Color Breakup Reduction by 180 Hz Stencil-FSC Method in Large-Sized Color Filter-Less LCDs

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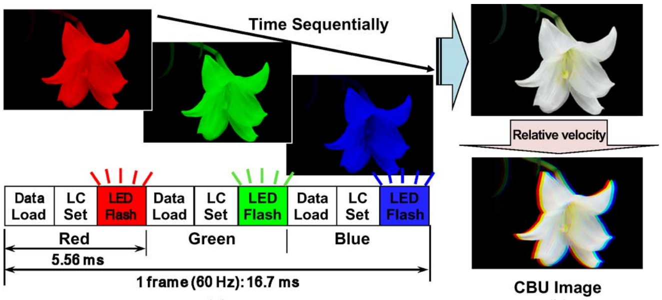
***Abstract*—Field-sequential color (FSC) is a high optical throughput technique for future green liquid crystal displays (LCDs). However, the FSC-LCD faces a lethal issue, color breakup (CBU) which degrades image clarity and prevents high level LCD-TV productions. We proposed the "180 Hz Stencil Field-Sequential-Color" method to redistribute intensities of the three primary color field-images to suppress CBU. By applying local color-backlight-dimming technology to FSC-LCDs, a low resolution colorful backlight panel combined with a high resolution color filter-less LC panel generated a "green-based multi-color" field-image which showed the most image luminance in the first field. Therefore, residual red and blue field-image intensities were reduced and effectively suppressed CBU when compared to field-rate increasing methods. In addition, to further implement hardware, the number of backlight divisions of 32×24 and a proper Gaussian point spread function profile were optimized via simulations while considering CBU reduction and image fidelity. Using optimized hardware parameters, the CBU phenomenon was suppressed by 50% of traditional RGB driving in simulation and was demonstrated on a 120 Hz 46-inch MVA LCD-TV.**

***Index Terms*—Color breakup (CBU), color filter-less, field-sequential-color (FSC), high-dynamic-range, stencil-FSC.**

I. INTRODUCTION

LIQUID crystal displays (LCDs) are greatly used in our daily display devices because they possess several advantages, such as high screen resolution, high brightness, light weight, and thin profile. However, traditional CCFL-LCDs are still low in optical throughput, and have an imperfect "dark" state. Using polarizes and color filters in CCFL-LCDs results in approximately only 5% ~ 10% of optical throughput to yield a front-of-screen image.

Consequently, a high optical-throughput field-sequential-color (FSC) LCD without color filters has been proposed to reduce power consumption [1]–[3]. By rapidly displaying red (R), green (G), and blue (B) field-images time-sequentially, a full-color image was created by temporal color synthesis, as illustrated in Fig. 1(a). Without a color filter, FSC-LCDs are prized for higher light-emission efficiency, wider color gamut, lower material cost, and possibly three times higher screen resolution.



(a) (b)

Fig. 1. (a) FSC-LCD mechanism: Displaying red, green, and blue field-images at 180 Hz field rate. (b) CBU occurring while a relative velocity exists between the screen object and the human eye.

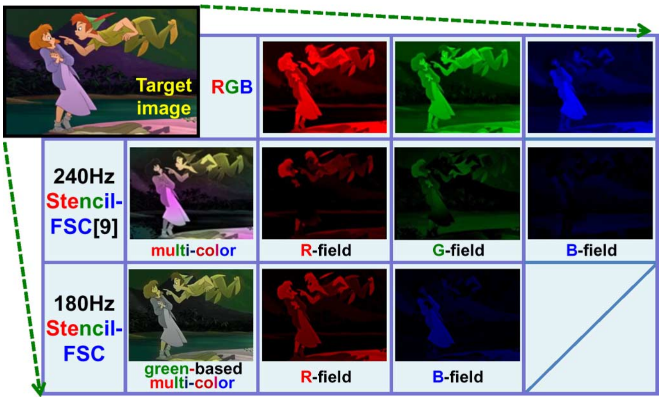


Fig. 2. Target image_*Ali Mountain* (© Taiwan Tourism Bureau, http://tiscsvr.tbroc.gov.tw), and each field-image using: (top) the conventional RGB-driving; (middle) 240 Hz Stencil-FSC; and (bottom) 180 Hz Stencil-FSC methods.

Unfortunately, when relative velocities exist between the screen object and the observer's eyes, a well-known visual artifact, color breakup (CBU) is perceived and degrades the image clarity [see Fig. 1(b)] [4]. CBU suppression has been implemented on digital light processing (DLP) projectors by inserting additional mono-color fields or increasing the field rate to 540 Hz or higher [5], [6]. Hence, most traditional CBU solutions for FSC-LCDs involved either increasing the field rate or inserting additional "mono-color" and "black" fields (RGBCY and RGBKKK) [7]–[9]. In an FSC-LCD, although LED backlights can be switched on and off rapidly, LC response time does not enable the implementation of many of the above methods in large-sized FSC-LCDs.

Accordingly, the 240 Hz (4-field) Stencil Field-Sequential Color (Stencil-FSC) method was proposed to cumulate major color information in the first field-image; the luminance of the other three primary-color images were reduced and effectively suppressed CBU (Fig. 2) [10]. Because of limited liquid crystal

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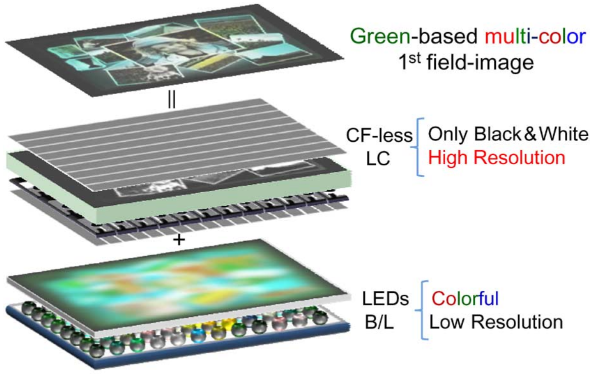


Fig. 3. A "green-based multi-color" image is yielded by a low resolution RGB-LED backlight and a high resolution color filter-less LC cell.

response time, this type of high field-rate, large-sized LCD has not been well developed in current display industries. For practical applications, therefore, we further reduce the Stencil-FSC field rate from 240 Hz (4-field) to 180 Hz (3-field) and named it the "180 Hz Stencil-FSC" method [11].

II. 180 Hz STENCIL-FSC METHOD

A. Concept and Algorithm

Concentrating the image intensity on a single field-image can reduce the human sensitivity to CBU. Additionally, the human eye is most sensitive to green color, the red and blue signals are therefore redistributed into the green field to create a "green-based field-image." When the separated colors do not contain green information, the CBU phenomenon is reduced.

By applying local color-backlight-dimming technology [12], [13] to FSC-LCDs, a low resolution colorful backlight panel combined with a high resolution color filter-less LC panel generated a "green-based multi-color" field-image which showed greater image luminance in the first field (Fig. 3). An input image was recalculated to obtain three primary-color backlight signals, BL_R, BL_G, and BL_B. Moreover, the LC transmittance values of R, G, and B fields, T_R, T_G, and T_B, were compensated using (1) [see Fig. 4(b)], where I_i^{full} and I_i denote image luminance; BL_i^{full} and BL_i denote intensities of the traditional full-on backlight and the HDR blurred backlight signal, respectively [14]. To fully display green information in the first field, the green LC signal (T_G) of each LC pixel was taken as the first field LC signal. From (2), the new red and blue-field LC signals (T'_R and T'_B) were determined for the red and blue field-images [see Fig. 4(c)].

$$\begin{aligned} I_i^{\text{full}} = I_i \Rightarrow BL_i^{\text{full}} \times T_i^{full} &= BL_i \times T_i \quad i = R, G, B \\ \Rightarrow \begin{bmatrix} T_R \\ T_G \\ T_B \end{bmatrix} &= \begin{bmatrix} BL_R^{\text{full}}/BL_R & 0 & 0 \\ 0 & BL_G^{\text{full}}/BL_G & 0 \\ 0 & 0 & BL_B^{\text{full}}/BL_B \end{bmatrix} \\ &\quad \times \begin{bmatrix} T_R^{\text{full}} \\ T_G^{\text{full}} \\ T_B^{\text{full}} \end{bmatrix} \end{aligned} \tag{1}$$

$$\begin{bmatrix} T'_R \\ T'_B \end{bmatrix} = \begin{bmatrix} T_R \\ T_B \end{bmatrix} - T_G. \tag{2}$$

To prevent T'_R or T'_B from being a negative value which indicates redundant red or blue light was propagated to the first field and resulted in the green saturation reduction. Green backlight determination (BL_G) was different from the red and blue backlight determination (BL_R and BL_B) methods. In this paper, the image was evenly divided into non-overlapping rectangles corresponding to the number of backlight divisions. We directly averaged the red and blue pixel values that subtended the rectangular region in front of each given backlight division independently as red and blue backlight signals (BL_R and BL_B). BL_G was calculated by averaging the green LC pixel signals and then took its square root to enhance the signal [11]. Therefore, if the average red, green, and blue pixel signals in a certain backlight division are similar values, the BL_G will be larger than BL_R and BL_B. Consequently, most compensated red and blue LC signals (T_R and T_B) will be larger than green signal (T_G) which avoids negative T'_R and T'_B and maintains image fidelity.

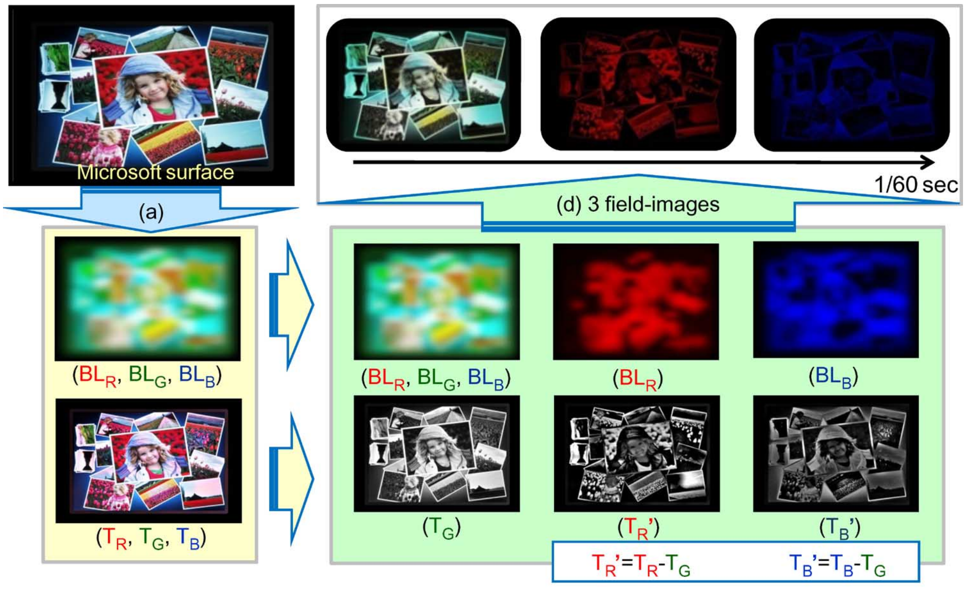
After determining each field-image backlight and LC signals, the LC signals were put on the color filter-less panel as a stencil mask, the RGB-LED backlights were painted onto each mask sequentially to produce a field-image. According to the stencil concept, the three primary-color backlight signals (BL_R, BL_G, and BL_B) and the green LC signal (T_G) were combined to display a high luminance green-based color image in the first field. Likewise, combining the BL_R with T'_R and BL_B with T'_B, created residual less-luminance red and blue field-images [Fig. 4(d)]). Finally, displaying these three field-images at 180 Hz generated less CBU and a vivid color image. The direct and simple 180 Hz Stencil-FSC signal processing also heightened the dynamic contrast and lowered power consumption because local color-backlight-dimming technology was used.

B. Optimization and Simulation

To suppress CBU more efficiently and maintain image fidelity, the point spreading function (PSF) of a backlight division and the number of backlight divisions while using the 180 Hz Stencil-FSC method were optimized according to the eight high contrast ratio or rich color content test images [Fig. 5(a)]. In addition, to simulate a relative velocity between the screen object and the human eye, a CBU image was produced by composing the three field-images with 60 total pixel shifts which is equivalent to a velocity of about 180 cm/sec. The PSF was simulated as a Gaussian distribution in this optimization ((3)). By controlling the standard deviation (S.D.) of the Gaussian distribution (σ_{x} and σ_{y}), the PSF was modulated [Fig. 4(b)]. To help determine the optimal arrangement of backlight divisions, twelve different configurations were formed as shown in Fig. 5(c)

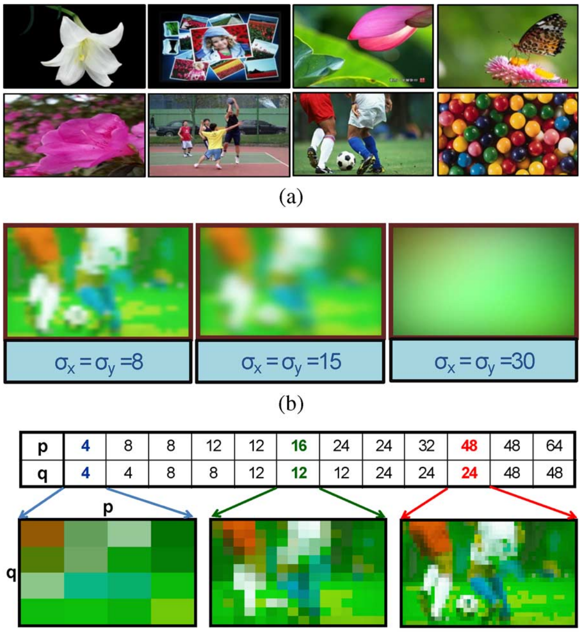
$$g(x, y) = e^{-\left(\frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}\right)} \tag{3}$$

Based on the spatial extension of CIELAB [15], the color difference of the CIEDE2000 (ΔE_{00}) was calculated [16], [17] to evaluate CBU reduction and image fidelity. After summing up ΔE_{00} of each pixel between a test image and its CBU image $(\Sigma\Delta\text{E}_{00})$, a *relative CBU* index was defined as the ratio of total color difference between $\text{p} \times \text{q}$ backlight division and conventional RGB-driving, as shown in (4). The average ΔE_{00} between test images and 180 Hz Stencil-FSC simulated images was utilized to evaluate image fidelity.



(b) (c)

Fig. 4. 180 Hz Stencil-FSC algorithm. (a) Input image, *Girl* (©Microsoft); (b) local color-backlight-dimming technology; (c) backlight and LC signal; and (d) three yielded field-images.



p	4	8	8	12	12	16	24	24	32	48	48	64
q	4	4	8	8	12	12	12	24	24	24	48	48

(c)

Fig. 5. (a) Eight test images: *Lily*, *Girl*, *Lotus**, *Butterfly**, *Blossom*, *Basketball*, *Soccer*, and *Color Ball*. (b) Simulated backlight intensity distribution in various Gaussian standard deviation: $\sigma_x = \sigma_y = 8$, 15, and 30. (c) Simulation backlight division combinations with three corresponding backlight images for the test image_*Soccer*. (p is the column number and q is the row number). (*: taken by Jacky Lee, http://jac3158.com/blog).

$$\text{relative CBU} \equiv \frac{\sum \Delta E_{00}(\text{Target}, \text{Stencil})_{p*q}}{\sum \Delta E_{00}(\text{Target}, \text{RGB\_driving})} \times 100\% \qquad p, q: \text{division number}. \quad (4)$$

Considering to CBU suppression and image fidelity, the proper PSF was optimized for each backlight division first and is shown in Fig. 6. A larger number of backlight divisions required smaller σ_x and σ_y which suggested that backlight intensity distribution was localized. Using the optimized PSF, the number of backlight divisions was furthermore analyzed. Fig. 7 shows the number of backlight divisions versus CBU reduction and image fidelity respectively. From the simulation results, both CBU reduction and image fidelity tended to be

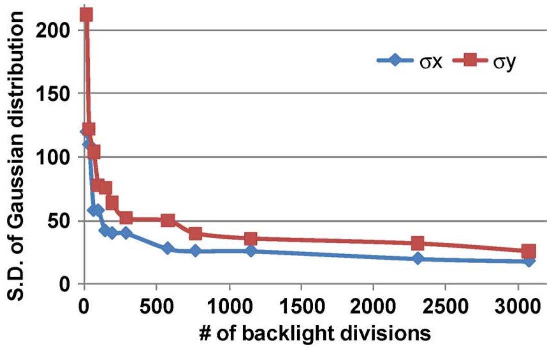
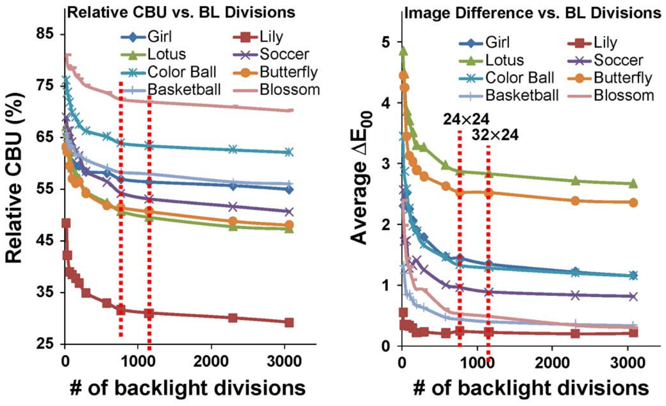


Fig. 6. Optimized S.D. (σ_x and σ_y) of a Gaussian PSF for different number of backlight divisions.



(a) CBU reduction (b) Image fidelity

Fig. 7. Simulation results of the optimized number of backlight divisions in the eight test images. (a) *Relative CBU* versus. the number of BL divisions and (b) average ΔE_{00} versus. the number of BL divisions.

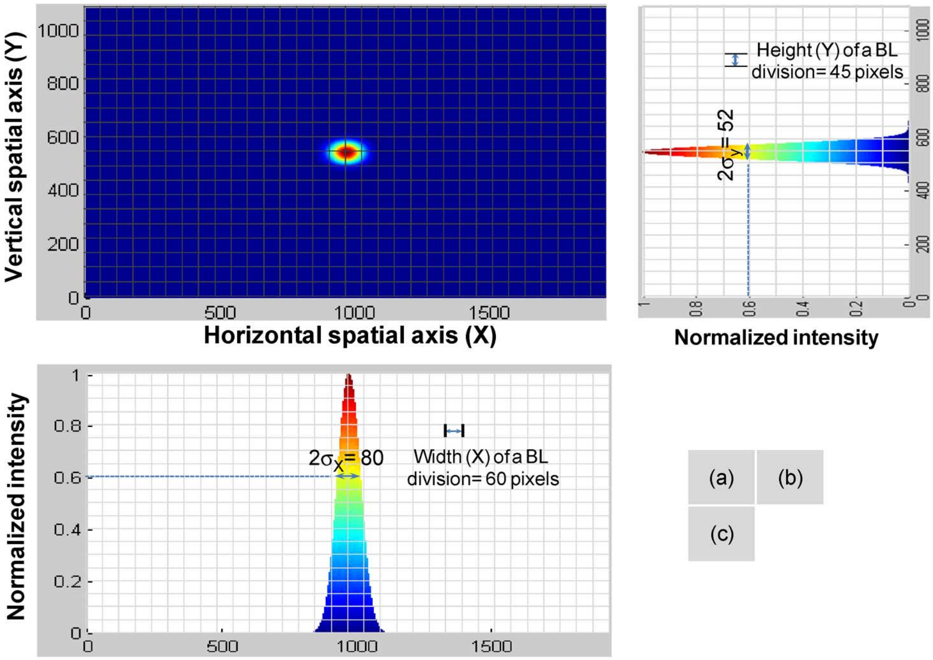


Fig. 8. The optimized Gaussian PSF with $\sigma_{\mathrm{x}} = 40$ and $\sigma_{\mathrm{y}} = 26$ in the 32 × 24 backlight division combination. PSF views from (a) vertical, (b) lateral (y-direction), and (c) bottom (x-direction).

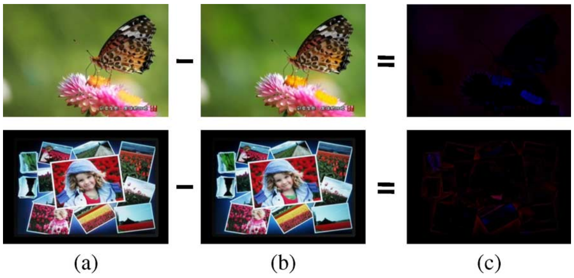


Fig. 9. (a) Simulated images after 180 Hz Stencil-FSC processing. (b) Two test images of *Butterfly* and *Girl*. (c) Image differences between simulated and test images.

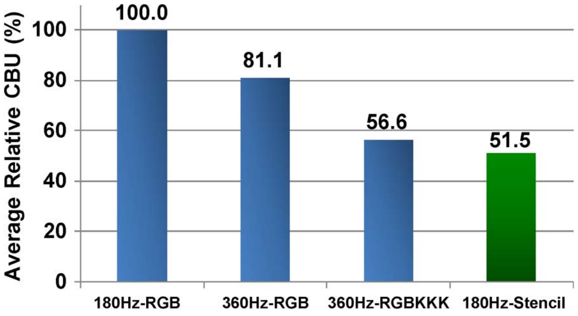


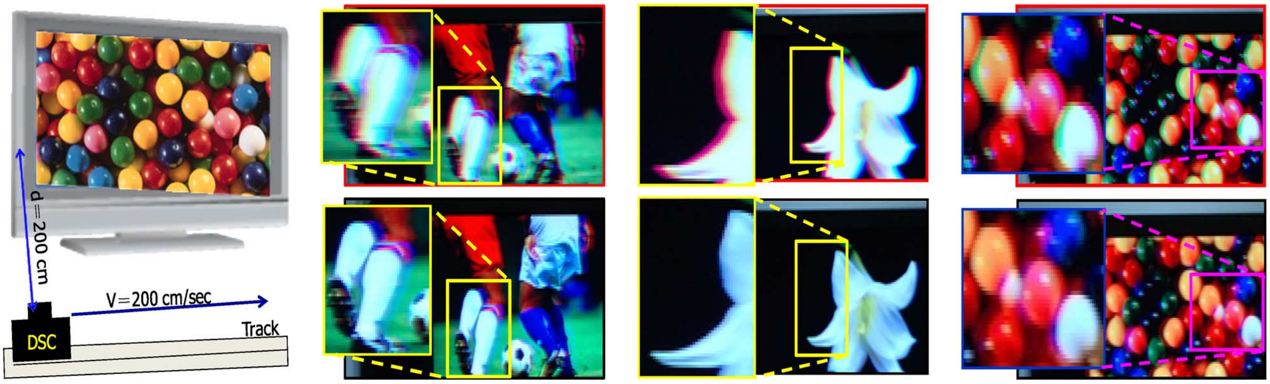
Fig. 10. Average *relative CBU* by different CBU reduction methods and 180 Hz Stencil-FSC for the eight test images.

independent of the number of backlight divisions after 32 × 24 (768). In addition, the average $\Delta\mathrm{E}_{00}$ values after 32 × 24 were less than 3 which indicated higher image fidelity. Considering CBU reduction and practical applications, 32 × 24 with a Gaussian PSF of $\sigma_{\mathrm{x}} = 40$ and $\sigma_{\mathrm{y}} = 26$ might be the optimal parameters for using the 180 Hz Stencil-FSC method, as shown in Fig. 8. Two test images, *Butterfly* and *Girl*, were simulated. Fig. 9 shows their simulated images and image differences with average $\Delta\mathrm{E}_{00}$ of 2.5 and 1.4 respectively at 32 × 24 backlight divisions.

C. Comparison to RGBKKK and 240 Hz Stencil-FSC

Comparing to the RGBKKK and 240 Hz Stencil-FSC methods, full-HD (1920 × 1080 resolution) images were simulated. Eq. (5) explains each required time in an FSC-LCD, where f is frame rate (60 Hz), N and n are the number of fields and effective scanning backlight divisions respectively [18]. t_{TFT}, t_{LC}, and t_{LED} are the data addressing time, LC response time, and LED-BL flashing time. We assumed the addressing time for each gate-line was 5 μs, LED-BL flashing time was 1.5 ms, and there were 5 ($n = 5$) effective scanning backlight divisions in the Stencil-FSC system. The 180 Hz Stencil-FSC method only required 3 fields to show a colorful image, therefore, the LC had 3 ms to completely response which maintained the image brightness and avoid color shift occurring. The 240 Hz Stencil-FSC method required 4 fields, it meant one more field was required and resulted in the compression of available time. If image brightness would be maintained, the LC response time should be much shorter to 1.6 ms [19]. If LC response could not be speeded up, the LED-BL response time would be compressed and the LED pulse intensity should be enhanced to maintain image brightness. Once, the LED intensity vs. power was operated at nonlinear region, and then the power consumption would also be raised. That is the reason why the power consumption using 180 Hz Stencil-FSC was lower than 240 Hz Stencil-FSC (Table I). The RGBKKK also had the same issue. Therefore, its power consumption might be larger than 68 W of using conventional RGB-driving method.

$$\frac{1}{Nf} = \frac{t_{\mathrm{TFT}}}{n} + t_{\mathrm{LC}} + t_{\mathrm{LED}} \tag{5}$$

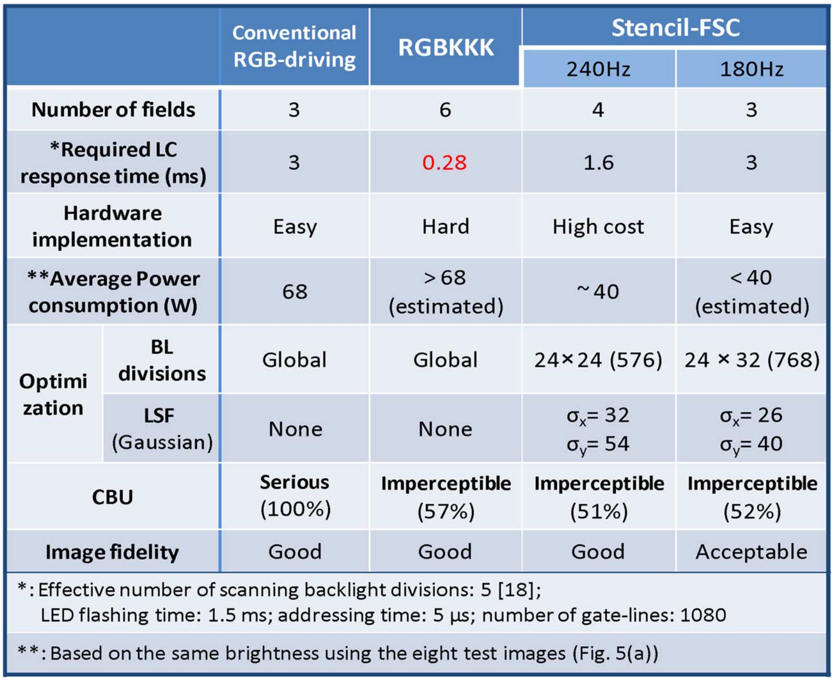


(a) (b) (c) (b)

Fig. 11. (a) Experimental setup for capturing CBU images. Experimental photos using conventional RGB-driving (top) and 180 Hz Stencil-FSC methods (bottom) of (b) *Soccer*, (c) *Lily*, and (d) *Color Ball*.

TABLE I

COMPARISONS BETWEEN THE CONVENTIONAL RGB-DRIVING, RGBKKK [9], 240 Hz STENCIL-FSC [10], AND 180 Hz STENCIL-FSC



		Conventional RGB-driving	RGBKKK	Stencil-FSC	
				240Hz	180Hz
Number of fields		3	6	4	3
***Required LC response time (ms)**		3	0.28	1.6	3
Hardware implementation		Easy	Hard	High cost	Easy
****Average Power consumption (W)**		68	> 68 (estimated)	~ 40	< 40 (estimated)
Optimization	**BL divisions**	Global	Global	24×24 (576)	24 × 32 (768)
	LSF (Gaussian)	None	None	σ_x= 32 σ_y= 54	σ_x= 26 σ_y= 40
CBU		**Serious** (100%)	**Imperceptible** (57%)	**Imperceptible** (51%)	**Imperceptible** (52%)
Image fidelity		Good	Good	Good	Acceptable

*: Effective number of scanning backlight divisions: 5 [18];
LED flashing time: 1.5 ms; addressing time: 5 μs; number of gate-lines: 1080

**: Based on the same brightness using the eight test images (Fig. 5(a))

D. Comparison to Other Reduction Methods

CBU suppression using 180 Hz Stencil-FSC was compared to methods of double field rate (360 Hz-RGB) and black-fields insertion of 360 Hz-RGBKKK [9] by simulations. The field-images of each test image were separated in 60 pixels/frame, and ΔE_{00} of the eight test images using these three suppression methods were calculated and then divided by ΔE_{00} using 180 Hz RGB-driving (i.e., index of *relative CBU*). The average *relative CBU* values using the 360 Hz-RGB, 360 Hz-RGBKKK, and 180 Hz Stencil-FSC methods were 81.1%, 56.6%, and 51.5% respectively (Fig. 10). Obviously, 180 Hz Stencil-FSC was more effective than only increasing the field rate while considering CBU suppression and hardware implementation.

E. Verification on a 120 Hz 46-inch MVA LCD

The 180 Hz Stencil-FSC method was verified on a 120 Hz 46-inch MVA LCD. The pictures of *Soccer, Lily, and Color Ball* were used as the test images, and CBU images were taken by a digital still camera which was set up 2 meters from the LCD on a moving stage with a horizontal velocity of 200 cm/sec to simulate eye movement, as illustrated in Fig. 11(a). Because the 180 Hz Stencil-FSC method put most image luminance in the first field, the CBU phenomenon was much slighter when compared to the conventional RGB-driving method (Fig. 11).

III. CONCLUSION

Using a "multi-color" field image instead of a conventional "single-color" field, we proposed the "180 Hz Stencil-FSC" method to suppress the color breakup (CBU) phenomenon. Using local color-backlight-dimming technology, a high luminance green-based multi-color image was generated on a color filter-less LCD. Therefore, the luminance of residual red and blue color images was greatly reduced and effectively suppressed CBU. From the optimization results, 32 × 24 backlight divisions with two directional standard deviations of the Gaussian point spread function ($\sigma_{\mathrm{x}} = 40$ and $\sigma_{\mathrm{y}} = 26$) suppressed CBU by 50% and made CBU almost imperceptible. Using the 180 Hz Stencil-FSC method, the average image color differences of CIEDE2000 ($\Delta\mathrm{E}_{00}$) were less than 3 indicating acceptable image fidelity. Additionally, the algorithm processing of the 180 Hz Stencil-FSC method was also direct and simple, only including backlight determination, liquid crystal compensation, and simple subtraction. As a result, the 180 Hz Stencil-FSC LCD has potential for future large-sized "Eco-Display" applications.

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