# Flexible Cholesteric LCDs by Colloidal Self-Assembly

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## Abstract

*We describe a new approach for fabrication of cholesteric liquid crystal displays on flexible substrates based on drying-assisted self-assembly of uniform droplets of liquid crystal. Key steps in the process include creating a close-packed monolayer of microsized droplets of liquid crystal in a polymer matrix on a conductive plastic surface, chemically crosslinking the polymer matrix to preserve the close-packed microcellular architecture, applying a protective overcoat containing a contrast control agent, and then applying a conductive ink by screen printing. The very uniform close-packed microcellular array of liquid crystal droplets may be fabricated on a large scale on moving web coating machines. Displays prepared by this technology exhibit low switching voltages, high contrast, and good brightness.*

## Introduction

There is currently a transition in the marketplace from the bulky cathode ray tube (CRT) display devices to the lighter and more compact flat panel devices for applications ranging from desktop and laptop computers to TVs. It is expected that the next generation of electronic display devices will be thinner, even lighter, and flexible or conformable [1]. These flexible electronic displays are also likely to find application in automobiles, signage, e-paper, and e-books. Furthermore, it is anticipated that the displays will be fabricated via efficient roll-to-roll (RTR) manufacturing processes.

A promising approach for flexible electronic displays is based on polymer-dispersed cholesteric or chiral nematic liquid crystal (CLC) materials. The materials enable construction of reflective displays that are bistable. Furthermore, the electro-optic response is such that it is possible to operate large-area multiplexed displays based on simple passive-matrix addressing [2]. However, the performance of these materials has so far fallen short of optimum in terms of drive voltage, contrast, and brightness, particularly in potentially low-cost single-substrate devices. The problem lies in the architecture of polymer-dispersed liquid crystal (PDLC) films. The preparation of monolayer films with uniform cell dimensions by processes such as coating or printing remains a challenge.

Here we demonstrate a new single-substrate approach for fabrication of polymer-dispersed cholesteric liquid crystal displays that exhibit electro-optic properties approaching glass cell and two-substrate devices. The single-substrate approach 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. It is preferable to start with a single conductive surface and build the device by potentially lower cost, higher throughput processes such as coating or printing. Our approach is based on two main ideas: (1) that relatively uniform droplets of the CLC material (with polydispersities less than 20%) may be prepared by the limited coalescence or Pickering emulsion method using particulate stabilizers [3,4], and (2) the droplets undergo drying-assisted self-assembly on the surface of indium tin oxide (ITO) to create a close-packed (pseudo hcp) monolayer. The mechanism of two-dimensional ordering of droplets has been described by Denkov et al.[5]. The process is driven by capillary attraction when the surfaces of the droplets protrude from the water layer. In other words, the droplets spontaneously self-assemble into a close-packed array when the level of water in a drying film is approximately equal to the height of the droplets provided there is no resistance to self-assembly such as anchoring of the droplets to the surface of ITO or a high viscosity of the medium. The uniformity of packing and surface roughness depends on the droplet size distribution. Narrower size distributions result in more ordered (hexagonal close-packed or hcp) arrays and lower surface roughness.

## Results and Discussion

Figure 1 shows the close-packed monolayer structure of PDLC films comprising droplets of CLC material prepared by limited coalescence that have been combined with an aqueous solution of polymer, spread on ITO coated polyethylene terephthalate (PET), and dried. The CLC material was a combination of MDA-01-1955 (74.6 wt%) and MDA-00-3506 (25.4 wt%) with a reflection band centered at 590 nm. Both constituents were obtained from Merck, Darmstadt, Germany. The droplets prior to coating and drying had a mean diameter of 9.7 μm with a coefficient of variation of 0.14. After coating and drying, the initially spherical droplets became ellipsoidal in shape with a thickness close to 5 μm. The root mean square (rms) surface roughness of the dried film was 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 between the electrodes is about ten times the pitch of the chiral nematic helix [6]. 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) and low switching voltage, the latter being directly proportional to the thickness of the film.

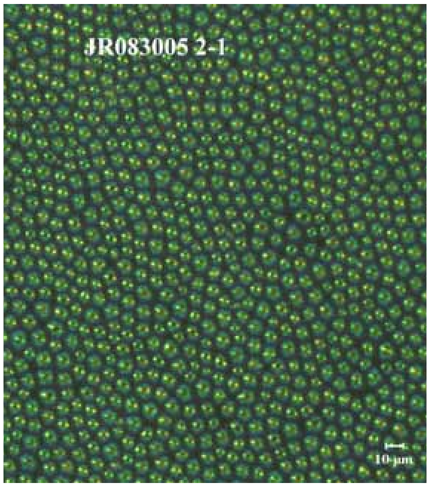

***Figure 1**. Reflected light optical micrograph of close-packed monolayer of CLC droplets prepared by drying-assisted self-assembly*

The polymer in the PDLC film is subsequently crosslinked to allow a water-based protective overcoat containing dispersed carbon black or other contrast control agent to be applied without disturbing the close-packed architecture. Figure 2 shows a roll of the polymer-dispersed CLC display fabricated on a moving web coating machine after the protective overcoat has been applied. A conductive ink formulation is screen-printed over the protective overcoat to complete construction of the device.

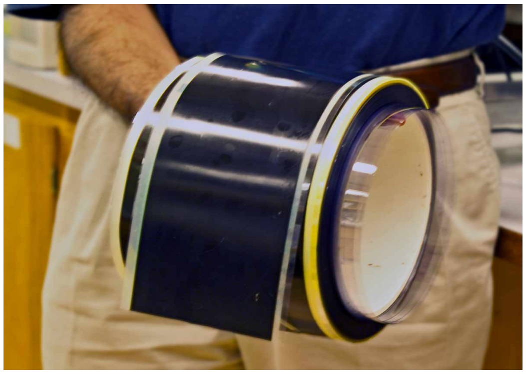

***Figure 2**. Roll of polymer-dispersed CLC display with close-packed monolayer architecture after the protective overcoat (containing dispersed carbon black) has been applied*

Figure 3 shows the electro-optic response of the device. The horizontal axis indicates the amplitude of the addressing voltage pulse, and the vertical axis indicates reflectance measured at 0 V and 2 s after application of the voltage pulse. The latter was a square wave with a frequency of 1 kHz 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 or bright state, and the closed circles represent the response when the material was initially in the focal conic or dark 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.

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 polymerization-induced phase separation 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.

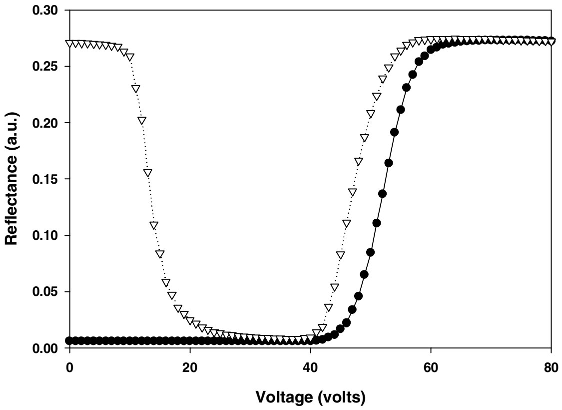

*Figure 3. Electro-optic response of flexible single-substrate CLC display based on colloidal self-assembly*

In summary, we have demonstrated a single-substrate bistable and passive matrix-addressable electronic paper device based on a close-packed polymer-dispersed cholesteric liquid crystal film on a flexible surface. The device has been successfully fabricated on moving web coating machines and exhibits electro-optic performance approaching glass cell and two-substrate constructions.

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## Author Biographies

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*David M. Johnson received his B.S. in computer engineering from the Rochester Institute of Technology. David has been the lead electrical engineer for Kodak's flexible cholesteric liquid crystal displays focusing on drive schemes, electronics, and prototype development. Currently he is responsible for electronics and firmware designs for alternate display technologies in Kodak's Display Science and Technology Center.*

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