Low-power control of haze using a liquid-crystal phase-grating device with two-dimensional polymer walls

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Abstract: We propose a two-dimensional (2D) polymer-walled liquid-crystal (LC) phase-grating device, which can be used to control the haze with a very low power. 2D polymer walls can be formed in an LC cell through ultraviolet light irradiation while applying an in-plane electric field through phase separation induced by the spatial elastic energy difference. The transparent and translucent states can be realized by applying vertical and in-plane electric fields to the 2D polymer-walled LC cell, respectively. The cell can be operated with a very low power as the transparent [translucent] state is maintained even after the applied vertical [in-plane] electric field is removed. It consumes power only during state switching. The fabricated device exhibits outstanding performances, such as a very low operating voltage (< 10 V), low haze (< 2%) in the transparent state, high haze (> 90%) in the translucent state, and short switching time (< 2 ms), compared to those of other bistable LC devices, which can be used to control the haze.

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1. Introduction

Low-power-consumption techniques for electronic devices are very important as they can extend the battery life of portable appliances or reduce the energy loss by electronic components in vehicles, showrooms, laboratories, buildings, etc. Liquid crystals (LCs) whose optical properties can be easily controlled by applying a weak external electric field are widely used in various electronic devices, particularly in display applications [1,2]. Recently, extensive studies based on the intrinsic features of the LC materials have been carried out for smart window or window display applications. Unlike traditional LC display devices, in which power is consumed by both backlight and driving circuits, smart window and window display devices use natural light without the requirement of a separate backlight so that the power is consumed only for driving of the device. The devices can be switched between transparent and translucent states by controlling the haze value through either light scattering [3–20] or diffraction [21–24]. Usually, LCs can be switched by applying an electric field; they relax to the initial state when the applied electric field is removed. Such monostable LC devices require a continuous application of an electric field to maintain either the transparent or translucent state.

Bistable switching of LCs is very attractive for a device with a low power consumption, as it consumes power only during switching between the states. Several approaches to enable bistable switching of LCs have been reported, such as surface anchoring energy transition [25,26], balance of the elastic free energy under a bend–splay or splay–twist transition [27–31], two-orthogonal LC alignment directions induced by topologically patterned surfaces [32–35], inherent properties of the ferroelectric LC [36], cholesteric LC (ChLC) [14–19], and smectic-A LC (SmA-LC) [20,24,37–39]. Among them, ChLC and SmA-LC can be used to control the haze value. Bistable switching of a ChLC cell between the planar and focal-conic states can be achieved, although a complex driving scheme is required for switching. The ChLC device can maintain either the transparent or translucent state even after the applied
The electric field is removed [14–19]. Several studies have been performed to improve the performance or to simplify the driving scheme through polymer stabilization [14–16] or ion doping [17–19] in ChLC cells. However, these devices still have various disadvantages, such as a low haze in the translucent state, high operating voltage, and slow switching. In an SmA-LC cell based on the bistable electrooptic effect in the SmA-LC phase [20,24], each electric-field-induced state can be maintained indefinitely owing to the high viscosity of the LC in the SmA phase. Although the SmA-LC cell exhibited an excellent performance in both transparent and translucent states, the disadvantages of a high operating voltage and long switching time should be addressed [24]. In addition, the operating temperature range of the SmA-LC cell should be widened for further applications.

In this study, we propose a two-dimensional (2D) polymer-walled LC device with bistable switching capability between the transparent and translucent states. The common electrode on each substrate is separated from interdigitated electrodes by an insulating layer. The interdigitated electrodes on both substrates are positioned at right angles to each other. When an in-plane electric field is applied to a vertical-alignment cell containing an LC/reactive monomer (RM) mixture, a large spatial elastic energy difference is induced along the direction perpendicular to the interdigitated electrodes on each substrate. Owing to the phase separation induced by the spatial elastic energy difference, 2D polymer walls are formed in the LC cell through ultraviolet (UV) irradiation while applying an in-plane electric field.

When the vertical electric field applied to the 2D polymer-walled cell is removed, LC molecules remain vertically aligned owing to the vertical anchoring with the vertical alignment layer on each substrate. In this state, the cell is transparent as no light is diffracted. On the other hand, when the in-plane electric field applied to the 2D polymer-walled cell is removed, the LC molecules remain homogeneously aligned owing to the in-plane anchoring between the LC and polymer structure where the induced large spatial phase difference is maintained. Therefore, the 2D polymer-walled cell can be switched to the translucent state owing to the strong diffraction effect. The proposed device consumes power only during switching between the transparent and translucent states. Moreover, the voltage required for switching between the two states is significantly lower than those of other bistable LC devices, which can be used to control the haze value.

2. Results

2.1 Formation of 2D polymer walls

In order to induce a large spatial elastic energy difference for phase separation of the LC/RM mixture, we can employ the effect of 2D confinement on the switching of nematic LCs. In the 2D-confined cells, when an electric field is applied to an LC cell with interdigitated electrodes, LC molecules are reoriented in the opposite direction at the edges of the interdigitated electrodes and domain boundaries where there is no change in the azimuth or polar angle of the LC director emerge [40–45]. At these domain boundaries, the LC molecules are not rotated by the elastic torque caused by neighboring rotated molecules, which leads to a large spatial elastic energy difference. Therefore, with the help of the phase separation induced by the spatial elastic energy difference, fine polymer walls could be formed at the domain boundaries of the cell through the UV-curing process without photomasks [46].

The polymer walls formed in the LC cell can contribute to the orientation of the LCs in the lateral direction so that a bistable LC phase-grating device could be realized using three-terminal electrodes [46]. However, the haze in the translucent state of a one-dimensional polymer-walled LC phase-grating cell may not be sufficiently high for practical applications [21–23].

In order to obtain a high haze in the translucent state of the device, we employed a 2D grating LC cell as the reaction template, as shown in Fig. 1, by which a large spatial phase difference can be induced regardless of the azimuth angle [22]. The common electrode on
each substrate is separated from the interdigitated electrodes by an insulating layer. The interdigitated electrodes on each substrate are positioned at right angles to each other. Initially, the LCs are vertically aligned so that no spatial elastic energy difference exists in the LC cell. When an electric field is applied between the interdigitated and common electrodes on each substrate, the LCs with a positive dielectric anisotropy are oriented along the direction of the applied electric field. The LC molecules on the right side of the boundary A are tilted down in the opposite direction with respect to those on the left side of the boundary A. At the boundaries A and B, the LC molecules are not rotated by the elastic torque caused by neighboring rotated molecules so that the elastic energy is very high, which induces a large spatial elastic energy difference along the direction perpendicular to the interdigitated electrodes. Therefore, a large spatial elastic energy difference can be induced in the x-direction near the bottom substrate, as shown in Fig. 1(a); it can also be induced in the y-direction near the top substrate, as shown in Fig. 1(b). The in-plane component of the applied electric field is very high at the boundaries B, whereas no in-plane component of the applied electric field exists at the boundaries A. The employed LCs typically have higher dielectric and elastic constants than the RM. Therefore, according to the previously reported mechanisms of the phase separation [46–50], RMs are expected to drift to the boundaries A where there is no in-plane component of the applied electric field; the elastic energy is very high if an LC/RM mixture is injected into the cell and an electric field is applied to the cell. In addition, in the middle, away from the two substrates, there is a small spatial difference in the elastic energy, as shown in Fig. 1(c), as the in-plane component of the electric field is very weak so that most of the LCs in the middle, away from the two substrates, remain unrotated. Based on these spatial elastic energy distributions, we expect that 2D polymer walls could be formed in the LC cell.

The fabrication process for the formation of 2D polymer walls through the phase separation in the LC mixture utilizing the spatial elastic energy difference is shown in Figs. 2(a)–2(c). First, we prepared an LC/RM mixture, in which Merck E7 and RM257 were used as the host LC and UV-curable monomer, respectively. The LC/RM mixture was composed of 98.0% host-LC E7 and 2.0% UV-curable monomer RM257 containing a small amount of the photo-initiator Irgacure 651. The LC/RM mixture was stirred for 24 h, followed by an ultrasonic-wave treatment for 2 h. Subsequently, we prepared two substrates with interdigitated electrodes whose widths and distance between them were 2.8 and 6 μm, respectively. We coated a vertical alignment layer on each substrate, which was baked for 1 h at 230 °C. The cell was assembled using silica spacers with a diameter of 20 μm. The interdigitated electrodes on each substrate were positioned at right angles to each other, as shown in Fig. 2(a). The prepared LC/RM mixture was injected into the empty cell through capillary flow.

In order to induce the phase separation of the LC/RM mixture, an in-plane electric field was applied between the common and interdigitated electrodes on each substrate, as shown in
Fig. 2(b). In this case, a large spatial elastic energy difference is induced along the direction perpendicular to the interdigitated electrodes on each substrate so that the RMs move to the boundaries A of Fig. 1 where there is no in-plane component of the applied electric field and the elastic energy is very high. Under the applied electric field, the LC cell was exposed to UV light with an intensity of 2 mW/cm². Polymer walls are formed at the center of the interdigitated electrodes and at the middle of the gaps between them, which correspond to the boundaries A in the LC cell shown in Fig. 2(c). Consequently, 2D polymer walls with a cross shape are formed owing to the spatial energy difference generated in directions perpendicular to each other near the top and bottom substrates.

![Diagram showing the photopolymerization process](image)

Fig. 2. Photopolymerization process for the fabrication of the LC cell with 2D polymer walls: (a) preparation of an empty cell with double-layered electrodes on each substrate, (b) UV exposure for polymerization under an applied in-plane electric field after injection of the LC/RM mixture into the empty cell, and (c) completion of the LC cell with 2D polymer walls.

In order to identify the polymer structures formed in the cell, we removed the LCs from the fabricated cell using an organic solvent, and then carefully separated the two substrates. In this case, polymer structures are embedded in either the top or bottom substrate, as shown in Fig. 3(a). We acquired top-view images of the substrate with the embedded polymer structures using polarized optical microscopy (POM), scanning electron microscopy (SEM), and atomic force microscopy (AFM), as shown in Figs. 3(b)–3(d), respectively. The substrate with polymer structures exhibits 2D brightness patterns between crossed polarizers, as shown in Fig. 3(b), owing to the weak birefringence of the bundles of the polymerized RMs where the positions of the bright lines correspond to the boundaries A of Fig. 1. The bright lines were observed not only in the direction parallel to the interdigitated electrodes on the substrate but also in the perpendicular direction. This intuitively indicates that polymer structures were formed along both x- and y-directions.

In order to further analyze the polymer structure, we acquired SEM and AFM images of the separated substrate with polymer structures. The polymer walls formed in the direction perpendicular to the interdigitated electrodes on the substrate hid the polymer walls formed in the direction parallel to the interdigitated electrodes, which overall yields a 2D structure, as shown in Fig. 3(c). The overlap of the orthogonal polymer structures can be well described with the above principles, although we can observe regions partially damaged during the process of removal of LCs and separation of the substrates. In addition, alternating thick and thin polymer structures were observed, which emerged from the use of electrode structures.
where the widths of the interdigitated electrodes were approximately one half of the gap between them. The polymer structure at the center of the interdigitated electrodes was thicker than that at the middle of the gaps between them. This effect is closely related to the director configuration and the spatial elastic energy distribution, which is dependent on the width of the interdigitated electrodes and the gap between them. In our experiments, the width of the interdigitated electrodes was approximately half the length of the gap between them. The elastic energy density at the center of the interdigitated electrodes is higher than that at the middle of the gaps between them because the LC molecules near the boundaries at the center of the interdigitated electrodes are more deformed. This resulted in the formation of a polymer structure at the center of the interdigitated electrodes thicker than that at the middle of the gaps between them.

These periodic 2D polymer structures could also be confirmed by AFM, as shown in Fig. 3(d). The surface profile of the substrate showed periodic microgrooves in the direction parallel to the interdigitated electrodes as well as in the direction perpendicular to the interdigitated electrodes. The regions of high root-mean-square roughness values correspond to polymer structures formed in the direction perpendicular to the interdigitated electrodes, while the regions of low root-mean-square roughness values correspond to those formed in the direction parallel to the interdigitated electrodes. These SEM and AFM results verify that the polymer structure was suitably located at the center of the interdigitated electrodes and middle of the gaps between them by the phase separation owing to the spatial elastic energy difference. Moreover, the polymer structure had a 2D shape owing to the spatial elastic energy difference created by the top and bottom interdigitated electrodes orthogonal to each other.

![Image](https://example.com/image.png)

Fig. 3. (a) Separation of the two substrates of the cell after the LC removal. (b) POM, (c) SEM, and (d) AFM images of the separated substrate.

### 2.2 Operation of the 2D polymer-walled LC cell

A 2D polymer-walled LC cell may be very favorable for device applications to control the haze value owing to its capability of bistable switching between vertically and homogenously aligned states. As described above, the 2D polymer walls are formed along the direction of the interdigitated electrodes placed on each substrate of the cell, and are partially in contact in
the bulk region of the cell. The polymer walls in the cell impose in-plane anchoring between the LC and polymer structure whose direction is perpendicular to the interdigitated electrodes on each substrate as the polymer chains were aligned along the LC orientation during the polymerization. Therefore, orientation forces of LC molecules exist along the lateral direction due to the polymer walls as well as along the longitudinal direction due to the alignment layers on the two substrates.

When a vertical electric field is applied to a polymer-walled cell, LC molecules are vertically aligned; the vertical anchoring due to the alignment layer on each substrate enables the LC molecules to remain vertically aligned after the removal of the applied vertical electric field. On the other hand, when an in-plane electric field is applied to the cell, LCs with a positive dielectric anisotropy are reoriented along the direction of the applied electric field. The homogeneous alignment of LC molecules is maintained after the removal of the applied in-plane electric field by the interaction between the LC molecules and polymer surfaces. In other words, bistable switching between the vertically and homogeneously aligned states can be achieved through orientational forces existing in both longitudinal and lateral directions. In the vertically aligned state, the incident light is not diffracted as there is no spatial phase difference so that the cell is transparent. Although periodic interdigitated electrodes or polymer walls can also cause diffraction, their contribution is negligible compared to that of the diffraction caused by the index modulation induced by the deformation of the LCs. On the other hand, in the homogeneously aligned state, a large spatial phase difference is induced regardless of the azimuth angle, as shown in Fig. 4. The 2D polymer-walled cell has a large spatial phase difference along both x- and y-directions as the interdigitated electrodes are formed on both substrates, as shown in Fig. 4(a). Moreover, the spatial phase difference along the diagonal direction was twice that along the x- or y-direction, as shown in Fig. 4(b), as more LC molecules are reoriented along the direction of the applied electric field owing to the interdigitated electrodes formed on each substrate. Therefore, the LC cell can be switched to a good translucent state with a high haze owing to the strong diffraction effect.

![Diffraction image](image)

Fig. 4. Calculated LC director distributions and phase difference profiles of the output light at the applied voltage of 20 V along the (a) x- or y- and (b) diagonal (D) directions.
In order to verify the bistable switching ability of the 2D polymer-walled cell, we measured the diffraction efficiency for the zeroth order and analyzed POM images and diffraction patterns, as shown in Fig. 5. We used a linearly polarized He–Ne laser beam (wavelength $\lambda = 543.5$ nm) as a light source whose polarization direction was perpendicular to the interdigitated electrodes. We measured the far-field intensity of the zeroth order using a photodiode placed 22.5 cm away from the LC cell.

When a vertical electric field was applied, the efficiency of the zeroth order increased with the applied voltage, as shown in Fig. 5(a). Owing to the vertical electric field applied to the cell, the LC molecules aligned vertically so that the spatial phase difference was reduced, which increased the light intensity of the zeroth order. This was confirmed through the POM images and diffraction patterns, as shown in Fig. 5(b). In addition to the change in the light intensity of the zeroth order, diffraction patterns with different angles were observed when a vertical voltage was applied to the cell. This was attributed to the formation of thicker polymer structures at the centers of the interdigitated electrodes than those at the middles of the gaps between them. The LC molecules near the middles of the gaps between the interdigitated electrodes can be switched with a lower voltage, whereas the LC molecules near the centers of the interdigitated electrodes require a higher voltage for switching owing to the strong anchoring attributed to the thicker polymer structures. Therefore, when a lower voltage is applied to the cell, only the LC molecules near the middles of the gaps between the interdigitated electrodes start to switch so that the grating period is doubled, which yielded diffraction patterns with reduced angles, as shown in Fig. 5(b). When the applied voltage was increased to 10 V, the LC molecules in the entire region were vertically aligned so that the incident light was not transferred to the higher orders and thus the diffraction disappeared.

When the applied vertical voltage was removed, the vertically aligned LC molecules tended to remain vertically oriented by the vertical anchoring owing to the alignment layer on each substrate. However, a slight change in the LC orientation was observed when the applied vertical voltage was removed. When a relatively low voltage was applied to the cell and subsequently removed, some LC molecules were relaxed by the in-plane anchoring provided by the polymer structure, as shown in Fig. 5(c), which led to a decrease in the zeroth-order light intensity. With the increase in the applied voltage to 10 V, a small change in the efficiency of the zeroth order was observed after the applied voltage was removed. If a voltage wave whose duration is not sufficiently long is applied to the cell, the intensity of the zeroth order may decrease as a fraction of the LCs could not remain vertically oriented and thus relax. In our experiment, when the duration was longer than 0.1 s, a small change in the efficiency of the zeroth order was observed after the applied vertical voltage was removed. In order to eliminate the effect of the pulse duration of the applied electric field on the light diffraction efficiency, all of the measurements were performed at 5 s after the vertical voltage was applied or removed.
When an in-plane electric field is applied to a vertically aligned LC cell, a spatial phase difference is induced regardless of the azimuth angle so that the incident light is strongly diffracted, leading to a decrease in the zeroth-order light intensity, as shown in Fig. 6(a). The diffraction patterns show that the diffraction energy is well transferred from the zeroth order to the higher orders, as shown in Fig. 6(b). The same vertical electric field was applied before an in-plane electric field was applied for switching to the diffracted state.

When the applied in-plane voltage is removed, the LC molecules tend to remain homogeneously aligned owing to the in-plane anchoring by the polymer walls. The interaction between the LC molecules and polymer surfaces largely depended on the electric-field-induced deformation of the LCs. When a relatively low voltage was applied, an increase in efficiency of the zeroth order was observed after the in-plane voltage was removed, as shown in Fig. 6(c). This implies that the in-plane anchoring by the polymer walls was not sufficient for LC molecules to maintain the state and thus some LC molecules were relaxed. This can be confirmed through the POM images and diffraction patterns in Figs. 6(a)–6(c). When the applied voltage increased to 6 V, the LC molecules were not relaxed so that a small change in the efficiency of the zeroth order was observed after the applied voltage was removed.

In this regard, it is required to apply an in-plane voltage to the cell for a sufficiently long time to prevent the change in the optical characteristics of the cell after the applied voltage is removed. This may originate from the nonuniform in-plane electric field in both longitudinal direction between the two substrates and lateral direction between the interdigitated electrodes. In our experiment, a relatively long duration (> 0.5 s) was required to prevent the change in the efficiency of the zeroth order after the applied in-plane voltage was removed.
2.3 Low-power control of the haze value

As described in the above paragraph, the bistable switching of the 2D polymer-walled cell could be achieved by applying vertical and in-plane electric fields. The diffraction efficiency was well maintained at a higher applied voltage, although a change in the diffraction efficiency was observed at a lower applied voltage after its removal due to the relaxation of some LC molecules.

In order to evaluate the optical performance of the 2D polymer-walled cell with the bistable switching capability, we measured the specular transmittance and haze using a haze meter (HW-65W, Murakami Color Research Laboratory, Tokyo, Japan), as shown in Figs. 7 and 8. When an in-plane voltage of 10 V was applied to the 2D polymer-walled cell, a spatial phase difference was induced regardless of the azimuth angle, owing to the electric-field-induced periodic LC profile, so that the cell was in a good translucent state owing to the strong diffraction effect. After the applied in-plane voltage was removed, the state was well maintained by the orientation force owing to the interfacial interaction between the LC and polymer. The specular transmittance and haze of the cell in the translucent state were 6.5% and 91.4%, as shown in Figs. 7(a) and 7(b), respectively. Owing to the high haze in the translucent state, the 2D polymer-walled cell could completely hide a printed paper behind it, as shown in Fig. 7(c).

For switching of the cell from the translucent to the transparent state, a vertical electric field was applied between the top and bottom common electrodes. With the increase in the applied vertical voltage, LC molecules were reoriented perpendicular to the two substrates so that the specular transmittance increased and the haze decreased, as shown in Figs. 7(a) and 7(b), respectively. This can also be visualized in Fig. 7(c). With the increase in the applied vertical voltage, the printed images under the cell were identified more clearly owing to the higher transmittance and lower haze. When the applied vertical voltage of 10 V was removed, the transparent state was well maintained although slight changes in the specular transmittance and haze were observed at a lower applied voltage. After the applied voltage of 10 V was removed, the specular transmittance and haze of the cell in the transparent state were 75.1% and 1.9%, respectively, which were almost equal to those when a vertical voltage was applied. Consequently, in the transparent state of the 2D polymer-walled cell, the background image could be clearly identified, as shown in Fig. 7(c).
In order to evaluate the optical performance of the 2D polymer-walled cell, we measured the specular transmittance and haze as a function of the applied in-plane voltage and compared them with those of a pure LC cell, as shown in Figs. 8(a) and 8(b), respectively. When the applied in-plane voltage was increased, a larger spatial phase difference was induced so that the specular transmittance and haze of the pure LC cell decreased and increased, respectively. At 9 V, the specular transmittance and haze of the pure LC cell in the translucent state were 4.5% and 94.1%, whereas those in the transparent state were 76.6% and 0.9%, respectively.

In the transparent state, the specular transmittance [haze] of the 2D polymer-walled cell was slightly lower [higher] than that of the pure LC cell. This was attributed to the refractive index mismatch between the LC and polymer matrices due to the polymer structure. The specular transmittance and haze of the 2D polymer-walled cell in the transparent state were 75.1% and 1.9%, respectively. When an in-plane electric field was applied to the 2D polymer-walled cell, the voltage-dependent specular transmittance and haze curves started to change at an even lower voltage than that of the pure LC cell and saturated at 6.5 V, as shown in Figs. 8(a) and 8(b), respectively. The operating voltage of the 2D polymer-walled cell was 27.8% lower than that of the pure LC cell. The reduction in the operating voltage originates from the in-plane anchoring by the polymer structure. The 2D polymer-walled cell could be switched at a lower applied voltage as the polymer walls force the LC molecules to be tilted down. A small change in optical performance was observed when the applied in-plane voltage of 6.5 V was removed, as shown in Figs. 8(a) and 8(b). In the translucent state of the 2D polymer-walled cell under an in-plane electric field, the specular transmittance and haze were 5.9% and 92.2%, whereas those after the applied field was removed were 6.5% and 91.4%, respectively. The 2D polymer-walled cell exhibited a sufficiently high haze in the translucent state even after the applied in-plane voltage was removed, though it was 2.8% lower than that of the pure LC cell. Therefore, in the translucent state, the 2D polymer-walled cell can hide the background view by the strong diffraction effect due to the large spatial phase difference regardless of the azimuth angle, whereas a clear background image could be observed in the transparent state, as shown in Fig. 8(c). The 2D polymer-walled cell can be operated with a
very low power as the voltage required for switching between the two states is very low and power is not required to maintain the state. Switching characteristics of the 2D polymer-walled cell are summarized in Fig. 9. Switching between the transparent and translucent states of the 2D polymer-walled cell could be achieved by applying an in-plane voltage of 6.5 V and a vertical voltage of 10 V. The transparent state could be switched to the translucent state by applying an in-plane voltage whereas the translucent state could be switched to the transparent state by applying a vertical voltage. Either state was well maintained after the applied voltage was removed although there was a slight change in the specular transmittance when the applied voltage was removed. Moreover, each state of the 2D polymer-walled cell was well maintained even after several tens of days.

![Graphs showing specular transmittance and haze values](image1)

**Fig. 8.** Measured (a) specular transmittance and (b) haze values of the fabricated pure LC and 2D polymer-walled cells, switched from the transparent to the translucent state. (c) Photographs of the pure LC and 2D polymer-walled cells placed on a printed paper, in the transparent and translucent states.

![Graph showing switching characteristics](image2)

**Fig. 9.** Switching characteristics of the 2D polymer-walled LC cell.
In order to confirm the switching time of the fabricated LC cells, we investigated their dynamic switching behaviors, as shown in Fig. 10. We defined turn-on [turn-off] time as the transient time from 90% [10%] to 10% [90%] of the specular transmittance. In order to measure the response time of the pure LC cell, a voltage of 9 V was applied to the cell for turn-on and then removed after several seconds. The measured turn-on and turn-off times were 2.57 and 4.79 ms, respectively. In the pure LC cell, LC molecules are confined by not only the two substrates but also virtual walls. The distance between these virtual walls is approximately one quarter of the pitch of the interdigitated electrodes [23]. Therefore, the pure LC cell had a short response time despite the large cell gap of 20 μm, which is attributed to the 2D confinement effect.

In contrast to the pure LC cell, the turn-on and turn-off switchings of the 2D polymer-walled cell require in-plane and vertical electric fields, respectively. We applied a vertical voltage of 10 V to the cell for turn-off switching and in-plane voltage of 9 V for turn-on switching. The measured turn-on and turn-off times were 1.64 and 0.56 ms, respectively. The total response time of the 2D polymer-walled cell is approximately 70% shorter than that of the pure LC cell. The 2D polymer-walled cell exhibited a faster turn-on switching even at a lower applied voltage owing to the in-plane anchoring by the polymer walls. Moreover, the turn-off switching of the 2D polymer-walled cell did not rely on the slow relaxation of the LCs but was controlled by applying an electric field, which yielded the very short turn-off time.

Finally, we compared the optical performance of the 2D polymer-walled cell with those of other bistable LC devices, which can be used to control the haze value, as summarized in Table 1. Ion-doped and polymer-stabilized ChLC devices based on light scattering exhibited relatively low haze values in their translucent states, and required very high voltages for switching between the transparent and translucent states. In addition, the turn-on and turn-off times were not sufficiently small for display applications. In these light-scattering devices, for a higher haze in the translucent state and faster switching, we can increase the polymer concentration, but the haze in the transparent state would also increase and the voltage for switching between the transparent and translucent states would further increase.

In contrast, a bistable SmA-LC device based on light diffraction exhibited a very high haze in the translucent state while maintaining a haze-free transparent state. Nevertheless, it required a high voltage for switching between the transparent and translucent states and had a long response time owing to the very high rotational viscosity of the SmA LC. The very
narrow temperature range of the SmA LC may also be a common concern for practical applications.

On the other hand, the 2D polymer-walled cell is robust against such problems owing to the use of the nematic LC, which has already been commercialized in display applications. The 2D polymer-walled cell based on light diffraction exhibited excellent optical performances in both transparent and translucent states. Moreover, for the 2D polymer-walled cell, the voltage required for switching between the transparent and translucent states was significantly lower and the response time was significantly shorter than those of other bistable LC technologies.

| Table 1. Electrooptical characteristics of bistable LC devices.          |
|-------------------------------------------------------------|----------------|----------------|----------------|
| Light scattering                                            | Light diffraction |
| Ion-doped ChLC [19]                                        | Polymer-stabilized ChLC [16] | SmA-LC [24] | 2D polymer-walled LC |
| TP state                                                   | T_{s} (%)       | 71.4           | 59.0           | 76.7          | 75.1         |
| Haze (%)                                                   | 4.4             | 25             | <1             | 1.9           |
| TL state                                                   | T_{s} (%)       | 12.8           | 14.2           | 6.1           | 65           |
| Haze (%)                                                   | 79.8            | 70.8           | 92.2           | 91.4          |
| Switching voltage TP → TL (V)                              | 90              | 120            | 45             | 65           |
| Switching time TP → TL (ms)                                | 114.9           | 6.4            | 56.1           | 1.6          |
| Switching time TL → TP (ms)                                | 15.0            | 3.9            | 11.9           | 0.6          |

Notes: TP: Transparent, TL: Translucent, and T_{s}: Specular transmittance.

3. Conclusion

We demonstrated a 2D polymer-walled LC device, which could be operated under a very low power as it could maintain the transparent or translucent state after the applied vertical or in-plane voltage was removed. The 2D polymer walls were formed in the LC cell through UV irradiation while applying an in-plane electric field owing to the phase separation induced by the spatial elastic energy difference.

The transparent [translucent] state could be maintained after the applied vertical [in-plane] field was removed. The proposed device exhibited outstanding characteristics, such as a very low operating voltage (< 10 V), low haze (< 2%) in the transparent state, high haze (> 90%) in the translucent state, and short switching time (< 2 ms), compared to those of other bistable LC devices, which can be used to control the haze value. We believe that this device is promising for power-saving smart window or window display applications.

4. Methods

4.1 Materials

All of the chemicals were purchased from commercial suppliers and used without further purification. In the preparation of the LC/RM mixture, we used Merck E7 as the host LC, with a dielectric anisotropy of \( \Delta \varepsilon = 13.8 \) (\( \varepsilon_{\parallel} = 19 \), \( \varepsilon_{\perp} = 5.2 \)), optical anisotropy of \( \Delta n = 0.2253 \) (\( n_e = 1.746 \), \( n_o = 1.522 \) at 589 nm, 20 °C), elastic constants of \( K_{11} = 11.1 \) pN, \( K_{22} = 10.3 \) pN, \( K_{33} = 17.1 \) pN, and rotational viscosity of \( \gamma_1 = 250 \) mPa·s. A UV-curable monomer RM257...
containing a small amount of the photoinitiator Irgacure 651 was used in our experiment. RM257 has a rod-like structure and can be easily aligned with LCs. The LC/RM mixture was composed of 98.0% host LC and 2.0% UV-curable monomer. The LC/RM mixture was stirred for 24 h, followed by an ultrasonic-wave treatment for 2 h.

4.2 Fabrication of the 2D polymer-walled LC cell

On each glass substrate, transparent interdigitated pixel electrodes and flat common electrodes were formed with an insulating layer (oxide) sandwiched between them. The widths and gaps of the interdigitated electrodes were 2.8 and 6 μm, respectively. The thickness of the insulating layer was approximately 150 nm. A thin polyimide layer was then spin-coated onto the inner surface of each substrate and baked at 230 °C for 1 h. Subsequently, silica spacers with a diameter of 20 μm were employed to maintain the cell gap uniformity. The interdigitated electrodes were formed on both substrates, positioned at right angles to each other. Finally, the prepared LC/RM mixture was injected into the cell through capillary action. Under the applied electric field, the LC cell was exposed to the spatially uniform UV light radiation (wavelength $\lambda = 315$-400 nm) with a small intensity of 2 mW/cm$^2$ to polymerize the RM. The polymer walls were formed through curing of the RM under an applied electric field based on the phase separation due to the spatial elastic energy difference.

4.3 Methods and measurements

In order to confirm the spatial elastic energy distributions and phase profiles of the output light of the LC cell, numerical calculations were performed using the commercial software package TechWiz LCD 2D (Sanayi System Co., Ltd, Korea). For the numerical estimation of the LC director distributions, the Ericksen–Leslie equation coupled with the Laplace equation was solved using the finite-element method. The optical analysis was performed using the extended 2 × 2 Jones matrix method.

In order to observe the polymer structure, nonreactive LCs were removed with an organic solvent (cyclohexanone), while the polymer structure remained in the cell. We then carefully separated the two substrates of the cell after the LC removal. Optical texture observations on each separated substrate were carried out using a POM (Nikon L-UEPI, Japan) with a digital camera (Toshiba IK-637K, Japan), SEM (Model Supra 40 VP, Zeiss, Germany), and AFM (Model Nanosurf Easyscan 2, Nanosurf Inc., USA).

In order to confirm the diffraction characteristics of the fabricated cell, we measured the diffraction efficiency for the zeroth order while increasing the applied voltage. A linearly polarized He–Ne laser beam (wavelength $\lambda = 543.5$ nm) was used as the probe beam. The intensity of the zeroth order in the far-field was detected by a photodiode (Model 818-BB-21, Newport, USA) placed at a distance of 22.5 cm. During the optical measurement, the LC cell was driven by a square-wave voltage at a frequency of 1 kHz. The applied voltage was controlled by a LabVIEW (National Instruments) system.

In order to measure the optical performances of the fabricated cells, we used a haze meter (HW-65W, Murakami Color Research Laboratory, Tokyo, Japan). Specular [diffuse] transmittance $T_s$ [$T_d$] is the ratio of the intensity of the light that emerges from the LC cell, which is parallel (within a small angle range of 2.5°) [not parallel] with the light entering the cell, to that of the light entering the LC cell. The total transmittance $T_t$ is the sum of the specular transmittance $T_s$ and diffuse transmittance $T_d$. The haze $H$ can be calculated as the ratio $H = T_d/T_t$.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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