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Independent control of haze and total transmittance with a dye-doped liquid crystal phase-grating device

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This paper presents a dye-doped liquid crystal (LC) phase-grating cell that is switchable between transparent, dark, and opaque states. The device can control haze and transmittance independently. Initially, LC and dye molecules are twist-aligned to make the cell opaque but haze-free due to the absorption of incident light without scattering. Switching to the transparent state could be achieved by applying a vertical electric field, whereas switching to the opaque state could be achieved by applying an in-plane electric field. It exhibited several advantages, such as a low switching voltage (<18 V) and fast response time (<30 ms).

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1. INTRODUCTION

Dye-doped liquid crystal (LC) light shutters, which can be responsive to an electric field [1–7], light [8–11], and temperature [12–14], have been widely studied because they can control not only light absorption but also light scattering simultaneously. It can hide the objects behind windows by light scattering and provide a black color by light absorption. Light absorption can be obtained by doping dichroic dyes to LCs, whereas light scattering can be obtained by forming polymer structures in LCs. However, forming polymer structures causes disadvantages [6,10], such as the degradation of dichroic dyes, high operating voltage, and haze in the transparent state. Recently, we have reported LC phase-grating cells [15–17], which can be used to control the haze by light diffraction instead of light scattering by polymer structures. They exhibit several advantages in control of the haze, such as a low haze and wide viewing angle in the transparent state, high haze in the translucent state, low operating voltage, and fast response time.

Most dye-doped LC light shutters can only be switchable between the transparent and opaque states because they cannot control the light scattering and light absorption independently. Although dye-doped cholesteric [2,5,6] and ion-doped [14,18] LC light shutters are switchable between those three states, they may have disadvantages, such as a high operating voltage, slow response (>300 ms), and reliability issues. Moreover, switching among three states in these devices can only be controlled by increasing the applied voltage.

In this paper, we propose a dye-doped LC phase-grating cell for independent control of haze and transmittance by applying a vertical or an in-plane field. In the initial dark state, LCs and dye molecules are twisted so that the incident light is absorbed without light scattering, which implies that the view is not blocked even when it is darkened. It can be switched to the transparent state by applying a vertical electric field or to the opaque state by applying an in-plane electric field. In opaque state, it exhibits a high haze due to the strong diffraction effect caused by the large spatial phase difference. The device exhibited several advantages, such as a low switching voltage (<18 V) and fast response time (<30 ms). Moreover, it could be switched between the transparent, dark, and opaque states independently, making this technology a new candidate for multipurpose smart windows or window displays.

2. OPERATING PRINCIPLE

To control the haze and transmittance in a dye-doped LC phase-grating cell, interdigitated electrodes were formed on both substrates, as shown in Fig. 1. The common electrode on each substrate was separated from the interdigitated electrodes by an insulating layer. The interdigitated electrodes on each substrate were oriented at right angles to each other.

Initially, dye and LC molecules are homogeneously aligned in the direction parallel to the interdigitated electrodes on each substrate, so that the dye and LC molecules are 90°-twisted. We can use this state as the dark state. Although we can increase the twist angle for lowering the transmittance in the initial haze-free opaque state, the operating voltage and response time will also increase significantly [18,19]. It is possible to orient dye and LC molecules vertically by applying a vertical electric field to the cell so that the cell could be switched to the transparent state. It was also possible to orient dye and LC molecules along the applied electric field direction by applying an in-plane field to the cell so that their periodic refractive index distribution can

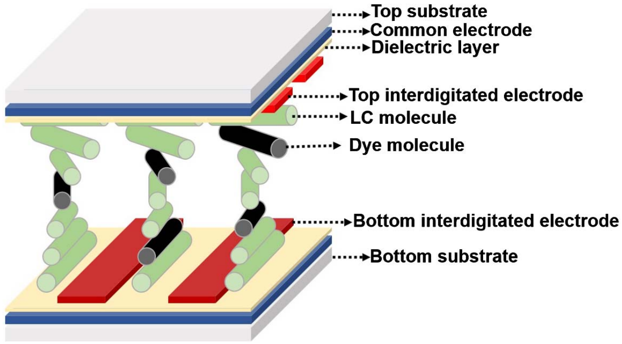

Fig. 1. Structure of a dye-doped LC phase-grating cell.

generate a large spatial phase difference irrespective of the azimuth angle. At that stage, light diffraction and absorption occur at the same time, which results in the opaque state.

3. CELL FABRICATION

To evaluate the electro-optical characteristics of the device, a dye-doped LC phase-grating cell with crossed interdigitated electrodes was fabricated. The parameters of the LC material (E7, Merck) are as follows: the elastic constants $K_{11} = 11.1$ pN, $K_{22} = 10.3$ pN, $K_{33} = 17.1$ pN, optical anisotropy $\Delta n = 0.2253$, dielectric anisotropy $\Delta\varepsilon = 13.8$, and rotational viscosity $\gamma_1 = 250$ mPa · s. LC was mixed with 2 wt. % black dichroic dye (X12, BASF). A thin polyimide layer (PIA-X610-33C, JNC) was spin-coated onto each substrate and baked at 230°C for 30 min. The polyimide layer was mechanically rubbed to align the LCs. The rubbing direction was set parallel with the interdigitated electrodes. The cell was assembled with a gap of 10 μm, which was maintained through the use of silica spacers. The LC mixture was then injected into the empty cell. The width of the interdigitated electrodes on each substrate was 2.8 μm, and the gap between them was 4 μm. The polarizer was not used in our measurements.

For a low total transmittance in the dark state, an LC material with low birefringence could be employed to reduce the influence of the waveguiding effect for the visible light [18,19]. The birefringence of the LC material (MAT-11-571) was 0.0749, and the cell gap was set to 6 μm. Numerical calculations were performed using the finite-element method and a 2 × 2 extended Jones matrix method with the commercial software package, TechWiz LCD (Sanayi System Company, Ltd., South Korea). The device structure and parameters used in the experiment were the same as those used for the numerical calculations.

4. EXPERIMENTAL RESULTS AND DISCUSSION

An electric field applied to the LC phase-grating cell induces diffraction of the incident light. A large spatial phase difference causes a high diffraction efficiency, which in turn results in a translucent state with a high haze. To confirm the dependence of the spatial phase change on the azimuth angle in the opaque state, phase profiles of the output light were calculated, as shown in Fig. 2. When an in-plane electric field is applied to the LC phase-grating cell, a large spatial phase is induced along the x as well as the y direction because interdigitated electrodes are formed on both substrates. Moreover, the spatial phase difference is induced along the diagonal direction, too [16]. Because of the large spatial phase difference, a very high haze value could be obtained in the opaque state.

The electro-optical performance of the proposed LC cells was measured using a haze meter (HM-65W, Murakami Color Research Laboratory), which contains an unpolarized white light source covering from 380 to 780 nm. The specular [diffuse] transmittance, T_s [T_d], refers to the ratio of the power of the beam that emerges from a sample cell, which is parallel (within a small 2.5° range of angles) [not parallel] to a beam entering the cell, to the power carried by the beam entering the sample. The total transmittance, T_t, is the sum of the specular transmittance T_s and the diffuse transmittance T_d. The haze H can be calculated as the ratio $H = T_d/T_t$. The measured electro-optical characteristics of the fabricated cell are shown in Fig. 3. Initially, the cell was in the dark state. The total transmittance, specular transmittance, and haze of the fabricated cell in the dark state were 32.5%, 31.9%, and 1.8%, respectively. For switching to the transparent state, a vertical field was applied to the cell. As the applied vertical voltage was increased, the dye and LC molecules were reoriented along the vertical direction, increasing the total and specular transmittances while maintaining the haze-free state, as shown in Fig. 3(a). At a vertical voltage of 13 V, the total transmittance, specular transmittance, and haze were 58.6%, 58.0%, and 1.1%, respectively.

For switching to the opaque state, an in-plane field was applied to the cell. When the in-plane field was applied, the dye and LC molecules were reoriented along the direction of the applied electric field, inducing a large spatial phase difference, resulting in a strong diffraction of the incident light. As the applied in-plane voltage was increased, the specular transmittance decreased, and the haze increased as a result of the strong diffraction, while the total transmittance remained almost the same, as shown in Fig. 3(b). At an in-plane voltage of 18 V, the total transmittance, specular transmittance, and haze were 32.9%, 3.4%, and 92.8%, respectively. It should be noted that both vertical and in-plane switching can be obtained with a low operating voltage below 20 V.

The transmission spectra of the proposed dye-doped LC phase-grating cell measured with a spectrometer (MCPD 3000, Photal) are shown in Fig. 4. As the applied vertical voltage was increased, the transmittance gradually increases by decreasing the light absorption, as shown in Fig. 4(a). As the applied in-plane voltage was increased, the transmittance gradually decreases by increasing the diffraction of the incident light.

Photographs of the fabricated LC cell placed on top of a printed paper in the dark, transparent, and opaque states are shown in Fig. 5. A printed image placed directly behind the cell in the transparent state could be identified clearly, whereas a printed image could be observed with reduced transmittance in the dark state. In the opaque state, the fabricated LC cell could completely obscure objects placed behind it and present a black color through the simultaneous control of haze and transmittance.

The dynamic switching behavior of the fabricated LC cell was also investigated, as shown in Fig. 6. For switching to the opaque state, an in-plane voltage of 18 V was applied to the fabricated cell and then removed after several seconds for

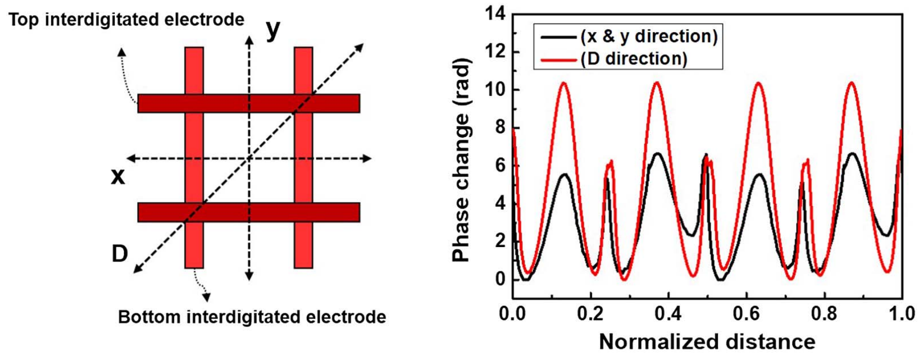

Fig. 2. Calculated phase profiles of the output light along x, y, and diagonal (D) directions.

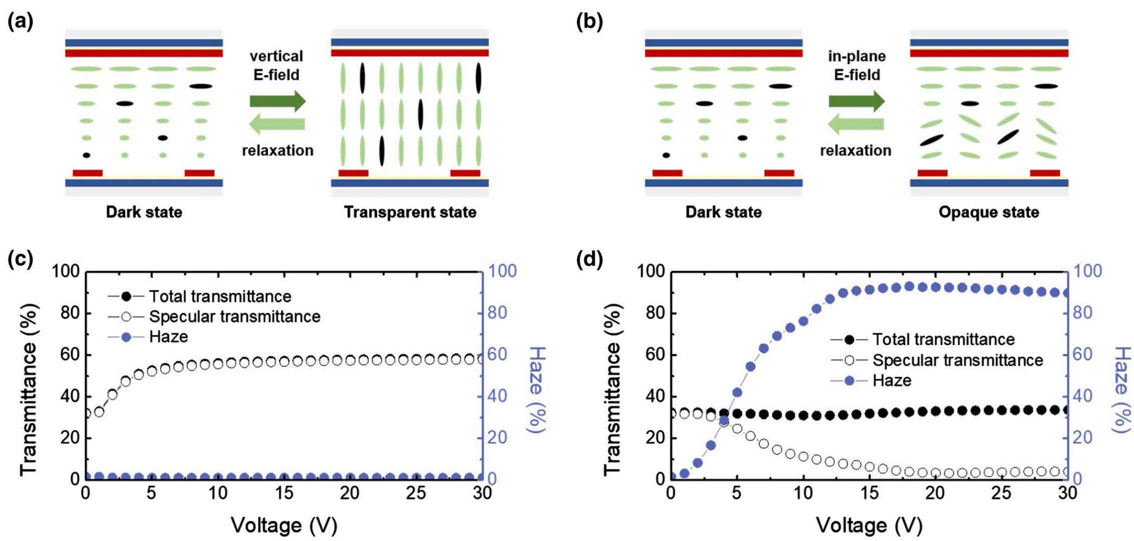

Fig. 3. Operating principle of a dye-doped LC phase-grating cell driven with (a) vertical and (b) in-plane voltages. Measured total transmittance T_t, specular transmittance T_s, and haze of the fabricated LC cell as functions of the applied (c) vertical and (d) in-plane voltages.

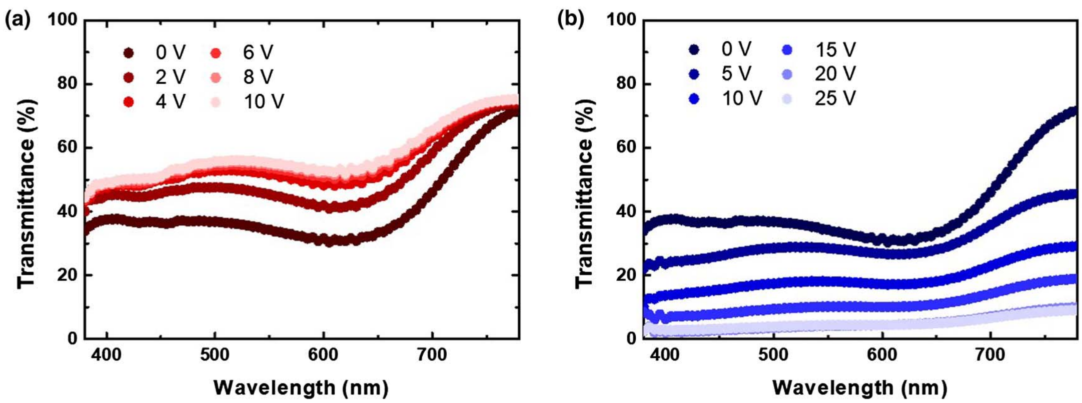

Fig. 4. Transmission spectra of the fabricated LC cell as a function of the applied (a) vertical and (b) in-plane voltages.

turn-off switching. The turn-on and turn-off times were measured as 1.81 ms and 3.29 ms, respectively, as shown in Fig. 6(a). The switching time between the dark and opaque states was relatively short, despite a large cell gap of 10 μm, which may be attributed to the confinement effect [20,21].

For switching to the opaque state, a vertical bias electric field was continuously applied, while an in-plane field was applied to control the switching to the opaque state. The turn-on and turn-off times were measured as 1.04 ms and 0.69 ms, respectively. Switching between the transparent and opaque states was

Fig. 5. Photographs of the fabricated LC cell placed on top of a printed paper in the dark, transparent, and opaque states.

very fast because the switching process was forcibly controlled by applying an electric field. On the other hand, switching from the transparent state to the dark state was relatively slow, as shown in Fig. 6(b), because it relied on the slow relaxation of the LCs. For switching from the dark to the transparent state, a vertical voltage of 13 V was applied to the cell for turn-on switching and then removed after several seconds for turn-off switching. The turn-on and turn-off times were measured as 1.39 ms and 28.88 ms, respectively. It should be noted that both vertical and in-plane switching can be obtained with a fast response time within 30 ms.

A large difference in transmittance between the dark and the transparent states could be provided by using an LC material with low birefringence. This phenomenon originates from the reduced waveguiding effect. The measured total transmittance in the dark state could be decreased from 32.5% to 25.2%, whereas the total transmittance in the transparent state is almost the same. However, the cell fabricated using an LC with a low birefringence exhibited a relatively low haze of 65.8% compared with a high haze of 92.8% for a high-birefringence LC. These results, summarized in Table 1, demonstrate that an LC material with a low birefringence can be used to reduce the total transmittance in the dark state, although the haze in the opaque state will be lowered.

As we mentioned above, we can decrease the total transmittance in the dark state by increasing the twist angle or changing an LC material with a low birefringence. However, both methods have a trade-off between transmittance in the dark state and operating voltage, the transmittance in the transparent state, haze in the opaque state, and response time [18,19]. For low power consumption, an initially transparent light shutter could be required in various applications [5,6,15]. The proposed dye-doped LC phase-grating cell can also be fabricated so that it is transparent initially by using the inverse twisted-nematic mode [18]. In this case, as well, the phase-grating cell can control the haze by an in-plane voltage and the transmittance by a vertical voltage, independently.

5. CONCLUSION

The electro-optical characteristics of a dye-doped LC phase-grating cell capable of the control of haze and transmittance were investigated. Unlike previously reported LC light shutters, the proposed LC phase-grating cell can be used for independent control of haze and transmittance by applying a vertical or an in-plane field. The device could be switched between the transparent, dark, and opaque states, making this technology a new candidate for multipurpose smart window or window displays. The device exhibited several advantages, such as a low switching voltage (<18 V) and fast response time (<30 ms).

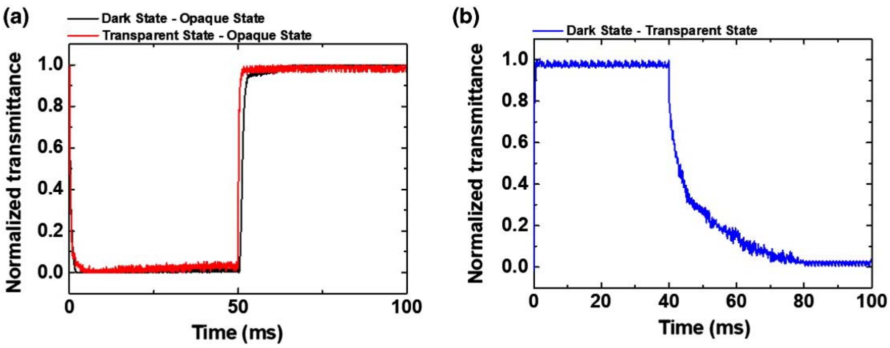

Fig. 6. Measured temporal switching behaviors of the fabricated LC cell: (a) switching between the dark or transparent state and the opaque state; (b) switching between the dark and transparent states.

Table 1. Measured Total Transmittance T_t, Specular Transmittance T_s, and Haze H of the Fabricated Dye-Doped High- and Low-Birefringence LC Cells in the Transparent, Dark, and Opaque States

	Transparent			Dark			Opaque		
Δn	T_t(%)	T_s(%)	H(%)	T_t(%)	T_s(%)	H(%)	T_t(%)	T_s(%)	H(%)
0.2253	58.6	58.0	1.1	32.5	31.9	1.8	32.9	3.4	92.8
0.0749	59.9	58.9	1.0	25.2	24.8	1.6	39.5	13.5	65.8

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