New Developments in Full Color Flexible Reflective Cholesteric Liquid Crystal Displays

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Abstract

We present recent developments in full color bistable reflective cholesteric liquid crystal displays on flexible substrates. The approaches include stacking of three reflective layers (red, green and blue) on top of each other or a spatial separation (area sharing approach) of reflective layers from each other within one layer. Stacking is possible due to selective reflection properties of cholesteric layers. Each layer of the display can be addressed independently to vary the reflectance of each color yielding many possible colors. The advantage of the approach is that the display is producing a full brightness of each primary color. The advantage of the area sharing approach is its superior contrast and simplicity, as only one layer is required; that can significantly reduce the cost of the device. The developed cholesteric materials for full color displays can be easily laminated between the flexible substrates, and, possible, coated or printed. We are currently successfully implementing the developed technologies enabling low cost, low power, low weight and rugged display applications, such as writing tablets, electronic skins and electronic books.

1. Introduction

Modern display technologies ranging from high resolution TVs and eBooks to relatively low resolution signage displays require low power, low weight and low cost. To be competitive modern display devices should be capable of producing full color images. Color is very important part of human perception. Color can attract or distract, affect the emotional state of a human being, change the body pressure and raise the appetite. For the display device, while an aesthetic component is also important, using color is mostly about visualizing the information in a more clear, more attractive and enhanced way in comparison with a monochrome display.

Kent Displays is a world leader in development of bistable reflective cholesteric liquid crystal displays (ChLCDs) branded as Reflex™ displays [1,2]. Utilizing plastic substrates the developed displays are thin, rugged and flexible. Thanks to Reflex technology they consume no power after switching to the required state.

Cholesteric liquid crystal (ChLC) is a type of nematic liquid crystal (LC) doped with a so-called *chiral dopant* to force the liquid crystal molecules to continuously twist into a helical spiral with a certain pitch p forming a periodic structure capable of the reflecting 50% of the incident light [3]. ChLC can be switched between two stable states, the so-called *planar* or reflective and transparent/slightly scattering *focal conic* states, Figure 1. The display contrast between bright planar state and dark focal conic state is created by coating the bottom substrate with absorbing layer (black paint) to absorb the light passing through the layer. In a perfect planar state only right or left circular polarized light gets reflected depending on the handedness of the cholesteric helix, Figure 1. For the normal incidence the reflection of light occurs within a certain bandwidth $\Delta\lambda = (n_{\parallel} - n_{\perp})\,p$, where $n_{\parallel}, n_{\perp}$ are the components of refractive index locally parallel and perpendicular to the director (a unit vector representing the preferred orientation of LC molecules). Cholesteric pitch p which is defined through the concentration of a chiral dopant c and *helical twisting power* (HTP) of a chiral dopant as follows: $p = \dfrac{1}{c \cdot HTP}$. HTP is a function of a chiral dopant and LC host used. As ChLC layer with a fixed pitch is capable to reflect only a portion of light spectrum then to achieve a full color display several approaches may be utilized.

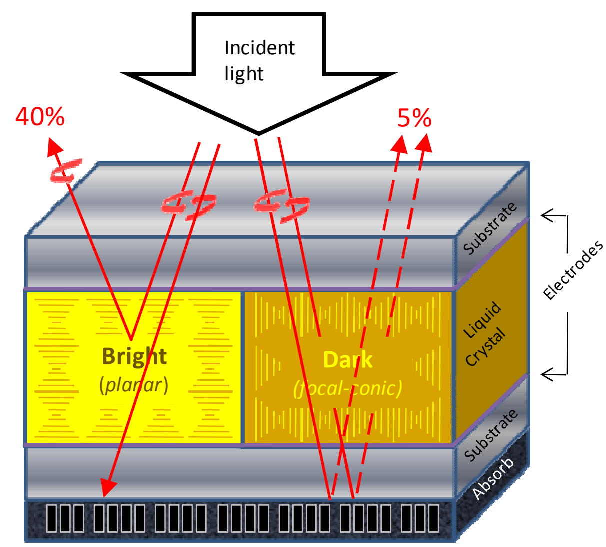

***Figure 1.** Schematic of a single layer ChLCD. The display can be switched between reflective planar and transparent focal conic states. The absorbing layer extinguishes the light passing through the cholesteric layer creating the contrast of the device.*

2. Achieving full color ChLCDs

In conventional full color LCDs each pixel is divided into 3 segments or sub-pixels, which are covered by red, green and blue (R G B) color filters, respectively. As the transmission of each sub-pixel can be electrically controlled independently, the transmitted light can yield many possible colors due to additive nature of color. Since ChLC is a natural light reflector, there is no need for additional color filters; to create three primary R G B colors stacking [4] and pixelization [5, 6] approaches can be used as discussed in the following sections.

2.1. Stacking approach

In the stacking approach, 3 layers of ChLC with pitches tuned to reflect R G B primary colors, respectively, are laminated on top of each other as shown schematically in Figure 2.

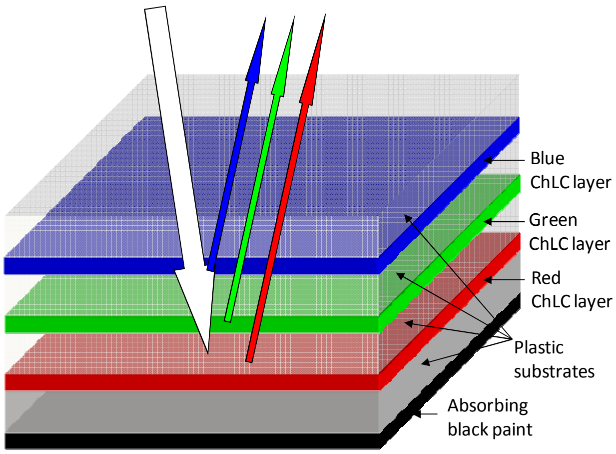

Figure 2. Schematic of full color three layer stacked ChLCD.

Adjacent layers share one substrate, where there are conductive electrodes on both sides of the shared substrate. The layer order is defined for maximum reflectance of each wavelength. Due to selective reflection properties a blue ChLC layer switched to the planar state reflects only blue wavelengths while transmits all others. In turn, a green ChLC layer reflects only green portion of spectrum while red ChLC layer only the red portion. Each layer of the display can be addressed independently to vary the reflectance of each color yielding many possible colors. The advantage of this approach is that the display produces the full brightness for each primary color. However, as the number of surfaces grows, the reflectance of the bottom layers is reduced by the Fresnel losses caused by the mismatch of refractive indices at the interfaces; plastic/conductor, conductor /LC. This drawback can be reduced by utilizing a specifically engineered index-matched ITO plastic (IMITO) or conductive polymer coatings providing better refractive index matching properties.

2.1.1. Display design

Utilizing the stacking approach, three layer single pixel flexible ChLCD can be built by sequentially laminating R G and B layers on top of each other. Each ChLC layer is made using Polymerization Induced Phase Separation (PIPS), a technique where the mixture of ChLC/monomer is laminated between two PET substrates with conductive electrodes and cured under UV light [7]. The resulting display is thin (depending on the substrate thickness it can be 65 μm), flexible, rugged, pressure insensitive (thanks to the polymer matrix), low power and bright, Figures 3, 4.

To further increase the reflectance of the ChLCD the electrodes with higher transparency can be used. Also, the brightness of ChLCD can be dramatically enhanced by the use of of a stacked system with cholesteric materials of opposite handedness [8]. To improve the color purity of the device absorbing dyes or absorbing filters to cut the unwanted reflection

Figure 3. Full color stacked ChLCD switched to different colors. Top row colors: black, red, green, blue, respectively. Bottom row colors: pink, cyan, yellow, white, respectively. By utilizing grayscale driving scheme many additional color combinations may be produced.

from the interfaces and from the imperfection of the cholesteric helix (specifically the light scattering in blue portion of spectrum) can be utilized as discussed in Refs. [9, 10]. The state of the art stacked Reflex displays are being built on a roll-to-roll line and have operating temperatures from -20°C to +70°C, contrast ratio 3.0 (for the specular component included), and an of operating voltage of 28V. The targeted applications for these devices are consumer skin-type displays capable of changing the case color of a cell phone or MP3 player, for example; the displays can be also fully integrated into the electronic device.

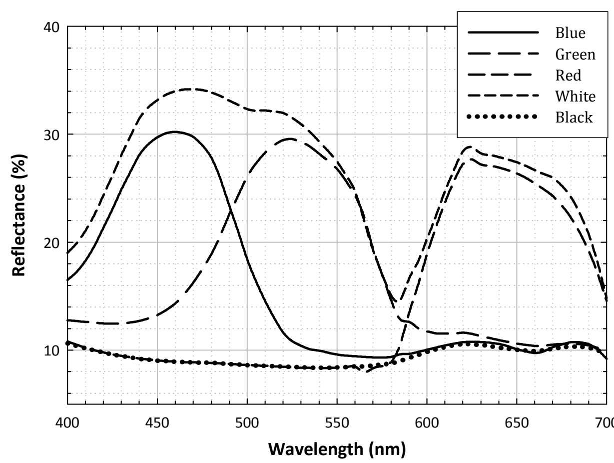

Figure 4. Typical reflection spectra from single pixel full color triple stack Reflex display made from plastic substrates with conductive polymer coatings. Red, green, blue, white and black states are shown. The measurements are for the specular component included.

2.2. Pixelization approach

Full color ChLCD can be also achieved by spatially separating R G B reflective layers from each other within one pixel similar to conventional full color LCDs, Figure 5. The difference is

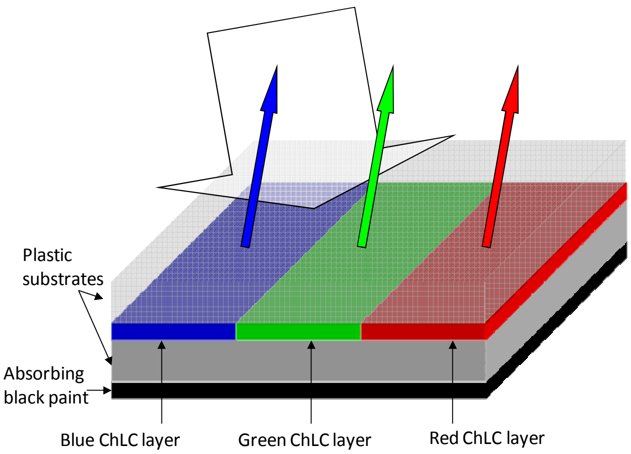

Figure 5. *Schematic of full color single layer area sharing ChLCD.*

that there is no need for color filters as each sub-pixel can be tuned to reflect R G or B colors independently. The advantage of the approach is its simplicity, as only one layer is required; that significantly reduces the cost of the device. Also, the contrast ratio of the spatial color device is improved as there are no additional interfaces. However, the brightness of the display is decreased by approximately 3 times in comparison with the stacked approach. There are also challenges in placing pixels reflecting different colors side by side including the precise placement of the colors in a high resolution repeating pattern and in keeping R G B reflecting materials physically separated from each other as the diffusion process may lead to color mixing. The solutions to those problems include: inkjet printing to individually fill mixtures reflecting R G and B onto a substrate that uses polymer banks to separate the colors [11], controlled vacuum filling of each color into the correct sub-pixels (pixelized vacuum filling) [12], and vacuum filling of a phototunable mixture which is described here.

2.2.1. Display design

To create the display, a panel was filled with blue ChLC mixture containing a phototunable chiral dopant and then exposed to UV irradiation to tune the reflected color of the appropriate sub-pixels to green and red [13]. The UV dosage required to photochemically alter the chirality of the dopant varies depending on the substrate, resolution, temperature and cell gap. In this design an ITO coated glass panel patterned with 720 rows and 320 columns was assembled with polymer walls separating the rows. The rows were then vacuum filled with a UV tunable ChLC that reflects blue light.

Using photo masks and varying dosage of UV light, it was possible to color each row so that the resulting array contains 240 red, green and blue rows and 320 columns at 80ppi creating an active area of 102 mm by 76 mm translating to a 1/4 VGA with an aperture ratio of 87%. The polymer walls acted as both a diffusion barrier, preventing the colors from mixing as well as a spacer maintaining the separation of the two patterned ITO substrates that make the panel, Figure 6. The walls maintain a cell gap of 4 ± 0.2 μm. Each pixel in the panel has 3 sub-pixels: red, green and blue, that can each be passively addressed by row and column voltages to the bright planar state, dark focal conic state or any grayscale level.

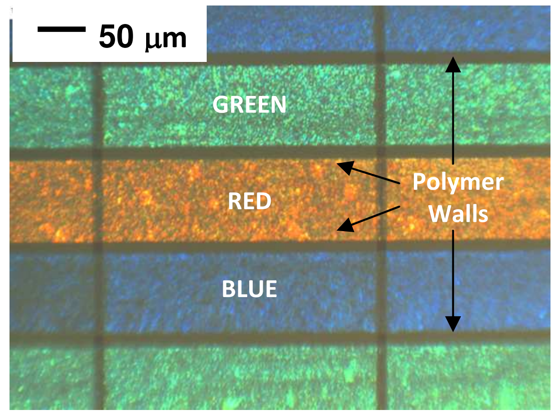

Figure 6. *A microscope picture of the panel showing the sub-pixels colored to red, green and blue separated by polymer walls.*

Figure 7. *Picture of the full color single layer ChLCD panel showing a color graphic image.*

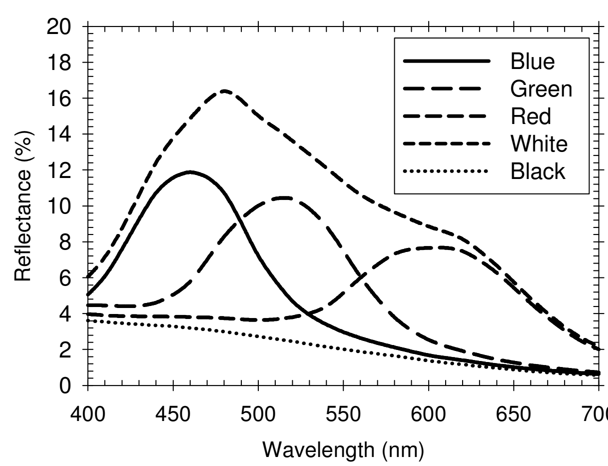

Figure 8. *The reflectance spectra of 1/4 VGA spatial color display showing the red, green, blue, white and black states. The measurements are for the specular component excluded.*

The display has a high reflective contrast ratio (6:1, Figure 7), a low driving voltage (18V), excellent color saturation and high reflectance, Figure 8. Due to the high contrast ratio, it is also viewable in poor lighting conditions. The display shows no color mixing after 1000 hours at 60°C.

3. Conclusions

We developed two approaches for achieving full color reflective bistable ChLCDs, stacking and area sharing. Stacking approach is rather simple and consists of sequential lamination of R G B ChLC layers separated by substrates on top of each other. Stacking allows the display to achieve the full brightness of each color at the expense of increasing the number of substrates. Area sharing or pixelization approach consists of spatially separating R G B reflective rows from each other within one pixel. The advantage of the approach is the superior contrast ratio and its simplicity, as only one layer is required; that significantly reduces the cost of the device.

Full color electronic devices, especially eBooks, are in great demand nowadays. Full color displays are more competitive, more attractive and allow to visualize the content in more enhanced way. Kent Displays is successfully commercializing the ChLC technologies enabling a number of novel devices, such as writing tablets, displays for smart card applications, full color electronic skin displays and electronic books [14]. Writing tablet device is a unique environmentally friendly product offering a significant reduction in paper consumption. Full color version of the product is currently under development.

Acknowledgements

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