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Liquid crystal cell asymmetrically anchored for high transmittance and triggered with a vertical field for fast switching

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Abstract: The optical performance of an asymmetrically surface-anchored liquid crystal (LC) cell driven with three-terminal electrodes is demonstrated. The transmittance of an asymmetrically anchored cell is considerably higher than that of a symmetrically anchored cell. However, the slow response of an asymmetrically anchored cell makes its practical application difficult. In this work, we demonstrate that the slowest GTG response time from a high to low grey level in an asymmetrically anchored cell can be reduced to less than 0.7 ms by applying a vertical trigger pulse with three-terminal electrodes while maintaining the high transmittance of an asymmetrically anchored cell.

1. Introduction

A liquid crystal display (LCD) has been one of the most influential flat-panel displays for decades, and it has been most widely used for TVs, monitors, and smartphones [1–4]. LCD performance has been improved rapidly with better viewing angle, response time, and transmittance. Virtual reality (VR) and augmented reality (AR) devices have recently emerged as key research targets in the display industry and require display panels that could provide much higher resolution and contrast ratio and faster response time than those provided by the current LCD [5–9]. Although the resolution offered by an LCD is higher than that offered by its competitors, improvements are needed in terms of power efficiency and response time [8,10–11].

The fringe-field switching (FFS) mode has been one of the LC modes most widely used for displays owing to the wide viewing angle and small color shift [4,12]. Various studies have aimed to improve the performance of an FFS cell. For applications to VR and AR, the response time of an LC cell must be reduced further. The turn-on time of an FFS cell can be reduced by employing overdriving technology [13,14]. However, reducing the turn-off time is not easy because it relies on slow relaxation, which depends mainly on the physical parameters of LCs. Although various technologies may reduce the turn-off time, they may also decrease the transmittance [15–19].

The FFS mode was developed to increase the transmittance of an in-plane switching (IPS) cell. The LC molecules above electrodes in an FFS cell can be rotated so that the transmittance of the cell is higher than that of an IPS cell. Recently, it was demonstrated that the transmittance of an IPS cell could be increased dramatically by employing asymmetrical surface anchoring. [20,21]. The transmittance of the LC cell can be greatly increased because the very weak anchoring energy at one of the two substrates allows LC molecules in an asymmetrically anchored cell can be rotated more easily between the electrodes. However, a challenge in employing asymmetrical surface anchoring is the long turn-off time when compared with symmetrical surface anchoring.

In this paper, we demonstrate the achievement of a fast response and high transmittance simultaneously by driving an asymmetrically surface-anchored LC cell with three-terminal electrodes. Two different alignment materials were used for different anchoring energies on the substrates. The strong anchoring energy at only one substrate keeps the orientation of the LC

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molecules uniform. When a fringe-field is applied, the LC molecules between the electrodes can be easily rotated thanks to weak anchoring energy. Therefore, the LC cell exhibits a high transmittance. However, the slow turn-off switching of an asymmetrically anchored cell makes its practical application difficult.

To reduce the turn-off switching time of an asymmetrically anchored cell without decreasing the transmittance, we employ three-terminal electrodes with which we apply a vertical trigger pulse to an LC cell just before switching [22,23]. We confirmed that the fabricated asymmetrically anchored cell driven with the three-terminal electrodes could provide both high transmittance and fast response at the same time. We expect that the LC cell can be used for applications requiring very high performance, such as VR/AR devices.

2. Operation principle

To achieve fast response time and high transmittance simultaneously, we employ an asymmetrically surface-anchored LC cell driven with three-terminal electrodes, as shown in Fig. 1. A strong-anchoring alignment layer is coated on the top substrate, and a weak-anchoring alignment layer is coated on the bottom substrate to create asymmetric anchoring energies on the two substrates. In previous studies, asymmetrical surface anchoring was employed in an IPS cell. However, when a vertical trigger pulse is applied to an IPS cell, the vertical electric field between interdigitated electrodes and the top electrodes is not uniform, as shown in Fig. 2(a), which may lead to a smaller decrease in the turn-off time and higher light leakage during the turn-off process. To apply a uniform vertical electric field between the two substrates, we employed the FFS interdigitated electrodes shown in Fig. 2(b).

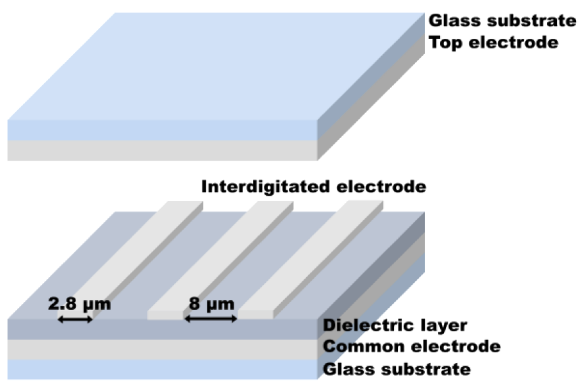

Fig. 1. Schematic of a three-terminal electrode structure.

The operation principle of an asymmetrically surface-anchored LC cell driven with three-terminal electrodes is presented in Fig. 3. In this study, we employed the drive scheme reported in [22,23] to achieve a fast response time. LC molecules are initially aligned homogeneously with typical rubbing angles of 5–20° with respect to the interdigitated electrodes to obtain a high transmittance. The transmission axis of the bottom polarizer coincides with the rubbing direction of the bottom substrate, and the transmission axis of the top polarizer is perpendicular to that of the bottom polarizer.

When a fringe-field is applied to the LC cell, LC molecules are rotated along the direction of the applied fringe field to switch the LC cell from the dark to the bright state. In a symmetrically anchored cell with strong and identical anchoring energies at both substrates, the LC molecules near each substrate are hardly rotated. In contrast, in an asymmetrically anchored cell, the LC molecules near the bottom substrate are easily rotated because of the low anchoring energy at the bottom substrate.

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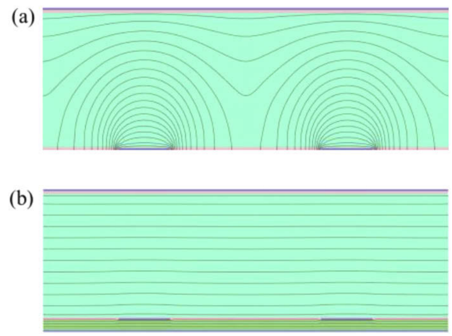

Fig. 2. Calculated equipotential lines in three-terminal-electrode (a) IPS and (b) FFS cells when a vertical electric field (8 V, 1 kHz) was applied.

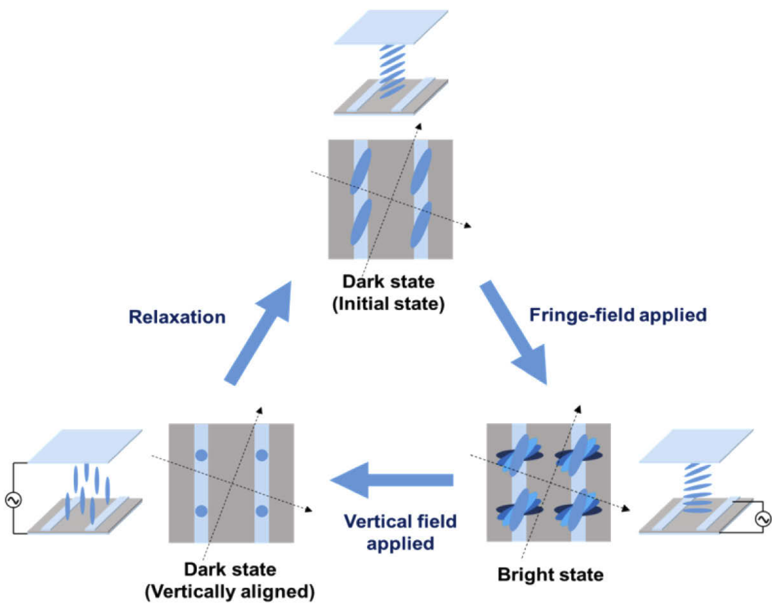

Fig. 3. The operation principle of an asymmetrically anchored LC cell driven with three-terminal electrodes.

For the turn-off switching, the applied fringe field is removed. However, the switching process does not rely on the slow relaxation of the LC molecules. Instead, the application of a vertical trigger pulse orients the LC molecules vertically to reduce the turn-off time dramatically, because LCs are switched not by only the elastic torque but also by the applied vertical electric field. When the vertical electric field is removed, the LC molecules relax to their initial homogeneous alignment state so that they are oriented parallel to one of the absorption axes of the polarizers. Thus, the LC cell returns to the initial dark state.

To evaluate the effect of the surface anchoring energy on the electro-optical characteristics in an asymmetrically anchored cell, the Ericksen-Leslie equation coupled with the Laplace equation was solved numerically using the finite element method. The Ericksen-Leslie equation has been used to describe the motion of the LC director. Numerical calculations were performed using the TechWiz LCD 2D commercial software package (Sanayi System Company, Ltd., Incheon, Korea).

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As shown in Fig. 4(a), the transmittance of an LC cell increases with the decrease of the azimuthal anchoring energy at the bottom substrate. The calculated transmittance of a symmetrically anchored cell, in which the azimuthal anchoring energy at the bottom substrate was 3×10^{-4} J/m^2, was 22.2% at an applied voltage of 4.8 V. The calculated transmittance of an asymmetrically anchored cell, with azimuthal anchoring energy at the bottom substrate of 10^{-6} J/m^2 was 28.3% at 4.5 V, 27.5% higher than a symmetrically anchored cell. The lower the surface anchoring energy at the interdigitated electrode surface, the higher the transmittance and the lower the operating voltage. However, the polar anchoring energy, which is higher than 4×10^{-6} J/m^2, shows no significant effect on the transmittance of an LC cell, as shown in Fig. 4(b).

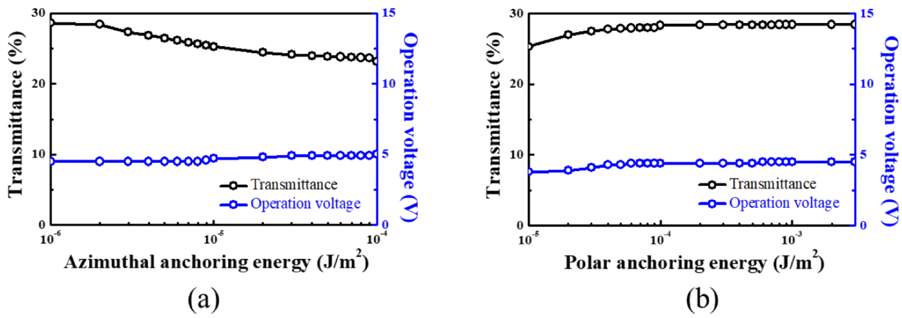

Fig. 4. Calculated transmittances as functions of the (a) azimuthal and (b) polar anchoring energies.

We calculated the dynamic switching behavior of asymmetrically and symmetrically anchored LC cells driven with three-terminal electrodes. The turn-on and turn-off times of a symmetrically anchored cell at an applied voltage of 4.8 V were 7.68 ms and 0.54 ms, respectively. The response times of an asymmetrically anchored cell whose bottom-substrate anchoring energy was 10^{-6} J/m^2 were similar to those of a symmetrically anchored cell; the turn-on time of 7.68 ms and a turn-off time of 0.56 ms at the applied voltage of 4.5 V, as shown in Fig. 5. These results indicate that the LC cell can still maintain a fast response even if a low anchoring energy material is used to increase the transmittance.

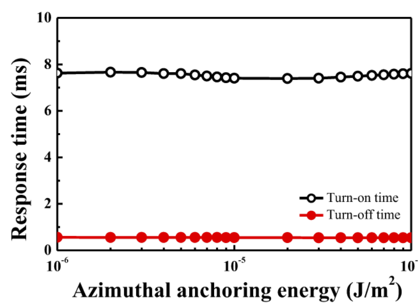

Fig. 5. Calculated response time as functions of the azimuthal anchoring energy.

3. Cell fabrication

To conduct asymmetric surface anchoring in an LC cell, we chose poly (methyl methacrylate) (PMMA, Sigma-Aldrich, USA) as an alignment layer for weak surface anchoring at the bottom substrate. The substrate was subjected to several cleaning processes. Spin coating and solvent-induced phase separation were used to coat PMMA on the substrate. We dissolved 1.5 wt% of

PMMA in toluene and spin-coated the solution at 5000 rpm for 30 s. The coated substrate was annealed at 120 °C for 1 h. The thickness of the PMMA layer was 40 nm.

For the three-terminal electrodes, we used an ITO-coated glass as the top substrate. The ITO glass substrate was cleaned through several processes and coated with commercial polyimide alignment material by spin coating at 3000 rpm for 60 s. The measured azimuthal and polar anchoring energy of the polyimide alignment material is 3.3×10^{-4} J/m^2 and 2.0×10^{-3} J/m^2, respectively. The coated ITO glass substrate was pre-baked on a hot plate at 1 h. Both substrates were rubbed with cotton after the baking process.

The rubbing angle was 10° with respect to the interdigitated electrodes. Next, the cell was assembled using silica spacers with a diameter of 4.2 µm. The positive LC mixture was injected into the empty cell by capillary action at room temperature. The specific physical parameters of the LC mixture are as follows; optical anisotropy $\Delta n = n_e - n_o = 0.1169$ ($n_e = 1.605$ and $n_o = 1.488$ at 589.3 nm and 20 °C) and dielectric anisotropy $\Delta\varepsilon = 7$ ($\varepsilon_\perp = 10.2$ and $\varepsilon_\parallel = 3.2$).

A symmetrically anchored cell with three-terminal electrodes was fabricated as a reference cell to compare its electro-optical characteristics with those of an asymmetrically anchored cell. For a symmetrically anchored cell, we coated the same polyimide alignment material used for strong anchoring in an asymmetrically anchored cell on each substrate. The symmetrically anchored cell was assembled using silica spacers with a diameter of 3.7 µm. The LC, the same as that used in an asymmetrically anchored cell, was injected into an empty cell by capillary action at room temperature.

4. Experimental results

We measured the transmittance–voltage curves of the fabricated cells with a xenon lamp, which emits wavelengths ranging from 185 nm to 2000 nm (MC-961C, Otsuka Electronics Co., Ltd), as shown in Fig. 6. The measured results summarized in Table 1 show a good agreement with the calculated results. At maximum transmittance, an asymmetrically surface-anchored cell exhibited 1.3 times higher transmittance and slightly lower operation voltage than a symmetrically surface-anchored cell. To compare viewing angle characteristics, as shown in Fig. 7, we measured viewing angle characteristics of an asymmetrically anchored LC cell was similar to that of a symmetrically anchored LC cell.

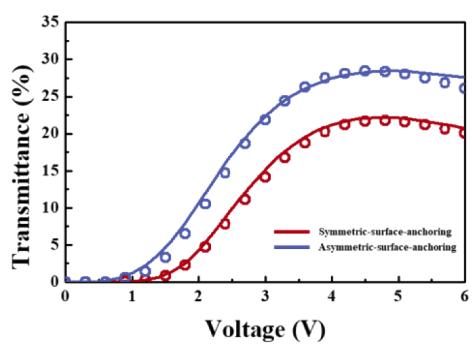

Fig. 6. Measured and numerically calculated voltage-transmittance curves of symmetrically and asymmetrically anchored cells (circles: measured, lines: calculated).

To investigate the cause of the transmittance difference between symmetrically and asymmetrically anchored cells, we observed polarized optical microscopy (POM) images of the fabricated LC cells and calculated the transmittance distributions. Figures 8(a) and 8(b) show periodically alternating bright and dark regions in the POM images of the two LC cells in the bright state. The dark regions are brighter in an asymmetrically anchored cell than in a symmetrically

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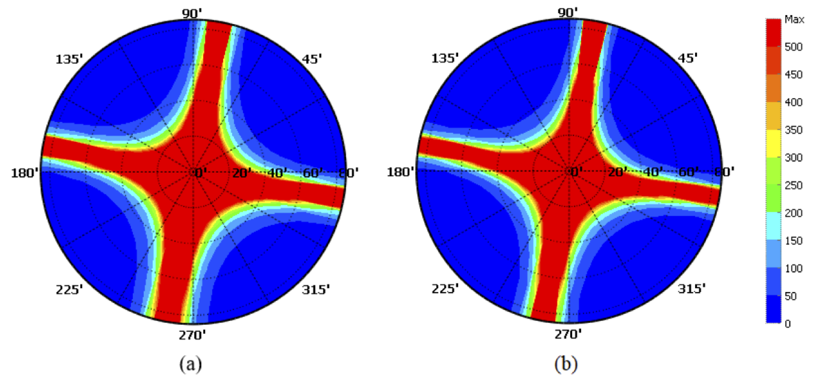

Fig. 7. Measured iso-contrast contours of (a) asymmetrically and (b) symmetrically anchored LC cells. The transmission axis of polarizer and analyzer are 10° and 100°, respectively. The applied voltage of asymmetrically and symmetrically anchored LC cell are 4.5 V and 4.8 V, respectively.

Table 1. Measured and numerically calculated transmittance and operating voltage of symmetrically and asymmetrically anchored cells.

	Transmittance (%)		Operation voltage (V)
	Dark state	Bright state	
Symmetrically anchored cell	0.03 (0.01)	22.2 (21.8)	4.8 (4.8)
Asymmetrically anchored cell	0.04 (0.01)	28.4 (28.3)	4.5 (4.5)

anchored cell. Figures 8(c) and 8(d) present the transmittance distributions of asymmetrically and symmetrically anchored cells in the bright state, respectively. An asymmetrically anchored cell exhibits not only a much higher transmittance over the entire cell area but also a more even transmittance distribution than a symmetrically anchored cell. Therefore, the transmittance of an asymmetrically anchored cell is much higher than that of a symmetrically anchored cell.

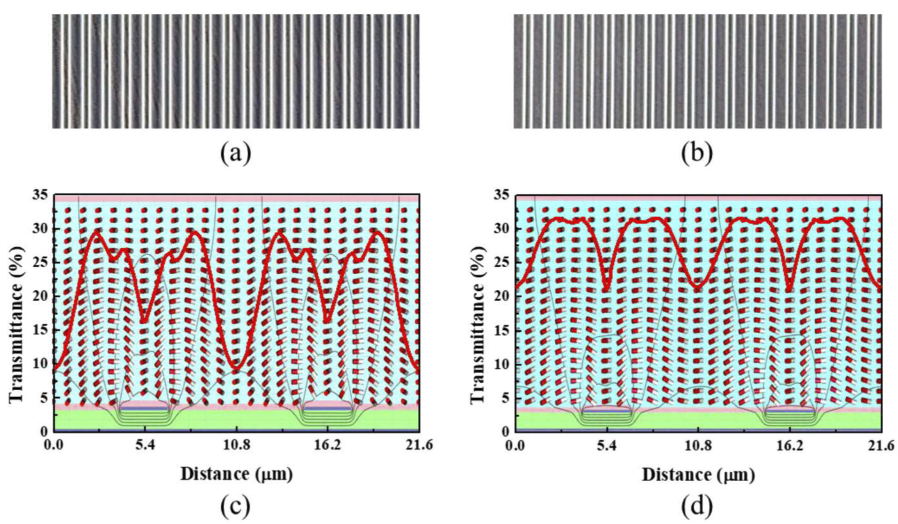

Fig. 8. Polarized optical microscopy images of (a) symmetrically and (b) asymmetrically anchored cells. Transmittance and LC director of (c) symmetrically and (d) asymmetrically surface-anchored cells.

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Not only the electro-optical characteristics but also the twist deformation of an asymmetrically anchored cell is different from that of a symmetrically anchored cell when a voltage is applied to the cell. To clarify the effect of the surface anchoring energy on the twist deformation of the LC molecules in each cell, we numerically calculated the LC director distribution. The calculation was performed at the electrode edge A and the center of between-electrodes B, because the electric field intensity there is the strongest and the weakest, respectively, as shown in Fig. 9(a). The azimuth and polar angles of the LC molecules calculated at A and B are shown in Figs. 9(b) and 9(c), respectively. At the electrode edge, the in-plane component of the applied electric field is very high so that the LC molecules are rotated primarily by the electric field. In this area, the LC molecules of an asymmetrically anchored cell are rotated up to 66°, but those of a symmetrically anchored cell are rotated to only 52.39° because of strong surface anchoring energy at the bottom substrate. At the center of between-electrodes, there is a small in-plane component of the electric field so that the LC molecules are rotated dominantly along the direction of the surrounding LC molecules. In this area, the LC molecules of an asymmetrically anchored cell are rotated up to 41.41°, but those of a symmetrically anchored cell up to 19.82° because of the strong surface anchoring energy at the bottom substrate. In all regions, the closer they are to the bottom substrate in an asymmetrically anchored cell, the more the LC molecules are rotated. However, in a symmetrically anchored cell, the LC molecules are rotated mostly in the bulk region, whereas those near each substrate are rarely rotated. In addition, the azimuthal angle of the LC molecules in an asymmetrically anchored cell is not significantly different from that of a symmetrical-anchored cell. Because the twist deformation in an asymmetrically anchored cell is different from that in a symmetrically anchored LC cell, the rotation angle alone does not explain the difference in transmittance. Further research is needed on the effects of the rotation angle and LC director distribution on the transmittance of LC cells.

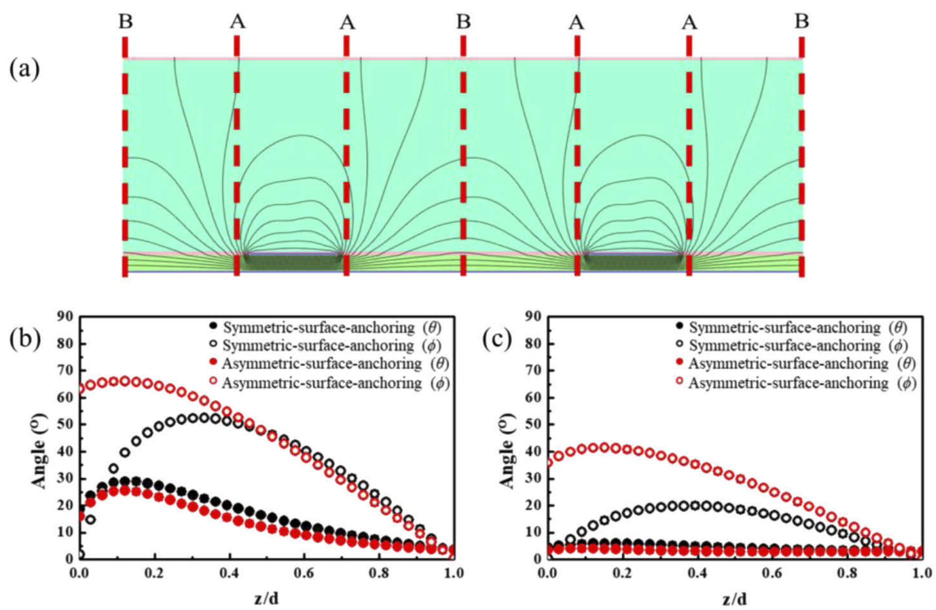

Fig. 9. (a) Equipotential lines in a three-terminal-electrode cell; Distributions of calculated azimuthal and polar angles (b) at the electrode edge and (c) at the center of between-electrodes.

We investigated the dynamic switching behavior of the fabricated LC cells. We defined the turn-on time as the transient time from 10% to 90% of the maximum transmittance (and vice versa for the turn-off time). The measured turn-on and turn-off switching behavior of each LC

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cell are shown in Figs. 10(a) and 10(b), respectively. The measured response time of each LC cell under the maximum transmittance condition is summarized in Table 2. The turn-on time of an asymmetrically anchored cell was slightly shorter than a symmetrically anchored cell, regardless of whether the vertical pulse is applied. The floating voltage built by the vertical trigger pulse may distort the electric field applied for turn-on or grey-to-grey switching, which can lower the transmittance of the LC cell. To avoid any distortion of the electric field distribution, we discharged the top electrode just before we apply a fringe field to the cell. We measured the turn-off time of the fabricated cells with and without a vertical trigger pulse. When a vertical trigger pulse was not applied, the turn-off switching of an asymmetrically anchored cell was much slower than that of a symmetrically anchored cell. In this case, the turn-off switching depends on the elastic torque, which is highly affected by the surface anchoring energy of the bottom substrate. When a vertical trigger pulse was applied, the turn-off times of both cells exhibited submillisecond switching. The amplitude of the applied vertical pulse applied to trigger the turn-off switching was 8 V. In this case, the turn-off switching depends on the electric field intensity, which is rarely affected by the surface anchoring energy of the bottom substrate. The turn-off time of each LC cell was considerably reduced, and there was no significant difference between the two, even with a very weak surface anchoring energy.

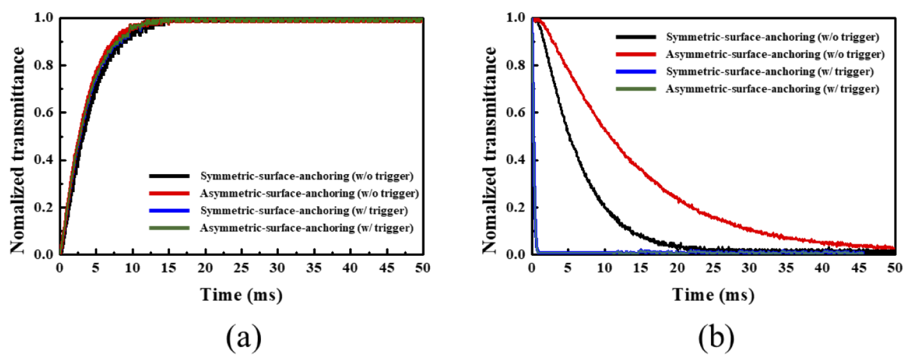

Fig. 10. Measured (a) turn-on and (b) turn-off switching behavior of symmetrically and asymmetrically anchored cells. The voltages applied to symmetrically and asymmetrically anchored LC cells were 4.8 V and 4.5 V, respectively.

Table 2. Measured response time of symmetrically and asymmetrically anchored cells.

	Response time (ms)			
	Turn-on time		Turn-off time	
	Without vertical trigger pulse	With vertical trigger pulse	Without vertical trigger pulse	With vertical trigger pulse
Symmetrically anchored cell	8.71	8.78	7.55	0.39
Asymmetrically anchored cell	7.85	7.85	28.46	0.64

We also measured the grey-to-grey (GTG) response time of the fabricated LC cells. Figure 11 shows the measured GTG response times of symmetrically and asymmetrically anchored LC cells with and without a vertical trigger pulse. As for switching from a high to low grey level, the slowest GTG response time of an asymmetrically anchored LC cell driven with a vertical trigger pulse was 0.69 ms. It is much faster than asymmetrically and symmetrically anchored LC cells without a vertical trigger pulse whose slowest GTG response times from a high to a low grey level were 37.41 ms and 11.97 ms, respectively. It is also faster than a symmetrically anchored

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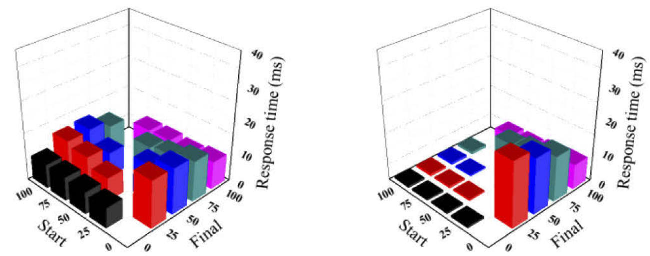
cell driven with a vertical trigger pulse whose slowest GTG response times from a high to low grey level was 4.40 ms. As for switching from a low to high grey level, the GTG response time was rarely affected by a trigger pulse in asymmetrically as well as symmetrically anchored LC cells. However, it is well known that the GTG response time from a low to high grey level can be reduced easily by employing the overdrive technique [13] instead of the three-terminal driving.

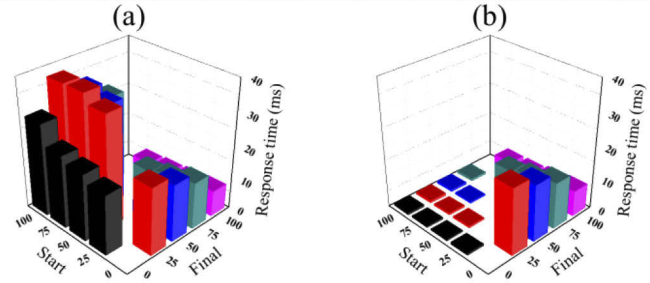


%		Final level				
		0	25	50	75	100
Start level	0		14.89	14.57	12.75	8.71
	25	6.34		11.15	10.62	7.88
	50	6.88	7.29		9.66	8.42
	75	7.43	10.10	7.71		8.22
	100	7.55	11.48	11.97	9.56	

(a)

%		Final level				
		0	25	50	75	100
Start level	0		14.92	14.57	12.84	8.78
	25	0.56		11.15	10.62	8.48
	50	0.70	3.21		9.66	8.72
	75	0.53	3.23	3.22		8.22
	100	0.39	3.24	4.40	0.41	

(b)



%		Final level				
		0	25	50	75	100
Start level	0		20.61	17.55	14.27	7.85
	25	18.29		12.10	11.89	7.21
	50	20.63	34.59		10.53	6.74
	75	22.46	37.41	31.20		6.27
	100	28.46	37.23	32.76	27.69	

(c)

%		Final level				
		0	25	50	75	100
Start level	0		20.56	17.62	14.26	7.85
	25	0.57		12.12	11.87	7.21
	50	0.51	0.50		10.55	6.42
	75	0.52	0.48	0.47		6.35
	100	0.64	0.68	0.70	0.69	

(d)

Fig. 11. Measured GTG response time of (a) a symmetrically anchored cell without a vertical trigger pulse, (b) symmetrically anchored cell driven with a vertical trigger pulse, (c) asymmetrically anchored cell without a vertical trigger pulse, and (d) asymmetrically anchored cell driven with a vertical trigger pulse.

5. Conclusion

We introduced an asymmetrically surface-anchored LC cell driven with three-terminal electrodes. Thanks to a weak surface anchoring energy at the bottom substrate, the transmittance of the fabricated LC cell can be 1.3 times higher than a symmetrically anchored cell. We confirmed that the slowest GTG response time from a high to a low grey level in an asymmetrically anchored cell can be reduced to less than 0.7 ms with no decrease of the transmittance by applying a vertical trigger pulse to the cell. We believe this method to be a potential candidate for high-performance applications, such as VR/AR devices, that require high transmittance and fast switching at the same time.

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Disclosures

The authors declare no conflicts of interest.

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