A Novel Transparent Color Liquid Crystal Display using Azo-benzene Dye Layer

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ABSTRACT

We proposed a guest-host type transparent liquid crystal (LC) display using a dichroic dye color filter (DDCF) with single layer. This device with dark, color and transparent mode can show good optical performance. As measured results, we confirmed the excellent light efficiency and high contrast ratio (~357:1) in transparent mode.

1. Introduction

Nowadays, liquid crystal display (LCD) devices are pioneering the new market for 3-dimensional display, e-book and transparent LCD in addition to conventional LCD such as in-plain switching [1], patterned vertical alignment [2], fringe field switching [3]. These advance LC modes have various advantages such as wide-viewing angle, high contrast ratio, fast response time and so on. However, all of the advanced LCDs represent the poor light efficiency because both the two polarizers and a color filter severely decrease the optical transmittance. As a result, only we can see the light less than 10%. The G-H LC device is one of the polarizer-free LC modes, which can successfully achieve the dark state and bright state. The brightness of a G-H LC cell can be controlled by applying an external electric-field. In order to realize the color of the conventional G-H LC modes, Uchida et. al. proposed the three-stack layer G-H using subtractive color mixture [4]. Although it could show the high brightness and color, the device structure is very complicated and the characteristic of multiplexing operation was not good.

In this paper, we propose the guest-host (G-H) LC device which is consist of a polarizer, an LC layer with a small amount of black dye molecules and a DDCF. Contrary to the subtractive color mixture, the DDCF has the red, green and blue sub-pixels so that it realizes the color state by using additive color mixture. In addition, the other dichroic dye layers were successfully eliminated. In order to confirm the optical transmittance, we fabricated the novel G-H LC cell with the DDCF and measured the optical performance.

2. Electro-optical principle of the proposed Guest-Host liquid crystal

Figure 1 shows the transmission mechanism of dichroic dye. When the direction of the incident polarized light and optical axis of the mixture of LC with dichroic dye is parallel to each other, color mode can be performed because the incident light is entirely absorbed by black dichroic dyes as shown in Fig 1(a). In case of that the direction of the polarized light is perpendicular to the optical axis of dichroic dyes; however, the light is totally transmitted by passing through the short axis of dyes without any absorption. Therefore, transparent state can be achieved in Fig. 1(b).

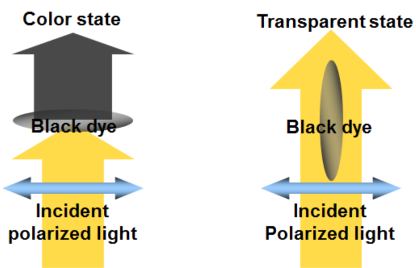

Fig. 1(a) Fig. 1(b)

Fig.1. Transmission mechanisms of mixture of LC with dichroic dye: (a) color state and (b) transparent state

Fig 2 shows the optical structure for proposed LC devices switchable from initially homogeneous state to color state or transparent state. A LC layer with a few black dichroic dye molecules is placed between a polarizer and DDCF. A transparent common electrode is coated on the upper glass substrate of a conventional fringe-field-switching LC cell. The DDCF which can transmit or absorb

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the light dependent on an input polarization is on the outside of a top substrate and its long axis is perpendicular to the bottom rubbing direction. The LC layer is homogeneously aligned parallel to transmission axis (TA) of the polarizer. The electrode configuration which is composed of a top common electrode, a bottom common electrode and patterned electrode has been widely used for various applications [5-6]. In the no voltage, the dark state is realized by black dichroic dye in an LC layer. The color mode operation of the proposed LC device is achieved by vertical electric field between top and bottom common electrode. On the other hand, a fringe *E*-field between patterned electrode and bottom common electrode induces the transparent state of the proposed optical configuration.

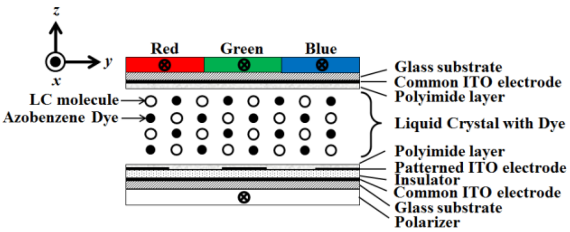

Fig. 2. The illustration of the proposed G-H optical configuration

The polarization states of each operation mode are shown in Fig. 3. When the dichroic dye molecules are mixed with LCs, they follow the movement of the LC directors. By controlling the dye molecules and LCs, dichroic dye is able to absorb the light along the principal molecules axis and to transmit light easily along the perpendicular direction. In the absence of applied voltage, the light passing through the input polarizer will become the linear polarization state parallel to *x*-direction. The black dichroic dye molecules blended with LCs are homogeneously aligned in the LC layer. The linearly polarized light is vanished by the dye- doped LC layer (DDLC) so that we can obtain the dark state as shown in Fig. 3(a). To achieve the color state, a vertical electric field between the bottom and top common electrode is applied to the DDLC layer as shown in Fig. 3(b). The LCs are perpendicularly aligned due to the vertical *E*-field. Then, the principal axis of black dichroic dye can be perpendicular to the *x*-*y* plane. The polarization of the light in front of the DDCF stays parallel to the absorption axis (AA) of the DDCF, because the light passing through the DDLC layer does not experience optical retardation, so that we can achieve a bright or color state by using additive color mixture method. By applying the fringe *E*-field between the patterned electrode and bottom common electrode, the transparent state is obtained as shown in Fig. 3(c) because of the twist- deformed LC configuration on the bottom surface layer. The whole LC director profile of the proposed device is almost similar to the 90° twisted nematic LC cell, even if LC molecules at the surface layer do not change the initial position due to the strong anchoring strength of the polyimide. The polarization of an input light passing through the bottom polarizer is crossed to the optical axis of the LC and the AA of the black dye. Then, when the proposed LC cell has enough high cell gap to satisfy the Mauguin condition [7], it penetrates the DDLC layer without the decrease of light intensity and will be rotated by 90° in front of the DDCF, which parallels the TN of the DDCF. Thus, the proposed optical configuration in the transparent mode achieves the maximum bright (or clear) state by three times theoretically since each sub-pixel (R, G, B) is able to transmit the other wave lengths in visible spectrum range as well as the wavelength of their colors.

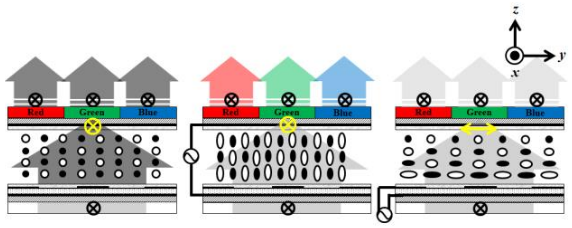

Fig. 3(a) Fig. 3(b) Fig. 3(c)

Fig. 3. Operation of the proposed G-H LC cell : (a) dark state, (b) color state, and (c) transparent state

3. Experiments and discussions

Fig.4 illustrates the fabrication process of a DDCF. First, a B mixture was spin- coated outside the upper glass substrate. The substrate with B mixture was exposed to a UV source (150mW/cm^2, 15s) through a photo mask, followed by prebaking for 5 min at 60℃. Then, the developer (Developer, Osaka Organic Chemical) washed out an unexposed area. In order to avoid the contamination problem from other mixtures, we employed the NOA68 on the patterned B mixture after attaching a masking tape to unexposed area. The NOA68 which can almost transmit the visible wavelengths was exposed to a UV light source with an irradiance of 25mW/cm^2 for 30s. Except for the UV irradiance intensity (R: 30mW/cm^2 and G: 100mW/cm^2), the DDCF fabrication process of the R and G area was the same as the B area. Also, we repeated the fabrication process of the R region twice to expand the color gamut of the DDCF. Cells were assembled with three different cell gaps at 11μm, 20μm and 32μm, respectively. The DDLC mixture was prepared by mixing nematic LCs (MLC-7037, Merck) and black dye with a mixing ratio of 97.33 : 2.66 wt%. The parameters of the used LC are as follows: K_{11} = 12.3pN, K_{22} = 6pN, K_{33} = 13.2pN, γ = 59mPa·s, $\varepsilon_{//}$ = 8.1, $\Delta\varepsilon$ = 5, n_e = 1.607, n_o = 1.4926. The black dichroic dye is a mixture of three dyes (AC1 and AG1, Nematel, GARI-02, Osaka Organic Chemical) to absorb the light over all visible wavelengths. The mixture was injected into prepared empty cells with the DDCF.

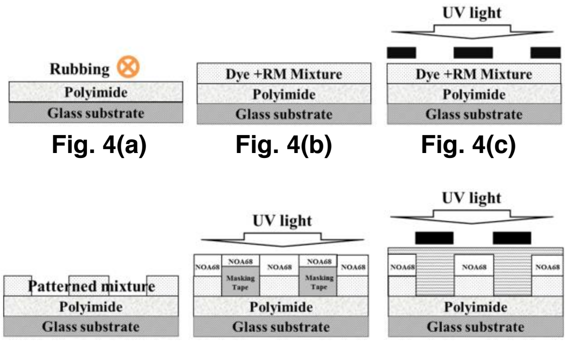

Fig. 4(a) Fig. 4(b) Fig. 4(c)

Fig. 4(d) Fig. 4(e) Fig. 4(f)

Fig. 4. Fabrication process of a DDCF: (a) rubbing on a polyimide, (b) spin-coating of a mixture of dichroic dye and RM, (c) UV exposure through a photo mask, (d) development of unirradiated UV area, (e) attachment of masking tape and (f) NOA68 coating and UV exposure.

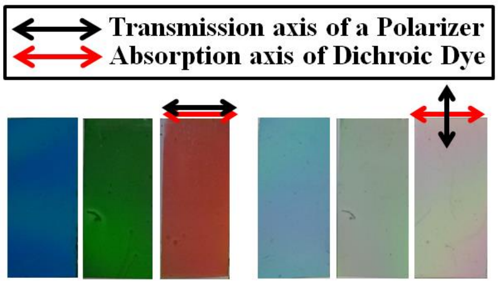

Fig. 5 (a) Fig. 5 (b)

Fig. 5. The light intensity through the fabricated DDCF dependent on the input polarization state: (a) color state and (b) transparent state

Figure 5 shows the light intensity through the DDCF dependent on the input polarization state. The red and blue double arrows represent the transmission axis of a polarizer and transmission axis of a dichroic dye, respectively. When the input polarization state is coincident with absorption axis of the DDCF, each color is successfully realized. In order to optical transmittance of the proposed G-H LC cell, LC cells which had the homogeneous polyimide (AL16301K, JSR Micro Korea) on the upper and lower substrate are assembled such that the top and the bottom rubbing direction were anti-parallel. The cell gaps were fixed at 11um, 20um and 32um. Finally, the positive LC (ML-7037, Merck) and black dichroic dye (GARI2-02 and GARI2-03, Osaka Organic Chemical Industry) were injected into the empty cell. By using a spectrometer (SPTR-100, Sesimlcd) and polarization microscope (ECLIPSE E600, Nikon), the measured chromaticity diagram of a DDCF is shown in Fig. 6. The □ and ○ indicate the coordinate when the light passed through the principal (□) and transmission (○) axis of the DDCF, respectively.

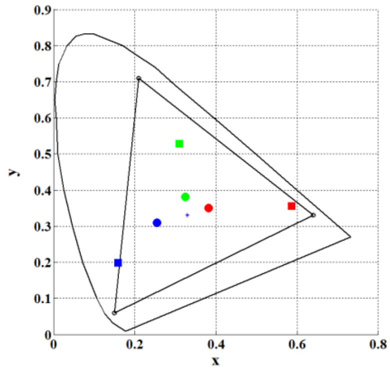

Fig. 6. The color gamut of a dichsroic dye color filter

The tri-angle in Fig. 6 is the NTSC color gamut. The area of color gamut of a DDCF is 37.2% compared to that of the NTSC and each sub-pixel can transmit the about two over thirds light. The measured cell gap - transmittance of each color in the dark state is shown in Fig. 6. In Fig. 6, the total light leakages of the each gap (32μm, 20μm and 11μm) are 0.11, 0.915 and 3.615 respectively. The LC cell with 32μm cell gap achieved the most superior dark state among three different cell gaps. Although the same LC mixture was injected into the LC cells, the LC cell with 32μm cell gap has the enough height to absorb the light passing through DDLC layer. Among three sub-pixel area in a DDCF, the light leakage of the R area in the dark state is more severe than the others because the absorption ability of the DDLC layer from 640nm to 680nm is poor. As a result, the residual light passing through R sub-pixel in a DDLC records the highest light leakage in the dark state twice more than that of G sub-pixel.

The measured cell gap - transmittance of each color in the dark state and the bright state is shown in Fig. 7. In Fig. 7(a), the total light leakages of the each gap (32μm, 20μm and 11μm) are 0.11, 0.915 and 3.615 respectively. The LC cell with 32μm cell gap achieved the most superior dark state among three different cell gaps. Figure 7(b) represents the transmittance at 9V in the transparent state. The transmittance of each sub-pixel in the transparent state is over twice higher than in the color state. However, its optical performance in the transparent state is lower than expected. Although the LC and black dye molecules on the patterned electrodes are rotated to the E-field direction, their alignments were not crossed to the TA of the polarizer so that the input light does not propagate the TA of black dichroic dye. Also, the light intensity is slightly reduced even if the light goes into the TA of black dichroic dye.

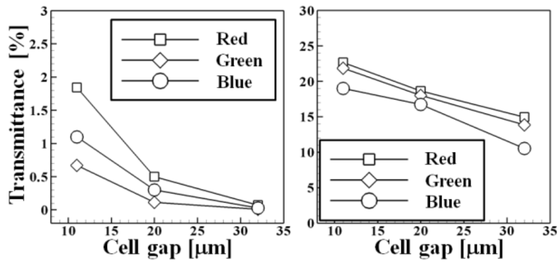

Fig. 7(a) **Fig. 7(b)**

Fig. 7. Optical transmittance of the proposed G-H LC cell: (a) dark state and (b) bright state

The contrast ratio of the LC cell with 32μm gap achieves 135.5 and 357.7 in color and transparent state, respectively. If we use the material with high dichroic ratio or optimize the mixing ratio between LC and dichroic dye, we can achieve the higher transmittance and contrast ratio.

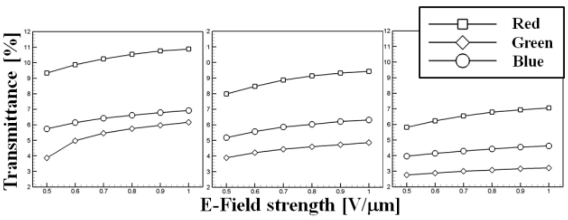

Fig. 8(a) **Fig. 8(b)** **Fig. 8(c)**

Fig. 8. Optical transmittance of proposed G-H LC cell with (a) 11um, (b) 20um and (c) 32um in color state

Figure 8 shows the voltage–transmittance (*V–T*) of the color state of each LC cell. As respected, the LC cell with the 11μm gap represents the highest bright state. The stronger vertical *E*-field strength between bottom and top common electrodes induces the more homeotropic LC alignment near the surface layers of a DDLC. Thus, the total transmittance at 1 V/μm is improved by about 20% compared to that at 0.5 V/um.

4. Conclusion

We proposed an optical configuration for the G-H LC cell that is switchable between conventional ECB mode and transparent LC mode. The novel G-H LC mode consists of the DDCF and the DDLC which can control the output polarization dependent on the applied *E*- field. The DDCF on the proposed LC device can transmit the polarization of an input light passing through the DDLC layer when fringe-field switching is applied to the LC cell and realizes the color expression by using additive color mixture method so that it can reduce the thickness of the G-H LC cell due to elimination of other G-H layers. We expect that the proposed device can be used for applications with transparent and low power consumption.

5. Acknowledgement

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6. References

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