Image Saturation Improvement for 180 Hz Stencil-FSC LCD With Side-Lit LED Backlight

Fang-Cheng Lin, Yi-Pai Huang, Chang-Yi Teng, and Han-Ping D. Shieh

***Abstract*—The green-based 180 Hz Stencil-FSC method was proposed to effectively suppress color breakup for a field-sequential-color liquid crystal display (FSC-LCD). Nevertheless, this method has an issue on green color desaturation. Therefore, we further propose the "limited backlight signal ratio" (LBSR) to determine a proper backlight signal to increase image color saturation and simultaneously suppress color breakup. To realize a thin and high image quality eco-display, in addition, the light spread function model and the number of backlight divisions for a side-lit backlight are optimized and combined with the LBSR stencil-FSC method.**

***Index Terms*—Color breakup, color filter-less, field-sequential color (FSC), light spread function, side-lit, stencil-FSC, Taguchi method.**

I. Introduction

Nowadays, liquid crystal displays (LCDs) are widely applied in our display products because of their high screen resolution, high brightness, light weight, and thin profile. However, conventional LCDs using cold cathode fluorescent lamps backlight are thick and power consuming. Therefore, the development of display technologies aims at thin and low power consumption using locally controllable light-emitting diodes (LEDs) as a backlight module.

A conventional LCD with color filters uses spatial color mixing mechanism to yield full-color images. However, the optical throughput of this kind LCD is between 5%–10% only. In contrast, a field-sequential color (FSC) LCD without color filters is developed by sequentially displaying three primary R, G, and B field-images to yield a full-color image [1]–[3]. Consequently, an FSC-LCD benefits from higher optical throughput, lower material cost, wider color gamut, and three times possibly higher image resolution compared to a color-filter LCD. Besides, a side-lit panel using an LED backlight module is developed to make the panel thinner [4]. The advantages of thinner and lower power consumption LCDs are attractive to consumers and friendlier to our environments.

However, FSC-LCDs suffer from the color breakup phenomenon when there has relative velocity between human eyes and the displayed images [5]. Color breakup causes discomfort and degrades image clarity. In the past years, several color breakup suppression methods have been reported [6]–[16]. Considering the current LC response time, the "green-based 180 Hz Stencil-FSC" method (Fig. 1) was proposed to efficiently suppress color breakup with three fields only [13]. Since human eye is more sensitive to green primary color, the concept of green-based 180 Hz Stencil-FSC displayed high luminance and rough color with whole green information in the first field to yield a "greenish field-image." Consequently, the luminances of the rest red and blue field-images were substantially reduced. When the separated color fields did not contain the pure and high intensity color information, color breakup was suppressed. However, if a displayed image contains plenty of green information, the green color is desaturated while using green-based 180 Hz Stencil-FSC, as shown in Fig. 2. The main reason is due to the backlight signal of the first-field (multi-color field) is determined for minimizing the color breakup. Thus, the red and blue compensated LC signals T'_R or T'_B in Fig. 1(c) might be a negative value, which means too much red or blue light are displayed in the first field and desaturated green color, as shown in Fig. 2.

Therefore, we propose a method, limited backlight signal ratio (LBSR), to determine optimized backlight signals for the first field. By further combining the proposed LBSR method and side-lit multi-color LED backlights, Stencil-FSC is more promising for high image quality and slim large-sized eco-LCD applications.

II. Concept and Algorithm

A. Limited Backlight Signal Ratio (LBSR) Method for Direct-Lit Backlight

To prevent redundant light from propagating to the first field and desaturating green color, the LBSR method is proposed for 180 Hz Stencil-FSC to provide proper backlight signals and avoid redundant colors displaying in the first field and clipping phenomenon [17] in other fields, as shown in Fig. 3.

Utilizing the local color-backlight-dimming technology [18], [19], the signals of backlight and compensated LC are recalculated by (1), where I_i^{full} and $\mathrm{BL}_i^{\mathrm{full}}$ are the luminance of an input image and a full-on backlight, respectively. T_i^{full} and T_i are each R, G, and B sub-pixels transmittance of an input image and a compensated image while locally dimming the color backlight. To prevent the clipping effect and redundant light from displaying in the first field, green backlight signals are determined by the maximum T_i^{full} of each backlight division, as shown in (2-1). The compensated LC signals are calculated by

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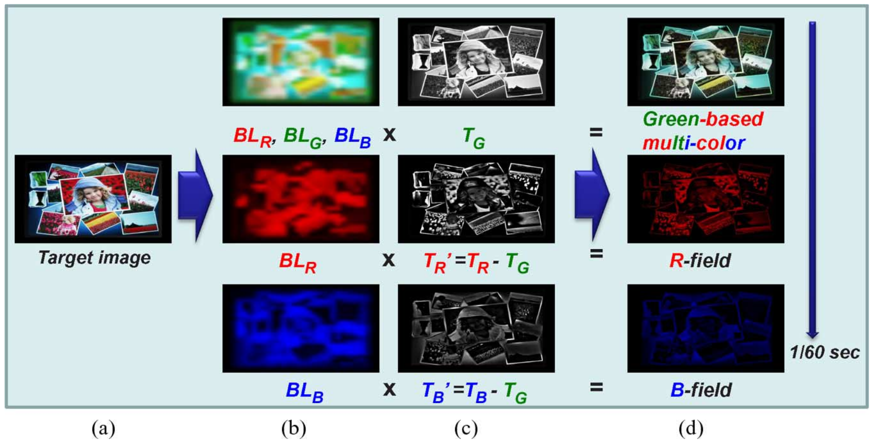


Fig. 1. Green-based 180 Hz Stencil-FSC algorithm [13]. (a) Target image, girl (©Microsoft). (b) Backlight images. (c) LC signals. (d) Three yielded field images.

TABLE I
FORMULA OF LIMITED BACKLIGHT SIGNAL RATIO METHOD
(WHERE BL_R AND BL_B ARE THE SIGNALS OF RED AND BLUE BACKLIGHT LUMINANCE IN EACH BL DIVISION)

	Criteria	BL Signal	Equation
R	$0 \le T'_R = T_R - T_G \le 1$	$\frac{T_R^{full}}{1+T_G^{full}/BL_G} \le BL_R \le \frac{T_R^{full}}{T_G^{full}} \times BL_G$	(3-1)
B	$0 \le T'_B = T_B - T_G \le 1$	$\frac{T_B^{full}}{1+T_G^{full}/BL_G} \le BL_B \le \frac{T_B^{full}}{T_G^{full}} \times BL_G$	(3-2)

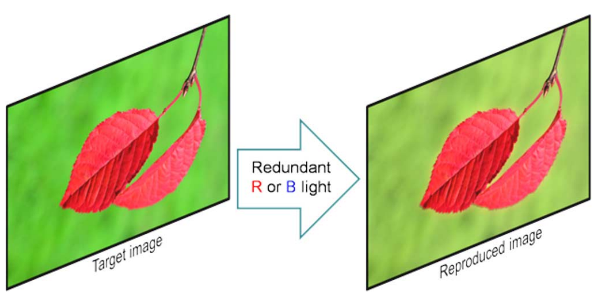


Fig. 2. Redundant red and blue colors propagate through the first field resulting in green color desaturation while using green-based 180 Hz Stencil-FSC.

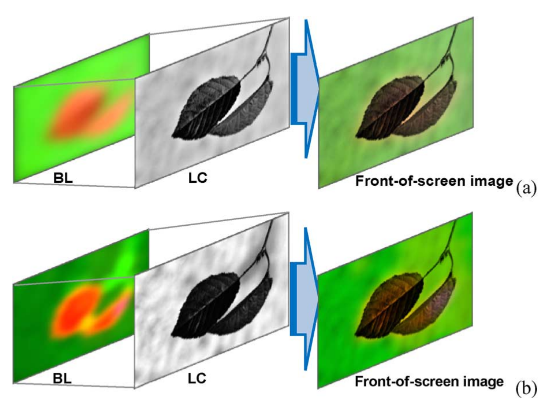


Fig. 3. Two backlight images, LC driving signals, and front-of-screen images for the first field of a test image-*Red Leaf*, using: (a) original green-based and (b) proposed LBSR Stencil-FSC methods.

(2-2), which guarantees that all green information can be displayed in the first field with less compensated LC signals

$$I_i^{\mathrm{full}} = I_i \rightarrow \mathrm{BL}_i^{\mathrm{full}} \times T_i^{\mathrm{full}} = \mathrm{BL}_i \times T_i, \quad i = \mathrm{R,G,B} \quad (1)$$

$$\mathrm{BL}_G = \max\left(T_G^{\mathrm{full}}\right) \quad (2\text{-}1)$$

$$T_G = \frac{\mathrm{BL}_G^{\mathrm{full}}}{BL_G} \times T_G^{\mathrm{full}} = \frac{T_G^{\mathrm{full}}}{\mathrm{BL}_G} \quad (2\text{-}2)$$

where $\mathrm{BL}_i^{\mathrm{full}} = 1$ (conventional full-on backlight signals), BL_G is the green backlight signal using LBSR in each BL division, and T_G is the compensated LC signal of each green sub-pixel.

Using the LBSR Stencil-FSC method, the new LC signals of the second and third fields, T'_R and T'_B, were derived the same as those in green-based Stencil-FSC as shown in Fig. 1(c). To prevent T'_R or T'_B from being a negative value which denotes redundant light results in green color desaturation, the T'_R and T'_B should be larger than zero. Meanwhile, to prevent the clipping phenomenon, the T'_R and T'_B should be equal or smaller than one. Therefore, the backlight signals are derived by the relationships of the formula in (3-1) and (3-2), as shown in Table I.

B. LBSR for Side-Lit LED Backlight

Comparing direct-lit with side-lit backlight types, the side-lit backlight is promising to make panel thinner. A side-lit light spread function (LSF) model is essential to simulate the light intensity distribution for each backlight division. Different from a direct-lit type using a 2D Gaussian LSF [13], the proposed side-lit LSF model used one horizontal Gaussian profile

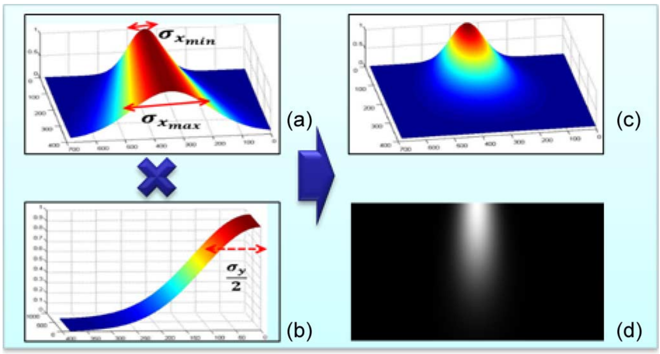


Fig. 4. Different axes intensity distribution of a side-lit LSF using (a) Gaussian profile with various standard deviation σ_x in horizontal direction and (b) half Gaussian profile in vertical direction. Intensity distribution of a side-lit LSF (c) mesh LSF and (d) illustration of a side-lit LED backlight spreading.

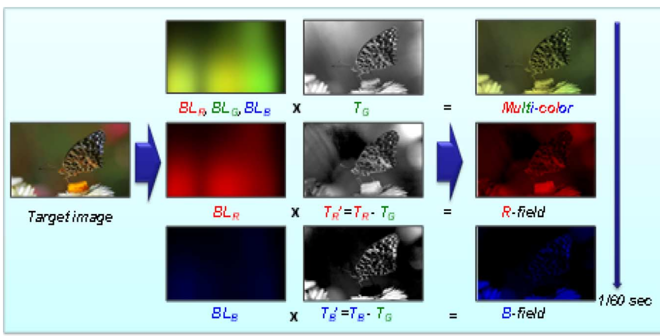


Fig. 5. Side-lit 180 Hz LBSR Stencil-FSC algorithm.

TABLE II
PARAMETERS OF A SIDE-LIT LSF WITH FIVE LEVELS OF EACH FACTOR (% OF PANEL WIDTH)

Level / Factor	1	2	3	4	5
σXmin	1.6%	3%	5%	7%	9%
σXmax	1.1 x σXmin	1.3 x σXmin	1.5 x σXmin	1.7 x σXmin	1.9 x σXmin
σY	20%	25%	30%	35%	40%

with various standard deviation σ_x (4-1), and multiplied a half Gaussian profile in y-direction (4-2) to simulate a side-lit dispersed light, where x and y represent the width and height of a panel (in an unit of pixels), respectively. An LSF of a side-lit LED backlight is given and shown in Fig. 4. Consequently, combining the LBSR method with a side-lit LSF in the algorithm, as shown in Fig. 5, the Stencil-FSC is more promising for a slim color filter-less LCD.

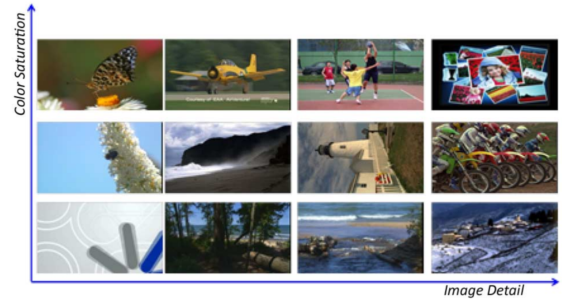
$$G_{\text{horizontal}}(x,y) = \sum_{\sigma_x=\sigma_{x\min}}^{\sigma_x=\sigma_{x\max}} \exp\left(-\left(\frac{x^2+y^2}{2\sigma_x^2}\right)\right) \quad \text{(4-1)}$$

$$G_{\text{vertical}}(x,y) = \exp\left(-\left(\frac{x^2+y^2}{2\sigma_y^2}\right)\right). \quad \text{(4-2)}$$

According to (4-1) and (4-2), the parameters $\sigma_{x\min}$, $\sigma_{x\max}$, and σ_y were optimized and modulated to change the intensity

a (row)	2							
b (column)	1	4	8	16	24	32	48	64

(a)



(b)

Fig. 6. (a) 8 simulated backlight divisions; (b) 12 test images: *Butterfly** (*: taken by Jacky Lee, http://jac3158.com/blog), *Aircraft*, *Basketball*, *Girl*©Microsoft, *Flower*, *Coast*, *Lighthouse*, *Racing*, *Pattern*, *Wood*, *Ocean*, and *Snow*.

distribution of an LSF. Table II lists each factors of an LSF with five levels which are chosen to be satisfied the luminance uniformity being larger than 80% for a backlight panel requirement [20]. The luminance uniformity requirement is calculated by (5)

$$\text{Uniformity} = \frac{\{\text{Min.}\,(\text{Lum.}(i))\,|i=1\sim 25\}}{\{\text{Max.}\,(\text{Lum.}(i))\,|i=1\sim 25\}} \times 100\% \geq 80\%. \quad (5)$$

Using a parameter-design of the Taguchi method [21], the L_{50} ($2^1 \times 5^{11}$) table of an orthogonal array was utilized to determine the optimal hardware parameters in the simulation. The analytical standard is to find the largest signal-to-noise (SN) ratio of the larger-the-better characteristic defined as (6) in the Taguchi method

$$\text{SN} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (6)$$

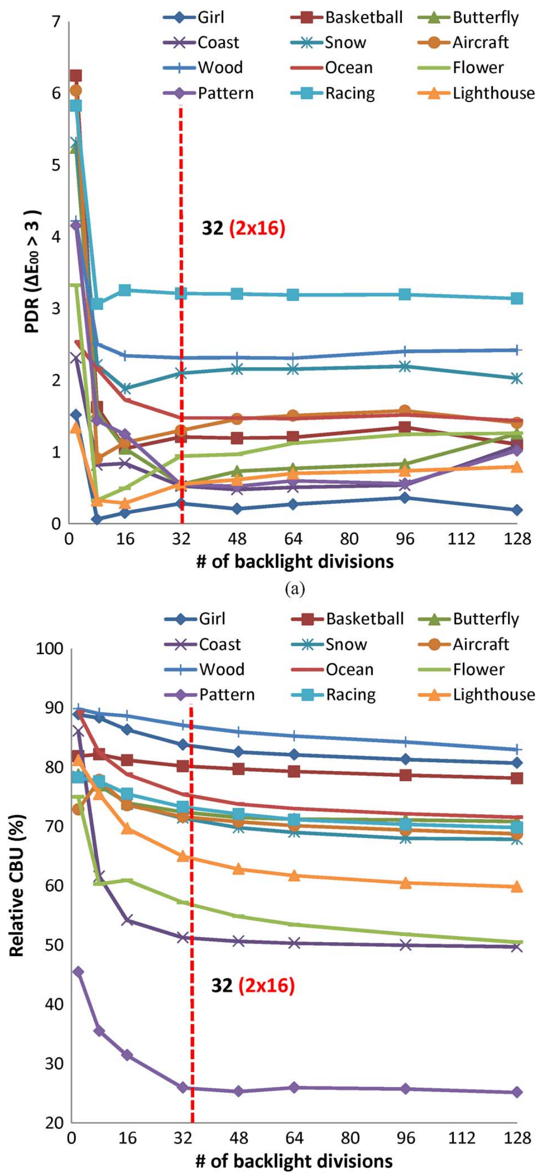
where y_i is the percentage of ΔE_{00} less than 3 which means an acceptable color difference to human eye [22], [23].

III. OPTIMIZATION AND SIMULATION

The maximum number of LEDs used in the simulation was supposed to be 128 pcs, and the maximum backlight division was supposed to be 2 (top-down) by 64 (left-right) [see Fig. 6(a)], which meant the maximum division was 128 with 1 pcs LED in each division. Twelve images with different color saturation and image detail were tested, as shown in Fig. 6(b).

A. Evaluation Indices

The color difference of CIEDE2000 (ΔE_{00}) was calculated to evaluate the image fidelity and color breakup reduction. To quantify the image distortion, a pixel distortion ratio, PDR($\Delta E_{00} > 3$), is defined by (7). PDR is a 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 an acceptable threshold value, $\Delta E_{00} = 3$ [22], [23]. The less PDR represents the higher image fidelity. Additionally, after summing up ΔE_{00} of each pixel between a test image and its color breakup image ($\Sigma\Delta E_{00}$), a *relative CBU* index



(a)

(b)

Fig. 7. Simulation results using the 12 test images of the number of backlight divisions versus (a) pixel distortion ratio (PDR) and (b) *relative CBU*. (a) Image distortion. (b) Color breakup reduction.

is defined as the ratio of total color difference between $a \times b$ backlight divisions and the conventional RGB-driving method, as shown in (8); the less value represents the less color breakup

$$\mathrm{PDR}(\Delta E_{00} > 3) \equiv \frac{\#\text{ of color distorted pixels}}{\#\text{ of total pixels}} \times 100\% \quad (7)$$

$$\text{relative CBU} = \frac{\sum \Delta E_{00}(\text{Target}, \text{Side} - \text{lit})_{a*b}}{\sum \Delta E_{00}(\text{Target}, \text{RGB}_{\text{driving}})} \times 100\% \quad (8)$$

where a, b is the number of backlight divisions.

B. Optimization and Simulation Results

The optimization results are shown in Fig. 7, both image distortion and color breakup reduction reach asymptotic end values at 2×16 backlight divisions in these 12 various test images. To effectively maintain image fidelity and suppress color breakup, therefore, the optimal backlight division was 2×16 using the proposed LBSR method on a side-lit backlight module. The optimal side-lit LSF parameters of a backlight division were determined to satisfy a uniformity of 91%, as shown in Table III.

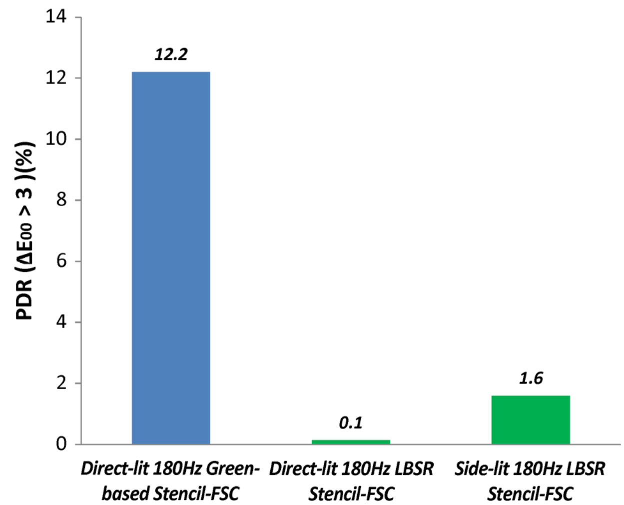


Fig. 8. Comparison of PDR between direct-lit green-based and proposed LBSR methods in direct-lit and side-lit Stencil-FSC methods.

TABLE III
OPTIMAL LSF HARDWARE PARAMETERS OF THE SIDE-LIT BACKLIGHT DIVISION

Optimal Hardware Parameters	BL division	$\sigma_{x_{min}}$	$\sigma_{x_{max}}$	σ_y	Uniformity
	32 (2x16)	3%	5%	20%	91%

Using the optimized LSF and 2×16 backlight divisions, the proposed side-lit LBSR Stencil-FSC is compared to direct-lit (24×32 backlight divisions) green-based and LBSR Stencil-FSC methods. Here, the LSFs of both direct-lit Stencil-FSC are assumed a Gaussian profile with $\sigma_x = 46$ pixels and $\sigma_y = 26$ pixels, respectively. From Fig. 8, the average PDRs of side-lit and direct-lit LBSR are as low as 1.6% and 0.1%, respectively. The data are much less than that of using the green-based Stencil-FSC method (12.2%). Furthermore, a plenty of green information image, *Red Leaf*, was simulated as shown in Fig. 9. The ΔE_{00} images using LBSR are much darker than that of using green-based Stencil-FSC. In ΔE_{00} histograms, the larger ΔE_{00} distribution using green-based Stencil-FSC is much reduced and redistributed at the lower ΔE_{00} region when using the LBSR Stencil-FSC methods. In other words, the proposed LBSR method can greatly improve the color distortion.

For color breakup suppression, additionally, the proposed LBSR in direct-lit and side-lit Stencil-FSC methods reduce *relative CBU* to 57.3% and 64.4%, respectively. The CBU suppression is slightly less than that of using the green-based Stencil-FSC method (average $relative\ CBU = 52.6\%$), as shown in Fig. 10. The reason is the red and blue luminance in the first field using the proposed method is less than that of the green-based method. These results in higher luminance

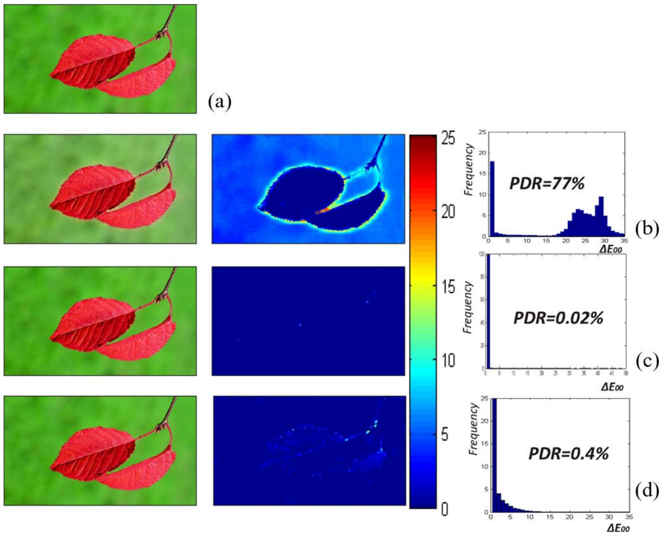


Fig. 9. Simulation results of image fidelity. (a) Target image *Red Leaf*. FSC images, distortion images and histograms of CIEDE2000 by the three modes of Stencil-FSC methods: (b) direct-lit green-based, (c) direct-lit LBSR, and (d) side-lit LBSR.

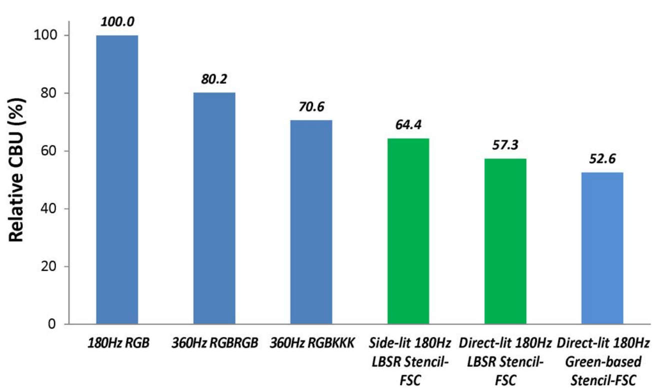


Fig. 10. Comparison *relative CBU* between prior color breakup suppression methods (RGBRGB [8], RGBKKK [8], and direct-lit green-based Stencil-FSC [13]) and the proposed LBSR methods in direct-lit and side-lit Stencil-FSC methods.

displaying in the rest red and blue fields. Therefore, the color breakup is less suppressed but is still acceptable from the experimental photos verified on a 120-Hz 46-inch LCD as discussed in next section.

IV. Experimental Results

Since a 180 Hz side-lit color filter-less LCD was lacked, the proposed method was emulated by flashing three field-images on a 120 Hz 46-inch MVA LCD, i.e., with a frame rate of 40 Hz, as shown in the left images of Fig. 11. Color breakup images were captured by a shaking camera to simulate eye movement, and the exposure time of the camera was set to 1/40 seconds to capture a complete frame image. Using this emulation, since the exposure time of the camera was set to 1/40 seconds which was correspondence to the frame rate to capture a complete frame image, the color breakup result would be almost the same compared to a real 180 Hz color filter-less LCD without considering the LC response time. If the LC response time is insufficient for a 180 Hz field rate (with the same frame rate), the color saturation will be decreased (lower image quality) and less color breakup is seen.

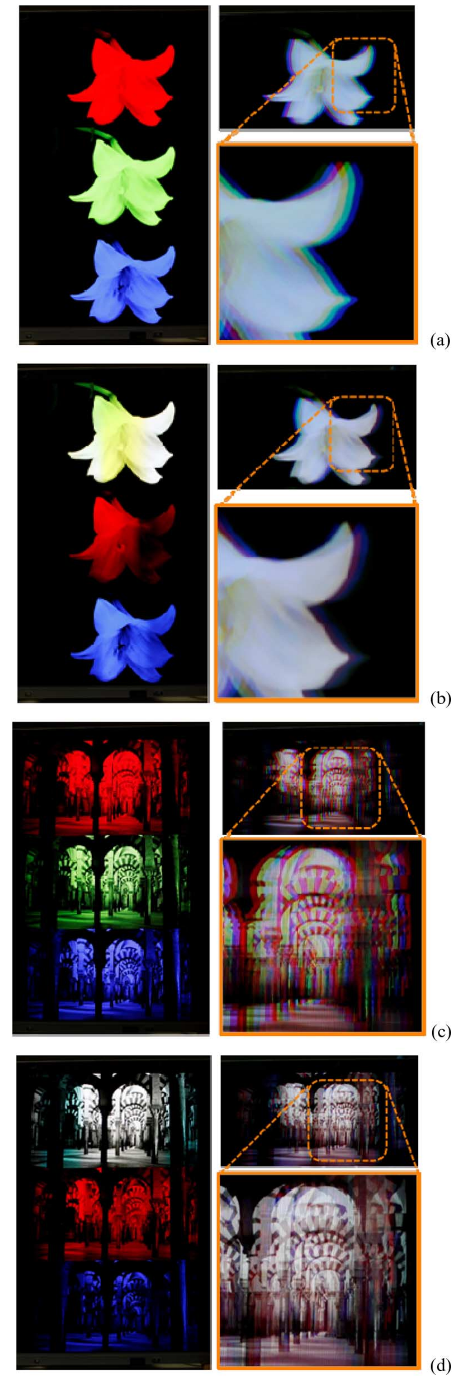


Fig. 11. Three field-images (left) and experimental color breakup photos (right). *Lily* and *Gallery* using (a), (c) the conventional RGB-driving method and (b), (d) the side-lit LBSR Stencil-FSC method.

Using the proposed side-lit LBSR Stencil-FSC method, color breakup was effectively suppressed compared to using the conventional RGB-driving method. Moreover, utilizing the LBSR method in the direct-lit Stencil-FSC algorithm, the color breakup reduction was also better than that in side-lit condition because of the more flexibility of the backlight divisions, as shown in Fig. 12. Therefore, we concluded that the proposed

TABLE IV
COMPARISON BETWEEN THE DIRECT-LIT GREEN-BASED STENCIL-FSC METHOD AND LBSR STENCIL-FSC IN DIRECT-LIT AND SIDE-LIT TYPES

Features \ Methods	Direct-lit			Side-lit
	RGB-driving	Green-based Stencil-FSC	LBSR Stencil-FSC	LBSR Stencil-FSC
Panel thickness (mm)	~30			<10
Backlight divisions	1× 1 (Global)	24× 32	24× 32	2× 16
Image fidelity [PDR(ΔE_{00}>3), %]	0 (good)	12.2 (acceptable)	0.1 (good)	1.6 (good)
Relative CBU (%)	100	52.6	57.3	64.4
Power consumption* (W)	76	52	23	38

* Evaluated using the video of IEC 62087 for a 65-inch LCD

Note: Power consumption of a 65-inch white light LED backlight LCD is around 150 W

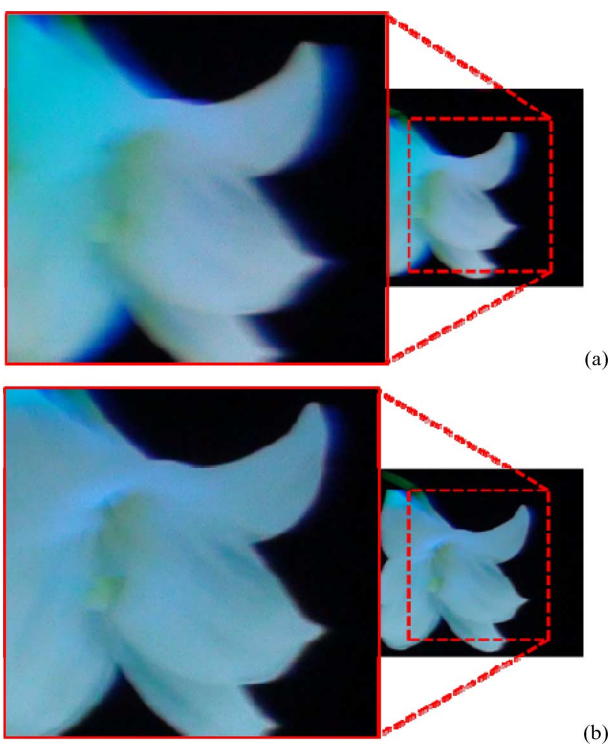


Fig. 12. Experimental color breakup photos of LBSR method in: (a) side-lit and (b) direct-lit Stencil-FSC methods.

LBSR method in direct-lit and side-lit Stencil-FSC methods well maintained image fidelity and effectively suppressed color breakup simultaneously.

To evaluate the power consumption of the LBSR method, the IEC: 62087 video (around 10 min long) was utilized. The power consumptions of all frames were computed according to driving values of backlight signals. From the calculating results in Fig. 13, the average power consumption of the direct-lit green-based, direct-lit LBSR, and side-lit LBSR Stencil-FSC methods were 52, 23, and 38 W, respectively. The average power consumptions of the direct-lit and side-lit LBSR Stencil-FSC methods were lower because the determined backlight signals in the second and the third fields of the LBSR method were lower than those of using the direct-lit green-based Stencil-FSC method.

Finally, the characteristics of direct-lit green-based, direct-lit LBSR, and side-lit LBSR Stencil-FSC methods are summarized in Table IV. The panel thickness of the proposed side-lit method was promising less than 10 mm with only 2×16 backlight divisions. The side-lit LBSR method much reduced image distortion to a $\mathrm{PDR}(\Delta E_{00} > 3)$ of 1.6%. It also further saved around 20% power consumption compared to green-based Stencil-FSC. From the experimental photos, color breakup was also well suppressed. Therefore, the proposed LBSR method is good to be applied on the Stencil-FSC concept.

V. CONCLUSION

We proposed a thin and low power consumption side-lit technology on a color filter-less LCD. To prevent redundant light and clipping phenomenon while using the green-based 180 Hz Stencil-FSC method, the limited backlight signal ratio (LBSR) method was proposed to further improve the image quality and simultaneously suppress color breakup. Additionally, the model of a side-lit LED light spread function (LSF) was utilized to simulate the intensity distribution of a slim LED backlight. From simulation results, the optimal backlight divisions was 2 × 16 and the LSF parameters were obtained as $\sigma_{x\,\min} = 3\%$, $\sigma_{x\,\max} = 5\%$, $\sigma_y = 20\%$ of panel width and reached a 91% backlight luminance uniformity. The proposed method improved image fidelity by more than a factor of 7 compared to prior green-based 180 Hz Stencil-FSC. Color breakup was almost imperceptible via experimental results as well. Moreover, the average power consumption was 38 W only which was equipment to 50% of a conventional RGB-driving FSC-LCD. As a result, the novel LBSR method applied on a side-lit 180 Hz Stencil-FSC is promising for slim eco-display applications.

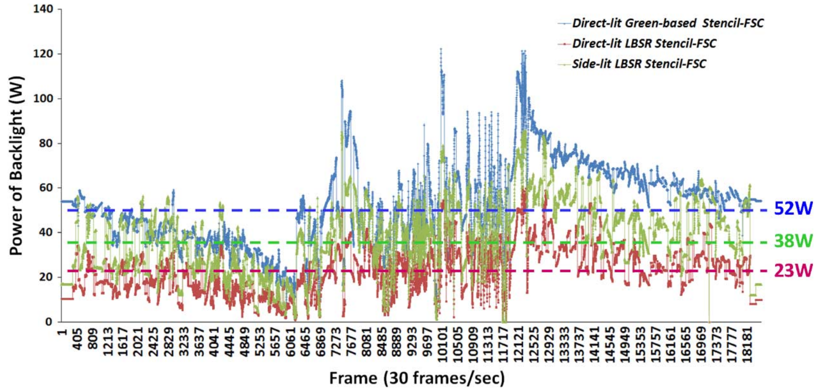


Fig. 13. Evaluated backlight power consumption of each frame using the IEC: 62087 video for three color breakup suppression methods.

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REFERENCES

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

[2] T. Miyashita *et al.*, "Wide-viewing-angle display mode for active-matrix LCDs using a bend-alignment liquid-crystal cell," *J. Soc. Inf. Display*, vol. 3, no. 1, pp. 29–34, 1995.

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

[4] H. G. Hulze *et al.*, "Power savings by local dimming on a LCD panel with side lit backlight," in *SID Symp. Dig. Tech. Papers*, 2009, vol. 15, pp. 749–752.

[5] T. Järvenpää, "Measuring color breakup of stationary image in field-sequential-color," *J. Soc. Inf. Display*, vol. 13, pp. 139–144, 2005.

[6] P. C. Baron *et al.*, "Can motion compensation eliminate color breakup of moving objects in field-sequential color displays?," in *SID Symp. Dig. Tech. Papers*, 1996, vol. 27, pp. 843–846.

[7] E. H. A. Langendijk *et al.*, "Suppression of color breakup in color-sequential multi-primary projection displays," *J. Soc. Inf. Display*, vol. 14, no. 3, pp. 325–329, 2006.

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

[9] Y. P. Huang, K.-H. Chen, C.-H Chen, F.-C. Lin, and H.-P. D. Shieh, "Adaptive LC/BL feedback control in field sequential color LCD technique for color breakup minimization," *J. Display Technol.*, vol. 4, no. 3, pp. 290–295, Sep. 2008.

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

[11] F. C. Lin *et al.*, "Color breakup suppression and low power consumption by stencil-FSC method in field- sequential LCDs," *J. Soc. Inf. Display*, vol. 17, no. 3, pp. 221–228, Mar. 2009.

[12] F. C. Lin, Y.-P. Huang, C.-H. Wei, and H.-P. D. Shieh, "Color filter-less LCDs in achieving high contrast and low power consumption by stencil field-sequential-color method," *J. Display Technol.*, vol. 6, no. 3, pp. 98–106, Mar. 2010.

[13] F. C. Lin, Y.-P. Huang, and H.-P. D. Shieh, "Color breakup reduction by 180 Hz stencil-FSC method in large-sized color filter-less LCDs," *J. Display Technol.*, vol. 6, no. 3, pp. 107–112, Mar. 2010.

[14] H. C. Cheng, L. Rao, and S.-T. Wu, "Color breakup suppression in field-sequential five-primary-color LCDs," *J. Display Technol.*, vol. 6, no. 6, pp. 229–234, Jun. 2010.

[15] F. C. Lin, Y. Zhang, and E. H. A. Langendijk, "Color breakup suppression by local primary desaturation in field-sequential color LCDs," *J. Display Technol.*, vol. 7, no. 2, pp. 55–61, Feb. 2011.

[16] Y. Zhang, F. C. Lin, and E. H. A. Langendijk, "A field sequential color display with local primary desaturation backlight scheme," *J. Soc. Inf. Display*, vol. 17, no. 3, pp. 242–248, 2011.

[17] L. Kerofsky and S. Daly, "Brightness preservation for LCD backlight dimming," *J Soc Inf Display*, vol. 14, pp. 1111–1118, 2006.

[18] H. Seetzen *et al.*, "High dynamic range display systems," *SIGGRAPH, ACM Trans. Graphics*, vol. 23, no. 3, pp. 760–768, 2004.

[19] F. C. Lin, Y.-P. Huang, L.-Y. Liao, H.-P. D. Shieh, T.-M. Wang, and S.-C. Yeh, "Dynamic backlight gamma on high dynamic range LCD TVs," *J. Display Technol.*, vol. 4, no. 2, pp. 139–152, Jun. 2008.

[20] K. H. Tang *et al.*, "The development of luminance uniformity measurement for CNT-BLU based on human visual perception," *J. Chinese Inst. Ind. Engineers*, vol. 28, no. 3, pp. 179–191, 2011.

[21] Y. Q. Zheng*, Theory and Practice of Taguchi Method*, 2nd ed. Taipei, Taiwan: Chinese Society for Quality, 1988.

[22] G. Sharma *et al.*, "The CIEDE2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations," *Color Res. Appl.*, vol. 30, no. 1, pp. 21–30, 2005.

[23] Y.-K. Cheng, Y.-P. Huang, Y.-R. Cheng, and H.-P. D. Shieh, "Two-field scheme: Spatio-temporal modulation for field sequential color LCDs," *J. Display Technol.*, vol. 5, no. 10, pp. 385–390, Oct. 2009.

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