Control of gray scale inversion in a film-compensated twisted nematic liquid crystal display using beam steering optical film

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Commercially available, twisted nematic (TN), liquid crystal cells have intrinsic problems such as light leakage in the dark state, gray scale inversion, and brightness nonuniformity in gray scales when the viewing direction deviates from the normal axis. Film compensation of a TN cell has solved the first problem but the second remains unsolved, which has hindered its applications to large displays. This letter proposes the use of a beam steering film to prepare a TN cell free of gray scale inversion in wide viewing directions.
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Liquid crystal displays (LCDs) play an important role in human to machine interfaces. Twisted nematic (TN) LCDs, which first appeared in the 1970s,[1,2] are mainly used for portable personal digital assistants and notebook computers. However, they show limited viewing angles due to their asymmetric director orientation in gray scale, which limits their applications to relative small size displays. For applications to large size LC television, LC modes such as in-plane switching,[3] multidomain vertical alignment,[4,5] optically compensated bend,[6,7] and fringe-field switching,[8,9] which are free of gray scale inversion in wide viewing directions, have been commercialized.[10]

In normally white, TN mode, the LC molecules are twisted 90° from the top to bottom substrate with crossed polarizers, and the cell appears bright with no bias voltage as a result of the light modulation associated with the polarization rotation effects. In the bright state, the TN cell shows excellent uniformity in brightness according to the viewing direction because of the symmetric LC orientation. However, with an applied voltage greater than the Fréedericksz transition, the mid-director begins to tilt upward along the field direction, i.e., in one direction. This causes nonuniformity in luminance along the viewing direction, which is known as excessive brightness and darkness along the vertical direction because the phase difference is strongly dependent on the viewing direction.[11,12] In addition, at a sufficiently high voltage, the TN cell shows a good dark state in the normal direction. However, strong light leakage occurs in the oblique viewing directions due to the existence of a residual phase difference, δ. These intrinsic problems in luminance nonuniformity in the gray scales and light leakage in the dark state cause strong gray scale inversion, particularly along the vertical direction.

Many approaches have been applied to solve these intrinsic problems. Initially, two- or four-domain TNs were developed to solve the asymmetry in luminance in the gray scales but these have not been commercialized due to difficulties in fabrication.[13] In another approach, the residual phase difference in the dark state was removed using an optical compensation film associated with a polymerized discotic material, which significantly improved the contrast ratio (CR), which is defined as the ratio of white to dark luminance, in all viewing directions.[12] The optical compensation film called "wide view" (WV) has been widely commercialized in LCD monitors using the TN mode because it is easy to apply to a normal TN cell by simply attaching the film to the cell. However, the first solution has the problem of light leakage in the dark state while the second has problems in gray scale inversion as well as excessive brightness and darkness problems. In addition, the image quality of the TN cell is also related to the light distribution from the backlight. If all the light passes through the TN cell in the normal direction, a change in the phase difference dependent on the viewing direction will not be an issue. However, light passing through the TN cell propagates only along the normal direction so that the luminance decreases rapidly in the oblique viewing directions, resulting in a narrow viewing angle. The third solution proposed to solve the above-mentioned problem, a collimated backlight plus diffuser film, appears ideal but has never been commercialized, possibly due to difficulty in fabricating these films.

This letter proposes a cell structure that overcomes the intrinsic problems of the WV-TN cell. Using a beam steering film above the cell, the gray scale inversion is totally suppressed and the TN cell shows a high image quality in wide viewing directions, which introduces the possibility of applying the TN cell to even larger size displays.

In order to evaluate the image quality of the LCDs, two TN, thin-film transistor (TFT)-LCDs of 19.0 in. SXGA resolution were made: one with a WV film (WV-TN cell) and the other with a WV film plus beam steering film (BSF) (BSF-TN cell). Figure 1 shows the cell structures of both cells. In both cells, the cell retardation value was 0.40 μm with the WV film at both the top and bottom substrates.

The image quality of the WV-TN cell, i.e., the isoluminance contours at three gray levels, white, midgray and dark states, and the isocontrast contour, was first evaluated. The maximum luminance in the normal direction was 257 cd/m^2. While the uniformity was excellent in the white state, as expected, it deteriorated with the asymmetric contour in

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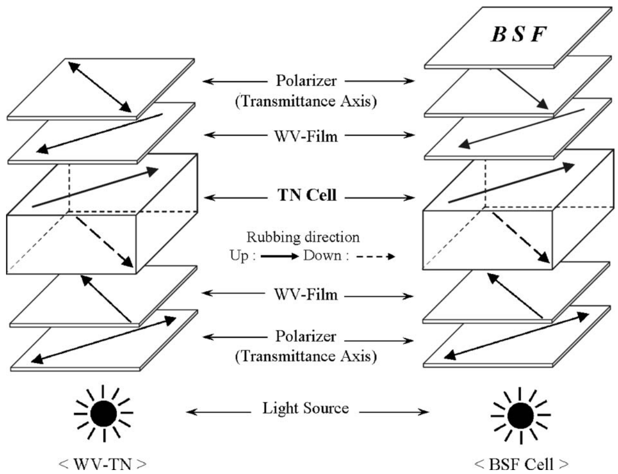

FIG. 1. Cell structures of the TN cells with (a) the WV film and (b) the beam steering film.

midgray, particularly along the vertical direction, i.e., the relative luminance larger than 50% with respect to the luminance in the normal direction was less than 20° and 40° in the downward and upward directions, respectively. Nevertheless, light leakage in the dark state was well controlled in the WV-TN cell. Consequently, CR was larger than 20 at polar angles over 60° in all directions except in the downward direction. In evaluating the LCD image quality, the degree of gray scale inversion should also be evaluated. The uniformity of the nine gray levels along the vertical directions was evaluated, as shown in Fig. 2. Except for a gray G8, the luminance was smaller and larger along the downward and upward directions, respectively, than that in the normal direction. In addition, the WV-TN cell still showed gray scale inversion (the region free of gray scale inversion was only +30° and −20° from the polar angle) as well as asymmetry in luminance along the vertical direction. These results are consistent with a previous report.[12]

The nonuniformity of the luminance in the gray levels was investigated. Except for the white state, the luminance of the gray levels in the normal direction increased by up to 10%–25% depending on the gray levels (which is known as excessive brightness) and then decreased further in the upward direction while that in the downward direction decreased rapidly (known as excessive darkness). In addition, the luminance decreased rapidly to the extent of an almost complete absence of luminance at a polar angle of over approximately 30° in the downward direction, so that the image

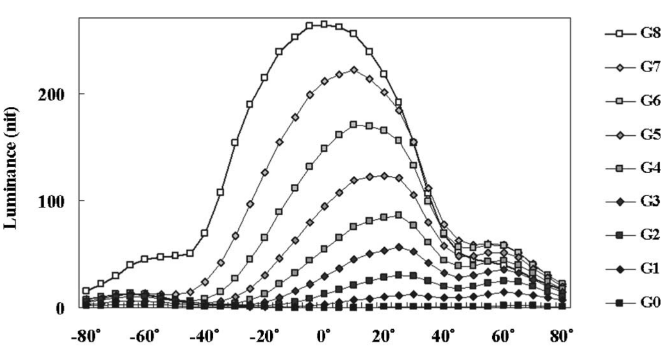

FIG. 2. Viewing angle dependence of the eight gray levels along the vertical direction of the WV-TN cell.

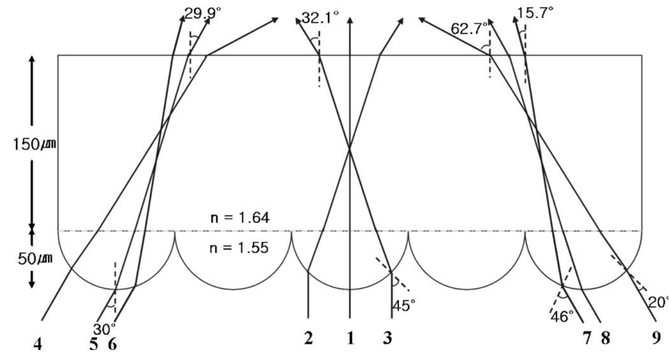

FIG. 3. Profile of the beam direction after passing through the BSF layer in relation to the incident angles normal to the surface.

could not be seen by the viewer even though the CR values remained high in these viewing directions.

In order to solve these problems, several BSF films were evaluated. BSF steers the incident beam in the desired direction. If BSF redirects some of the upward propagating light in the downward direction without changing the light intensity in the normal and downward directions, the luminance uniformity in the gray scale is greatly improved and the level of gray scale inversion is suppressed. Of the many films examined, this letter presents BSF film with the lens of a semispherical shape, of height 50 μm, on the base film, of thickness 150 μm, as shown in Fig. 3. The lens and the base film have refractive indices of 1.55 and 1.64 at 550 nm, respectively. The propagation of incident light after passing through BSF was calculated for two cases: (i) the beam incident to the normal direction and (ii) the beam incident at ±30° with respect to the normal direction, as shown in Fig. 3.

To define the beam direction, Snell's law,[14] $n_1 \sin \theta_1 = n_2 \sin \theta_2$, was applied, where n_1 and n_2 indicate refractive indices of media 1 and 2, and θ_1 and θ_2 indicate the incident and refracted angles of media 1 and 2 with respect to the normal to the surface at the point where the incident light strikes the surface, respectively. When the incident light passes through point 1 of BSF in the normal direction, the outgoing beam propagates straight without changing direction. However, when the incident light strikes points 2 and 3, the incident beams in the normal direction were deflected to the right and the left directions, respectively, with an angle of 32.1°, as shown in Fig. 3. This indicates that when the beams coming from the WV-TN cell in the normal direction pass through BSF, they split into three directions: front, left, and right. As a result, the luminance in the normal direction will decrease whereas that at the left and right will increase and thereby increase the luminance in the downward direction of the WV-TN cell and improve the excessive darkness problem. The beams incident at ±30° with respect to the normal direction were calculated. Considering rays 4, 5, and 6 incident at −30°, the beams that passed through BSF were deflected with angles of +62.7°, +29.9°, and +15.7° to the right directions, respectively, while rays 7, 8, and 9 were deflected to directions opposite to rays 4, 5, and 6. This indicates that BSF acts as a diffuselike film that scatters light. Therefore, the decrease in the ratio of the luminance with increasing viewing angle from the normal direction is reduced compared with the WV-TN cell.

Summarizing the role of BSF, the luminance in the normal direction is decreased but the beams lost in this direction are split into the oblique directions. In addition, the beams

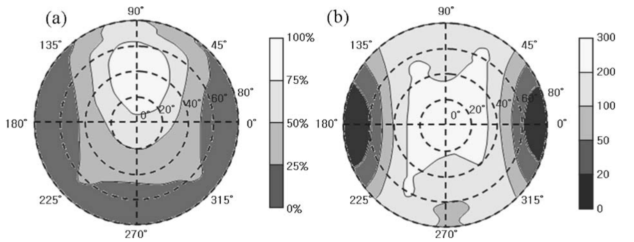

FIG. 4. Isoluminance contour of the BSF-TN cell at the (a) midgray and (b) isocontrast contour.

FIG. 6. (Color online) Photographs of the 19.0 in. TFT-LCD of the WV-TN without (right) and with (left) the BSF layer at a polar angle of −50°.

incident to BSF with an arbitrary angle deflect some portion of the light more outward than those of the incident beam after passing through the film, thereby reducing the decrease rate in luminance with increasing viewing direction. A noticeable finding is that the adhesive layer having *n* larger than 1 was not counted in this calculation, which affects the beam direction depending on its refractive index.

Figure 4 shows the measured isoluminance contours at midgray of the BSF-TN cell which was positioned without adhesive layer between the panel and the film. The maximum luminance in the normal direction was 138 cd/m^2, which was much lower than that of the WV-TN cell, as expected. The uniformity in the white and midgray states was significantly improved compared with that of the normal cell. Considering the uniformity of the midgray, a relative luminance larger than 50% with respect to the luminance in the normal direction was larger than 20° and 60° in the downward and upward directions, respectively. In particular, the region in which the relative luminance was larger than 25% was greatly extended compared with that of the WV-TN cell, as shown in Fig. 4(a). In addition, the dark state was well controlled by the WV film, and the luminance uniformity in the white state was improved so that a CR larger than 50 existed at a polar angle over 80° in the vertical direction and larger than 20 existed at a polar angle over 60° in the horizontal direction, which was much better than that of the normal, as shown in Fig. 4(b).

Finally, the viewing angle dependency of the nine gray levels for the BSF-TN cell was measured, as shown in Fig. 5. As expected, a high luminance, larger than 50 nit at G8, was maintained even at a large polar angle, ±80°, due to BSF, while it was less than 25 nit in the WV-TN cell. The excessive brightness and darkness in the gray levels remained but they were improved compared with the normal cell. Hence, the gray scale inversion was completely eliminated. Figure 6 shows real images of the TFT-LCDs of WV-TN, with and without BSF, in the downward direction at a polar angle of 50°. As clearly indicated, the image was distorted in the normal cell, as a result of gray scale inversion, but was not in the BSF-TN cell structure that has been proposed here, because of the removal of gray scale inversion.

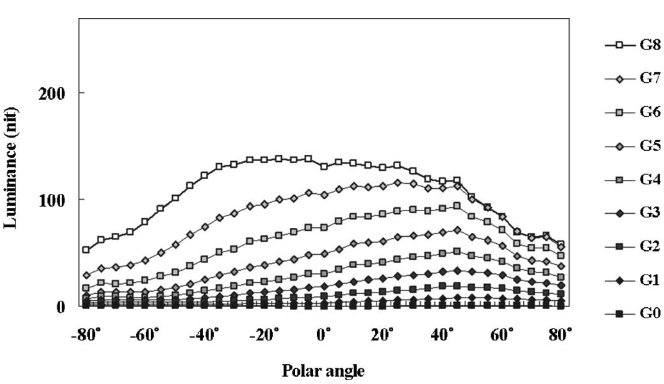

FIG. 5. Viewing angle dependence of the eight gray levels along the vertical direction of the BSF-TN cell.

In summary, this letter has reported a new cell structure in which the longstanding, intrinsic problems associated with gray scale inversion in WV-TN were solved with the application of BSF on the top of the WV-TN LCDs. The proposed cell exhibited a CR larger than 10 and was free of gray scale inversion up to a polar angle of 80° in all viewing directions. As a further advantage, this technology is easy to apply to the TN cell. The sacrifice of luminance in the normal direction can be compensated for by increasing the intensity of the input light, by further optimizing the BSF layer, and by utilizing the high light efficiency of the TN cell[10] compared with other LC modes.

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