

Reverse-mode Light Dimming Device using Liquid Crystal Phase Grating for Flexible Smart Windows

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ABSTRACT

We have developed a reverse-mode light dimming device using a liquid crystal (LC) phase grating instead of a polymer network to achieve a flexible smart window with strong resistance to external forces. By optimizing the pitch and height of the LC phase grating, we realized a light dimming device with high transparency in a voltage-off state and confirmed its effectiveness for flexible smart window applications.

1. Introduction

With growing awareness of environmental issues in recent years, there has been an increasing demand for the realization of light dimming devices capable of electrically controlling light transmittance for improvement in energy utilization efficiency.

Light dimming devices provide light-shading and heat-blocking properties, enabling control of indoor temperatures. As they are expected to reduce energy consumption, the global market for light dimming devices has been growing. Among these, flexible reverse-mode light dimming film, which is in a transparent state when the voltage is off, is expected to be realized due to its easy installation.

Generally, reverse-mode light dimming devices utilize polymer-network liquid crystals (PNLCs) with a vertically aligned polymer network formed in the liquid crystal layer. When the voltage is off, the molecular orientation of the liquid crystal and polymer is vertically aligned, resulting in a transparent state. When voltage is applied and the molecular orientation of the liquid crystal changes, light is scattered due to the refractive index difference between the polymer and liquid crystal.

However, reverse-mode PNLCs have the problem that external forces, such as bending or impact, would disturb the alignment direction of polymers, causing a decrease in transmittance in the transparent state (Fig. 1). This has been a challenge in developing flexible light-dimming films.

To address this issue, we have proposed a novel structure that utilizes a liquid crystal phase grating within the liquid crystal cell using LC polymers instead of polymer networks. This structure, which does not use polymer networks, exhibits strong resistance to external forces and is considered an effective structure for achieving flexible reverse-mode light-dimming films.

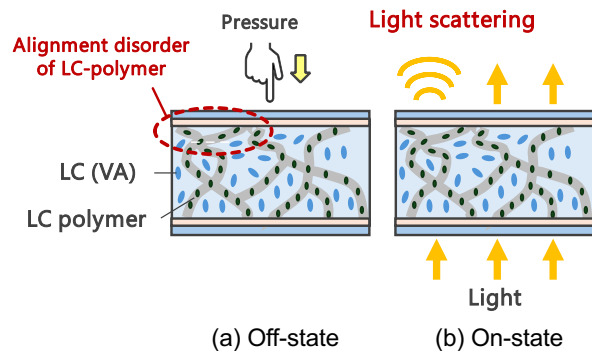


Fig.1 Scattering of Reverse Mode Dimming Film under External Force Application.

2. Proposed Device Structure

2.1 Principle

Figure 2 shows the device structure proposed in this study. The proposed structure uses an LC phase grating fabricated using an LC polymer in the LC cell instead of conventional polymer network structures. The LC polymer is cured in a state of vertical alignment to the substrate. In a voltage off state, the liquid crystal molecules align vertically along the LC polymer, resulting in a transparent state. When voltage is applied, the liquid crystal molecules align parallel to the structure and light is diffracted due to the difference in refractive index between the liquid crystal and the polymer.

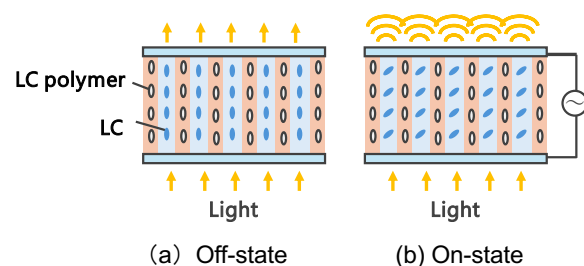


Fig.2 Reverse-mode light dimming device using LC phase grating.

2.2 Fabrication of Light Dimming Device

We fabricated the light-dimming device shown in Fig. 3 by stripe-pattern UV-curing an LC polymer onto a glass substrate with comb electrodes, rotating the substrate 90 degrees to stack it, and then injecting the liquid crystal. By stacking two liquid crystal diffraction gratings orthogonally, this structure does not require alignment layers or spacers. Furthermore, diffracting incident light

multiple times provides the advantage of reduced optical interference and polarization dependence.

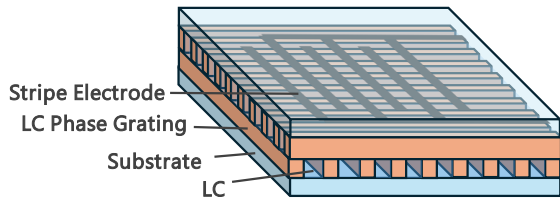
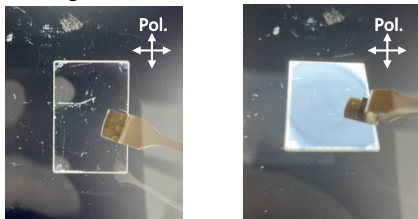


Fig.3 Fabricated device structure.

3. Evaluation of Vertical Aligned LC Phase Grating

Figure 4 shows the observation results of the fabricated LC polymer film before patterning under crossed polarizers. When the substrate is placed parallel to the polarizers, it appears black state; when tilted, it appears bright state, confirming the vertical alignment. Figure 5 shows the angle-phase retardation property of the LC polymer film measured by the spectroscopic ellipsometer (J.A. Woollam). The phase retardation is zero at an angle of 0 degrees, confirming that the LC polymer film exhibits vertical alignment. Figure 6 shows the observation results when a laser is incident on the patterned LC phase grating. From Fig. 6, the transmitted light is diffracted, confirming that the LC phase grating was successfully fabricated through patterning.



(a) Normal observation (b) Oblique observation

Fig.4 Observation of the LC-polymer film under crossed polarizers.

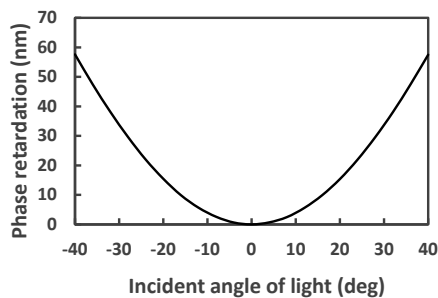


Fig.5 Angle-Phase Retardation property of LC-polymer film.

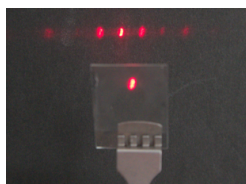


Fig.6 Diffraction by the LC phase grating.

4. Device Optimization

4.1 Optimization of Diffraction Grating Pitch

To optimize the diffraction property, LC gratings were fabricated with pitches of 2 μm , 4 μm , 10 μm , and 20 μm , and their shapes and optical characteristics were evaluated. Figure 7 shows cross-sectional observation results of each fabricated liquid crystal phase grating using a laser microscope (Keyence), while Fig. 8 shows observation results under crossed polarizers using a polarizing microscope. Figure 7 shows that the height of the fabricated LC gratings decreased with a narrower pitch due to light interference during UV irradiation. Figure 8 shows that while the LC grating exhibits a dark state when vertically aligned, a bright state was observed in the structural valleys. This indicates that the uniformity of the alignment direction decreased due to shape disorder.

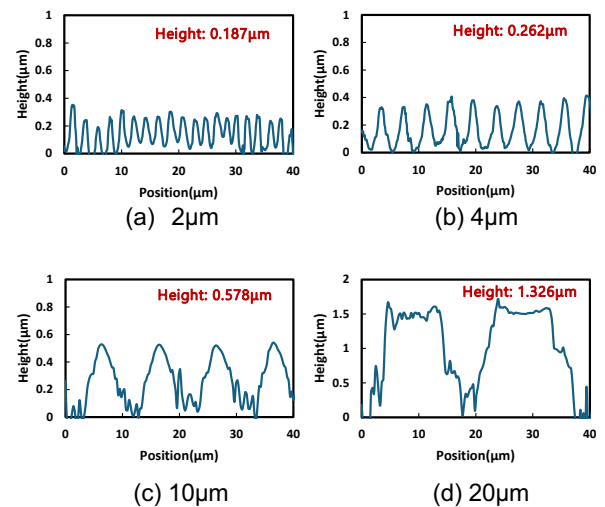


Fig.7 Cross-sectional view of fabricated LC grating.

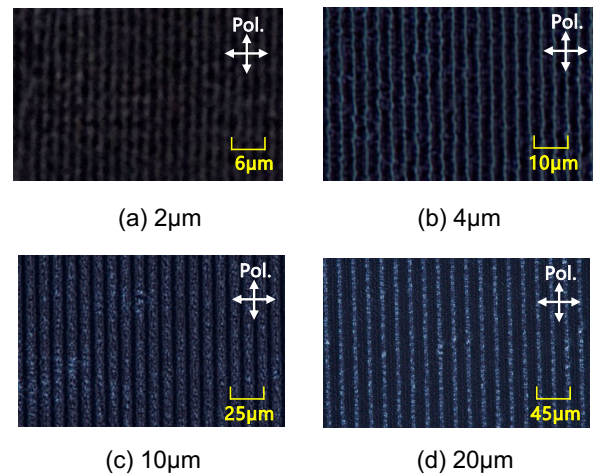


Fig.8 Observation under a polarizing microscope.

Furthermore, to evaluate the diffraction characteristics of each pitch diffraction grating, parallel light was incident and the angle-intensity properties were measured. The measurement results are shown in Fig. 9. Figure 9 shows

that the narrower the pitch, the wider the diffraction angle becomes due to interference conditions. However, for a pitch of 2 μm , the reduced height of the fabricated diffraction grating resulted in insufficient phase difference, causing the intensity of the zero-order light to become too strong. Therefore, the optimal pitch at this stage is considered to be 4 μm .

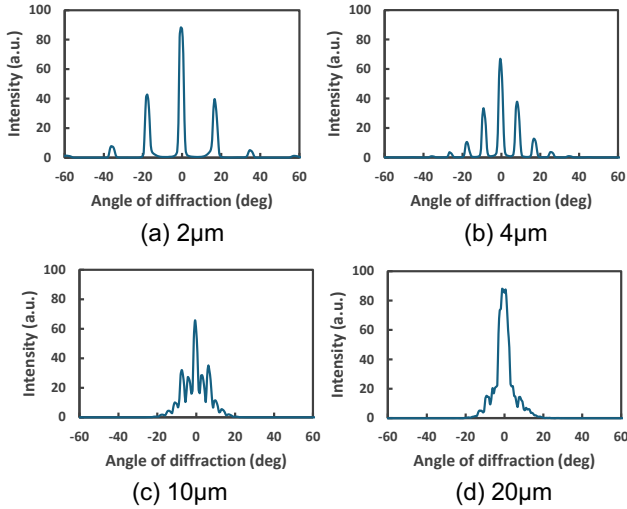


Fig. 9 Angle-luminance properties of each pitch.

4.2 Optimization of the Height of LC Phase Grating

To optimize the height of the LC grating, gratings were fabricated with varying heights of 0.26 μm , 0.46 μm , 0.51 μm , and 0.55 μm , and their diffraction characteristics were evaluated. Figure 10 shows the measured angle-intensity properties when parallel light was incident on the diffraction grating. From Fig. 10, we found that as the structure height increases, the zero-order light becomes smaller, while the intensity of the first-order light and subsequent orders becomes stronger, indicating that light is diffused over a wider range.

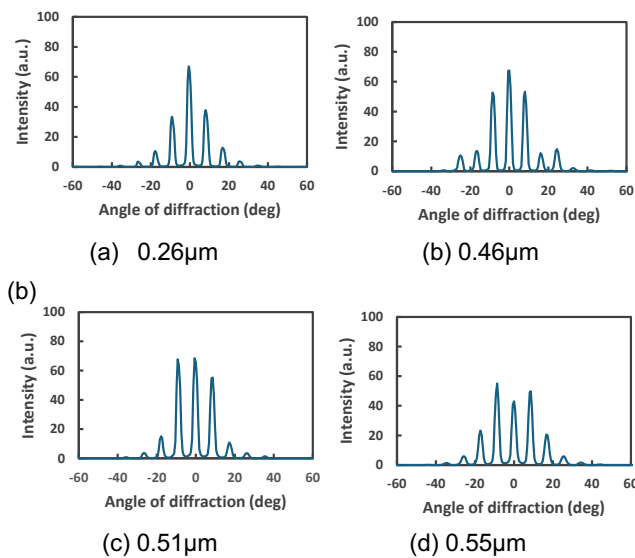


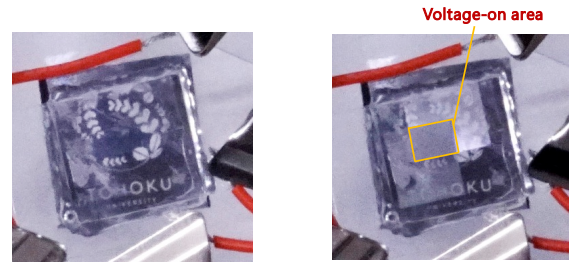
Fig.10 Angle-luminance properties of each height.

5. Optical Characteristics of Light Dimming Device

The proposed light dimming device was fabricated by stacking the LC phase grating. Figure 11 shows the photo of the fabricated device. Figure 11 shows that the device is transparent when the voltage is off (Fig.11a) and exhibits light scattering in the voltage-applied area (Fig. 11b). To evaluate the scattering intensity during both voltage-on and off states, the haze value was measured. Table 1 shows the comparison of haze values with a commercial product. The haze value H represents the degree of scattering of transmitted light and is defined by the following equation.

$$H = \frac{\tau_t}{\tau_d} \times 100 (\%) \quad (1)$$

τ_t is the total light transmittance, and τ_d is the diffused light transmittance. From the results in Table 1, the fabricated device exhibited a lower haze value compared to the commercial product when the voltage off state, demonstrating higher transparency than conventional devices. On the other hand, the haze at voltage-on is lower compared to commercial products. This is due to the lower height of the LC grating, and fabricating a higher grating is a future challenge.



(a) Off-state (b) On-state
Fig.11 Fabricated light dimming device.

Table 1 Comparison of Haze values of Light dimming device.

Sample		This Work	Reference Product
Haze (%)	Off-state	4.5	10
	On-state	59.1	99

6. Conclusions

We proposed a new structure of a reverse-mode LC light dimming device using two orthogonally stacked vertically aligned LC phase grating for a flexible light dimming film. By optimizing the pitch and height of the LC phase grating, we realized a light dimming device with high transparency in a voltage-off state. Our light dimming device has the advantages of high tolerance to external forces and improving the haze value when the voltage-on state remains a future challenge.

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