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Transflective Liquid Crystal Display with a High Aperture Ratio using Electrophoretic Particles for a Switchable Mirror

Kwang-Soo Bae[a], Young Wook Kim**[b], Gwang-Hei Choi[a], Jeong Uk Heo[b],**

Chang-Jae Yu*[a,b,c] and Jae-Hoon Kim*[a,b,c]

Abstract

This paper proposes a transflective liquid crystal display (LCD) in a whole-pixel switchable configuration with a high aperture ratio using an electrophoretic particle layer (EPL). The switchable transflective LCD consisted of the liquid crystal layer as a display unit, and the EPL as a switchable mirror. The switching of the EPL between the mirror for the reflective mode and the transparency for the transmissive mode was performed by controlling electrophoretic nanoparticles with an applied voltage in a three-electrode structure. The single pixel was used as the whole transmissive or reflective mode that corresponded to the switchable EPL mirror. Thus, a transflective LCD with a high aperture ratio was obtained.

Keywords: Transflective LCD, electrophoretic particle, reflective mode, transmissive mode

1. Introduction

Transflective liquid crystal displays (LCDs) have been widely studied for mobile applications such as mobile phones, personal digital assistants, and electronic books because their superior device performance can be achieved under indoor and outdoor environments [1]. The conventional transflective LCDs consist of two sub-pixels for the transmissive and reflective modes. In such transflective LCDs, the optical path in the reflective region is twice as long as that in the transmissive region due to the forward and backward light propagations in the reflective region. The optical path difference between two sub-pixels generally gives rise to a mismatch of the electro-optic properties of the two regions. To solve this problem, various transflective LC modes, such as LC structures with different cell gaps in a single LC mode [1-3], and different modes in a single cell gap [4-7], have been reported. Although these transflective LCDs have good optical characteristics, however, they have unavoidable drawbacks such as their complicated process and the degradation of the display performance such as with respect to the aperture ratio.

In this study, a switchable transflective LCD with a high aperture ratio using an electrophoretic particle layer (EPL) as a switchable mirror is proposed. The LC layer, as the display unit, is stacked on top of the EPL, which is controlled by the configuration of the applied field in a three-electrode structure with an in-plane electrode on the bottom substrate and a common electrode on the top substrate for switching the transflective feature. In this transflective LCD, a whole pixel can be used as a display region in the transmissive and reflective modes. Thus, a switchable transflective LCD with a high aperture ratio was achieved.

2. Structure and Operating Principle of the Transflective LCD

Fig. 1 shows a schematic diagram of a transflective LCD that consists of an LC layer attached to two crossed polarizers and a functional EPL injected with electrophoretic nanoparticles [8]. A single-substrate LC cell was prepared as an optical switching device. It was fabricated by laminating a functional polymer cover film [9]. Here, the top glass substrate that is used in conventional LC cells was substituted as the polymer cover film. To produce alignment

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* Member, KIDS; **Student Member, KIDS
Corresponding author: Jae-Hoon Kim
[a] Department of Information Display Engineering, Hanyang University, Seoul133-791, Korea
[b] Department of Electronics and Computer Engineering, Hanyang University, Seoul 133-791, Korea
[c] Department of Electronics and Communications Engineering, Hanyang University, Seoul 133-791, Korea
E-mail: jhoon@hanyang.ac.kr **Tel:** +82-2-2220-034 **Fax:** +82-2-2298-0345

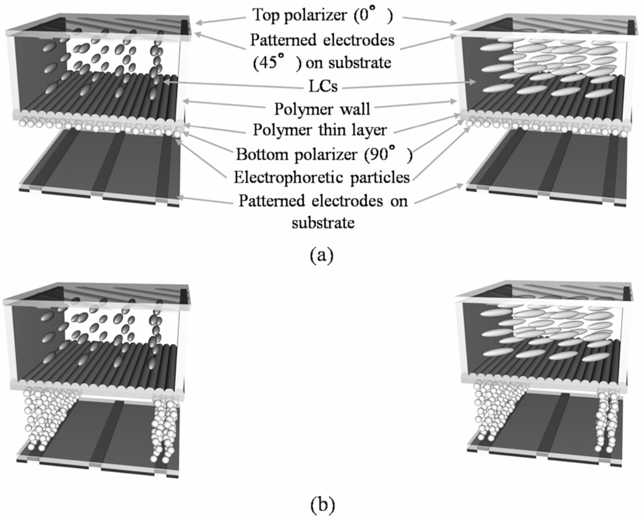


Fig. 1. Schematic of the structure of the transflective LCD with the EPL, showing the dark and bright states of (a) the reflective mode and (b) the transmissive mode.

properties, a groove structure was formed on the polymer film [10]. In addition, the parallax problem was prevented with thick glasses of the stacked structure of the two cells. The interdigitating electrodes were patterned on the bottom substrate to produce an in-plane field in the LC layer without electrodes on the top polymer cover film. The width and intervals of the electrodes were 4 μm and 7 μm, respectively. To maintain the cell thickness and isolate the LC molecules, the polymer wall structures were patterned on the bottom substrate with a striped shape and with a width of 30 μm and a height of 3 μm, using the photolithographic method with a conventional photoresist, SU-8 (MicroChem. Co.). The direction of the polymer walls was parallel to the groove structure on the polymer cover film, and was rotated by 45° with respect to the in-plane field direction by the patterned interdigitating electrodes on the bottom substrate. The interval between the neighboring polymer walls was 300 μm. On the bottom substrate, a polyimide (PI) layer (Nissan Chemical Ind., Ltd.) for homogeneous LC alignment was spin-coated and cured. The rubbing direction of the PI layer was parallel to that of the polymer walls. Thus, the LC molecules that were aligned by the rubbing method initially lay along the direction of the polymer walls, where the LC distortion induced by the boundary effect of the polymer walls was eliminated. The LC cell was placed between crossed polarizers, with the direction of one polarizer parallel to that of the polymer walls (and groove). Under an applied voltage, the LC molecules with a positive dielectric anisotropy rotated parallel to the applied field direction (perpendicular to the interdigitating electrodes) and thus, produced phase retardation.

The switchable mirror unit for changing display modes between the reflective and transmissive modes was fabricated with 50nm-diameter TiO_2 nanoparticles that were dispersed in DI water as a solvent (7 wt.%). The cell thickness of the EPL was maintained with 20μm spacers. To control the electrophoretic particles, the in-plane electrode on the bottom substrate and the common electrode on the top substrate were patterned [11]. Since the nanoparticles were charged with negative polarity, they moved to the positively charged electrodes via electrostatic force. In the reflective mode, when the common electrode on the top substrate was charged with positive polarity, the white nanoparticles moved to the top substrate, and thus, the EPL functioned as a reflector. On the other hand, in the transmissive mode, a positive voltage was applied to one of the in-plane electrodes to tightly accumulate the nanoparticles in the black matrix region. In such situation, the white nanoparticles moved to the positively charged electrodes, and thus, the transmissive light from the backlight unit passed through the EPL.

Fig. 2 shows the operating principles of the transflective LCD with the EPL as a switchable mirror. In the reflective mode, in the absence of an applied voltage, the linearly polarized incident light from the front polarizer kept its polarization state after passing through the planar LC cell that was aligned parallel to the polarization of the incident light and thus, was blocked by the crossed polarizer. In the same LC configuration, in the transmissive mode, the incident light that passed the rear polarizer from the backlight also maintained its polarization state through the LC layer and thus, was blocked by the crossed front polarizer.

When the voltage was applied above a certain threshold voltage, the LC molecules rotated along the applied filed direction, in the in-plane electrodes. Under the crossed polarizers, the rotation of the LC molecules from the direction parallel to that of one of the crossed polarizers gave rise to phase retardation in the LC layer. When the phase retardation of the LC layer was λ/2, in the reflective mode, the linearly polarized light (0°) that came in from the front polarizer rotated by 90° after passing through the LC layer, and was reflected on the EPL mirror. At this time, the common electrode of the EPL was charged with a positive polarity, and thus, the white nanoparticles moved to the top

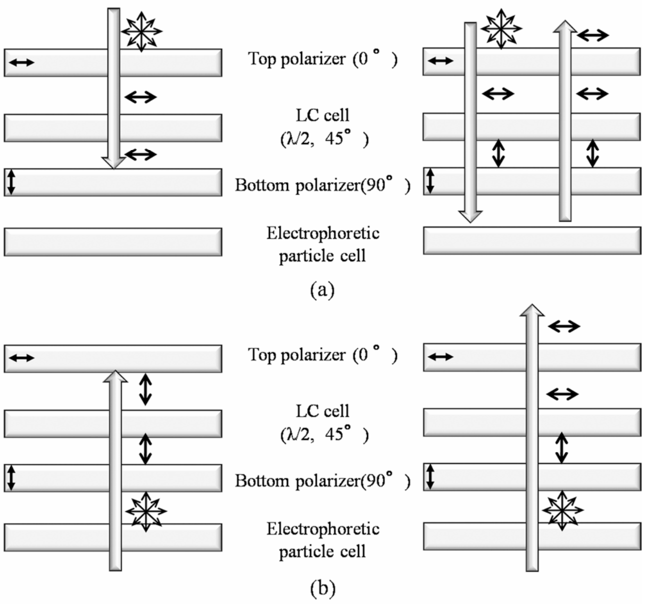


Fig. 2. Schematic of the operating principles of the proposed transflective LCD using the EPL in (a) the reflective mode and (b) the transmissive mode.

substrate. The reflected light propagated again along the λ/2 LC layer and rotated by 90°. As a result, the reflected light passed the front polarizer, and thus, a bright state was obtained. In the transmissive mode, the EPL acted as a transparent dummy layer through the application of the in-plane field and the aggregation of the electrophoretic nanoparticles on the positively charged electrodes that were blocked by a black matrix. In this circumstance, the incident linearly-polarized light (90°) rotated by 90° after passing through the λ/2 LC cell and the crossed front polarizer (0°).

3. Results and Discussion

Fig. 3 shows the microscopic textures of the switchable EPL cell between the reflective mode and the transmissive mode. Fig. 3 (a) shows the transmissive texture of the EPL that acted as a mirror for the reflective mode by applying the positive polarity to the common electrode on the top substrate (30 V). The white nanoparticles moved to the top substrate and reflected the incident light. When the voltage was applied to the in-plane electrodes, the electrophoretic particles moved to the positively charged electrodes that were below the black matrix, as shown in Fig. 3(b). In this situation, the EPL was transparent, except in the anode regions, and the incident light from the backlight unit passed through the EPL.

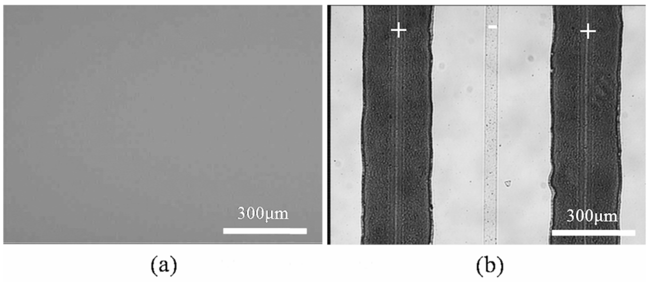


Fig. 3. Transmissive microscopic textures of only the EPL cell without polarizers when it acted as (a) a mirror for the reflective mode by applying the positive polarity to the top common electrode, and (b) a transparent dummy layer for the transmissive mode by applying the positive polarity to one of the in-plane electrodes.

Fig. 4 shows the microscopic textures and the measured voltage-transmittance (V-T) curves of the switchable transflective LCD. In the absence of an electric field, the LC orientation was initially parallel to one of the crossed polarizers, and thus, a dark state was obtained because the LC molecules were aligned homogeneously along the rubbing direction, which coincided with the transmission direction of the polarizers in both the reflective and transmissive modes. When the voltage of 20 V was applied to the LC layer, the LC molecules were rotated by 45° with respect to the crossed polarizers due to the in-plane electrodes in the LC cell. As a result, the LC layer rotated the polarization of the incident light by 90°, and thus, a bright state was obtained. Here, the black stripes represent the polymer walls that maintained the cell thickness.

From the measurement of the electro-optic (EO) transmittance of the proposed transflective LCD, a contrast ratio of

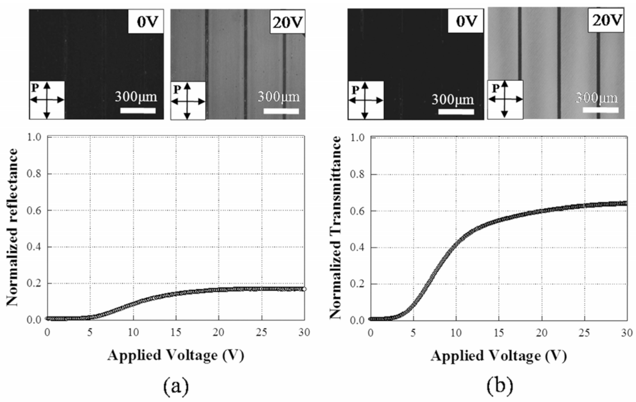
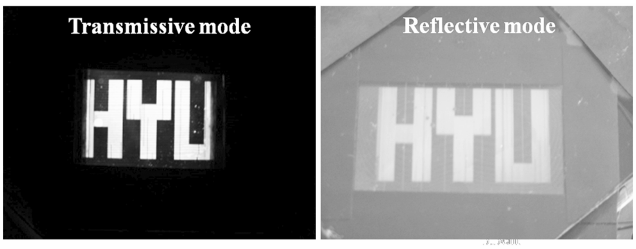


Fig. 4. Microscopic textures and measured V-T curves of the proposed transflective LCD using an electrophoresis particle cell, showing the dark and bright states in (a) the reflective mode and (b) the transmissive mode.

over 10:1 was achieved for the reflective EPL with a 25% reflectance in the reflective mode, as shown in Fig. 4(a). In the transmissive mode, the transmittance was reduced by about 25% compared to the planar LC cell without the EPL, due to the blockage of the incident light by the aggregated electrophoretic nanoparticles. In this case, the contrast ratio of the transmissive LC cell was measured as about 110:1.

A 2-inch prototype of the switchable transflective LCD that showed the logo of "HYU" was demonstrated, as shown in Fig. 5. Electrodes shaped into the characters "HYU" were directly patterned, and a voltage was applied to the characters. Figs. 5(a) and (b) show the images taken in the transmissive mode and the reflective mode in the presence of the applied voltage, respectively. It should be noted that the light sources in the two modes differed, and thus, it is impossible to directly compare their performance. As expected in the EO transmittance, the display performance in the transmissive mode was better than that in the reflective mode. The contrast ratio of the manufactured prototype was about 120:1 in the transmissive mode and 12:1 in the reflective mode. When the dispersed electrophoretic particles were driven to the top substrate by the vertical D.C. voltage for driving to the transmissive mode, the measured switching time was about 200 ms. In the reflective mode, when the voltage was applied to the interdigitated electrodes, the electrophoretic particles completely moved to the positively charged electrodes after 1 second. The tardy switching time of the electrophoretic particles in each mode can be improved by the optimized conditions of the weight percent and the electrode designs.



(a) (b)

Fig. 5. Images of the 2-inch diagonal prototype of the switchable transflective LCD in (a) the transmissive mode and (b) the reflective mode.

4. Summary

A switchable transflective LCD with a high aperture ratio under a single LC mode and a single cell gap was proposed. The switchable transflective LCD consisted of the LC layer as the display unit, and the EPL as the switchable mirror for switching of display modes between the transmissive and the reflective modes. In this structure, the whole pixel could be used in both the transmissive and reflective modes without dividing it into sub-pixels for each display mode in a single pixel. Thus, the aperture ratio of the display could increase. This proposed transflective LC mode could be applied to very bright transflective LCDs.

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