Single pixel transmissive and reflective liquid crystal display using broadband cholesteric liquid crystal film

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Abstract: We propose a single mode transflective liquid crystal display (LCD) which is operated as the transmissive and reflective modes in a single pixel without dividing into sub-pixels. The single pixel transflective LCD was composed of the cross-polarized nematic LCD as a light modulator and the broadband cholesteric liquid crystal film (BCLCF) as a half mirror. The BCLCF, simply prepared by the exposure of ultraviolet light to the mixture of the nematic LC and the reactive mesogen with chirality, selectively reflects a certain circular polarization but transmits the orthogonal circular polarization in entire visible light. The electro-optical properties in both transmissive and reflective modes coincide with each other.

OCIS codes: (120.2040) Displays; (230.3720) Liquid-crystal devices.

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1. Introduction

With increasing the digital contents, the mobile display system which can be used for contacting the information irrespective to time has been widely demanded. In the mobile display, the power consumption and the outdoor readability are the most important issues due to the battery limitation and the ubiquitous environment. Therefore, the importance of transflective liquid crystal displays (LCDs) with low power consumption and outdoor readability has been increased [1,2]. Transmissive LCDs have been applied to numerous displays due to their good electro-optic (EO) performances. However, they have the major drawbacks of high power consumption by backlight source and low readability in outdoor environment. On the other hand, reflective LCDs have no built-in backlight source due to the utilization of the ambient light as the light source for display images. By these characteristics, reflective type has attractive things such as lighter weight, thinner thickness, and lower power consumption. However, the reflective type is not readable when the device is used under dim environment.

Transflective LCDs is a display mode for resolving the weakness and strengthening the strength of both transmissive and reflective types. It has been extensively researched for mobile display applications such as tablet personal computer, e-book, and mobile phone due to its superior performance under both indoor and outdoor environments. The individual pixels of a conventional transflective LCD are consisted of two sub-pixels for the transmissive and reflective parts. To obtain the equivalent electro-optic (EO) characteristics, the divided sub-pixels have to experience the different optical paths since the phase retardation passing through the reflective region is twice as large as that through the transmissive region. The double cell gap design is a method of producing the optical path difference between two sub-pixels of the transflective LCD [3,4]. Despite the good optical characteristics of transflective LCD with the different cell gaps in two modes, the double cell gap design results in high cost and low yield in manufacturing. Recently, several single cell gap designs having the periodically patterned electrodes or coexisting two different modes have been proposed for the simple fabrication [5–9]. In such single cell gap methods, the optical path difference can be induced by the special electrode structure or dual LC modes. However, the degradation of the EO performances induced by dividing each pixel in two regions can be unavoidable.

In this paper, we proposed a transflective LCD which has no need for dividing into the sub-pixels by having a simple stacked structure of nematic LC layer as the optical switcher and a broadband cholesteric liquid crystal film (BCLCF) as the multi-functional film which can be a reflector and a circular polarizer [10,11]. Due to optical characteristics of the cholesteric liquid crystal (CLC) layer which can reflect a selective circular polarization and transmit the other, we could obtain the transflective LCD using the whole pixels without dividing into the sub-pixels in both modes by the simple fabrication. For the selective reflection in entire visible light, the CLC layer with the broadband pitch gradient were fabricated by the exposure of ultraviolet (UV) light to the LC/photo-polymer mixture. Our transflective LC cell has the superior electro-optic performance to the previous device using the additional functional film for resolving the reverse images between transmissive and reflective mode in the previous work [12]. In the BCLCF, no applied voltage is required for switching the display modes from transmissive to reflective modes and vice versa.

2. Cell configuration and operating principle

Figure 1 shows a schematic diagram of our transflective LCD with a BCLCF in a single pixel configuration without dividing into sub-pixels. The single pixel transflective LCD consists of the cross-polarized LCD as a light modulator and the BCLCF as a half mirror which selectively reflects a certain circular polarization but transmits the orthogonal circular

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polarization in entire visible light. The BCLCF was performed by the helical structure with the pitch gradient covering entire visible range through the exposure of UV light to the mixture of the nematic LC and reactive mesogen (RM) with chirality [13].

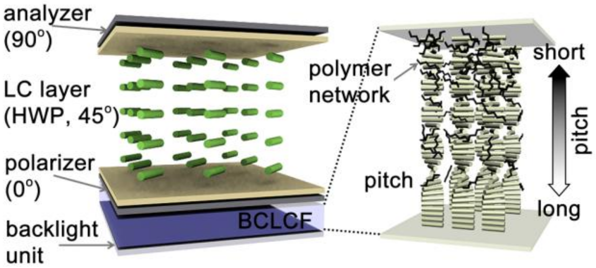

Fig. 1. Schematic diagram of our proposed transflective LCD consisting of the cross-polarized nematic LCD as a conventional light modulator and the BCLCF as a half mirror. The BCLCF was performed by the helical structure with the pitch gradient covering entire visible range through the polymerized RMs.

In a transmissive mode, the BCLCF acts as an optical window transmitting incident light from a backlight unit (BLU). The light passing through the BCLCF enters the cross-polarized LCD and acts the same role as the incident light from the BLU in the conventional LCDs except for the intensity reduction. Therefore, the display performances are governed by the only EO properties of the used LCDs. It should be noted that various LCD modes based on an LC birefringence are adoptable to the light modulator. For a bright state, the LC layer acts as a half-wave plate (HWP) and converts the polarization orthogonally. In a reflective mode, the light passing through the cross-polarized LCD is selectively reflected from the BCLCF. The reflected light acts the same role as the transmitting light through the BCLCF in the transmissive mode. The selectively reflected light is circularly polarized and its handedness coincides with the helical sense of the BCLCF. In this situation, the reflected intensity is reduced to half of the bright state in the transmissive mode due to twice intensity reduction between the BCLCF and polarizer.

The optical pathways of the polarization states in both transmissive and reflective modes are represented on the Poincaré Sphere as shown in Fig. 2. For a bright state in the transmissive mode, the randomly polarized light from the BLU is circularly polarized with left handedness passing through the BCLCF with a right-handed helix. As shown in Fig. 2(a), the left-handed circular polarization (depicted by "in" on the Poincaré Sphere) is linearly polarized by a polarizer and thus polarization state moves to $+ S_1$ (0°) on the Poincaré Sphere. Here, the optical intensity is reduced to half of an incident light. Hereafter, the dashed arrows on the Poincaré Sphere represent the polarization transition with intensity reduction. The LC layer acting as the HWP converts the polarization state from $+S_1$ to $-S_1$ (90°). The resulting polarization coincides with an analyzer and thus a bright state is obtained. On the other hand, when no phase retardation is produced in the LC layer, the polarized light at the $+S_1$ passing through the polarizer is blocked by the crossed analyzer as shown in Fig. 2(b).

In the reflective mode, the incident light with linear polarization of 90° from the analyzer is rotated to 0° by the LC layer acting as the HWP ("LC_1" path from $-S_1$ to $+S_1$) and thus transmits the polarizer as shown in Fig. 2(c). The 0°-polarized light is selectively reflected with the right-handed circular polarization ($+S_3$) with intensity reduction from the BCLCF with a right-handed helix ($+S_1 \rightarrow +S_3$). Now, the reflected polarization is represented by the left-handed circular polarization ($-S_3$) due to coordinate inversion ($+S_3 \rightarrow -S_3$). The reflected light experiences the same optical pathways of the transmitting light through the BCLCF in the transmissive mode, where the polarization state is converted from $-S_3$ to $+S_1$ by the polarizer, and from $+ S_1$ to $-S_1$ by the LC layer through "LC_2" path. As shown in Fig. 2(d), for a dark state in the reflective mode, the incident light with 90°-polarization is blocked by the polarizer (0°).

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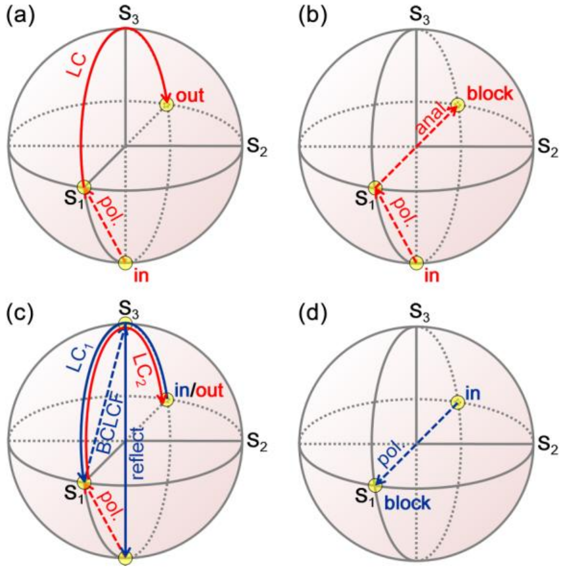

Fig. 2. Optical pathways for the (a) bright and (b) dark states in the transmissive mode, and for the (c) bright and (d) dark states in the reflective mode represented on the Poincaré Sphere. Here, the dashed arrows represent the polarization transition with intensity reduction. Red arrows represent the polarization transition from rear to front panels, while blue ones show the polarization paths from front to rear panels.

3. Experiments

The BCLCF was fabricated by UV exposure to the CLC mixture of host nematic LC (87 wt.%, E. Merck E48), RM monomer with chirality producing a right-handed helical structure (12 wt.%, E. Merck RMM703), and photoinitiator (1 wt.%, Ciba Speciality Chemicals Igacure651). The CLC mixture was stirred in an isotropic phase for 24 h and injected between sandwiched glass substrates with a cell gap of 6 μm by capillary action in the isotropic phase. The inner surfaces of the sandwiched substrates were coated with polyimide alignment layer (Nissan Chemical RN1199) and rubbed antiparallelly for planar alignment. After injection of the CLC mixture, we cooled slowly down to room temperature for obtaining a stabilized planar texture and exposed UV light (0.12 mW/cm^2) for 4 min to produce broadband spectrum covering entire visible range [13–15].

For convenience sake, a homogeneously aligned nematic LC mode was used for the optical modulation. The nematic LC used in this work was MLC6233 (E. Merck) whose optical anisotropy and dielectric one are $\Delta n = 0.0901$ and $\Delta\varepsilon = 4.3$, respectively. The SE7492 (Nissan Chemical) was spin-coated on top of the indium-tin-oxide evaporated substrates, followed by unidirectional rubbing to promote planar alignment. The rubbing axis of the homogeneously aligned LC layer made an angle of 45° with respect to one of crossed polarizers so that the LC layer acted as the HWP in the absence of an applied field. The cell gap was maintained using glass spacers of 3.5 μm thick. The UV-visible spectrophotometer (JASCO) and the polarizing optical microscope (Nikon E600 Wpol) were used for investigating the optical properties of the BCLCF and the transflective LCD, respectively. Note that any LC modes are applicable to our transflective LCD as an optical modulator.

4. Results and discussion

The measured spectra in both transmissive and reflective modes of the BCLCF are shown in Fig. 3. The broadband spectra in the BCLCF were produced by the stable pitch gradient of the CLC though the photo-polymerization of the RMs. When UV light was irradiated to the CLC mixture with the chiral RMs, the UV intensity gradient was induced according to the direction

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perpendicular to the substrates. The UV intensity gradient generates the anisotropic phase separation normal to the substrates due to the diffusion of the chiral RM monomers driven by a concentration difference [16]. As a result, the network structure with the different polymer density produces the stable pitch gradient of the CLC from 460 to 760 nm [17]. Due to the selective reflection of the circular polarized light coinciding with the cholesteric pitch and the helical sense of the CLC, the wide pitch gradient of the CLC gives rise to the broadband reflective spectrum and the complementary transmissive spectrum covering the entire visible range as shown in Fig. 3.

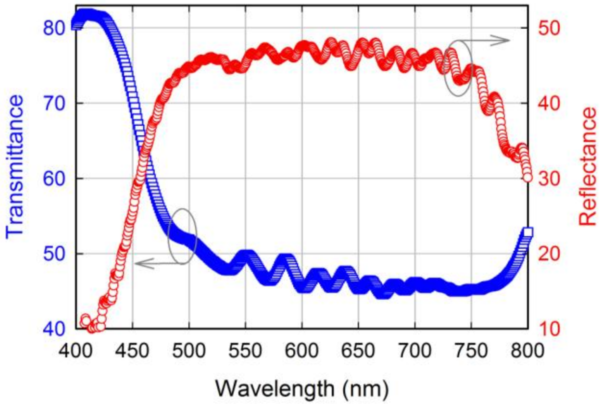

Fig. 3. Measured spectra of the BCLCF in the transmissive (transmittance) and reflective (reflectance) modes.

The transflective LCD was finally fabricated by assembling the above BCLCF to the homogeneously aligned nematic LC cell under crossed polarizers as shown in Fig. 1. The operation of the transflective LCD was observed with the microscopic textures and the EO measurements as shown in Fig. 4. In the absence of an applied voltage, the LC layer acts as the HWP and thus the bright state is obtained in both transmissive and reflective modes as aforementioned. With increasing the applied voltage, the phase retardation in the LC layer is decreased, and thus the transmittance and the reflectance are gradually reduced as shown in Fig. 4. Although the maximum reflectance is almost half of the maximum transmittance due to the extra-reduction of intensity between the BCLCF and the polarizer, the normalized EO properties in both transmissive and reflective modes coincide with each other. The contrast ratio is about 200:1 in the transmissive mode (Fig. 4(a)) and 50:1 in the reflective mode (Fig. 4(b)).

In the light of the aforementioned idea of the transflective LCD without dividing into two sub-pixels, we demonstrated a 2-inch prototype with direct electrode patterns of a logo “HYU DDLAB” as shown in Fig. 5. The white level in the transmissive mode (Fig. 5(a)) exhibits higher brightness than that in the reflectance mode (Fig. 5(b)) since the transmittance is intrinsically twice of the reflectance and the BLU for the transmissive mode is brighter than the ambient light for the reflective mode in our experiments. In the actual transflective LCD embedded with the BLU, the nonselective light could reach the interface with the BLU in the reflective mode. However, the reflected light does not affect the normalized EO properties in our transflective LCD because the EO properties in both transmissive and reflective modes depend on the only cross-polarized LC layer acting as the optical modulator. Although the reentering light to the cross-polarized LC layer increases the transmittance (actually reflectance in the reflective mode), the normalized EO properties are not changed since such increase of the transmittance is proportional to the reflectance without the reentry from the BLU.

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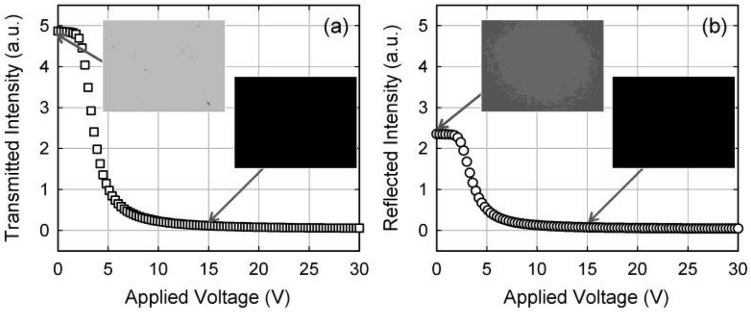

Fig. 4. Measured electrooptic properties and corresponding microscopic textures in the (a) transmissive and (b) reflective modes.

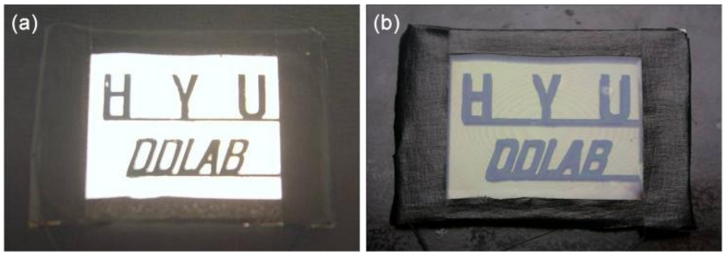

Fig. 5. 2-inch prototype of our single mode transflective LCD operated at the (a) transmissive and (b) reflective modes. The external electric field was applied in the "HYU DDLAB" parts.

5. Conclusion

We proposed and demonstrated the single mode transflective LCD, consisting of the cross-polarized LC cell as the light modulator and the BCLCF as the half mirror, without dividing into two sub-pixels. The BCLCF half mirror was simply prepared with the photo-polymerization of the CLC mixture with the chiral RMs generating the cholesteric structure with the pitch gradient covering entire visible range. The BCLCF selectively reflected the circular polarization coinciding with the helical sense of the CLC but transmitted the orthogonal circular polarization in entire visible light. In our transflective LCD, no EO disparity between the transmissive and the reflective modes was observed. In addition, various LCD modes based on the LC birefringence are adoptable to our transflective LCD as the light modulator. It should be expected that the single mode transflective LCD proposed here could be applicable to the mobile displays with the good EO performances.

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