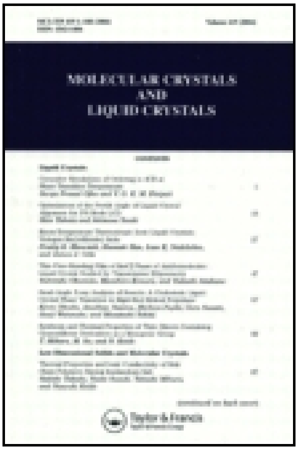

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Optical Design of a Normally-Black Twisted-Nematic Liquid Crystal Mode with Achromatic Dark State

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We propose an optical configuration to compensate dispersion characteristics in the dark state of a normally-black twisted-nematic (NB-TN) liquid crystal display (LCD). By optimization of parameters with a parameter space diagram (PSD), the high contrast-ratio (CR) over 500:1 could be obtained using two +A plates. Furthermore, excellent dispersion characteristics were also obtained in the bright state. We confirmed the performance of the proposed method and structure through both the numerical calculations and the experiments.

Keywords: liquid crystal display; normally black mode; twisted nematic

INTRODUCTION

Liquid crystal displays (LCDs) are widely employed owing to the low operating voltage, light weight and thinness. There are various LCD modes, such as twisted nematic (TN), vertical alignment (VA), in-plane switching (IPS), and fringe-field switching (FFS). Among them, the TN mode is widely used due to many merits, such as the superior dispersion characteristics, the large cell-gap tolerance, and the high aperture ratio [1–4].

The TN mode can be realized with two polarizers either parallel or perpendicular to each other. The former is the NB-TN mode, while the latter is the normally-white TN (NW-TN) mode. Because of the

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superior dark state at normal viewing direction, the TN mode has been mainly used in the normally white mode until now. However, the readability is much sensitive to bad pixels because the turned-off pixel in the NW-TN mode always shows the bright state, by which the CR can become significantly lower. Although the NB-TN mode suffers from the poor dark state, it can be preferred because of higher CR in the low operating voltage and easiness of viewing angle compensation. Also, the NB-TN mode is potentially profitable because there is no light leakage caused by to bad pixels. To obtain the high CR in the NB-TN mode, an optical configuration composed of four in-plane negative wave plates has been reported [5]. However, many wave plates can increase the cost, and negative in-plane plates are not common.

In this paper, we propose an optical configuration of the NB-TN mode with high CR. By using two uniaxial films, one is a half-wave plate (HWP) and the other is a +A plate, we confirmed the achromatic dark state of the NB-TN mode through numerical simulation and experiments.

OPTICAL CONFIGURATION

Changes of the polarization state of an incident light, with wavelengths of 450 nm (B), 550 nm (G), and 650 nm (R), passing through the TN layer are shown on the S_1-S_2 plane of the Poincare sphere in Figure 1(a). Although B, G, and R are incident with the same polarization state, those passed through the TN layer show polarization states different from one another, as shown in Figure 1(b). Because of these dispersion characteristics of the NB-TN mode, the dark state of the NB-TN mode shows a light leakage.

To improve dispersion characteristics of the NB-TN mode, we designed to disperse the incident light before entering the TN layer. We assumed that dispersed B, G, and R of the incident light would be converged at (0, −1, 0) on the Poincare sphere after passing the TN layer as shown in Figure 2, provided that initially they have different polarization states. Accordingly, we expected that the NB-TN mode could show the superior dispersion characteristics.

In order to disperse the incident light, we propose an optical configuration composed of a HWP and a +A plate, placed between the TN layer and the polarizer as shown in Figure 3. Because the transmission axis (TA) of the polarizer is optional and the HWP is placed after polarizer, we get polarization states of B, G, and R passed the polarizer and the HWP shown in Figure 4(a). Here, the OA of the HWP is half of the angle between the input director of the TN layer and the TA of the polarizer. Then, G is always placed at (1, 0, 0) on the Poincare sphere

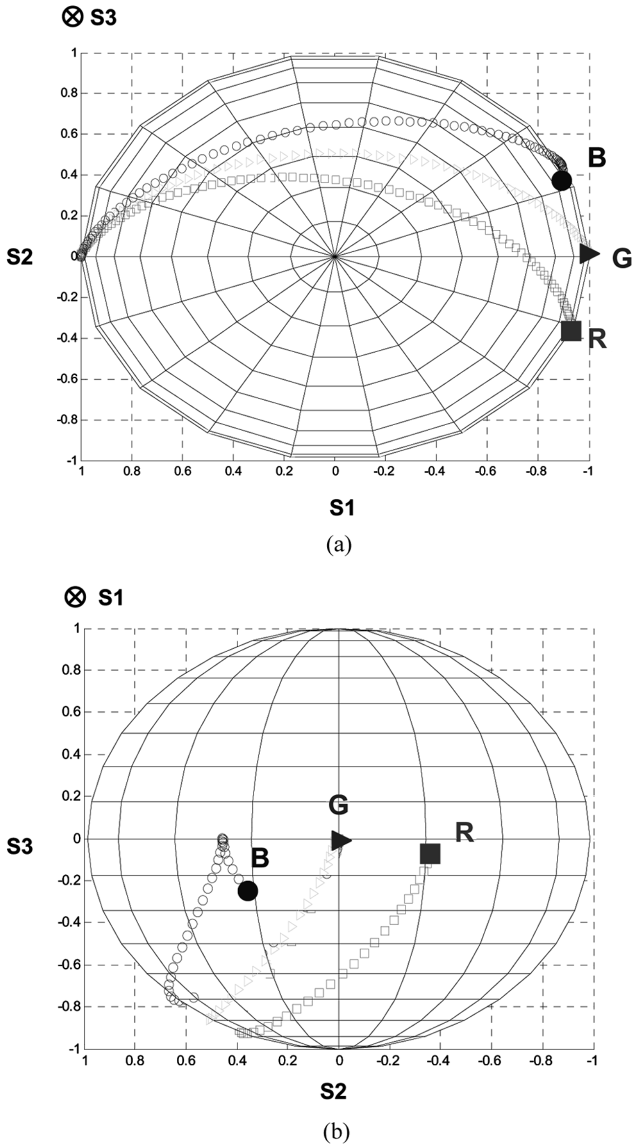


FIGURE 1 Changes of B, G, and R (a) on the S_1-S_2 plane and (b) on the S_2-S_3 plane after 0° linearly polarized light is passed through a 90° TN layer.

before entering the TN layer. The +A plate is placed between the HWP and the TN layer to move B and R near the equator on the Poincare sphere, as shown in Figure 2. Polarization states of B and R are

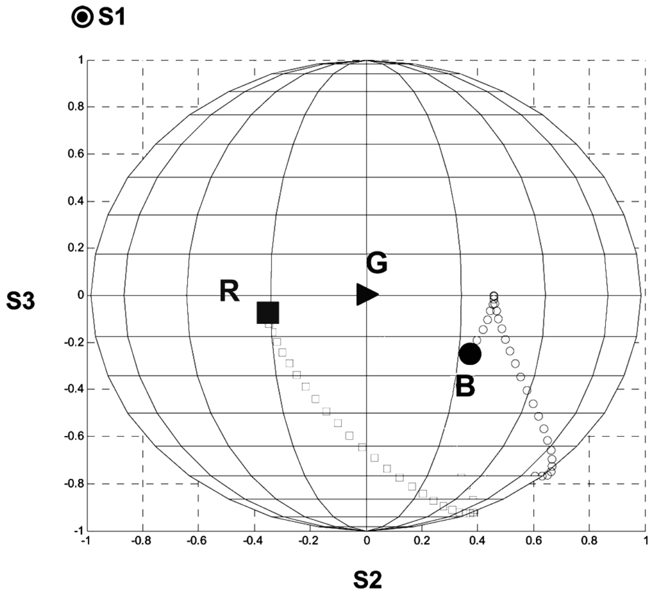


FIGURE 2 Polarization states of B, G, and R on the S_2-S_3 plane after 90° linearly polarized light is passed through a −90° TN layer.

rotated clockwise around G on the S_2-S_3 plane of the Poincare sphere by the +A plate. The OA of the +A plate is −90° so that G always has to be placed at (1, 0, 0) on the Poincare sphere and others have to be rotated clockwise. Polarization states of B, G, and R after passing

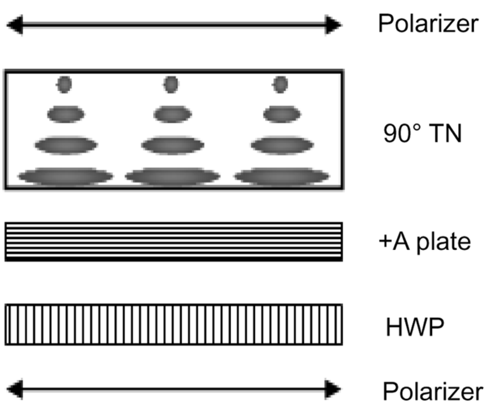


FIGURE 3 Optical configuration of a NB-TN cell proposed to improve dispersion characteristics.

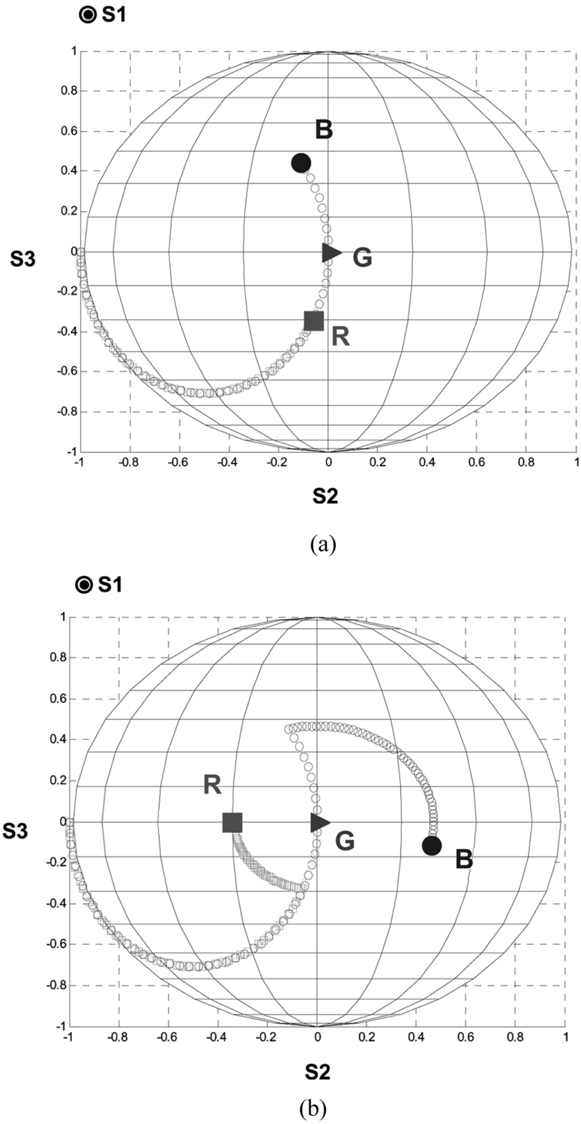
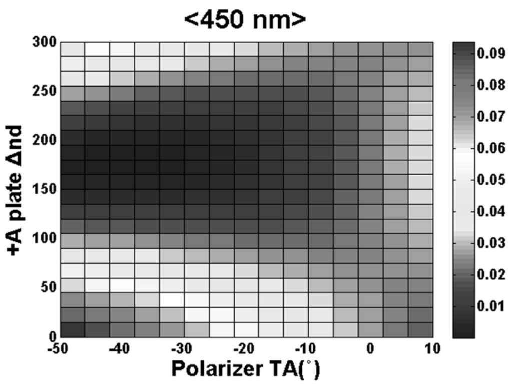


FIGURE 4 B, G, and R on the Poincare sphere (a) after passing through a polarizer and a HWP and (b) after passing through a +A film.

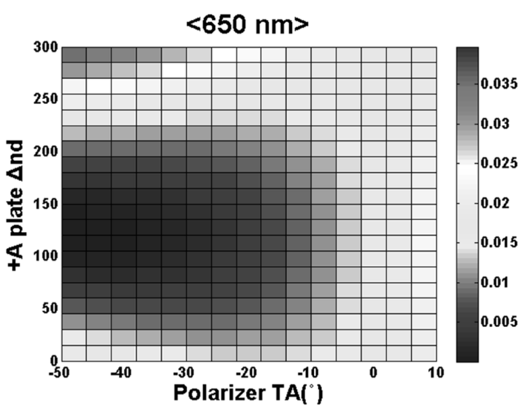
the +A plate are shown in Figure 4(b). Through this principle, we can control the polarization states of B, G, and R to offset the dispersion after passing the TN layer.

SIMULATION RESULTS

From the proposed structure, we can consider two parameters. One is the TA of the polarizer which decides the OA of the HWP. The other is the retardation value of the +A plate, of which the OA is $-90°$. To obtain optimum parameter values, we used the parameter space diagram (PSD) [5]. The transmittances of B and R in the initial dark state are shown in Figure 5, respectively. Because G is always placed at (1, 0, 0) on the Poincare sphere before entering the TN layer, G is not considered in the PSD. In order to obtain the superior dark state of the NB-TN mode, we should find the lowest transmittance from the PSD of B and R in Figure 5.



(a)



(b)

FIGURE 5 PSD at two wavelengths, (a) 450 nm and (b) 650 nm.

As a result, (−45°, 145 nm), (−37°, 165 nm), and (−40°, 170 nm) were chosen as the TA of the polarizer and the retardation value of the +A plate. The polarization states of B, G, and R are shown on the Poincare sphere after passing through the compensated NB-TN mode by using the selected optimum parameters, shown in Figure 6. We could expect the achromatic dark state because polarization states of R and B before entering the analyzer are very close to each other.

The calculated dispersion characteristics in the dark state were obtained by using parameter values through the PSD, as shown in

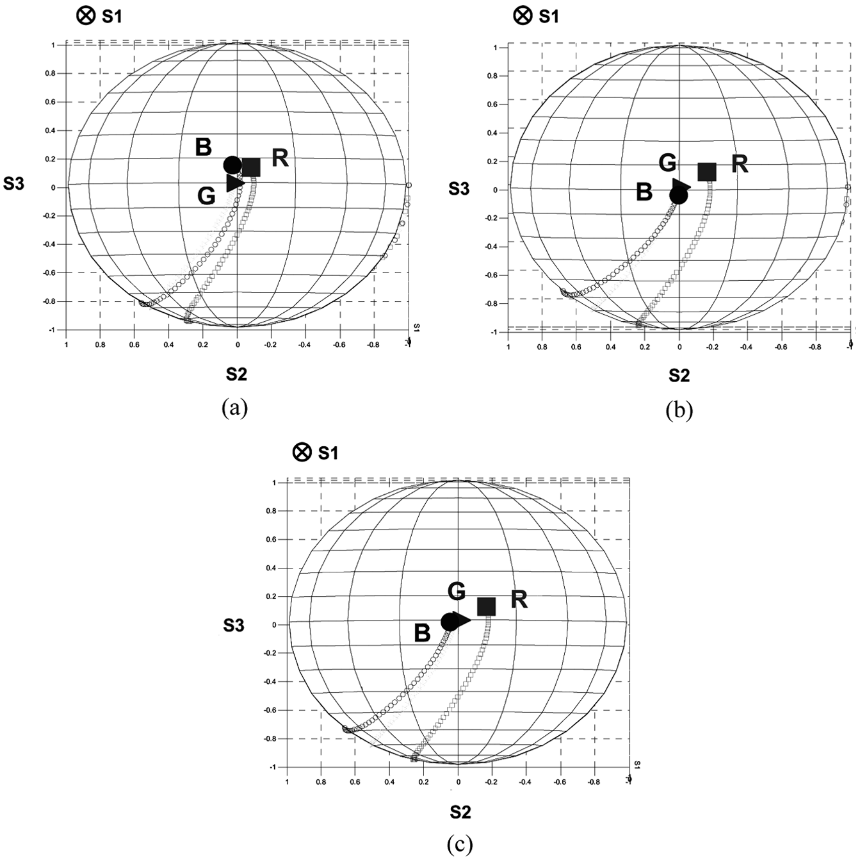
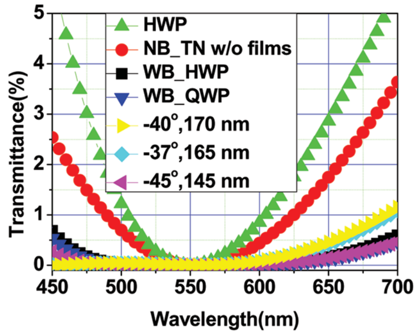
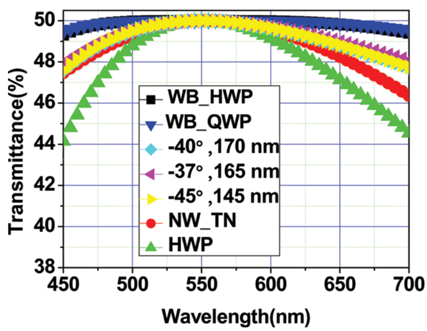


FIGURE 6 B, G, and R points on the Poincare sphere after passing through the compensated TN layer, retardation value of the +A plate and TA angle of the polarizer are (a) (−45°, 145 nm), (b) (−40°, 170 nm), and (c) (−37°, 165 nm).



(a)



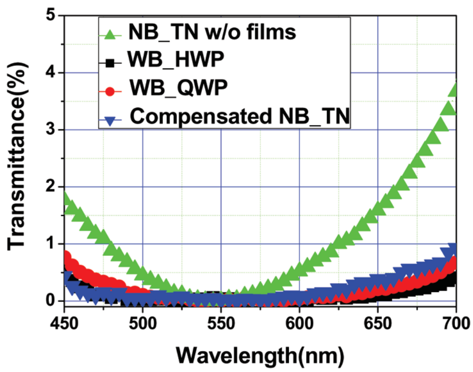
(b)

FIGURE 7 Calculated transmission spectra of a NB-TN cell without and with compensation under various wave plate combinations.

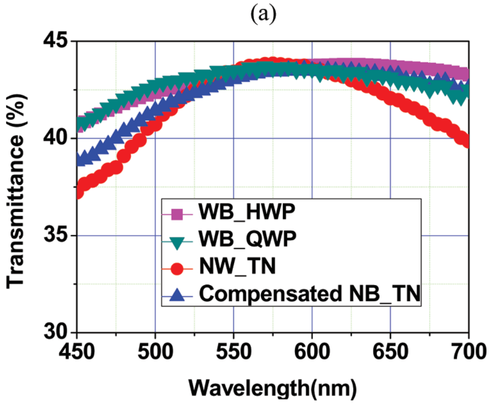
Figure 7(a). For comparison, a wide–band HWP configuration consisting of two HWPs with OA of 22.5° and 67.5°, and a wide-band QWP configuration consisting of three HWPs with OA of 15°, 75°, and 15° are considered, between the parallel polarizers with TA of 0° [8]. In a case of −45° and 145 nm, especially, the compensated NB-TN mode shows the dispersion characteristics superior to the conventional NB-TN mode and other optical film combinations, in the visible wavelength from 450 to 700 nm. An angle between TAs of the polarizer and the analyzer is less than 90°, by which superior dispersion characteristics in the bright state are also confirmed, as shown in Figure 7(b).

EXPERIMENTAL RESULTS

To experimentally confirm the proposed method, a TN cell was fabricated. Cell parameters were as follows. cell-gap: 6.01 μm, LC: ZLI-3412-000 (from Merck, Δn: 0.0792, Δε: 5.3). These conditions suffice the first condition of a 90° TN device ($\Delta nd = 476\,nm$) [9]. The polyimide used in this experiment was RN-1702 (Nissin Chemical). Rubbing directions of the top and the bottom substrates were perpendicular to each other to make a 90° TN cell. The retardation value of available +A plate was 159 nm, which was different from simulation results. Hence, through the PSD again, −42° was obtained as the proper angle of TA of the polarizer. In the dark state, dispersion characteristics of various optical plates, the conventional NB-TN cell, and the compensated NB-TN cell were measured as shown in Figure 8(a). The compensated NB-TN cell has the dispersion characteristics superior to other plates. The dispersion characteristics in the bright state were superior as well, as shown in Figure 8(b). In the bright state, the NW-TN cell is compared instead of the NB-TN



(a)



(b)

FIGURE 8 Measured transmission spectra of a NB-TN cell (a) in the dark state and (b) in the bright state.

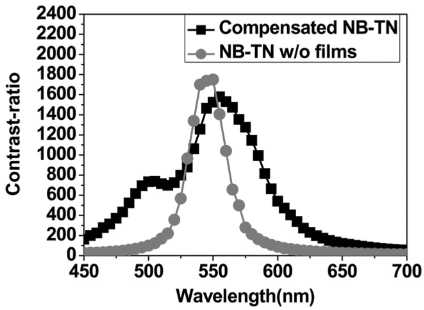


FIGURE 9 Measured wavelength dependence of CR in NB-TN cells with and without compensation.

cell because dispersion characteristics of the conventional NB-TN cell are comparable to those of parallel polarizers. Although dispersion characteristics are slightly worse than wide-band plates at longer wavelengths because parameters are different from those used in numerical calculation, dispersion characteristics of compensated NB-TN shows the superior dispersion characteristics compared with numerical calculation over the entire visible wavelength region.

The CR was calculated by dividing the sum of transmittance in the bright state by that in the dark state, in visible wavelengths from 450 to 700 nm. In the numerical calculation, the conventional NB-TN mode shows low CR of 50:1 and the compensated NB-TN mode shows high CR over 500:1. In the case of the experiment, the conventional NB-TN cell shows the CR of 40:1 and the compensated NB-TN cell shows the CR over 200:1 by obtaining high CR more than 100:1, even at short and long wavelengths, as shown in Figure 9.

SUMMARY

In summary, an optical design has been proposed to compensate dispersion characteristics of the NB-TN mode. By using a HWP and +A plate, we could achieve the superior dispersion characteristics in the bright state as well as in the dark state. High CR over 500:1 could be obtained in the numerical calculation. Experimentally, the compensated NB-TN cell showed high CR over 200:1.

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