Color Management for Flexible Cholesteric-LCD under LED Illumination

Wei-Chung Cheng, Huang-Ming P. Chen** and Jih-Fon Huang†*
**US Food and Drug Administration, Silver Spring, MD 20993, U.S.A.*
***National Chiao Tung University, Hsinchu 30050, Taiwan*
†Industrial Technology Research Institute, Hsinchu 31040, Taiwan

Abstract

The reflective cholesteric liquid crystal display suffers from voltage-induced color shift and viewing angle-dependent color shift. In this paper, three solutions are presented to overcome these problems. First, four types of cholesteric liquid crystals were synthesized and characterized to find the best mixture with the lowest voltage-induced color shift and reflectance reduction. Secondly, 5-primary (red, yellow, green, cyan and blue) cholesteric liquid crystals were synthesized such that the color gamut and reflectance were enhanced. Finally, the viewing angle-dependent color shift was characterized and then compensated by adjusting the chromaticity of the red/green/blue LED light sources.

Introduction

Thanks to its reflectivity, flexibility, bi-stability, and roll-to-roll process, the cholesteric liquid crystal display (ChLCD) is an attractive technology for making large-sized displays for outdoor or indoor applications. As a reflective display, the ChLCD reflects ambient light without color filter, polarizer and backlight, which equate to manufacturing cost, form factor, and power consumption. As a flexible display, ChLCD can be used in e-paper or installed on curved surfaces such as automotive dashboards. As a bi-stable display, the cholesteric liquid crystals may exist in one of two stable orientations (black and white) and retain the same image for months without consuming power. ChLCD can be manufactured by roll-to-roll processes so the display width is virtually limitless, perfect for large-sized banner applications [1].

The major drawbacks of ChLCD are the slow refresh rate, especially with low temperatures, and color shift. The ChLCD color shifts as the voltage increases (Figure 1) and as the viewing angle changes (Figure 2). Such color shifts can be too profound to be accepted when high-quality images are demanded.

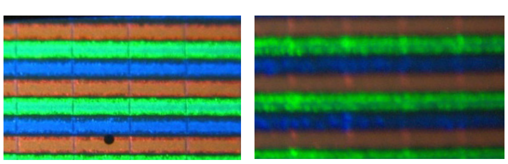

***Figure 1**. Voltage-depend color shift of ChLCD. When voltage applied (right), the colors shift toward blue and the reflectance decreases.*

***Figure 2**. Viewing angle-dependent color shift of ChLCD. As the viewing angle increases, red shifts to green, green shifts to blue, and blue shifts to black.*

In this paper, three solutions to the color shift problems of ChLCD are proposed. To solve the voltage-induced color shift, four different cholesteric liquid crystals were synthesized in lab in order to find the best mixture which has the lowest color shift and luminace reduction. Next, five different colors of cholesteric liquid crystals were synthesized to prototype a 5-primary ChLCD – red, yellow, green, cyan and blue. Finally, the viewing angle-dependent color shift was characterized and modeled. A compensation method of adjusting the red/green/blue LED light sources will be introduced.

Cholesteric Liquid Crystals

A cholesteric liquid crystal is a type of liquid crystals with a helical structure. The layers are organized with no positional ordering in between, but a director axis which varies with layers. The variation of the director axis tends to be periodic in nature. The period of this variation is the pitch, which determines the reflected color. The cholesteric liquid crystals have three types of textures – *planar*, *focal conic*, and *homeotropic* [1-3].

Optically, the cholesteric liquid crystals may be in one of the three states – *transparent*, *scattering*, and *reflecting*, which are determined by the previous state and the applied voltage. The scattering spectrum determines the apparent color of the ChLCD. By controlling the voltage, we can change the ChLCD between different states and thus change its apparent color.

However, when electric field is applied to the helical axis, a color shift toward blue occurs due to two reasons: (1) The pitch contracts because of the applied voltage. (2) The ChLCD plane perturbs due to the Helfrich deformation when the voltage exceeds the threshold [4-5].

In addition, the ChLCD colors also change when the viewing angle increases. The reason is that the light travels a longer distance inside the layers, which is equivalent to a thicker pitch [6].

Material Optimization

To lower the voltage-dependent color shift of ChLCDs, a negative dielectric anisotropic ($\Delta\varepsilon$) nematic LC material was doped into the positive nematic hosts. In this study, four different materials were synthesized.

Preparation of ChLCD Cells

The samples were prepared in a class 10,000 clean room. Empty cells were assembled, which consisted of two layers of glass coated with polyimide (PIA-X201-G01), acting as planar alignment layers. The polyimide was rubbed to form a pretilted angle of approximately 4º. The cell was assembled such that the rubbing directions of the layers were anti-parallel, and the cell gap, measured by an interferometer, was tuned to be 8um.

Four different nematic hosts from Merck were prepared: *1153 pure*, *1153 60%*, *1744 pure*, and *1744 55%*. The properties of nematic hosts properties were listed in Table 1. The chiral dopants, (s)-dioctan-2-yl biphenyl-4, 4'-dicarboxylate, were mixed with nematic hosts to have a selective reflection at 555±5 nm. The 1153 60% and 1744 60% mixtures were specially prepared for Ä*å* closed to 1 for reducing color shift.

Reflectance Characterization

The Δε of each sample was measured by Liquid Crystal Analysis System 3 (LCAS 3) and shown in Table 1. The spectra of the reflective light intensity are measured by using a spectrometer (Perkin Elmer Lambda 950) with standard D65 incident light in normal direction. The samples were driven by a waveform generator (WFG 600) under 1KHz square wave and parallel to the helix axis.

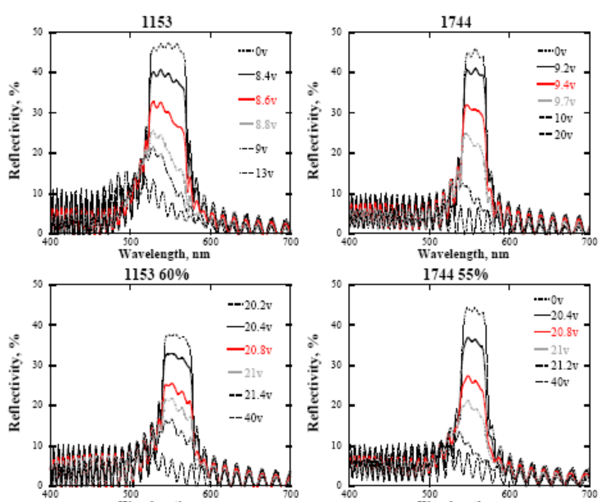

Figure 3. *Reflective spectra for 1153 and 1744 mixtures for 555nm green.*

Table 1: Properties of the synthesized cholesteric liquid crystals.

	n_e	n_o	Δn	$\Delta\varepsilon$	$\Delta\lambda$
1153 pure	1.6677	1.5056	0.1621	11.1	48.4nm
1153 60%	1.6074	1.4861	0.1213	1.57	37nm
1744 pure	1.5725	1.482	0.0905	7.8	30nm
1744 55%	n/a	n/a	0.091	1.3	36nm

In Table 1, $\Delta\theta$ is the reflective bandwidth. The narrower the reflective bandwidth, the higher the color saturation. The reflective spectra are shown in Figure 3. Colors start to shift toward blue and reflectance reduces severely after 8.6, 9.4, 20.8, and 20.8V in 1153 pure, 1744 pure, 1153 60%, and 1744 55%, respectively.

Color Characterization

The color difference, ΔEab, was measured to access the relationship between color shift and voltage. $\Delta ab=\sqrt{\Delta a^2+\Delta b^2}$ was also used for evaluating the chromaticity difference without considering the luminance reduction.

Figure 4 shows the changes of ΔL, Δab, and ΔEab under applied voltage. Three stages can be observed. Take 1153 60% (blue dot lines) as an example: 0-20V is the planar texture, 20-60V is the focal conic texture, and 60-80V is the homeotropic texture. The ChLCD is driven between planar and focal conic textures to produce "dark" and "bright" states. Therefore, an ideal material should have a large ΔL and a large ΔEab when driven by a low voltage. In addition, to produce smooth grayscales within the focal conic texture, an ideal material should have mimimal ΔL variation to maintain its lightness and minimal ΔEab variation to avoid color shift. Therefore, according to the results, the 1744 stands out because of its low driving voltage, low ΔL for brighter image and ΔEab for less color shift.

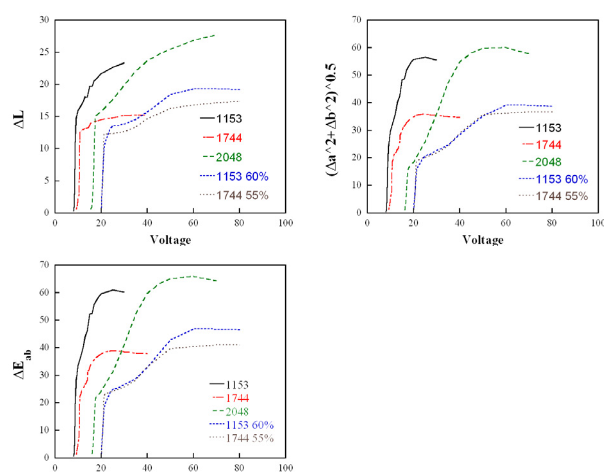

Figure 4. *Measured lightness reduction and color shift of different materials. The pure 1744 has the minimum lightness reduction and minimum color shift under low driving voltage.*

Multiple-Primary ChLCD

To enlarge the color gamut and reduce color shift of ChLCD, the 1744 was used to synthesize 5 different colors – red, yellow, green, cyan, and blue. As a non-spectral color, magenta is not feasible as a primary in ChLCD. After the same characterization procedure, the reflective spectra and color gamuts are shown in Figure 5.

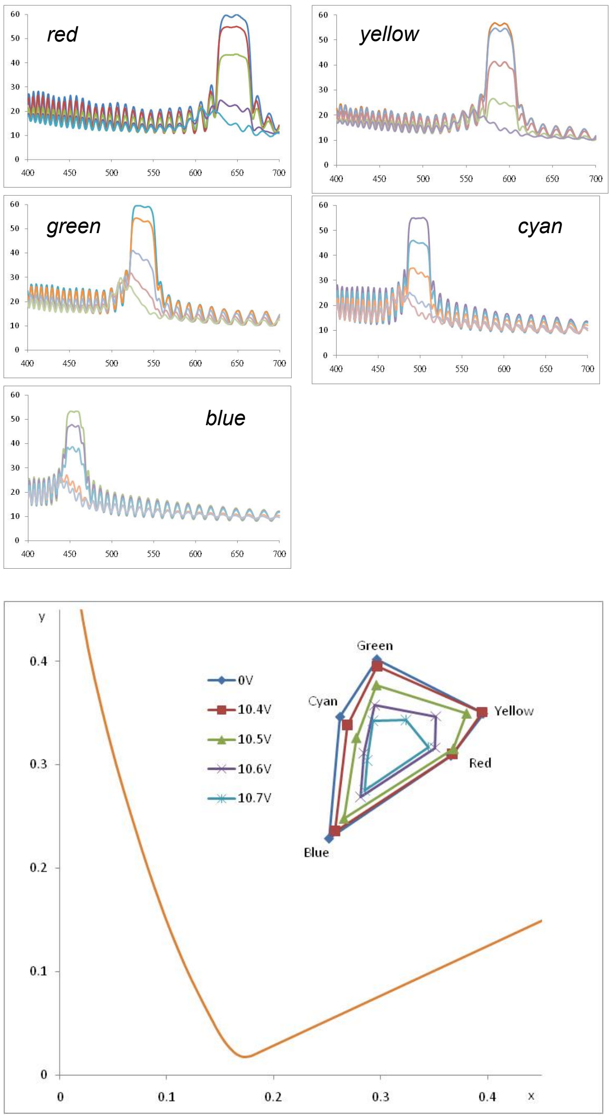

Figure 5. *Spectra/gamuts of red, yellow, green, cyan, and blue when driven under 10.3, 10.4, 10.5, 10.6, and 10.7V. The primaries shift toward blue as the voltage increases. The yellow and cyan primaries are more saturated than mixed colors of red, green, and blue.*

The color shift of the primaries can be modeled as follows.

$$\begin{bmatrix} x \\ y \\ R \end{bmatrix}_{Red} = \begin{bmatrix} -0.5920 & 0.9808 \\ 0.0222 & 0.0804 \\ -0.1486 & 1.7394 \end{bmatrix} \begin{bmatrix} V \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ R \end{bmatrix}_{Yellow} = \begin{bmatrix} -0.1884 & 2.3476 \\ -0.0164 & 0.5200 \\ -0.3206 & 3.6054 \end{bmatrix} \begin{bmatrix} V \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ R \end{bmatrix}_{Green} = \begin{bmatrix} -0.0104 & 0.4043 \\ -0.1570 & 2.0228 \\ -0.3729 & 4.1590 \end{bmatrix} \begin{bmatrix} V \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ R \end{bmatrix}_{Cyan} = \begin{bmatrix} 0.0654 & -0.4105 \\ -0.1116 & 1.4971 \\ -0.1633 & 1.8831 \end{bmatrix} \begin{bmatrix} V \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ R \end{bmatrix}_{Blue} = \begin{bmatrix} 0.0900 & -0.6772 \\ 0.1257 & -1.0685 \\ -0.0598 & 0.7663 \end{bmatrix} \begin{bmatrix} V \\ 1 \end{bmatrix}$$

where V is the voltage, R is the average reflectance, and (x,y) are the CIEXYZ coordinates.

The 5-primary ChLCD can produce more saturated and brighter colors in the yellow and cyan regions. For example, by mixing red and green, the most saturated yellow is (0.3290,0.3583). By mixing green and blue, the most saturated cyan is (0.2755,0.3205). Both are much duller than the new primaries (Figure 5).

Illumination Compensation

In addition to the ChLCD reflectance spectra, the color variation of ChLCD also depends on the incident light and the viewing angle. To reduce the color variation, our approach is to tweak the lighting according to the viewing angle [7-8].

We characterized the color variation of a sample ChLCD, which consists of RGB stripes (Figure 6), in different viewing angles. The sample ChLCD was illuminated by an off-the-shelf LED projection light, in which the RGB channels can be adjusted independently (Figure 7). First, the LED lights were tuned to emulate a D50 ambient light. Then the angular color variation was measured at different viewing angles between 0 and 45 degree. Finally, the LED lights were tuned to recover the color variation against the color coordinates measured at 0 degree.

Setup

A lighting and viewing environment was set up in a darkroom. The ChLCD target was hung at 180cm from floor. A colorimeter (Minolta CS200) was placed at 160cm to simulate the viewer's height.

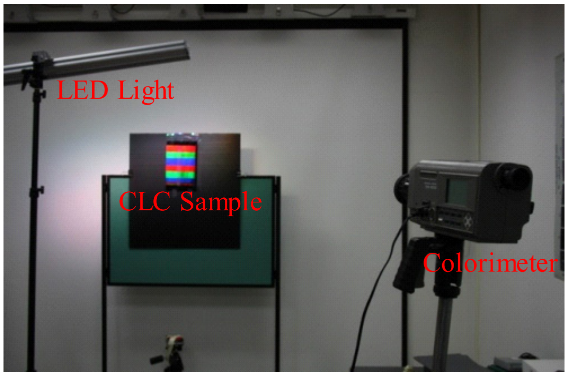

Figure 6*. The configuration of target, illuminant, and observer.*

A linear LED projection light was used as the illuminant. It has 12 sets of RGB LEDs. Each channel can be adjusted independently. The light was lift at 200cm.

Figure 7*. RGB LED projection light.*

The luminance and chromaticity of illuminant were controlled by tuning the RGB channels, which were driven by a DMX512 amplifier/controller.

Measurement under LED Illumination

At the beginning, the LEDs were tuned to correlated color temperature (CCT) 4889K, CIEXYZ x=0.3477, y=0.3595. The spectra were measured as shown in Figure 8.

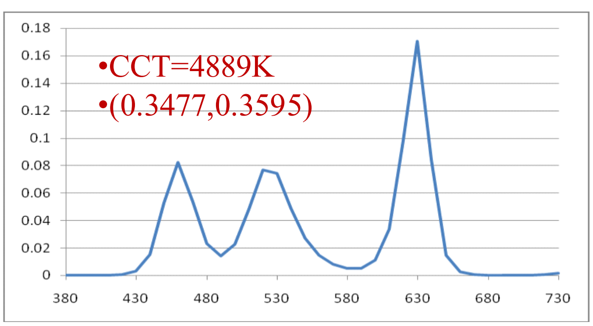

Figure 8. *LED spectra when tuned to CCT=4889.*

For each of the RGB stripes on the ChLCD sample, the color coordinates were measured at different angles including 0, 22.5, 37.5, and 45 degree (Figure 9).

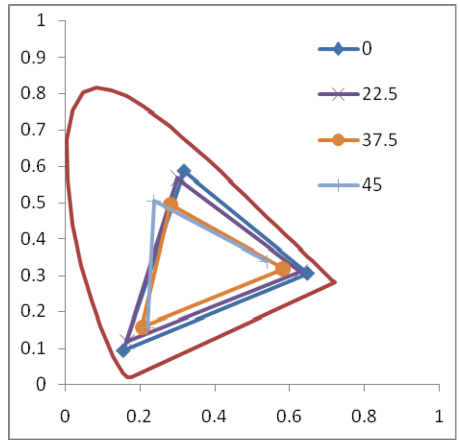

Figure 9*. Measured CIEXYZ coordinates at different viewing angles under LED illumination.*

As the viewing angle increases, the chroma decreases and the hue shifts toward shorter wavelength (so-called *blue shift*). For example, the red shifts toward dark orange, and the green shifts toward dark cyan. However, the blue just gets darker in the visible band because ultraviolet was not included in the measurement.

Based on the measurement results, the viewing angle-dependent color shift under direct LED lighting can be modeled as follows.

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Red} = \begin{bmatrix} -0.0023 & 0.6598 \\ 0.0006 & 0.3017 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Green} = \begin{bmatrix} -0.0013 & 0.5930 \\ -0.0016 & 0.3251 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Blue} = \begin{bmatrix} 0.0013 & 0.1473 \\ 0.0014 & 0.0907 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

where θ is the viewing angle and (x,y) is the CIEXYZ color coordinate.

Figure 10*. Setup for measuring viewing angle-dependent color shift under daylight.*

Measurement under Daylight

The measurement was repeated under daylight for reference (Figure 10). Figure 11 shows the spectrum of sun light at noon. Figure 12 shows the viewing angle-dependent color shift.

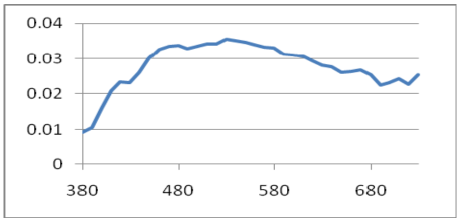

***Figure 11**. Spectrum of sun light.*

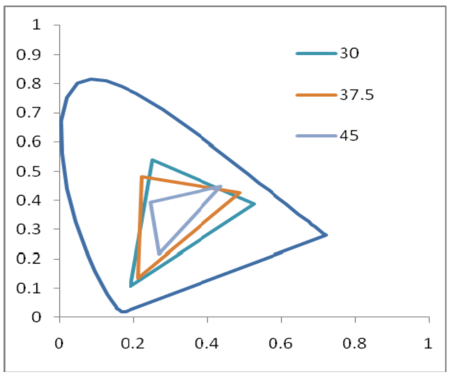

***Figure 12**. Measured CIEXYZ coordinates at different viewing angles under sun light.*

The viewing angle-dependent color shift under daylight can be modeled as follows.

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Red} = \begin{bmatrix} -0.0060 & 0.7099 \\ 0.0040 & 0.2699 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Green} = \begin{bmatrix} -0.0004 & 0.2542 \\ -0.0098 & 0.8396 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \end{bmatrix}_{Blue} = \begin{bmatrix} 0.0051 & 0.0329 \\ 0.0075 & -0.1270 \end{bmatrix} \begin{bmatrix} \theta \\ 1 \end{bmatrix}$$

RGB LED Compensation

After characterizing the viewing angle-dependent color shift, we looked for the corresponding sprectra of the LED lights that compensate for the color shift. We manually adjusted the RGB mix ratio of the LED lights (Figure 8) such that the reflected color can be recovered to the original color coordinates at 0 degree. The results are shown in Figure 13-15.

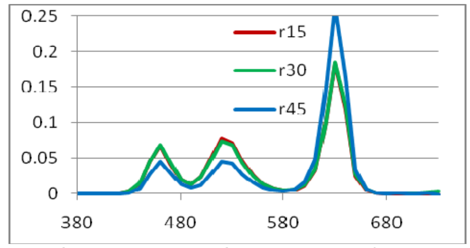

***Figure 13**. Compensating RGB LED lights for the <u>red</u> at 15 (r15), 30 (r30), and 45 degree (r45).*

For the red ChLCD, the LED lights needed to be tuned toward red to compensate for the color shift to orange (although theoretically infrared should have been used). The blue and green channels were reduced while the red channel was increased (Figure 13).

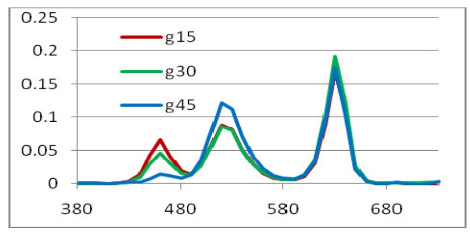

***Figure 14**. Compensating RGB LED lights for the <u>green</u> at 15 (g15), 30 (g30), and 45 degree (g45).*

For the green ChLCD, the LED lights needed to be tuned toward greenish yellow by lowering the blue channel while increasing green channel. The hue of yellow compensates for the blue shift of green ChLCD (Figure 14).

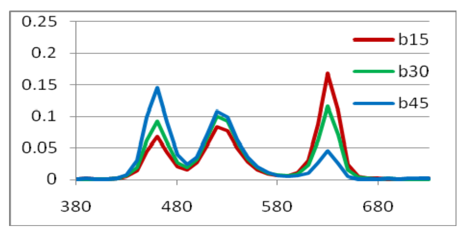

***Figure 15**. Compensating RGB LED lights for the <u>blue</u> at 15 (b15), 30 (b30), and 45 degree (b45).*

For the blue ChLCD, the LED lights needed to be tuned toward cyan by increasing the green and blue channel while lowering the red channel. The hue of cyan compensates for the blue shift of the blue ChLCD (Figure 15).

Conclusions

The cholesteric liquid crystal display is suitable for large-sized low-power, bi-stable applications, but its color shift prolems are not acceptable when color accuracy is demanded. To cope with voltage-dependent color shift, we synthesized different materials and found the best one with minimal color shift and reflectance reduction. We also synthesized 5-primary ChLCD for enlarged color gamut and enhanced reflectance. To cope with viewing angle-dependent color shift, adjustable LED lights were used to compensate for the color shift.

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Author Biography

Wei-Chung Cheng received his Ph.D. from Electrical Engineering-Systems, University of Southern California, Los Angeles, California in 2003. He was on the faculty of Department of Photonics and Display Institute, National Chiao Tung University, Hsinchu, Taiwan between 2005 and 2008. In 2009, he joined the Division of Imaging and Applied Mathematics, Office of Science and Engineering Laboratories, Center for Devices and Radiological Health, US Food and Drug Administration. His research interests include medical imaging/display, color engineering, applied human vision and display-human interaction.

Huang-Ming Philip Chen received his Ph.D. in Materials Science in 2003 from University of Rochester, New York, U.S.A. After his post doctoral research at Center for Optoelectronics and Imaging at University of Rochester, Dr. Chen joined the faculty of Display Institute of National Chiao Tung University in August 2004. His current research focuses on fast response liquid crystals, chiral-nematic liquid crystals for display components and ink jet printing process for device fabrication. He is currently members of American Chemical Society, Materials Research Society and Society for Information Display.

Jih-Fon Huang received his M.S. in Electronics Engineering from National Chiao Tung University in 1984. When he worked on the R&D of plasma display panel and TFT-LCD in AUO between 1996 and 2004, his work focused on the development of pixel design, circuit design and system structure. Since he joined Industrial Technology Research Institute in 2004, his research interest is the design of flexible display systems. He is also on the board of Color Association of Taiwan.