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Printed black internal conducting electrodes for flexible bistable cholesteric displays

H. M. Atkuri[a], D.-W. Lee[a], B.-O. Choi[b], C.-H. Kim[b] and J. L. West[a,*]

[a]*Liquid Crystal Institute, Kent State University, Kent 44240, OH, USA;* [b]*Korea Institute of Machinery & Materials, Daejeon 305-343, South Korea*

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We report flexible, bistable cholesteric displays utilizing polyester (PET) substrates with printed internal black electrodes. The black electrodes consist of carbon ink dispersed in butyl carbitol using a patented roll-to-roll gravure-offset printing. A transparent conducting polymer printed on PET serves as the counter electrode. The electro-optic material is a chiral nematic mixture dispersed in a low-concentration polymer binder. The device can be switched between scattering (black) and reflective (vibrant green) states upon application of an electric pulse. The internal black electrode enhances the contrast of the display and simplifies the roll-to-roll manufacture of flexible displays.

Keywords: bistable cholesteric LCD; internal black electrodes; flexible substrates; liquid crystal displays

1. Introduction

The display industry has placed increasing emphasis on the development of flexible displays [1]. This interest is driven by the desire to decrease their weight and increase their ruggedness. The ability to bend and shape the displays opens up entirely new markets, while the ability to manufacture using a roll-to-roll process lowers cost and allows much larger displays. Virtually all flat-panel display technologies (i.e., LCD, OLED, PLED and electrophoretic displays) are being considered for use on flexible substrates [2]. In this paper, we focus on bistable cholesteric materials that are compatible with commercial plastic substrates.

Bistable cholesteric reflective materials were first reported in the early 1990s by Doane et al. [3]. These cholesteric materials can be electrically switched between two stable states. A lower voltage pulse places the material into a lightly scattering focal conic state, while a higher voltage pulse puts the material into a reflective planar state. When the pitch length is on the order of the wavelength of visible light, the focal conic state is lightly scattering, while the planar state is colored. A high-contrast display is produced by painting the back of the displays black. In this configuration, the displays appear black in the focal conic state and colored in the planar state [4].

The early development of the cholesteric materials utilized glass substrates, and the first generation of products were glass based. The bistable cholesteric materials have several advantages for use with flexible plastic substrates. The materials are stable to both oxygen and moisture, eliminating the need for sophisticated barrier layers. They do not require polarized light and are, therefore, suitable for use with birefringent substrates. Finally, because of their bistability and the details of their electro-optic response, high-resolution images can be produced using simple passive matrices.

The first example of a flexible bistable cholesteric display was reported in 1995 [5]. This display utilized commercially available indium tin oxide (ITO)-coated PET substrates. In 2010, Kent Displays introduced the first flexible bistable cholesteric product, the Boogie Board™, made using flexible substrates in a roll-to-roll process.

As noted above, the contrast of the cholesteric displays is enhanced by painting the back of the displays black. Residual scattering in the focal conic state reduces the contrast of the displays. In this paper, we investigate reduction of the effect of the residual scattering in the focal conic state by including the black absorber inside the displays.

2. Experimental

The bistable cholesteric displays were fabricated by sandwiching the cholesteric materials between transparent substrates. The back substrate is a 7mil transparent PET film with an internal black conducting electrode. The black electrode was printed on the substrate using a patented gravure-offset printing technology [6]. The black conductor consists of a carbon ink dispersed in butyl carbitol. The coated material was cured at 120°C for 20 min. The printed black conducting electrode had a relatively rough surface. We, therefore, planarized the electrode using a standard

*Corresponding author. jlwest@kent.edu

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polyimide (P2555 from Nissan). The counter electrode was either ITO-coated glass or a PET substrate coated with transparent conducting polymer based on polyethylene-dioxythiophene (PH 1000, Baytron) using electrostatic deposition.

The chiral nematic material consisted of 58% of the eutectic nematic mixture E44, and two chiral additives, 21% CE2 and 21% CB 15, all from Merck. To this mixture was added 4% NOA 65 from Norland. NOA 65 is a clear, colorless, liquid photopolymer that will cure when exposed to ultraviolet (UV) light. The chiral nematic/polymer mixture was heated to 60°C and was then sandwiched between the two substrates with 8 μm spacers used to control thickness. The resulting film was UV cured for 10 min. The sample was then cooled to room temperature.

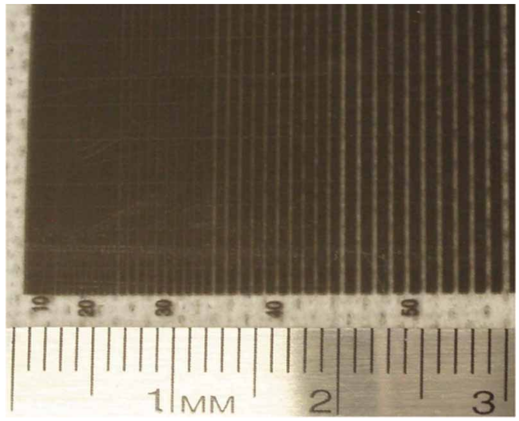

Figure 2. Electrode patterns produced on a PET substrate using gravure-offset printing proces.

3. Results and discussion

We demonstrated an increase in the contrast of bistable cholesteric displays by incorporating a black absorbing layer inside the displays. Elimination of the intervening transparent substrate between the cholesteric material and the absorbing black layer reduces the impact of the forward scattered light in the focal conic state. This effect is shown in Figure 1. By removing the transparent back substrate from the optical path of the displays, we eliminated reflection of the scattered light back to the observer. This will produce a blacker focal conic state and increase the contrast of the displays.

We combined the black absorbing layer with the back electrode of these displays using a black conducting ink. The internal black conducting electrode was printed as a continuous or patterned layer on a transparent PET substrate. Figure 2 shows various electrode lines printed on the PET substrate. These patterns were printed on a continuous sheet of plastic, demonstrating the adaptability of this process to roll-to-roll manufacturing. The resulting electrode was flat black with 2.5 kΩ resistance. Because the ink includes carbon black particles, the printed electrodes have a rough surface. The roughness of the surface resulted in non-uniformity in the cholesteric materials and also in electrical shorting of the finished displays. We, therefore, planarized the back substrate using a spin-coated layer of polyimide. This resulted in a much more uniform display. The front electrode is either an etched ITO glass substrate or a patterned PH1000 layer on a PET substrate.

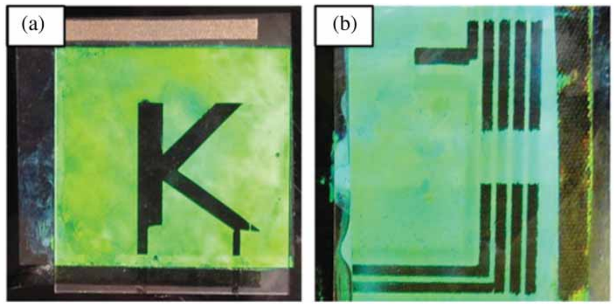

Figure 3. (a) Bistable cholesteric display with a continuous internal black conducting electrode and a patterned ITO-coated glass front substrate or (b) a patterned internal black conducting electrode and a continuous transparent conducting polymer electrode on a polyester front substrate.

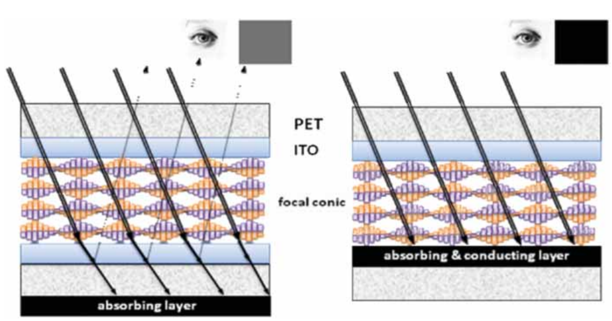

Figure 1. The optical path of the forward scattered light in the focal conic state of a bistable cholesteric display shown for an external (left) and an internal (right) black absorbing layer.

Figure 3 shows the resulting displays. Figure 3(a) shows a display made using a back substrate with a continuous black electrode printed on the PET substrate with a front glass substrate having a transparent conducting ITO electrode. The image is produced by the 'K' etched in the ITO conducting layer. The letter K is in the focal conic state and is dark black, while the remainder of the display is in the green-colored planar state. Figure 3(b) shows a display with a patterned black electrode printed on the back substrate and with a continuous PH1000 conducting polymer electrode electrostatically printed on the front PET substrate. The black image is produced by the black conducting lines printed on the back substrate as shown previously in Figure 2. Both images demonstrate the increase in contrast achieved by reducing the scattering and lowering the reflectivity of the black focal conic state.

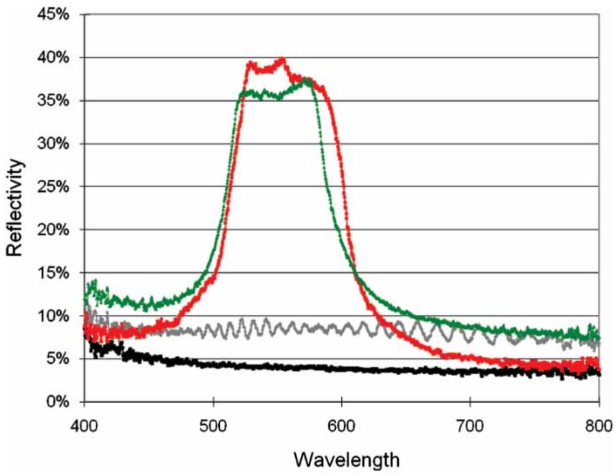

Figure 4. Reflectivities in the planar and focal conic states of a bistable cholesteric display either with an external black absorbing layer (green for the planar state and gray for the focal conic) or with an internal black conducing electrode (red for the planar state and black for the focal conic). (Color online)

Figure 4 compares the reflectivity of a bistable cholesteric display with the internal and external black electrodes. The reflectivity of the focal conic state is lower at all wavelengths when using an internal black electrode (black line). This produces a darker black state and increases the contrast of the display. It is important to note that the internal black electrode also reduces the background reflectivity of the planar state. This is seen by the lower base line reflectivity at longer wavelengths, >620 nm (red line). This is because the imperfect planar texture in this display also scatters some light. This is in addition to the Bragg reflection of the planar state. This will produce a purer color in the planar state when using the black conducting electrode. When measured at the reflection maximum of 550 nm, the reflectivity of the focal conic state is cut in half, going from 8% to 4%, while the reflectivity in the planar state is slightly increased. The result is a brighter, higher contrast display. The manufacturing process is also simplified by eliminating the need to print a black absorbing layer on the back of the display.

4. Summary

In this paper, we report the use of black conducting inks for the interior back electrode required to produce a bistable cholesteric display on flexible substrates. Combining the back electrode with the black film greatly increases the contrast. This is achieved by reducing the amount of scattered light observed in the focal conic state. The internal absorber also reduces the amount of background light scattering in the planar state, producing a purer perceived color. Both of these effects increase the contrast and visual appearance of the bistable cholesteric display. The simple printing process is easily incorporated into a continuous roll-to-roll manufacturing line. Our future research will focus on producing smoother and more conductive black electrodes. We will also focus on increasing the display resolution.

Acknowledgements

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