Optical Engineering

SPIEDigitalLibrary.org/oe

Viewing angle controllable liquid crystal display under optical compensation

Soo In Jo
Seul Gee Lee
You-Jin Lee
Jae-Hoon Kim
Chang-Jae Yu

SPIE

Viewing angle controllable liquid crystal display under optical compensation

Soo In Jo
Seul Gee Lee
You-Jin Lee
Jae-Hoon Kim
Chang-Jae Yu
Hanyang University
Department of Electronic Engineering
Seoul 133-791, Korea
E-mail: cjyu@hanyang.ac.kr

Abstract. We investigated a viewing angle control of a liquid crystal display (LCD) under optical compensation for the enhancement of viewing angle characteristics in a wide viewing angle mode. The viewing angle controllable (VAC) LCD was operated in the configuration of three terminal electrodes consisting of a fringe-field-switching electrode at a bottom substrate and a common electrode at a top substrate. Using Poincaré sphere analysis, the optical compensation for the VAC LCD was designed so that the viewing angle characteristics were much improved in the wide viewing mode while they were degraded in the narrow viewing mode. [DOI: 10.1117/1.3622761]

Subject terms: liquid crystal display; viewing angle; optical compensation; wide viewing; narrow viewing; Poincaré sphere.

Paper 110498R received May 12, 2011; revised manuscript received Jul. 12, 2011; accepted for publication Jul. 18, 2011; published online Sep. 1, 2011.

1 Introduction

Mobile displays have attracted great interest for portable electronic devices such as smart phones, electronic books, and tablet devices, with the advances of the wireless communication environment. Liquid crystal displays (LCDs) have been the most promising technologies for the small mobile displays, as well as the large television applications, because of their superior performances such as high resolution and low power consumption. The wide viewing angle (WVA) characteristics in the advanced LCDs, including the patterned vertical alignment (VA) mode,[1] the multidomain VA mode,[2] the in-plane switching (IPS) mode,[3] and the fringe-field-switching (FFS) mode,[4] play an important role in the popularization of smart phones and tablet devices as well as television applications. As currently available mobile electronic devices become more affordable, privacy protection has recently become one of the crucial issues in display functionality. Sometimes these devices would share information with other people. If information sharing was not desired, the devices should be secured from other people in public places. A viewing-angle-controllable (VAC) LCD, which is switchable between WVA characteristics in the public mode and the narrow viewing angle (NVA) characteristics in the private mode, is urgently required to correspond to a need of privacy protection in mobile environment.

Various VAC LCDs, such as the double panel system, two backlight systems, and the LCD mode with a thermally variable retarder, have been proposed to control the viewing angle characteristics of the LCDs.[5–9] Although these VAC LCDs exhibit good switchability of the viewing angle characteristics, an additional panel or backlight are inevitably required. Recently, the dual liquid crystal (LC) mode in a single panel was proposed in a configuration of three terminal electrodes consisting of a FFS electrode on a bottom substrate and a common electrode on a top substrate.[10–13] Here, the WVA feature was obtained by operating a conventional FFS mode. The NVA feature was obtained by the FFS operation under a bias field between the bottom and top common electrodes. Although these single-paneled VAC LCDs exhibited excellent switchability of the viewing angle characteristics, the optical compensation, widely used in the WVA LCDs, has not been considered for the VAC LCDs thus far.

In this work, we investigated the VAC LCDs under optical compensations to enhance the viewing angle characteristics in the WVA mode. The structure of three terminal electrodes was used for operating the VAC LCD in the single panel.[10–12] Here, the conventional FFS operation exhibited the WVA characteristics, while the NVA mode was obtained by the vertical field between the top and bottom electrodes under varying FFS voltages. To investigate effects of optical compensation on the viewing angle characteristics in the NVA mode, two basic designs of the optical compensation for the IPS or FFS modes are discussed: the configurations of the positive A-plate/positive C-plate (AC), and the positive A-plate/negative A-plate (AA).[14] From Poincaré sphere analysis, it was found that the AA compensation much degraded the viewing angle characteristics in the NVA mode rather than the AC compensation. In the WVA mode, both compensations similarly enhanced the viewing angle characteristics.

2 Structure and Experiments

Figure 1 shows schematic diagrams of the VAC LCD with three terminal electrodes consisting of an FFS electrode on a bottom substrate and a common electrode on a top substrate. In the WVA mode, the structure and the operating principle are the same as those of the conventional FFS mode.[4] In our case, the initial rubbing direction was rotated by 12° from the direction of the grid electrode on the bottom substrate as shown in Fig. 1(a). Since the polarizer is parallel to the rubbing direction, the dark state was obtained in the absence of an applied voltage. When the external voltage was applied to the FFS electrodes, the LC molecules were rotated by about 45° from the initial rubbing direction, and thus the bright state was achieved as shown in Fig. 1(b). In the NVA mode, the bright state was the same as that in the WVA mode. The vertical arrangement of the LC molecules by the vertical field between the top common electrode and the

0091-3286/2011/$25.00 © 2011 SPIE

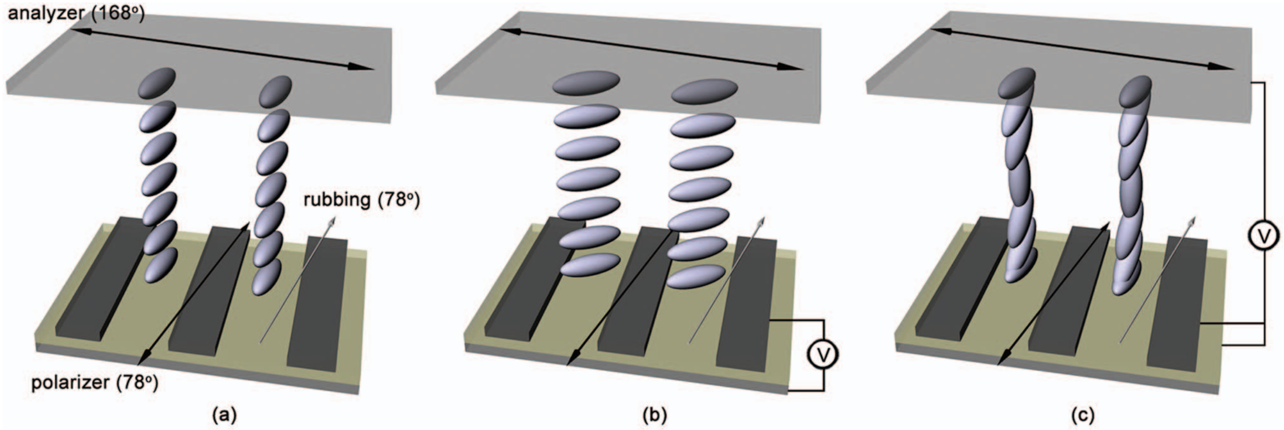

Fig. 1 Schematic diagrams of the VAC LCD with three terminal electrodes. (a) Dark state in the WVA LC mode, (b) bright state in both WVA and NVA LC modes, and (c) dark state in the NVA LC mode. (Color online only.)

bottom FFS electrodes gave rise to the dark state as shown in Fig. 1(c). Here, due to the large leakage of transmittance for the obliquely incident light, the NVA feature was exhibited. The Poincaré sphere analysis for the optical compensations were carried out in two configurations, shown in Figs. 1(a) and 1(c), representing the dark states.

The VAC LC sample was fabricated by assembling the common indium tin oxide glass substrate and the FFS electrode substrate. The width and the interval of the grid electrodes were 3 and 5 μm, respectively. After cleaning the substrates, the planar alignment layer (JSR AL22620) was coated and rubbed antiparallel for promoting the uniform planar alignment. Here, the rubbing direction was rotated by 12° from the direction of the grid electrode. The cell thickness of the assembled substrates was maintained by the use of 4 μm glass spacers. The LC (Merck MLC-6012, $\Delta\varepsilon = 8.2$, $n_e = 1.5798$, and $n_o = 1.4782$) were injected into the assembled cell by capillary action in the isotropic phase. The viewing angle properties under the optical compensation were calculated with the LCD simulating program, TechWiz (Sanayi System).

3 Results and Discussion

Figure 2 shows the microscopic textures of the VAC LCD at various gray levels under crossed polarizers and the viewing angle characteristics in the WVA and the NVA modes. As mentioned above, the electro-optic (EO) behavior in the WVA LC mode was exhibited by the conventional FFS operation with increasing the voltage between the bottom common electrode and the grid electrodes. In the NVA mode, the bright state was also obtained by the FFS operation, and the applied voltage between the bottom common electrode and the grid electrodes acted as an offset voltage in the NVA mode. Under such offset voltage, the EO transmittance decreased and finally reached the dark state as the vertical field between the top and the bottom common electrodes increased. To reduce the operating voltage and obtain the complete dark state, the offset voltage would have to be reduced while increasing the vertical field strength.

The contours of the contrast ratio of our VAC LCD sample in the WVA and the NVA modes are shown in Fig. 3. Here, the outer contour represents a contrast ratio of 10:1. As expected, the typical viewing angle characteristics of the FFS LCD without an optical compensation were measured in the WVA mode as shown in Fig. 3(a). In the NVA mode, the bright and dark states corresponded to the planar alignment and the vertical alignment, respectively. Therefore, the NVA mode was almost similar to the electrically controlled birefringence mode.[15]

Even in the advanced LCD modes with the WVA properties, which included the IPS and FFS modes, the design of the optical compensation was required to improve the image quality at the off-axes. Two basic designs of the optical compensation for the IPS or FFS modes[2] are shown in Figs. 4(a) and 4(b). One configuration of the optical compensation for the WVA mode consists of the positive C-plate and the positive A-plate. The A-plate's optic axis was parallel to the LC direction in the dark state as shown in Fig. 4(a) (AC compensation). The other configuration was composed of the negative A-plate positioned perpendicular to the LC direction, and the positive A-plate was parallel to the LC as shown in Fig. 4(b) (AA compensation). In both compensations, the LC layer acted as the positive A-plate in the WVA mode and the positive C-plate in the NVA mode. For optimal design of the compensation in the WVA mode, it was assumed that the polar and the azimuthal directions of the incident light used

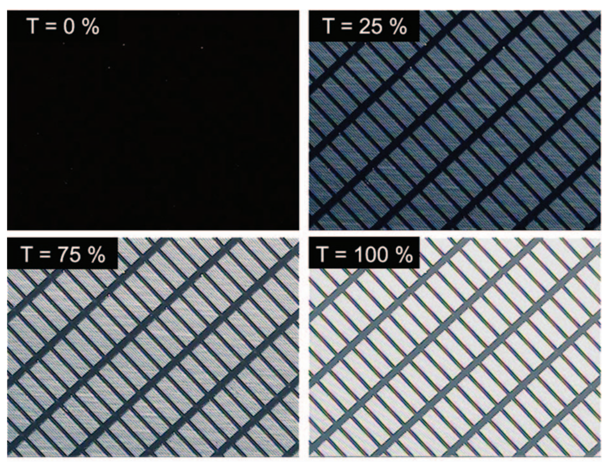

Fig. 2 Microscopic textures of the VAC LCD at various gray levels. (Color online only.)

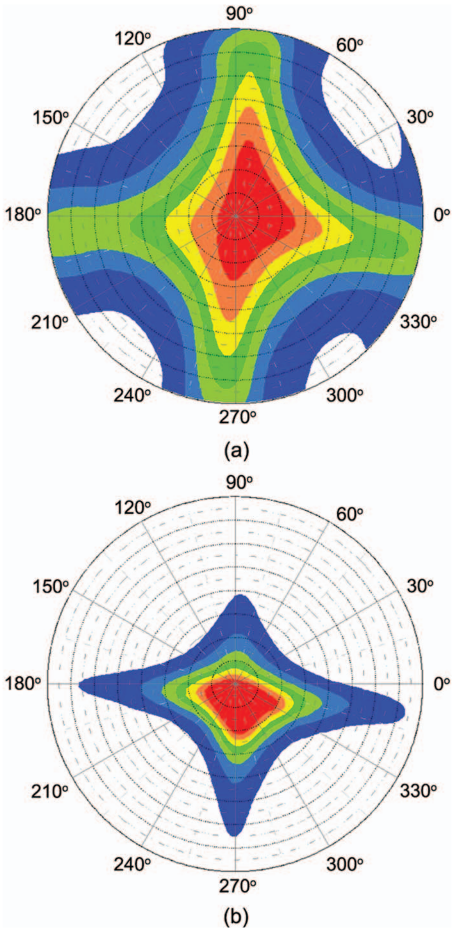

Fig. 3 The contours of the contrast ratio of the VAC LCD in (a) the WVA LC mode and (b) the NVA LC mode. In both modes, the outer contour represents a contrast ratio of 10:1. (Color online only.)

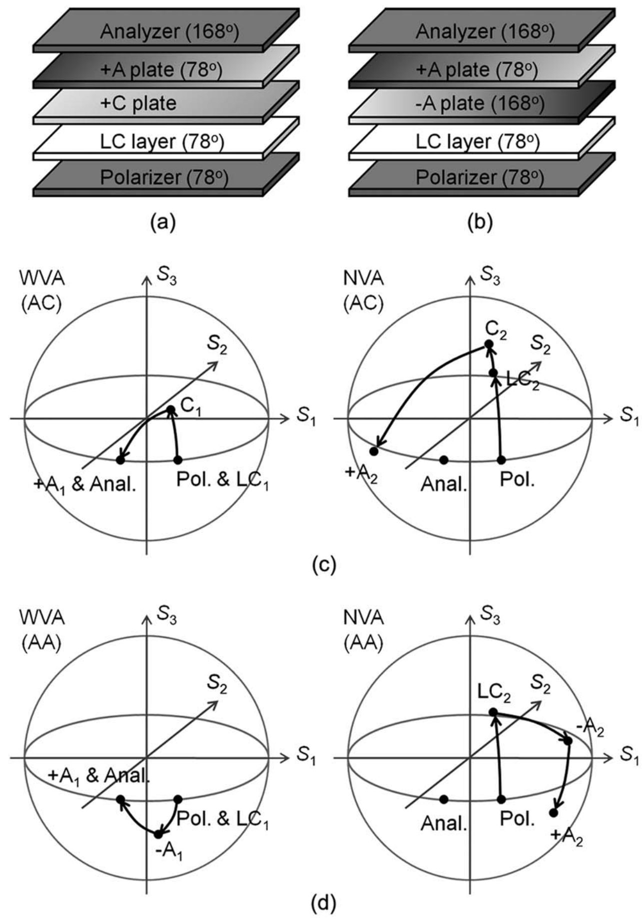

Fig. 4 Optical compensations for the VAC LCD using (a) the positive A-plate/positive C-plate (AC) and (b) the positive A-plate/negative A-plate (AA), and the corresponding polarization states in the WVA and the NVA LC modes for (c) the AC compensation and (d) the AA compensation on the Poincaré sphere. Letters, *LC*, *C*, $+A$, and *A*, represent the polarization states passing through the LC layer, the positive C-plate, the positive A-plate, and the negative A-plate, respectively. The subscripts 1 and 2 represent the WVA LC mode and the NVA LC mode, respectively.

were 70° and 33°, respectively. Here, the azimuthal direction of the incident light was determined by one of the bisectional angles between two crossed polarizers. The corresponding polarization states passing through each optical film in both AC and AA compensations were represented on the Poincaré sphere as shown in Figs. 4(c) and 4(d).

The transmittance leakage for an obliquely incident light under crossed polarizers was originated from the disagreement between the absorption direction ("Anal" on the Poincaré sphere) of the analyzer and the polarization ("Pol") passing through the polarizer. This disagreement was governed by the polar direction of the obliquely incident light. At first, to investigate the viewing angle characteristics in the NVA mode under the optical compensation, the compensation conditions had to be determined in the WVA mode. In the AC configuration, as shown in Fig. 4(a), since the directions of the polarizer and the planar aligned LC layer exhibiting the dark state in the WVA mode coincided with each other, the polarization state remained on the Pol point after passing the LC layer. Passing the positive C-plate and the positive A-plate successively, the polarization state reached "$+A_1$" through "C_1" as shown in Fig. 4(c). At the optimal condition of the compensation, the polarization "$+A_1$" coincided with the polarization state Anal. Using the formulas of the spherical triangle in the unit sphere, the phase retardations of the positive C-plate and of the positive A-plate were determined to be 1.5866 and 1.0297, respectively, at an incident polar angle of 70 deg. In the NVA mode, using these retardations, the polarization state was estimated after passing the vertically aligned LC layer, the positive C-plate, and the positive A-plate, successively. Here, the vertically aligned LC layer acted as a positive C-plate with a retardation of 0.7853 for MLC-6012 at the incident polar angle of 70 deg. The polarization state passing the positive A-plate finally arrived at a point "$+A_2$" (-0.6219, -0.7778, -0.0915), far from the point Anal (0.1000, -0.9948, 0.0127). This disagreement between the points of $+A_2$ and Anal produced an extra-retardation of 0.7807. Similarly, in the AA configuration, as shown in Fig. 4(b), the phase retardations of the negative A-plate and the positive A-plate were determined to be -1.0518 and 1.0518, respectively, at the optimal condition of the compensation in the WVA mode. In the NVA mode under the AA compensation, the polarization state passing the positive A-plate finally arrived at a point $+A_2$ (0.7274, -0.5836, -0.3609) far from the point Anal as shown in Fig. 4(d). This disagreement between the points of $+A_2$ and Anal produced an extra-retardation of 0.8649. It should

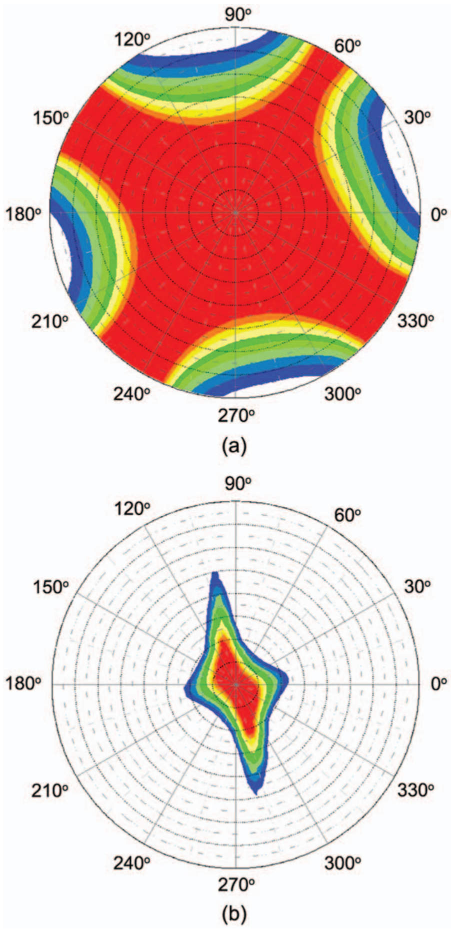

Fig. 5 Simulated contours of the contrast ratio under the AA compensation in (a) the WVA LC mode and (b) in the NVA LC mode. Here, outer contour represents a contrast ratio of 100:1. (Color online only.)

be noted that the extra-retardation in the bare NVA mode without any compensation was produced by the disagreement between the absorption direction of the analyzer and the polarization passing through the vertically aligned LC layer. It was calculated to be 0.6820. Although the viewing angle characteristics in the NVA mode were degraded in both compensation configurations, the NVA property was much more degraded under the AA compensation than under the AC compensation.

Figure 5 shows the viewing angle characteristics simulated with the TechWiz LCD simulation program in the WVA and NVA modes under the above AA compensation. Here, the outer contour represents a contrast ratio of 100:1. The WVA property was greatly improved while the NVA property was subtly degraded. These approaches for the compensation were directly applicable to the IPS- or FFS-based VAC LCDs in the configuration of the three terminal electrodes.[10–12] However, in the FFS mode, using the tilted LC molecules by a biased vertical field for the extreme NVA property,[11] the optical compensation to enhance the WVA property also improved the NVA property. In addition, the contours with maximum contrast ratio shifted from the center of the polar chart to an edge corresponding to the LC-tilted direction. Therefore, it is difficult to design the optimal compensation in both WVA and NVA modes.

4 Conclusion

We investigated the VAC LCDs under optical compensations for the enhancement of their viewing angle characteristics using Poincaré sphere analysis. The VAC LCD was operated in the configuration of three terminal electrodes consisting of a fringe-field-switching electrode on the bottom substrate and a common electrode on the top substrate. The WVA mode was operated by the conventional FFS mode and the NVA mode by the electrically controlled birefringence mode under an offset FFS voltage. The effect of the optical compensations in the AC and AA configurations on the viewing angle characteristics in the NVA mode was systematically investigated. From Poincaré sphere analysis, it was found that the AA compensation much degraded the viewing angle characteristics in the NVA mode rather than in the AC compensation mode. However, both compensations similarly enhanced the viewing angle characteristics in the WVA mode. These approaches for compensation are expected to be applicable to the various IPS-/FFS-based VAC LCDs in the configuration of three terminal electrodes.

Acknowledgments

This work was supported by a grant (F0004121-2010-32) from Information Display R&D Center, one of the Knowledge Economy Frontier R&D Programs funded by the Ministry of Knowledge Economy of the Korean Government, and by Samsung Electronics Co., Ltd.

References

1. K. H. Kim, K. Lee, S. B Park, J. K. Song, S. N. Kim, and J. H. Souk, "Domain divided vertical alignment mode with optimized fringe field effect," in *18th International Display Res. Conf. Asia Display*, Society for Information Display, Seoul, Korea pp. 383–386 (1998).
2. A. Takeda, S. Kataoka, T. Sasaki, H. Chida, H. Tsuda, K. Ohmuro, T. Sasabayashi, Y. Koike, and K. Okamoto, "A super-high image quality multi-domain vertical alignment LCD by new rubbing-less technology," in *SID International Symposium Dig. Tech. Paper*, Vol. 29, Society for Information Display, Anaheim, CA, USA, pp. 1077–1080 (1998).
3. M. Oh-e and K. Kondo, "Development of super-TFT-LCDs with in-plane switching mode," *Appl. Phys. Lett.* **67**, 3895–3897 (1995).
4. S. H. Lee, S. L. Lee, and H. Y. Kim, "Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching," *Appl. Phys. Lett.* **73**, 2881–2883 (1998).
5. H. S. Jin, H. S. Chang, J. K. Park, S. K. Yu, S. S. Lee, and I. J. Chung, "Novel Viewing-Angle Controllable TFT-LCD," in *SID International Symposium Dig. Tech. Paper*, Vol. 37, Society for Information Display, San Francisco, CA, USA, pp. 9–12 (2006).
6. K. Takatoh, S. Kobayashi, S. Kimura, N. Okada, T. Kanetsuna, N. Hirama, S. Kurogi, S. Sekiguchi, and K. Uemura, "New Peeping Prevention Technology to Control Viewing Angle Properties of TFT-LCDs," in *SID International Symposium Dig. Tech. Paper*, Vol. 37, Society for Information Display, San Francisco, CA, USA 1340–1343 (2006).
7. K.-W. Chien, Y.-J. Hsu, and H.-M. Chen, "Dual Light Source for Backlight Systems for Smart Viewing-Adjustable LCDs," in *SID International Symposium Dig. Tech. Paper*, Vol. 37, pp. 1425–1428 (2006).
8. E. Jeong, Y. J. Lim, J. M. Rhee, S. H. Lee, G.-D. Lee, K. H. Park, and H. C. Choi, "Viewing angle switching of vertical alignment liquid crystal displays by controlling birefringence of homogeneously aligned liquid crystal layer," *Appl. Phys. Lett.* **90**, 051116 (2007).
9. S. Gwag, I.-Y. Han, C.-J. Yu, H. C. Choi, and J.-H. Kim, "Continuous viewing angle-tunable liquid crystal display using temperature-dependent birefringence layer," *Opt. Express* **17**, 5426–5432 (2009).
10. J.-I. Baek, Y.-H. Kwon, J. C. Kim, and T.-H. Yoon, "Dual-mode switching of a liquid crystal panel for viewing angle control," *Appl. Phys. Lett.* **90**, 101104 (2007).
11. J. I. Baek, K.-H. Kim, S. R. Lee, J. C. Kim, and T.-H. Yoon, "Viewing angle control of a fringe-field switching cell by electrical tilting of liquid crystal," *Jpn. J. Appl. Phys.* **47**, 1615–1617 (2008).
12. E. Jeong, Y. J. Lim, M. H. Chin, J. H. Kim, S. H. Lee, S. H. Ji, G.-D. Lee, K. H. Park, H. C. Choi, and B. C. Ahn, "Viewing-angle controllable liquid crystal display using a fringe- and vertical-field driven hybrid aligned nematic liquid crystal," *Appl. Phys. Lett.* **92**, 261102 (2008).

13. M. S. Kim, Y. J. Lim, S. Yoon, S.-W. Kang, S. H. Lee, M. Kim, and S.-T. Wu, "A controllable viewing angle LCD with an optically isotropic liquid crystal," *J. Phys. D: Appl. Phys.* **44**, 145502 (2010).
14. X. Zuh, Z. Ge, and S.-T. Wu, "Analytical solutions for uniaxial-film-compensated wide-view liquid crystal displays," *J. Display Tech.* **2**, 2–20 (2006).
15. M. F. Schiekel and K. Fahrenschon, "Deformation of nematic liquid crystals with vertical orientation in electrical fields," *Appl. Phys. Lett.* **19**, 391–393 (1971).

Biographies and photographs of the authors not available.