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Fabrication of Flexible LCD by Laminating Photo-curable Polymer Cover Film

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We fabricate a flexible liquid crystal display (LCD) by laminating a thin photo-curable polymer film on a plastic substrate. In our structure, the cover film is tightly adhered to the bottom structure which has periodic rigid walls on the flexible substrate. This guarantees the stable LC structure under external deformations which is critical to realize flexible LCD. The LC molecules can be aligned homogeneously by micro-grooves formed on the photo-curable polymer film.

1. Introduction

Flexible displays have attracted much attention due to their good portability in the ubiquitous era such as light weight, thin packing, and flexibility [1]. Among the currently competing technologies, flexible LCDs are considered to be the most attractive ones since they have well-established technologies guaranteeing superior visibility with low power consumption. But, to realize a practical flexible LCDs, the serious obstacles should be solved, for example, non-uniform electro-optic (EO) properties under external mechanical distortions originated from LC distortion or cell gap variation [1- 4].

Recently, we showed that such problems could be effectively solved by using pixel-isolated liquid crystal (PILC) mode [5, 6], where the mechanical stabilization for LC molecules alignment and the cell gap uniformity were guaranteed by a polymer wall structure formed by anisotropic phase separation techniques. However, anisotropic phase separation techniques of LC/pre-polymer mixtures were very cumbersome to make the polymer walls and the adhesion between two substrates is rather weak [4- 6]. Therefore, simple fabrication processes for stable flexible LCDs have been continuously proposed. Among them, flexible LCDs on a single plastic substrate are considered to be suitable devices for cost effective roll-to-roll process [3, 7, 8].

In this work, we propose a simple fabricating method of single substrate flexible LCDs by laminating thin photo-curable polymer film to the photo-resist (PR) walls on the flexible plastic substrate. Due to the micro-grooves on the photo-curable polymer film, LC molecules can be aligned homogeneously. With this method, we can simply obtain a stable flexible LCD by adopting a cost-effective roll-to-roll process.

2. Experiments

Figure 1 shows the schematic diagram of proposed single substrate LCD with the laminating technique of the photo-curable polymer film. First, we prepare the photo-curable polymer (NOA65, Norland Ltd.) film as the top substrate.

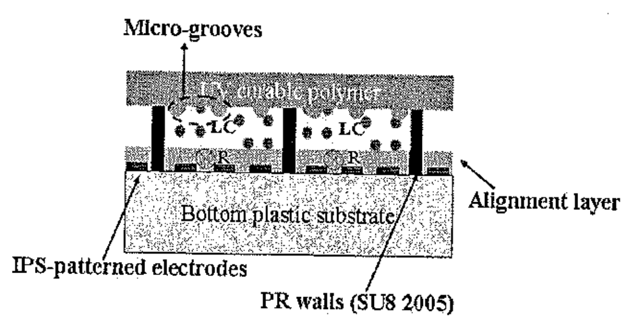


Figure 1. The schematic diagram of proposed single substrate flexible LCD by laminating photo-curable polymer film

The elastomeric PDMS (poly-dimethysilozane) (GE silicon) layer is uniformly formed by spin-coating on the glass substrate. Due to highly hydrophobic properties of the PDMS layer, no material can be coated uniformly on the PDMS. After weakening its hydrophobicity by O_2 plasma treatment, we can obtain a uniform photo-curable prepolymer film by spin-coating. UV is irradiated in a short time to reduce liquidity of the film and photo-initiator density on the spin-coated NOA65 film surface. Then, micro-groove structure are imprinted on the weakly cured NOA65 film using a PDMS master mold with micro-grooves by the replica molding method [11]. After stabilizing the imprinted micro-grooves on the NOA65 film by UV exposure, the PDMS master mold is removed from the NOA65 film. Due to adhesion difference between the top interface (NOA65 surface on the PDMS mold) and the bottom interface (NOA65 surface on the PDMS layer supporting the laminating process), the PDMS mold can be easily removed from the NOA65 film without damaging it. Through these processes, the thin photo-curable polymer film with micro-grooves in partially cured state is prepared on the flexible PDMS supporting film for the lamination process as the top substrate.

Before laminating the photo-curable polymer film with micro-groove structures, we prepare the bottom plastic substrate with periodic walls. Interdigital electrodes for operating the LC molecules by in-plane electric field are formed on a bottom plastic substrate. We used indium-tin-oxide as the transparent interdigital electrodes. Then, patterned PR walls are formed on the bottom plastic substrate for sustaining the cell gap uniformity and isolating the LC molecules. The direction of the PR walls is 45° inclined with respect to the periodic interdigital electrodes. The polymer walls (width: 30μm, height: 8μm) were fabricated by the conventional photolithographic method using a negative photoresist, SU-8 (MicroChem. Co.). On the plastic substrate, polyimide (PI) layer is spin-coated and cured to induce the planar alignment of LCs. In our experiment, RN1199 (Nissan Chemical Ind., Ltd.) was used. The rubbing direction of the PI was same with the wall direction to reduce LC distortion induced by the geometrical effect on LC anchoring of the PR wall structure. After completing the bottom substrate, the photo-curable polymer film with micro-groove structure is laminated on the polymer wall structure of the bottom plastic film by roll pressing. The groove direction of the NOA65 film is parallel to that of rubbing in the bottom substrate. Therefore, in the absence of electric field, the initial LC texture has a uniform planar geometry. The final structure for confining LC molecules in the PILC mode is prepared by removing the PDMS layer followed by full curing of the photo-polymer with final UV exposure. In spite of the chemical modification of the surface of the PDMS supporting layer, the adhesion between the NOA65 film surface and the PDMS surface is weaker than it between the NOA65 film surface on the PR walls, thus the PDMS layer can be easily detached from the NOA65 film without giving damages on the attachment between the NOA65 film and the PR walls.

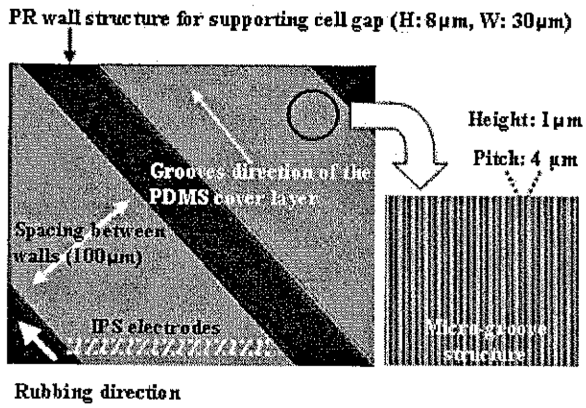
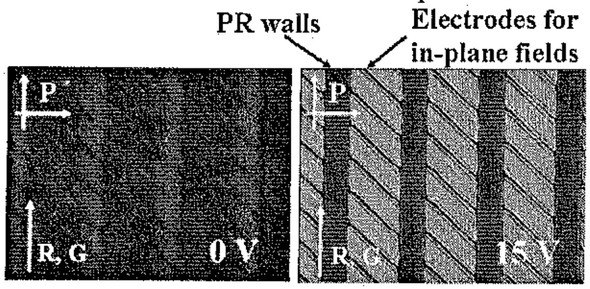


Figure 2. The polarizing microscopic texture of the single substrate LCD by laminating process

Finally, we can obtain the final structure by filling LCs. In our experiment, E7 (Merck Co.) was used. Cured NOA65 film has two roles. One is to provide a boundary surface to confine flow-like LC molecules in a uniform cell thickness with tight adhesion to the top of the PR wall structure through the photo-cured molecules. The other is to work for stable LC anchoring surface through the formed micro-groove pattern. In these procedures, the PDMS layer is used due to the surface energy of it can be easily modified and it has elastomeric properties which are essential in our lamination process.

3. Results and Conclusion

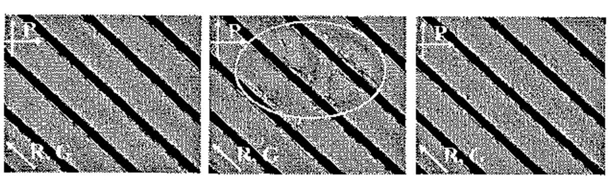
Figure 2 shows the microscopic images of the fabricated flexible LCD, observed under the crossed polarizers. The rubbing direction of LC alignment layer on the bottom substrate and the direction of the micro-grooves on the photo-curable polymer film are rotated as 45° with respect to the transmission axis of the polarizers. Due to the micro-groove structure on the laminated photo-curable polymer film, we could observe that LC molecules were aligned uniformly. On the PR walls, there was no light leakage, which showed that there was no infiltration of LCs in those areas during LC filing and the cover film layer was fully attached to the wall structures in our lamination process.



(a) (b)

Figure 3. The microscopic textures at applied voltages of (a) 0V, (b) 15V under the crossed polarizers

Figure 3 shows the electro-optic (EO) characteristics of our sample with the in-plane switching (IPS) electrodes. The width and the spacing of the electrodes were 10μm and 30μm, respectively. In Fig. 3 (a), the LC orientation in the field-off state (0V) was parallel or orthogonal to the transmission axes of the polarizers. Thus, the dark state was observed. As increasing the applying voltages, the textures (Fig. 3 (b)) became brighter due to in-plane LC reorientation along the field direction. All the LC textures under the applied voltages were also highly uniform.



(a) (b) (c)

Figure 4. Alignment texture of (a) before, (b) after mechanical pressure and (c) passed 30 seconds with sharp tip.

Figure 4 shows alignment textures before and after pressing with sharp tip. Right after the external pressure, we can see the color change due to the reorientation of LC molecules. After 30 seconds, the alignment is recovered and the alignment texture is exactly same as the initial texture before pressure. Even with various bending conditions, we confirmed that the EO characteristics are not much changed. This verifies that the good mechanical stability of LC alignment in the proposed structure can be achieved by laminating technique.

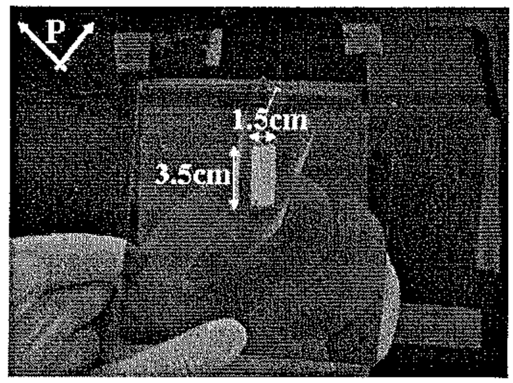


Figure 5. The prototype of single substrate flexible LCD in the bent state

Figure 5 shows the prototype of our single substrate flexible LCD in the bent state. The contrast ratio and response time were about 130:1 and 20ms, respectively. From the results, we confirmed that the EO characteristics of single substrate flexible LCD by our laminating method is comparable to that of conventional LCDs with glass substrates.

We proposed a new fabrication method of sigle substrate flexible LCD. Our technique enables the mechanically stable LC structure with tight bonding of two substrates. Due to the azimuthal anchoring of the micro groove structure on the photo-curable polymer film, we can obtain various modes without restriction on single substrate. With the proposed methods, fabrication of flexible LCDs can be achieved by roll-to-roll process on a single substrate.

4. Acknowledgements

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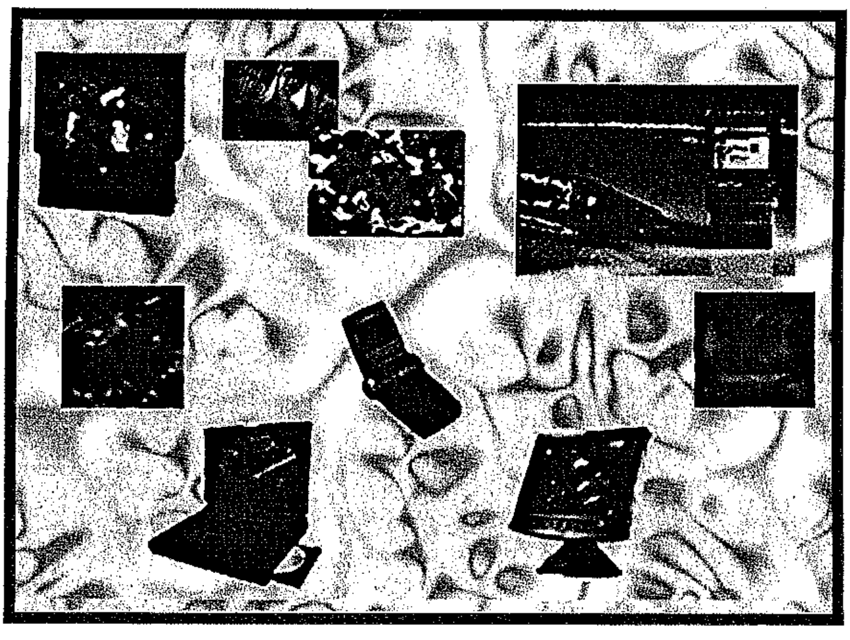

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P19. Fabrication of Flexible LCD by Laminating Photo-curable Polymer Cover Film

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