Continuous viewing angle-tunable liquid crystal display using temperature-dependent birefringence layer

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Abstract: We demonstrated a continuous viewing angle controllable liquid crystal display (LCD) adopting a thermally variable retardation layer (TVRL) using nematic liquid crystal with transparent electric-heating lines to control temperature. The simulated and experimental results of the proposed LCD show continuous and symmetric viewing angle characteristics by tuning the retardation of TVRL using Joule heating.

OCIS codes: (230.0230) Optical devices; (230.3720) Liquid-crystal devices

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#105274 - $15.00 USD Received 12 Dec 2008; revised 24 Feb 2009; accepted 18 Mar 2009; published 20 Mar 2009

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1. Introduction

Various liquid crystal display (LCD) modes, such as patterned vertical alignment (PVA), multi-domain VA (MVA) mode, in-plane switching (IPS) mode, fringe field switching (FFS) mode, and optically compensated bend (OCB) mode have been developed extensively for TV applications to have wide viewing angle characteristics [1-10]. With an explosive increase in mobile electronic devices such as personal digital assistants, mobile phones, and notebook computers, privacy protection has recently become a crucial factor for display functions. Sometimes displayed information should be shared with other people and sometimes it should be secured from others in public places. To respond to such needs in a mobile environment, a display with controllable viewing angles is desirable in order to change between public and private modes. Such a display should offer a wide viewing angle (WVA) for public sharing and a narrow viewing angle (NVA) for private use.

To control the viewing angle, various methods adopting a dual backlight system or two LC panels (side and main panel) have been proposed [11-16]. However, with the dual backlight system, it may be difficult to control the viewing angle continuously because there are only two light paths for NVA and WVA. On the other hand, with two LC panels, even though they can exhibit a continuous viewing angle, they cannot have symmetric viewing angles at intermediate viewing angle ranges due to the one directional switching of LCs (monodomain) in the side panel that controls the viewing angle. To create a symmetric viewing angle in an intermediate viewing range, it requires muti-domain LC pixels in the side panel which align well to pixels of main panel via a complicated fabrication process.

In this letter, we demonstrate a continuous viewing angle controllable LCD adopting a thermally variable retardation layer (TVRL) using LC with transparent electric-heating lines to control temperature. The proposed LCD shows continuous and symmetric viewing angle characteristics by tuning the retardation using Joule heating. This LCD is relatively simple to fabricate.

2. Principle of viewing angle control and experimental preparation

Figure 1 is a schematic diagram of how to obtain WVA and NVA in the proposed LCD structure. Here, in the main panel of the proposed display, we choose the fringe field switching (FFS) nematic mode which shows WVA characteristics without any compensation film. The TVRL is composed of a homeotropically aligned LC layer between two plastic substrates. Patterned transparent electrodes for Joule heating are formed on one substrate to control temperature. In the nematic phase, the liquid crystal molecules exhibit short range orientational order characterized by the order parameter, which is related to the angular distribution of the long axis of the molecules about the director. The short range order of an LC decreases slowly as temperature increases, and drops abruptly to zero in the isotropic phase of the LC. Since such an order parameter is associated with the birefringence (Δn), Δn is a continuous function of temperature in the nematic phase. When the TVRL is in the isotropic phase which does not have any optical anisotropy in all viewing directions by heating as shown in Fig. 1(a), the optical characteristics of the LCD will be determined by only the main panel (FFS panel). In this case, when voltage is not applied, the FFS mode, in which the LCs are aligned parallel to the transmissive axis of the light-input polarizer shows an excellent dark state, because the input light of 0° linear polarization, which passes through LC layer without changing the polarization, is blocked perfectly by the output polarizer with a 90° transmissive axis. The bright state can be achieved when the LC director is rotated by

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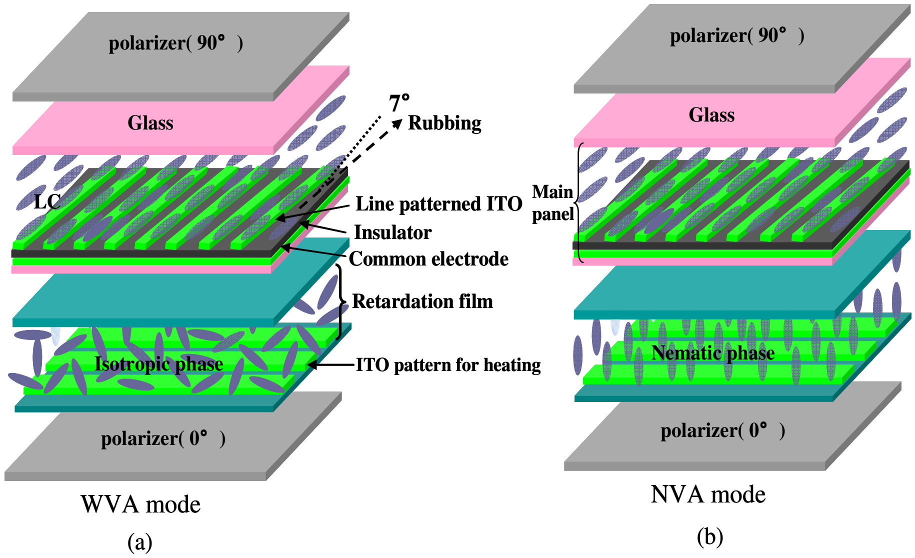

Fig. 1. Schematic diagram of the proposed viewing angle-tunable LCD structure: (a) narrow viewing angle using the nematic phase of TVRL; (b) wide viewing angle using

ideally 45˚ by the horizontal field. In this case, the input light of 0˚ linear polarization is rotated about 90˚ at the LC layer. Consequently, the FFS mode connected with TVRL having optically isotropic state exhibits WVA, an optically high contrast ratio for all viewing directions due to the absence of polarization changes in the light while in the dark state, even when light is obliquely incident. On the other hand, when the TVRL without heating is in the vertically aligned nematic phase as shown in Fig. 1(b), it does not have any optical anisotropy in normal incidence of light. Thus, the LCD shows a good image-quality in front view because the TVRL does not have an effect on main panel optically in front view. However, in side view with obliquely incident light, it has an influence optically on the main panel because the vertically aligned LC has optical anisotropy at oblique incident. Consequently, the LCD shows the leakage of light at side view of the dark state. This is the reason why the FFS mode connected with TVRL having vertically aligned nematic phase leads to NVA, an optically high contrast ratio for only front view. As a result, we will obtain both the WVA and NVA in the LCD by tuning the retardation of the TVRL through well controlled thermal heating.

We used AL60702 (JSR) as a homeotropic LC alignment layer of TVRL and SE-7492 (Nissan Chemicals), which yields a pretilt angle of 6˚ after general rubbing, as the LC alignment layer of FFS cell. The width and gap of the interdigitated electrode (line patterned electrode) of FFS cell were 4 and 5 um, respectively. The bottom (common) electrode was separated from the interdigitated electrode by a 200 nm thick layer of SiNx functioning as an insulator. The electrode material used here was indium-tin oxide. The cell gap of the FFS and the thickness of the TVRL were 3.4 μm and 5.5 μm, respectively. The LCs injected into the FFS cell and TVRL were MAT-03-151 (Merck, Δn=0.104 at 20°C) and E7 (Merck, Δn=0.2249 at 20°C), respectively.

Figure 2 shows the experimental characteristics of temperature-dependent birefringence of E7 LC used in the TVRL. The nematic-isotropic transition temperature of E7 is 58°C. Transparent indium-tin-oxide (ITO) was used in the heating electrode of TVRL to avoid a loss of transmittance. The temperature was controlled by the voltage and current of the power supply based on measured temperature. The inset is the temperature as a function of applied voltage. The power consumption for heating in the isotropic phase of E7-TVRL was about 1 W for a 3 cm x 3 cm area. The refractive indices decrease linearly as temperature increases. According to Wu’s model [17-18] the temperature-dependent refractive indices of LC can be

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described with

$$n_e \approx a - bT + \frac{2}{3}\Delta n(0)(1 - T / T_c)^{\beta}, \quad (1)$$

$$n_O \approx a - bT - \frac{1}{3}\Delta n(0)(1 - T / T_c)^{\beta}, \quad (2)$$

where T_c and $\Delta n(0) = n_e(0)-n_o(0)$ are clearing temperature and the birefringence of LC at T=0 K, respectively. β is a material constant. The open circles and squares represent experimental data for E7 supplied from Merck. The lines in Fig. 2 were fitted by Wu's model of Eqs. (1) and (2). When a=1.7432, b= 5×10^{-4} (K^{-1}), $\Delta n(0)$ = 0.3435, and β =0.1938, the experimental data for E7 agree well with Wu's model. To ensure rapid transition between WVA and NVA, it is better to use an LC which has a relatively low nematic-isotropic transition temperature, like 4-n-pentyl-4'-cyanobiphenyl (5CB) LC which has a transition temperature of 34°C. The LC also reduces the power consumption.

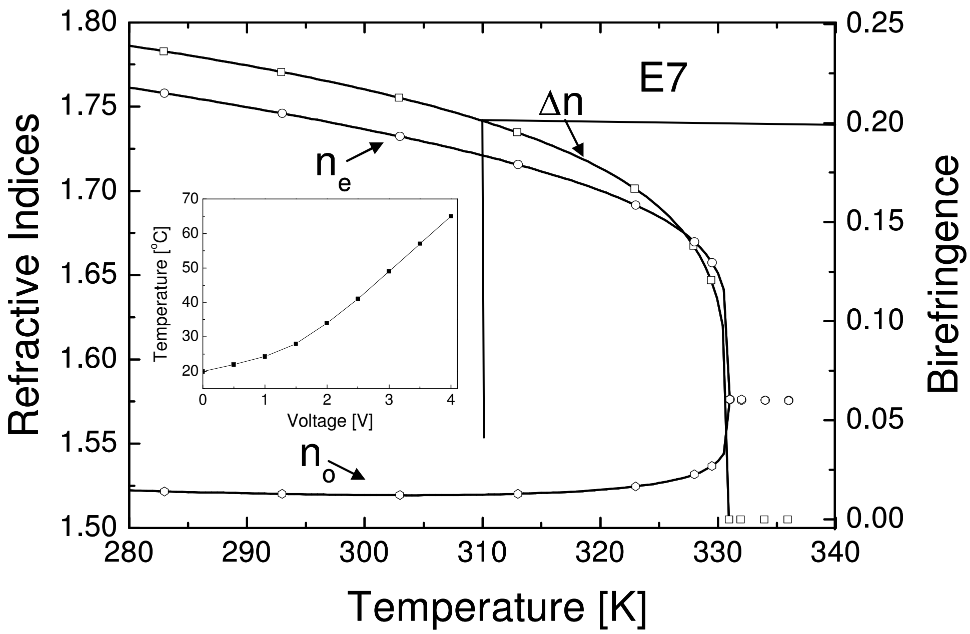

Fig. 2. Temperature-dependent refractive indices and birefringence of E7 LC at wavelength λ=560 nm. Squares and circles represent experimental data, and solid lines are fittings using Wu's model.

3. Simulation and experimental results

Based on the experimental results of temperature-dependent LC birefringence, we completed a simulation using a commercial LCD simulator from TechWiz LCD. Figure 3 shows continuous viewing angle characteristics depending on the temperature-dependent birefringence of TVRL. In the simulation, we set the cell gap and birefringence of the FFS cell to 3.6 μm and 0.1, respectively. The thickness of TVRL was 5 μm. As expected, the simulation results demonstrate a symmetric viewing angle as well as a continuous viewing angle change with changing birefringence of TVRL, which is controlled by temperature.

Figure 4 is the experimental results of viewing angle characteristics of FFS LCD with the different temperatures of E7-TVRL. The viewing angle was measured by DMS-900 (Autronic

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Melchers Co.,). As shown in Fig. 4, we can obtain a contrast ratio (CR) greater than 10:1 from almost all viewing areas in the contours with polar angle limits of 80˚ with TVRL in an isotropic phase (60°C). The WVA characteristics came from the properties of

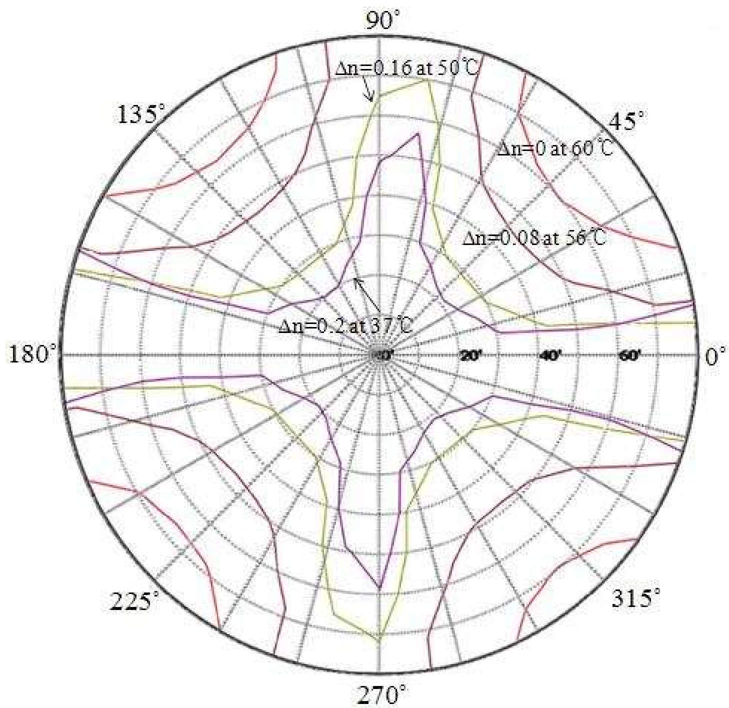

Fig. 3. Simulated results of viewing angle depending on the birefringence of TVRL determined by temperature in the proposed viewing angle controllable FFS mode.

FFS. If we decreased the temperature of TVRL in the nematic phase (20°C), CR values greater than 10:1 are limited to 20˚ in the diagonal direction. We can control viewing angle characteristics for intermediate viewing angle ranges by adjusting the temperature between 20°C and 58°C. Moreover, the viewing angle characteristics are symmetric in all ranges of viewing angles.

Figure 5 shows the photo images taken in front and the side view from the 45˚ direction with crossed polarizers in the dark state of the FFS cell with TVRL. Figures 5 (a) and 5 (c) is when TVRL is in 20°C (nematic phase) and Figs. 5 (b) and 5 (d) is when TVRL is in 60°C (isotropic phase). The images in the front view have almost the same dark state whenever TVRL is nematic or in the isotropic phase as shown in Figs. 5 (a) and 5 (b), respectively. However, the side view in the nematic phase of TVRL shows considerable light leakage as shown in Fig. 5 (c). However, in the isotropic phase, TVRL has a good dark state, as shown in Fig. 5 (d). As estimated from the numerical calculation and experimental results, continuous viewing angle is realized very simply in the proposed LCD structure.

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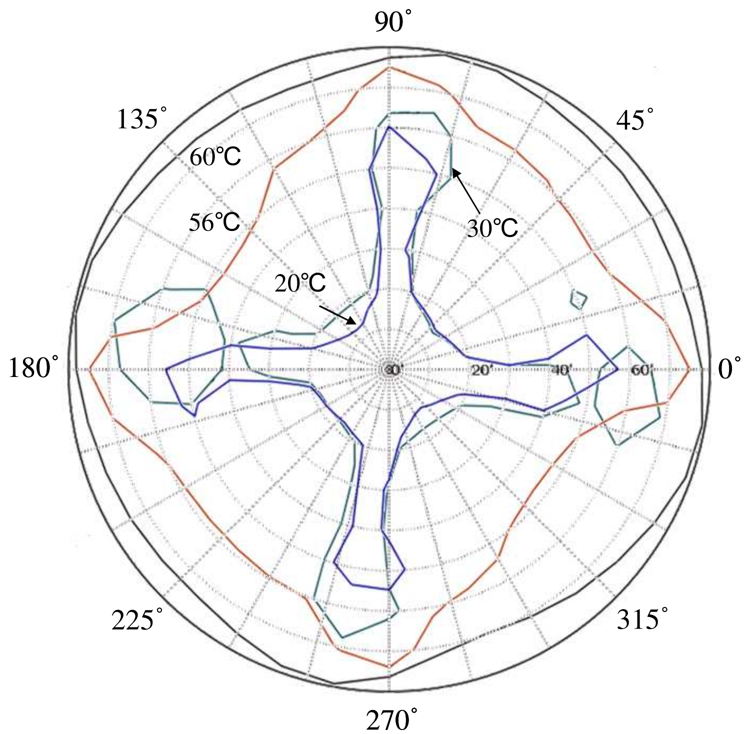
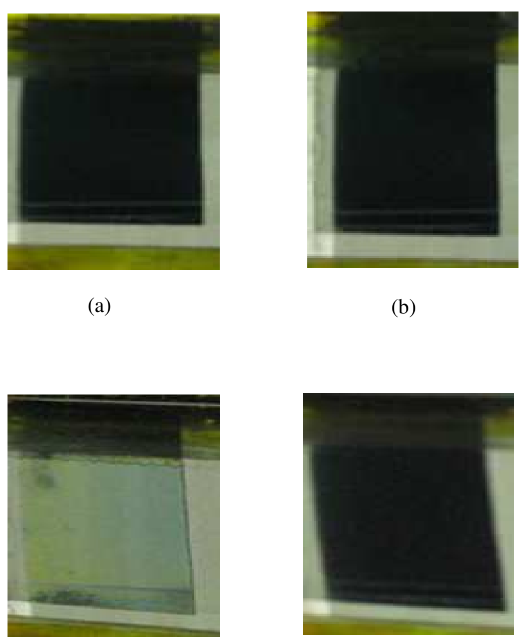


Fig. 4. Measured results of viewing angle according to the temperature of TVRL in the proposed viewing angle controllable FFS mode.



(a) (b)

(c) (d)

Fig. 5. Photo-images in the dark state of a FFS-TVRL cell; (a) in front view when TVRL is in the nematic phase (20°C), (b) in front view when TVRL is in the isotropic phase (60°C), (c) in side view when TVRL is in the nematic phase (20°C), (d) in side view when TVRL is in the isotropic phase (60°C).

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4. Conclusion

In summary, we proposed a continuous viewing angle controllable LCD by using a temperature-dependent retardation film. By changing the birefringence of the film with Joule heating, the viewing angle of the FFS LCD can be controlled continuously. Therefore, we believe that the proposed LC display is suitable for mobile phones, notebook computers, and E-books with viewing angle controllable function.

Acknowledgments

This work was supported by LG display and the Korea Research Foundation Grant funded by the Korean Government (MOEHRD)" (KRF-2006-005-J04103).

#105274 - $15.00 USD Received 12 Dec 2008; revised 24 Feb 2009; accepted 18 Mar 2009; published 20 Mar 2009