Fabrication of Polymer Spacers for Flexible Nano-Phase-Separated LCDs with High Contrast Ratio

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ABSTRACT

We have developed a flexible NPS-VA-mode LCDs with high contrast ratio using the thin plastic substrates and bonding polymer spacers. We successfully achieved a precise control of polymer spacer structures by optimizing the monomer concentration and a high curvature performance without the flow of LCs.

1. INTRODUCTION

Flexible liquid crystal displays (LCDs) using plastic substrates are a promising technology for new display applications such as curved automotive displays, roll screen TVs, and wearable devices due to their excellent characteristics such as high impact resistance as well as their high reliability at high temperatures.

In the development of flexible LCDs, it is important to suppress the curvature deformation of the plastic substrates, the flow of LCs, and the shift of photo spacers to achieve the sheet-type LCDs with high image quality even in a small radius of curvature.

To solve these problems, we have demonstrated that it is possible to achieve the flexible LCDs with a small radius of curvature less than 5 mm by using the composite structure using the post shaped photo spacers and the bonding polymer spacers and the 10 µm thick transparent polyimide substrates [1].

However, when the non-liquid crystalline acrylic monomers are used for the polymer spacers, the contrast ratio decreases because of light leakage due to the degradation of alignment uniformity of LCs in the vicinity of the polymer spacers [2]. Whereas, a liquid crystalline monomer is effective to improve the alignment uniformity of LCs, however, it has been difficult to precisely control the polymer spacer structure in LCs because of its high compatibility with the LC materials.

In this paper, we investigated a precise control of the polymer spacer structures and the polymer precipitation in the pixel area by using nano-phase-separated (NPS) LCs to achieve the flexible LCDs with high contrast ratio.

2. FLEXIBLE NANO-PHASE-SEPARATED LCDS

Nano-phase-separated (NPS) monomer is a liquid crystalline monomer and it forms a nano-sized polymer network in LCs and can achieve a low driving voltage, fast switching speed, high contrast ratio, and high transmittance without light scattering [3]. Also, we reported that the NPS-LCs can suppress the flow of LCs during the bending process by controlling the viscosity of the LCs, and are suitable for flexible LCDs [4]. In the next section, we investigated the formation of polymer spacers in NPS-LCs by the UV pattern exposure to further improve the contrast ratio and the curvature performance of sheet type LCDs.

3. EXPERIMENT

We fabricated the LC cells as the following procedure. We coated a vertical alignment film (SE-4811, Nissan Chemical) onto the glass substrate and conducted a rubbing treatment. The thickness of the upper substrate was 200 µm and the thickness of the lower substrate was 1.1mm. After spraying a spacer particle of 3 um in diameter, we fabricated an empty cell. 0.5 wt% of polymerization initiator was added to the LC mixture (NA-1220NPS, DIC) and the LC mixture was injected into empty cells via capillarity. The photomask pattern was a lattice-shaped. The width of the irradiated area was 10 µm and the pitch was 110 µm. We irradiated the cell with UV light delivered through a photomask at room temperature using a collimated UV light source (JATEC) with a wavelength of 365 nm. The integrated UV intensity was set to 5.4 J/cm^2. After UV pattern-exposure, we irradiated the entire surface of the LC cell with UV light at 12 J/cm^2.

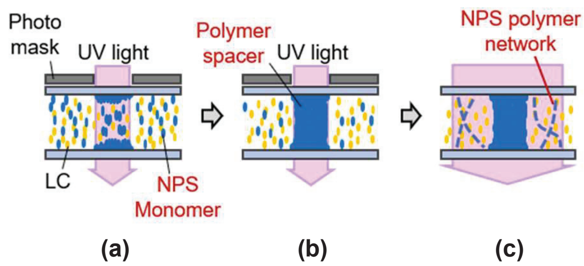


Fig. 1 Fabrication process of polymer spacer by patterned UV exposure. (a)Pattern UV exposure, (b) Formation of polymer spacer, and (c) 2nd UV exposure.

The polymer aggregation structure and the optical characteristics of LC cells such as the driving voltage and the response time of LCs in the pixel region strongly depend on the monomer concentration. Therefore, we investigated the effect of the monomer concentration on the polymer aggregation structure and the optical properties LCs in the pixel region. Three types of monomer concentrations were prepared; a normal concentration of NPS-LCs, and 1.75 and 2 times the concentrations of normal NPS-LCs.

The evaluation of the fabricated LC cells was carried out by measuring a voltage-transmittance characteristic, a decay switching time, and a haze value at the voltage on and off states, as well as an observation of the polarizing microscope images of the polymer wall structure under the Crossed-Nicol polarizers. Haze value was measured using a haze meter (HM-150, Murakami Color Research Laboratory Co., Ltd.). The haze value indicates the ratio of the total light transmittance and the diffused light transmittance and is defined by the following equation.

$$\mathrm{Haze}(\%) = \frac{\mathrm{Diffuse\ transmission}}{\mathrm{Total\ transmission}} \times 100 \qquad (1)$$

When the monomer concentration in the LCs in the pixel area is high, the response is faster due to the anchoring force by the polymer network, while the driving voltage and the light scattering become high. As a result, we can find the optimum state of the polymer network formed in the pixel region by the above-mentioned evaluation procedure.

4. RESULTS AND DISCUSSION

A normalized graph of the voltage-transmittance characteristics of fabricated LC cells at each monomer concentration is shown in Fig. 2. The haze values at the voltage on/off states and the decay switching time are also shown in Table 1. The characteristics of NPS LCs without polymer spacers are also shown for comparison. As shown in Fig. 2 and Table 1, the transmittance and the haze values at voltage off state are extremely low in all monomer concentrations. This result indicated that a high contrast ratio was achieved in our NPS LC cells. As the monomer concentration increases, the haze value at the voltage on the state increases, and the decay switching time decreases. This result indicates that the polymer network in the pixels area increases.

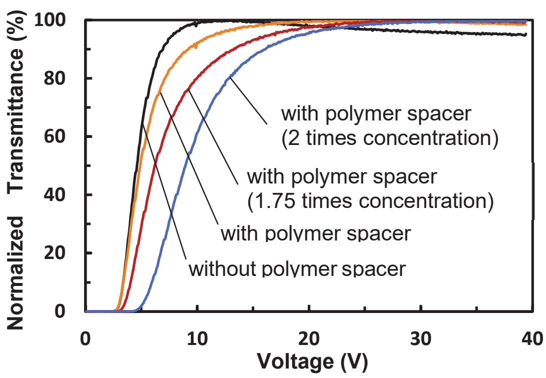


Fig. 2 Voltage-transmission characteristics of NPS LCs with polymer spacer as a function of monomer concentration.

The microscope images of the polymer aggregation structure in the NPS-LCs are shown in Fig. 3. In any concentration, there was no light leakage in the voltage off state due to the disordered LC alignment in the vicinity of the polymer spacers. These results indicate that our NPS LCs achieve a high contrast ratio and the NPS-LC and the polymer spacer were successfully formed by the optimization of the concentration of NPS monomer.

Table. 1 Decay time and haze value of NPS LCs as a function of monomer concentration.

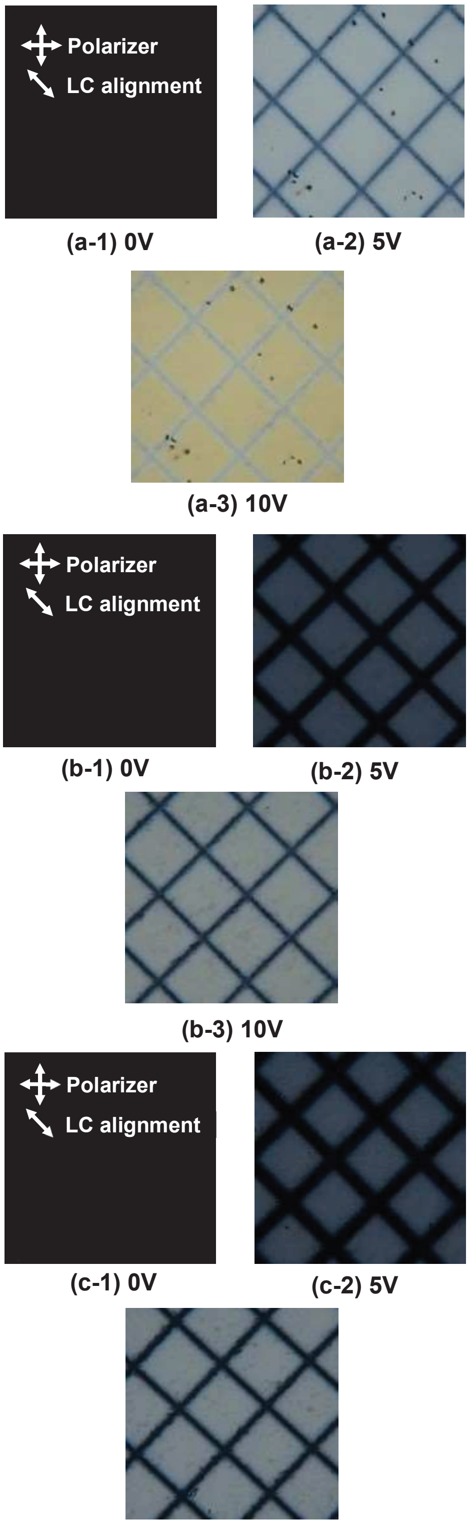
Monomer concentration	Response time of decay (ms)	Haze (%)	
		Voltage off	Voltage on
without polymer spacer	1.7	1.0	2.9
with polymer spacer	1.7	0.4	1.3
with polymer spacer (1.75times concentration)	1.6	0.9	6.2
with polymer spacer (2 times concentration)	1.6	1.2	8.7

However, when the high voltage is applied, the transmittance at the polymer spacer changes in a low monomer concentration condition (Fig. 3a). This result indicates that the polymer spacer is not sufficiently structured, and the orientation of liquid crystal molecules incorporated into the polymer structure changes with applied voltages. On the other hand, when the monomer concentration is high, the orientation of LCs in the polymer structure does not change even when the high voltage is applied. This result shows that a good polymer structure was successfully formed, however, the haze value is also slightly higher, and the width of the polymer structure becomes thicker than that of the photomask. Since the width of the polymer structure becomes narrower as the applied voltage increased, we considered that the driving voltage becomes higher due to the increase of anchoring force in the vicinity of the polymer structure.

To examine the increase of the anchoring force in the vicinity of the polymer spacers, we calculated the UV irradiation pattern at the LC layer by the lattice-shaped photomask using the angular spectrum method [5]. We considered that the UV irradiation pattern at the LC layer was affected by the diffraction of the fine-pitch photomask.

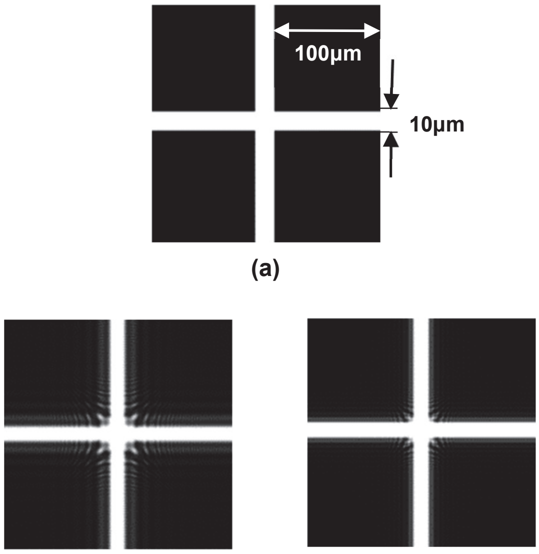
The results of the calculation of UV irradiation pattern concerning the thickness of the upper-substrates are shown in Fig. 4. From these figures, we found that the exposure area by the 200 μm thick substrate becomes wider than that of the photomask. Therefore, we confirmed that the thin plastic substrate is necessary to precisely control the structure of polymer spacers (Fig. 4c).

Finally, we fabricated flexible NPS-LCD using polycarbonate substrates. The thickness of the substrates is 80 μm and the 3 μm photo spacers are fabricated by a photolithography technique. We confirmed that there was no light leakage in the dark state during the bending process and we successfully achieved the high-quality flexible LCD with high contrast ratio.



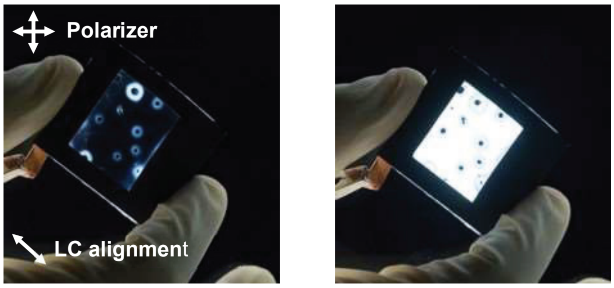
(c-3) 10V

Fig. 3 Polarizing microscope images of polymer aggregation structure. (a) Normal concentration NPS LC, (b) Optimized (1.75 times) concentration NPS LC, (c) High (2 times) concentration NPS LC.



(b) (c)

Fig. 4 Calculation result of UV irradiation pattern at the LC layer as a function of substrate thickness. (a) Photomask pattern, (b) 200 μm, and (c) 80 μm.



(a) (b)

Fig. 5 Fabricated flexible NPS VA-mode LCD in bending state. This LCD uses photo spacers, polymer spacers, and polycarbonate substrates. (a) off state (0V) and (b) on state (10V).

5. CONCLUSION

In this paper, we investigated the formation of bonding-type polymer spacers with NPS-LCs to realize the flexible LCDs with high contrast ratio. We clarified that a good polymer spacer structure can be formed by optimizing the concentration of NPS monomers. It was also shown that the polymerization of monomers in the vicinity of the wall must be suppressed to reduce the driving voltage and improve the optical characteristics of NPS LCs.

We successfully achieved a high-quality flexible NPS-LCD and a high curvature performance without the flow of LCs by the precise control of polymer spacer structures. Our flexible NPS-LCD has the advantages of high contrast ratio, fast switching speed, so it is promising for future sheet-type display applications such as curved automotive displays and roll screen TVs, and wearable devices.

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