Improvement of off-axis color shift on hybrid viewing-angle device using dual $\gamma$-voltage method

Shih-Bin Liu SID Member$^{1,2}$ | Yanbing Qiao$^2$ | Zhongfei Zou$^2$ | Chia-Min Yu$^2$ | Xiaojun Guo SID Member$^1$ | Te-Chen Chung$^2$

Abstract
We have mass production on one kind of liquid crystal display (LCD) device with hybrid viewing-angle (HVA), which can be switched between the wide viewing-angle (WVA) and narrow viewing-angle (NVA) by one button. This device adopts the single cell design that with lower cost, and utilizes the optical properties of electrically tilted LC to achieve the function of NVA display. An issue has received less attention in the past and been indeed found in the production process. It is that the off-axis color shift will appear in NVA mode. We put forward one method to improve this issue here, which is combined with the concepts of Gray Frame Insertion (GFI) and Impulse-type driving. By switching the voltage between two different $\gamma$ values, the color shift will be perfected on the produce.

KEYWORDS
color shift, hybrid viewing angle, LCD, optical properties

1 | INTRODUCTION

In the wake of sharp increase in this requirement of multi-media application for the public, various displays are widely used by different purposes and circumstances. Just because display devices are everywhere, the privacy in public places is attracting more and more attentions. Especially for some groups, like business people, the demand for viewing-angle switchable displays is urgent. For the reason that it can prevent a peeping sight beyond a certain angle by switching the visible angle, and attain this function of peep prevention to ensure information security for user.

Many related research on the viewing-angle switching technology of liquid crystal display (LCD) device have been reported,$^{1-7}$ but it is still a technological challenge about one viewing-angle controllable (VAC) liquid crystal (LC) panel which possess the mass conditions, such as the conveniences of production, low cost, and so on. There are various methods to realize a narrow viewing-angle (NVA) of LCD with the privacy protection. For example, a sticking privacy film, sub-pixel,$^{1-4}$ double LC cell,$^{5,6}$ and double backlight$^7$ techniques all belong it, but each one of them is with different disadvantages. These shortcomings of the sticking privacy film are with a fixed viewing-angle region that cannot be switched and the luminance of LCD will lose in great seriousness. This technique of sub-pixel will cause a low aperture ratio, and its driving mode is too complicated. Furthermore, the double LC cell and double backlight both will raise the cost of production and increase the weight and thickness of display devices.
We adopt the single cell design that with lower cost, and utilize the optical properties of electrically tilted LC to achieve this challenge and realize the mass production. After overcoming many difficulties of production process, this kind of product with hybrid viewing-angle (HVA) of LCD panel that can be switched by one button is accomplished. The brightness, contrast ratio (CR), and transmittance of LCD panels are frequently discussed.

**FIGURE 1** — Schematic of the proposed viewing-angle controllable FFS LC orientation with A, WVA mode and B, NVA mode

**FIGURE 2** — Real images of the 13.3 inch prototype by A, vertical looking, B, side-looking in WVA mode, and C, side-looking in NVA mode; and also D, the measuring areas on the LCD panel for display measurement systems
in the NVA mode of VAC technology, but this research of color shift on the NVA mode is seldom discussed. Nevertheless, the off-axis color shift of LCD panels will be indeed observed at NVA during the production process. This issue of color shift on LCD panel will affect the usage impressions of electronic products from the consumers, which is a very important parameter of industrial design for display panels that need to be practical produced.

2 | BASIC STRUCTURE AND OPERATING MECHANISM

The basic structure of our VAC device is composed of three terminal electrodes. A bottom substrate provided with a first electrode and a second electrode which display the respective roles of common and pixel electrode, and a third electrode on top substrate are the main body of proposed device. This third electrode is supposed to bias electrode and with switchable voltage to produce adscititious electric field. If no additional voltage is imposed on the third electrode, only the weakly dropout voltage exists in the space between top and bottom substrates at the outset. Although long-axis of LC molecules that close to upper layer are deviated from the pre-tilt angle (such as Figure 1A, a little bit of leakage will not vary the exhibition of pattern and still keep display on the conventional fringe-field switching (FFS) mode, which is named as wide viewing-angle (WVA) mode.

When an external voltage is applied to the bias electrode, these LC molecules are sharply rotated away the direction of initial pre-tilt angle by the vertically electric field, and thus this vertical arrangement of LC molecules between the top and bottom layers gives rise to a large leakage of transmittance for the obliquely incident light.

![FIGURE 3](image-url) — Variations of luminance with viewing angle of the 13.3 inch prototype in NVA mode, which A, along the transverse direction and B, along the longitudinal direction on the LCD panel. The insets show the trend of luminance along these two directions.
This exhibited feature of transmittance for obliquely viewing angle on LCD is called as NVA mode here. By controlling the voltage of third electrode on upper side, i.e. color filter side, the switchover of WVA and NVA modes can be realized, and that operational architecture is briefly shown in Figure 1.

3 | PROTOTYPE AND PROPERTY MEASUREMENT

By applying this principle of the above, we have the capacity to produce these VAC LCD panels of different sizes and take a 13.3 inch demo prototype as an example here. These performances of visual effect are observed at normal and oblique angles (Azimuth = 0°, Polar = 55°) of 13.3 inch prototype in the WVA mode, which are shown as the real images of Figure 2A and 2B. In this mode, the CR can be larger than 800, even exceeds 1,000, on this center of LCD at normal viewing-angle. The CR is also bigger than 10 at 85° for oblique angle, than image clearness can be still kept at oblique viewing-angle. Figure 2C shows the photograph of 13.3 inch prototype in the NVA mode at the same oblique angle as that in WVA mode. It obtains one indistinct image that comes from ultra low CR by a large leakage of transmittance.

Optical properties of the LCD on prototype are measured on a Display Measurement Systems, employing the standard setups. It can observe the comprehensive information of the LCD panel, including the brightness, color coordinate, CR, cell transmittance, and so on, and also canprobe into the gamma value and gray response by utilizing a module control function. In order to obtain more accurate observation for optical properties of the LCD, we chose the nice points that are equally distributed on the panel, which it is shown in the Figure 2D.

3.1 | Brightness features of unimproved prototype

The polar angle dependence of the brightness of a 13.3 inch prototype with NVA mode is illustrated in Figure 3. These variations of brightness at three points along the transverse direction on this LCD panel, which are left (open leftward triangle, point 4), center (close square, point 5), and right (open rightward triangle, point 6), can be observed in the Figure 3A. And it at another three points along the longitudinal direction, which are up (open upward triangle, point 2), center (close square, point 5), and down (open downward triangle, point 8), can be observed in the Figure 3B. These insets of two figures show the trend of brightness along two different directions at normally viewing angle (Polar = 0°). In the transverse direction, the variation of luminance is a fluctuation and this maximum appears at the center point. However, a declining trend of luminance can be observed along the longitudinal direction, from upper point to lower point, on this LCD panel of demo prototype.

3.2 | Color coordinate and color shift in NVA mode

Figure 4 shows this polar angle dependence of the 1931 CIE coordinate \((x, y)\) of a 13.3 inch prototype in NVA mode are displayed at center point, where the Figure 4A is about \(x\) coordinate and the Figure 4B is about \(y\) coordinate. These signs W, K, R, G, B, Y, P, and C mean the panel presents a picture with white, black, red, green, blue, yellow, pink, and cyan colors, respectively. The appearance of color shift can be found explicitly by adjusting the viewing angle from these various patterns of a LCD panel.

In order to define the standard of color shift, we use these following formulas to normalize the variation of color coordinate for our prototype:

![Figure 4](image-url)
\[ \Delta x = \langle (R_x - G_x) + (R_x - B_x) + (G_x - B_x) \rangle 
- \langle (R_x - G_x) + (R_x - B_x) + (G_x - B_x) \rangle_{50^\circ, \text{central}} \]  
(1)

\[ \Delta y = \langle (G_y - R_y) + (G_y - B_y) + (R_y - B_y) \rangle 
- \langle (G_y - R_y) + (G_y - B_y) + (R_y - B_y) \rangle_{50^\circ, \text{central}} \]  
(2)

where the \( x \) and \( y \) severally mean the CIE \( x \) and \( y \) coordinate, \( \langle \rangle \) bespeaks the average for calculation, and the \( R \), \( G \), and \( B \) mean the different colors that red, green, and blue, respectively. The evaluation criterion, 50\(^\circ\) and central point, come from our specification of products. When the obliquely viewing angle is larger than 50\(^\circ\), the CR of LCD on our product in NVA mode will be very small,\(^{13}\) and then an image of pattern will be indistinct to achieve the function of privacy protection.

Figure 5 shows the variations of \( \Delta x \) and \( \Delta y \) with polar angle of the 13.3 inch prototype in NVA mode, which using the conventional IVO driving method. The details of color shift along transverse direction and along longitudinal direction on the LCD panel can be presented explicitly with different scale. The insets of Figure 5A and 5D severally indicate the actual direction of measuring points on the LCD panel, which are transverse direction and

![Figure 5](image-url)
longitudinal direction. There exist differences between the color shifts of these two different directions, that it can be clearly observed from the data.

3.3 | Off-axis image distortion and improved method

Except that an image will become fuzzy at the oblique viewing angle larger than 50°, it will appear the gray inversion and color shift at the same time in our case. In the general way, we can quantify the characterization of off-axis image quality by an off-axis image distortion index, \( D(\theta, \phi) \),\(^{18,26–29}\) which is defined as

\[
D(\theta, \phi) = \left( \frac{\left| \Delta B_{i,j}(on-axis) - \Delta B_{i,j}(off-axis, \theta, \phi) \right|}{\Delta B_{i,j}(on-axis)} \right)_{i,j=0-255}
\]

Here, \( \Delta B_{i,j} \) is the brightness difference between the \( i \)-th and \( j \)-th gray levels, and \( \langle \rangle \) bespeaks the average for all cases of arbitrary gray levels. \( D(\theta, \phi) \) value is put in the range from 0 to 1 in a generally way, where a smaller value indicates a better off-axis image quality with a lesser image distortion.

In an attempt to ameliorate the off-axis image distortion of our produce, we utilize an Impulse-type Gray Frame Inserting to lessen the problem of color shift. By switching the driving voltage between two different \( \gamma \) values for image displaying, one way that combined with the concepts of Gray Frame Insertion (GFI)\(^{30,31}\) and Impulse-type driving\(^{32–34}\) is proposed for improving this disadvantage. This means of abating off-axis color shift is called as the dual \( \gamma \)-voltage method, and the performance is discussed in the text.

4 | ACTUAL IMPROVEMENT OF OFF-AXIS COLOR SHIFT

The variations of color deviation with viewing angle in CIE coordinate are depicted by various triangles in Figure 6. Left is with unimproved image driving method in 13.3 inch prototype, and right is with a new driving method, dual \( \gamma \)-voltage method, in 14.0 inch prototype. Comparing with 14.0 inch prototype, a biggish color

![FIGURE 6](image-url)
deviation of white pattern appears on 13.3 inch prototype in NVA mode, which uses an unimproved image driving method of color inversion. This distinction between the two different driving methods in NVA mode can be clearly observed in the insets with various oblique viewing angles that are from 0° to 85°. Figure 7 redraws these color deviations with off-axis viewing angles at the central point of LCD panel from two image driving methods, it is for easy comparison. The advantage of using dual γ-voltage method can be distinct observed, no matter that in the x or y color coordinates. The degrees of color deviations of 14.0 inch LCD panel using the modified driving method all are lower than ones of 13.3 inch LCD panel without modifying. It obviously indicates that this improved scheme is indeed feasible and effective.

In order to further understand the variations of color shift, Δx and Δy, along the transverse and longitudinal directions on the LCD panel between these two different image driving methods, modified and unimproved ones, we take out the data from 40° and 70° side-looking and

FIGURE 7 — Color uniformity performance of gray level inversion with various oblique viewing direction

FIGURE 8 — Color dispersion performance with oblique viewing angle 40° and 70° along the transverse direction on the LCD panel

FIGURE 9 — Color dispersion performance with oblique viewing angle 40° and 70° along the longitudinal direction on the LCD panel
then draw them into independent diagrams. This segmentation of color coordinate, which mentioned above, along a transverse direction on the LCD panel of two prototypes with disparate image driving method is shown as Figure 8. Here Figure 8A shows the details of 13.3 inch prototype with unimproved driving method, and Figure 8B shows the details of 14.0 inch prototype with new driving method named dual $\gamma$. In addition, these similar diagrams along a longitudinal direction with disparate image driving method are shown as Figure 9A that is about 13.3 inch prototype and Figure 9B that is about 14.0 inch dual $\gamma$ prototype.

The variations of color shift in transverse direction from our prototypes are not large that is similar with the variation of brightness from 13.3 inch prototype along the same direction, which as mentioned above, and it presents a horizontal distribution overall. Corresponding to the largish change of brightness in

**FIGURE 10** — Comparison of the testing patterns of B, C, D, the 13.3 inch prototype and E, F, G the 14.0 inch dual $\gamma$ prototype with NVA mode at different oblique viewing angles. And A, top picture is the real image of testing pattern with normal viewing direction.
longitudinal direction of 13.3 inch prototype, there are also biggish differences between these changes of color shift in longitudinal direction with the different location on LCD panel. At 70° viewing angle on the 13.3 inch sample, this changing degree of color deviation is inversely proportional to the variation of brightness with the change of location, where it is decreasing from upper one to lower one. It is well to remind that a manifestation of diagram about the gray inversion at large oblique viewing-angle is to change the Δx and Δy from positive to negative. And its scale of magnitude on behalf of how well the gray inversion is doing, such as the 14.0 inch dual γ prototype with smaller scales of Δx and Δy and with inconspicuous gray inversion. The overall variation of brightness on LCD panel is represented by this average of five points on panel. These magnitudes of that are 350 nits and 215 nits respectively, and the change rate is about 38.57%.

Real images of the 13.3 inch and 14.0 inch dual γ prototypes by side-looking in NVA mode at viewing angle 50°, 60°, and 70° separately are displayed in the Figure 10. This testing pattern which we used by vertical looking is shown in Figure 10A, it is regarded as one evaluation criterion. Comparisons of the testing pattern of 13.3 inch prototype by NVA mode at viewing angle 50°, 60°, and 70° are severally displayed in Figure 10B, 10C, and 10D, and the same ones of 14.0 inch dual γ prototype are severally displayed in Figure 10E, 10F, and 10G. These details show us that this improvement of new dual γ method is not obvious at the obliquely viewing angle 50°, the boundary of gray inversion. But a distinct improvement exists at viewing angle 60° and 70°, where the extent of color shifts is larger at first, and it can be identified by naked eye as the places with labels in these figures. So that the amelioration of new image driving method is truly effective in NVA mode, especially in this range which the oblique viewing-angle is bigger than 50°.

5 CONCLUSION

The HVA LCD device that can be switched by one button is developed, which utilize these LC molecules after electrical tilting. It provides a privacy protection at this polar angle more than 50° along the transverse direction, and retains a relatively high quality of image presentation in NVA mode like one of WVA mode. Although the disadvantage of color shift at oblique viewing angle exists in this kind of products, but we can use the method of dual γ-voltage to improve the defect. By this way that combined the concepts of Gray Frame Insertion and Impulse-type Black Insert, the off-axis color shift will be improved on the HVA produces. The switchable voltages between two different γ values can reduce the extent of color shift and this actual effect of improvement can be obviously discovered from the real images of our HVA products.

ORCID

Shih-Bin Liu https://orcid.org/0000-0002-0429-9703

REFERENCES

1. Lim YJ, Jeong E, Chin MH, Ji S, Lee GD, Lee SH. Viewing angle switching of patterned vertical alignment liquid crystal display. J. Phys. D: Appl. Phys. 2008;41:085110.
2. Lim YJ, Jeong E, Kim YS, Jeong YH, Jang WG, Lee SH. Viewing Angle Switching in Fringe-Field Switching Liquid Crystal Display. Mol. Cryst. Liq. Cryst. 2008;495:186–193.
3. Lim YJ, Kim JH, Her JH, et al. Viewing angle switching of liquid crystal display using fringe-field switching to control off-axis phase retardation. J. Phys. D: Appl. Phys. 2010;43:085501.
4. Kim MS, Lim YJ, Yoon S, et al. A controllable viewing angle LCD with an optically isotropic liquid crystal. J Phys D Appl Phys. 2010;43:145502.
5. Jeong E, Lim YI, Rhee JM, et al. Viewing angle switching of vertical alignment liquid crystal displays by controlling birefringence of homogeneously aligned liquid crystal layer. Appl Phys Lett. 2007;90(051116).
6. Jeong E, Chin MH, Lim YJ, et al. Switching of off-axis viewing quality in twisted nematic liquid crystal display by controlling phase retardation of additional liquid crystal layers. J Appl Phys. 2008;104:033108.
7. Chien KW, Hsu YI, Chen HM. Dual light source for backlight systems for smart viewing-adjustable LCDs, SID 06 Digest, 37, 38–3, pp.1425–1427 (2006).
8. Matsumoto S, Kawamoto M, Mizunoya K. Field-induced deformation of hybrid-aligned nematic liquid crystals: New multicolor liquid crystal display. J Appl Phys. 1976;47(3842).
9. Lu YQ, Liang X, Wu YH, Du F, Wu ST. Dual-frequency addressed hybrid-aligned nematic liquid crystal. Appl Phys Lett. 2004;85:3354.
10. Mendoza CI, Reyes JA. Light propagation and transmission in hybrid-aligned nematic liquid crystal cells: Geometrical optics calculations. Appl. Phys. Lett. 2006;89:091912.
11. Baek JI, Kwon YH, Kim JC, Yoon TH. Dual-mode switching of a liquid crystal panel for viewing angle control. Appl Phys Lett. 2007;90(101104).
12. Jiang LM, Su ZF, Yu CM, Liao P, Chung S. Viewing angle controllable LCDs with hybrid aligned nematic LC. Proceedings of IDW/AD'16, LCTp3–8, 2016:225–227.
13. Zhu MQ, Zhang SN, Huang X, Liao P, Chung S, Jia B. The optical properties of viewing angle controllable LCD. Proceedings of IDW'17, LCT8–3, 2017:219–221.
14. Lu R, Hong Q, Ge Z, Wu ST. Color shift reduction of a multi-domain IPS-LCD using RGB-LED backlight. Opt. Exp Dermatol. 2006;14(13):6243–6252.

15. Lu R, Nie X, Wu ST. Color performance of an MVA-LCD using an LED backlight. J. Soc. Inf. Disp. 2008;16(11):1139–1145.

16. Jiao M, Ge Z, Wu ST. Broadband Wide-View LCDs With Small Color Shift. J. Display Technol. 2009;5(8):331–334.

17. Kim HY, Song IS, Baik IS, Kim SY, Lee SH. Color characteristics of the fringe-field switching liquid crystal mode depending on E- and O-modes. Curr Appl Phys. 2007;7(2):160–167.

18. Park JH, Oh SW, Huh JW, Yoon TH. Four-domain Electrode Structure for Wide Viewing Angle in a Fringe-field-switching Liquid Crystal Display. J. Display Technol. 2016;12(7):667–672.

19. Gwag IS, Lee YJ, Kim ME, Kim JC, Yoon TH. Viewing angle control mode using nematic bistability. Opt. Express. 2008;16(4):2663–2669.

20. Jo SI, Lee SG, Lee YJ, Kim JW, Yoon TH. Viewing angle control of a fringe-field switching liquid crystal display using a vertical bias field. J. Inf. Disp. 2016;17(1):25–30.

21. Lee SH, Lee SL, Kim HY. Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching. Appl Phys Lett. 1998;73(20):2881–2883.

22. Baek JS, Kim KH, Lee SR, Kim JC, Yoon TH. Viewing Angle Control of a Fringe-Field Switching Cell by Electrical Tilting of Liquid Crystal, Jpn. J. Appl. Phys., 2008;47(3):1615–1617.

23. Adachi M. Controllable-Viewing-Angle Display Using a Hybrid Aligned Nematic Liquid-Crystal Cell, Jpn. J. Appl. Phys., 2008;47(10):7920–7925.

24. Jeong E, Lim YJ, Chin MH, et al. Viewing-angle controllable liquid crystal display using a fringe- and vertical-field driven hybrid aligned nematic liquid crystal. Appl Phys Lett. 2008;92(26):1102.

25. Kim SS. Super PVA Sets New State-of-the-Art for LCD-TV, SID 04 Digest, 2004;35(15–4):760–763.

26. Kim SS. The World’s Largest (82 in.) TFT-LCD, SID 05 Digest, 2005;36(66–1):1842–1847.

27. Lu R, Wu ST, Lee SH. Reducing the color shift of a multidomain vertical alignment liquid crystal display using dual threshold voltages. Appl Phys Lett. 2008;92:051114.

28. Lu R, Wu ST, Lee SH, Li WY, Wei CK. New 8-domain MVA LCD with reduced color shift, SID 08 Digest, 2008;39(P-194):1938–1940.

29. Nose T, Suzuki M, Sasaki D, Imai M, Hayama H. A Black Stripe Driving Scheme for Displaying Motion Pictures on LCDs, SID 01 Digest, 2001;32(35–3):994–997.

30. Chen H, Ha T, Sung J, Han B. Smooth-Frame-Insertion Method for Reducing Motion Blur on OLED Panel, SID 08 Digest, 2008;39(33–4):472–475.

31. Hirakata JI, Shingai A, Tanaka Y, Ono K, Furushashi T. Super-TFT-LCD for Moving Picture Images with the Blink Backlight System, SID 01 Digest, 2001;32(35–2):990–993.

32. Kimura N, Ishihara T, Miyata H, Kumakura T, Tomizawa K, Inoue A, Horino S, Inaba Y. New Technologies for Large-Sized High-Quality LCD TV, SID 05 Digest, 2005;36(60–2):1734–1737.

33. Liao LY, Chen CW, Huang YP, Yeh SC. Fast MPRT with High Brightness LCD by 120Hz Local Blinking HDR Systems, SID 09 Digest, 2009;40(57–4):862–865.

AUTHOR BIOGRAPHIES

Dr. Shib-Bin Liu received the Ph. D. degree in physics from National Central University, Taiwan, China, in 2014. He joined the InfoVision Optoelectronics (IVO) Co., Ltd., Jiangsu, China in 2016 and is a Staff Engineer of Product Development Center. His enterprise postdoctoral research is cooperating with Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China.

Mr. Yanbing Qiao received his bachelor’s degree in electronic engineering from Chang An University, Xian, China, in 2005. He joined the InfoVision Optoelectronics (IVO) Co., Ltd., Jiangsu, China from 2005 to 2019, and he has served as the director of LCD technology development division in the Product Development Center.

Dr. Zhongfei Zou received the Ph.D. degree in Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science. He joined InfoVision Optoelectronics (IVO) Co., Ltd., Jiangsu, China in 2011 and is a Staff Engineer of Product Development Center.

Mr. Chia-Min Yu received the M. S. degree in electrical engineering from National Sun Yat-sen University, Taiwan, China. From 2004 to 2010, he worked in Product Development Department, AUO Corp., Taiwan, China. He joined InfoVision Optoelectronics (IVO) Co., Ltd., Jiangsu, China in 2010.
Dr. Xiaojun Guo received the Ph. D. degree in electronic engineering from University of Surrey, Guildford, UK, in 2007. He is currently a Professor with National Engineering Lab for TFT-LCD Materials and Technologies, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China. His current research interests are thin-film transistors and circuits for displays and flexible large-area electronics.

VP Te-Chen Chung received the M.S. degree in electrical engineering from National Central University, Taiwan, China. From 2000 to 2006, he worked in Product Development Center, Hannstar Display Corp., Taiwan, China. He joined InfoVision Optoelectronics (IVO) Co., Ltd., Jiangsu, China in 2006 and is charge of LCD Research and Development Center.