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Effects of Curing Temperature on Electro-Optical Characteristics of a Polymer-Stabilized In-Plane-Switching Liquid Crystal Cell

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Abstract: We investigated the electro-optic characteristics of a polymer-stabilized, in-plane-switching (IPS) liquid crystal cell as the UV curing temperature was varied. We found that the response time of an IPS cell could be reduced through low-temperature UV curing of a low concentration of polymer material. We also found that fast switching could be achieved at a low operating voltage and with little light leakage in the dark state. Low-temperature curing of the polymer structure could greatly reduce the average distance between polymer bundles even at low polymer concentrations. Therefore, the decrease in transmittance of a polymer-stabilized IPS cell could be minimized by increasing the cell gap without sacrificing the response time because of the sufficiently high anchoring strength of the polymer structure obtained through low-temperature UV curing.

Keywords: liquid crystals; liquid crystal device; in-plane switching; polymer network

1. Introduction

For the past few decades, liquid crystal displays (LCDs) have been used in a wide range of applications because of their excellent characteristics, such as wide viewing angle, high contrast ratio, low power consumption, and high resolution. However, the slow switching speed of LCs remains a critical issue for emerging next-generation LCD applications. The slow response of LCs can cause motion blur and severely degrade image quality. For next-generation outdoor displays, such as mobile devices, car navigation systems, or digital signage, short response times at low temperatures is particularly important. However, the switching of LCs is very slow at low temperatures because of the dramatically increased rotational viscosity [1–4]. There is an urgent need to reduce this response time in order to facilitate a wider range of applications for LCDs.

Among commercialized LC modes, the in-plane switching (IPS) mode [5–7], which is based on the in-plane rotation of homogeneously aligned LCs, exhibits outstanding performance in terms of viewing angle, color shift, and pressure resistance for touch panels. However, IPS cells exhibit a relatively slow response because their response time is primarily governed by the twist elastic constant K_{22} , which is approximately half of the splay elastic constant K_{11} and bend elastic constant K_{33} . The thin cell gap can reduce the response time of an IPS cell because the LC response time is proportional to the square of the cell gap d . However, the thin cell gap requires a high LC birefringence Δn to achieve a high transmittance, which accompanies an increase in the LC rotational viscosity γ_1 .

Meanwhile, LC/polymer mixtures, which are composites consisting of LCs and polymer networks, have been used for various applications [8–16], such as light shutters, switchable windows, photonics devices, and displays. For display applications, polymer stabilization has been used to improve the electro-optic characteristics, especially the response time of LC devices [13–16]. Although a higher

concentration of polymer materials can contribute to a smaller average domain size of the polymer network and thus reduce the response time, several negative effects exist such as the decrease in transmittance, increase in operating voltage, and dark-state degradation. In polymer-stabilized vertical-alignment (VA) cells, both LCs and polymers are aligned perpendicular to the two substrates in the initial dark state. Normally, incident light propagates in the direction parallel to the common optic axis of the LC and polymer material, and encounters the ordinary refractive indices of the LC and polymer material. The index difference between these two materials is usually very small. The polymer material usually produces multi-domain structures only in the direction perpendicular to the optic axis, but not in the direction of light propagation. Therefore, the light scattering effect is negligible.

In contrast, in a polymer-stabilized IPS cell, the common optic axis of the LC and polymer material is parallel with the two substrate surfaces in the initial dark state. Normally, incident light propagates in a direction perpendicular to the common optic axis of the LC and polymer material, and encounters the extraordinary refractive indices of the LC and polymer material. The index difference between the two materials is usually not negligible if the polymer material is not properly chosen. The polymer material produces multi-domain structures in the direction perpendicular to the optic axis. The incident light will experience the alternating index of the LC and polymer as it propagates through the multi-domain structures, causing the light scattering in a polymer-stabilized IPS cell to have a large impact on the dark-state light leakage when compared with a polymer-stabilized VA cell [15]. To overcome this issue while maintaining a short response time, we need to decrease the average domain size at a fixed concentration of polymer material.

In the meantime, it was reported that the average domain size of a polymer structure decreases as the curing temperature decreases [17–19]. In addition, the LC viscosity increases exponentially as the curing temperature decreases, which slows the polymer diffusion. The reduced polymer diffusion rate will decrease the average domain size. Therefore, low-temperature UV curing can reduce the average domain size at a fixed polymer material concentration.

We investigated electro-optic characteristics of a polymer-stabilized IPS cell as the UV curing temperature was varied. We found that the response time of the IPS cell could be reduced through the low-temperature UV curing of a low concentration of polymer material. We also found that fast switching could be achieved at low operating voltages and with little light leakage in the dark state.

Moreover, the decrease in the transmittance of a polymer-stabilized IPS cell could be minimized by increasing the cell gap without sacrificing the response time, due to the sufficiently high anchoring strength of the polymer network obtained through low-temperature UV curing.

2. Cell Fabrication

Polymer-stabilized LCs are constructed from mixtures of LCs and monomers. The monomers are usually mesogenic with rigid cores and flexible tails, similar to the structure of LC molecules. To confirm the effect of curing temperature on electro-optic characteristics, IPS cells were fabricated. In the IPS cells, the pixel and common electrodes were placed in an interdigitated pattern on the bottom substrate. The width of the interdigitated electrodes and the gap between them were 2.8 and 4 μm , respectively. UV-curable reactive mesogen (RM) was mixed with LCs with a positive dielectric anisotropy to form polymer structures in the IPS cells.

The physical properties of the host LC were as follows: optical anisotropy $\Delta n = 0.1169$; dielectric anisotropy $\Delta \epsilon = 7$; elastic constants $K_{11} = 13.1$, $K_{22} = 5.95$, $K_{33} = 13.6$ pN; and rotational viscosity $\gamma_1 = 61$ mPa·s. LCs were mixed with 1 wt% of RM (RM257, Merck) and 0.3 wt% of photoinitiator (Irgacure 651, BASF, Ludwigshafen, Germany). The mixture was stirred for 24 h, after which it was subjected to ultrasonic waves for 2 h. We coated a homogeneous alignment layer (PIA-5310, JNC, Tokyo, Japan) on each substrate, which was baked for 1 h at 230 °C. We then rubbed each substrate surface with a cotton cloth. The anti-parallel rubbing direction was set to 10° with respect to the interdigitated electrodes. The cell was assembled using silica spacers with a diameter of 3.5 μm .

Finally, the LC/monomer mixtures were injected into the cell and the cell was exposed to a UV source with an intensity of 20 mW/cm² for 10 min as we varied the curing temperature from 20 to −20 °C.

3. Experimental Results and Discussion

Recently, Yang et al. developed a simple phenomenological model to estimate the turn-off time of a polymer-stabilized LC cell [15]. They derived a formula by introducing an effective aligning field of the polymer network, which can be used to investigate the effect of polymer networks on LC molecules. According to this model, the turn-off time of a polymer-stabilized IPS cell can be expressed as:

$$\tau_{off} \approx \frac{\gamma}{[K_{22}(\frac{\pi}{d})^2 + \frac{\pi^2 K_{22}}{2D^2}]} \quad (1)$$

where γ , K_{22} , d , and D are the rotational viscosity coefficient, twist elastic constant, cell gap, and average distance between two neighboring bundles, respectively. The first term in the denominator of Equation (1) is governed by the anchoring between the two substrates, while the second term is associated with the anchoring effect by the polymer network. According to Equation (1), the turn-off time is reduced as the average distance D between two neighboring bundles decreases, due to the increase in the anchoring effect by the polymer network. One of the methods for reducing D is to increase the RM concentration, but this has its pros and cons. It increases the anchoring effect by the polymer network and decreases the turn-off time. However, it also leads to an increase in operating voltage and light leakage in the dark state caused by the light scattering effect [15].

To overcome the issues mentioned above, a method is required to reduce the average distance between two neighboring bundles in a polymer-stabilized IPS cell at a fixed polymer concentration, which would enable us to prevent the degradation of the other characteristics of the devices while maintaining a short response time. The electro-optic properties of a polymer-stabilized LC cell depend on several fabrication parameters, such as the UV-curable monomer material, monomer concentration, UV intensity, and curing temperature. In particular, the curing temperature impacts the morphology of the polymer, which strongly affects the electro-optic properties of a polymer-stabilized LC cell. As the curing temperature decreases, the LC viscosity increases exponentially, which slows polymer diffusion [17–20]. Lower curing temperatures produce finer polymer networks and generate polymer-stabilized LCs with a smaller average distance between two neighboring bundles (or domain size).

To investigate the curing temperature effects on the electro-optic characteristics of a polymer-stabilized IPS cell, voltage-transmittance (V-T) curves were measured as the amplitude of a 1 kHz square voltage pulse was varied, as shown in Figure 1. As the curing temperature decreases from 20 °C to −20 °C, the maximum transmittance of the polymer-stabilized IPS cell decreases from 21.5% to 12.2%, while the threshold voltage V_{th} (operating voltage V_{op}) increases from 2.75 V (5.5 V) to 4.2 V (7.5 V). The decrease in the maximum transmittance is caused by the limited rotation of LC molecules due to the shorter distance between the bundles. In contrast, the increased threshold and operating voltages are caused by the enhanced anchoring provided by the polymer networks due to the shorter distance between the bundles.

We also measured the temporal switching behavior of IPS cells with an RM concentration of 1 wt% as we varied the curing temperature from −20 °C to 20 °C, as shown in Figure 2. 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 times of the IPS cell cured at 20 °C were 10.2 and 10.9 ms, respectively, whereas those of the cell cured at −20 °C were 3.3 and 4.0 ms, respectively. As the curing temperature decreases, the response time dramatically decreases as a result of the enhanced anchoring provided by the polymer networks caused by the shorter distance between the bundles. The response time of the IPS cell fabricated by curing 1 wt% of RM at −20 °C was five times faster than that of a conventional IPS cell. It is comparable to that of an IPS cell fabricated by curing 3 wt% of RM at 20 °C. Our experimental results indicate that low-temperature curing is effective in reducing

the response time with a relatively lower RM concentration. Curing at low temperatures makes it possible to lower the RM concentration while maintaining a short response time, which can minimize the deterioration of the other characteristics, such as the operating voltage and light leakage in the dark state.

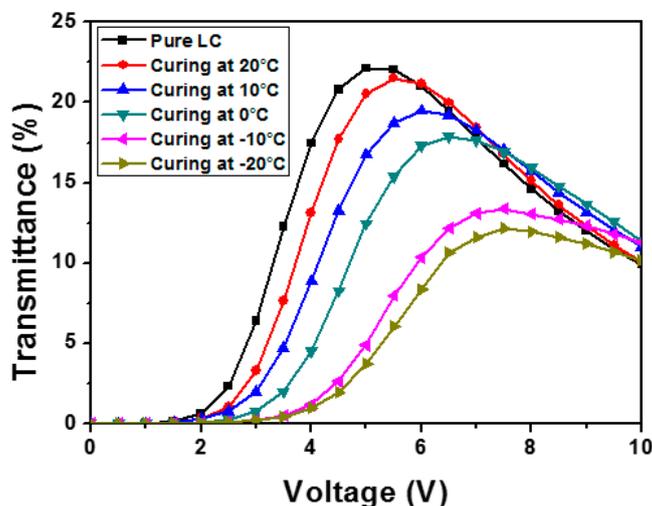


Figure 1. Measured V-T curves of a conventional IPS cell and polymer-stabilized IPS cells cured at 20, 10, 0, -10 , and -20 °C.

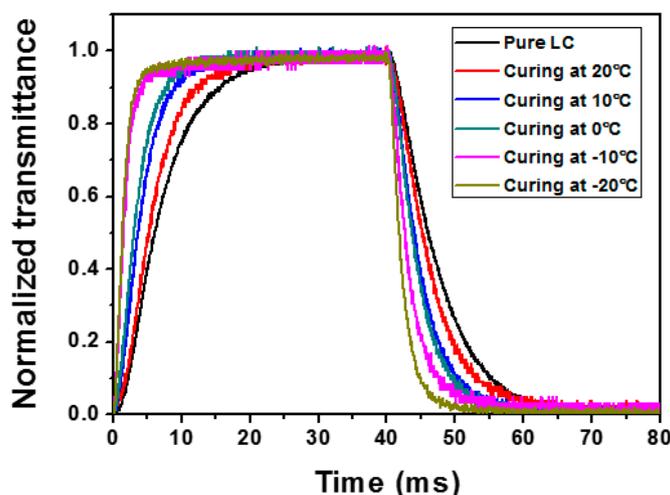


Figure 2. Measured optical switching behaviors of a conventional IPS cell and polymer-stabilized IPS cells cured at 20, 10, 0, -10 , and -20 °C.

Figure 3 presents the threshold voltage, operating voltage, and transmittance in the dark state of polymer-stabilized IPS cells as functions of the curing temperature. The measured electro-optic characteristics of polymer-stabilized IPS cells are also summarized in Table 1. The polymer-stabilized IPS cell with 1 wt% of RM exhibits a much lower threshold and operating voltage than that with 3 wt% of RM, regardless of the curing temperature, as shown in Figure 3a. In addition, the IPS cell fabricated by curing 1 wt% of RM at -20 °C exhibits a better dark state than that fabricated by curing 3 wt% of RM at 20 °C, as shown in Figure 3b. The high density of polymer networks in bulk can cause light leakage in the dark state because of light scattering caused by the refractive index mismatch between the LC and polymer. This is the reason why an LC cell with a low RM concentration exhibits a low light leakage in the dark state. It was reported that the dark-state light leakage in a polymer-stabilized

IPS cell could be reduced by increasing the order parameter of the LC/polymer composites through low-temperature UV curing [20]. As shown in Figure 3b, low-temperature curing does not deteriorate the dark state in a polymer-stabilized IPS cell despite the reduced distance between two neighboring bundles, because the LC molecules can be aligned with a higher order parameter value.

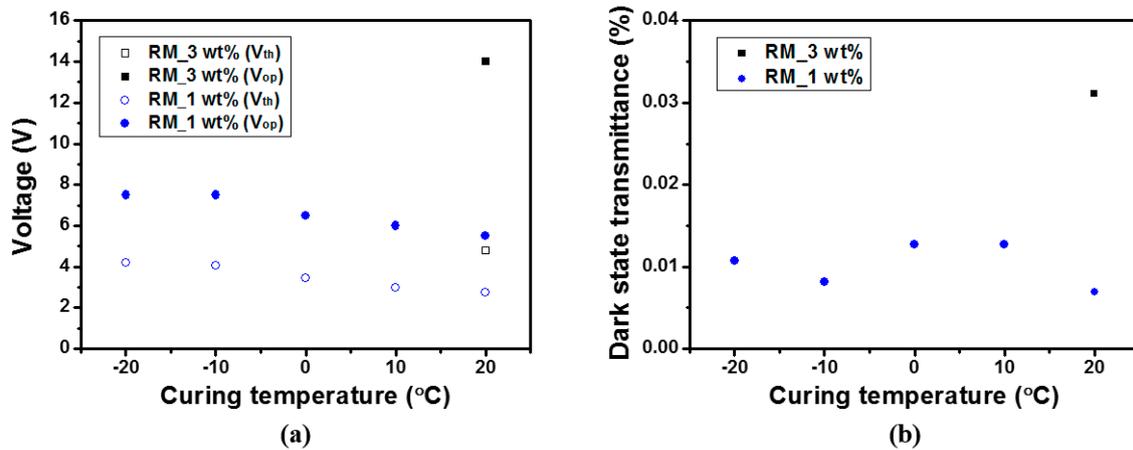


Figure 3. (a) Threshold and operating voltages and (b) transmittance in the dark state of polymer-stabilized IPS cells with RM concentrations of 1 and 3 wt% as functions of the curing temperature.

Table 1. Measured electro-optical characteristics of IPS cells fabricated by curing 3 wt% of RM at 20 °C and 1 wt% of RM at −20 °C.

	Voltage (V)		Transmittance (%)		Response Time (ms)	
	V_{th}	V_{op}	Dark	Maximum	Turn-on	Turn-off
Pure LC	2	5	0.004	22.1	13	12.9
RM: 3 wt% (cured at 20 °C)	4.8	14	0.031	10.3	1.9	3.1
RM: 1 wt% (cured at −20 °C)	4.2	7.5	0.010	12.2	3.3	4.0

To better understand the operation of a polymer-stabilized IPS cell, we plotted the normalized transmittance curves as a function of the applied voltage, as shown in Figure 4. The IPS cell with 3 wt% of RM exhibits a higher threshold voltage owing to the smaller average distance between two neighboring bundles and a higher operating voltage than that with 1 wt% of RM. The transmittance increases irrespective of the monomer concentration as the applied voltage increases, whereas the slope of the V-T curve is strongly dependent on the monomer concentration. In LC/polymer composites, part of the applied voltage is shielded by the polymer because of its dielectric properties, which results in the reduced effective voltage on the LC layer, dependent on RM concentration. Consequently, the IPS cell with 3 wt% of RM exhibits a higher operating voltage than that with 1 wt% of RM. In contrast, the IPS cell fabricated by curing 1 wt% of RM at −20 °C exhibits a V-T curve with a slope similar to that cured at 20 °C. The voltage shift only exists as a result of the enhanced anchoring provided by the polymer networks owing to the smaller average distance between two neighboring bundles. Therefore, the IPS cell fabricated by curing 1 wt% of RM at 20 °C exhibits a relatively low operating voltage while maintaining a short response time owing to the decreased distance between two neighboring bundles.

As described above, low-temperature curing of the polymer structure is more effective at reducing the response time because it can minimize the degradation of other characteristics, such as the dark-state light leakage and operating voltage, because of the low polymer concentration. Nevertheless, as the curing temperature was lowered, the transmittance severely decreased, as shown in Figure 1. To minimize the transmittance decrease, we can increase the cell gap of a polymer-stabilized LC cell [14]. We measured the V-T curves of IPS cells with 1 wt% of RM as we varied the cell gap from 3.5 to 4.3 μm , as shown in Figure 5. As the cell gap is increased, the maximum transmittance increased.

When the cell gap was 4.3 μm , the maximum transmittance of the polymer-stabilized IPS cell was 17.2% at an applied in-plane voltage of 7 V, which corresponds to 77.8% of the maximum transmittance of a conventional IPS cell. Although the maximum transmittance of the polymer-stabilized IPS cell is still lower than that of a conventional IPS cell, the transmittance decrease is minimized. Although the cell gap was increased for higher transmittance, the response time remained almost constant, as shown in Table 2. In other words, the increased cell gap of a polymer-stabilized IPS cell does not sacrifice its response time because of the reduced average distance between two neighboring bundles by low-temperature curing of the polymer material. In a polymer-stabilized IPS cell, the cell-gap dependence of the response time can be reduced significantly because the anchoring strength of the polymer network becomes sufficiently large [14].

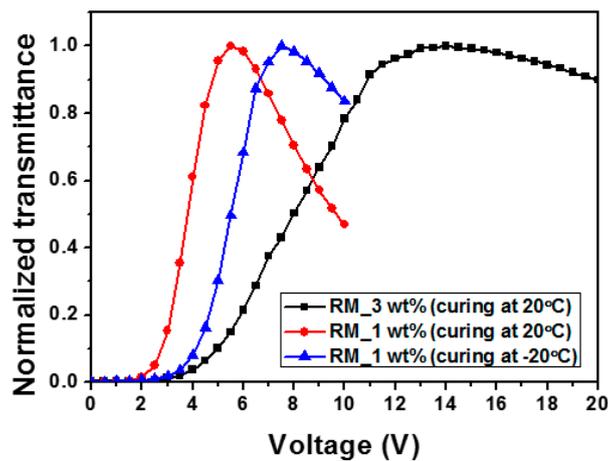


Figure 4. Normalized V-T curves of IPS cells fabricated by curing 1 and 3 wt% of RM at 20 °C, and 1 wt% of RM at −20 °C.

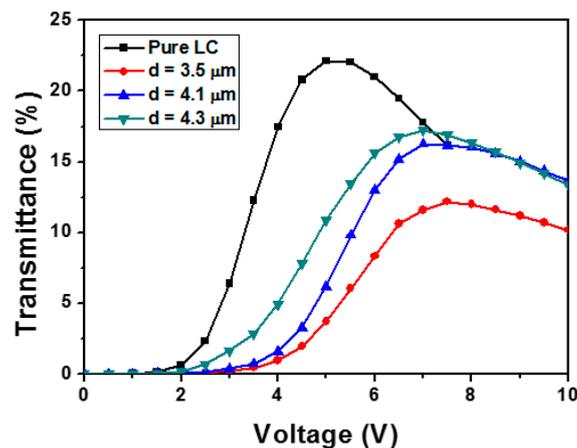


Figure 5. Measured V-T curves of a conventional IPS cell (cell gap $d = 3.5 \mu\text{m}$) and IPS cells fabricated by curing 1 wt% of RM at −20 °C as the cell gap d varied from 3.5 to 4.3 μm .

Table 2. Dependence of the measured electro-optical characteristics of IPS cells, fabricated by curing 1 wt% of RM at −20 °C, on the cell gap.

Cell Gap (μm)	Operating Voltage (V)	Transmittance (%)	Turn-on Time (ms)	Turn-off Time (ms)
3.5	7.5	12.2	3.3	4.0
4.1	7	16.3	4.7	4.6
4.3	7	17.2	4.6	4.7

4. Conclusions

We investigated the effects of curing temperature on the electro-optical characteristics of polymer-stabilized IPS cells. We found that the response time of a polymer-stabilized IPS cell could be reduced with a low concentration of polymer material through low-temperature UV curing. We also found that fast switching could be achieved at low operating voltages and with little light leakage in the dark state. Moreover, the decrease in the transmittance of a polymer-stabilized IPS cell could be minimized by increasing the cell gap without sacrificing the response time because of the sufficiently large anchoring strength of the polymer network obtained through low-temperature UV curing. We believe that the formation of polymer structures at low temperatures can be an effective tool for reducing the response time while minimizing the degradation of other electro-optic characteristics.

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Conflicts of Interest: The authors declare no conflict of interest.

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