High-Image Reproduction by the Low-Field-Rate Stencil-LPD Method for Field-Sequential-Color LCDs

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***Abstract*—Color breakup is a lethal issue to conventional field-sequential-color LCDs. Several methods have been proposed to solve this problem. However, these solutions are either more than 180 Hz—the currently used LC mode is not sufficiently fast for this field rate—or they degrade the image quality while using a field rate of 120 Hz. To overcome these limitations, a 120 Hz Stencil Local Primary Desaturation, Stencil-LPD, is presented in this work. The 120 Hz Stencil-LPD method provides reduced but sufficient saturated backlight color to precisely present an image with less color distortion or color breakup. After optimizing a number of backlight segments, the experimental results demonstrate that the image fidelity is significantly improved and color breakup is greatly suppressed compared to the existing methods.**

***Index Terms*—color breakup, field-sequential-color, FSC, local-primary-desaturation, LPD, stencil.**

I. INTRODUCTION

CONVENTIONAL color-filter-type liquid crystal displays (LCDs) suffer from high power consumption. In contrast to conventional LCDs, a field-sequential-color (FSC) LCD sequentially flashes red, green and blue field-images to form a full-color image without color filters [1]–[4]. Therefore, it has higher optical throughput, higher resolution, and lower power consumption. Hence, FSC-LCDs are more promising as next generation eco-displays.

Although FSC-LCDs have many advantages, they also have a significant limitation, namely, the color breakup phenomenon. Color breakup is caused by the relative movement between the human eye and the displayed image [5]. Color breakup degrades the image quality and leads to discomfort in human eyes. Several solutions for this problem have been proposed under the multi-field driving scheme [6]–[11]. Alternatively, the 240 and 180 Hz Stencil-FSC method [12]–[16] gathers the most luminance in a multi-color field and reduces the luminance of the residual field-image to successfully suppress color breakup. The local primary desaturation (LPD) method proposed by Phillips [17], [18] also provides less but sufficient saturated primary backlight signals to reduce the color difference between each of the two fields to effectively prevent color breakup. Before a rapid response liquid crystal, such as blue-phase [19], [20], is developed for commercialization, a low-field-rate FSC-LCD should be developed.

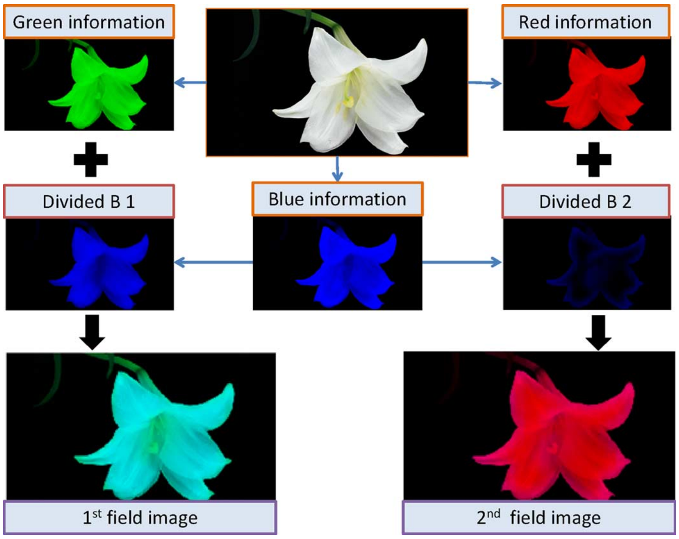

Fig. 1. Concept of the Two-Color-Field method [23].

Considering the current commercial LC response time, a 120 Hz driving scheme has more potential to be implemented. Therefore, some two-field-driving methods were further proposed. The first idea was to apply two specific color filters to two fields (2F2CF) such that the image would not be distorted because of the lack of degree of freedom [21]. However, the most significant issue, color breakup, arises with the full-color gamut display. Therefore, Yuning *et al.* implemented the LPD concept on the 2F2CF to successfully prevent color breakup [22].

Although 120 Hz-related methods have performed well for color breakup suppression, the need for color filters still limits the optical throughput, which in turn constrains power reduction. Thus, this work focuses on those methods without color filters. Cheng *et al.* proposed the Two-Color-Field method, which divided the least information of the primary colors into two parts, as shown in Fig. 1 [23]. The divided primary was then combined with the other two primary color fields as backlight signals. In this manner, severe image distortion would occur because some parts of color cannot be displayed. Using the

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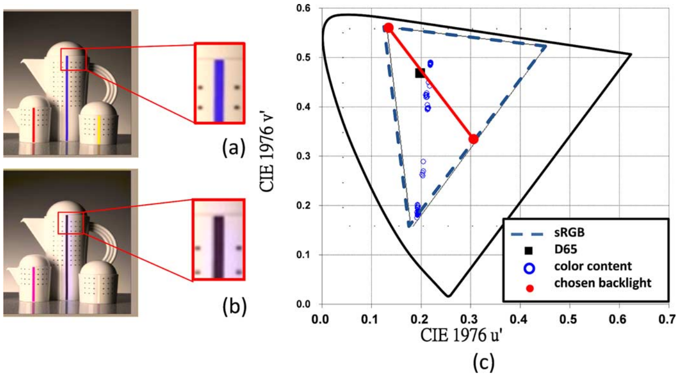


Fig. 2. Teapot image with: (a) the original image; (b) the reproduced image using the Two-Color-Field method; and (c) the chromaticity distribution of the magnified part of (a) in the CIE1976 u′v′ color space.

teapot image as an example, Fig. 2 shows the chromaticity distribution of a single segment, i.e., the enlarged part. The blue string on the teapot image was distorted. Moreover, the color breakup issue was not suppressed well because the Two-Color-Field method applied the primaries with the maximum display gamut, as shown by the red dots in Fig. 2(c).

Therefore, this paper proposes a Stencil Local Primary Desaturation, Stencil-LPD, method driving at a field rate of 120 Hz to both maintain the image fidelity and suppress color breakup without using color filters. The 120 Hz Stencil-LPD method provides proper backlight signals that contain a sufficient amount of color information of each backlight segment to precisely display the target image. The results of precisely reproduced images, including image fidelity and color breakup will be presented. The optimization of the backlight segments is also discussed.

II. CONCEPT AND ALGORITHM

The idea of the 120 Hz Stencil-LPD method comes from both the LPD method and Stencil-FSC method [24], [25]. Apparent from the previous Two-Color-Field FSC-LCDs that apply the primary colors on the maximum gamut of display, the backlight signals are chosen according to the color content of each backlight segment. In contrast to the LPD, this method shows the most represented colors instead of desaturated primary colors. In this case, multiple colors with the majority of the color information are displayed in a single field instead of monocolor without color filters. Less color information is sacrificed using the 120 Hz Stencil-LPD method compared to the previous Two-Color-Field method.

The algorithm is then divided into two parts, namely, backlight determination and LC calculation, as presented in Fig. 3. In this work, all of the input color information is transferred from sRGB, $(\mathrm{RGB})_0$, of which gamma is 2.2 with D65 as the white point, to tri-stimulus values in the CIEXYZ color space as the target signals, $(\mathrm{XYZ})_0$, using

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix}_{sRGB2XYZ} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{linear}} \tag{1}$$

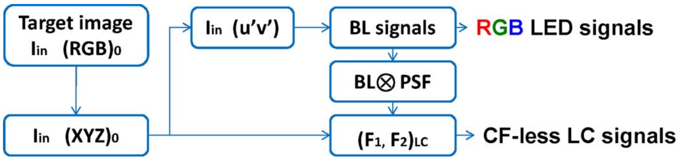
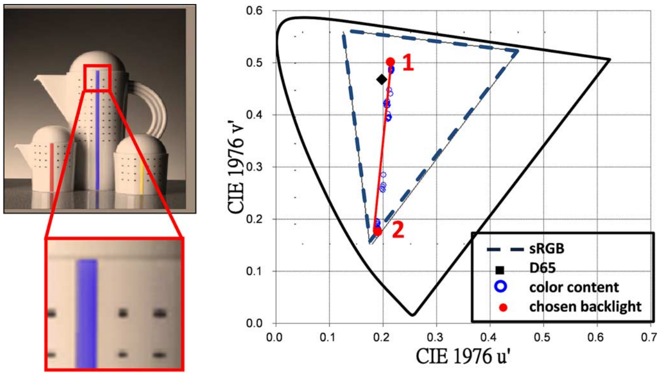


Fig. 3. Flowchart of the 120 Hz Stencil-LPD method.



(a) (b)

Fig. 4. Proposed 120 Hz Stencil-LPD method. (a) Reproduced image of a teapot. (b) Pixel chromaticity distribution on the CIE 1976 u′v′ color space.

A. Backlight Determination

To determine the most represented colors to be used as backlight signals, the chromaticity of each pixel was plotted on the CIE1976 u′v′ uniform color diagram as the blue circle shown in Fig. 4. Therefore, the information trend of every color can be obtained by the distribution. The tendency of the color content has been established according to the regression formula presented below; the two most represented colors are then determined as the backlight signals in a single backlight segment

$$L : m \times u' + v' - c = 0, \tag{2}$$

where $m = \sum_{i=1}^{n}\left(u'_i - \overline{u'}\right)\left(v'_i - \overline{v'}\right)/\sum_{i=1}^{n}\left(u'_i - \overline{u'}\right)^2$ *is the slope of the calculated regression line and* $c = \overline{v'} + m \times \overline{u'}$ *is the constant that causes the regression line to meet the distribution of chromaticity.*

The chromaticity of each pixel is viewed as a coordinate set, $(\mathrm{u'}, \mathrm{v'})$, on the color diagram, and the regression line is denoted by L. Colors among the connected line between the two chosen colors, points 1 and 2 shown in Fig. 4, can now be displayed. Compared to Fig. 2 using the previous Two-Color-Field, the backlight colors using the proposed 120 Hz Stencil-LPD method are considerably closer to the image content for the two-field images.

B. LC Calculation

After determining the backlight colors and calculating the backlight intensity distribution by BL $\otimes$ PSF, as shown in Fig. 3, the backlight intensity distribution was also transferred to the CIEXYZ color space to calculate the compensated LC signals. The relationship among the target $(\mathrm{X}_0, \mathrm{Y}_0$, and $\mathrm{Z}_0)$, the

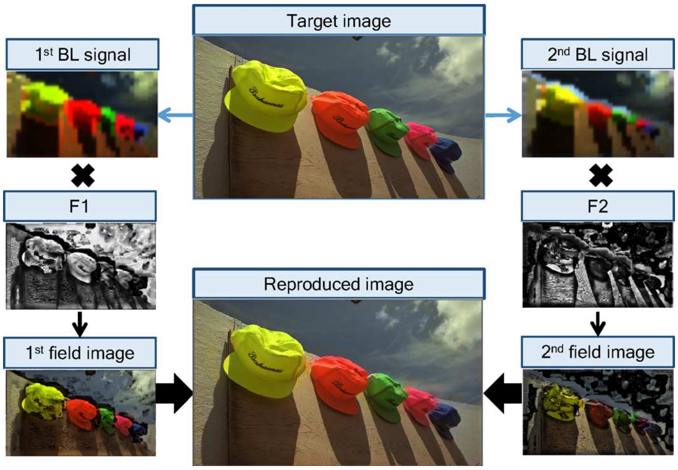


Fig. 5. Driving scheme of the proposed 120 Hz Stencil-LPD method, including a target image of hats, images of the backlight signals and LC signals and reproduced images of the two-field images.

backlight contribution $((\mathrm{XYZ})_1, (\mathrm{XYZ})_2)$, and the LC signals $(\mathrm{F}_1, \mathrm{F}_2)$ of the two fields are shown in (3).

$$\begin{bmatrix} \mathrm{X}_0 \\ \mathrm{Y}_0 \\ \mathrm{Z}_0 \end{bmatrix}_{\text{Target}} = \begin{bmatrix} \mathrm{X}_1 & \mathrm{X}_2 \\ \mathrm{Y}_1 & \mathrm{Y}_2 \\ \mathrm{Z}_1 & \mathrm{Z}_2 \end{bmatrix}_{\text{BL}} \begin{bmatrix} \mathrm{F}_1 \\ \mathrm{F}_2 \end{bmatrix}_{\text{LC}}$$

$$\Rightarrow \begin{bmatrix} \mathrm{F}_1 \\ \mathrm{F}_2 \end{bmatrix}_{\text{LC}} = \begin{bmatrix} \mathrm{X}_1 & \mathrm{X}_2 \\ \mathrm{Y}_1 & \mathrm{Y}_2 \\ \mathrm{Z}_1 & \mathrm{Z}_2 \end{bmatrix}_{\text{BL}}^{-1} \begin{bmatrix} \mathrm{X}_0 \\ \mathrm{Y}_0 \\ \mathrm{Z}_0 \end{bmatrix}_{\text{Target}}. \quad (3)$$

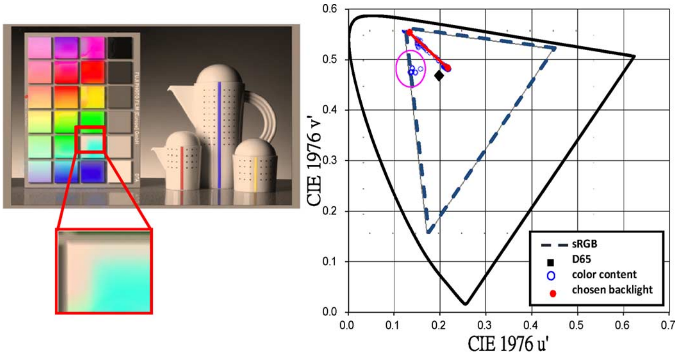
A problem arises because no particular inverse matrix in linear algebra exists for a 3×2 matrix of the backlight distribution with tri-stimulus. Hence, the least squares method was utilized to determine the signals with the minimum error.

By synchronously displaying the LC signals of the first field (F_1) with the first backlight signals and the LC signals of the second field (F_2) with the second backlight signals, the reproduced image can now be displayed with less distortion and color breakup, as shown in Fig. 5. Using the 120 Hz Stencil-LPD method, the backlight module provides the most significant colors and modulates the LC signals to retain the details of the image.

C. Optimization of the Number of Backlight Segments

Although the 120 Hz Stencil-LPD method could effectively help the reproduced image avoid large image distortion by choosing proper backlight signals, slight distortion may remain because a two-field driving scheme lacks the third degree of freedom to display all of the information. As shown in Fig. 6, when an excessive amount of image content appears in a single backlight segment, some colors cannot be displayed, which causes distortion. The number of backlight segments to reproduce the image shown in Fig. 6 was 32, ×24 with an image resolution of 1920×1080.

The best technique to solve this problem is to increase the number of backlight segments such that the content of each segment can be reduced. However, increasing the number of backlight segments increases the cost and computation complexity of the display. The number of backlight segments should be optimized considering the tradeoff between image quality and the cost of hardware loading.



(a) (b)

Fig. 6. (a) Distortion occurring in parts of the teapot image that contains an excessive amount of color information in one single backlight segment. (b) Chromaticity distribution (blue circles) and absent information that was not displayed (in the magenta circle).

Fig. 7. Nine test images varying in color saturation and image complexity. The figures from the top left corner toward the right are hats, parrots, temple, red leaves, teapot*, basketball, lily, big ben, and house (*teapot was taken by Jens Rubbert, http://jensru.jalbum.net/Jens_Rubbert).

Nine test images with various color saturations and image complexities, as shown in Fig. 7, are selected to optimize the number of backlight segments while using the proposed 120 Hz Stencil-LPD method. An image resolution of 960×540 is assumed in this optimization. The seven sets of backlight segments shown in Table I are applied for this optimization. This study considers the two factors of image distortion level and power consumption to determine the optimized number of backlight segments. In the area of image distortion level, the CIEDE2000 $(\Delta\mathrm{E}_{00})$ [26], [27] is used as the scale for estimating the color difference, of which the acceptable criterion is 3. Based on CIEDE2000, the pixel distortion ratio (PDR) index, which is calculated by the number of distorted pixels divided by the number of total pixels and expressed by (4), is used to evaluate the image distortion level. In this index, a pixel is considered distorted if it has a color difference that is larger than a threshold of $\Delta\mathrm{E}_{00} = 3$.

$$\mathrm{PDR}\,(\Delta\mathrm{E}_{00} > 3) = \frac{\#\,\text{of}\,\Delta\mathrm{E}_{00} > 3\,\text{pixels}}{\#\,\text{of total pixels}} \times 100\%. \quad (4)$$

Fig. 8 shows that the color distortion and power consumption of the test images decreases as the number of backlight segments increases. Thus, the compensation by the LC module

TABLE I
BACKLIGHT SEGMENT COMBINATIONS, WHERE a AND b ARE THE NUMBER OF HORIZONTAL AND VERTICAL DIVISIONS, RESPECTIVELY

a	16	16	32	32	64	80	96
b	9	12	18	24	36	45	54

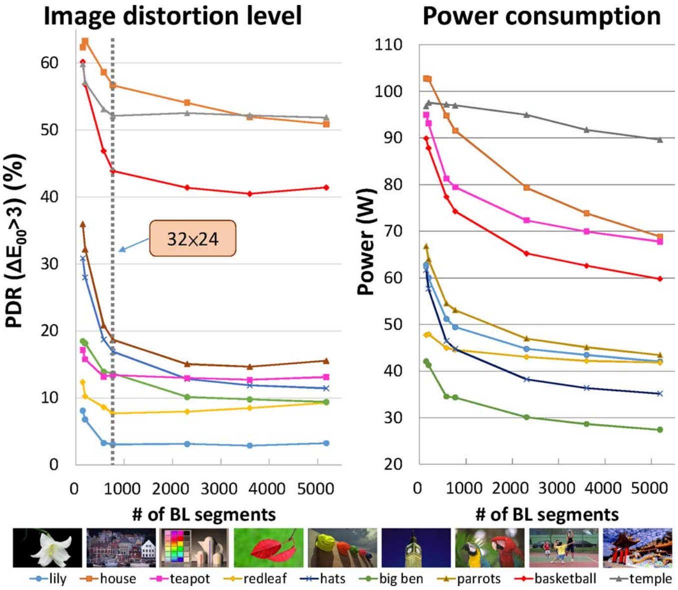


Fig. 8. Simulation results with the index of $\mathrm{PDR}(\Delta E_{00} > 3)$ and power consumption in the various backlight segments.

becomes more adequate as the number of independent backlight segments increases. Additionally, in this manner, the backlight signals could be more accurate because less color content is included. Simultaneously, the higher resolution of the backlight distribution implies that the LEDs are only turned on when needed in each segment, resulting in lower power consumption. The power consumption decreases provided that the backlight segment increases without a saturated trend; therefore, the optimized number of backlight segments can be determined by examining only the image distortion level. Thus, the backlight segment of 32×24 might be the optimized value because the color difference only varies slightly and exceeds this backlight combination.

The results of the image distortion level in this study show that the distortion becomes more perceptible as the complexity of the test image increases, even if the number of backlight segment increases, e.g., in the house, temple and basketball images. This phenomenon occurs because although the backlight solution is higher, an excessive amount of content occurs in one segment, limiting the ability to maintain image quality.

Moreover, the reproduced teapot image in Fig. 9(a) illustrates that the distortion still exists with the optimized backlight segments, which implies that the proper number of backlight segment is more than 32×24. Thus, a qualitative method is employed to obtain a proper set of backlight segments. Therefore, the reproduced image with 64×36 segments is shown in Fig. 9(b). The distorted area is removed because of the color information covered in a single backlight segment.

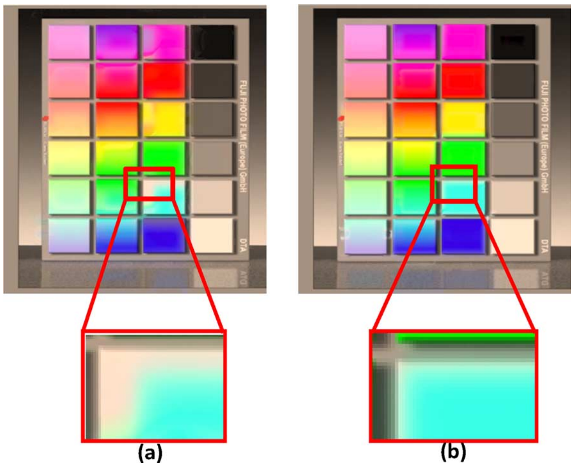


Fig. 9. Segment of the reproduced teapot image with (a) 32×24 and (b) 64×36 backlight segments.

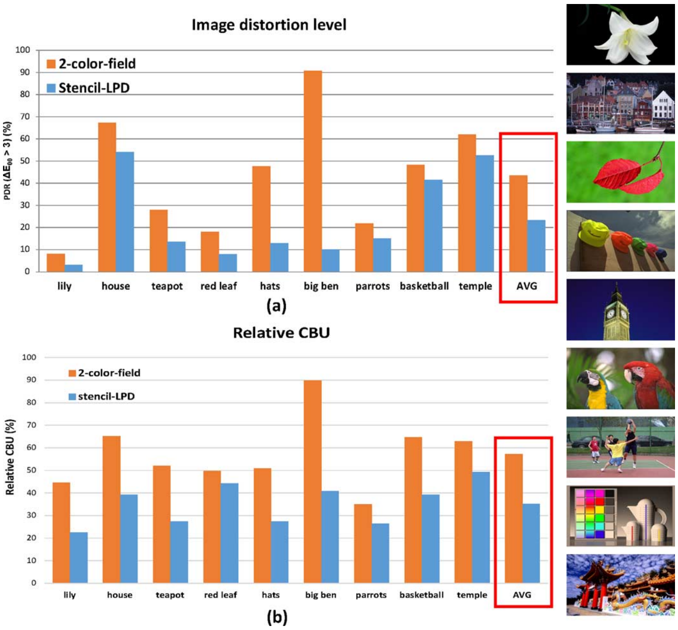


Fig. 10. Results of (a) the image distortion level and (b) the relative CBU with the optimized backlight segments of 64×36 compared to the Two-Color-Field method.

An interesting finding in this study is that an increasing number of backlight segments cannot have a smaller image distortion level (a lower PDR value). Thus, whether the PDR index is appropriate to describe the image distortion level remains unclear. This question is discussed in Section IV.

III. SIMULATION AND EMULATION RESULTS

Compared to the prior Two-Color-Field method proposed by Cheng *et al.* [23] with the same number of backlight segments (64 × 36), Fig. 10(a) indicates that the 120 Hz Stencil-LPD method improved the image fidelity by an average factor of two, with average pixel distortion ratios of 23.40% and 43.51% for the Stencil-LPD and Two-Color-Field methods, respectively. The proper backlight signals provided by the 120 Hz Stencil-LPD method covered the majority of the image content in each divided segment.

(a) (b) (c)

Fig. 11. Reproduced teapot images by the (a) Two-Color-Field method, (b) original image and (c) 120 Hz Stencil-LPD method emulated on a 120 Hz 23.6” MVA LCD.

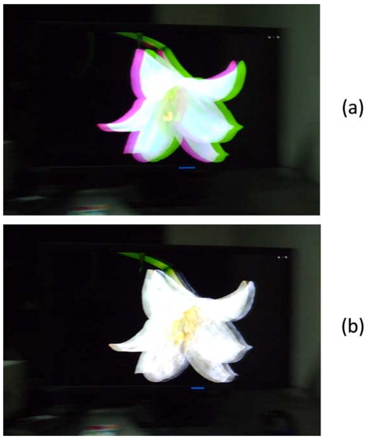


Fig. 12. Color-breakup images emulated on a 23.6” MVA LCD by waving the camera using the (a) Two-Color-Field and (b) 120 Hz Stencil-LPD methods.

TABLE II

COMPARISON OF THE CONVENTIONAL RGB-DRIVING, 2F2CF [21], TWO-COLOR-FIELD [23] AND THE PROPOSED 120 Hz STENCIL-LPD METHOD (BASED ON NINE TEST IMAGES AS SHOWN IN FIG. 7)

	Conventional LCDs	RGB Driving	2F2CF	Two-color-field	120Hz Stencil-LPD
			Phillips	NCTU	
Optical throughput	1x	3x	1.5x	3x	3x
Resolution	1x	3x	1.5x	3x	3x
Color filter	3	0	2	0	0
Field rate (Hz)	60	180	120	120	120
Image fidelity PDR(ΔE_{00}>3)	0	0	0	43.51%	23.40%
Color breakup		Serious	Acceptable	Acceptable	Imperceptible

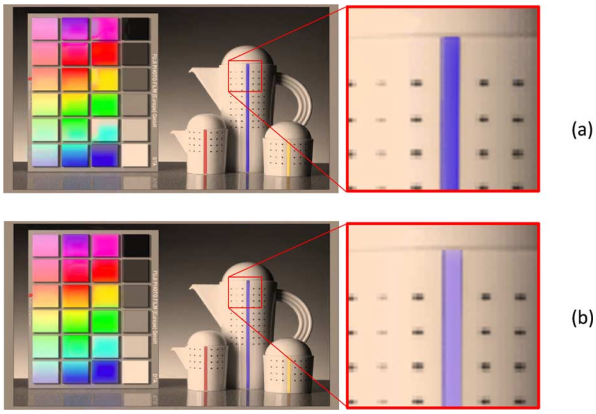


Fig. 13. Reproduced teapot images of the partial blue bar according to the number of backlight segments: (a) 32×24 – good performance and (b) 64×36 – desaturated.

Additionally, regarding the color breakup reduction, the index of the relative CBU (color breakup) is defined by (5) as the ratio of the total color difference between the reproduced images of both the Stencil-LPD method and Two-Color-Field method under the optimized 64×36 backlight segments. The conventional 180 Hz RGB-driving is used to assess the degree of color breakup. The color breakup was simulated by moving 20 pixels per frame.

$$\text{relative CBU} \equiv \frac{\sum^{\Delta} \mathrm{E}_{00}(120\ \text{Hz driving})_{a*b}}{\sum^{\Delta} \mathrm{E}_{00}\,(180\ \text{Hz RGB driving})} \times 100\% \quad (5)$$

where a, b are the backlight segment numbers.

The 120 Hz Stencil-LPD method also results in less color breakup than the Two-Color-Field method because the color saturation of the two displayed backlight fields were efficiently reduced but sufficiently represent the image content, as shown in Fig. 10(b). The relative CBU is reduced by 61.4%, with values of 35.2% and 57.2% using the Stencil-LPD and Two-Color-Field methods, respectively.

Furthermore, the reproduced images of both the Two-Color-Field driving scheme and proposed Stencil-LPD method were emulated on a 120 Hz 23.6” MVA LCD (EIZO Foris 2421) for a frame rate of 60 Hz, as shown in Fig. 11. Regarding the image fidelity, the proposed 120 Hz Stencil-LPD method demonstrated a higher image saturation, especially in the blue color content. A digital camera (Olympus XZ-1) was waved to simulate the eye saccadic movement and captured a color breakup image, as shown in Fig. 12. The test image of Lily with a bright white flower at a black background which is the most critical case to observe color breakup was utilized to evaluate the color breakup suppression. The rainbow fringe occurs in the Two-Color-Field method while there is only motion blur on the edge in the image produced by the 120 Hz Stencil-LPD method.

Finally, Table II compares the conventional RGB-driving, 2F2CF [21], Two-Color-Field [23] and the proposed Stencil-LPD methods. The results for both the image fidelity and color breakup are effectively improved when using the Stencil-LPD method.

IV. DISCUSSION

Although the optimized number of backlight segments has been determined as 64×36 and the distortion of the color patches is solved, the value of the image distortion level does not drastically decrease from 32×24, as shown in Fig. 8. Using the teapot test image as an example, the color of the blue bar on the teapot becomes desaturated and the color patches are improved (Fig. 13) as the backlight segments change from 32×24 to 64×36. This unexpected desaturation occurs when the higher resolution of the backlight distribution causes smaller backlight segments to display the blue bar, as illustrated in Fig. 14. The crosstalk from the adjoined backlight segments (beige color) desaturates the blue color after convolving with a point spread function of a backlight segment. To resolve this issue, a more centralized distribution of the point-spread function is needed

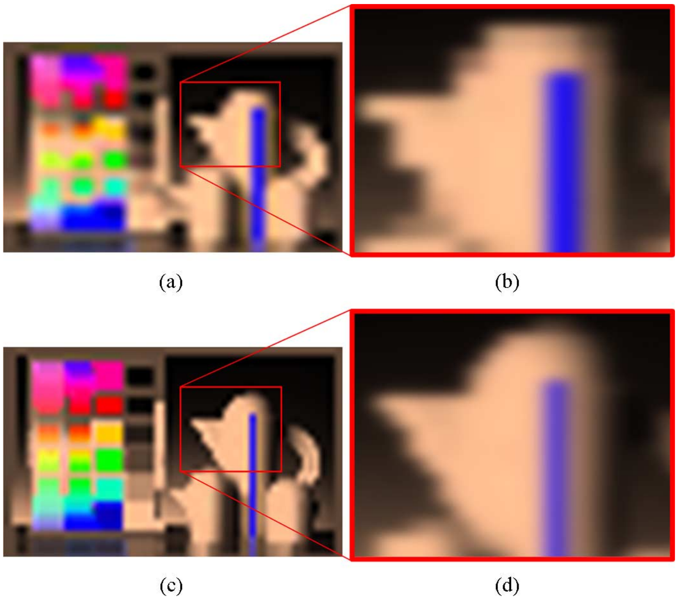


Fig. 14. The images of backlight signals (left side (a) and (c)) and the backlight distributions after convolving with a point spread function (right side (b) and (d)) with backlight segment of both 32×24 (upper line) and 64×36 (bottom line).

so that the affection by the surrounding segments with the non-saturated colors will be less significant.

V. CONCLUSION

This study proposed the 120 Hz Stencil-LPD method for low-field-rate FSC-LCDs to enhance image quality while simultaneously suppressing color breakup. The backlight module was segmented and locally controlled to provide fewer but sufficient saturated color backlight signals for the input images. The number of backlight segments was also optimized as 64×36 to maintain image quality. In terms of image quality improvement, the average PDR($\Delta E_{00} > 3$) for the nine test images was enhanced by a factor of two compared to previous Two-Color-Field algorithm. Additionally, the relative CBU was also reduced by 61.4% compared to the use of the previous Two-Color-Field method. As a result, the 120 Hz Stencil-LPD method is promising for next-generation displays with high transmission, resolution, and image quality or even for an LCD TV without a color filter.

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