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Fabrication of a dye-doped liquid crystal light shutter by thermal curing of polymer

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We report a thermal curing method for fabrication of a dye-doped polymer-stabilized liquid crystal (PSLC) light shutter, which can prevent the decrease in absorption and discoloration of the dye caused by the UV curing process. We found that the measured transmittance in the opaque state of a dye-doped PSLC cell fabricated by thermal curing was approximately 35% lower than that of a dye-doped PSLC cell fabricated by UV curing. Thermal curing can be an alternative approach for fabrication of a dye-doped PSLC light shutter which can be used to provide high visibility of a see-through display.

1. Introduction

Recently, see-through displays using organic light-emitting diodes (OLEDs) have drawn much attention as one of the next-generation displays [1,2]. However, see-through displays exhibit poor visibility because objects behind the display panel are also seen along with the displayed images. Moreover, the color black cannot be displayed because the operation of an OLED relies on light emission. The poor visibility of a see-through OLED display can be overcome by placing a light shutter at the back of the display panel. By switching a light shutter, we can operate a see-through display in either high-visibility or see-through modes [3–9]. The high-visibility mode of a see-through display can be realized by using a light shutter that simultaneously uses light scattering [10–14] and absorption effects [15–17]. For this reason, dye-doped liquid crystal (LC) light shutters are being extensively studied [18–21]. In particular, an initially-transparent dye-doped polymer-stabilized liquid crystal (PSLC) light shutter has been actively studied [8,9,20,21].

To fabricate a dye-doped PSLC light shutter, polymerization of the monomer material doped in the LC mixture is indispensable. Among the various polymerization methods, such as photopolymerization, thermal polymerization, and electron beam polymerization [22,23], UV curing has been most widely used in various devices because of its easy, fast, and efficient process [24].

When UV light is incident to an LC mixture doped with photo-initiators, it is absorbed by photo-initiators to yield excited species that easily decompose to free radicals. A free radical has an unpaired valence electron, which makes free radicals chemically very reactive towards other substances. These free radicals initiate polymerization by reaction with monomer molecules, and this process is followed by successive addition of monomer molecules to growing polymer chains or networks [25–28]. During the UV curing process, the doped dye molecules will inevitably be exposed to the UV light [5,18] and damaged by free radicals, which can lead to the decreased absorption and discoloration of the dye molecules. As a result, a dye-doped PSLC cell fabricated by UV curing can exhibit performance degradation and discoloration of dye molecules.

In this work, we demonstrate fabrication of a dye-doped PSLC light shutter by thermal curing, which can prevent the decrease in absorption and discoloration of dye molecules caused by the UV curing process. Because polymerization by thermal curing does not require the UV exposure, a dye-doped PSLC light shutter fabricated by thermal curing can provide a superior black color in the opaque state.

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2. Absorption decrease and discoloration of dye

Fig. 1 shows the configuration of a dye-doped PSLC cell. Initially, the light shutter is transparent because the LC and dye molecules are aligned perpendicular to the substrate. Therefore, both light scattering and absorption by LC and dye molecules are minimized in the initial state. When a vertical electric field is applied, the cell is switched to the opaque state. Randomly oriented LC and dye molecules cause light scattering and absorption to occur at the same time. When the applied voltage is removed, the cell returns to its initial transparent state.

To fabricate a dye-doped PSLC cell by UV curing, an LC mixture including monomer, photo-initiator, and dye can be used. Such an LC mixture is injected by capillary action between the two substrates, and exposed to the UV light to polymerize the inherent monomer. However, the color of a dye-doped PSLC cell can change from black to blue-green by the UV exposure process, as shown in Fig. 2.

We prepared the two kinds of LC mixtures to investigate the discoloration of dye molecules. One is negative LC (RTA93000-100, TNI: 71 °C, Δn: 0.2, $\Delta\varepsilon$: -5.5, HCCH) doped with 1% of black dye (S-428, Mitsui) and 0.5% of photo-initiator (Irgacure 651, Ciba). The other is the same LC doped with 1% of the same black dye but without photo-initiator. Each LC mixture was injected into an empty cell with a cell gap of 10 μm. Each substrate for an empty cell was prepared by coating a homogeneous polyimide alignment layer and rubbing in the anti-parallel direction to align LC and dye molecules. Finally, each cell was exposed to UV light with an intensity of 5 mW/cm^2 using a mercury arc lamp.

To investigate the degradation of dye molecules by the UV exposure, we measured the polarization-dependent transmission spectra of the fabricated test cells by using the linearly polarized light. Fig. 3 shows a schematic view of the transmittance measurement of the fabricated cells. The polarizer located in front of an unpolarized white light source (MC-916C, Photal Otsuka Electronics) will allow only the component polarized along its transmission axis to pass through it. To measure the polarization-dependent transmission spectra of the fabricated cells, the transmission axis of the polarizer was arranged perpendicular or parallel to the rubbing direction of the fabricated cells. To confirm the degradation of dye molecules by the UV exposure, we measured the transmittance $T_\perp$ [$T_\parallel$] of a test cell when the polarization of the incident light is perpendicular [parallel] to the rubbing direction as we varied the UV exposure time.

As shown in Fig. 4(a), the measured $T_\perp$ and $T_\parallel$ of a test cell without photo-initiator were rarely changed by the UV exposure. Likewise, the measured $T_\perp$ of a test cell with photo-initiator also rarely changed by the UV exposure. Whereas, the measured $T_\parallel$ of the cell with photo-initiator was considerably increased by the UV exposure, as shown in Fig. 4(b). These results indicate that absorption of the incident light polarized along the absorption axis of dye molecules was decreased seriously by the UV exposure in the LC cell with photo-initiator. Especially, the increased transmittance for wavelengths ranging from 400 to 550 nm was considerably high, as shown in Fig. 4(b). Consequently, we can observe the discoloration from black to blue-green caused by the UV exposure. In summary, the UV exposure to an LC mixture including photo-initiator caused the decreased absorption and discoloration of the dye molecules.

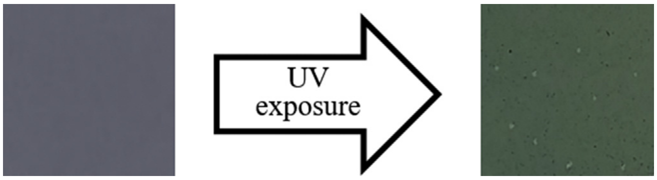


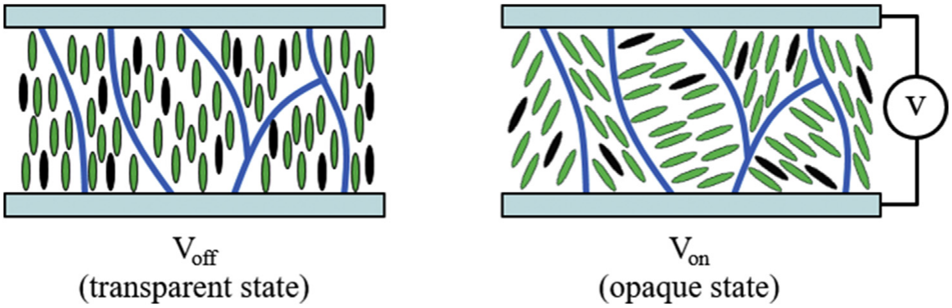
Fig. 2. Photographs of a dye-doped PSLC cell before and after the UV exposure.

We fabricated additional test cells to investigate the dependency of $T_\perp$ and $T_\parallel$ on the UV intensity. An LC mixture including 1% of dye and 0.5% of photo-initiator was characterized with the above-mentioned measurement method. Fig. 5 shows the measured dependence of the transmittance of the fabricated test cells on the UV intensity. The measured $T_\perp$ values of the test cells were not affected by the UV intensity. Whereas, as the UV intensity was increased, the measured $T_\parallel$ of the test cells was increased rapidly.

To check the dependence of the transmittance on the amount of photo-initiator, we fabricated test cells with a fixed amount of dye. Fig. 6 shows dependence of the measured transmittances of dye-doped cells on the amount of photo-initiator. We can prevent the degradation of dye during the UV exposure by reducing the amount of photo-initiator. However, as mentioned above, the photo-initiator is used to form polymer chains or networks in the UV polymerization method. Therefore, reducing the amount of photo-initiator to prevent degradation of dye is not acceptable in the fabrication of a dye-doped PSLC cell by UV curing. To avoid the degradation of dye molecules in a dye-doped PSLC cell, a polymerization method which does not rely on UV curing is necessary. For this purpose, we demonstrate the fabrication of a dye-doped PSLC cell by thermal curing.

3. Experimental results and discussion

We fabricated test cells to verify the performance of a PSLC cell fabricated by thermal curing. A vertical alignment polyimide layer was spin-coated to the top and bottom indium-tin-oxide glass substrates, and ball-type spaces were used to maintain the cell gap



V_{off}
(transparent state)

V_{on}
(opaque state)

Fig. 1. Configuration of a dye-doped PSLC cell.