

## 6.4: Single Substrate Coatable Multicolor Cholesteric Liquid Crystal Displays

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### Abstract

*This paper describes new ultra-thin multicolor cholesteric liquid crystal displays with all functional layers coated sequentially on a single flexible substrate. Shared electrode driving is implemented for the first time to drive a passive matrix multicolor emulsion based displays comprising of three stacked layers of cholesteric droplets embedded in a polymer matrix.*

### 1. Introduction

Cholesteric liquid crystal displays (ChLCDs) have earned growing popularity due to their pure reflective nature, bistability, low power consumption, high brightness and contrast. The application of glass ChLCDs currently ranges from small displays for electronic books, map readers, instrumentation displays, and handheld devices to large area signage displays. ChLCDs are particularly well suited for update-on-demand applications, because the image can be retained without any applied power. The bistable nature of the technology means that power is needed only to update an image [1].

The main existing research efforts are focused on the development of the next generation of flexible ChLCDs with improved electro-optical performance. In these efforts, one of the challenges is the development of full color displays with high brightness. Selective reflectance of ChLCs allows for implementation of color displays by stacking display layers with different pitch lengths on top of each other. This additive color approach results in elimination of color area sharing and enables high brightness of the reflected light due to the fact that full area of the display reflects each color. However, it raises the importance of the transmission losses in multiple conducting electrodes and substrate layers in the stack design.

Typical glass full color ChLCDs have a triple stack of primary colors and each color layer is addressed by its own pair of indium-tin oxide (ITO) electrodes. This brings the total number of conducting electrodes up to 6 and the number of substrates to 4 or 6 [2-3], depending on the approach. Reducing the number of conducting electrodes and increasing their transmission are critical for achieving high reflectivity. This is especially true for the bottom and middle display layers.

Recently we have demonstrated a new web compatible technology for fabrication of flexible monochrome ChLCDs coated on a single substrate [4-5]. All display functional layers from bottom-up are sequentially coated on thin plastic, paper, or textile substrates using conventional coating and printing techniques. The display layer consists of micron sized ChLC droplets encapsulated in polymer a matrix created by emulsification methods. Encapsulation of liquid crystal enables the deposition of rugged

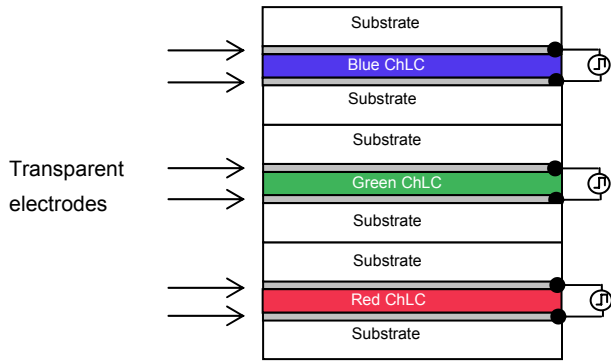
cholesteric thin films which are pressure insensitive and flexible. Transparent flexible conducting polymers are used for top and bottom electrodes. Ruggedness of the encapsulated ChLC layer, flexibility of the conducting polymer electrodes, and the use of a single substrate provide highly conformable reflective displays, which can be folded, flexed, and draped during image addressing.

The goal of this paper is to advance our coatable single substrate display approach further from monochrome to multicolor display. We present, for the first time, emulsion-based multicolor cholesteric displays using sequential coating for color stacking of liquid crystal layers of different pitch length. Implementation of shared electrode concept to reduce the number of driving electrodes is used for the first time to drive the color display layer stack. The paper describes display fabrication, display performance, and shared electrode driving for direct drive and multiplexed addressing.

### 2. Color Stacking in ChLC Displays

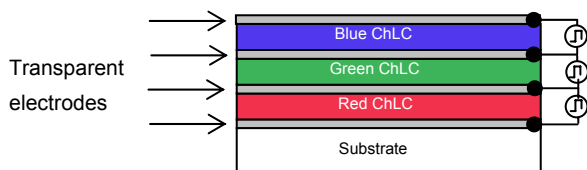
Unique optical properties of cholesteric LCs allow for fabrication of full color displays by stacking several display elements. Helical molecular structure of the cholesteric liquid crystal assemblies either in right handed or left handed helices resulting in maximum reflectance of 50% of the incident light with one handedness of circular polarization. Wavelength selectivity permits Bragg reflection at certain wavelengths determined by helical pitch of the ChLC material. The incident light with all other wavelengths is fully transmitted through the liquid crystal layer. The transmitted light is available for further reflection if cholesteric display elements with different pitch lengths are stacked on top of each other.

This enables high reflectivity due to the fact that the full area of each pixel can reflect each color. The absence of the light absorption by cholesteric LCs allows for fabrication of full color displays with triple stacking of primary colors. Typically, for the triple color stack with glass or plastic substrates three individual displays with primary colors are assembled on top of each other bringing the number of substrates and transparent electrodes to six. Figure 1 shows the conventional implementation of cholesteric color displays with stacking three individual displays each driven independently by its own pair of electrodes. Due to some index mismatch and light absorption in the electrode material each electrode contributes to the display reflectivity losses especially due to the fact that light reflected from display passes twice through each electrode. This makes the transmission of electrode material and the number of electrodes critical for the display reflectance.



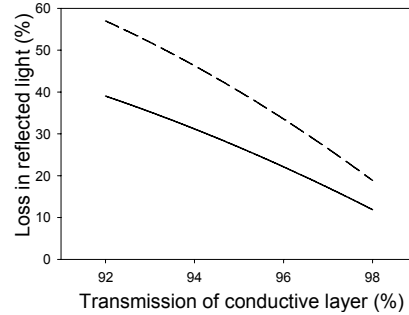
**Figure 1.** Schematic illustration of the conventional color stacking for ChLCDs. To drive the color stack six substrates and transparent electrodes are employed. Each display layer is addressed independently by its own pair of electrodes.

We have developed a new concept of coatable multicolor displays with a single substrate and reduced number of addressing electrodes. Figure 2 illustrates the concept of coatable multicolor stack. Each display layer can be addressed individually with shared electrodes which reduces number of electrodes to four. For shared electrode design each color layer has one or two common electrodes. A common electrode provides driving voltage to two display layers at one time.



**Figure 2.** Schematic illustration of the proposed color stacking for coated ChLCDs with four transparent electrodes. All display layers are coated on single substrate.

The use of only one substrate results in thin and highly flexible color display which can be coated on any desired substrate, while shared electrodes provide an improvement in the display reflectivity. Figure 3 demonstrates the results of simple calculation to compare reflected light losses for bottom display layer in triple stack for conventional color stacking approach (dashed curve) and proposed shared electrode design (solid curve). It is especially important when conducting polymers are used as an electrode material. Conducting polymers are attractive alternative to conventional ITO and provide flexibility and ease of processing. However, typical conducting polymers exhibit some light absorption which results in a decrease of the display brightness.

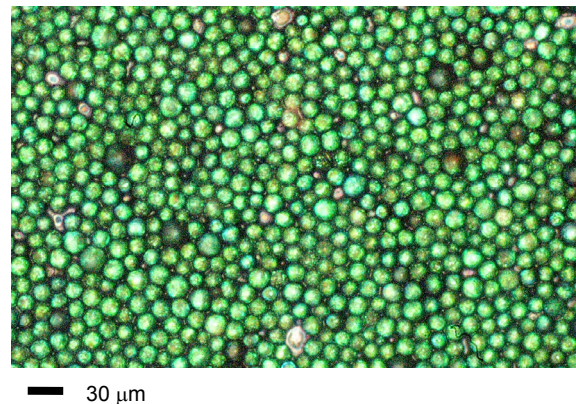


**Figure 3.** Improvement in reflectivity from bottom ChLC layer in triple color stack for shared electrode design (solid curve) in comparison with the conventional color stacking approach (dashed curve). The curves are calculated for typical transmission values of the best available conducting polymers showing the surface resistance of 1-2 kΩ/sq.

### 3. Display Fabrication

#### 3.1 Emulsification

The coatable material for display layers consists of a water-based cholesteric emulsion prepared using a membrane emulsification technique which allows for forming uniformly sized liquid crystal droplets [6]. The droplet size can be controlled by the membrane pore size and pressure of nitrogen gas carrier pushing liquid crystal through the porous glass membrane. This method allows us to achieve a narrow droplet size distribution with a desirable mean droplet size. Figure 4 shows a polarizing microscope image for the single droplet layer coated from typical emulsion with the mean droplet size of 18 μm. Size uniformity is beneficial for dense droplet packing during coating and drying processes and results in higher display reflectivity.

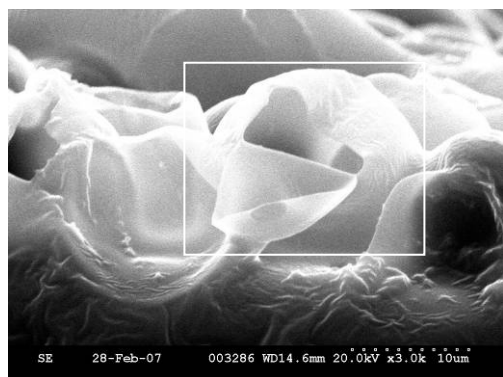


**Figure 4.** Polarizing optical microscope image of the cholesteric droplets in the display layer. The scale bar is 30 microns.

After emulsification we introduce an extra step for microencapsulation of each individual liquid crystal droplet by a thin impermeable polymer shell. The polymer shell thickness is small (around 100-200 nm) in comparison with the droplet size (12-20 μm) and only minimally reduces the display brightness.

Moreover, the thin shells do not hinder the droplet flattening during drying which is important for high brightness. Despite the small thickness, the shells are continuous and do not allow the liquid crystal to permeate through. This enables the coating of ChLC layers with different pitch length on the top of each other without any liquid crystal mixing.

Figure 5 shows an SEM image of an empty polymeric shell to demonstrate the shell thickness. The display layer was frozen in liquid nitrogen and mechanically cut to expose ruptured droplets at the edge of the coating.



**Figure 5. SEM image of a ruptured polymeric shell. The thickness of the shell (shown inside the white rectangle) is estimated to be less than 200 nm.**

Addition of a small concentration of a film forming polymer binder to the cholesteric microencapsulated emulsion enables the creation of solid films after water drying. The spherical droplets undergo some flattening during the drying process.

### 3.2 Display Coating

The multicolor displays were built from bottom-up by coating and printing the display layers on the top of each other on a single substrate. The conducting polymer based on PEDOT:PSS, poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) is the chosen electrode material because it can be printed from a water-based solution and can be cured at low temperature. Moreover it provides better flexibility than conventional ITO. Use of water-based solutions is critical for printing directly on the display layer to keep its integrity and to prevent dissolving of coated and dried layers.

The first conducting polymer electrode (E1) is screen-printed either on thin plastic substrate or planarized fabric substrate to create a patterned electrode. The LC emulsion (LC1) is then coated using a knife-over-roll method on the substrate with the conducting electrode (E1) and the water from the emulsion is allowed to evaporate. The next conducting polymer electrode (E2) is deposited over the encapsulated layer (LC1) using air brushing method with a stencil for patterning and is cured at room temperature. Then, the emulsion (LC2) with a different ChLC pitch length is coated on the top of the E2 electrode. The third conducting polymer electrode (E3) is air-brushed over the LC2 layer using a stencil with electrodes orthogonal to the E2. The last emulsion layer (LC3) with a different ChLC pitch length is coated

on the top of the E3 electrode. The last conducting polymer electrode (E4) electrode is air-brushed over the LC3 layer using stencil with electrodes orthogonal to E3. The very last layer is a protective clear thin polymer layer coated on the top to enhance the durability of the display. Flexible printed circuits are bonded using conductive tape over the conducting polymer electrodes.

The thickness of individual encapsulated LC layers is in the range of 12  $\mu\text{m}$ . Drying of all wet coatings is performed at room temperature. It should be noted that the conducting polymer electrodes can be also ink-jet printed providing the path for higher display resolution.

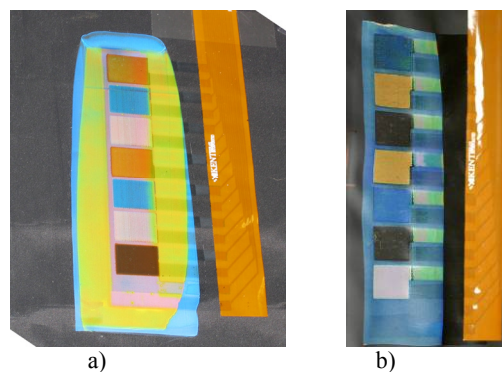
## 4. Shared Electrode Display Driving

Two different driving schemes have been implemented for the shared electrode design: direct drive and multiplexing.

### 4.1 Direct Drive

The most basic system for demonstrating a shared electrode design is a single pixel. The bistability of the cholesteric liquid crystal permits each LC layer to be updated in sequence without the need for a refresh. In this simple direct drive design, arbitrary drive waveforms may be applied for updating each LC layer in sequence, with no voltage appearing across the other layers by proper application of drive waveforms to the electrodes.

A variation of this system has been implemented for a seven pixel display comprised of two LC layers with all pixels sharing a common electrode. Electrode E2 is common to all seven pixels in both layers. Arbitrary drive waveforms can be placed across the pixels in either LC layer without affecting the other one by driving all the electrodes for the inactive layer (E1 or E3) equal to the common (E2). Figure 6 shows photographs of fully functional double color cholesteric displays coated on a PET substrate (Figure 6a) and on a rayon fabric (Figure 6b) driven with direct drive. Each pixel consists of two individually addressed layers with yellow and blue ChLCs. Depending on the switching state of the layers the display is able to exhibit white, black, blue and yellow colors. Each of the seven pixels can exhibit any of the four colors.



**Figure 6. Photographs of double color stack cholesteric displays with the direct drive addressing scheme using one shared electrode: a) display coated on a 5 mil PET substrate; and b) display coated on a rayon fabric substrate.**

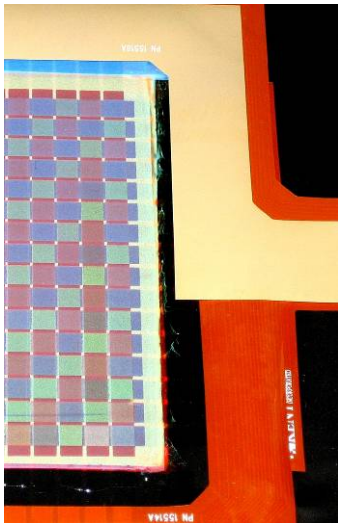
## 4.2. Multiplexing

While relatively simple to implement, the direct drive scheme is possible for only limited resolutions. Higher resolution graphical displays require a multiplexed approach. Fortunately, ChLCDs have a voltage threshold which is capable of supporting multiplexing.

The update scheme for multiplexed displays is similar to the direct drive approach in that, once again, each LC layer is updated in sequence. However, the update of a layer now involves a scan across the rows (commons) for the layer being updated. Typical multiplex row and column (segment) select and non-select waveforms are used for driving a layer such that the selected row gets image content while the remainder of the layer experiences a non-select voltage below its threshold.

The new constraint added by the shared electrode design is that previously updated layers must experience only voltages below their thresholds as subsequent layers are updated. Accomplishing this task requires the ability to switch the functionality of electrodes between row and column modes depending on which layer is currently updating. Note that electrode layers E1 and E3 are orthogonal to electrodes E2 and E4 as required for a matrix addressing scheme.

This driving scheme has been implemented for a coated display comprised of three LC layers (red, green, and blue) with E2 and E3 electrodes serving as shared electrodes. Figure 7 shows a photograph of the multiplexed triple color stacked ChLCD fabricated on a PET substrate with coated RGB layers and four electrodes, where two are shared.



**Figure 7. Triple color stack cholesteric display coated on a 5 mil PET substrate with the passive matrix multiplexing scheme using four electrodes where two are shared.**

The update sequence for the triple stack permits each layer to be driven with a unique set of drive parameters. The only requirement is that the nonselect waveforms generated when driving one layer have voltages below the thresholds of the previously updated layers. This requires a thoughtful ordering of the update sequence.

The detailed description of the multiplexing approach and complete update sequence will be published elsewhere.

## 5. Conclusions

We have demonstrated the feasibility of fully coated multicolor ChLCDs on a single substrate. The shared electrode design increases the display brightness by reducing the number of driving electrodes. In the future, multicolor ChLCDs can be coated on highly flexible single substrates on roll-to-roll lines at low cost facilitating new applications for rollable, foldable and conformable displays.

## 6. Acknowledgements

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## 7. References

- [1] D.-K. Yang, and J. W. Doane, "Cholesteric liquid crystal/polymer gel dispersion: reflective display application" *SID Symposium Digest*, **23**, pp.759-762, 1992.
- [2] D. Davis, A. Khan, X.Y. Huang, J. W. Doane, "Eight-Color High Resolution Reflective Cholesteric LCDs", *SID Symposium Digest*, **29**, pp. 901-904, 1998.
- [3] X.Y. Huang, A. Khan, D. Davis, N. Miller, J. W. Doane, "Gray Scale of Bistable Reflective Cholesteric Displays", *Proc. 18<sup>th</sup> Asia Display*, **18**, pp. 883-886, 1998.
- [4] I. Shiyanovskaya, A. Khan, S. Green, G. Magyar, J. W. Doane, "Single Substrate Encapsulated Cholesteric LCDs: Coatable, Drapable and Foldable", *SID Symposium Digest*, **36**, pp.1556-1559, 2005.
- [5] I. Shiyanovskaya, A. Khan, N. Miller, K. Bellamy, D. Marhefka, et al., "Novel Coated and Transferred Cholesteric Liquid Crystal Display", *Proc. IDRC.*, **25**, pp.180-183, 2005.
- [6] I. Shiyanovskaya, A. Khan, G. Magyar, S. Green, O. Pishnyak, and J. W. Doane, "Substrate-Free Cholesteric Liquid Crystal Displays", *Proc. IDRC.*, **26**, pp.32-34, 2006.