# Color Breakup Suppression in Field-Sequential Five-Primary-Color LCDs

Hui-Chuan Cheng, Linghui Rao, and Shin-Tson Wu, *Fellow, IEEE*

***Abstract*—Field-sequential-color liquid crystal displays (FSC LCDs) exhibit a $\sim 3\times$ higher optical efficiency and $3\times$ higher resolution, but the color breakup (CBU) degrades the image quality and limits the practical applications. In this paper, we propose a method to reduce CBU by using five-primary LEDs instead of three. Without increasing the sub-frame rate as three-primary LCDs, we can suppress the CBU by utilizing proper color sequence and weighting ratios. The color gamut achieves 140% NTSC and the white brightness increases by more than 13%, as compared to the three-primary LCDs.**

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

## I. INTRODUCTION

LOW power consumption is a critical requirement for all liquid crystal display (LCD) devices, especially for large screen TVs. The two most lossy components in a LCD system are polarizer and color filters. The polarizer transmits ~45% of the incident backlight, while each color filter only transmits ~30% of the incoming white light. To overcome the light loss from polarizer, backlight recycling using a reflective polarizer has been widely implemented [1], [2]. To avoid the dramatic absorption loss from color filters, field-sequential-color (FSC) using red (R), green (G) and blue (B) LEDs has been proposed [3]–[5]. A FSC LCD offers two important advantages over the color filters-based LCD: 1) its optical efficiency is improved by ~3X and 2) the device resolution is improved by 3X.

In an FSC LCD, each primary color appears sequentially. If the field's frequency is fast enough, the observer's eyes could integrate the sequential fields and perceive the original colored images. A big challenge for FSC LCDs is the need of fast LC response time in order to suppress the color breakup (CBU) [6]–[10]. CBU is the most disturbing defect that degrades the image quality in FSC displays. CBU can be observed in stationary or moving images. It manifests when there is a relative speed between the images and observers' eyes, and the observer will see the color splitting patterns or rainbow effect at the boundary between two different colors. Several methods have been reported to reduce CBU, e.g., one can increase the field frequency to 540 Hz or even up to 1000 Hz [11]. This approach has been widely used in FSC projectors. For direct-view LCDs, several other methods have been proposed, such as inserting another color or black fields [12], [13], motion compensation technique [14], four-color fields arrangement [15], and Stencil-FSC method [16]. However, most of these methods still require fast LC response time. Some methods even sacrifice the display brightness and some are restricted by the uncertainty of observers' motion.

In this paper, we propose a practical way by using five-primary-color technique for direct-view FSC LCDs without enhancing frame rate. Meanwhile, our design not only widens the color gamut but also increases the white brightness, as compared to the three-primary LCDs.

## II. MULTI-PRIMARY FSC LCDS

The two-dimension time and location diagram is usually used to evaluate CBU (Fig. 1). By integrating images of consecutive frames along the trace of saccadic eye motion, we can evaluate the color and brightness variations of rainbow-like CBU patterns. From the simulated CBU (Fig. 2), it shows that the three-primary FSC displays with sub-frame frequency of 540 Hz (i.e., frame rate of 180 Hz) have the CBU width of $N$ pixels. $N$ is determined by the relative speed between the images and observers' eyes. Fig. 2(b) and (d) shows the CBU width for higher and lower frame rates, respectively. We observe that the higher frame rate causes a less noticeable CBU. There is no doubt that increasing the frame rate is an effective way to suppress CBU. However, the requirement for fast LC response time makes this method a challenge. Without increasing the LC frame rate, here we propose a five-primary method for compressing the CBU to an acceptable level.

The five-primary [R, G, B, yellow (Y), and cyan (C)] color LCD has been shown to exhibit a very good color reproduction and brightness [17]–[19]. Using a conventional cold cathode fluorescence lamp (CCFL) backlight with five-primary color filters, we can achieve ~90% color gamut and 20% higher brightness, as compared to three-primary. Because of the better color reproduction and optical efficiency, in this paper, we extend the five-primary approach to FSC LCDs.

According to the two-dimension time and location diagram shown in Fig. 1(b), the CBU width for five-primary is 5/3 times more than the three-primary under the same frame rate. Therefore, it is naturally expected that five-primary could suffer from larger CBU as compared to three-primary displays. Some psychophysical experiments about the comparison of CBU visibility between three-primary and five-primary displays have been reported [20]. Surprisingly, the results indicate that,

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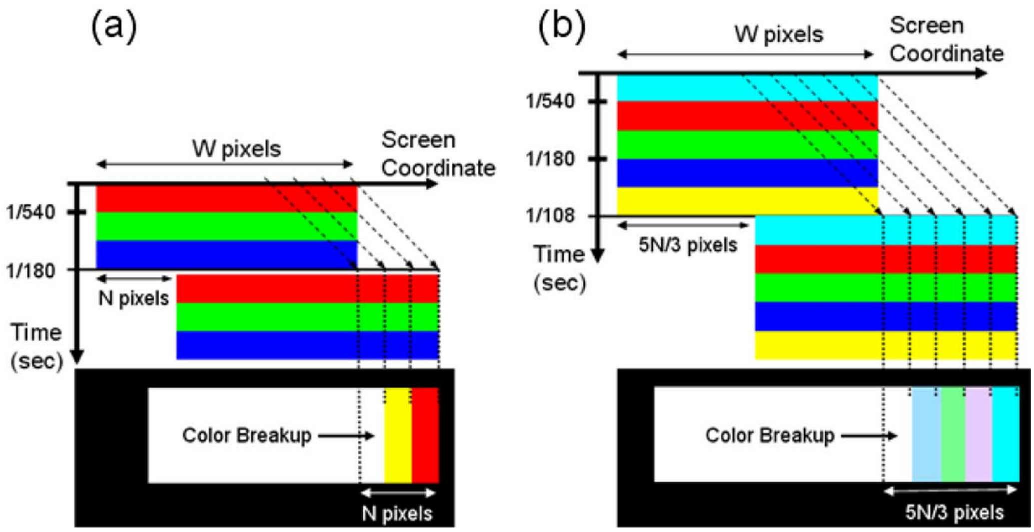


Fig. 1. Two-dimension time and location diagram. The upper parts of each diagram represent the moving white objects with width of $W$ pixels. The lower parts are simplified CBU patterns without considering the brightness variation. The slant dashed arrows show the eyes tracking along the movement of object.

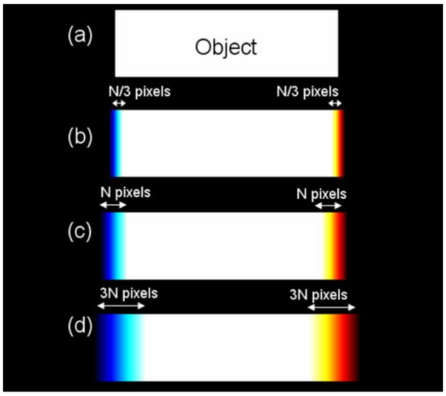


Fig. 2. Simulated CBU for three-primary display. (a) White object. (b) $\text{Frame rate} = 540$ Hz. (c) $\text{Frame rate} = 180$ Hz. (d) $\text{Frame rate} = 60$ Hz.

TABLE I
COLOR RATIOS FOR STANDARD ILLUMINANT D65

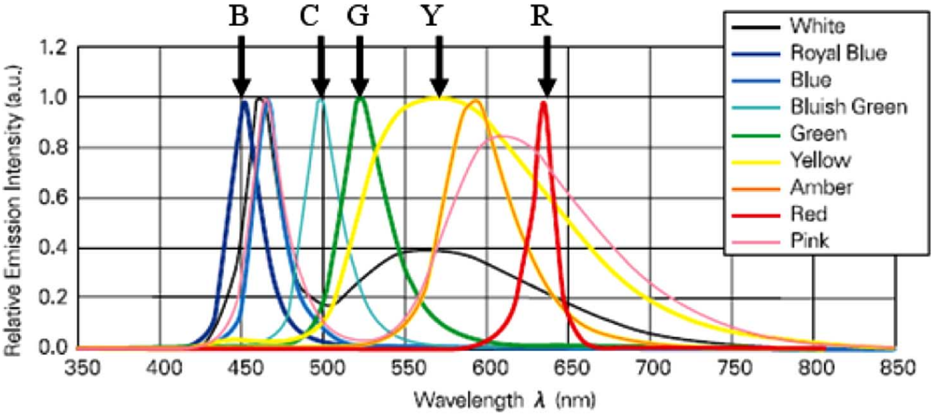
| Three-primaryDisplay | | | |
|---|---|---|---|
| R (%) | G (%) | B (%) | W (%) |
| 26.80 | 67.68 | 5.52 | 100.00 |

| Five-primaryDisplay | | | | | |
|---|---|---|---|---|---|
| R (%) | G (%) | B (%) | Y (%) | C (%) | Brightness (a.u.) |
| 1.11 | 8.38 | 4.96 | 78.03 | 7.52 | 128.16 |
| 10.96 | 22.10 | 4.58 | 51.45 | 10.91 | 194.36 |
| 15.46 | 37.40 | 4.99 | 36.28 | 5.88 | 275.61 |
| 13.32 | 22.78 | 4.17 | 44.66 | 15.07 | 223.89 |
| 13.33 | 20.90 | 4.08 | 45.80 | 15.89 | 218.35 |
| 12.14 | 20.53 | 4.29 | 48.73 | 14.31 | 205.20 |
| 12.36 | 18.90 | 4.04 | 48.33 | 16.37 | 206.91 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

most of the time, CBU for five-primary is less visible than three-primary. However, thus far there is no further study and systematic analysis for this result. In our simulations based on five-primary, we develop a method to compress CBU by optimizing the color sequence and weighting ratios.

When a three-primary LCD displays a specific color, there is a unique color ratio corresponding to this color. However, there are numerous possibilities for five-primary. Here, we adopt the commercialized LEDs from Nichia in our simulations. The spectra and luminance intensity are shown in Fig. 3. From Table I, we find that there are many choices for the five-primary to reproduce the same white color coordinate of standard illuminant D65 (i.e., $x = 0.3127, y = 0.3290$). In order to choose the best solution among these infinite combinations, we take some basic rules and requirements into considerations. First, we abide to the MacAdam limits [21] which set the theoretical maximum relative reflection between a specific color and white under D65 illumination. This theorem tells us a reasonable relationship of brightness between each primary should be $\mathrm{Y} > \mathrm{G}, \mathrm{G} > \mathrm{R}, \mathrm{G} > \mathrm{B}, \mathrm{G} > \mathrm{C}$, and $\mathrm{C} > \mathrm{B}$. Second, we consider the capability of LED brightness of different colors. In the real design of LED backlight, we tend to use the same numbers of LEDs for each primary. We also prefer each LED to work at its maximum luminance, so that we can minimize the number of LEDs. For example, if we choose a ratio of R:G:B to be 10:37:5, it is an acceptable ratio based on the brightness ratio of 10:37.7:9.3 shown in Fig. 3. However, the ratio of 10:37:12 would not be a good choice because we need more blue LEDs to fulfill the design. Third, we would like to optimize the brightness. Table I also shows that different ratio would lead to a different brightness and we prefer the ratios with higher brightness. After considering the above-mentioned three criteria, we obtain a set of ratios for R:G:B:Y:C to be 12.36:18.90:4.04:48.33:16.37.

Based on the preliminary color ratios, we simulate the CBU with different color order as Fig. 4 shows. The left side shows the color order and the right side is the corresponding CBU patterns. In comparison to the CBU of three-primary in Fig. 4(a), the five-primary has a broader CBU as we expected from time and location diagram [see Fig. 1(b)]. However, we can find some



| | Red | Green | Blue | Yellow | Cyan |
|---|---|---|---|---|---|
| Luminance Intensity (mcd) | 10k | 37.7k | 9.3k | 6.15k | 6.4k |

Fig. 3. LED spectra and luminance intensities. (Ref. Nichia Co.).

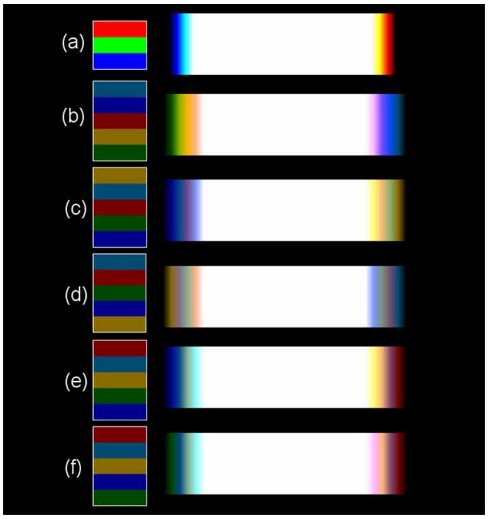


Fig. 4. Simulated CBU with different color appearing sequence.

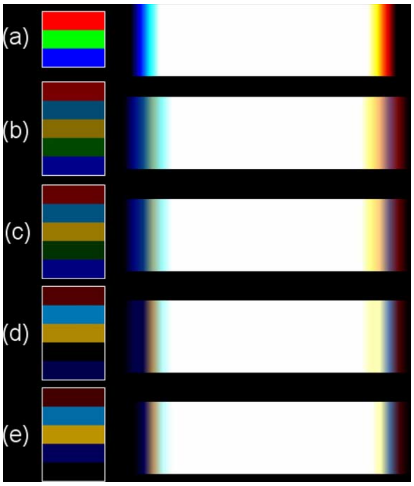


Fig. 5. Simulated CBU with different color weighting ratios.

better color orders that cause a weaker perceived CBU. For example, Fig. 4(e) and (f) exhibit a smaller CBU than those from Fig. 4(b)–(d). It is because the high brightness colors, such as yellow and cyan which are in the middle, tend to merge with the white color. Similarly, the lower brightness colors of red and blue tend to merge with the black background. Due to the lower color contrast and luminance contrast, we perceive that the CBU is compressed.

Although we can continue to optimize the color sequence of RCYGB or RCYBG, we still observe the CBU in five-primary FSC display. To further reduce CBU, we propose to boost the ratio of yellow and cyan brightness; meanwhile, to reduce the red, green, and blue ratios. From Fig. 5(b) to (e), the CBU is gradually suppressed when the ratio of red, blue, and green is decreased. The CBU reduction is more pronounced if we could get rid of green completely while reproducing white color. Because of the weaker red and blue colors, these colors are almost merged to the black background. Our eyes also tend to trace the brighter color fields, such as yellow and cyan, thus, we feel these two colors are merged to the white object. Here, we rearrange the sequence of green to be the last in order to get the least CBU [see Fig. 5(e)]. In comparison to the CBU of three-primary [see Fig. 5(a)], we effectively compress the CBU by adjusting the color order and weighting ratios.

When we want to realize the lower brightness ratio of R, B, or G, we use the liquid crystal cell to modulate the brightness instead of dimming or turning off the backlight. Therefore, the backlight emits each primary sequentially as the normal FSC backlight. There will be no need to change the electronic control of our five-primary backlight system.

Table II shows some choices of color ratios leading to a fairly small CBU for five-primary in representing white color. We would choose the most appropriate ratio after considering the least color shift ($\triangle uv$) at different viewing angle [17], [22], highest brightness, and least CBU. Usually, the solution for the

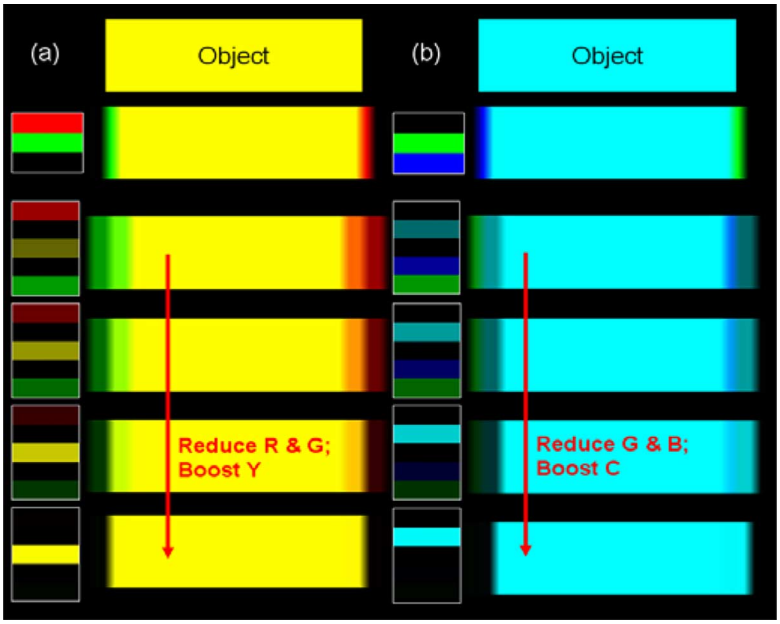


Fig. 6. Simulated CBU of yellow and cyan objects.

TABLE II
COLOR RATIOS AND COLOR SHIFT IN IPS MODE LCDs

| R (%) | G (%) | B (%) | Y (%) | C (%) | Brightness (a.u.) | △uv |
|---|---|---|---|---|---|---|
| 0.93 | 0.00 | 13.39 | 43.84 | 41.84 | 467.62 | 0.0361 |
| 0.92 | 0.00 | 13.22 | 43.29 | 42.57 | 473.55 | 0.0358 |
| 0.91 | 0.00 | 13.29 | 42.64 | 43.16 | 480.78 | 0.0357 |
| 0.75 | 0.00 | 13.25 | 44.13 | 41.86 | 464.52 | 0.0360 |
| 0.75 | 0.00 | 13.45 | 44.03 | 41.77 | 465.56 | 0.0361 |
| 0.74 | 0.00 | 13.31 | 43.59 | 42.36 | 470.30 | 0.0359 |
| 2.31 | 0.00 | 13.11 | 40.67 | 43.91 | 485.82 | 0.0358 |
| 1.77 | 0.00 | 13.24 | 41.63 | 43.35 | 492.14 | 0.0359 |
| 1.75 | 0.00 | 13.09 | 41.14 | 44.02 | 484.61 | 0.0356 |

least color shift might not be the same as that for the highest brightness or least CBU, and we need to compromise between these factors. If the CBU is acceptable, we could choose the ratio with the highest brightness. When showing the lower gray level of white (i.e., lower brightness), we could choose the ratio with the least color shift but not necessarily with the highest brightness.

Fig. 6 shows the simulated CBU for yellow and cyan objects. It is easy to realize that a five-primary LCD has no CBU when displaying these two color tones. Unlike a three-primary LCD which generates yellow by mixing red and green, or cyan by mixing green and blue, the five-primary LCD can just use yellow or cyan LEDs to display these two colors. Ideally, there would be no CBU.

Fig. 7 shows another two arbitrary colors represented by three-primary and five-primary LCDs. Based on the similar method of showing white color object, we boost the ratio of yellow and cyan to get compressed CBU in five-primary. Under proper color sequence and weighting ratios, the CBU of a five-primary display is not always larger than that of three-primary. On the contrary, after optimization the five-primary LCD could exhibit a smaller CBU than the conventional three-primary.

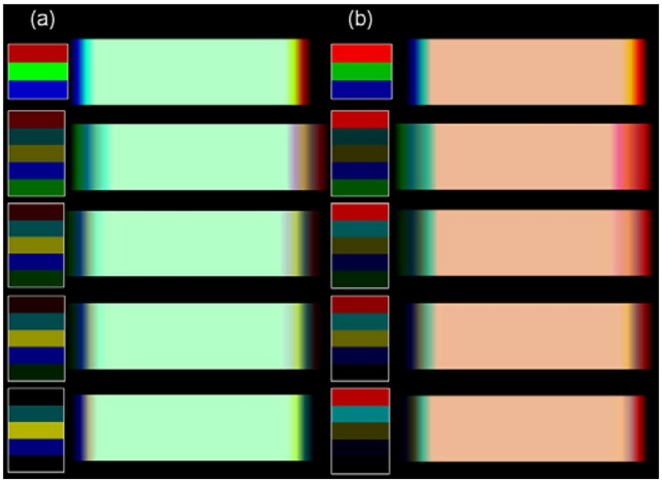


Fig. 7. Simulated CBU of two arbitrary colors. The bottom figures show compressed CBU after adjusting the color weighting ratios.

Fig. 8 shows the color coordinates of LEDs and color gamut of our five-primary display. Because of the additional yellow and cyan sources, the color gamut could achieve ~140% NTSC and it provides a very good color reproduction.

We also compare the brightness and numbers of LEDs required between three-primary and five-primary FSC LCDs. In Table III, the luminance intensity means the capability or maximum brightness of a single LED. To satisfy the color ratio we want, we estimate the LED number for each color. Brightness in Table III means the actual brightness of each color when showing the white color. We notice that not all the LEDs emit light at its maximum luminance. When showing the white color (CIE illuminant D65), the three-primary LCDs have the total brightness of 37.31 (a.u.) during each frame time (i.e., 3/540 Hz). For the five-primary LCDs, the total brightness would be 70.23 (a.u.). However, under the same sub-frame rate

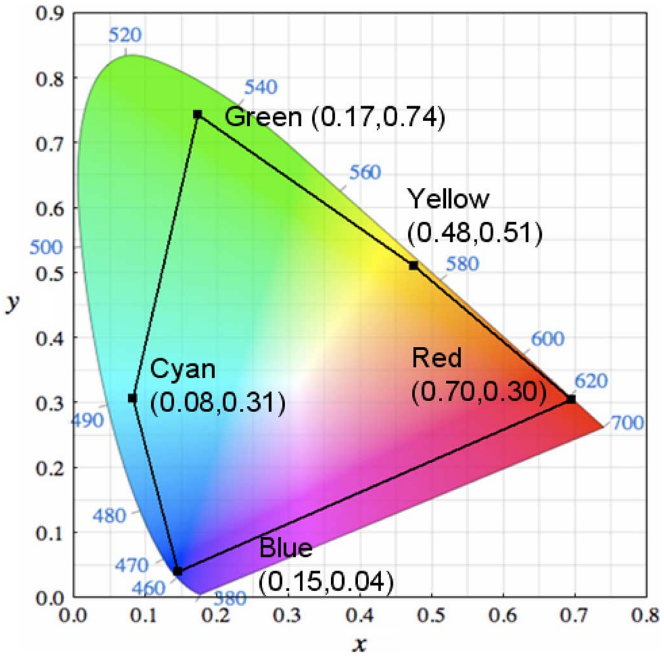


Fig. 8. Color coordinates and gamut for five-primary LCDs.

TABLE III
REQUIRED LED NUMBERS FOR SHOWING WHITE COLOR
(CIE ILLUMINANT D65)

| Three-primary LCD | | | |
|---|---|---|---|
| | R | G | B |
| Ratio (%) | 26.80 | 67.68 | 5.52 |
| Luminance Intensity (mcd) | 10k | 37.7k | 9.3k |
| LED Number | 1 | 1 | 1 |
| Brightness (a.u.) | 10 | 25.25 | 2.06 |
| Total Brightness: 37.31 | | | |

| Five-primary LCD | | | | | |
|---|---|---|---|---|---|
| | R | G | B | Y | C |
| Ratio (%) | 1.77 | 0.00 | 13.24 | 41.63 | 43.35 |
| Luminance Intensity (mcd) | 10k | 37.7k | 9.3k | 6.15k | 6.4k |
| LED Number | 1 | 1 | 1 | 5 | 5 |
| Brightness (a.u.) | 1.24 | 0.00 | 9.30 | 29.24 | 30.45 |
| Total Brightness : 70.23 | | | | | |

(i.e., 540 Hz) as three-primary, the five-primary LCDs take more time (i.e., 5/540 Hz) to complete each frame. Therefore, the brightness that we perceive in five-primary FSC LCDs should be multiplied by a factor of 3/5. After considering the field sequential factor for five-primary, we find the brightness of 42.14 (a.u.) in reality. Therefore, the brightness for five-primary is 13% higher than three-primary FSC LCDs.

## III. DISCUSSION

From our simulations, we can suppress CBU effectively by choosing proper color order and ratios in the five-primary LCDs. However, a major challenge in our design is the relative low brightness of yellow and cyan LEDs (as of today). From Table III, we realize that the LED numbers we need for yellow and cyan are much more than other primaries. Actually, many LED manufacturers already delve into developing high power yellow and cyan LEDs, and they have obtained promising results and progress recently. We believe this issue could be resolved in the near future.

Another difficulty we encounter is how to present our simulated CBU correctly in the three-primary displays. In the three-primary displays, we combine red and green to generate yellow, or green and blue to generate cyan. However, in the five-primary display, there are particular yellow and cyan sources that are more saturated and brighter. Therefore, it is impossible to display the same yellow and cyan colors in three-primary display as shown in five-primary displays. In addition, as restricted by the limited brightness of green we cannot generate and display very bright yellow and cyan when showing the simulated patterns of CBU in a three-primary display. The intrinsic difference between three-primary and five-primary displays becomes a problem during our optimization process. It causes an uncertain issue when we compromise between the CBU, color shift, and brightness to get the best ratio of each primary. This problem can be easily resolved once we use the five-primary display in the simulations and psychophysical experiments.

## IV. CONCLUSION

We have developed a method to reduce CBU in five-primary FSC displays. With the same sub-frame rate as three-primary, we effectively compress the CBU by adjusting the color order and ratios. In our simulations, the color gamut is 140% NTSC which provides a very good color reproduction. The brightness is also increased by 13% in comparison to three-primary displays. We believe that once the CBU is reduced to an acceptable level, FSC LCDs would become an emerging display technology.

## REFERENCES

[1] M. F. Weber, C. A. Stover, L. R. Gilbert, T. J. Nevitt, and A. J. Ouderkirk, “Giant birefringent optics in multilayer polymer mirrors,” *Science*, vol. 287, pp. 2451–2456, 2000.

[2] Y. Li, T. X. Wu, and S. T. Wu, “Design optimization of reflective polarizers for LCD backlight recycling,” *J. Display Technol.*, vol. 5, no. 8, pp. 335–340, Aug. 2009.

[3] F. Yamada, H. Nakamura, Y. Sakaguchi, and Y. Taira, “Sequential-color LCD based on OCB with an LED backlight,” *J. SID*, vol. 10, pp. 81–85, 2002.

[4] J. H. Lee, X. Zhu, and S. T. Wu, “Novel color-sequential transflective liquid crystal displays,” *J. Display Technol.*, vol. 3, no. 1, pp. 2–8, Mar. 2007.

[5] S. Gauza, X. Zhu, W. Piecek, R. Dabrowski, and S. T. Wu, “Fast switching liquid crystals for color-sequential LCDs,” *J. Display Technol.*, vol. 3, no. 3, pp. 250–252, Sep. 2007.

[6] L. Arend, J. Lubin, J. Gille, and J. Larimer, “Color breakup in sequentially scanned LCDs,” in *SID Symp. Dig. Tech. Papers*, 1994, vol. 25, pp. 201–204.

[7] S. T. Wu, “Nematic liquid-crystal modulator with response time less than 100- $\mu$s at room temperature,” *Appl. Phys. Lett.*, vol. 57, pp. 986–988, 1990.

[8] Z. Ge, L. Rao, S. Gauza, and S. T. Wu, “Modeling of blue phase liquid crystal displays,” *J. Display Technol.*, vol. 5, pp. 250–256, Jul. 2009.

[9] Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, “Electro-optics of polymer-stabilized blue phase liquid crystal displays,” *Appl. Phys. Lett.*, vol. 94, pp. 101–104, 2009.

[10] K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, “Submillisecond gray-level response time of a polymer-stabilized blue-phase liquid crystal,” *J. Display Technol.*, vol. 6, no. 2, pp. 49–51, Feb. 2010.

[11] M. Mori, T. Hatada, K. Ishikawa, T. Saishouji, O. Wada, J. Nakamura, and N. Terashima, “Mechanism of color breakup in field-sequential-color projectors,” *J. SID*, vol. 7, pp. 257–259, 1999.

[12] H. Yamakita, M. Sakai, Y. Taniguchi, J. Asayama, and K. Adachi, "Field-sequential color LCD driven by optimized method for color breakup reduction," in *Int. Display Workshop*, 2005, vol. 12, pp. 83–86.

[13] K. Sekiya, T. Miyashita, and T. Uchida, "A simple and practical way to cope with color breakup on field sequential color LCDs," in *SID Symp. Dig. Tech. Papers*, 2006, vol. 37, pp. 1661–1664.

[14] N. Koma and T. Uchida, "A new field-sequential-color LCD without moving-object color break-up," *J. Soc. Inf. Display*, vol. 11, pp. 413–417, 2003.

[15] C. H. Chen, F. C. Lin, Y. T. Hsu, Y. P. Huang, and H. P. Shieh, "A field sequential color LCD based on color field arrangement for color breakup and flicker reduction," *J. Display Technol.*, vol. 5, no. 1, pp. 34–39, Jan. 2009.

[16] F. C. Lin, Y. P. Huang, C. M. Wei, and H. P. Shieh, "Color-breakup suppression and low-power consumption by using the Stencil_FSC method in field-sequential LCDs," *J. Soc. Inf. Display*, vol. 17, pp. 221–227, 2009.

[17] 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 Symp. Dig. Tech. Papers*, 2009, vol. 40, pp. 927–930.

[18] S. Roth, N. Weiss, M. B. Chorin, I. B. David, and C. H. Chen, "Multi-primary LCD for TV applications," in *SID Symp. Dig. Tech. Papers*, 2007, vol. 38, pp. 34–37.

[19] H. C. Cheng, I. Ben-David, and S. T. Wu, "Five-primary color LCDs," *J. Display Technol.*, vol. 6, no. 1, pp. 3–7, Jan. 2010.

[20] E. Langendijk, S. Swinkels, D. Eliav, and M. Chorin, "Suppression of color breakup in color-sequential multiprimary projection displays," *J. Soc. Inf. Display*, vol. 14, pp. 325–329, 2006.

[21] J. H. Lee, D. N. Liu, and S. T. Wu, *Introduction to Flat Panel Displays*. New York: Wiley, 2008.

[22] 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.

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