the whole LGP.

We now examine the effect of the apex angle γ_2 of the second prism array, which is present on the upper surface of the LGP, as shown in Fig. 1(b), on the degree of collimation along the light source direction. Figure 2(b) shows the HWHM angle for the horizontal direction and the relative OC energy as a function of the apex angle γ_2. Clearly, the optimal condition of satisfying both the smallest HWHM and the largest OC energy is given by $\gamma_2=100$ deg at which the degree of collimation and the amount of the OC light flux are maximized. At the apex angle of $\gamma_2=100$ deg, the HWHM angle for the horizontal direction is $H=17.6$ deg, and the relative OC energy is about 72%. The measured polar-angle-dependent luminance distribution of the light from the collimated BLU with two microprism arrays on both sides of the LGP is shown in Fig. 2(c). For the angular dependence of the normalized luminous intensity along the horizontal (in the x direction) polar angle H and along the vertical (in the y direction) polar angle V, the experimental data for $H=17$ deg and $V=10$ deg, measured along the horizontal and vertical directions, respectively, were found to agree well with the simulation results, as shown in Fig. 2(d). The luminance uniformity, defined as the ratio of the minimum to the maximum, was given as about 80%, which was the average value measured at nine points spaced equally throughout the BLU.

3 Construction of Novel Wide Viewing Angle TN Panel

In our wide viewing TN LCD panel of 2.3-in in diagonal, the TN LC was sandwiched between the lower substrate, whose rubbing direction was 135 deg, and the upper substrate, whose rubbing direction was 45 deg. The rear polarizer with a transmission axis of 45 deg and the front polarizer with a transmission axis of 135 deg were attached to the outsides of the two substrates. The two polarizers were compensated with commercial wide-view films. This configuration provides O-mode waveguiding in the normally white mode.[9] In contrast to a conventional film-compensated TN LC panel, schematically shown in Fig. 3(a), we used a diffusive adhesive (DA) film, where spherical particles were dispersed in a transparent medium so that scattering occurs as a result of the index mismatch between the particles and the binding medium, producing both haze value and transmittance over 90%. The haze value, defined as the ratio of the transmitted diffusive intensity to the total intensity, was measured using an industry-standard hazemeter (HR-100, Murakami Color Research Lab, Tokyo, Japan). The DA film (developed by a polarizer company) was attached to the front polarizer, as shown in our novel TN panel configuration in Fig. 3(b). The collimated light from our BLU employing the LGP with microprism arrays was found to experience less residual birefringence through the TN LC and to diffuse more uniformly by the DA film. Thus, wide viewing characteristics were achieved in all directions.

4 Results and Discussion

We first describe the viewing angle characteristics of our novel LCD panel compared to those of a conventional TN LCD having a compensation film of WV-EA film (FUJIFILM, Tokyo, Japan).[15] Figures 4(a) and 4(b) show the isocontrast contours, measured with a conoscope (EZContrast 160R, Eldim, France), of the WV-TN LCD and our LCD panel, respectively. The isocontours of our LCD were greatly improved, particularly in the horizontal direction. Figure 4(c) shows the contrast ratios of the two LCDs in the horizontal and vertical directions as a function of polar angle. It was found that the polar angle at the contrast ratio of 100:1 was extended from ± 33 deg to ± 46 deg. Note that the viewing characteristics of our LCD remain essentially the same as those of the WV-TN LCD in the normal direction (at the polar angle of zero).

We now discuss grayscale inversion in our LCD panel using nine levels (from $G0$ to $G8$) that are equally distributed from gray 0 ($G0$: black) to gray 255 ($G8$: white). We

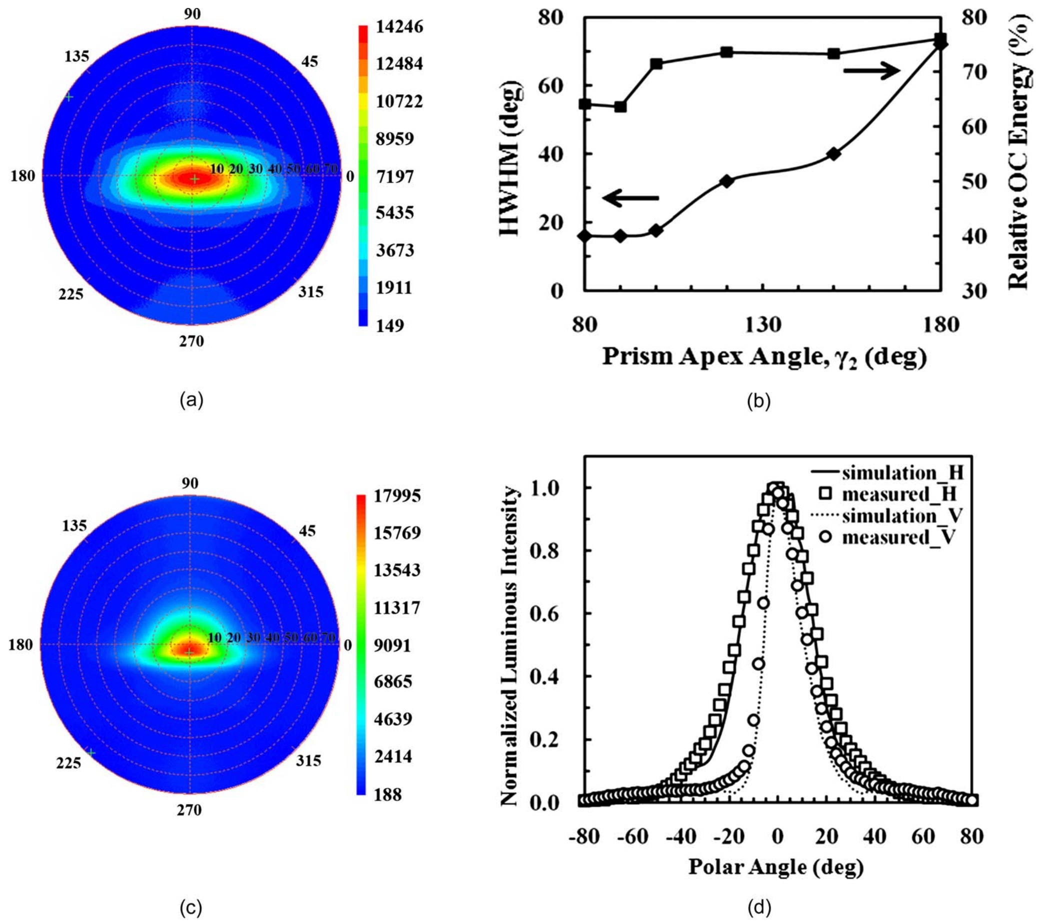


Fig. 2 Luminous intensity distribution of the OC light in our collimated BLU: (a) the polar angle–dependent isoluminance distribution measured from our BLU with a first prism array on the lower surface of the LGP; (b) the dependence of the HWHM and the relative OC energy on the apex angle γ_2 of the second prism array placed on the upper side of the LGP; (c) the polar angle–dependent isoluminance distribution measured from our BLU with two microprism arrays on both sides of the LGP; and (d) cross-sectional distributions in the horizontal (H) and vertical (V) directions. Open symbols (squares and circles) and lines (solid and dotted) denote the measured and simulation data, respectively. The upper symbols (squares) and curve (solid line) represent the luminance intensity in the horizontal direction as a function of the polar angle.

determined the polar angle at which the luminance of any lower gray level undergoes inversion to a higher gray level. The luminance of a conventional WV-TN LCD and that of our novel LCD were plotted as a function of the polar angle in Figs. 5(a) and 5(b), respectively. As shown in Fig. 5(a), the WV-TN LCD shows the asymmetry in luminance and grayscale inversion beyond the polar angles of −23 deg and +22 deg along the vertical direction. This is typically observed in most WV-TN LCDs.[9] In our LCD, the region free of grayscale inversion was extended to −27 deg and +53 deg for the polar angle along the vertical direction, meaning that it was widened by nearly a factor of 2. Moreover, the asymmetry in luminance was much diminished, as shown in Fig. 5(b). Another point is that the integrated OC intensity over the angular distribution in our LCD (about 340 $\mathrm{lm/m^2}$) is still comparable to that in the WV-TN LCD. This indicates that the overall light efficiency is not sacrificed, although a DA film is used in front of the panel.[16]

Let us examine the off-axis image distortions using the average luminance difference[17] between two arbitrary gray

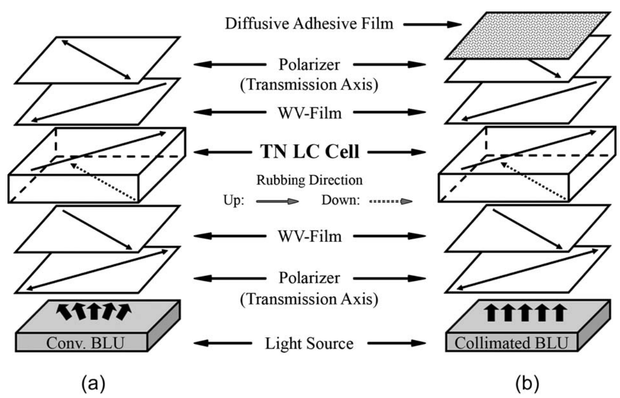


Fig. 3 Schematic diagrams showing two configurations of (a) a film-compensated TN LC panel and (b) our novel wide viewing angle TN LC panel.

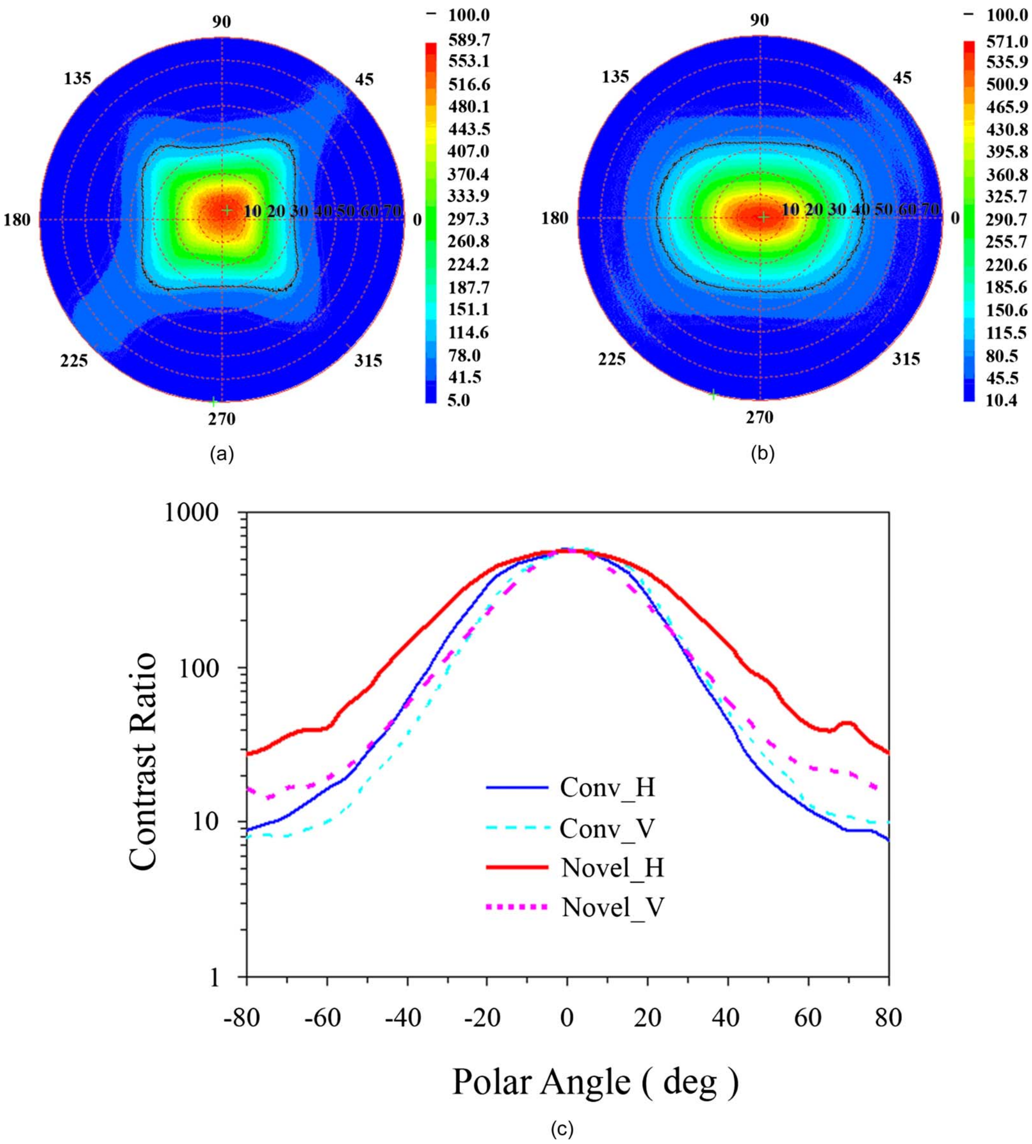


Fig. 4 Isocontrast contours and the polar angle–dependent CR: (a) the isocontrast contours of a conventional WV-TN LCD and (b) the isocontrast contours of our novel LCD. The thick solid line in each case represents the CR of 100:1. The cross-sectional curves in the horizontal (*H*) and vertical (*V*) directions are shown in (c). A set of two red or blue curves (solid and dashed) represent the CRs of our novel LCD and the conventional WV-TN LCD, respectively. (Color online only.)

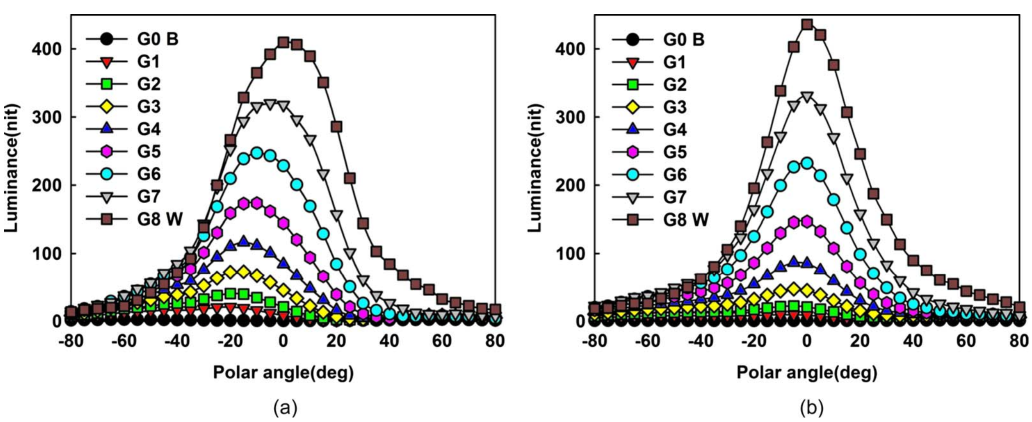


Fig. 5 Luminance curves as a function of the polar angle at nine gray levels (*G*0 to *G*8) between the black and white states in the vertical direction: (a) the WV-TN LCD and (b) our novel LCD.

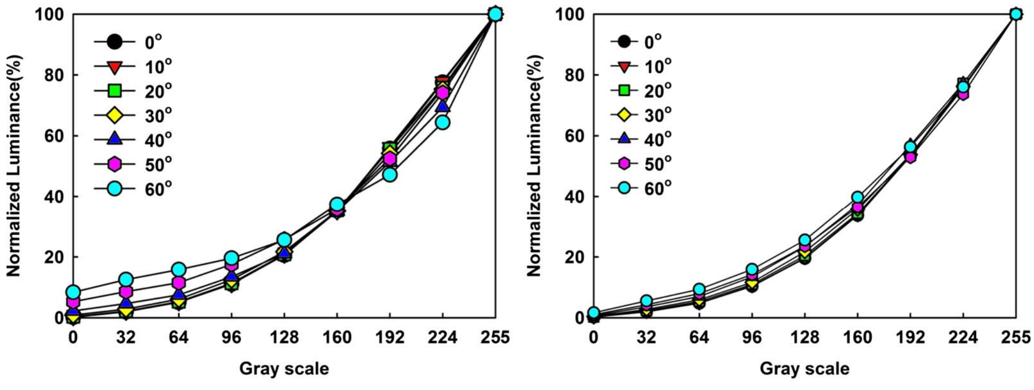
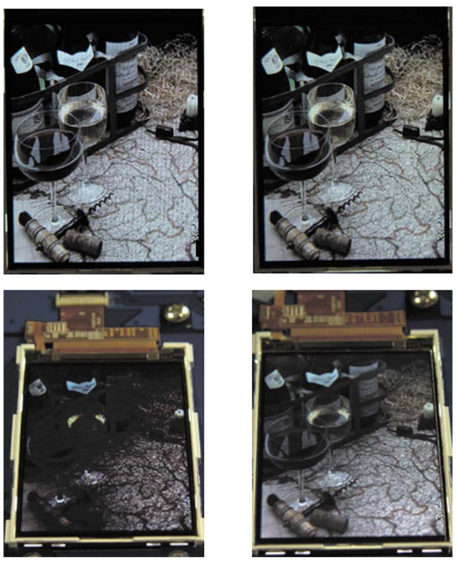


Fig. 6 The normalized luminance curves as a function of the gray scale at seven different polar angles (normal and right-side off-axis viewing directions): (a) the WV-TN LCD and (b) our novel LCD.

levels in the range between *G*0 (gray 0) and *G*8 (gray 255) defined in Fig. 5. The off-axis image distortion can be estimated by the amount of the luminance gamma difference between the normal (the on-axis gamma value of 2.2) and the off-axis images measured at the polar angle of 60 deg. Figures 6(a) and 6(b) show the normalized luminance curves of the WV-TN LCD and our novel LCD, respectively, along the normal and six different right-side off-axis viewing directions up to the polar angle of 60 deg. It is clear that the difference in the off-axis luminance was greatly reduced in our novel LCD. For the WV-TN LCD, the off-axis image gamma distortion along the horizontal direction was given as 0.416, while for our LCD, it was 0.208. Accordingly, the off-axis image quality of our LCD was improved by 50% compared to the WV-TN LCD.

Last, actual images displayed on the WV-TN LCD and our novel LCD, both of them 2.3-in in diagonal, at angles of 0 deg (normal) and 40 deg (downward) are shown in Figs. 7(a) and 7(b), respectively. It is clear that our LCD gives much less off-axis image distortion and wider viewing characteristics.



(a) (b)

Fig. 7 Photographs of actual images in 2.3-in in diagonal LCDs taken at two different polar angles of 0 deg and 40 deg in the downward direction: (a) the WV-TN LCD and (b) our novel LCD

5 Conclusion

We developed a novel wide viewing liquid crystal display with improved off-axis image quality in a twisted nematic configuration. The wide viewing angle characteristics were obtained using a highly collimated backlight system, into which an embedded diffusing unit and a light guiding plate with two microprism arrays were implemented, through the reduction of the residual liquid crystal phase retardation at oblique angles. The optimal geometrical parameters of the microprism arrays such as the base angles and the apex angles were determined from numerical simulations using a Monte Carlo ray tracing simulation and analysis program. The off-axis image distortions in our novel LCD were found to be improved by 50% compared to those in a film-compensated TN LCD.

Our embedded approach will be easily applicable for large-size LCDs, including monitors and television sets requiring less grayscale inversion and reduced off-axis image distortions in all viewing directions.

Acknowledgments

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