Colloidal Self-Assembly Route to Flexible Cholesteric LCDs and Other High-Efficiency Displays

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Abstract

We describe a unique process based on colloidal self-assembly that results in a uniform (almost hexagonally close-packed) layer of liquid crystal domains over large areas leading to single-substrate cholesteric LCDs with low switching voltages, excellent contrast, and high brightness. Extension to guest-host LCDs is also discussed.

1. Introduction

Flexible cholesteric liquid crystal displays (ChLCDs) constitute a potentially attractive option for low-power digital signage. These polarizer-free displays are reflective and may be read in ambient light without a backlight for illumination. Furthermore, the displays are bi-stable. Power is needed only at the time of writing the display and is not required to maintain the image after it has been written. These features result in significantly lower power consumption compared to conventional LCDs (that require polarizers and backlights and are not bi-stable). An added advantage of ChLCDs is that the electro-optic response is such that it is possible to operate large-area multiplexed displays based on simple passive-matrix addressing [1]. However, a major drawback is the relatively high switching voltages caused by nonuniformity of the coated liquid crystal layer leading to high driver cost. A significant challenge is to achieve flexible displays by single-substrate, roll-to-roll (R2R) fabrication methods that demonstrate driving voltages and overall electro-optic response comparable to capillary-filled glass cell displays.

A single-substrate construction typically involves coating or printing a polymer-dispersed liquid crystal (PDLC) film on a conductive plastic surface followed by a barrier layer and a layer of conductive ink. This is to be contrasted with the traditional method for fabrication of LCD screens wherein two sheets of conductive glass are maintained at a fixed separation using spacers, and the liquid crystal material is imbibed between the glass sheets. The architecture of the PDLC film is critical for achieving good performance in single-substrate formats. In particular, it is important to achieve films of very uniform thickness and low surface roughness over large areas as the switching voltage is directly related to the thickness of the film.

Broadly speaking, PDLC films may be made either by emulsion methods or by phase separation methods. In the classic emulsion method, the liquid crystal is simply mixed with an aqueous solution of polymer and emulsified by a suitable shearing device. The resulting emulsion is coated onto a conductive substrate and dried to form the PDLC film. While the method is straightforward to implement, it gives very broad droplet size distributions that lead to films of uneven thickness that lead to poor performance. Phase-separation methods exemplified by the polymerization-induced phase separation (PIPS) process [2] provide PDLC films with narrower droplet size distributions; however, they are difficult to implement on a large scale, particularly in a single-substrate format.

Here we demonstrate a new approach for fabrication of single-substrate PDLC films leading to devices exhibiting electro-optic properties approaching glass cell and two-substrate devices [3,4]. Our approach is based on three main ideas: (1) that relatively uniform droplets of liquid crystal material (with polydispersities less than 20%) may be prepared at high throughput by the limited coalescence or Pickering emulsion method using particulate stabilizers [5,6], (2) the droplets undergo drying-assisted self-assembly (DASA) [7] on the surface of indium tin oxide (ITO) to create a close-packed (pseudo hcp) monolayer, and (3) the close-packed assembly of droplets may be permanently fixed or preserved to allow integration with other functional layers in the device. We first discuss application of the method to flexible ChLCDs and then briefly discuss extension to flexible guest-host LCDs.

2. Results

Figure 1 shows DASA of droplets of liquid crystal (diameter close to 10 µm) that have been prepared by limited coalescence and then combined with aqueous gelatin and subsequently spread on ITO-coated polyethylene terephthalate (PET). The micrograph shows two-dimensional ordering of droplets by capillary attraction when the height of water in the drying film is approximately equal to the diameter of the coated droplets. The transition from the disordered (wet) region (lower left portion of the micrograph) to the fully ordered close-packed and dry region (upper right corner) is evident.

Figure 1. Drying-assisted self-Assembly (DASA)

Figure 2 is a micrograph of a final close-packed monolayer of cholesteric liquid crystal (CLC) droplets in transmitted light. The droplets are composed of a mixture of MDA-01-1955 and MDA-00-3506. Both components were obtained from Merck, Darmstadt, Germany. The proportion of MDA-01-1955 and MDA-00-3506 was adjusted to give a reflection band in the visible region. The fully dried monolayer has a uniform thickness close to 5 µm and the root mean square (rms) surface roughness is less than 0.2 µm. Calculations have shown that for a CLC material of given handedness, close to maximum reflectance is obtained if the thickness of the CLC material is about ten times the pitch of the chiral nematic helix [8]. For CLC materials that reflect visible light, a uniform thickness close to 5 µm is most desirable for obtaining maximum brightness in conjunction with high contrast (because of reduced back-scattering).

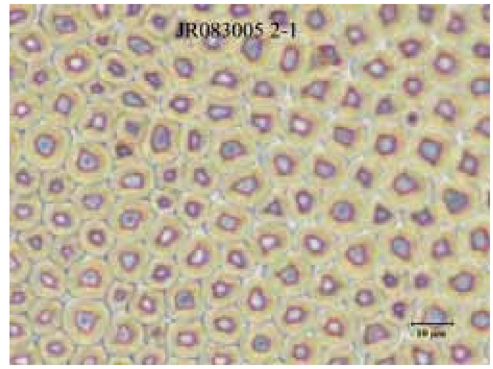

Figure 2. Close-packed PDLC array

The binder in the close-packed PDLC film (shown above) is cross-linked to preserve the architecture prior to applying a protective overcoat containing a contrast control agent such as dispersed carbon black. A conductive ink formulation is printed over the protective overcoat and cured to complete construction of the device. A schematic of the completed device is shown in Figure 3.

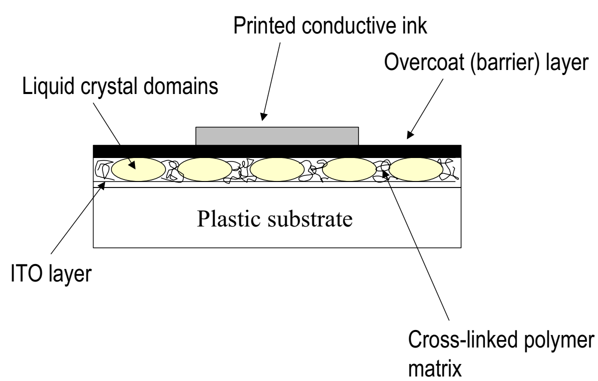

Figure 3. Schematic of single-substrate display device

The electro-optic response of the device is shown in Figure 4. The horizontal axis indicates the amplitude of the addressing voltage pulse, and the vertical axis indicates reflectance measured 0 V and 2 s after application of the voltage pulse. The latter was a square wave with a frequency of 1000 Hz and duration of 100 ms. Reflectance was measured using an X-rite 938 spectrodensitometer. The open triangles represent the response when the CLC material was initially in the planar texture, and the closed circles represent the response when the material was initially in the focal conic state. A voltage pulse higher than 63 V switched the display into the bright state and a voltage pulse between 27 and 41 V switched the display into the dark state. Voltages less than 8 V did not influence the state of the display. Once switched, the image was stable without power in both the bright and dark states

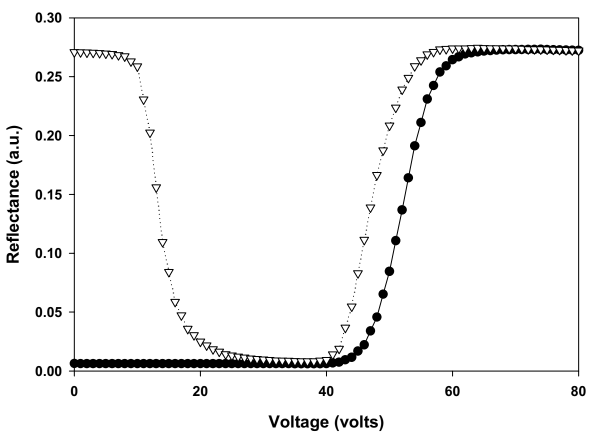

Figure 4. Electro-optic response of CLC display device

The maximum voltage (63 V) is consistent with the geometry of the device considering the voltage drop across the CLC material and the thickness of the protective overcoat, and it is only marginally higher than voltages measured in two-substrate PDLC devices prepared, for example, by the PIPS process. The display has a peak reflectance of approximately 32%, and the contrast ratio under diffuse illumination excluding specular reflection (measured using a six-inch integrating sphere) is about 9. The 45/0 contrast ratio is about 30. Figure 5 is a photograph of an image on a 32 × 32 passive-matrix display.

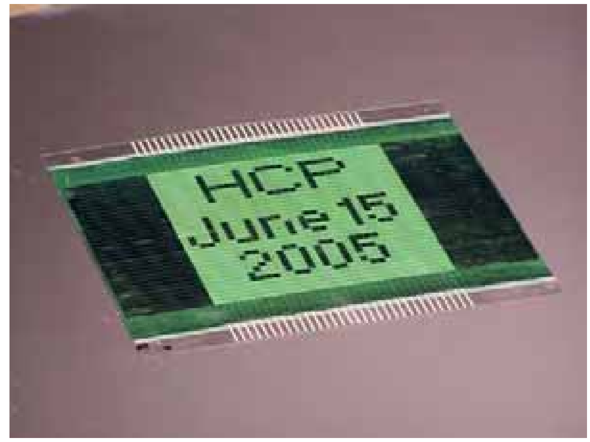

Figure 5. Example of 32 × 32 passive matrix flexible cholesteric liquid crystal display

Although ChLCD devices such as the one shown above have many desirable features suitable for digital signage applications, one may argue that they have more of an “electronic” appearance rather than a paper-like or ink-on-paper appearance that may be important in some situations. The color of cholesteric liquid crystal displays is based on Bragg reflection, which for on-axis viewing is given by $\lambda = nP$, where λ is the wavelength of reflected light, n is the refractive index of the cholesteric liquid crystal mixture, and P is the pitch of the cholesteric or chiral nematic helix. The color of guest-host PDLC displays is based on the absorption of light by a dichroic dye in a nematic host and bears a closer resemblance to ink on paper. Guest-host PDLC displays are also polarizer-free and operate without backlights.

Conventional methods for fabricating guest-host PDLC displays suffer from some of the same problems outlined earlier. Furthermore, ultraviolet (UV) radiation used in the PIPS process may cause degradation of dichroic dyes. There may also be partitioning of dye into the polymer matrix during phase separation with resulting loss in performance. To overcome these difficulties, Masutani et al. [9] have suggested a method wherein a porous polymer matrix is first prepared by a two-substrate PIPS process to obtain uniform domain size and subsequently is filled with a liquid crystal formulation containing dichroic dye. Clearly, it is much preferable to obtain a PDLC display having uniform domain size by a single-substrate fabrication process.

Figure 6 shows an initial version of a flexible guest-host PDLC display based on the nematic liquid crystal mixture BL087 from Merck containing 1 wt % dichroic dye Blue AB4 from Nematel (order paramenter ~0.7) prepared by the process described in Figures 1–3 with the exception that the barrier layer now comprised titania particles in place of carbon black to provide a white background. The blue (off) and white (on) states are clearly distinguished. A contrast ratio close to 3 is obtained at 40 V when the display is driven by a 1000 Hz square wave. The use of dyes with higher order parameters, coupled with improvements in barrier layer technology, should enable single-substrate guest-host flexible displays with high contrast ratios, and low switching voltages.

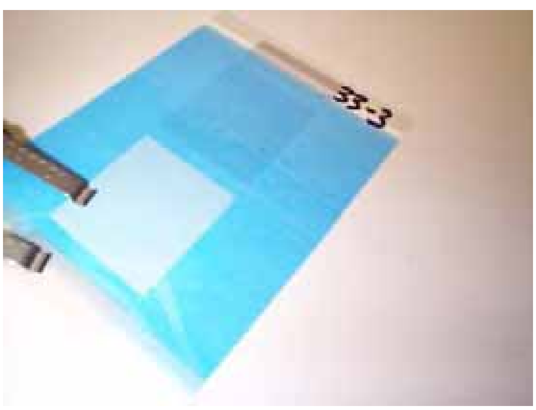

Figure 6. Single-substrate guest-host PDLC display

3. Conclusion

We have demonstrated a new emulsion-based single-substrate fabrication process for PDLC displays. The approach enables high-performance flexible LCDs at low cost. Examples of both cholesteric and guest-host displays have been given.

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5. References

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