Viewing Angle Switching of Tristate Liquid Crystal Display

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Abstract

A tristate liquid crystal display characterized by two distinct dark states and one bright state has been presented. These two dark states contribute to two different viewing angles. We demonstrate a single panel of vertically aligned cell whose viewing angles can be directly selected from two sets of driving voltage.

1. Introduction

Over the past few years, liquid crystal display (LCD) has experienced a tremendous expansion in the electronics industry, primarily because of its radical technical improvements. As one of the attractive technologies, wide viewing angle allows one to view the display over a wide-range field of eyeshot with good legibility. Most often, it is not a concern of the user for the security of displayed contents. However, for the cases when he is performing transaction on the automated teller machines (ATMs), or working on a laptop in public where there are a number of people in the immediate area, the hazard of exposure of personal privacy and confidential data must be taken great care of. In order to guarantee a safe protection, the viewing angle under the said situations should be narrowed as much as only the user himself in front of the display can clearly see the image or text on the screen. When the ATMs are not in use playing advertisements or the user is handling non-private information on his laptop monitor, a wide viewing angle mode would be favored again. To meet those needs, an optical system with switchable viewing angle settings depending on situation and user's preference is required.

Lately developed prototypes of viewing angle switchable LCDs are mainly made up of a thin film transistor (TFT)-LCD panel to control the gray level and one or two additional LC panels to control the viewing angle.[1-7] Unfortunately, these are not appropriate to the portable displays in that additional panels would involve extra weight and thickness, and increase not only power consumption but also manufacture cost. An alternative method is to subdivide the pixel into major pixels and minor pixels of which minor pixels are responsible for viewing angle control.[8] In this case, the critical issue is that the aperture ratio will be greatly reduced, so will the light throughput per unit area and even the resolution. In this paper, to solve those problems, we propose a tristate LCD which is free of complex design using merely a single panel, addressable with TFT and effective in switching the viewing angle.

2. Operational Principle

From the viewpoint of optics of LCD, the viewing angle, defined as contour of isocontrast ratio, is chiefly dominated by the dark state dependent on the observation angle. For this reason, most of LCDs have a well compensated dark state upon which a wide viewing angle is obtained. Customarily, under crossed polarizers, the dark state corresponds to the zero retardation; besides, there can be a plurality of dark states available for any given light provided the retardation equals an integer multiples of its wavelength. These dark states, in fact, will exhibit different viewing characteristics due to the dissimilar directional properties of the LC directors, which implies that variable viewing angle characteristics can be constructed on such LCDs that have at least two dark states. The eligible modes for this purpose include mixed-mode twist nematic (MTN), vertically aligned (VA), electrically controlled birefringence (ECB), and optically compensated bend (OCB) modes. Of the above mentioned modes, it is advantageous to choose the VA mode as a paradigm of viewing angle switchable LCD as it is easy in optical compensation and multi-domain formation;[9-11] however, the same principle equally adapts to the MTN, ECB or OCB mode. Incidentally, the twist nematic (TN), in-plane switching (IPS), and fringe field switching (FFS) modes have to be excluded out of consideration on account of the only one possible dark state no matter how the retardation changes.

The operational principle of tristate LCD, among other things, is schematically illustrated in Fig. 1. When no voltage is applied, LC directors line up in a homeotropic fashion, in Fig. 1(a), exhibiting zero retardation at the direction normal to the substrate; moreover, the off-normal retardation will be counteracted by the negative C-film. This is designated as the first dark state. In contrast, the other dark state called second dark state can be obtained at such a voltage that rotates the LC directors, in Fig. 1(c), to the extent that its normal retardation appears to be an exact full wavelength. Unlike the first dark state, the second one holds only within a limited range, beyond which it will cause light leakage at oblique direction as the alignment of LC directors is no longer phase-matched with the optic axes of the negative c-film. The bright state is achieved at an intermediate voltage, at which the LC directors are reoriented towards a certain direction, as shown in Fig. 1(b), having the retardation equal to a half wavelength. It is very important to notice that along the above direction there will be a minimum of transmittance that is undesirable in practical application. To overcome this drawback, the LC directors should be aligned in multiple directions via four-domain techniques.[12)]

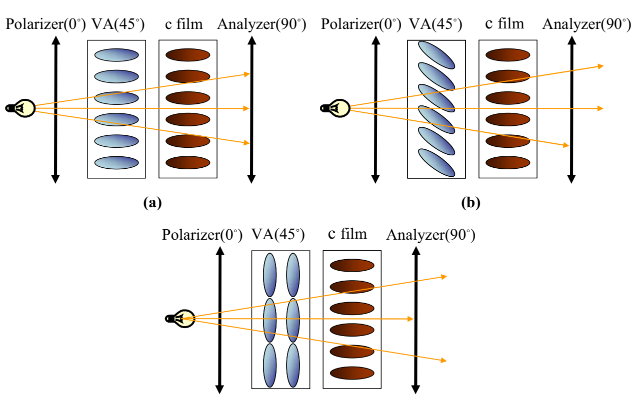

Fig. 1. Operational principle of the tristate LCD: (a) first dark state, (b) bright state, and (c) second dark state.

In numerical calculation, the optical transmittance of a homogeneously aligned nematic LC layer between crossed polarizers is formulated as

$$T = \sin^2(2\phi)\sin^2\left(\frac{\Gamma}{2}\right), \qquad (1)$$

where ϕ is the angle between the LC director and the transmission axis (TA) of the analyzer, and Γ is the phase retardation. In eq. (1), if we fix the angle ϕ at $\pi/4$ and neglect its dependence on the polar angle θ, the transmittance can be considered as a function of the retardation Γ of LC layer alone, or rather, the residual retardation after optical compensation of the negative C film. We calculated this residual retardation with respect of the polar angle θ by combining the retardations of LC layer and negative C film, as shown in Fig. 2, where, for the sake of simplicity, the LC directors in two dark states are assumed to be either perpendicular or parallel to the substrate surface and both Δnd (product of the refractive anisotropy and the thickness) for LC and negative C film are set as 550nm. The algorithm of the retardation calculation is described in the ref. 13. As shown in Fig. 2(a), the residual retardation of the first dark state is below 36nm, a yield of transmittance less than 4.2%; such a small amount of light leakage can barely affect the dark state. For the second dark state, referring to Fig. 2(b), a decrease of retardation from 550nm to 80nm will give rise to a non-monotonic transmittance rising up to 100% at 53˚ and then falling down to 19% at 90˚. This substantial change in retardation or transmittance vs. the polar angle will profoundly deteriorate the dark state. We shall point out that those dark states as well as bright state are observed for a monochromatic light of wavelength of 550nm. For real color display containing RGB pixels, the retardation conditions to meet dark or bright state for each color pixel must be discriminated from one another.

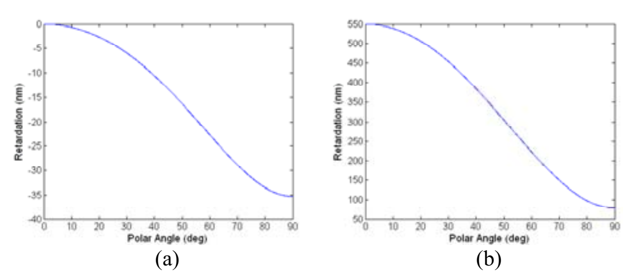

Fig. 2. Calculated retardation for (a) first dark state, and (b) second dark state.

3. Results and discussion

According to the previous concept, to satisfy the condition that all wavelengths of interest can reach the second dark state, Δnd, a decisive factor, should not be less than the longest wavelength. Specifically, the cell parameters used in our simulation and experiment are given as the LC material of MDA-01-2306 (Merck Co.) with the dielectric anisotropy (Δε=-5.0, ε//=3.9, ε⊥=8.9), refractive anisotropy (Δn=0.1204, n_o=1.4850, n_e=1.6054), cell gap thickness of 6.4 um and surface tilt angle of 89˚. As a result, the total Δnd of LC is 770nm, on the other hand, that of the negative C film (Δn=0.002, n_o=1.502, n_e=1.5) for optical compensation is optimized at 690nm.

Figure 3 plots the voltage-transmittance curves for the red (R: 650nm), green (G: 550nm), blue (B: 450nm) and white light, respectively, where the bright and dark states are satisfied at different voltages, and the white light apparently cannot arrive at an absolute second dark state owing to the wavelength dispersion. Thus, each of RGB pixels should be driven with different voltage regime to meet the retardation conditions. The voltage ranges for driving R, G, B pixels are in turn 0~2.85, 0~2.68, and 0~2.52V for wide viewing operation, and 2.85~7.12, 2.68~4.37, and 2.52~3.45V for narrow viewing operation. In practice, the switch between the wide and narrow viewing modes by electrically selecting the corresponding voltage regime can be easily done on the TFT driving circuit in which each RGB pixel is independently addressed. We also would like to suggest finding the LC material that has larger dielectric anisotropy or better wavelength dispersion properties so that the driving voltage, especially for the red light, is reduced as low as 5V in order to be compatible with the existing TFT.

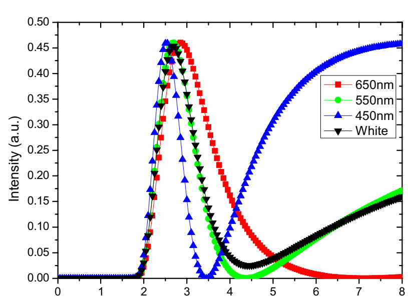

Fig. 3. Voltage-transmittance curves for R (650nm), G (550nm), B (450nm), and white light.

The viewing angle characteristics of the two viewing modes are examined on the optical configuration of Fig. 1, which is comprised of an entrance polarizer (TA=0˚), four-domain vertically aligned nematic cell set at 45˚ relative to the transmission axis of polarizer, a negative C-film and

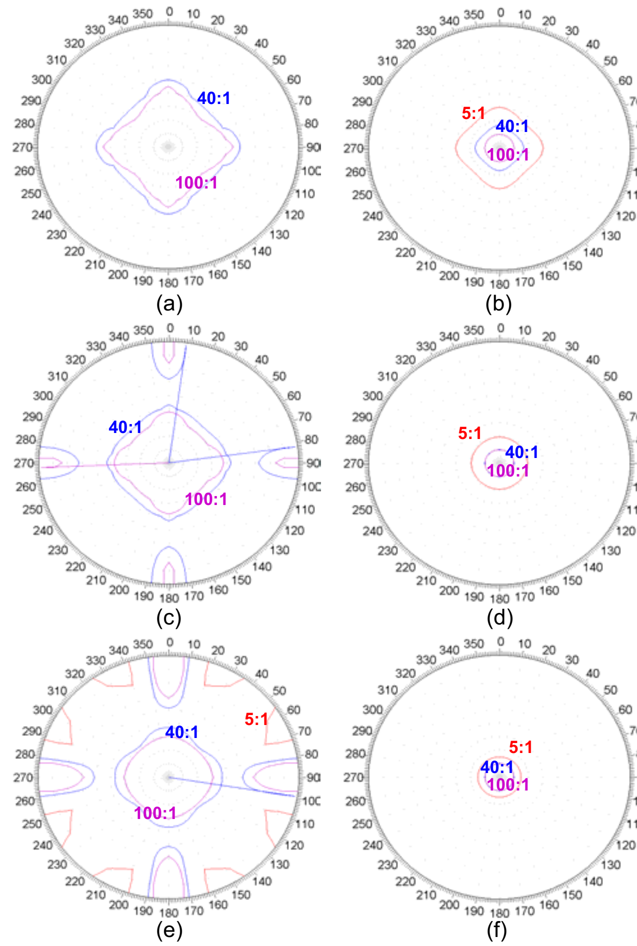

Fig. 4. Calculated viewing angles for (a) R, (c) G, and (e) B at wide viewing mode and (b) R, (d) G, and (g) B at narrow viewing mode.

an exit polarizer (TA=90˚). Isocontrast ratio contours are calculated for each RGB pixel (R stands for red at 650nm, G for green at 550nm, B for blue at 450nm), which is as shown in Fig. 4. In the wide viewing mode, all RGB pixels demonstrate super wide viewing cone covered by contrast ratio greater than 5:1 almost everywhere (except for blue) benefiting from the phase-matched compensation for the first dark state. The fourfold-like symmetry pattern is a direct consequence of four-directionally aligned VA cell. Note that the contrast ratio is not simply a monotonous function of the polar angle; hence, higher value of contrast ratio can be found in both the vertical and horizontal direction. This is in agreement with the statement that the transmittance of bright state will come to a minimum at certain direction along the tilted LC director and then bounces up again. In the narrow viewing mode, the entire viewing cone of contrast ratio of 5:1 is restricted within 30˚ for red, 20˚ for green, and 15˚ for blue. The reason why the viewing angle becomes wider with longer wavelength can be partially understood from the fact that, at higher voltage required for the bright state of the longer wavelength, the LC directors are reoriented nearer to the substrate, shifting that minimum of bright state to a steeper angle; in other words, bright state is improved for the longer wavelength.

To validate the viewing angle switching of tristate LCD, we fabricated several test cells covered by the stripe RGB color filters and took pictures at the front and a skew angle of about 45 deg under two viewing modes. The cell parameters are consistent with those used in simulation. It is necessary to mention that the real color filters will more or less transmit wavelengths of some bandwidth centered at the primary colors, which means the second dark state merely established on a specific wavelength will see a small amount of light leakage, even though, this may not be enough sensitive to the digital camera. In the normal direction, Figs. 5(a) and 5(c) show the first dark state in the wide viewing mode and second dark state in the narrow viewing mode, respectively. When the observation angle shifts to 45 deg, the photograph taken in the wide viewing mode remains as dark state, as shown in Fig. 5(b), whereas, that taken in the narrow viewing mode, in Fig. 5(b), appears like bright state, since the RGB pixels can be clearly distinguished. If an image is displayed using narrow viewing mode, its original quality will be extremely distorted at the direction other than screen front, thereby restraining the legibility into a relatively narrower angle.

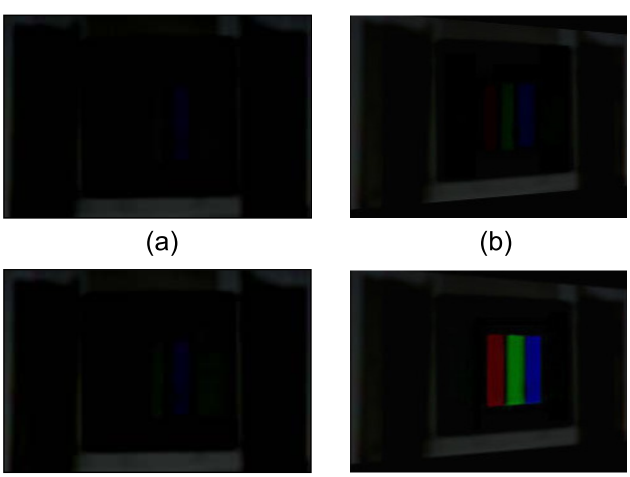

Fig. 5. Pictures of the test cell which are taken at (a) the front and (b) a skew angle of about 45 deg for wide viewing mode, and (c) the front and (d) a skew angle of about 45 deg for narrow viewing mode.

4. Summary

We have developed a viewing angle switchable tristate LCD allowing both wide viewing mode operation for sharing the information and narrow viewing mode operation for protecting the information. The viewing angles can be easily controlled electrically with a single panel of LCD requiring no additional modules and manufacture cost. More importantly, it is totally compatible with the existing TFT driving circuit. We explained its operational principle using vertically aligned nematic cell. However, the same principle equally applies to MTN, ECB or OCB mode and there could be a lot of variations with those modes. We are looking forward to its promising application as an economical and efficient viewing angle switchable LCD.

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