180Hz Stencil-FSC 法及 RGBW 四合一 LED 用於無彩色濾光片之液晶顯示器

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摘　要

近年來，溫室效應所帶來的氣候變遷，已嚴重影響地球生態。因此，如何「減緩地球毀壞的速度」成為各領域科學家努力的議題。在顯示器方面，不需要彩色濾光片的場色序法顯示技術能夠提升光使用效率，並且有高影像解析度，高色彩飽和度，以及低成本的優點。然而此技術有一先天上的問題，色分離現象，此現象會降低影像品質，甚至讓觀賞者感到不適。雖然目前已提出許多解法，然而這些方法仍然面臨許多問題，如液晶反應速度不足使影像失真……等等。

對於抑制色分離，我們提出了 240Hz, 180Hz Stencil-FSC 法及 Two-Color-Field 法有效抑制色分離現象。但其中 180Hz Stencil-FSC 法演算法中有漏光問題。

為了解決此漏光問題，本篇論文提出「適應性基底之 180Hz Stencil-FSC 法」，根據輸入影像選取第一色場適合之主色能有效降低漏光以維持影像正確性；其平均影像失真(ΔE_{00})小於一，色分離只有傳統場色序法的 59%。此法也用 46 吋的 MVA-LCD 實際驗證，其色分離幾乎看不見。

另一方面，本篇論文也提出 RGBW 四合一 LED 背光系統進一步降低場色序型顯示器的耗能；影像中的白色部分由高效率的白光 LED 呈現取代低效率的紅、綠、藍 LED 混色，剩下的色彩部份才由原色 LED 呈現，如此一來顯示器的耗能可以再進一步降低。而我們提出的解法也應用於 RGBW 四合一 LED 背光

系統上。然而 Two-Color-Field 法在一個場裡只有兩種原色色彩，不能用 RGBW LED 降低耗能，因此此篇論文也修改其演算法，提出 120Hz Stencil-FSC 法。在耗能評估上，三種 Stencil-FSC 法應用於 RGBW LED 的背光耗能能夠分別降至傳統場色序法顯示器的 62%，52%及 24%。因此 Stencil-FSC 法加上 RGBW 四合一 LED 背光系統能夠在低耗能下提供高影像品質。

180Hz Stencil-FSC Method With RGBW 4-in-1 LEDs for Color Filter-Less LCDs

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Abstract

The Global warming issue has become more seriously in recent years. Therefore, how to reduce the speed of earth damage becomes a hot issue in many research areas. In the display area, field-sequential-color (FSC) technology not requiring color filter was proposed to enhance light transmittance of LCDs. It has some advantages like high image resolution, high color gamut, and low material cost. However, FSC technology has a fatal drawback, color breakup (CBU) phenomenon. CBU phenomenon seriously decreases image quality. Therefore, there are some CBU suppression method were proposed. However, those methods also have some issues like low LC response time.

Therefore, our group proposed 240Hz, 180Hz Stencil-FSC methods and Two-color-field method to suppress CBU, however, the 180Hz Stencil-FSC method has a minor issue, color distortion.

In this thesis, the "adaptive base 180Hz Stencil-FSC method" was proposed to reduce color distortion of 180Hz Stencil-FSC method. By determining the dominant color of first field, the color distortion was much reduced to average ΔE_{00}<1. The relative CBU was reduced to 59% of conventional RGB-FSC method. Furthermore, the adaptive base 180Hz Stencil-FSC method was verified in a 46" 120Hz MVA-LCD

and made CBU almost imperceptible.

On the other hand, this thesis also proposed RGBW 4-in-1 LEDs backlight system to further reduce the power consumption of FSC-LCDs. The gray/white part of image was generated using high efficiency white-light LED instead of low efficiency RGB LED. The remaining color part was generated using RGB LED. By this way, the power consumption of FSC-LCDs was further reduced. However, the two-color-field method could not reduce power with RGBW 4-in-1 LEDs because there were only two primary colors in each field. Therefore, this thesis modified the algorithm to be 120Hz Stencil-FSC method by making first field become a multi-color single field. Then 240Hz, adaptive base 180Hz, and 120Hz Stencil-FSC methods were applied on RGBW 4-in-1 LEDs backlight system and reduced optical power to 62%, 52%, and 24% of conventional RGB-FSC method respectively. Therefore, the Stencil-FSC method with RGBW 4-in-1 LEDs backlight system provide high image quality with low power consumption.

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Chapter 1

Introduction

Field-sequential-color liquid crystal display (FSC-LCD) is a kind of LCD which to enhance optical throughput and reduce power consumption of conventional LCD [1]. However, the color breakup (CBU) issue makes FSC-LCD seldom applied in the LCD industry [2]. In this chapter, FSC-LCD and CBU issue will be introduced, and then the motivation and objective of this thesis will be given. The final section is the organization of this thesis.

1.1 Field-Sequential-Color Liquid Crystal Displays (FSC-LCDs)

Global warming has influenced the earth more seriously in recent years. The average temperature has become higher and higher and the North Pole ice cap has continued melt. These effects have changed the climate of the earth, meaning our living environment has encountered an unprecedented threat. Therefore, reducing energy consumption has become an important topic in many research areas. In the display area, LCDs have become popular for commercial display products because of its thin volume and light weight and no radiation emitting. The structure of the LCD is illustrated in Fig. 1-1. On the bottom, backlight module provides a full-on white light source using Cold Cathode Fluorescent Lamps (CCFLs) or white light Light-Emitted-Diodes (LEDs). When light passes through optical films, uniform and directed light is obtained. Then, the backlight polarization state changes to linear state after passing a polarizer and goes through the LC layer to modulate light transmittance in each pixel. Finally, in each pixel, the light goes through red, green, and blue color filters (CFs) and the full color image is generated by spatial color mixing. However, conventional LCDs have disadvantages. First, light efficiency is very low. The polarizer blocks about 50 % of backlight, the CFs absorbs about 66% of backlight, and some light is blocked by optical films. Therefore, the light of final image is approximately only 5~7% of original backlight. Second, the pixel size is limited, in each conventional LCD pixel, there are three sub-pixels which control the red, green, and blue light, thus TFT manufacturing limits pixel size. Therefore, Field-Sequential-Color (FSC) LCDs not requiring CFs were proposed to enhance optical throughput and try to decrease pixel size.

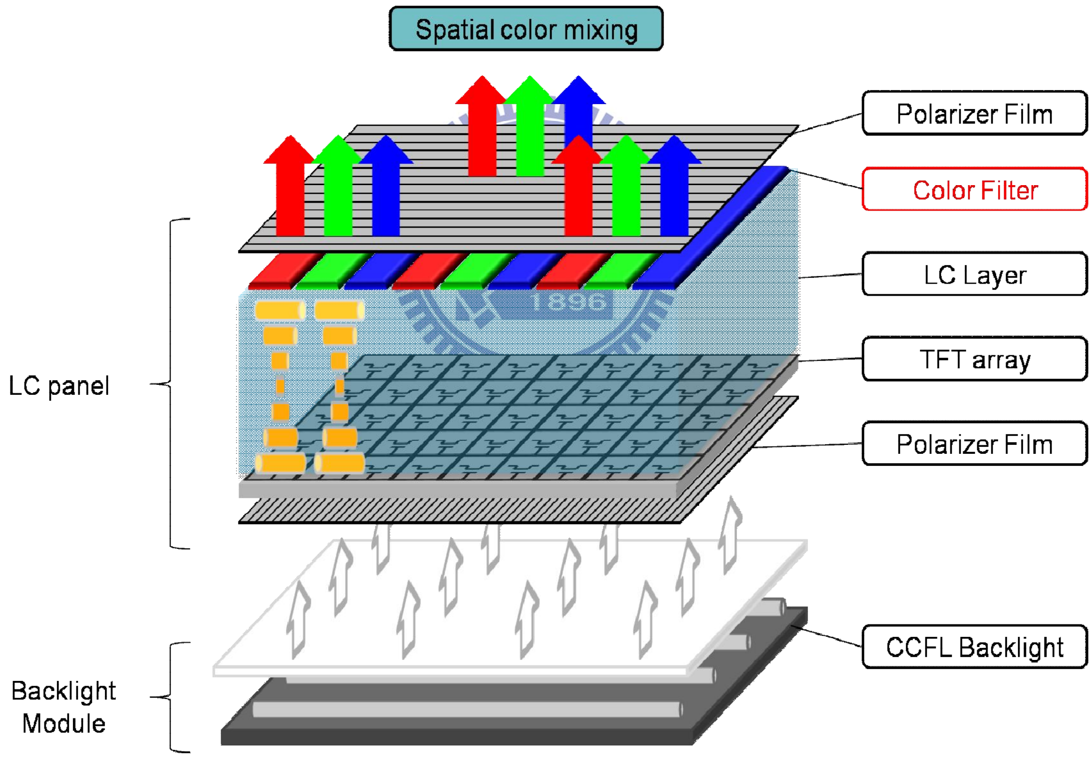


Fig. 1-1 Structure of conventional TFT-LCDs

The original concept of using the FSC technique to generate a color image was first proposed by Peter Goldmark in 1948 [3]. At that time, the FSC technique was applied to projector display systems such as digital light processing (DLP) [4]. Using the human eye duration of vision, color images integrate on eye retina rapidly, therefore, a full color image was generated. In recent year, fast response LED and LC were developed. Therefore, FSC technology started to apply to LCDs. The structure of the FSC-LCDs is illustrated in Fig. 1- 2. The backlight module is composed by three primary color LEDs and display red, green, and blue light time sequentially instead of full-on. Then light propagates through the TFT LC layer to get red, green, and blue images. These three field images display faster than human eye's time resolution. Therefore, a full color image was generated using temporal color mixing.

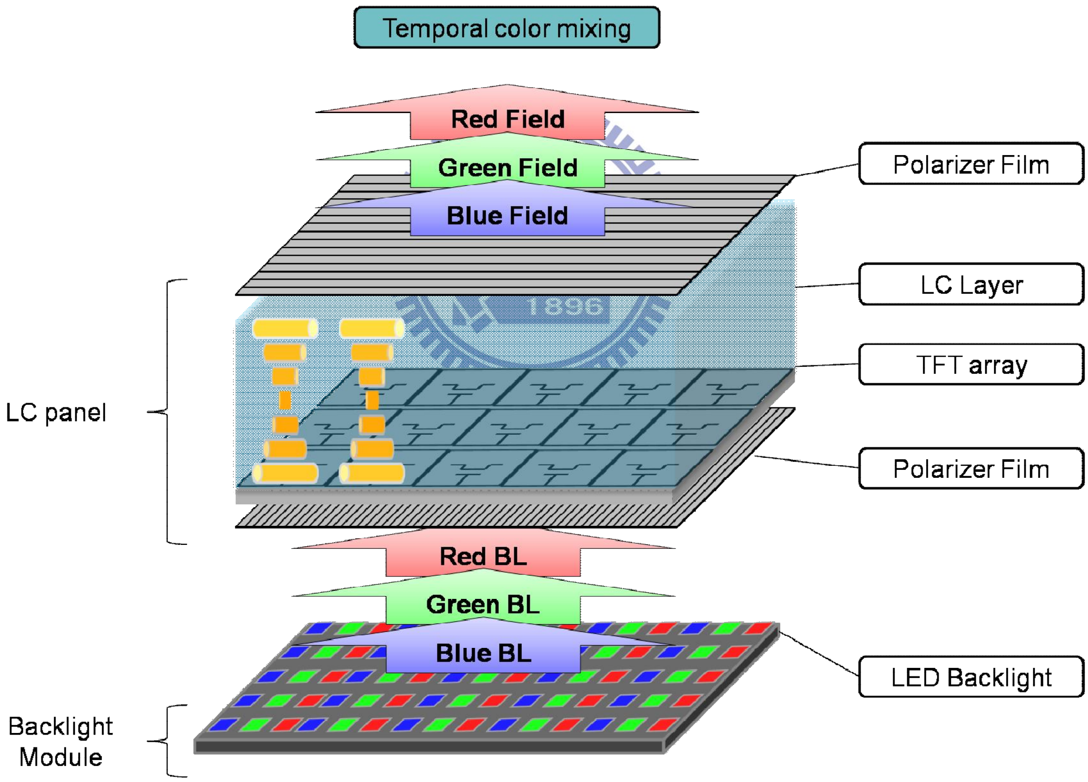


Fig. 1- 2 Structure of FSC-LCDs

The FSC-LCD driving scheme of each field (1/3f) includes TFT addressing time (t_{TFT}), LC response time (t_{LC}), and backlight flashing time (t_{BL}) as shown in Eq. 1-1 [5] where f indicates field rate. The timing chart is illustrated in Fig. 1- 3, In the first period, the TFT scans of entire the panel, then the LC twists toward the target gray level, then backlight turns on to show the field image, finally repeating these three times for red, green, and blue field, generates a full color image.

$$\frac{1}{3f} = t_{TFT} + t_{LC} + t_{BL} \qquad \text{Eq. 1- 1}$$

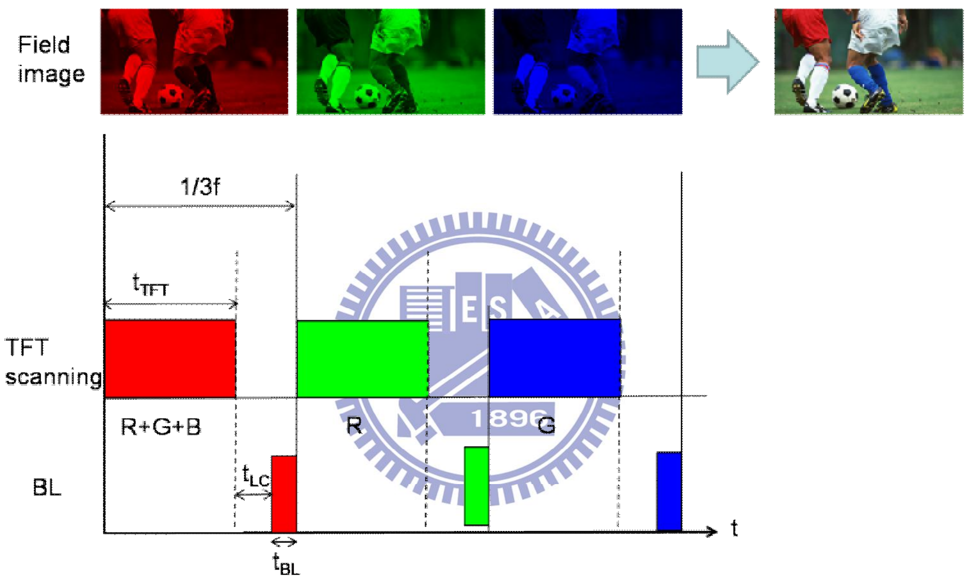


Fig. 1- 3 Timing chart of FSC-LCDs

FSC-LCDs have many attractive advantages. First, the FSC-LCD does not require CFs because of temporal color mixing. Therefore, the optical throughput is three times that of conventional LCDs. Second, the LCD manufacturing cost can be saved about 25%, so removing CFs is a good way to reduce LCD cost, the cost of every component in the LCD is shown in Fig. 1- 4. Third, the pixel size can be reduced because it does not need sub-pixel (Fig. 1- 5), therefore, the FSC-LCD resolution is three times that of conventional LCDs. Forth, by using RGB LED, the color gamut and NTSC is much enhanced, because of the sharp spectrum of primary color LEDs.

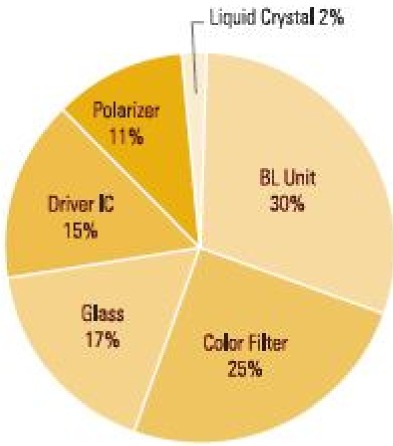
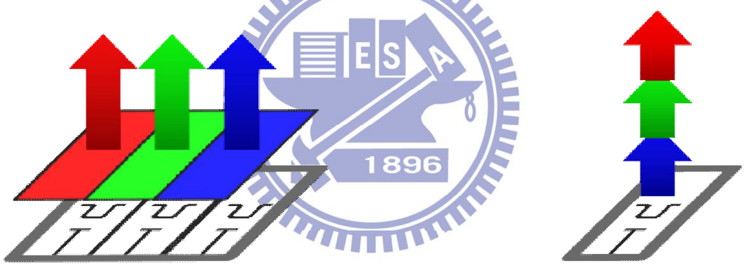


Fig. 1- 4 The component costs of TFT LCDs

(From Woori Investment & Securities)

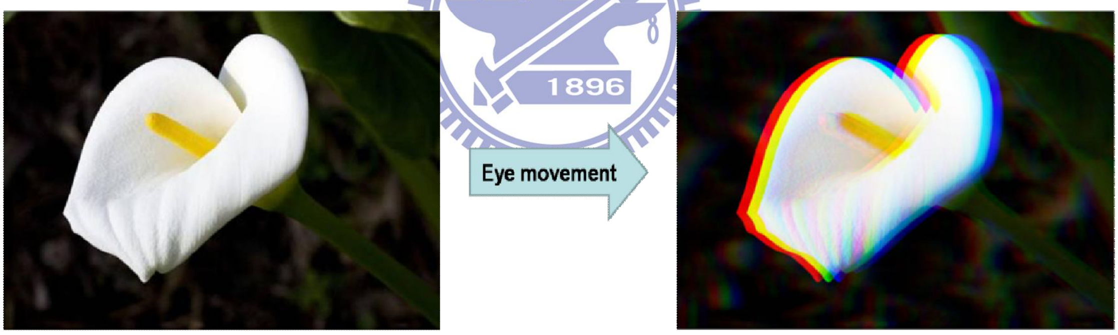


(a) (b)

Fig. 1- 5 Comparison of pixel size of (a) conventional LCDs and (b) FSC-LCDs

1.2 Color Breakup Phenomenon (CBU)

FSC-LCDs have low power consumption, low cost, high color saturation, and three times image resolution. However, there is a fatal flaw, color breakup (CBU), which occurs when there are relative velocities between human eyes and display objects. In that case, three primary color field images do not overlap perfectly on the retina and degrade image fidelity [6]. For example, if a FSC-LCD displays a white image, and the human' eye has a relative velocity with the image, red, green, and blue field images will projects at different position on the retina. Therefore, the human eye will perceive separated colors on the edge of the image as shown in Fig. 1- 6. CBU is the most serious issue in FSC-LCD which causes viewers to feel uncomfortable, and it may happen in both stationary image and moving image. The detailed mechanism will be described in section 2.1.



(a) (b)

Fig. 1- 6 (a) Target image and (b) CBU image

1.3 LED Backlight System

In order to display red, green, and blue light time sequentially in FSC-LCDs, the fast switching backlight system must be utilized. The first visible light LED was invented by Nick Holonyak, Jr. in 1962 [7]. He opened another window of illumination. During the following few decades, LED industry has developed rapidly. In recent year, LED started to apply on LCD backlight system. Comparing to the CCFL backlight, LED backlight system has many advantages. First, LED does not have mercury vapor, therefore, LED has no pollution issue. Second, the color gamut of LED is higher than CCFL backlight as shown in Fig. 1- 7 . The NTSC of CCFL is only about 82%, and NTSC of LED backlight is larger than 114% [8]. Furthermore, the LED backlight system can combine with high dynamic range technology to increase contrast ration and reduce power consumption. Therefore, fast switching RGB LED is adapted to be the backlight system of FSC-LCDs. The detail mechanism of RGB LED will be described in section 5.1.

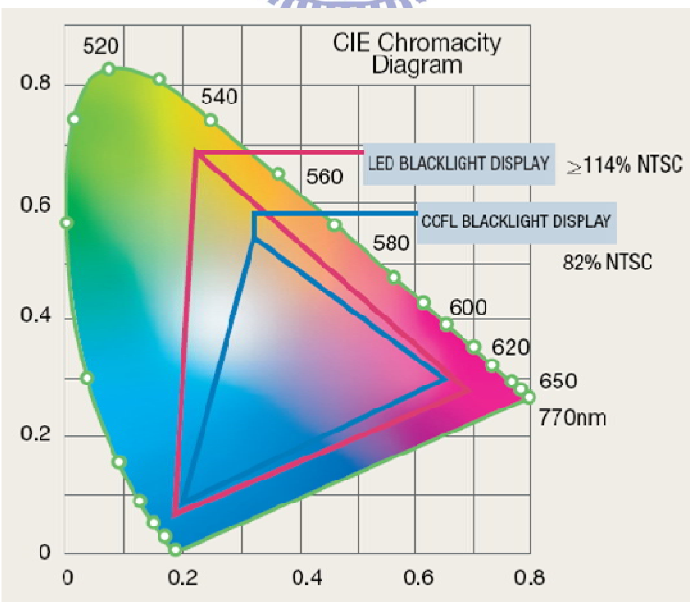


Fig. 1- 7 The color gamut of CCFL backlight (82% NTSC) and LED backlight (>114% NTSC)

1.4 Motivation and Objective

CBU is a very noisy phenomenon, and there are some CBU suppression methods. However the current LC response time is too slow to implement on hardware. That is why FSC-LCDs are not popular in the LCD industry, consumers will not buy a LCD which not comfortable for watching. Therefore, our group has proposed a low field rate 180Hz Stencil-FSC method. 180Hz Stencil-FSC method can suppress CBU effectively and can achieve easily by OCB mode LC [9][10] . However, the original 180Hz Stencil-FSC method still has an issue, color difference, in some images, the reproduced image may cause perceptible image distortion due to the algorithm. Therefore, the objective of this thesis is to modify and optimize of 180Hz Stencil-FSC method. By optimizing the algorithm, the average image distortion of reproduced image is expected to decrease to CIEDE 2000 value (ΔE_{00})<1 with minor CBU increases.

On the other hand, to reduce the power consumption of FSC-LCDs even more, the backlight system should be further improved. Currently, the average power efficiency of RGB-LED backlight is about 40 lm/W which is lower than CCFLs. Therefore, high power efficiency white light LED is adapted to added onto RGB-LED as a RGBW 4-in-1 LED. The white part of image is generated by white light LED, and the remaining color part of image is generated by RGB LED, by this way, the power consumption of FSC-LCDs is expected to be reduced comparing to RGB LED backlight system.

1.5 Organization

This thesis is organized as follows. In **Chapter 2**, the detailed mechanism of different kind CBU caused by different human eyes movement will be discussed at first. Then some CBU suppression methods will be mentioned, then the 180Hz Stencil-FSC methods will be described in detail, finally, the color difference CIEDE2000 will be introduced to evaluate the image difference and CBU. In **Chapter 3**, the concept of adaptive base 180Hz Stencil-FSC method and its algorithm will be described in detail. In **Chapter 4**, some hardware parameter of adaptive base 180Hz Stencil-FSC method will optimize to suppress CBU more effectively and some experimental result will be presented. In **Chapter 5**, RGB LED backlight system will be introduced, and the power consumption of FSC-LCDs using RGBW 4-in-1 LEDs will be discussed. Finally, conclusions and future works will be summarized in **Chapter 6**.

Chapter 2

Prior Color Breakup Suppression Methods

FSC-LCDs have achieved low power consumption and other benefits, however, CBU phenomenon makes FSC-LCDs seldom applied in the LCD industry, because CBU makes people feel uncomfortable when watching FSC-LCDs. In order to suppress CBU, the mechanism of CBU and some prior CBU suppression methods must be understood. Moreover, to evaluate a CBU suppression method, the color difference of CIEDE 2000 was introduced to evaluate image difference of target image and reproduced image, also the CBU phenomenon was quantified using CIEDE 2000 value.

2.1 Mechanism of CBU in Conventional LCDs

CBU is a very annoying phenomenon in conventional FSC-LCD. Ideally, the three primary color field images overlap perfectly on eye retina. However, human eyes do not focus only on a point on the LCD screen when watching TV, therefore, when there are relative velocities between human eyes and display objects, three primary color field images do not overlap perfectly, so viewer will perceive a rainbow like phenomenon on the edge of object, and this phenomenon is called CBU. CBU can be classified into two types depending on the eye movements: static CBU and dynamic CBU.

The mechanism of static CBU can be explained by Fig. 2- 1, Fig. 2- 1(a) is a stationary image, when perceiving this image, eyes will move between two bars with saccade movement, like the gray line in the figure. When moving with saccade, primary color images will separate, therefore. Therefore, static CBU is perceived as shown in Fig. 2- 1(b).

The other kind is dynamic CBU, dynamic CBU occurs in Smooth Pursuit Eye Movement (SPEM) in vision system [11]. The mechanism of dynamic CBU can be explained by Fig. 2- 2 [12].When a FSC-LCD is displaying a moving image, human eye will pursuit this image at the same velocity to observe the image as shown in Fig. 2- 2(a). Therefore, dynamic CBU is perceived by human eye. The spatial-temporal relation is shown in Fig. 2- 2(b), the horizontal axis is display position, and the vertical axis is time, and the black lines indicate eye trace line. After human eye's integration, dynamic CBU will be perceived. Both static and dynamic CBU seriously degrades image fidelity of FSC-LCDs. Several CBU suppression methods were proposed in recent years, the mechanism of those methods will be discussed in the next section.

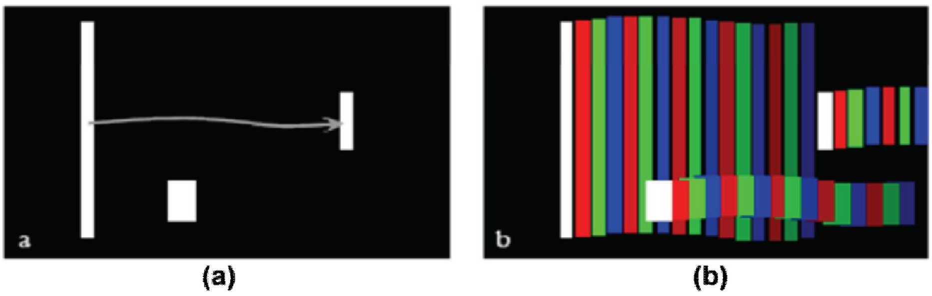


Fig. 2- 1 Mechanism of static CBU (a) stationary image with saccade eye movement (gray line), and (b) static CBU phenomenon

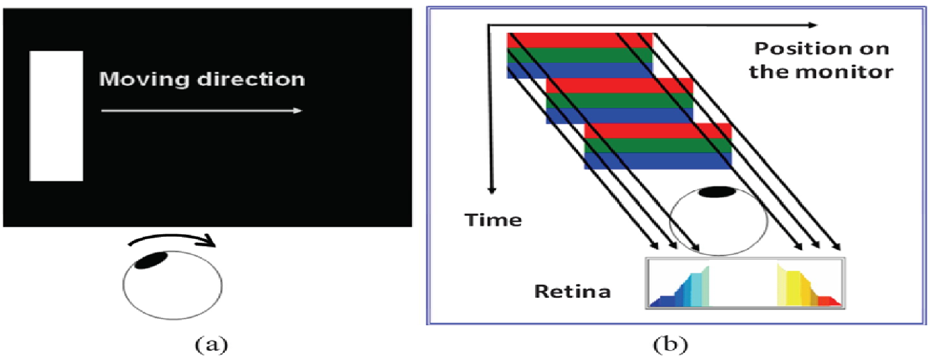


Fig. 2- 2 Mechanism of dynamic CBU (a) moving image with pursuit eye movement, and (b) dynamic CBU phenomenon perceived by eye

2.2 Prior CBU Suppression Methods

CBU phenomenon is the fatal drawback of FSC-LCDs, this phenomenon seriously degrades image fidelity and sometimes causes viewer feel discomfort when viewing FSC-LCD. Therefore, how to suppress CBU is a key issue in FSC technique, and many effective CBU suppression methods have been proposed including increase field rate, insert multi-primary color field, and utilize motion compensation as shown in Fig. 2- 3.

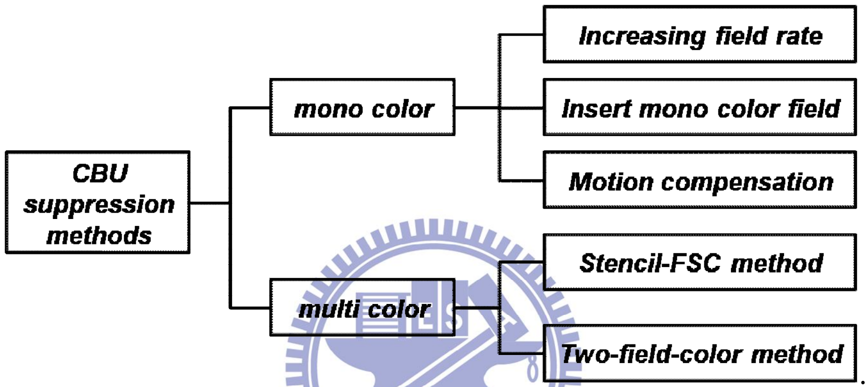


Fig. 2- 3 CBU suppression methods

2.2.1 Increasing Field Rate

Increasing field rate is an intuitive method to suppress CBU. The concept of this method is to reduce the separate width of each field. Therefore, higher the field rate, narrower the CBU width. If the CBU width becomes narrow, the human eye will be less sensitive to CBU [13]. For DLP projector, high field rate can be achieved using color wheel and its digital micromirror device (DMD). For LCD, the RGBRGB double frame rate was proposed [14]. Comparing to the conventional RGB-driving method, the CBU width of double field rate method is much narrower as shown in Fig. 2- 4. However, the current LC response time is too slow to implement on hardware.

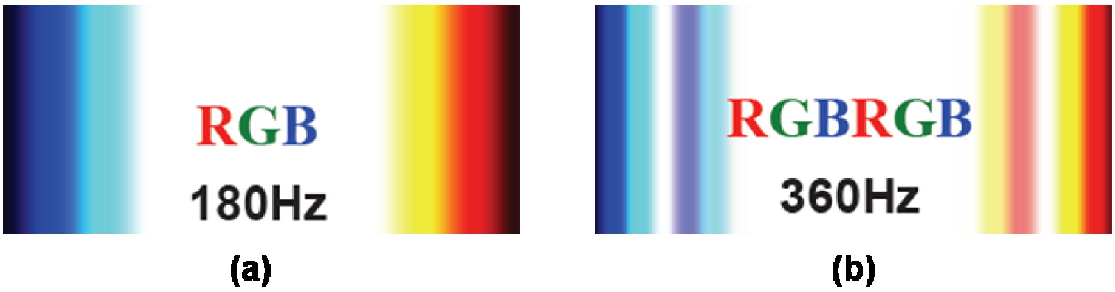


Fig. 2- 4 CBU image of (a) RGB and (b) RGBRGB

2.2.2 Inserting Multi-Primary Color Fields

The concept of inserting multi-primary color fields is to reduce the color difference between each field and prevent from the appearance of the sensitive color on the image edge. For example, the RGBCY method which was proposed by Tatsuo Uchida research group [15], the cyan and yellow field were inserted, the cyan and yellow are less sensitive by human eye comparing to the red ,green, and blue colors. Therefore, even there are relative velocities between human eye and display object, the separated color will less sensitive by human eye as shown in Fig. 2- 5. However, RGBCY method requires 300Hz field rate to be achieved, also limited by current LC response time.

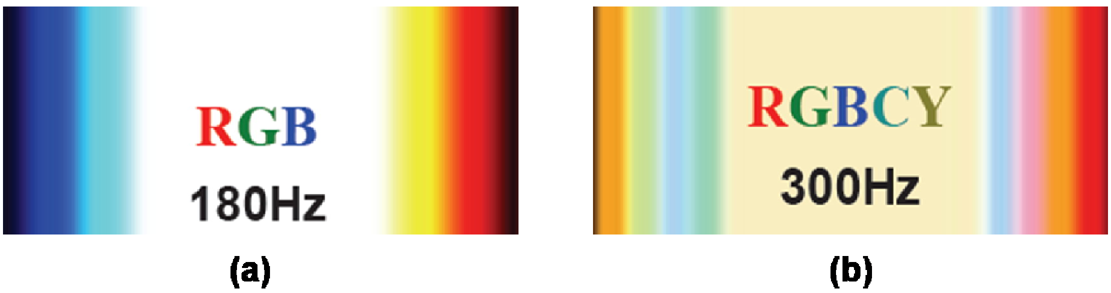


Fig. 2- 5 CBU image of (a) RGB and (b) RGBCY

2.2.3 Motion Compensation

The motion compensation method was proposed to suppress dynamic CBU, as section 2.1 mentioned, when LCD display a moving image, human eye will pursuit the image at the same velocity, therefore, the separated color will be perceived. In order to suppress dynamic CBU, the motion compensation method compensated image to make each frame at the same position of retina [16]. The compensation mechanism can be explained by Fig. 2- 6. The spatial-temporal relation shows that if an image is moving from display left to right, each field in one frame will shift a distance depending on the image speed. After human eye integration along the eye trace line, no separated color will be perceived. Therefore, the dynamic CBU with predictable eye movement can be almost imperceptible by motion compensation method. However, if the predicted direction of eye movement is wrong, this method will cause more serious CBU than conventional RGB-driving method as shown in Fig. 2- 7. All of red, green, and blue field images are totally separated. Therefore, if the eye movement is not the predict direction or there are more than one object moving with different direction, motion compensation method will be failed to suppress CBU.

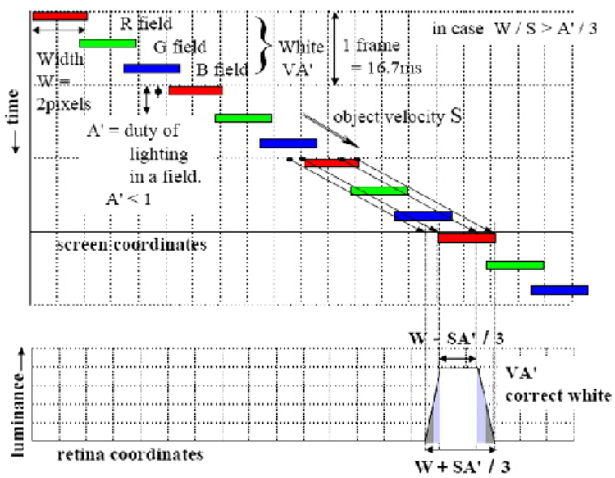


Fig. 2- 6 Motion compensation method. CBU phenomenon with predictable eye movement

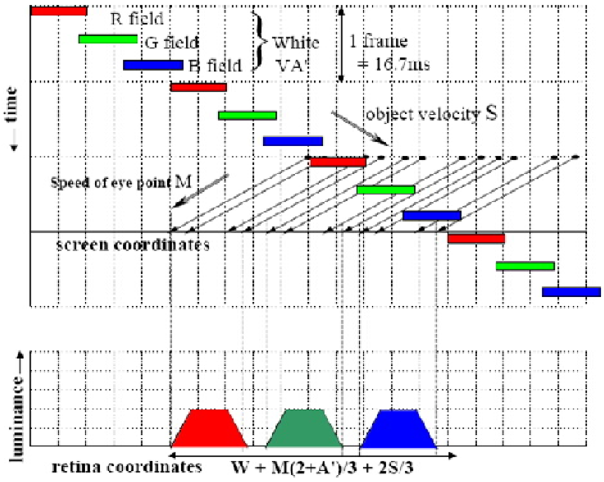


Fig. 2- 7 Motion compensation method. CBU with opposite eye movement

2.3 Stencil Field-Sequential-Color Method

The mentioned CBU suppression methods in section 2.2 were effective but hard to implement on hardware, because of the LC response time issue. In order to implement on hardware, the field rate of CBU suppression method must be reduced. Therefore, our group proposed Stencil field-sequential-color methods with low field rate 240Hz and multi-color single field to suppress CBU [17][18]. The concept is to display high luminance and rough color in the first field image, and the remaining fields were merely making up the image details as shown in Fig. 2- 8(a). Therefore, the intensity of the remaining color fields were very low, even CBU occurs, the separated colors were almost imperceptible. At current LC response time, 240Hz Stencil-FSC method could only achieve on small size FSC-LCD. In order to implement on large size FSC-LCDs, our group proposed 180Hz Stencil-FSC method as shown in Fig. 2- 8(b) [19]. The concept is similar to the 240Hz Stencil method, all the green information is displayed at first field and some red and blue information, therefore, the first field is still a multi-color field with high intensity. The remaining red and blue information is displayed at the other two fields. Therefore, the CBU is also almost imperceptible as shown in Fig. 2- 9. To achieve on commercial LC mode such as TN, MVA, or IPS, the field rate must be further reduced. Thus the two-color-field method was proposed [20]. The concept of two-color-field sequential method is displaying two color-mixing fields with 120Hz frame rate to generate a full color image as shown in Fig. 2- 8(c) [21].

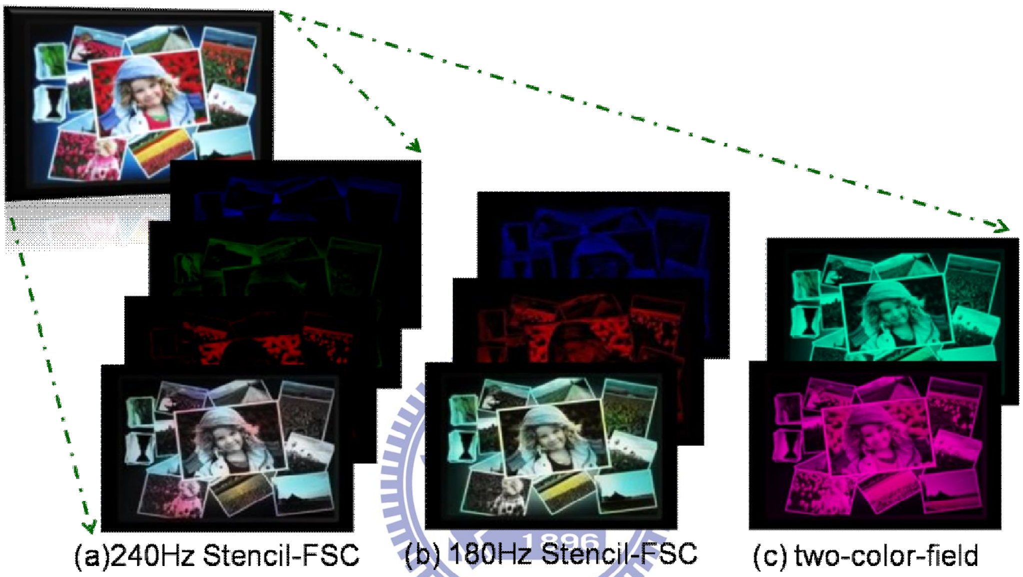
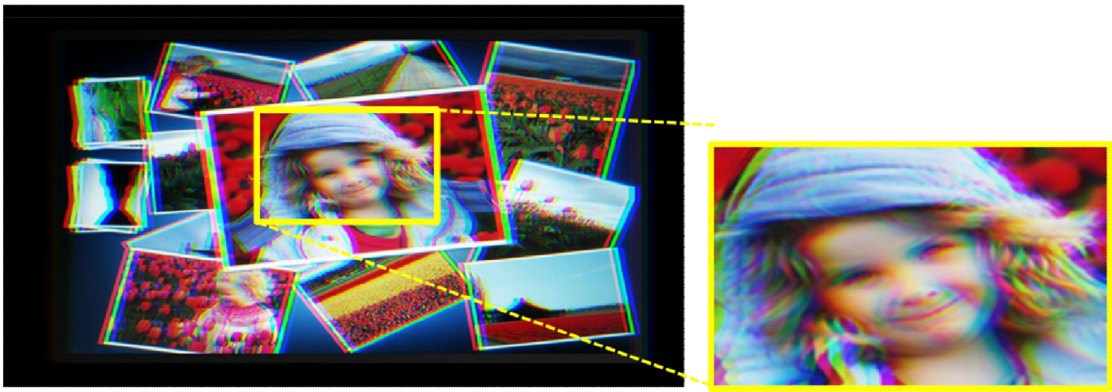


Fig. 2- 8 Concept of Stencil-FSC methods



(a) CBU image of RGB-driving method with target image *Girl*

(b) CBU image of 240Hz Stencil-FSC method with target image *Girl*

(c) CBU image of 180Hz Stencil-FSC method with target image *Girl*

Fig. 2- 9 CBU images of (a) RGB-driving, (b) 240Hz Stencil-FSC method, and (c) 180Hz Stencil-FSC method.

2.4 Image Distortion and CBU Evaluation Index: ΔE_{00}

Many methods are proposed to suppress CBU, but how to evaluate the quality of that method? The color reproducibility and improvement of CBU phenomenon are two main indexes have to be concerned. To evaluate the color reproducibility, utilizing the color difference is straight and convenient. To quantify colors, in 1920, Wright and Guild designed an experiment to estimate the wavelength in the visible region [22][23]. The experimental setup is shown in Fig. 2- 10. The top part is a reference light source which provides monochromatic light from 380nm to 780nm and at the bottom part is composed by three adjustable primary color lights (700nm, 546.1nm, and 435.8nm). At each wavelength of reference light source, the tester is asked to adjust the three primary colors to make the same color with light source and record the components of each primary color light. Therefore, the color mapping function: $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$ is obtained as shown in Fig. 2- 11. However, the experimental result of color mapping function includes negative number which would lead some calculation trouble, therefore, the experiment result of color mapping function is transformed to $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ as shown in Fig. 2- 12.

The color is determined by three components: light source (P), object reflectance (R), and color mapping function of human eye $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. Then the tristimulus values X, Y, and Z are defined as Eq. 2-1. Without considering luminance, the three dimensions XYZ tristimulus coordinate can be mapped to two dimensions using Eq. 2-2. This is the well-known CIE1931(x,y) color space established by Commission International de I'Eclairage (CIE) in 1931 as shown in Fig. 2- 13 [24][25].

$$X = \int P(\lambda)R(\lambda)\,\overline{x}(\lambda)d\lambda$$

$$Y = \int P(\lambda)R(\lambda)\,\overline{y}(\lambda)d\lambda \qquad \text{Eq. 2- 1}$$

$$Z = \int P(\lambda)R(\lambda)\,\overline{z}(\lambda)d\lambda$$

$$x=X/(X+Y+Z)$$

$$y=Y/(X+Y+Z) \qquad \text{Eq. 2- 2}$$

$$z=Z/(X+Y+Z)$$

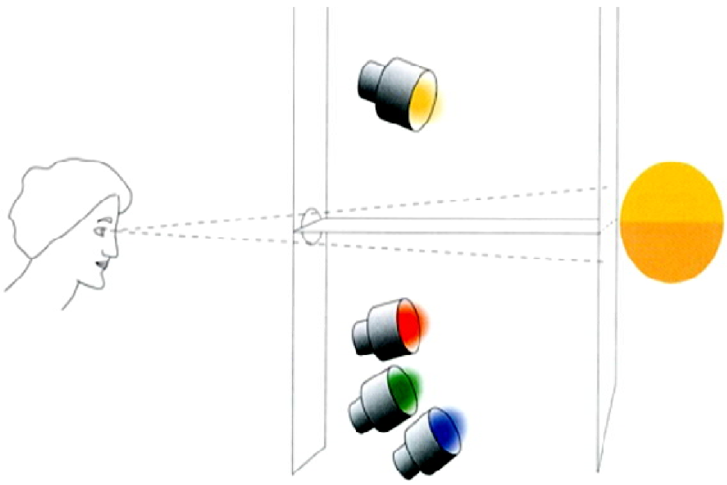


Fig. 2- 10 Setup of color mapping experiment

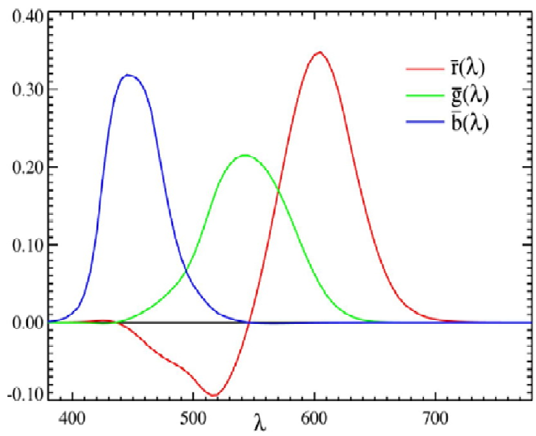


Fig. 2- 11 Experiment result of color mapping function

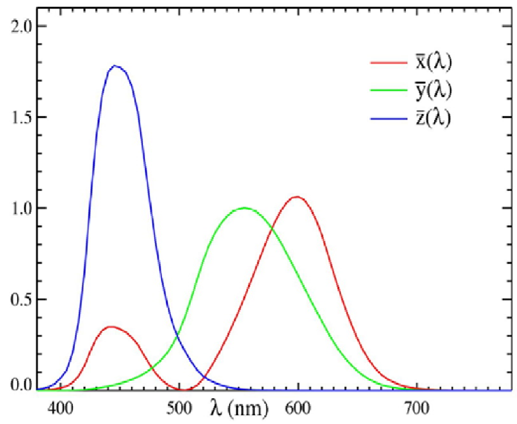


Fig. 2- 12 Color mapping function after transformation

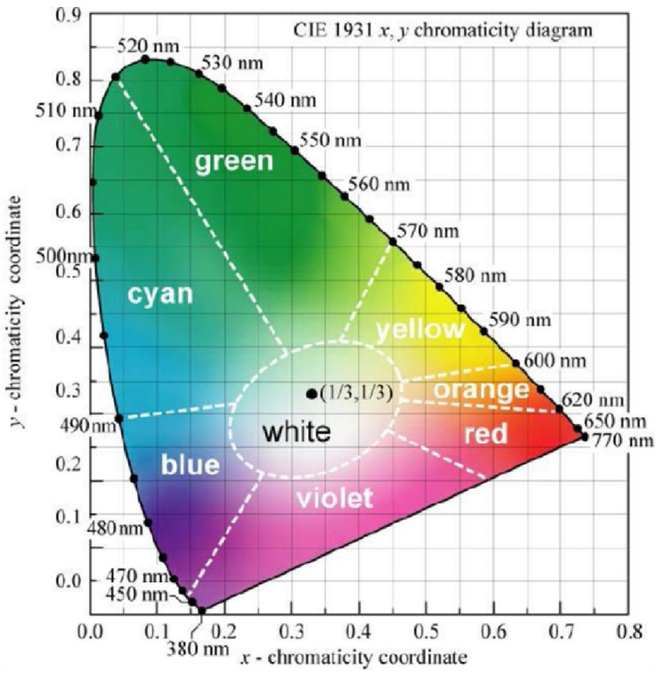


Fig. 2- 13 CIE1931(x,y) chromaticity diagram

However, the CIE1931 color space is not a uniform space as shown in Fig. 2- 14, the ellipse in the diagram denote that human cannot distinguish the color difference in the ellipse region, therefore, the other color space optimized color space CIELAB was proposed to overcome this issue [26][27]. The equation of CIELAB is shown in Eq. 2-3, *Xn*, *Yn*, and *Zn* are three tristimulus value of reference white. L^* represents lightness, a^* approximate redness-greenness, and b^* approximate yellowness-blueness. CIELAB provides a uniform chromaticity diagram as shown in Fig. 2- 15. Thus, the color difference formula CIEDE2000 was proposed based on CIELAB chromaticity diagram [28]. The equations of CIEDE2000 are shown in Eq. 2-4, the parameter SL, SC, and SH are the weighting function of lightness, chroma and hue difference, respectively (Eq. 2-5). KL, KC, and KH are the parametric factors adjusted according to different viewing parameters, for the lightness, chroma, and hue components, individually. RT function is intended to improve the performance of the color-difference equation for describing chromatic differences in the blue region. The CIEDE2000 considers more color conditions. Therefore, this thesis utilizes CIEDE2000 to evaluate color difference between original images and reproduced images which simulated by the proposed method.

Furthermore, the CBU phenomenon is quantified by CIEDE2000. The CBU occurs when field images do not overlap perfectly, thus, the primary color can be perceived on the image edge. Therefore, utilizing CIEDE2000 to evaluate the color difference on the edge between target image and reproduced image is a straight way to quantify CBU phenomenon

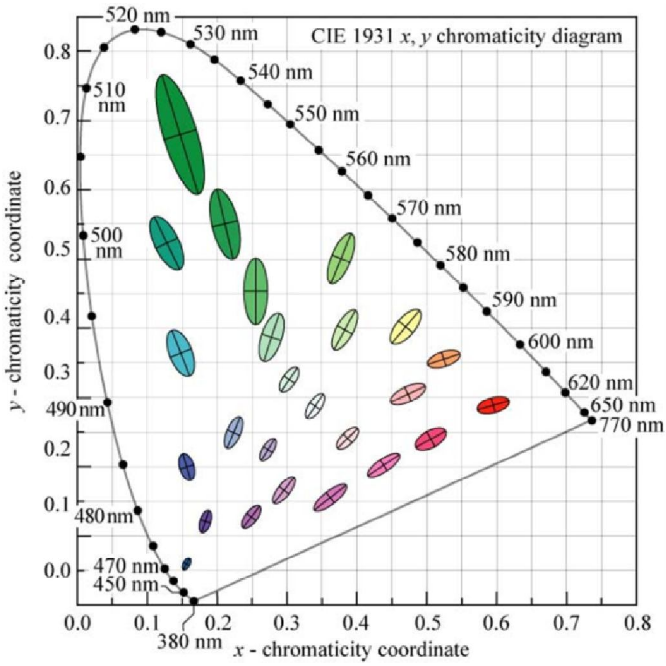


Fig. 2- 14 Macadam ellipses

$$L^* = \begin{cases} 903.3\frac{Y}{Y_n}; & \frac{Y}{Y_n} \le 0.008856 \\ 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16; & 0.008856 \le \frac{Y}{Y_n} \end{cases}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right];$$ Eq. 2- 3

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right];$$

Where $f(t) = \begin{cases} t^{1/3}; & t < (6/29)^3 \\ \frac{1}{3}(\frac{29}{6})^2 t + \frac{4}{29}; & otherwise \end{cases}$

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L^*}{K_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{K_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C^*_{ab}}{K_C S_C}\right)\left(\frac{\Delta H^*_{ab}}{K_H S_H}\right)}$$ Eq. 2- 4

$$S_L = 1, S_C = 1 + 0.045C^*_{ab}, and\ S_H = 1 + 0.0015C^*_{ab}$$ Eq. 2- 5

Where

$\Delta L^*, \Delta C^*_{ab}, \Delta H^*_{ab}$: *Differences of luminance, chroma, and hue*

K_L, K_C, K_H: *Parametric factors of luminance, chroma, and hue*

S_L, S_C, S_H: *Weighting function of luminance, chroma, and hue*

R_T: *Rotation function*

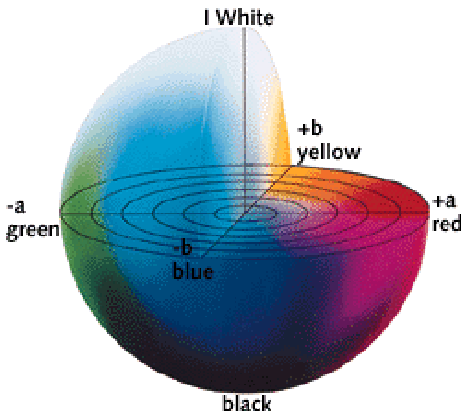


Fig. 2- 15 CIELAB chromaticity diagram

(Ref: www.sapdesignguild.org/.../index1.html)

2.5 Summary

The CBU caused by different eye movements have been introduced. In order to suppress CBU, many methods were proposed. However, these methods have their own difficulty to implement on hardware. The 180Hz Stencil-FSC method with low field rate could achieve on large size FSC-LCDs using OCB mode LC. However, the 180Hz Stencil-FSC method decreased green color saturation because of the redundant red and blue light propagate through the first field. Therefore, we proposed adaptive 180Hz Stencil-FSC method to avoid the redundant light. On the other hand, to evaluate image quality of CBU suppression methods, color difference and CBU were quantified using CIEDE2000.

Chapter 3

Adaptive Base 180Hz Stencil-FSC method

The 180Hz Stencil-FSC method can effectively suppress CBU, however, when the input image contents a majority of green information, the green saturation might be shrunk due to the redundant red or blue light leakage from first field LC. In order to reduce redundant color propagate through first field and enhance color saturation of 180Hz Stencil-FSC method, the adaptive base 180Hz Stencil-FSC method was proposed to avoid redundant color showing at first field image. In this chapter, the concept and algorithm of adaptive base 180Hz Stencil-FSC method will be introduced, and the optimization of colorful backlight will be given. Therefore, the image of adaptive 180Hz Stencil-FSC method with high image quality and almost imperceptible CBU could be obtained.

3.1Adaptive 180Hz Stencil-FSC Method

3.1.1 Concept

The 240Hz Stencil-FSC method suppressed CBU effectively with high contrast ratio and low power consumption. However, 240Hz large size LCD has not been well developed in current LCD manufacturing. Therefore, the field rate was reduced to 180Hz and the 180Hz Stencil-FSC method was proposed. The concept is to combine the green color field into first field. Human eye is most sensitive to green color, so if the primary color field images not include green information, human may percept less CBU. The original 180Hz Stencil-FSC method displays a green-base first field image, it means all the green information of target image is displayed at first field, and also some red and blue information. The human eye is most sensitive to green color, when the separated colors do not contain green color, the CBU is reduced. The concept of original 180Hz Stencil method is show in Fig. 3- 1. The first field image is the combination of red, green, and blue backlight (BL_R, BL_G, and BL_B) and green LC (T_G) signal, the second field image is the combination of red backlight (BL_R) and T_R'. The third field is the combination of blue backlight (BL_B) and T_B', where, $T_R' = T_G - T_R$ and $T_B' = T_G - T_B$. However, if the input image contains plenty of green information, the T_R' or T_B' might be a negative value. The negative value indicates redundant red or blue light was propagated to the first field as shown in Fig. 3- 2. Therefore, the green color saturation may shrink.

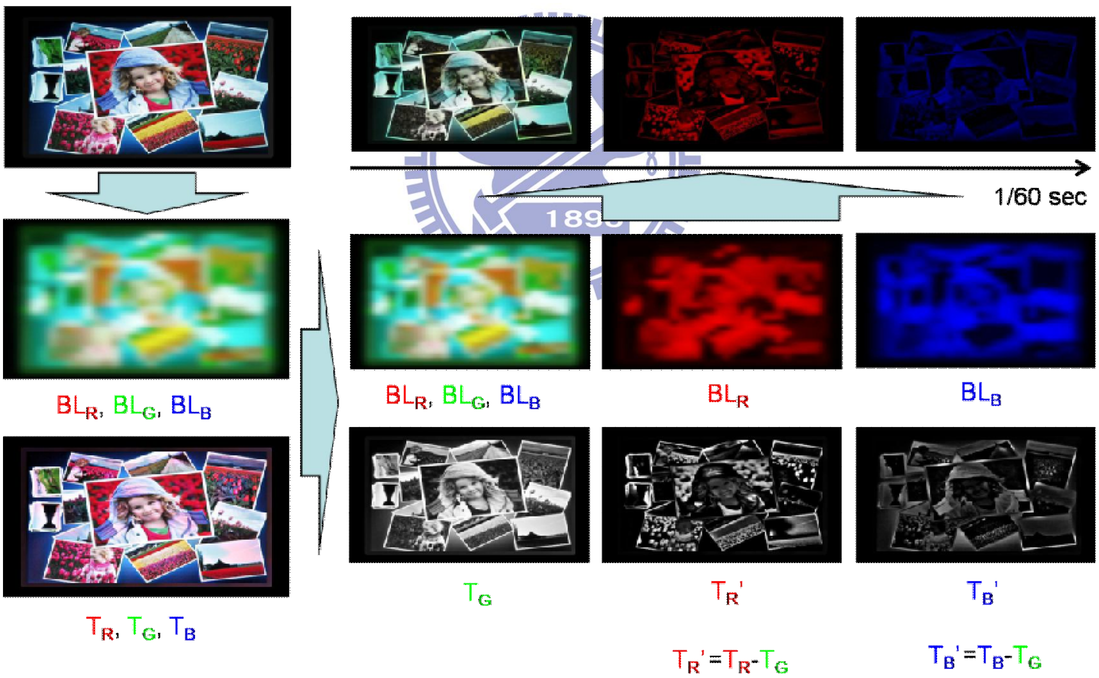


Fig. 3- 1 Concept of 180Hz Stencil-FSC method

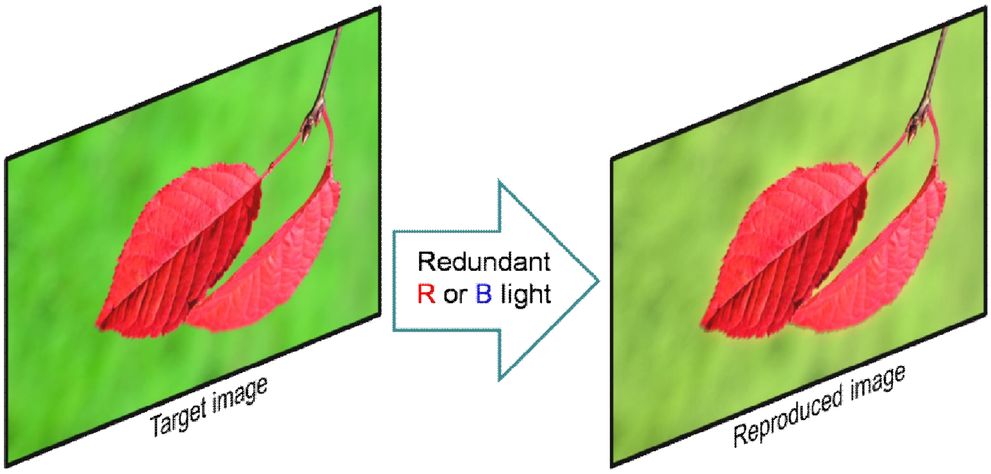


Fig. 3- 2 Redundant color propagates through first field resulting in reduction of green color saturation.

To prevent redundant color light propagated to the first field and resulted in reduction of green color saturation. The adaptive base 180Hz Stencil-FSC method was proposed to avoid negative LC value of second and third field. The base color of first field is not always green anymore. It depends on the content of input image. By choosing proper color as the base color of first field, the reproduced image will more approach to the target image. For example, when input a target image as shown in Fig. 3- 3(a), the original 180Hz with green-base first field image has some perceptible distortion because of the reduction of green saturation as shown in Fig. 3- 3(b). On the other hand, the 180Hz Stencil method with proper base color first field causes less negative values as shown in Fig. 3- 3(c). Therefore, the reproduced image is much approach to the target image than the image of original 180Hz Stencil image.

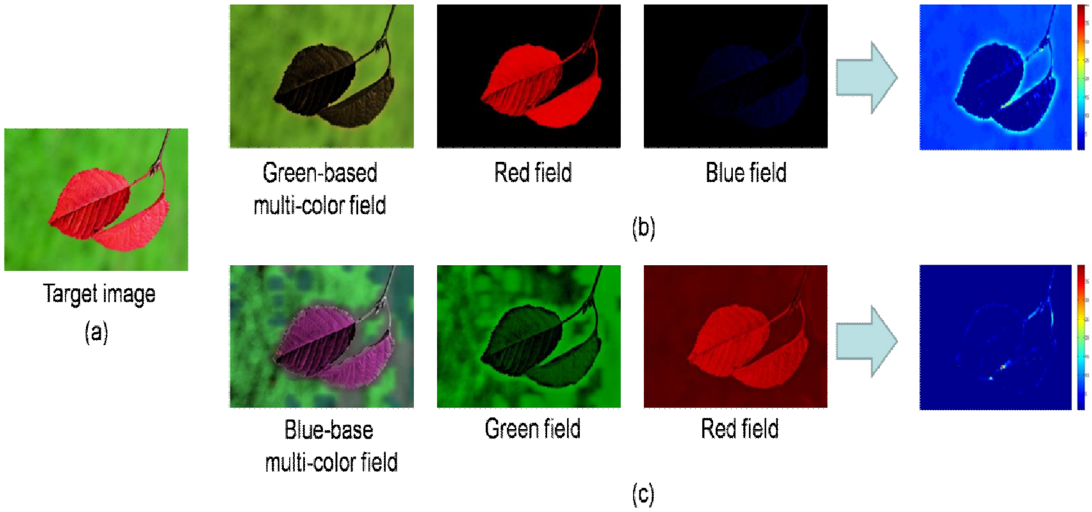


Fig. 3- 3 The (a) input target image and 180Hz Stencil-FSC method with (b) green-base first field and (c) blue-base first field

3.1.2 Display Module

In order to obtain a multi-color first field in adaptive base 180Hz Stencil-FSC method, the backlight signal of red, green, and blue must be controlled locally and independently. This technique is also called High Dynamic Range (HDR) technique and could be seen as a dual panel system: LED panel and LCD panel [29]. The flowchart is illustrated in Fig. 3- 4. At first, the LC signal (Io) with full-on white backlight is inputted, then the red, green, and blue backlight signal (I_{LED}) can be determined using average, maximum, root, Inverse of a Mapping Function (IMF) method [30] or Delta-Color Adjustment (DCA) method [31]. In order to obtain the compensated LC signal, the backlight distribution is gotten by convolution of backlight signal (I_{LED}) and light spread function (LSF), therefore, the compensated LC signal (I) is Io divided by the blurred backlight $LSF \otimes I_{LED}$. Finally, combining the backlight signal and compensated LC signal, a multi-color single field is obtained.

The HDR technique can locally control backlight based on the target image, therefore, the contrast ratio is much enhanced, the power consumption is reduced, and the color gamut is increased compared to the conventional full-on CCFL backlight system.

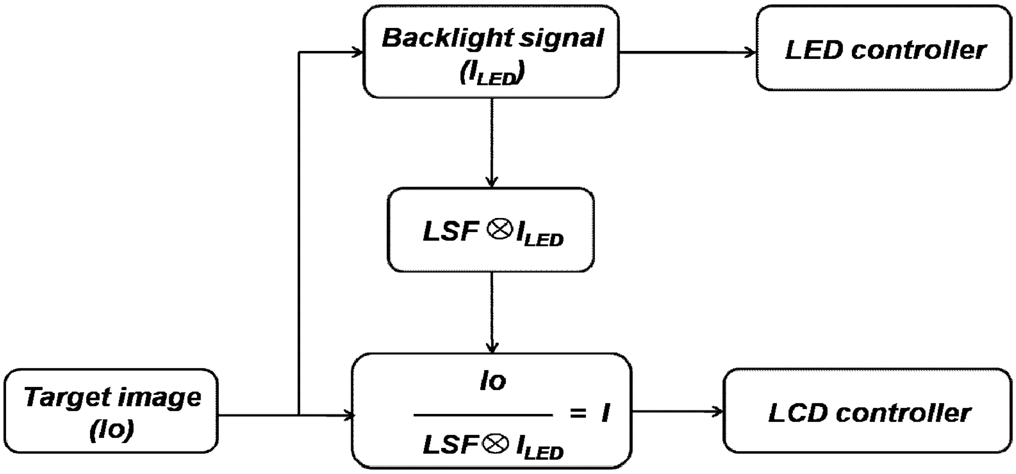


Fig. 3- 4 The flowchart of locally control backlight system

3.1.3 Algorithm

The adaptive base 180Hz Stencil-FSC method displays multi-color first field with adaptive base color to improve the green color saturation issue of original 180Hz Stencil-FSC method. Therefore, the most important thing is to determine which color to be the base color of first field. The flowchart of base color determination is illustrated in Fig. 3- 5. At first, the input image is divided into several regions based on the backlight division and the red, green, and blue information of each block is averaged individually as shown in Fig. 3- 5(b). Thus there are three values in each block: averaged red (R), green (G), and blue (B). According to the magnitude of these three values, the maximum (max), middle (mid), and minimum (min) is gotten. Then in each block, the max value minuses the mid value and marks the difference value as shown in Fig. 3- 5(c). Take the Target image Fig. 3- 5(a) as an example, the R, G, and B value of upper right corner block are 96, 135, and 59 gray level respectively, then the max (G=135) minuses mid (R=96) and mark the difference value as G' (G'=39).

After calculating all the blocks, the R', G', and B' values is averaged individually. Finally, the 1st, 2nd, and 3rd colors are determined by the minimum, maximum, and middle value of averaged R, G', and B' respectively, as shown in Fig. 3- 5(d).

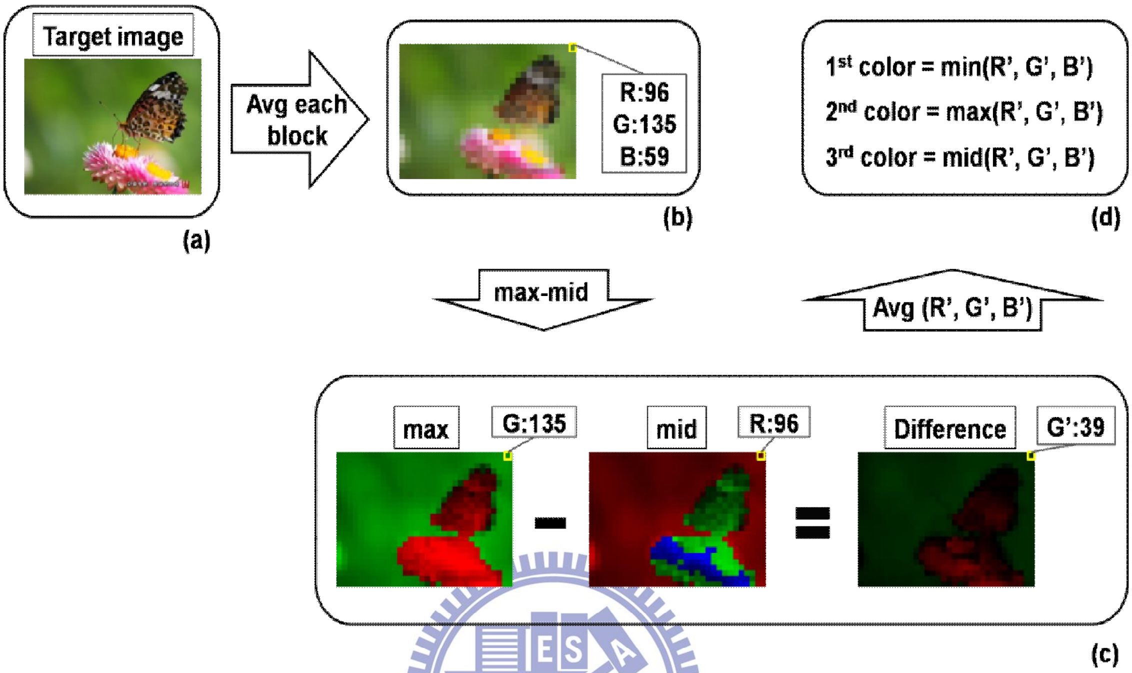


Fig. 3- 5 Flowchart of base color determination

After determining the base color of three fields, the three primary-color backlight signals BL_{st}, BL_{nd}, BL_{rd} were recalculated according to the input image. Moreover, the LC transmittance values were compensated using Eq. 3-1, where T_i^{full} and T_i denote image luminance; BL_i^{full} and BL_i denote traditional full-on backlight and HDR blurred backlight. It is worthy to mention that the BL_{st} is determined different from BL_{nd} and BL_{rd} to avoid T'_{nd} and T'_{rd} being negative value. The BL_{nd} and BL_{rd} is determined by the average value of 2nd and 3rd LC pixel signals directly (Average method*), and the BL_{st} is determined by the square root of averaged 1st LC pixel signals (Square root method**) to enhance the signal. The combination of BL and T signals formed three field images as shown in Fig. 3- 6. Finally, displaying these three fields at 180Hz generates a full color image.

$$T_i = (BL_i^{full}/BL_i) \times T_i^{full} \qquad i = st, nd, rd \qquad \text{Eq. 3- 1}$$

$$\begin{bmatrix} T'_{nd} \\ T'_{rd} \end{bmatrix} = \begin{bmatrix} T_{nd} \\ T_{rd} \end{bmatrix} - T_{st}$$

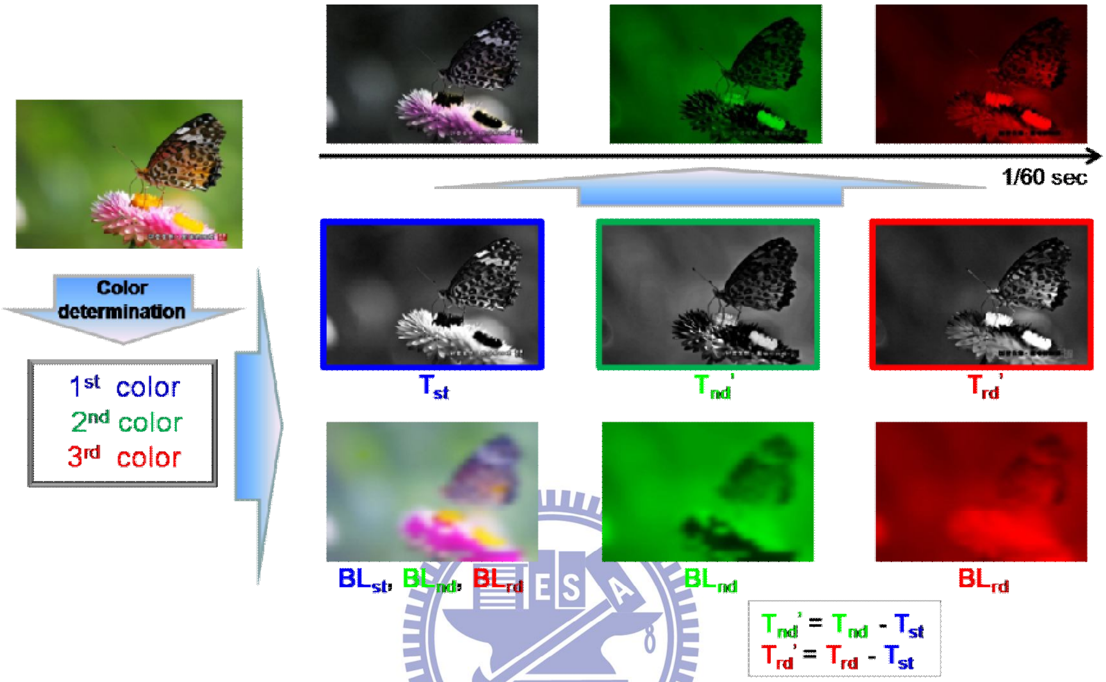


Fig. 3- 6 Flowchart of adaptive 180Hz Stencil-FSC method

*Averaged method: the backlight signal is determined by averaged the input signal of each block

**Square root method: the backlight signal is determined by square root of the averaged input signal of each block

3.2 Optimization for Colorful Backlight

The first field image of adaptive base 180Hz Stencil-FSC method was a colorful image and improved the image difference issue of original 180Hz Stencil method. However, when the backlight signal is not colorful enough, the redundant light still displays at first field and results in perceptible image difference. Therefore, the backlight signal must be optimized. In order to make backlight signal more colorful and reduce the difference of compensated LC signal. The original locally controlled backlight signal must be dimmed by a ratio (ex. 20%). The original backlight signal may results in image difference because of the redundant light showing at first field as shown in Fig. 3- 7(a). On the other hand, after dimming the backlight signal, it becomes more colorful. Therefore, the redundant light reduced and the reproduced color as shown in Fig. 3- 7(b).

Using four test images with different color contents, *Lotus*, *Cyan moon*, *Basketball*, and *Soccer* as shown in Fig. 3- 8, the simulation result is shown in Fig. 3- 9. From the simulation result, a smaller dimming ratio generates lower color difference image. However, if the dimming ratio is too low, the LC signal may exceed the maximum value and result in clipping effect. Therefore, the optimal dimming ratio might be 20%.

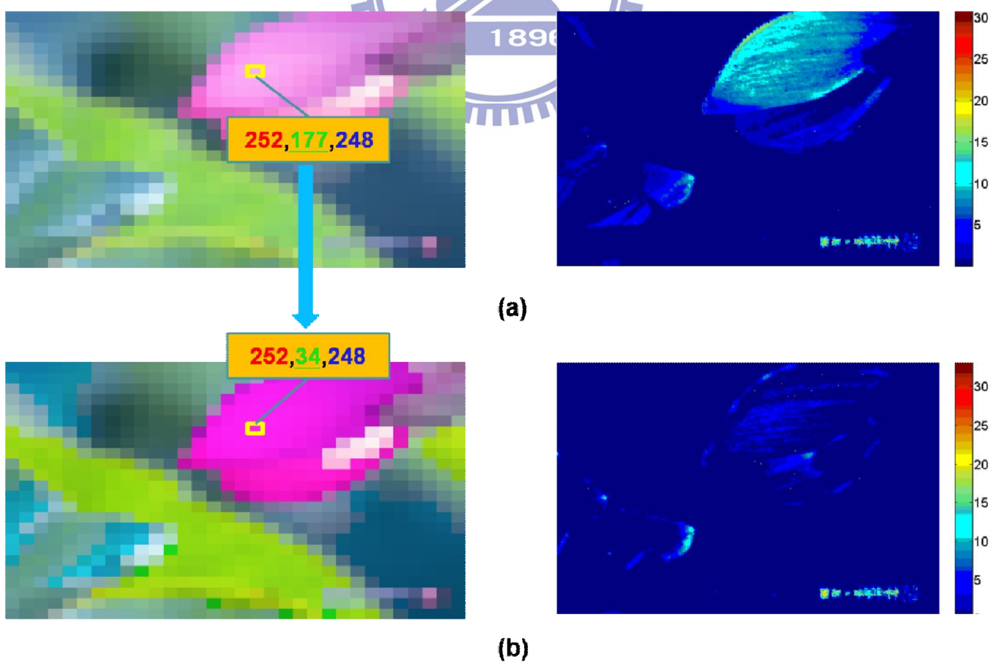


Fig. 3- 7 Adaptive base 180Hz Stencil-FSC method with (a) original backlight signal (left) and its color difference image (right), and (b) backlight signal dimmed by a ratio (left) and its color difference image (right).

(a) Lotus (b) Cyan moon (c) Basketball (d) Soccer

Fig. 3- 8 Four test images

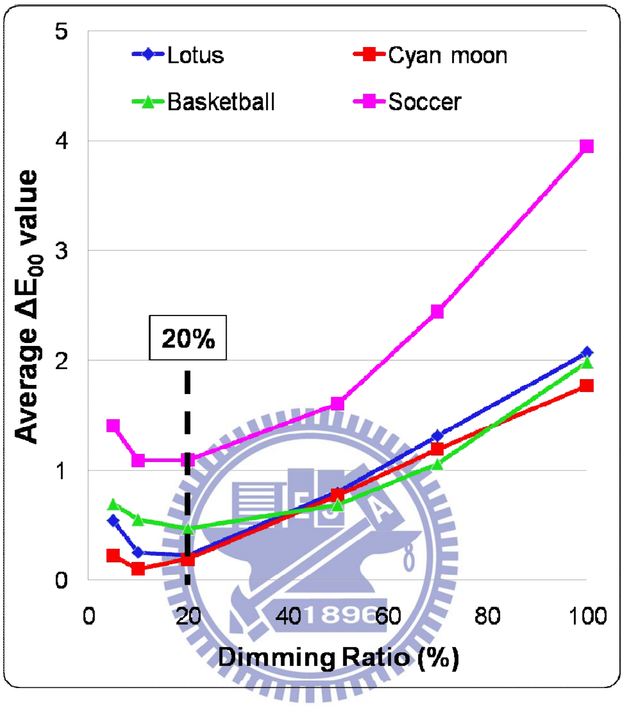


Fig. 3- 9 Simulation result for dimming ratio vs. average color difference (ΔE value)

3.3 Summary

Base on the concept of 180Hz Stencil-FSC method, the adaptive base 180Hz Stencil-FSC method with dynamic first base color was proposed to reduce the image difference between target image and reproduced image. The colorful backlight was achieved using locally controlled backlight technique. However, if the backlight signal is not colorful enough, the redundant light will display at first field, therefore, the backlight signal was optimized by a dimming ratio. Therefore, the reproduced image was more approach to the target image. Moreover, some hardware parameters will be considered, and the demonstration will be given in the next chapter.

Chapter 4

Optimization for Hardware Parameters and Demonstration

In order to implement the adaptive base 180Hz Stencil-FSC method on hardware and improve CBU suppression performance, the backlight distribution must be optimized. Two hardware parameters affected backlight distribution: point spread function (PSF) and backlight divisions. Therefore, these two parameters have optimized based on image difference and CBU suppression. After optimizing the hardware parameters, the adaptive base 180Hz Stencil-FSC method was verified on a 46-inch MVA LCD.

4.1 Optimization for Hardware Parameters

Using locally controlled color backlight technology, the backlight distribution is no longer a uniform white light, so the influence range of backlight distribution of one division determines the result of mixed light. Thus, the PSF of each backlight division and the number of backlight divisions must be optimized. In this thesis, the Gaussian distribution was utilized to approximate the real backlight distribution of each division as shown in Eq. 4-1. By controlling the standard deviation (S.D.) of Gaussian distribution (σ_x and σ_y), the PSF was modulated. In addition, the backlight division was divided into 12 combinations as shown in Fig. 4- 1.

$$g(x,y) = e^{-\left(\frac{x^2}{2\sigma_x{}^2}+\frac{y^2}{2\sigma_y{}^2}\right)} \qquad \text{Eq. 4- 1}$$

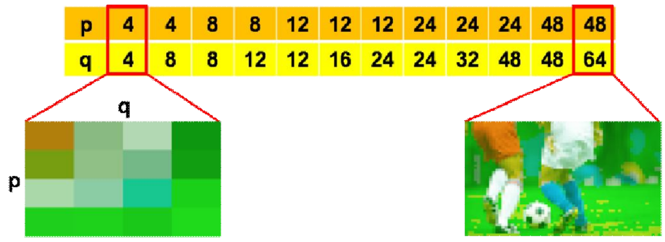


Fig. 4- 1 11 Combinations of backlight divisions

Color difference and CBU suppression are two indexes which evaluate image fidelity and are calculated using CIEDE2000 color difference (ΔE_{00}). To evaluate CBU suppression performance, the ΔE_{00} value between target image and CBU image of each pixel were summed up, then defined the relative CBU as the ratio of total color difference between proposed method and conventional RGB-driving method as shown in Eq. 4- 2. Twelve test images with different contrast ratios and color contents were utilized to optimize the adaptive base 180Hz Stencil-FSC method.

$$relative\ CBU \equiv \frac{\sum \Delta E_{00}(Target, Stencil)_{p*q}}{\sum \Delta E_{00}(Target, RGB_{driving})} \times 100\% \quad p, q: division\ number \quad \text{Eq. 4- 2}$$

The PSF of each backlight division was first optimized and the simulation result is shown in Fig. 4- 2. When the backlight division increased, the σ_x and σ_y value decreased to make backlight distribution more localized. After the PSF of each backlight division was optimized, the backlight division was further optimized. From the simulation result as shown in Fig. 4- 3 and Fig. 4- 4, the color difference and relative CBU decreased when backlight division increased because the backlight signal was closer to the target image. After 24x32 backlight divisions, the decreased trend of ΔE_{00} value was slight, therefore, considering hardware computation complexity and image fidelity simultaneously, 24x32 might be the optimal number of backlight divisions.

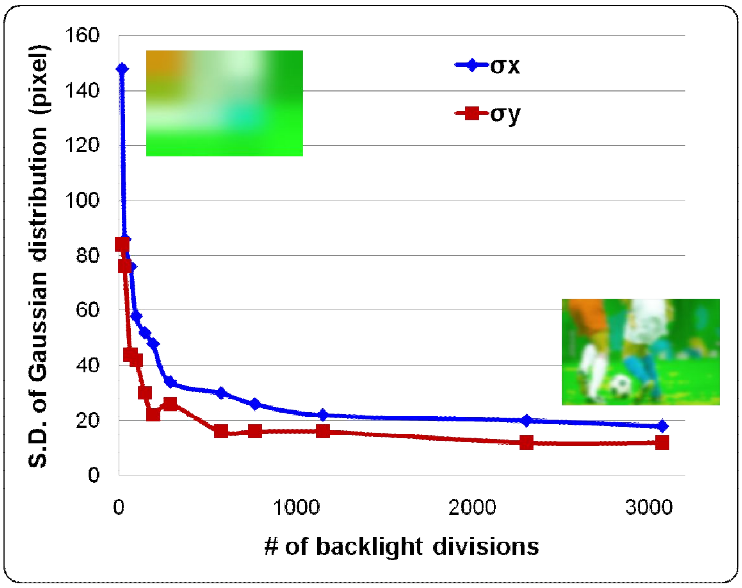


Fig. 4- 2 Optimized σ_x and σ_y value of each backlight divisions

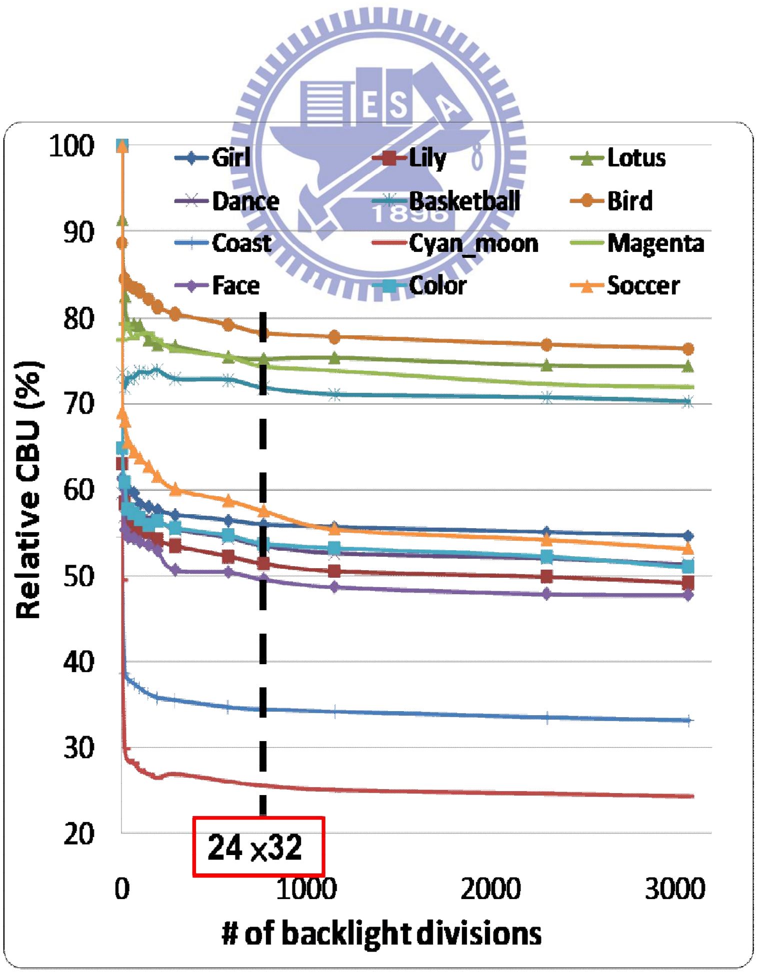


Fig. 4- 3 Optimization result of backlight divisions vs. relative CBU

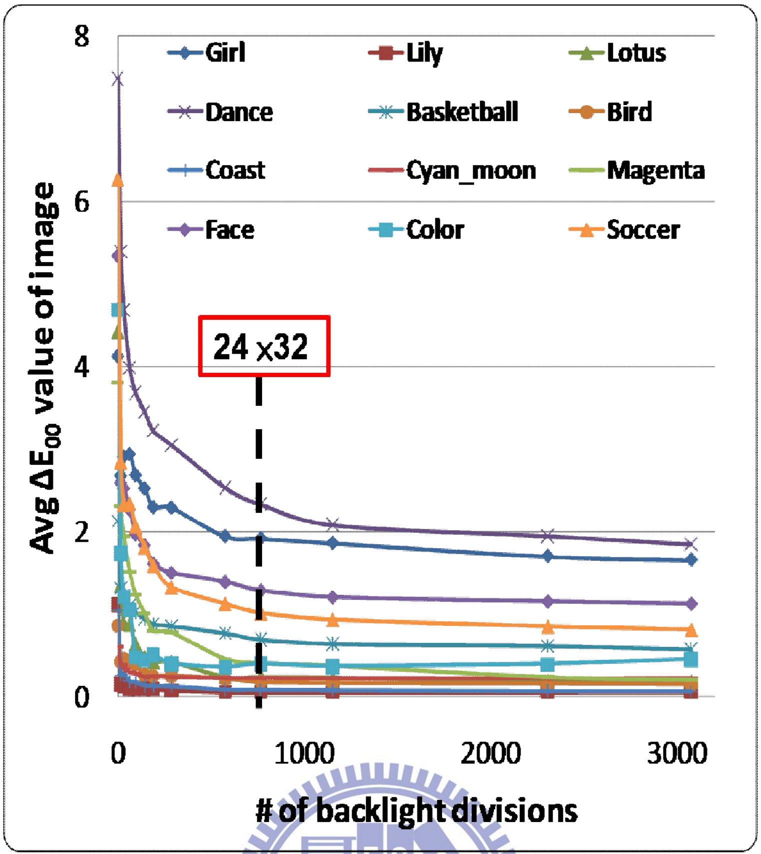


Fig. 4- 4 Optimization result of backlight divisions vs. ΔE_{00} value

After optimizing hardware parameters of the adaptive base 180Hz Stencil-FSC method, the color difference was much lower than the green base Stencil method was. Especially for the image with a majority of green information. Using the adaptive base 180Hz Stencil-FSC method, if green color is determined to be the first field base color, the performance will be the same with the original green base Stencil method. Therefore, the images using the adaptive Stencil with blue or red as the first base color were compared to the green base Stencil method as shown in Fig. 4- 5 and Fig. 4- 6. The ΔE_{00} value was lower than the green base Stencil method and the averaged ΔE_{00} value was lower than one. CBU suppression performance of the adaptive base Stencil was not as good as the green base Stencil method because the adaptive Stencil showed less image information in the first field to prevent redundant color, as shown in Fig. 4- 7. Nevertheless, compared to RGB-driving, RGBRGB, and RGBKKK methods using 70 test images, the adaptive base 180Hz Stencil-FSC method still suppresses CBU effectively as shown in Fig. 4- 8 and Fig. 4- 9. Therefore, after optimizing hardware parameters, the adaptive base 180Hz Stencil-FSC method achieved high image quality at a low field rate of 180Hz with minor CBU suppression sacrificing.

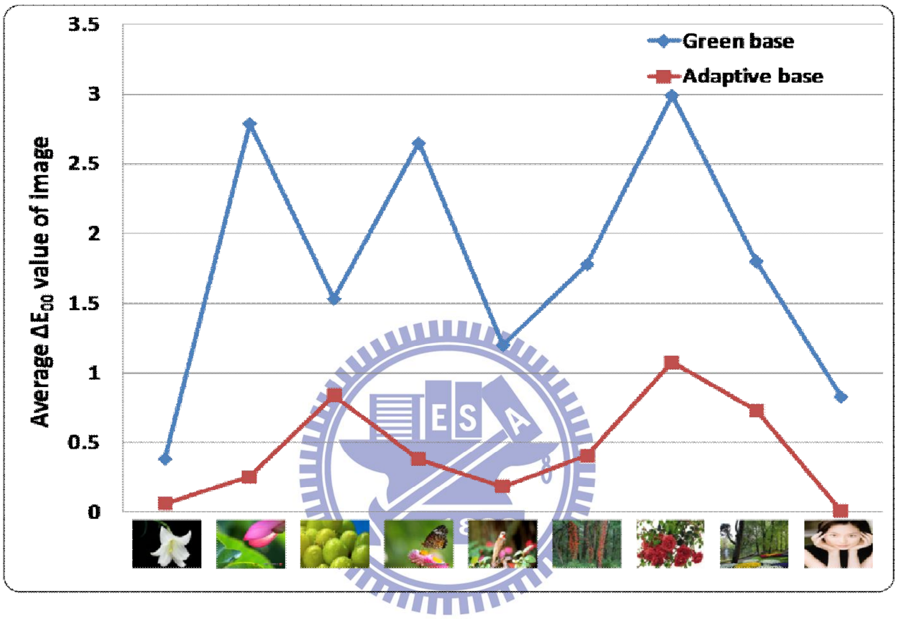


Fig. 4- 5 Comparison of ΔE_{00} value using green base and adaptive base 180Hz Stencil-FSC method

Fig. 4- 6 Comparison of the reproduced image using (b) green base and (c) adaptive base Stencil method

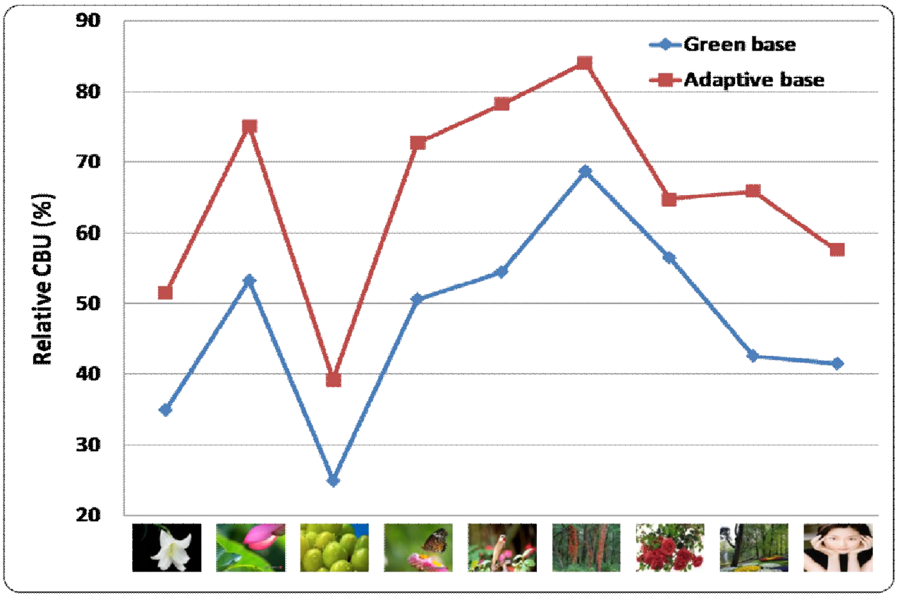


Fig. 4- 7 Comparison of CBU using green base and adaptive base 180Hz Stencil-FSC method

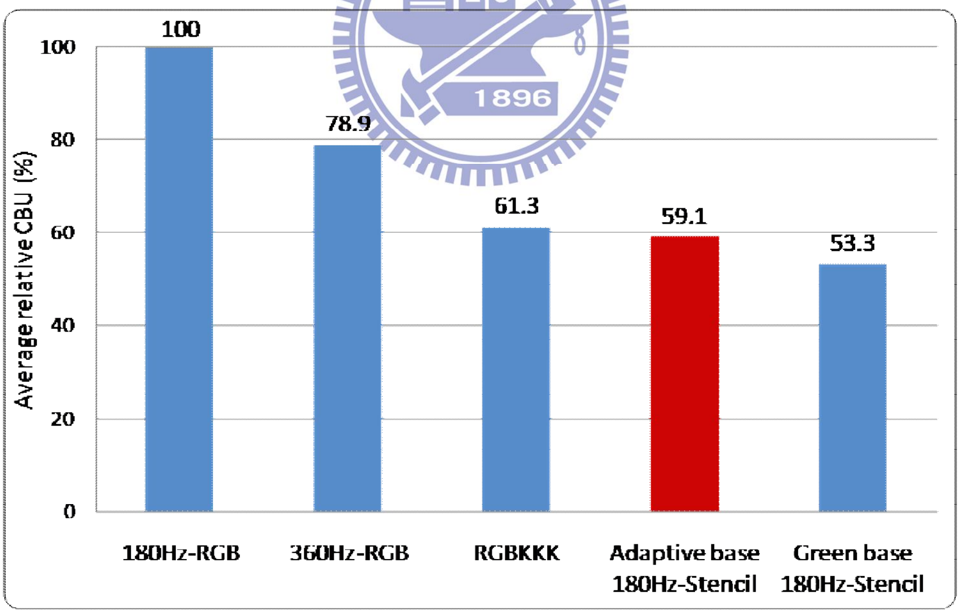


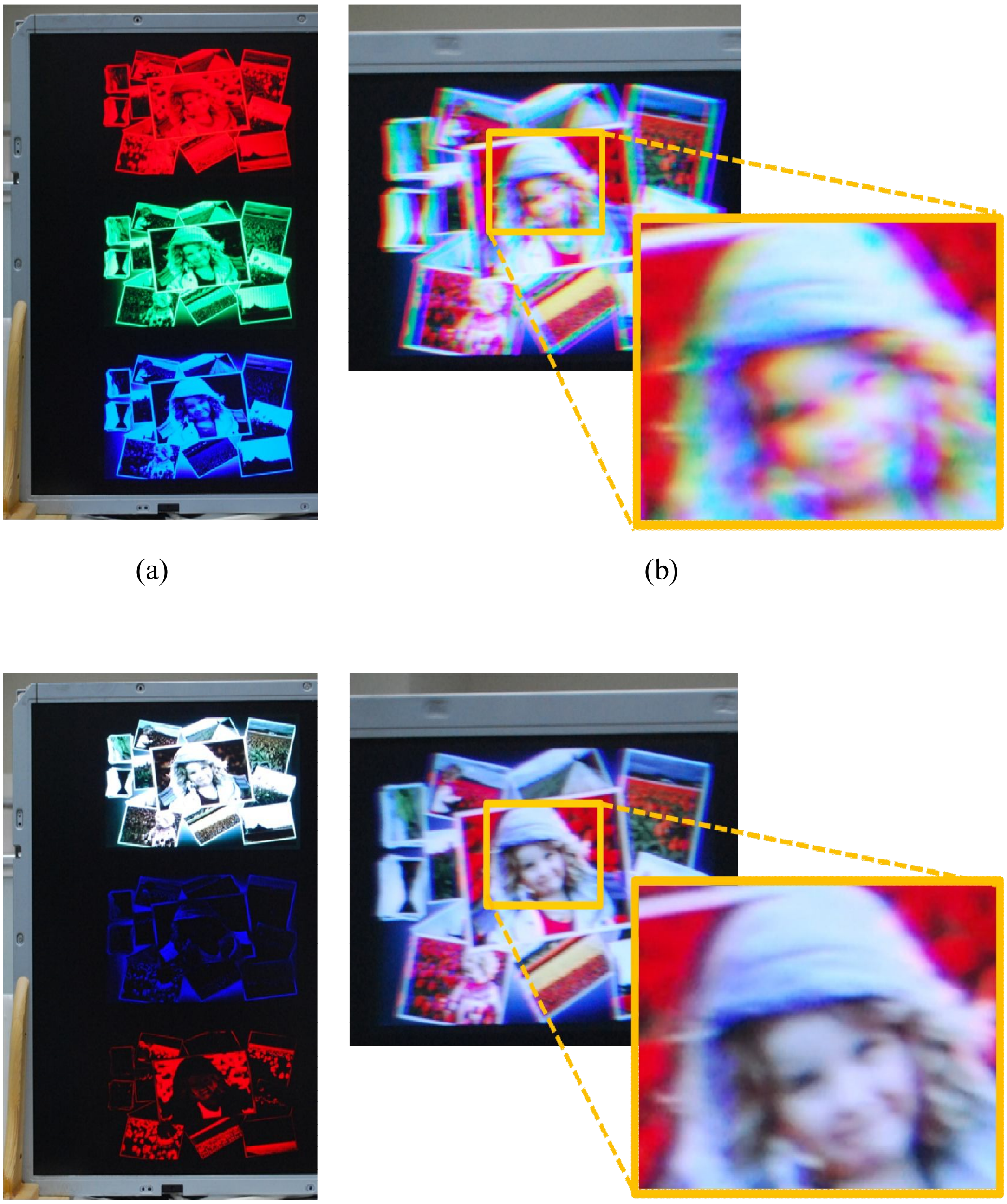
Fig. 4- 8 Comparison of different CBU suppression methods with 70 test images

Fig. 4- 9 CBU comparison of difference CBU suppression methods

4.2 Demonstration

The adaptive base Stencil-FSC method was verified on a 46-inch 120Hz MVA LCD as shown in Fig. 4- 10. CBU images of RGB-driving method and the adaptive base 180Hz Stencil-FSC method were compared. The CBU images were captured using a moving camera to simulate eye movement. Using the test images: *Girl, Face*, and *Lily*, the captured CBU images are shown in Fig. 4- 10, Fig. 4- 11, Fig. 4- 12 respectively.

Fig. 4- 10 Hardware: 46-inch 120Hz MVA LCD



(a) (b)

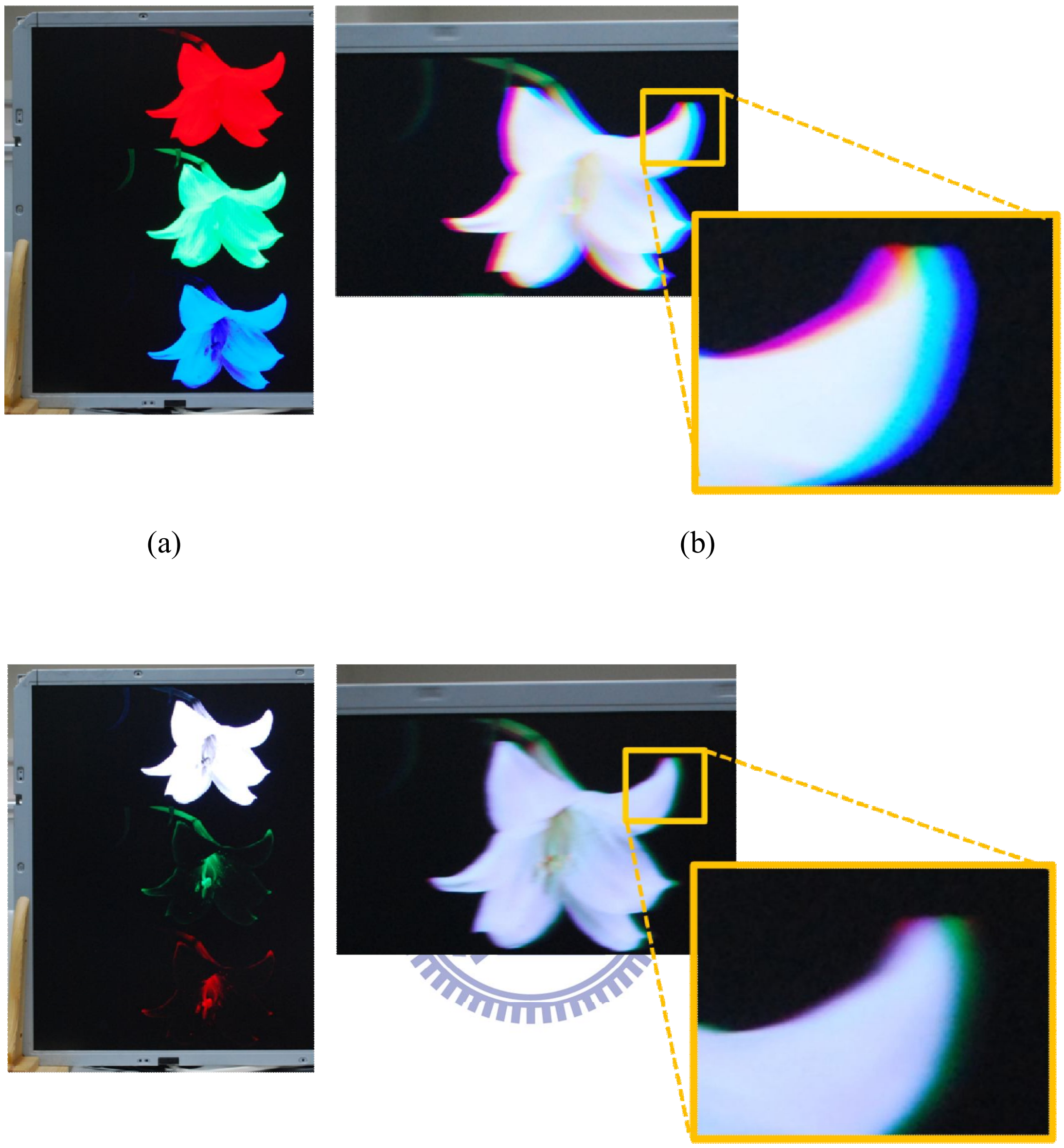
(c) (d)

Fig. 4- 10 Comparison of CBU image *Girl*. (a) Three fields of RGB-driving method and (b) its CBU image. (c)Three fields of adaptive base 180Hz Stencil-FSC method and (d) its CBU image

(a) (b)

(c) (d)

Fig. 4- 11 Comparison of CBU image *Face*. (a) Three fields of RGB-driving method and (b) its CBU image. (c)Three fields of adaptive base 180Hz Stencil-FSC method and (d) its CBU image



(a) (b)

(c) (d)

Fig. 4- 12 Comparison of CBU image *Lily*. (a) Three fields of RGB-driving method and (b) its CBU image. (c) Three fields of adaptive base 180Hz Stencil-FSC method and (d) its CBU image

4.3 Summary

In order to implement the adaptive base 180Hz Stencil-FSC method on hardware, the hardware parameters: PSF and backlight divisions were optimized. Considering hardware complexity and image fidelity, 24×32 might be the optimal number of backlight divisions. Comparing to the original green base 180Hz Stencil-FSC method, the adaptive base Stencil-FSC method reduced the averaged ΔE_{00} <1. Using 70 test images, the average relative CBU of the adaptive Stencil method was only about 59% of the conventional RGB-driving method. In addition, the adaptive base 180Hz Stencil-FSC method was verified on a 46 inch 120Hz MVA LCD and made CBU almost imperceptible.

The adaptive 180Hz Stencil-FSC method has high image quality and low CBU. However, the backlight system: RGB LED has a efficiency issue. The power efficiency of RGB LED is quite low and waste power. Therefore the RGBW 4-in-1 LEDs backlight system was proposed to further reduce the power consumption of FSC-LCDS. The detail concept will be described in the next chapter.

Chapter 5

RGBW 4-in-1 LEDs Backlight System for Stencil-FSC Methods

Using Stencil-FSC algorithm, the first field is a multi-color field. To create a multi-color single image in a single field in FSC-LCD, the backlight system must uses RGB LED backlight system combining with local color-dimming technology replacing the CCFL. However, the power efficiency of current RGB LED is lower than CCFLs. In order to reduce the power consumption of FSC-LCDs even more, the backlight system must be further improved. Therefore, the high efficiency white-light LED was added onto the RGB LED as a RGBW 4-in-1 LED. Moreover, in each field of two-color-field sequential method contented only two primary colors, thus, to apply on RGBW 4-in-1 LEDs backlight system, the two-color-field sequential method must be modified to be the 120Hz Stencil-FSC method.

5.1 RGBW 4-in-1 LEDs Backlight System

Backlight module is one of most important components in LCDs. it provides a light source to display a full color image. The current backlight module of FSC-LCD is RGB LED, which can switch very fast and has higher color gamut than CCFLs. The greatest advantage of RGB LED is it can combine with local color-dimming technology. The local dimming technology is a dual panel LCD: backlight module and LCD panel, as shown in Fig. 5- 1. The backlight module is a low resolution panel to control image contrast ratio, and the LCD panel is a high resolution panel to maintain image details. Combining backlight and LCD panel, a multi-color image could be generated. Local color-dimming technology has some advantages, such as high contrast ratio and low power consumption.

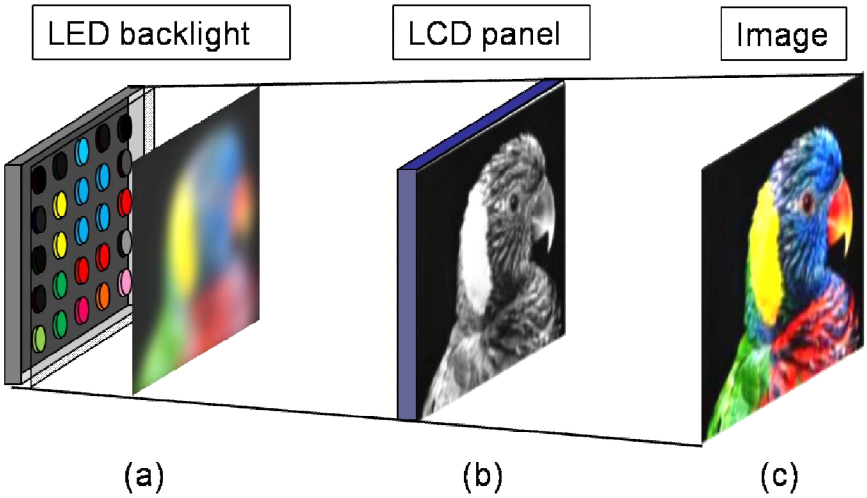


Fig. 5- 1 Dual panel LCD: (a) backlight module and (b) LCD panel. Combining (a) and (b), (c) a multi-color image could be obtained.

Currently, the power efficiency of RGB LED is about 25, 50, and 5 lm/W respectively, which are lower than CCFLs. To reduce power consumption of FSC-LCDs even more, the backlight module must be further improved. Therefore, the high efficiency (>100 lm/W) white-light LED was added onto RGB LED as a RGBW 4-in-1 LED. the gray/white part of multi-color image was generated using white-light LED, and the remaining color part of image was generated using RGB LED [32], so the most intensity of target image was displayed using high efficiency white LED instead of low efficiency RGB LED as shown in Fig. 5- 2. By this way, the power consumption of FSC-LCD could be further reduced.

To evaluate display power consumption, 25 images were captured from International Electrotechnical Commission's (IEC) document 62087 video according to the average picture level (APL) histogram of IEC's 62087 as shown in Fig. 5- 3 [33]. These images could roughly standard the APL histogram of typical broadcast TV content. Therefore, the power consumption of Stencil-FSC methods was evaluated using these 25 test images.

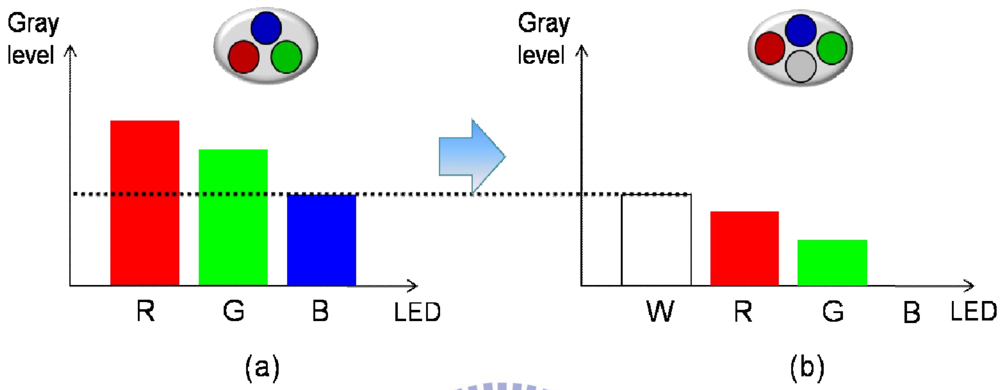


Fig. 5- 2 LED backlight systems. (a) RGB LED and (b) RGBW 4-in-1 LED

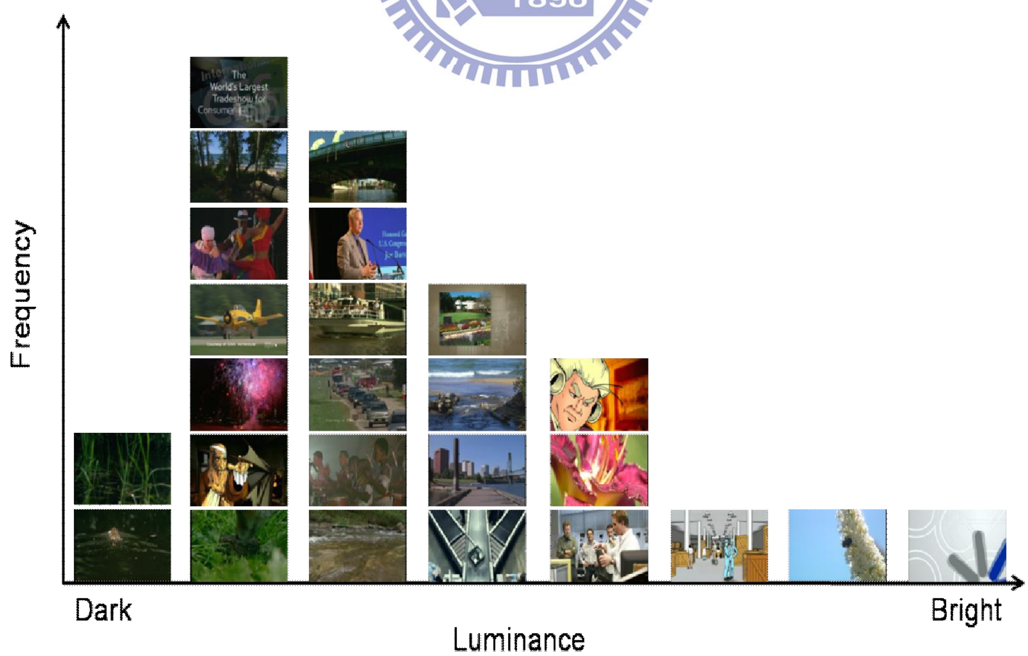


Fig. 5- 3 25 test images from IEC62087 video

5.2 RGBW 4-in-1 LEDs for 240Hz and 180Hz Stencil-FSC Methods

The first field of both 240Hz and 180Hz Stencil-FSC methods were multi-color fields, therefore, the multi-color first image could be generated using RGBW 4-in-1 LEDs instead of RGB LED without sacrificing image fidelity. The power consumption of 240Hz (BL divisions: 24×24) and 180Hz (BL divisions: 24×32)Stencil-FSC method were evaluated using both RGB LED and RGBW LED backlight systems. The power efficiency of R, G, B, and W LED were 25. 50, 5, and Ew lm/W respectively, where the Ew was a varying number from 50 to 290. The relative power was defined as Eq. 5-1. The power consumption only considered the optical power of LEDs, not included electrical power of IC.

$$Relative\ Power \equiv \frac{Power\ of\ Stencil-FSC\ method}{Power\ of\ RGB-FSC\ method} \times 100\% \qquad \text{Eq. 5- 1}$$

From the estimation result as shown in Fig. 5- 4, using RGB LED, the optical power consumption of 240Hz and 180Hz was about 89% and 78% of RGB-FSC method respectively due to the local dimming technology. Using RGBW 4-in-1 LEDs, the power consumption decreased when white LED efficiency increased. When using 110 lm/W white LEDs, the optical power consumption of 240Hz and 180Hz was only about 62% and 51% respectively. Therefore, using RGBW 4-in-1 LEDs backlight system, the power consumption of FSC-LCD with multi-color single field was further reduced without sacrificing image fidelity.

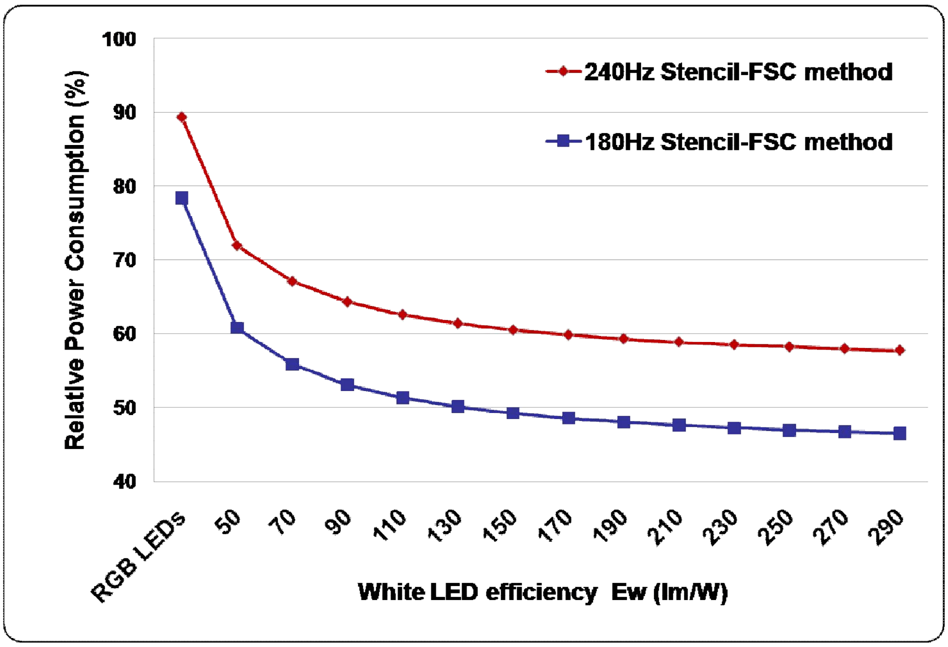


Fig. 5- 4 Relative power consumption of 240Hz and 180Hz Stencil-FSC method using both RGB LEDs and RGBW 4-in-1 LEDs

5.3 RGBW 4-in-1 LEDs for 120Hz Stencil-FSC Methods

The concept of two-color-field sequential method is displaying two color-mixing fields with 120Hz frame rate to generate a full color image. In each field of two-color-field method, one of whole R, G, or B information was displaying as the dominate color, and the remaining color information was divided into two fields to generate a full color image as shown in Fig. 5- 5(a). Therefore, three primary colors were displayed using only two fields. The two-color-field sequential method is the easiest method to implement on hardware because of low field rate. However, in each field of two-color-field method, there are only two primary colors. In order to apply on RGBW 4-in-1 LEDs backlight system, some third color information must be combined into first field. Originally, the color which divided into two fields was displayed using low resolution local controlled backlight and first field LC signal. To make first field become a multi color field, the dominate color of second field was also divided into two fields as shown in Fig. 5- 5(b). Thus, the modified method contented multi color in single field and called “120Hz Stencil-FSC method”.

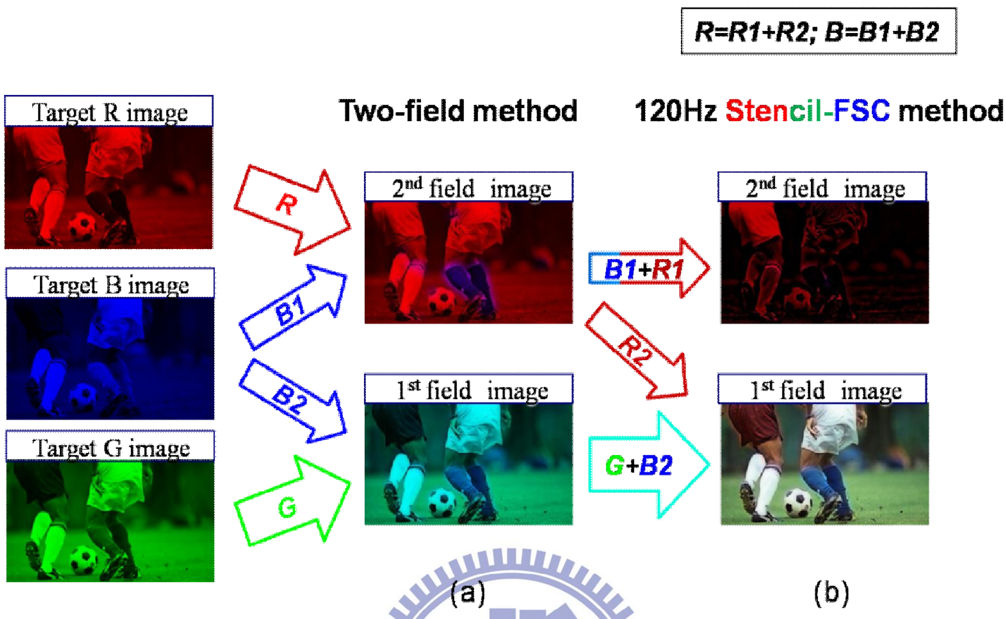


Fig. 5- 5 Concept of (a) two-color-field sequential method and 120Hz Stencil-FSC method

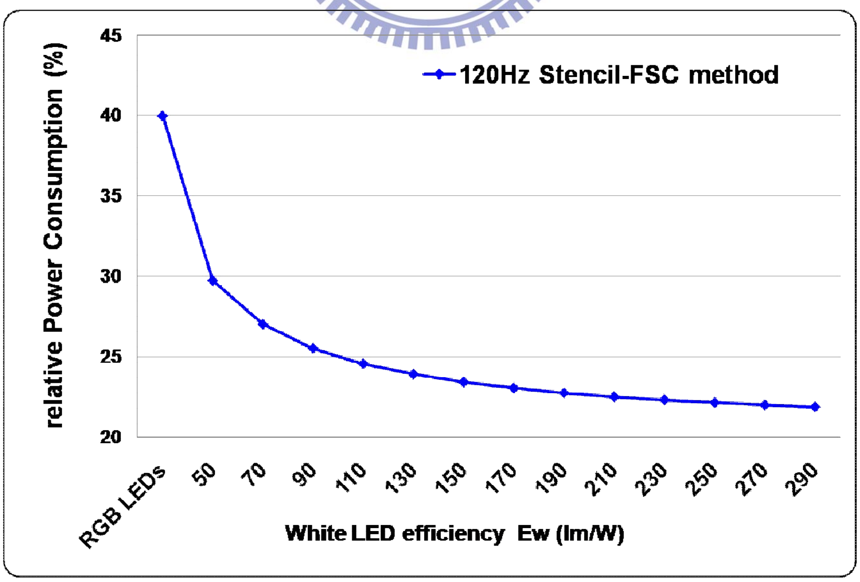


Fig. 5- 6 Relative optical power consumption of 120Hz Stencil-FSC method using RGB LEDs and RGBW 4-in-1 LEDs

The 120Hz Stencil-FSC method was applied on RGBW 4-in-1 LEDs backlight system. From the estimation result as shown in Fig. 5- 6, using RGB LEDs, the optical power consumption of 120Hz Stencil-FSC method was about 40% of RGB-FSC method. Using RGBW 4-in-1 LEDs, the optical power decreased when white-light LED efficiency increased. For example, using 110 lm/W white LED, the optical power was only about 25% of RGB-FSC method.

Using 120Hz Stencil-FSC method with RGBW 4-in-1 LEDs, the power consumption was further reduced. But, how about the image performance of 120Hz Stencil-FSC method. Actually, the color which divided into two fields caused some light leakage from LC signal. Because the color was displayed using low resolution backlight only, thus some redundant light might passed through LC signal and caused color difference. Nevertheless, when the number of backlight divisions was up to 45× 80, the color difference of 120Hz Stencil method and two-color-field method was similar as shown in Fig. 5- 7 and Fig. 5- 8. Therefore, the image quality of 120Hz Stencil-FSC method was acceptable.

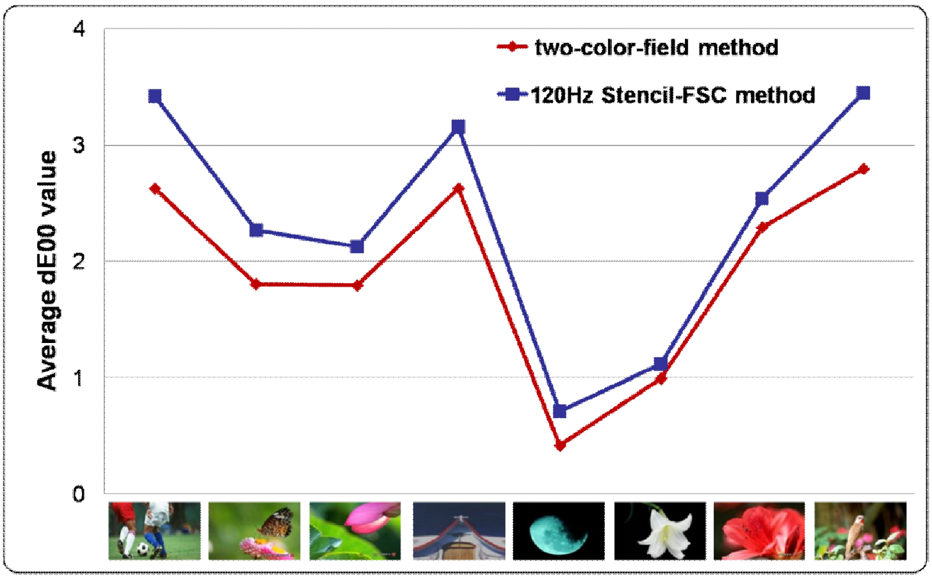


Fig. 5- 7 Average ΔE_{00} value of two-color-field method and 120Hz Stencil-FSC method

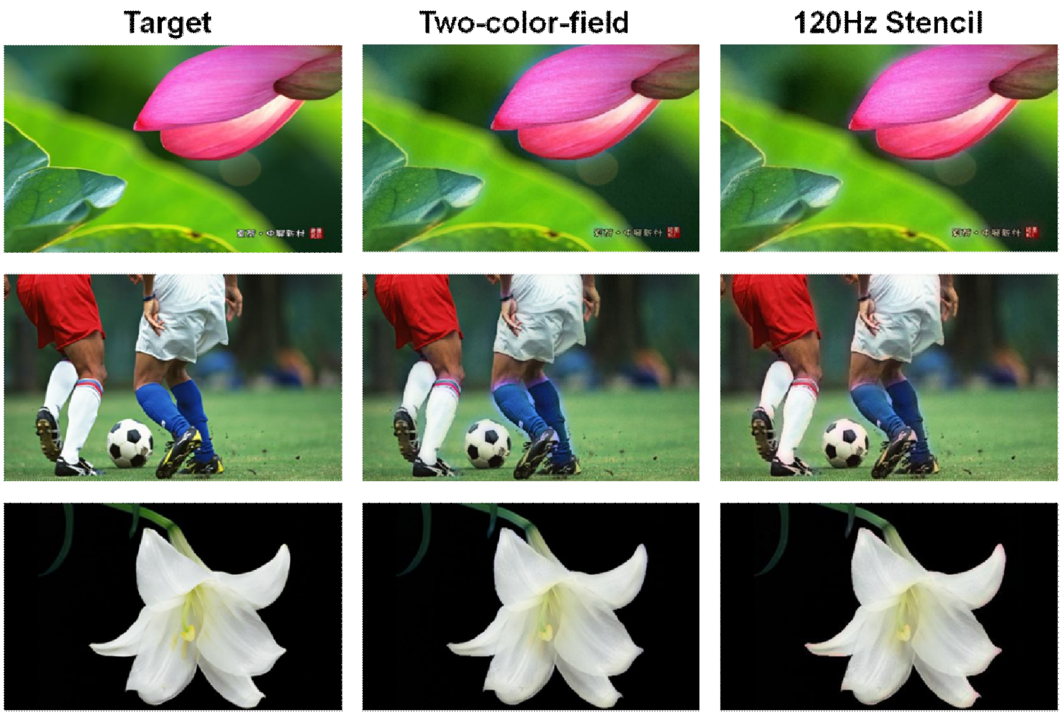


Fig. 5- 8 Comparison of target image (left), two-color-field method (middle), and reproduced image using 120Hz Stencil-FSC method (right)

On the other hand, the 120Hz Stencil-FSC method displayed more color and intensity at the first field, thus the CBU might be further reduced comparing to the two-color-field method. From the simulation result as shown in Fig. 5- 9, the average CBU of 120Hz Stencil-FSC method was only about 38% of conventional RGB-FSC method and suppressed CBU effectively as shown in Fig. 5- 10.

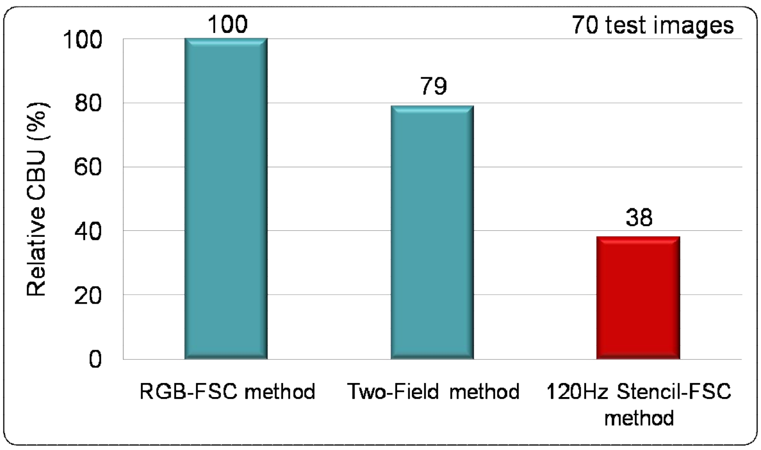
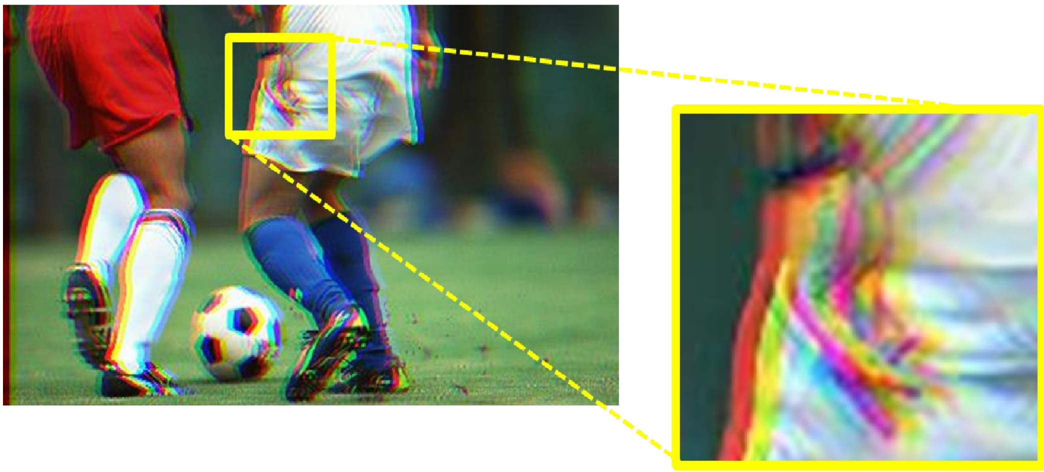
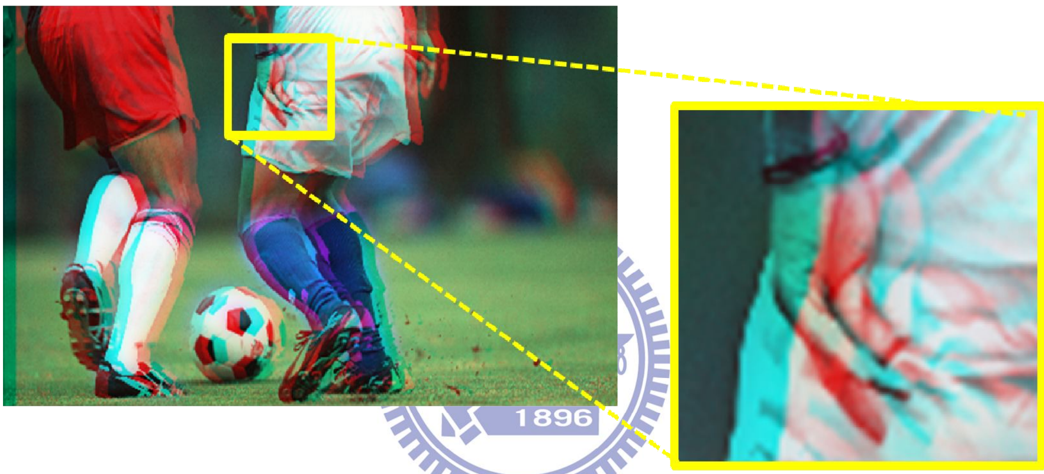


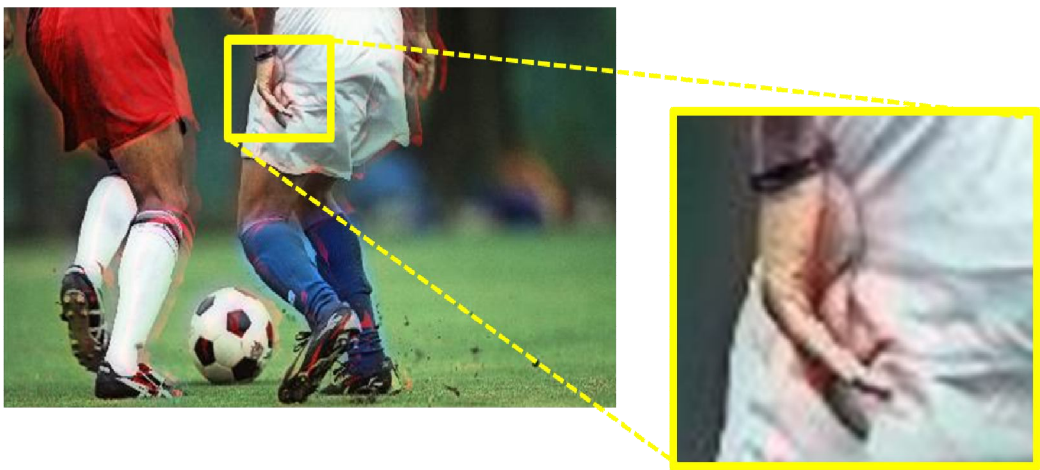
Fig. 5- 9 simulation result of CBU with different FSC methods



(a)



(b)



(c)

Fig. 5- 10 Comparison of CBU image *Soccer* (a) RGB-FSC method, and (b) two-color-field method, and (c) 120Hz Stencil-FSC method

5.4 Summary

In order to further reduced power consumption of FSC-LCDs, the backlight system was improved even more. The high efficiency white-light LED was added onto RGB LED to be a RGBW 4-in-1 LED. The gray/white part of image was generated using high efficiency white-light LED instead of mixing of RGB LED. Using 240Hz and 180Hz Stencil-FSC methods with RGBW 4-in-1 LEDs (110lm/W white-light LED), the optical power consumption of LED was further reduced to about 62% and 51% of conventional RGB-FSC method respectively. On the other hand, the two-color-field sequential method was modified to be the 120Hz Stencil-FSC method. The 120Hz Stencil-FSC method not only reduced the optical power consumption to about 25% of conventional RGB-FSC method, but also suppressed CBU effectively. The averaged CBU was about 38% of conventional RGB-FSC method with only minor image difference sacrificing. Consequently, by applying 120Hz (2-field) stencil-FSC method with RGBW 4-in-1 LEDs backlight, the power consumption could be around 35Watt only for a 32-inch LCD. (Our experiment 32-inch RGB-FSC display is 68Watt).

Chapter 6

Conclusions and Future Works

6.1 Conclusions

FSC-LCDs not requiring color filters display red, green, and blue images time sequentially to generate a full color image by temporal color mixing. Due to Color filter-less, FSC-LCDs have some attractive advantages, such as three times optical throughput than conventional LCDs, three times possible image resolution, and low material cost. However, the CBU phenomenon decreases the image fidelity of FSC-LCDs. CBU occurs when there are relative velocities between human eye and display objects. CBU seriously degrades image fidelity of FSC-LCDs. Therefore, our group proposed Stencil-FSC methods and two-color-field sequential method to suppress CBU. The concept is to display high luminance and rough color in the first field image and make CBU almost imperceptible. However, the 180Hz Stencil-FSC method has a green color saturation issue because of the redundant light propagated at first field.

In this thesis, the adaptive base 180Hz Stencil-FSC method was proposed to prevent the redundant light as first field. The dominant color of first field was not always green but chosen according to the input image and the backlight signal was dimmed to 20% making backlight signal more colorful. Furthermore, the hardware parameters PSF and backlight divisions were optimized. The optimal backlight division is 24x32 and its correspond LSF σ_x=26 and σ_y=16. After optimizing the hardware parameters, the adaptive base 180Hz Stencil-FSC method reduced the averaged ΔE_{00} <1 and the average relative CBU was only about 59% of conventional RGB-FSC method. In addition, the adaptive base 180Hz Stencil-FSC method was verified on a 46 inch 120Hz MVA LCD and made CBU almost imperceptible.

On the other hand, in order to reduce power consumption of FSC-LCDS, the backlight system was further improved. In this thesis, the RGBW 4-in-1 LEDs backlight system was proposed. The gray/white part of image was generated using high efficiency white-light LED instead of mixing of RGB LED, and the remaining color part of image was generated using RGB LED. By this way, the optical power consumption of LEDs could be further reduced. To apply on RGBW 4-in-1 LEDs backlight system, the two-color-field method was modified to be the 120Hz Stencil-FSC method. When number of backlight divisions is up to 45x80, the color difference was similar to the two-color-field method, and CBU was reduced to about 38% of conventional RGB-FSC method. The 240Hz, 180Hz, and 120Hz were applied on RGBW 4-in-1 LEDs backlight system, the optical power consumption of LEDs was reduced to about 62%, 51%, and 25% respectively. The comparison of three Stencil-FSC methods is shown in Table. 6- 1.

Table. 6- 1 Comparison of Three Stencil-FSC method

	Conventional RGB-FSC	Stencil-FSC		
		240Hz	Adaptive 180Hz	120Hz
Field Rate (Hz)	180	240	180	120
BL Divisions	Global	24 × 24	24 × 32	45 × 80
*Color Difference (Avg ΔE_{00})	--------	0.07	0.8	4.1
*CBU (%)	100	58.6	59.1	37.8
**Relative Optical Power of Backlight with RGBW LED (%)	100	62.6	51.3	24.6

*: with 70 test images
**: Based on the same brightness; with 110lm/W white-light LED

Therefore, using Stencil-FSC method with RGBW 4-in-1 LEDs, not only CBU could be suppressed effectively but also the power consumption was further reduced. Therefore, to slow down the earth destruction, the RGBW 4-in-1 LEDs with Stencil-FSC method has high potential to be the system for future "Eco-display" applications.

6.2Future Works

So far, the algorithm to simulate Stencil-FSC method was simplified. We did not consider the LC response time. However, actually, the LC response time affects color mixing between fields as shown in Fig. 6- 1. In one sub frame time, if the backlight turns on when the LC is not twist to the target gray level, the luminance will be lower than target luminance. Therefore, the simulation of Stencil-FSC algorithm is better to consider the LC response time. So the reproduced image can much more close to the real case. From the simulation result with considering LC response time, we can analyze the temporal crosstalk caused by the insufficient time for LC.

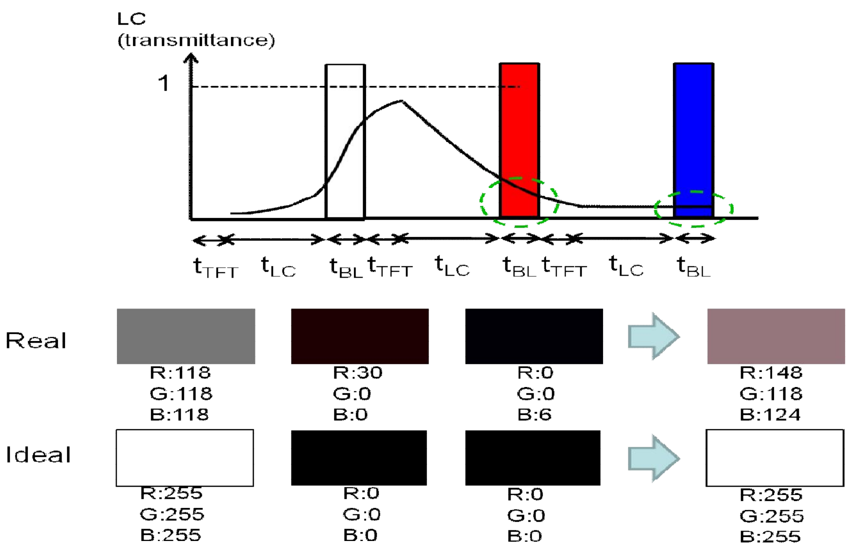


Fig. 6- 1 the color mixing of sub frames in FSC-LCDs with real case (consider LC response time) and ideal case

Furthermore, the final target is to implement Stencil-FSC methods on hardware. Therefore, description language of Stencil algorithm must be transformed from software language MATLAB to hardware language VERILOG as shown in Fig. 6- 2. Using VERILOG language, the BL and LC signal can input to hardware and realize Stencil method to the market in the future.

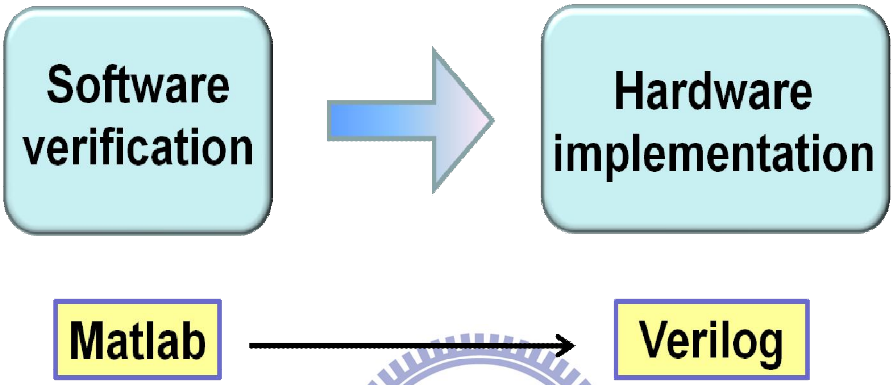


Fig. 6- 2 The chart of hardware implementation from software language Matlab to hardware language Verilog

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