(Invited) Stencil Field-Sequential Color Method for Color Breakup Suppression on 180Hz LCD-TV

Yi-Pai Huang, Fang-Cheng Lin, Chi-Chu Tsai, and Han-Ping D. Shieh

Display Institute, National Chiao Tung University, 30010 Hsinchu, Taiwan

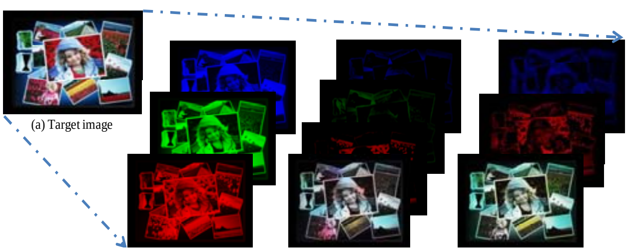
Abstract

We proposed the "180Hz Stencil-FSC" method to suppress color break-up (CBU) in field-sequential color (FSC) LCDs. Applying local color-backlight-dimming technology to FSC-LCDs, a "green-based multi-color" field-image was generated to show most image luminance at the first field 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 was optimized while considering CBU suppression 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 120Hz 46-inch MVA LCD-TV.

1. Introduction

A high optical throughput field-sequential color (FSC) LCD without color filters was proposed to further reduce power consumption [1]. After removing color filters, FSC-LCDs possesses many benefits, such as high optical throughput, wide color gamut, low material cost, and three times the possible screen resolution when compared to LCDs with color filters. However, when a relative velocity exists between the screen object and the observer's eyes, a well-known visual artifact, color break-up (CBU) is perceived and degrades the image clarity [2].

CBU suppression has been implemented on digital light processing (DLP) projectors by inserting additional mono-color fields or increasing the field rate to 540Hz or higher. Hence, most traditional CBU solutions for FSC-LCDs involved using either inserting additional "mono-color" fields (RGBY or RGBCY), inserting black-fields (RGBKKK), or increasing the field rate [3]-[6]. However, LC response time does not enable the implementation of many of the above methods in large-sized FSC-LCDs. Consequently, the 240Hz (4-field) Stencil-FSC method was proposed to display a rough color and high luminance multi-color image on the first field-image, the luminance of the other three primary-color images were reduced and then combined to form a vivid color image. As a result, less primary-light was seen separately, and CBU was suppressed as illustrated in Figure 1(c) [7][8].



(b) (c) (d)

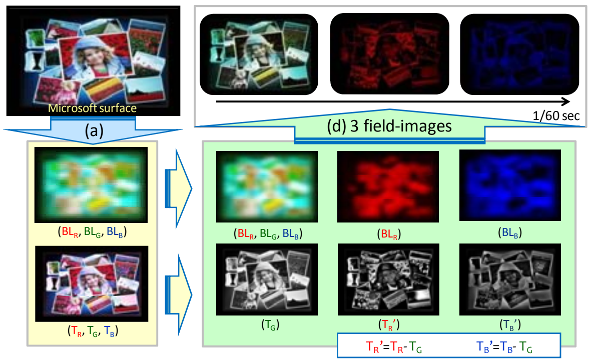
Figure 1. (a) Target image_ *Girl* (©Microsoft), each field-image using the (b) conventional FSC-LCD, (c) 240Hz (4-field) Stencil-FSC method, and (d) 180Hz (3-field) Stencil-FSC method.

However, the 240Hz LCD technology has not been well-popularized in the display industry. Therefore, the field rate is further reduced to 180Hz to make Stencil-FSC more feasible in this paper. Based on the simple and directly algorithm, the experimental results convince that not only CBU is suppressed but also image fidelity is almost maintained [9].

2. 180Hz Stencil-FSC Method

2.1 Concept and Algorithm

For practical applications, the number of field-images is reduced from 4 fields to 3 fields in this paper. Consequently, one of the rest three primary-color fields using 240Hz Stencil-FSC should be moved and fully displayed on the first field to maintain image fidelity. Because 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 (Figure 1(d)). Figure 2 illustrates the 180Hz Stencil- FSC algorithm.



(b) HDR tech. (c) Backlight and LC signals

Figure 2. 180Hz Stencil-FSC algorithm. (a) Input image, *Girl* (©Microsoft), (b) local color-backlight-dimming technology, (c) backlight and LC signals, and (d) 3 yielded field-images.

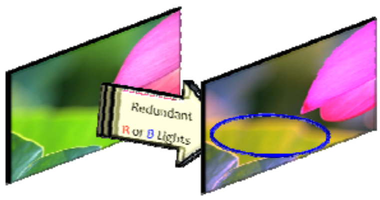


Figure 3. Redundant red or blue light propagates through the first green-based sub-frame resulting in reduction of green color saturation (blue circle part).

To create a green-based multi-color image on a color filter-less LCD, local color-backlight-dimming (or called high dynamic range, HDR) technology [9]-[12] was utilized (Figure 2(b)). 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 Eq. 1, 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 HDR blurred backlight signal. To fully display green information on the first field, the green LC signal (T_G) of each LC pixel was taken as the first field LC signal. From Eq. 2, the new red and blue-field LC signals (T_R' and T_B') were determined for the red and blue field-images (Figure 2(c)).

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

$$\begin{bmatrix} T_R^{'} \\ T_B^{'} \end{bmatrix} = \begin{bmatrix} T_R \\ T_B \end{bmatrix} - T_G \tag{2}$$

To prevent the T_R' or T_B' being a negative value which denotes redundant red or blue light propagates to the first field and resulted in the reduction of green saturation, as illustrated in Figure 3. Consequently, 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. Therefore, if the average red, green, and blue pixel signals in a certain backlight division are close, 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' occurring and maintains image fidelity.

After determining backlight and LC signals, 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 on 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 (Figure 2(d)). Finally, displaying these three field-images at 180Hz generated a less CBU and vivid color image.

2.2 Optimization and Simulation

To suppress CBU more efficiently and maintain image fidelity, the number of backlight divisions while using the 180Hz Stencil-FSC method was optimized according to six high contrast ratio or high color content test images. The number of backlight divisions was divided into twelve combinations (Figure 4).

We introduced the color difference of the CIEDE2000 (ΔE_{00}) [13] to evaluate the CBU reduction and image fidelity. After summing up ΔE_{00} of each pixel between a test image and its CBU image ($\Sigma\Delta E_{00}$), a *relative CBU* index was defined as the ratio of total color difference between p×q backlight division and the conventional RGB-driving, as shown in Eq. 3. Figures 5(a)(b) show the number of backlight divisions versus CBU reduction and image fidelity respectively.

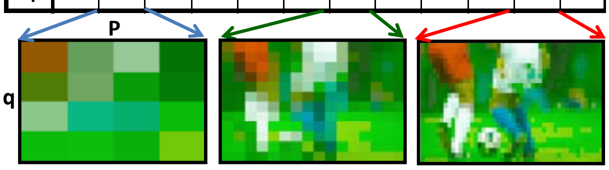
Both CBU reduction and image fidelity tend to be independent with the number of backlight divisions after 32×24 (768), as illustrated in Figure 5. In addition, the average ΔE_{00} values after 32×24 are less than 3 which denote higher image fidelity. Consequently, two test images, *Color Ball* with vivid color information and *Girl* with high image detail were simulated using the optimized conditions. Figure 6 shows their simulated images and CIEDE2000 error images with average ΔE_{00} values of 1.3 and 1.4 respectively at 32×24 backlight divisions. It is difficult to distinguish the differences from the original and simulated images but finding out the differential parts from the CIEDE2000 error images.

$$relative\ CBU \equiv \frac{\sum \Delta E_{00}(Target, Stencil)_{p*q}}{\sum \Delta E_{00}(Target, RGB\_driving)} \times 100\% \qquad p,q: division\ number \tag{3}$$

Considering CBU suppression and practical applications, 32×24 might be the optimal number of backlight divisions while using the 180Hz Stencil-FSC method.

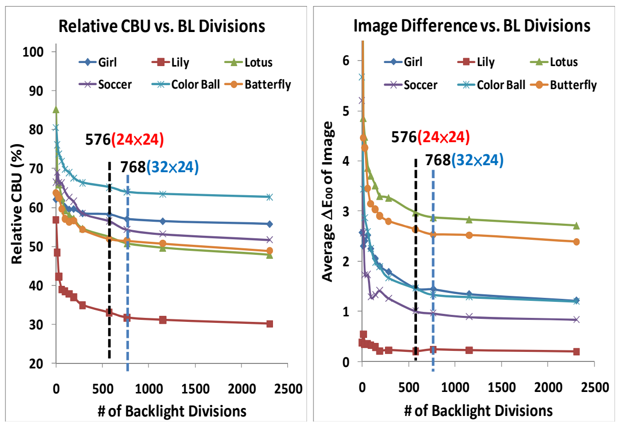
(a) Test images

p	1	4	8	8	12	12	16	24	24	32	48	48
q	1	4	4	8	8	12	12	12	24	24	24	48



(b) Backlight division combinations

Figure 4. (a) Six test images: *Lily*, *Girl*, *Lotus**, *Butterfly**, *Soccer*, and *Color Ball*. (b) 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)



(a) CBU Reduction (b) Image Fidelity

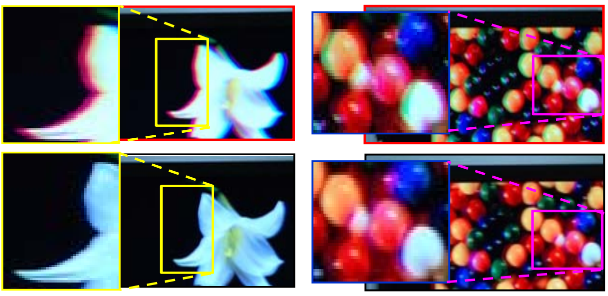
Figure 5. Simulation results of the optimized number of backlight divisions in six test images. (a) Relative CBU vs. the number of BL divisions and (b) Average ΔE_{00} vs. the number of BL divisions.

(a) Original images (b) Simulated images (c) Error images

Figure 6. (a) Two test images of *Color Ball* and *Girl*, (b) simulated images after 180Hz Stencil-FSC processing, and (c) CIEDE2000 error images between test and processed images with average ΔE_{00} of 1.3 and 1.4 respectively.

2.3 Verification on a 120Hz 46-inch MVA LCD

The 180Hz Stencil-FSC method was verified on a 120Hz 46-inch MVA LCD. The pictures of *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. Because 180Hz Stencil-FSC method put most image luminance on the first field, the CBU phenomenon was much slighter when compared to the conventional RGB-driving method, as illustrated in Figure 7.



(a) Lily (b) Color Ball

Figure 7. Experimental photos of *Lily* and *Color Ball* using the conventional RGB-driving (top) and 180Hz Stencil-FSC methods (bottom).

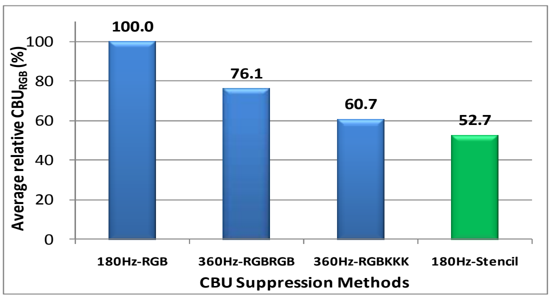


Figure 8. Average relative CBU by different CBU reduction methods and 180Hz Stencil-FSC for eighty test images.

2.4 Comparison with other Reduction Methods

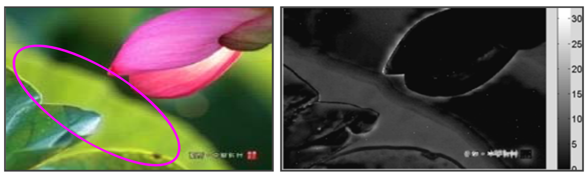
CBU suppression using 180Hz Stencil-FSC was compared to methods of double field rate (360Hz-RGB) and black-fields insertion of 360Hz-RGBKKK using simulations. The field-images of each test image were separated in 60 pixels/frame, and the average *relative CBU* value of eighty test images using these three suppression methods were 76.1%, 60.7%, and 52.7% respectively (Figure 8). Although 360Hz-RGBKKK reduced CBU by 40%; the slow LC response time prevented the 360Hz-RGBKKK from large-sized FSC-LCD applications. In conclusion, the 180Hz Stencil-FSC method was more effective than increasing the field rate, when CBU suppression and hardware implementation were considered.

3. Discussion

However, an issue resulted from only choosing green information as the base color for all images. The issue was especially apparent in the image which contained abundant green information, such as illustrated in the purple circle of Figure 9. To quantify the color distortion, a pixel color distortion (PCD) ratio is given by Eq. 4 which is defined as the ratio of the number of distorted pixels divided by the number of total pixels, where a distorted pixel means that its pixel color difference is larger than the acceptable value (ΔE_{00}>3).

$$PCD \equiv \frac{\#\ of\ color\ \ distorted\ \ pixels}{\#\ of\ total\ \ pixels} \times 100\% \tag{4}$$

For the test image, *Lotus*, its pixel color distortion (PCD) ratios was 40% using green-based concept and reduced green color saturation. As mentioned in section 2.1, the first field LC signals were taken from green color; in this case, the red and blue color LC signals were lower than green LC signals. Therefore, even though the red and blue backlight intensities under the purple circles were low, the red and blue lights also propagated through the first field and contributed redundant luminance resulting in reduction of green color saturation.



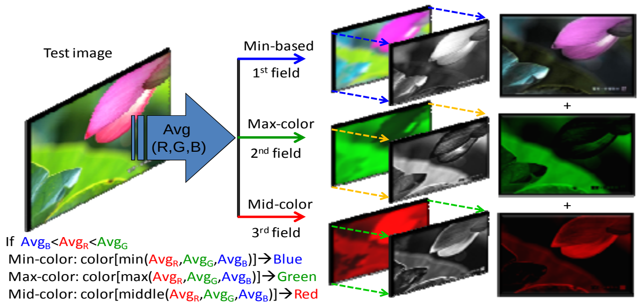
(a) Simulated images (b) Error images

Figure 9. Reduction of green color saturation in the test image, *Lotus*. (a) Simulated image after the 180Hz Stencil-FSC processing and (b) CIEDE2000 error images between test and processed images with PCD ratio of 40%.

To resolve the minor issue of reduction of green color saturation, the 180Hz Stencil-FSC algorithm was further improved. The distortion appeared when the first field LC signal (green LC signal in original algorithm) was not the minimum signal in each single pixel. Then, the redundant residual colors propagated through the first field. The solution was to dynamically choose the base-color for the first field instead of only using green base-color. The first base-color was chosen in accordance with the least color of the test image content. In other words, the green-based field was replaced with the minimum color field (named min-based field). The improved algorithm is shown in Figure 10.

The primary-colors of a test image were averaged first, and then sorted by their magnitudes. Take *Lotus* as an example, the average value of blue color was less than those of red and blue colors. The blue color was inferred the minimum color content with the most minimum pixel value for *Lotus* from the average values sequence. Consequently, the blue color was chosen as the based-color and shown in the first field. The improved algorithm avoided redundant lights and produced higher image fidelity.

The average ΔE_{00} of *Lotus* was further reduced from 2.9 to 0.3, while PCD ratio was simultaneously reduced from 40% to 2.5%. The simulated images are difficult to distinguish from the original images, as shown in Figure 11. Observing the CIEDE2000 error images (Figure 11 (c)), the color difference is almost imperceptible.



(a) (b) (c)

Figure 10. The improved algorithm of the 180Hz Stencil-FSC method. (a) Test image-Lotus, (b) backlight and LC images, and (c) three field-images yielded.

(a) (b) (c)

Figure 11. The improved 180Hz algorithm avoids the redundant lights propagating through the first field-image and maintains image fidelity. (a) The test image, *Lotus*, (b) simulated images after the improved 180Hz Stencil-FSC processing, and (c) CIEDE2000 error images.

4. Conclusion

Using a "multi-color" field image instead of a conventional "single-color" field, we proposed the "180Hz Stencil-FSC" method to suppress the color breakup phenomenon. Using the 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 optimization results, 32x24 backlight divisions suppressed CBU by 50% for eighty test images and made CBU almost imperceptible in experimental photos. Using 180Hz Stencil-FSC, the average image color differences of ΔE_{00} are less than 3. Additionally, the algorithm processing of the 180Hz Stencil-FSC method is also direct and simple, just including backlight determination, liquid crystal compensation, and simple subtraction. As a result, the 180Hz Stencil-FSC LCD is potent for future large-sized "Eco-Display" applications.

Acknowledgements

This work is supported by the NSC in Taiwan for Academic Projects No. NSC96-2221-E009-113-MY3. The authors would like to acknowledge Dr. Chun-Ho Chen and Mr. Ching-Ming Wei, National Chiao Tung University, Hsinchu, Taiwan for their valuable discussion.

References

[1] H. Hasebe and S. Kobayashi, "A full-color field sequential LCD using modulated backlight," *SID Symp. Digest Tech Papers* **16**, pp. 81–83 (1985).

[2] T. Jarvenpaa, et al., "Measuring Color Breakup of Stationary Image in Field-Sequential-Color," *J Soc Info Display* **13**, pp. 139-144 (2005).

[3] K. Sekiya, et al., "A Simple and Practical Way to Cope with Color Breakup on Field Sequential Color LCDs," *SID Symp. Digest Tech Papers* **37**, pp. 1661-1664 (2006).

[4] E. H. A. Langendijk, et al., "Suppression of color breakup in color-sequential multi-primary projection displays," *J. Soc. Info. Display* **14**(3), pp.325-329 (2006).

[5] Y. P. Huang, et al., "Adaptive LC/BL Feedback Control in Field Sequential Color LCD Technique for Color Breakup Minimization," *J. Display Technol.* **4**(3), pp. 290-295 (2008).

[6] C. H. Chen, et al., "A Field Sequential Color LCD Based on Color Fields Arrangement for Color Breakup and Flicker Reduction," *J. Display Technol.* **5**(1), pp. 34-39 (2009).

[7] F. C. Lin, et al., "Color Breakup Suppression and Low Power Consumption by Stencil-FSC Method in Field-Sequential LCDs," *J. Soc. Info. Display* **17**(3), pp. 221-228 (2009).

[8] F. C. Lin, et al., "Color Breakup Suppression and Low Power Consumption by Stencil-FSC Method in Field-Sequential LCDs," accepted by *J. Display Technol.* (2009/6).

[9] F. C. Lin, et al., "Color Breakup Reduction by 180Hz Stencil-FSC Method in Large-Sized Color Filter-Less LCDs," accepted by *J. Display Technol.* (2009/6).

[10] H. Seetzen, et al., "High Dynamic Range Display Systems," *SIGGRAPH 2004, ACM Transactions on Graphics*, **23**(3), pp. 760-768 (2004).

[11] F. C. Lin, et al., "Dynamic Backlight Gamma on High Dynamic Range LCD TVs," *J. Display Technol.* **4**(2), pp. 139-146 (2008).

[12] E. H. A. Langendijk, et al, "Contrast gain and power savings using local dimming backlights," *J. Soc. Info. Display*, **16**, pp. 1237-1242 (2009).

[13] M. R. Luo, et al., "The development of the CIE 2000 colour difference formula," *Color Research and Application*, **26**, pp. 340-350 (2001).