Evaluation of Capability to Maintain Thickness of LC layer of Flexible LCDs with Bonding Polymer Spacers

Takahiro Ishinabe† (member), Shogo Takahashi†, Yosei Shibata† and Hideo Fujikake† (member)

Abstract We measured the thickness of the LC layer of flexible liquid crystal displays (LCDs) in non-curved and curved states and evaluated a capability to maintain the thickness of the LC layer of flexible LCDs with bonding polymer spacers. We found that both the rigid spacers suppressing a compressive force and the spacers bonding two substrates were required to maintain the thickness of the LC layer of curved LCDs. We developed the composite spacer structure using the columnar photo spacer and the bonding polymer spacer; these maintained a constant thickness of LC layer over the entire liquid crystal cell and will improve the contrast ratio of flexible LCDs even in a small radius of curvature.

Keywords: Liquid crystal display, Flexible LCD, Polymer spacer, Photo spacer, Thickness of LC layer.

1. Introduction

Flexible liquid crystal displays (LCDs)1)-5) using plastic substrates have advantages of ultra-thin, lightweight, unbreakable, and enhance the portability and the design of display devices. These features enable layered displays which improves the functionality of display devices such as the high-contrast dual-layered LCDs6)7) and the viewing angle controllable LCDs8). Thus, flexible LCDs are attracting significant interest in terms of new applications, including curved automotive displays, large digital signs, high-contrast rollable televisions, and wearable devices.

In general, good LCD image quality requires a uniform thickness of the LC layer. The thickness of the LC layer is affected by the deformation of plastic substrates after bending as shown in Fig. 1, therefore it is important to suppress such deformation to improve the uniformity of the thickness of LC layer9). This allows the fabrication of flexible LCDs with high image quality even when the radius of curvature is small. Suppression of liquid crystal (LC) flow by the deformation of the plastic substrate is also important to improve the uniformity of the thickness of the LC layer during bending.

To solve these problems, we developed a bonding polymer spacer fabricated via patterned UV exposure as shown in Fig. 210)-12). This lattice-shaped polymer spacer effectively suppressed the deformation of the plastic substrate and the changes in the thickness of the LC layer on bending because the upper and lower substrates were bonded and the LC was confined inside the spacer structure. As a result, we achieved the foldable LCD using ultra-thin polyimide (PI) substrates and lattice-shaped bonding polymer spacers as shown in Fig. 3.
thickness of the PI substrate was 10 µm, the LC layer was 5 µm, and the total thickness of LCD including polarizers was 75 µm. The radius of curvature was less than 2 mm\textsuperscript{13}). However, a capability to maintain the thickness of the LC layer of flexible LCDs with bonding polymer spacers has not been quantitated. In this paper, we evaluated a capability to maintain the thickness of the LC layer of flexible LCDs by measuring the wavelength dependence of phase retardation of flexible LCDs in non-curved and curved states. In addition, we optimized the spacer structures to yield a high contrast ratio and high-level luminance uniformity, even when the radius of curvature was small.

2. Measurement of thickness of LC layer in a curved state

2-1. Plastic substrate for flexible LCDs

We measured the thickness of LC layer of flexible LCDs using plastic substrates by evaluating wavelength-dependent phase retardation of the homogeneously aligned LCs in a curved state. In general, the phase retardation of plastic substrates changes depending on the bending deformation of plastic substrates\textsuperscript{14,15}). This stress retardation makes it difficult to evaluate the phase retardation of the LC layer in a curved state. Therefore, we used the plastic substrate exhibiting low-level phase retardation that did not change on bending to measure the phase retardation of the LC layer in curved state\textsuperscript{16}). The stress retardation of plastic substrates depends on the photoelastic constant, the differences in the compressive and tensile stress generated on the inner and outer surfaces of the substrate, and the thickness of the plastic substrate. We have previously reported that the stress retardation of polycarbonate substrate with a low Young's modulus is extremely small if the substrate is < 200 µm in thickness from the calculation based on the finite element method \textsuperscript{17}).

Therefore, we experimentally evaluated the changes in phase retardation of the polycarbonate substrate after bending. The thickness of polycarbonate substrate (supplied by Teijin) was 80 µm and the radius of curvature was 7 mm. We measured the in-plane phase retardation at the center of the curvature. The measured result of the change in phase retardation of the polycarbonate substrate between non-curved and curved states is shown in Fig. 4. We confirmed that the change in phase retardation by the bending was almost zero; we could thus measure the phase retardation of the LC layer in a curved state when this polycarbonate substrate was employed.

2-2. Experiment

We measured the wavelength dependence of phase retardation of the homogeneously aligned LC cells in non-curved and curved states by using the spectroscopic ellipsometer (M-2000, J. A. Woolam) as shown in Fig. 5. We measured the in-plane phase retardation at the center of the curvature and the radius of curvature was 7 mm. The measurement spot size was 2 mm. The thickness of the LC layer of non-curved and curved LC cells was determined by numerical fitting of measured and calculated wavelength-dependent phase retardation of the LC cell. Figure 6 shows the principle of measurement of the thickness of the LC layer exploiting the wavelength dependence of the phase retardation of

Fig. 3 Flexible LCD using colorless polyimide (PI) substrate and bonding polymer spacer.

Fig. 4 Measured result of change in phase retardation of the polycarbonate substrate between non-curved and curved states.

Fig. 5 Measurement system of phase retardation of curved liquid crystal cells by using spectroscopic ellipsometer.
homogeneously aligned LC cells. In general, the measured thickness of the LC layer remains constant at different wavelengths if the LC is uniformly aligned in a curved state. However, if alignment uniformity is degraded by the bending deformation of the plastic substrate, the measured wavelength dependence of phase retardation differs from the wavelength dispersion of $\Delta n$ of the LC material; the measured thickness of LC layer is wavelength-dependent. Therefore, if a single wavelength was used in this measurement method, the reliability of the measurement result becomes low when the alignment uniformity degrades by the bending deformation of plastic substrates. Therefore, it is possible to evaluate a uniformity of LC alignment in a curved state and a reliability of measurement result of the thickness of the LC layer by measuring the wavelength dependence of the phase retardation of the LC layer.

2-3. Measurement of thickness of LC layer of LC cell using bead spacer

To evaluate the validity of our method, we measured the change in thickness of the LC layer between the non-curved and curved states of the flexible LCD using a bead spacer. Figure 7 shows the wavelength dependence of $\Delta n$ of the LC material (MLC-3019, Merck) used in this experiment.

We fabricated the homogeneously aligned LC cell in the following procedure. We coated a parallel alignment film (AL-1254, JSR) onto the polycarbonate substrate and conducted a rubbing treatment. The substrate thickness was 80 µm. After spraying a spacer particle, we fabricated an empty cell. Then, an LC material (a positive nematic liquid crystal; MLC-3019, Merck) was injected into the cell via capillarity.

The observational results on non-curved and curved LC cells under the crossed-Nicols polarizer are shown in Fig. 8. When the bead spacer was employed, both the LC and spacers flowed due to compressive force between the substrates; the thickness of LC layer significantly decreased and increased at the center and edges of the cell, respectively. The measured wavelength dependence of phase retardation of the LC cell and the thickness of the LC layer are shown in Fig. 9, respectively. The measured and calculated results were in good agreement and the measured thickness of the LC layer remained constant as the wavelength varied, therefore, we confirmed the LC alignment in the curved state was uniform and our measurement method was valid. The measured result of the thickness of the LC layer in the non-curved state $d_{nc}$ was 2.69 µm and in the curved state $dc$ was 0.09 µm. The change rate of the thickness of the LC layer between non-curved and curved states defined by the following equation was 96.7%.
We confirmed that the thickness of the LC layer greatly decreased by the flow of the LC and the spacers in the case of flexible LCDs using bead spacers.

3. Evaluation of capability to maintain thickness of LC layer of flexible LCDs using bonding polymer spacers

3-1. Fabrication of flexible LC cell using bonding polymer spacers

We fabricated flexible LC cells using polycarbonate substrates and bonding polymer spacers and evaluated the effects of spacer shape on the capability to maintain the thickness of the LC layer. The flexible LC cell was prepared as follows. We coated a parallel alignment film (AL-1254, JSR) onto the polycarbonate substrate and conducted a rubbing treatment. The substrate thickness was 80 µm. After spraying a spacer particle, we fabricated an empty cell. Then, an LC mixture (a positive nematic liquid crystal; MLC-3019, Merck) and isotropic monomer material were injected into the cell via capillarity. We irradiated the cell with UV light delivered through a photomask. The UV wavelength was 365 nm, the irradiation energy was 3.0 J/cm², and the process temperature was 25°C; we refer to these spacers as polymer spacer.

We fabricated two types of polymer spacer: columnar and lattice-shaped. The polymer spacer width was 10 µm and the pitch was 110 µm. We also prepared flexible LC cells using columnar spacers fabricated via photolithography for comparison; we refer to this spacer as a photo spacer. The width and pitch of the photo spacer were the same as those of the polymer spacer.

3-2. Measurement of thickness of LC layer of LC cells using bonding polymer spacers and photo spacer

Observational results on flexible LC cells in the non-curved and curved states under crossed-Nicol polarizers are shown in Fig. 10. The change rates of the thickness of the LC layer between the curved and non-curved states are listed in Table 1.

(a) Photo spacer

The change rate of the thickness of the LC layer of the LC cell using columnar photo spacers was as low as 5.7%.

![Image](image.png)

**Fig. 9** The wavelength dependence of (a) phase retardation and (b) the thickness of LC layer of LC cells in the non-curved and curved states.

Change rate(%) = \( \frac{d_{nc} - d_{c}}{d_{nc}} \times 100 \)  

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**Fig. 10** Observational results of flexible LC cells in the non-curved and curved states under crossed-Nicol polarizers. (a) columnar photo spacer; (b) columnar polymer spacer; (c) lattice-shaped polymer spacer.
at the center of curvature. However, the thickness of the LC layer was significantly greater at the edges of the cell because of the shearing force exerted by the deformation of plastic substrates as shown in Fig. 10(a).

Thus, a photo spacer can effectively maintain the thickness of the LC layer at the center of curvature during bending because the rigid photo spacer can suppress the compressive force by the deformation of plastic substrates, whereas a spacer bonding the upper and lower substrates is required to suppress the enlargement of the thickness of the LC layer caused by the shearing force exerted by the plastic substrate to improve a device flexibility.

(b) Columnar polymer spacer

When columnar polymer spacers were used, the change rate of the thickness of the LC layer was 62.0% and the thickness of the LC layer decreased greatly at the center of curvature. Furthermore, the thickness of the LC layer increased at the edges of the cell as shown in Fig. 10(b), even though the polymer spacer bonding the upper and lower substrates. We considered that the thickness of the LC layer decreased by the elastic deformation of the polymer spacers occurred by the compressive force by the deformation of plastic substrates at the center of curvature, while the enlargement force by the LC flow and the deformation of plastic substrates became larger than the bonding force of polymer spacers at the edge of the LC cell.

(c) Lattice-shaped polymer spacer

When lattice-shaped polymer spacers are used, the change rate of the thickness of the LC layer was as low as 5.6%. In addition, the thickness of the LC layer barely changes at the edges of the cell. We considered the confinement of the LC materials by the lattice-shaped spacers suppressed the LC flow and changes in the thickness of the LC layer at the center of curvature. The suppression of the LC flow also reduces the enlargement force at the edge of the cell and achieves a uniform thickness of LC layer over entire the cell in a curved state as shown in Fig. 10(c).

As a result, we found that the suppression of the compressive force to inhibit the LC flow, and the bonding of the upper and lower substrates to inhibit the enlargement of the thickness of the LC layer at the edges of LC cells are essential for remaining the thickness of the LC layer constant over the entire cell even at a small radius of curvature; use of the lattice-shaped polymer spacer is optimal when fabricating flexible LCDs. However, the lattice-shaped spacer degrades a contrast ratio because of the light leakage attributable to degradation of LC alignment uniformity at the spacer surfaces as shown in Fig. 11.

### 3-3. Capability to maintain the thickness of LC layer of LC cell using composite spacer

We created composite spacers using columnar photo spacers and polymer spacers. By exploiting the rigid photo spacers and the bonding effects of polymer spacers, we can suppress changes in the thickness of the LC layer over the entire cell and improved the contrast of flexible LCDs. Figure 12 shows microscopic images of

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**Table 1** Changes in the thickness of LC layer of the non-curved and curved states.

|                      | The thickness of LC layer (μm) | Change rate (%) |
|----------------------|-------------------------------|-----------------|
|                      | Non-curved | Curved    |                |
| Photo spacer         | 3.00       | 2.83      | 5.7            |
| Columnar polymer spacer | 2.79       | 1.06      | 62.0           |
| Lattice-shaped polymer spacer | 2.78       | 2.6       | 6.5            |

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**Fig. 11** Light leakage at the surface of lattice-shaped polymer spacers.

**Fig. 12** Microscopic images of flexible LC cells with composite spacers.
the composite spacers in the crossed-Nicol polarizers with different alignment directions. The transmittance became 40% of the lattice-shaped polymer spacer (see Fig. 11 and Fig. 12(b)) and we confirmed that the composite spacer structure was effective to improve the contrast ratio of flexible LCDs. Figure 13 provides observational results on curved LC cells obtained with these spacers under crossed-Nicol polarizers. The thickness of the LC layer before and after bending was 2.91 and 2.73 µm, respectively; the change rate of the thickness of the LC layer of this LC cell was thus only 6.2%. This change rate is equivalent to that of a lattice-shaped polymer spacer; the LCD exhibited a uniform thickness of LC layer over the entire cell even at a small radius of curvature. These results are attributed to the suppression of LC flow by the photo spacer and the enlarged force at the edge of the cell became lower than the bonding force of columnar polymer spacers. In addition, light leakage was less than that of lattice-shaped polymer spacers.

We also found that the composite spacer structure effectively improved the contrast ratio by suppressing scratching of the alignment layer by the photo spacers.

4. Conclusions

We quantitatively evaluated the capability to maintain the thickness of the LC layer of flexible LCDs. We measured the wavelength-dependence of the phase retardation of homogeneously aligned LC cells and obtained highly accurate values of thickness of the LC layer for curved LCDs. We found that the rigid photo spacer suppressing a compressive deformation of plastic substrates and inhibiting an LC flow, and the bonding of the upper and lower substrates to inhibit enlargement of the thickness of the LC layer at the edges of LC cells are essential to maintain the thickness of the LC layer over the entire curved LC cells. We also developed the composite spacer using columnar photo spacers and bonding polymer spacers; these maintained a constant thickness of LC layer over the entire LC cell; this will improve a contrast ratio of flexible LCDs by suppressing light leakage attributable to a degradation of LC alignment uniformity at the spacer surfaces and a scratching of the alignment layer, even those with small radius of curvature. It will thus be possible to produce high-quality flexible LCDs for new display applications such as curved automotive displays, large digital signs, and high-contrast rollable televisions.

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