Five-Primary-Color LCDs

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***Abstract*—We demonstrate a wide color gamut and high brightness LCD TV using a conventional cold cathode fluorescent lamp (CCFL) backlight with five-primary (red, green, blue, yellow, and cyan) colors. Without changing the CCFL backlight and pixel size, the color gamut is widened from ∼72% to ∼90% and meanwhile the white brightness is increased by more than 20%, as compared to the three-primary. We also validate our simulation results using a 32″ five-primary multi-domain vertical alignment LCD TV prototype. The agreement is reasonably good.**

***Index Terms*—Liquid crystal display (LCD), LCD TVs, multi-primary, wide color gamut.**

I. Introduction

For most liquid crystal displays (LCDs), wide viewing angle, high contrast ratio, fast response time, high brightness, low power consumption, and wide color gamut are important metrics. Recently, dramatic progress in LCD performance has been made in all aspects. The demand for a higher color gamut is ever increasing. Since the natural objects and cinema are significantly more colorful than the CRT TV standard, there is an urgent need to produce wider color gamut in order to reproduce the original colors with high fidelity.

In a conventional three-primary [i.e., red (R), green (G), and blue (B)] LCD with cold cathode fluorescent lamp (CCFL) as backlight, its color gamut is ∼72% NTSC, which is comparable to a CRT but inferior to a plasma display (∼95%). Several backlight related technologies have been developed for enhancing the color gamut of LCDs. 1) Laser diodes [1]—although laser diodes provide very pure primary colors, the speckle pattern produced by interference is still an unsolved problem. 2) RGB light emitting diodes (LEDs) [2]—due to a relatively narrow bandwidth of LEDs, the color gamut as wide as ∼120% has been achieved [3], [4]. A slim LCD TV using edge-lit LED has been recently introduced to commercial products. However, the heat sink design, lifetime of each color, and cost are still the major concerns. 3) Wide gamut CCFL (WG CCFL) [5]—also under development by many manufacturers, but it is not yet widely adopted because of the shorter lifetime and lower optical efficiency.

Another strategy for widening color gamut is to use more saturated RGB color filters (CFs). However, this approach suffers a drastic decrease in optical efficiency because the employed CFs have a narrower transmission bandwidth which leads to a lower transmittance.

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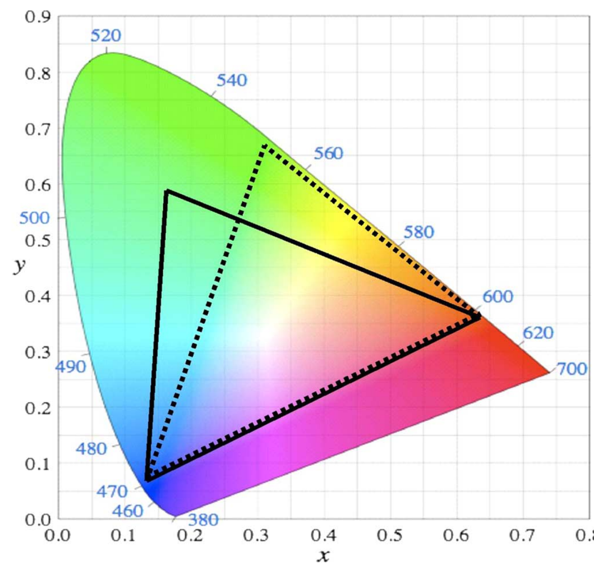

Fig. 1. Color gamut triangles with a different green primary.

Using multi-primary colors (more than RGB) to widen the color gamut has been demonstrated in projection displays and some direct-view LCDs [6]–[10]. However, the display brightness is reduced and cost increased because of increased number of color pixels and fabrication complicities.

In this paper, we propose a practical five-primary technique that not only widens the color gamut but also increases the white brightness. We will first discuss the operation principles, and show some simulation and confirming results using a 32″ LCD TV with five-primary colors (RGB plus yellow and cyan).

II. Multi-Primary Colors

As mentioned above, we can use highly saturated RGB color filters to enlarge the color gamut. However, this method reduces display brightness dramatically because of the lower transmittance of each color. Thus, it is not a preferred approach from the energy saving viewpoint. Fig. 1 depicts the color gamut curves of LCDs using two types of RGB primaries but at a different green primary. As shown by the dotted triangle, if we want to get good coverage of yellow then we cannot display a vivid cyan. On the contrary, if we shift the green point to cover more cyan, then we lose the fidelity of yellow, as the solid triangle shows.

To overcome the limitation of RGB primaries, we propose here a five-primary LCD by including yellow and cyan color filters. Fig. 2(a) shows the transmission spectra of conventional RGB color filters and Fig. 2(b) depicts the transmission spectra of our five primaries. The spectrum of yellow CF covers a portion of red and part of green in order to get more saturated

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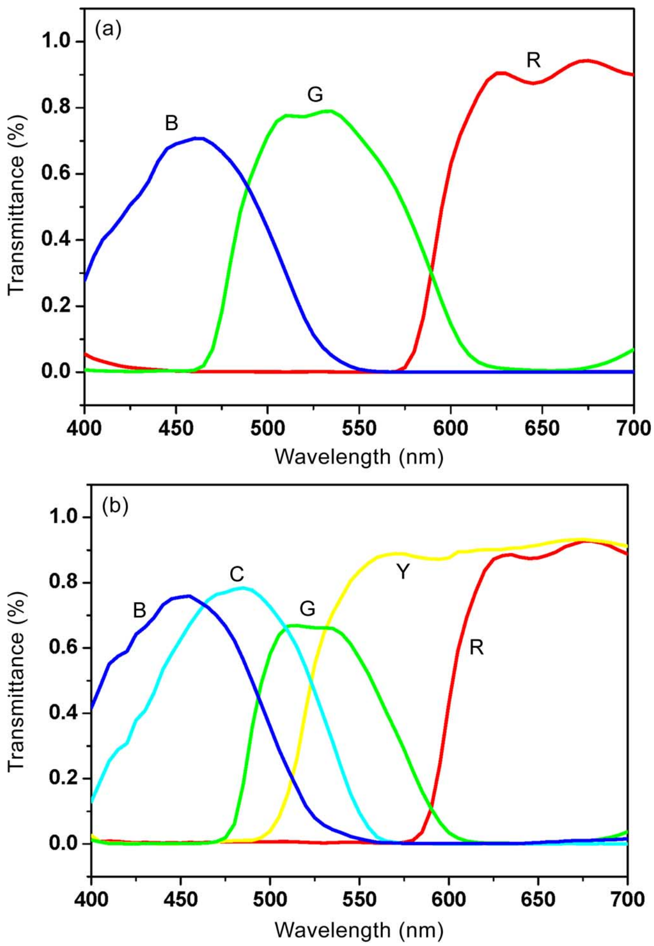

Fig. 2. Transmission spectra of (a) conventional RGB color filters and (b) five-primary RGBYC color filters developed.

yellow than the combination of standard green and red color filters shown in Fig. 2(a). Similarly, the cyan CF covers a portion of green and blue to get highly saturated cyan color. Meanwhile, we used a more saturated green color filter; its full-width–half-maximum is ~75 nm, as compared to ~100 nm for a typical green color filter. The narrower bandwidth makes the green color more saturated, but its transmittance is lower. There are two other important guidelines while choosing the primaries: 1) the white point at color temperature of D65 and 2) the proper relative luminance for each primary. According to the MacAdam limits [11], the color solid describes the colors near monochromatic can only achieve a very low luminance level except yellow. It also states the relative luminance of different color for objects. After having taken the MacAdam limits and practical color filter manufacturing capability into consideration, we optimized the color filter design and chose five-primary CF spectra as depicted in Fig. 2(b).

There are several kinds of color pixel arrangement and size designs [12]. In our simulations and application, we adopted the same sub-pixel size of three-primary for our five-primary approach because it is preferred by LCD manufacturers. We first used conventional CCFL (see Fig. 3) as backlight source and consider the transmission spectra of polarizers and liquid crystal in multi-domain vertical alignment (MVA) mode. Fig. 4 shows

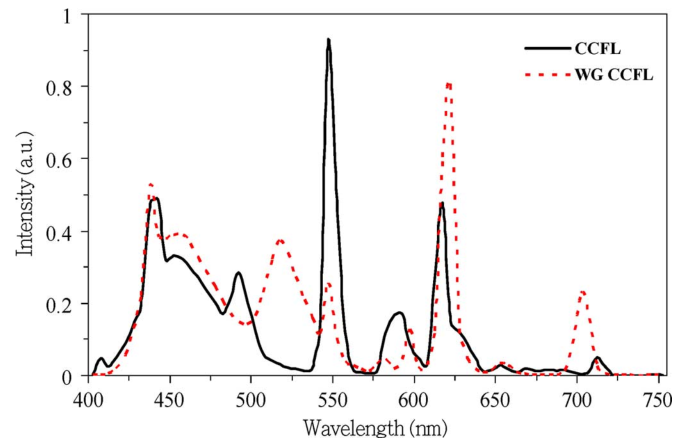

Fig. 3. Emission spectra of a conventional CCFL and WG CCFL.

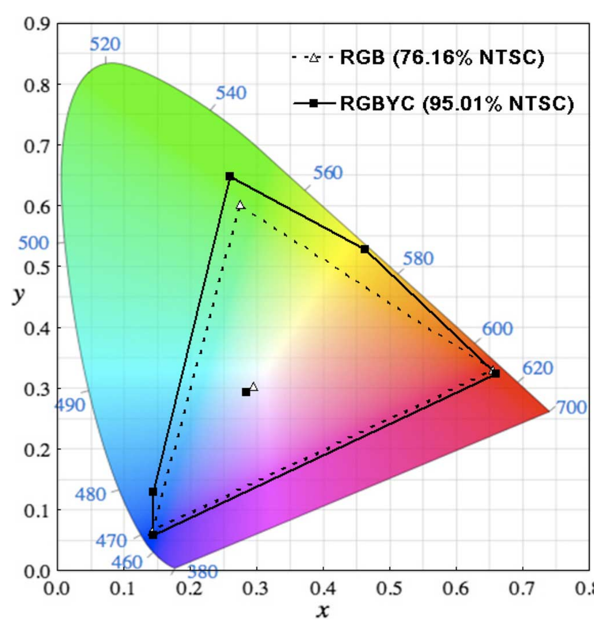

Fig. 4. Simulated color gamut of RGB (dashed lines) and RGBYC (solid lines) primaries using a MVA LCD.

TABLE I
SIMULATED RESULTS ON THE BRIGHTNESS AND COLOR COORDINATES OF 3- AND 5-PRIMARY LCDs

Three primary			
Color	Luminance (nit)	Chromaticity x	Chromaticity y
W	450.00	0.30	0.30
R	102.50	0.66	0.33
G	304.91	0.28	0.60
B	42.58	0.14	0.06

Five primary			
Color	Luminance (nit)	Chromaticity x	Chromaticity y
W	532.27	0.28	0.29
R	50.95	0.66	0.32
Y	258.01	0.46	0.53
G	138.37	0.26	0.65
C	59.60	0.14	0.13
B	25.34	0.15	0.06

our simulated color gamut for RGB and RGBYC MVA LCD TVs.

Table I lists the simulated color coordinates and luminance for each primary. From Table I, the color gamut of conventional RGB LCDs is ~76% NTSC. With five primaries, the color gamut increases to 96% NTSC with the same CCFL backlight. Moreover, the white luminance is increased by 21% for the five-primary LCD. The increase of white luminance is mainly contributed by the additional yellow and cyan colors. Because we employ more saturated CFs and our RGB pixel numbers are just 60% as compared to a conventional RGB display, we would expect a reduction of RGB luminance for the five-primary display. When the five-primary LCD displays a single primary color, say R, G, or B, the luminance would be lower than that of the three-primary one. However, in real situation, an object that reflects single color or narrow spectral bandwidth (i.e., pure color) will have a very low luminosity. It means the images rarely just show RGB primaries at the highest gray level. In fact, in a RGB-primary display the green luminance should be relatively high because of the need to produce bright yellow and standard white after combining with R and B. While in our five-primary LCD, we could afford to have a more saturated green primary to trade for a wider color gamut because we already have yellow primary.

To validate these assumptions, we chose some colorful and representative photos for image analysis. Fig. 5 shows three photos of the pixel color with respect to gray level distribution. We found in most cases the RGB sub-pixels are usually in the middle range between the maximum (255) and minimum (0) gray levels. The situation of high gray levels usually just happens when displaying yellow objects, e.g., the flowers shown in Fig. 5(b), or the bright white, e.g., the sky shown in Fig. 5(c). We realize that all the primaries need to be at the highest gray level while displaying higher luminosity of yellow or white. It means the luminance for RGB can be lowered if we have other sources to show yellow and white. Our five-primary design overcomes this problem well because it provides a higher yellow and white brightness than the conventional RGB LCDs due to the extra yellow and cyan. Although the luminance of our RGB colors is lower, it is still high enough to show and reproduce most colored images. When displaying the RGB color contents of an image, we can also adjust the gamma curve to get a better contrast ratio and brightness. According to the metamerism theory [11], there are unlimited choices of weighting ratios for five primaries to reproduce a particular mixed color. In the optimization process, we could choose a higher weighting ratio for Y, G, and C to reproduce a particular color since these three colors have a higher brightness. Therefore, after optimization of color conversion and gamut mapping from three-primary color space into five-primary signals, the decreased RGB brightness would not be a big issue in our five-primary LCDs. On the contrary, we find that five-primary LCDs exhibiting a higher brightness than RGB LCDs when displaying full color images.

III. Five-Primary LCD TVs and Comparison

Because most input image signals are in three-component format, such as RGB and YCbCr [13], a color conversion algorithm is needed in order to convert the three-primary input into five-primary signals. To do so, we applied the same algorithm developed for multi-primary projection TVs to LCD TVs [14].

Fig. 6 shows some pictures taken from our 32″ five-primary LCD TV prototype. The images of the five-primary LCD TV (left) look much more vivid and brighter than the traditional RGB LCD TV (right). The extra yellow and cyan primaries not only widen color gamut but also provide very good color reproduction.

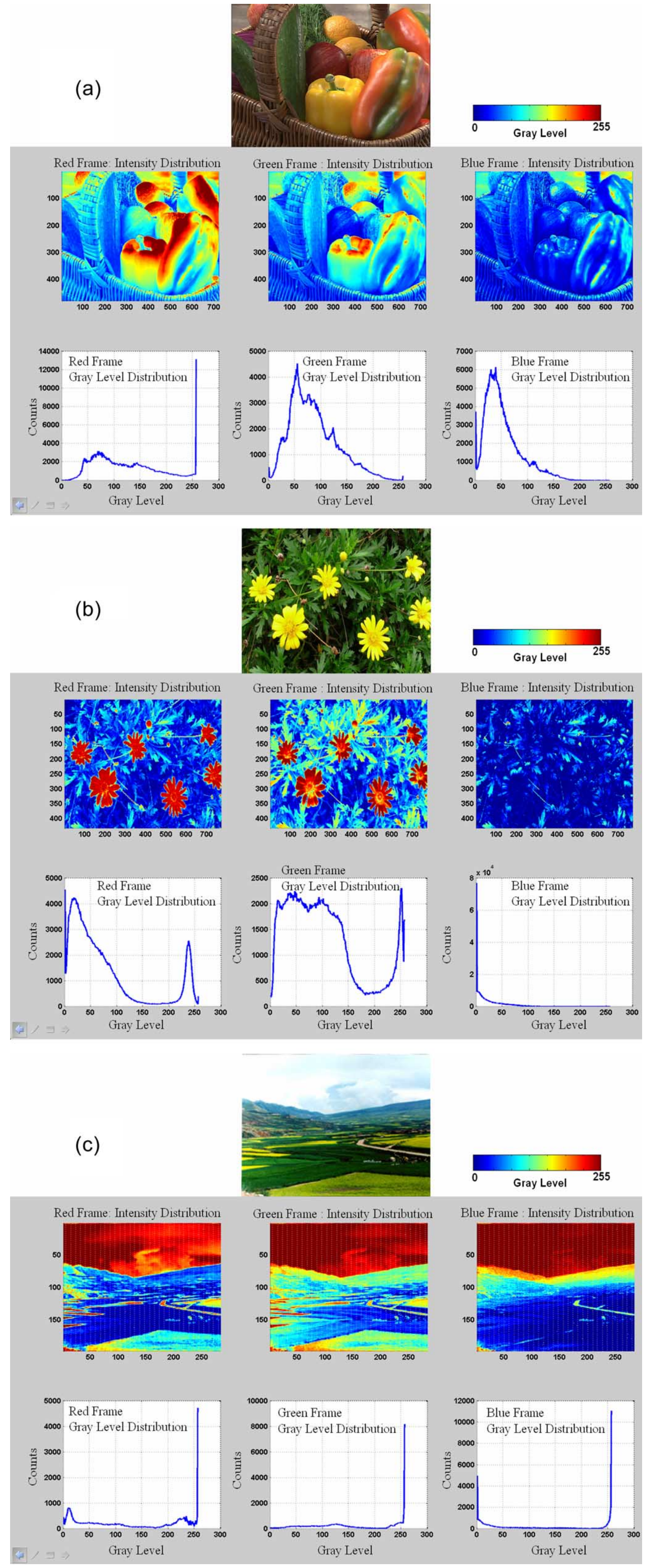

Fig. 5. Image analysis for gray level distributions. (a) A fruit basket, (b) Lotus in a pond, and (c) a pasture and sky.

The measured data are shown in Fig. 7 and Table II. The color gamut is increased by 26% and the brightness of white point is

Fig. 6. Photos from a 32″ MVA LCD TV prototype. Left column: five-primary (RGBYC); right column: conventional RGB primaries. Backlight: CCFL in both systems.

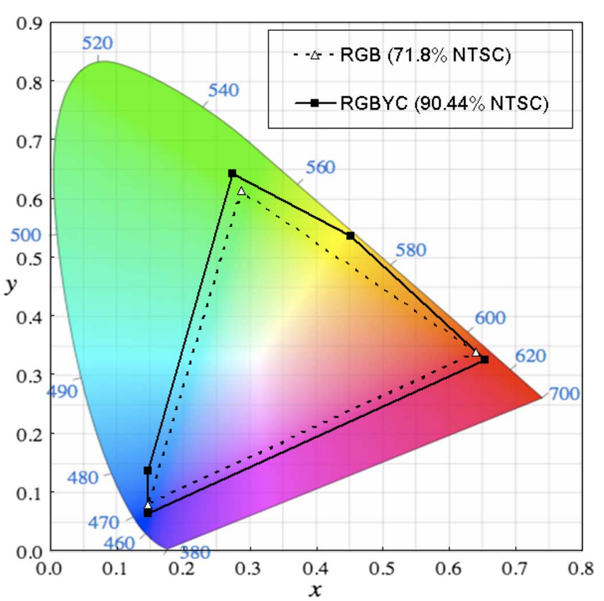

Fig. 7. Measured data for the RGB and RGBYC MVA LCD TVs.

also increased by 26%. The agreement between simulated and measured color gamut is within 5%. The possible errors might originate from the spectrum deviation in the mass production of color filters and CCFL.

As a promising solution for wide color gamut displays, we also compare the performance of our five-primary display with other competing approaches such as RGB-primary using wide gamut CCFL (WG CCFL) and RGB LEDs. Results are summarized in Table III. In our simulations using WG CCFL and RGB LED backlight in the RGB-primary system, the color gamut achieves ~90.23% and 120%, respectively. However, these three-primary based technologies still cannot reproduce good yellow and cyan colors like our five-primary LCD.

We also simulated our five-primary MVA LCD using WG CCFL backlight; its emission spectrum is shown in Fig. 3. Here, we assume the conventional CCFL and WG CCFL have the same luminosity. From our simulation results shown in Fig. 8 and Table IV, we find that the color gamut reaches ~114.07% NTSC and, moreover, the brightness of white point increases ~7%. Although the yellow brightness is reduced by ~20%, other four primaries experience brightness increase. The better spectrum match between our five-primary CFs and WG CCFL

TABLE II
MEASURED DATA FOR RGB AND RGBYC DISPLAYS

Three primary			
Color	Luminance(nit)	Chromaticity x	Chromaticity y
W	449.60	0.28	0.29
R	93.50	0.64	0.34
G	293.20	0.29	0.61
B	61.20	0.15	0.08

Five primary			
Color	Luminance(nit)	Chromaticity x	Chromaticity y
W	568.50	0.30	0.33
R	45.00	0.65	0.32
Y	290.60	0.45	0.54
G	163.80	0.27	0.64
C	50.90	0.15	0.14
B	26.50	0.15	0.06

TABLE III
PERFORMANCE COMPARISON OF WG CCFL, RGB LEDS, AND OUR FIVE-PRIMARY LCDS

	WG CCFL	RGB LEDs	RGBYC Primaries
Gamut Value	○	◎	○
Gamut Shape / Color Reproduction	×	△	◎
Brightness Efficiency	×	×	◎
Cost	○	×	◎
Signal Processing / Color Conversion Algorithm	◎	◎	△

×:Poor; △: Fair; ○: Good; ◎ Excellent

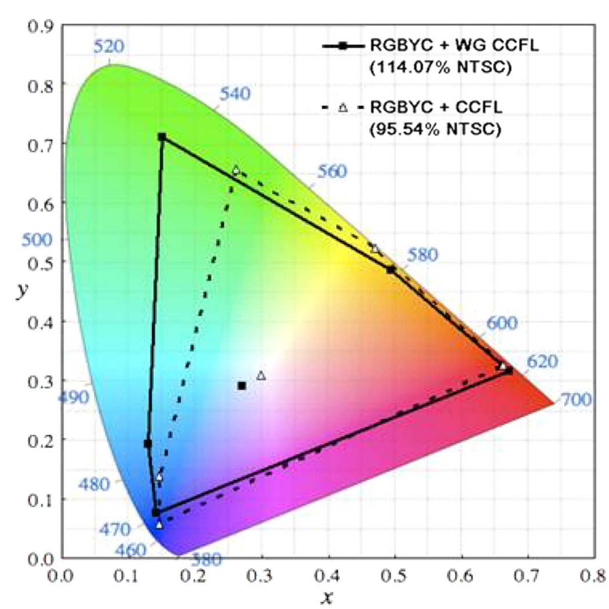

Fig. 8. Simulated color gamut of RGBYC-primary with conventional CCFL (dashed lines) and RGBYC with WG CCFL (solid lines) in a MVA LCD.

TABLE IV
SIMULATION RESULTS ON DISPLAY BRIGHTNESS AND COLOR COORDINATES OF OUR 5-PRIMARY MVA LCD USING CONVENTIONAL CCFL AND WG CCFL

	RGBYC + CCFL	RGBYC + WG CCFL			Luminance Gain
Color	Luminance[a] (nit)	Luminance[b] (nit)	Chromaticity x	Chromaticity y	(Luminance[b] / Luminance[a])
W	532.27	571.27	0.27	0.29	107.33%
R	50.95	70.57	0.67	0.32	138.52%
Y	258.01	206.80	0.49	0.49	80.15%
G	138.37	145.40	0.15	0.71	105.08%
C	59.60	107.98	0.13	0.19	181.18%
B	25.34	38.03	0.14	0.08	150.05%

is responsible for the significant increase in brightness. We believe that this could be the highest NTSC ratio ever achieved with such a high efficiency by using a WG CCFL backlight.

IV. CONCLUSION

We have successfully developed and demonstrated a five-primary LCD TV prototype. Using the same CCFL backlight and pixel layout and dimension, the color gamut of our five-primary display is more than 90% NTSC without sacrificing brightness. This technology is promising for wide color gamut displays. Moreover, $\sim$26% increase in white luminance give us the flexibility to reduce the light source density and power. Low power consumption is highly desirable from energy saving viewpoint. If a WG CCFL is employed, the color gamut of our five-primary MVA LCD is over 114%.

REFERENCES

[1] G. Hollemann, B. Braun, P. Heist, J. Symanowski, and U. Krause, “High-power laser projection displays,” in *Proc. SPIE*, 2001, vol. 4294, pp. 36–46.
[2] G. Harbers and C. Hoelen, “High performance LCD backlighting using high intensity red, green and blue light emitting diodes,” in *SID Dig. Tech. Papers*, 2001, vol. 32, pp. 702–705.
[3] R. Lu, Q. Hong, Z. Ge, and S. T. Wu, “Color shift reduction of a multi-domain IPS-LCD using RGB-LED backlight,” *Opt. Express*, vol. 14, pp. 6243–6252, 2006.
[4] R. Lu, S. Gauza, and S. T. Wu, “LED-lit LCD TVs,” *Mol. Cryst. Liq. Cryst.*, vol. 488, pp. 246–259, 2008.
[5] T. Igarashi, T. Kusunoki, and K. Ohno, in *Proc. EuroDisplay 2005*, pp. 233–236.
[6] E. Chino, K. Tajiri, H. Kawakami, H. Ohira, K. Kamijo, H. Kaneko, S. Kato, Y. Ozawa, T. Kurumisawa, K. Inoue, K. Endo, H. Moriya, T. Aragaki, and K. Murai, “Development of wide-color-gamut mobile displays with four primary-color LCDs,” in *SID Dig. Tech. Papers*, 2006, vol. 37, pp. 1221–1224.
[7] Y. C. Yang, K. Song, S. G. Rho, N. S. Rho, S. J. Hong, K. B. Deul, M. Hong, K. Chung, W. H. Choe, S. Lee, C. Y. Kim, S. H. Lee, and H. R. Kim, “Development of six primary-color LCD,” in *SID Dig. Tech. Papers*, 2005, vol. 36, pp. 1210–1213.
[8] H. Sugiura, H. Kaneko, S. Kagawa, M. Ozawa, H. Tanizoe, H. Katou, T. Kimura, and H. Ueno, “Improved six-primary-color 23-in. WXGA LCD using six-color LEDs,” in *SID Dig. Tech. Papers*, 2005, vol. 36, pp. 1126–1129.
[9] T. Ajito, T. Obi, M. Yamaguchi, and N. Ohyama, “Expanding color gamut reproduced by six-primary projection display,” in *Proc. SPIE*, 2000, vol. 3954, pp. 130–137.
[10] S. Ueki, K. Nakamura, Y. Yoshida, T. Mori, K. Tomizawa, Y. Narutaki, Y. Itoh, and K. Okamoto, “Five-primary-color 60-inch LCD with novel wide color gamut and wide viewing angle,” in *SID Dig. Tech. Papers*, 2009, vol. 40, pp. 927–930.
[11] J. H. Lee, D. N. Liu, and S. T. Wu, *Introduction to Flat Panel Displays*. Hoboken, NJ: Wiley, 2008.
[12] S. Roth, N. Weiss, M. Ben-Chorin, I. Ben-David, and C. H. Chen, “Multi-primary LCD for TV applications,” in *SID Dig. Tech. Papers*, 2007, vol. 38, pp. 34–37.
[13] P. Green and L. MacDonald, *Colour Engineering*. Hoboken, NJ: Wiley, 2002.
[14] S. Roth, I. Ben-David, M. Ben-Chorin, D. Eliav, and O. Ben-David, “Wide gamut, high brightness multiple primaries single panel projection displays,” in *SID Dig. Tech. Papers*, 2003, vol. 34, pp. 118–121.

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