Pseudo Zero-Dimension Dimming for Power Reduction in Field Sequential Color Liquid Crystal Display Systems

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***Abstract*—Expensive hardware is required by the conventional two-dimensional (2-D) light-emitting diode (LED) dimming technique to obtain high-contrast and low-power in the field sequential color (FSC) technique. Thus, based on real-time image data, the pseudo zero-dimension (0-D) LED dimming technique is proposed to further reduce power dissipation in the D-FSC technique, which allows the intelligent selection of an adequate color sequence. The multi-liquid crystal and backlight (LC/BL) algorithm utilizes the D-FSC technique in temporal and spatial domains. It not only utilizes the pseudo 0-D technique to effectively reduce the color breakup (CBU) effect without greatly increasing frame rate, but also to reduce power consumption. On the backlight module, CBU suppression can be substantially improved and power dissipation can be reduced by at least 12.5%. Power consumption can also be further reduced through the re-dimming improvement in the proposed pseudo 0-D dimming technique.**

***Index Terms*—Field sequential color (FSC), color breakup, dimming, light-emitting diode (LED) backlight, liquid crystal display (LCD).**

I. INTRODUCTION

AT PRESENT, liquid crystal display (LCD) is the most common thin electronic visual display. The field sequential color (FSC) technique is one of the most popular LCD technologies because it utilizes RGB light-emitting diode (LED) backlights to obtain a better color gamut than conventional white LED, cold cathode fluorescent lamp (CCFL), and external electrode fluorescent lamp (EEFL) backlights [1]. The FSC-LCD principle is to mix three primary colors (red, blue, and green) as a photogene occurs in the human visual system [2]. Conventional FSC technology extracts red, blue, and green sub-frames from one image and then reconstructs a full-color image in human eyes (Fig. 1) [3], [4]. The FSC technology has several advantages because it does not require a color filter. These advantages include reduced panel cost, elevated light transmission, reduced power consumption, reduced pixel space via a higher resolution, and satisfactory image saturation.

The LED backlight source is composed of a large number of tiny LED light-emitting units that allow it to successfully accomplish planarization of the light source. The tiny LED light-emitting unit can attain an accurate LED brightness control; thus, in accordance with the characteristics of the original image, amending the brightness in the small region can achieve high contrast ratio. The D-FSC technique can reduce the CBU effect, and proposes that the LED dimming technique should reduce power consumption and increase contrast ratio.

The well-known technology that enables the backlight source of the LCD display to be available in different regions with tuning luminance degrees in light and shade is called the local dimming technique. In broad terms, this technique can be roughly distinguished into three major categories: 0-dimension dimming technique (0-D), one dimension dimming technique (1-D), and two dimension dimming technique (2-D). The 2-D dimming technique utilizes the local dimming technology to its optimum effect.

How can 2-D local dimming greatly reduce the power consumption of an LCD monitor? Despite the flat light source, the backlight sources of CCFL or EEFL are generally in their maximum brightness state. The dark state exhibited by the screen is achieved through the reduction of the LC transmission rate, which does not reduce power consumption. The 2-D dimming technique is the simulation of self-luminous displays, such as various pixels on a PDP display. According to the image data, the brightness follows the screen brightness to change with. Therefore, while in the dark state, LED brightness will decrease, effectively reducing the overall power consumption of the backlight source. The before and after results yielded by 2-D dimming are shown in Fig. 2.

Thus, for the FSC technology to lower its power consumption while obtaining high color gamut, it needs to lessen its disadvantages, such as the Color Breakup (CBU) effect that results in deteriorated motion. Additionally, the SSC technology utilizes the dimming technique to improve power consumption and image quality [5], [6]. The CBU effect occurs when a relative velocity exists between the human eye and the image [7]. The R, G, and B color fields in the same image will form in different locations on the retina, resulting in the emergence of a small rainbow effect at the edge of the dynamic image [8]. The CBU effect not only reduces image quality, but is also a probable cause of eyestrain, which may hamper the popularity of the FSC-LCD display in the electronic visual display market [9].

The FSC display with a 180-Hz RGB pattern results in a critical CBU effect because of the low sub-frame rate [Fig. 3(a)] [10]. A double sub-frame rate RGB pattern can shorten the CBU width and make the human eye less perceptive of the CBU effect

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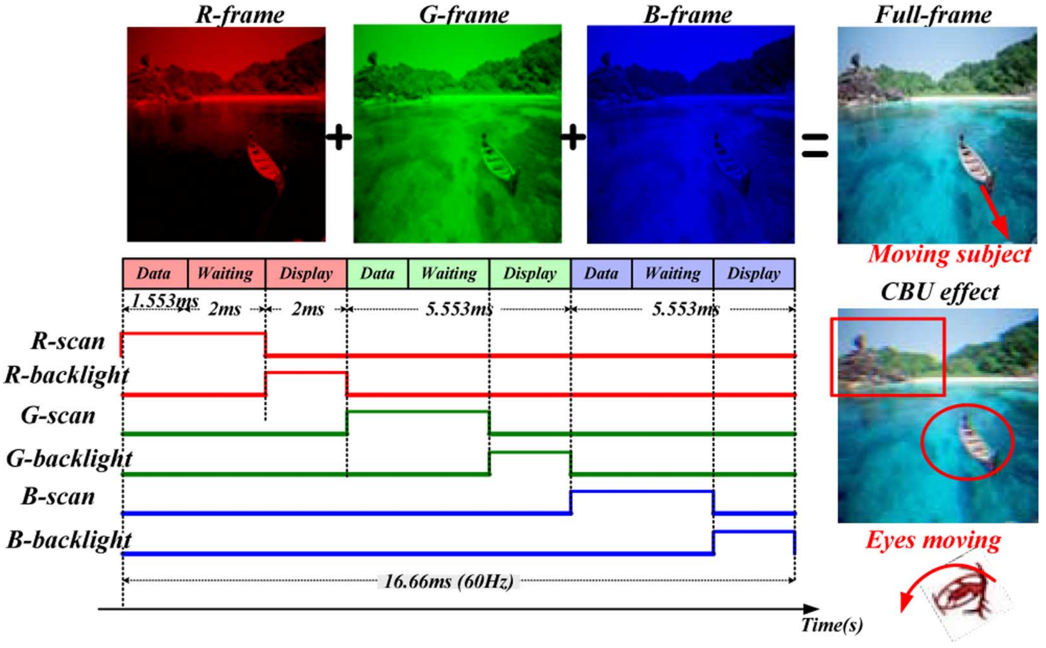


Fig. 1. Conventional FSC display with RGB three sub-frames.

(a) (b)

Fig. 2. (a) Before and (b) after results using 2-D dimming.

(a) (b)

(c) (d)

Fig. 3. FSC display is controlled by (a) conventional RGB pattern with a 180-Hz frame rate, (b) RGB pattern with a double frame rate, (c) RGBCY pattern with a 300-Hz frame rate, and (d) $\mathrm{RGBW}_{\max}$ pattern with a 240-Hz frame rate.

TABLE I

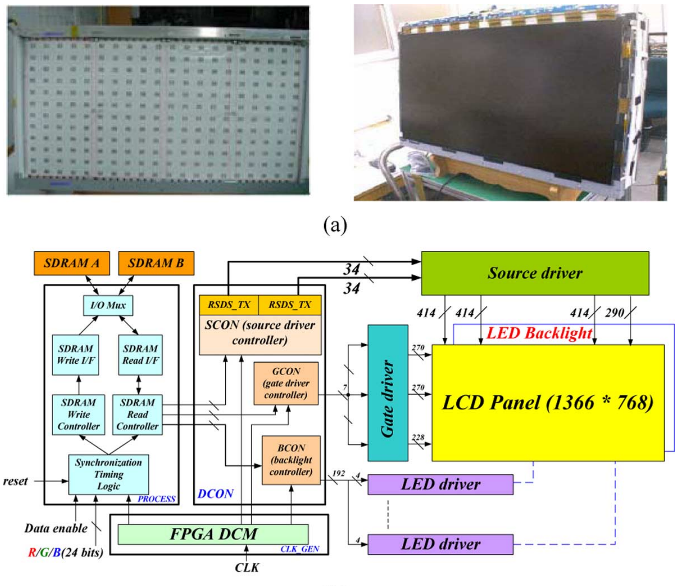
COMPARISON BETWEEN THREE PRIOR ARTS FOR REDUCING CBU EFFECT

Pattern	***Advantage***	***Disadvantage***
***RGBRGB* (*360Hz*)**	Good color gamut	High overhead in hardware
***RGBW$_{max}$* (*240Hz*)**	High brightness	Worse contrast
***RGBCY* (*300Hz*)**	Better color gamut	Large overhead in hardware

[11]–[13]. In addition, generating the color overlay by adding another sub-color field to minimize the color difference of the edge stagger causes the human eye to be less perceptive of the CBU [Fig. 3(c) and (d)] [14]–[16]. The FSC display contains the pattern RGBCY or $\mathrm{RGBW}_{\max}$ with a sub-frame rate of 300 or 240 Hz, respectively [17]. However, a higher sub-frame rate results in increasing cost and is limited by the response speed of the liquid crystal. The 240-Hz $\mathrm{RGBW}_{\max}$ pattern, which inserts a white sub-frame with a maximum gray level to reduce the gray level of RGB sub-frames, increases brightness but reduces image contrast. The comparison is listed in Table I.

Therefore, the D-FSC algorithm can alleviate the CBU effect [18]. The proposed algorithm presents a dynamic D-FSC technique geared toward the generation of the fourth sub-frame. As a result, the color intensity of the first three sub-frames is reduced. The fourth sub-frame can compensate for the color intensity and, at the same time, adjust the backlight to eliminate the CBU phenomenon. However, the fourth sub-frame should be dynamically adjusted in accordance with the image data, that is, the fourth sub-frame can be white, magenta, cyan, or yellow. Four modes, $\mathrm{RGBW}_{\min}$, RGBM, RGBC, and RGBY, can be selected to deal with various types of images [19]–[21].

In this study, the $\mathrm{RGBW}_{\min}$ pattern is made to be different from the $\mathrm{RGBW}_{\max}$ pattern to eliminate the disadvantages posed by the $\mathrm{RGBW}_{\max}$ pattern. The D-FSC algorithm presents a prediction approach to select the best mode for the current image data. A prototype of the RGB backlight module [Fig. 4(a)] is utilized in a 32-in LCD panel with a resolution of 1366^{*768} [Fig. 4(b)]. For the dynamic D-FSC technique, LED backlight dimming technology can be used to enhance contrast and power consumption [22], [23]. However, the 0-D LED dimming technique exhibits a limitation when the image projects high brightness over the whole area. Through the pseudo 0-D dimming technique, power consumption can be further reduced and contrast can be effectively improved simultaneously for the benefit of the dynamic D-FSC technique.



(a)

(b)

Fig. 4. (a) RBG backlight module. (b) 32-in color-filter-less LCD panel with a resolution of 1366^{*768}.

Although the general dynamic backlight technique can meet an image that exhibits high brightness, it must divide the panel into several blocks,blocks; otherwise the performance of the dimming technique will be reduced. However, the proposed pseudo 0-D technique in the D-FSC algorithm can avoid the high-brightness image to further reduce power consumption, that is, suppressed CBU and low power consumption can be simultaneously achieved.

The organization of this paper is as follows. The dynamic D-FSC technique is expressed in Section II. The section shows how the CBU effect is further reduced by the dynamic D sub-frame according to image data. Section III presents the pseudo 0-D LED dimming technique used in FSC-LCD to save power. Section IV exhibits how power consumption can be further reduced through re-dimming improvement, thus enhancing its power-saving performance. Finally, the conclusion is presented in Section V.

II. OPERATION OF THE D-FSC ALGORITHM WITH THE DYNAMIC FOURTH SUB-FRAME

The D-FSC technique contains four controlling patterns: $\mathrm{RGBW_{min}}$, RGBM, *RGBC*, and RGBY. The sub-frame rate is 240 Hz for all four patterns because the hardware overhead is virtually ignored.

A. $\mathrm{RGBW_{min}}$, RGBM, *RGBC, and* RGBY *Patterns*

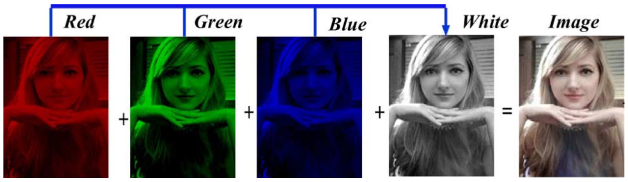


Fig. 5. $\mathrm{RGBW_{min}}$ pattern is used to form the D sub-frame.

TABLE II
DEFINITION IN THE $\mathrm{RGBW_{min}}$ PATTERN

	Conventional RGB	$RGBW_{min}$
Red	LC_R	LC_R-LC_{min}
Green	LC_G	LC_G-LC_{min}
Blue	LC_B	LC_B-LC_{min}
***D sub-frame* (*white*)**	-	LC_{min}=min(LC_R, LC_G, LC_B)

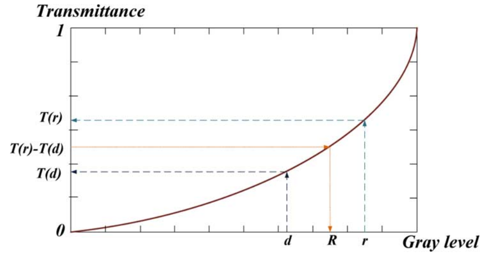


Fig. 6. Use the Gamma correction curve to obtain an accurate gray level after using the D-FSC technique.

The $\mathrm{RGBW_{min}}$ pattern (Fig. 5) for replacing the previous $\mathrm{RGBW_{max}}$ pattern can solve the problem of high-brightness. The $\mathrm{RGBW_{min}}$ pattern adopts four sub-frames to synthesize one color image. The first step is finding the minimum gray level $\mathrm{LC_{min}}$ of each pixel. The minimum gray level denotes. Then, the $\mathrm{LC_{min}}$ is deducted from three sub-frame gray levels, namely, LC_R, LC_G, and LC_B. The D sub-frame decided by the LC_{min} gray level compensated back to the fourth sub-frame to form a white backlight. The new gray level of each original color and the D sub-frame is shown in Table II. Compared with the $\mathrm{RGBW_{max}}$ pattern, the $\mathrm{RGBW_{min}}$ pattern will not reduce image contrast. The $\mathrm{RGBW_{min}}$ pattern can also effectively reduce brightness because contribution from the RGB color sub-frames is decreased.

Considering the deviation caused by Gamma effect [24], [25], the correct gray value can be obtained after re-converting the liquid crystal transmittance and passing it to the control engine (Fig. 6). T denotes the "gamma transform" function and T^{-1} denotes the "gamma inverse transform" function. R, G, and B represent the amended gray level value, whereas r, g, and b represent the original gray level value [26]. The value of d denotes the $\mathrm{LC_{min}}$ value. Therefore, the original algorithm must be revised to the following equations:

$$R = T^{-1}(T(r) - T(d)) \tag{1}$$

$$G = T^{-1}(T(g) - T(d)) \tag{2}$$

$$B = T^{-1}(T(b) - T(d)) \tag{3}$$

$$D = T^{-1}(\min(T(r), T(g), T(b), 1)). \tag{4}$$

After implementing the $\mathrm{RGBW_{min}}$ pattern, the exception is that the image that only contains magenta, cyan, and yellow may cause the image processing problem. The value of LC_{min} as the aforementioned colors is close to zero. This results in a CBU effect similar to that of the conventional RGB FSC method. Therefore, the dynamic D-FSC technique needs to include three additional controlling patterns to effectively address the shortcomings of the $\mathrm{RGBW_{min}}$ pattern. The additional patterns are

TABLE III
AMENDED GRAY LEVEL VALUES FOR THREE ADDITIONAL PATTERNS

	RGMC	RGBM	RGMY
R	$R=r$	$R=T^{-1}(T(r)-T(d))$	$R=T^{-1}(T(r)-T(d))$
G	$G=T^{-1}(T(g)-T(d))$	$G=g$	$G=T^{-1}(T(g)-T(d))$
B	$B=T^{-1}(T(b)-T(d))$	$B=T^{-1}(T(b)-T(d))$	$B=b$
D	$D=T^{-1}(\min(T(g),T(b),1))$	$D=T^{-1}(\min(T(r),T(b),1))$	$D=T^{-1}(\min(T(r),T(g),1))$

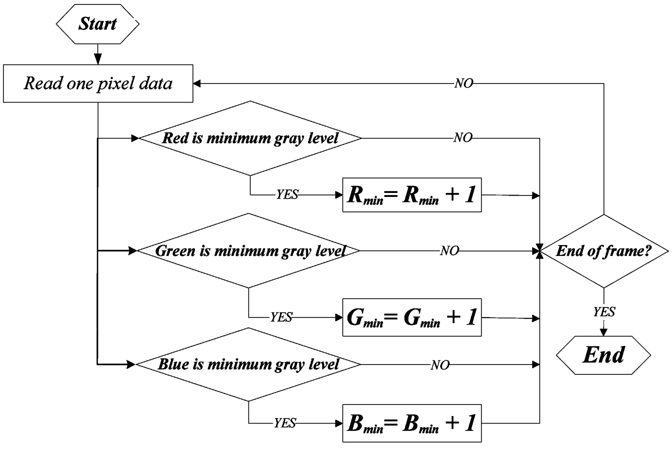


Fig. 7. Flowchart of the calculation for $R_{\min}$, $G_{\min}$, and $B_{\min}$ to determine the minimum gray level among RGB colors.

RGBM, $RGBC$, and RGBY. The amended gray level values for the three additional patterns are listed in Table III.

B. Selection of Adequate Pattern From the Four Patterns

According to the image data, the dynamic D-FSC technique should be switched between the four patterns, namely, $\mathrm{RGBW}_{\min}$, RGBM, RGBC, and RGBY, to obtain optimum performance in the suppression of the CBU effect. As shown in Fig. 4(b), immediate change of the required backlight after amending the gray level value is unlikely because the image data writing for LCD and the driving operation of LED backlight must be operated simultaneously. Therefore, in most cases, the sub-optimum solution is to take advantage of the continuous characteristic of the image data; that is, the FSC pattern determined by the current image data can be used to predict the adequate FSC pattern for the next image data.

The gray level of the RGB colors is the smallest. The number of the smallest value can then be calculated using three parameters, $R_{\min}$, $G_{\min}$, and $B_{\min}$, which can represent the minimum quantity value of the R, G, and B gray levels, respectively. After each image data is written to SDRAM, check which one contains the largest value among the values of $R_{\min}$, $G_{\min}$, and $B_{\min}$. The controlling flow chart is shown in Fig. 7. The flow chart for the D-FSC algorithm is shown in Fig. 8. If the three additional modes are not significant enough, the $\mathrm{RGBW}_{\min}$ pattern will be adopted.

The spatial technique can be further utilized in the D-FSC technique to further reduce the CBU phenomenon and thus improve image quality. The original 1×1 LED-backlight panel is divided into smaller blocks as depicted in Fig. 9(a). The entire LED backlight panel is divided into 4×4 small blocks, and the coordinates denote the horizontal and vertical positions, with the origin taken at the upper left corner. According to the selection procedure, all LED backlight blocks are independently controlled by the four FSC patterns to enhance efficiency and reduce the CBU phenomenon [Fig. 9(b)] [27], [28]. As a result, the D-FSC technique can utilize temporal and spatial methods to greatly reduce the CBU effect.

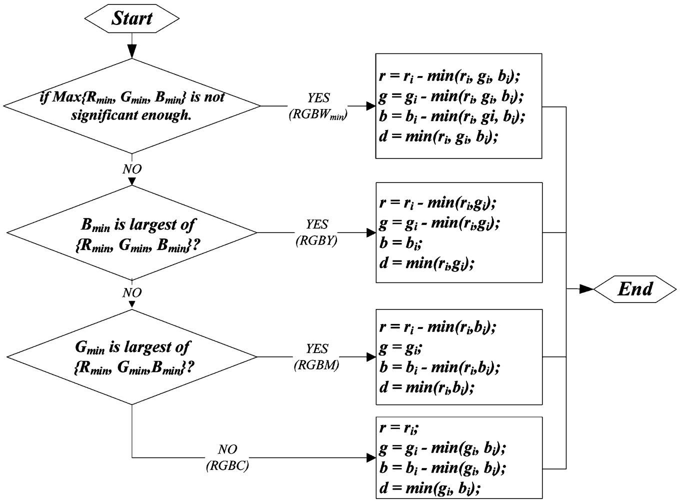


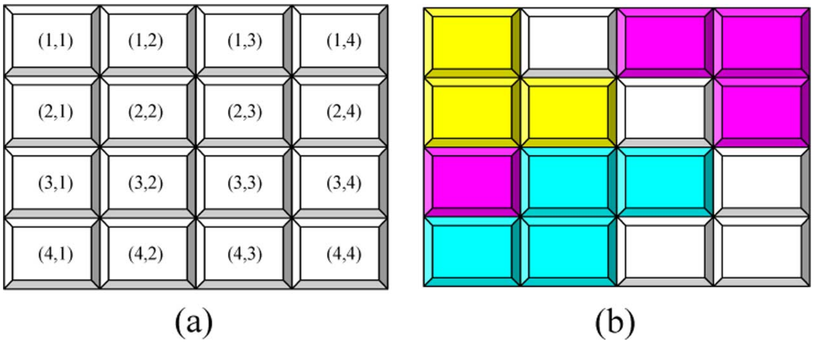
Fig. 8. Flowchart for the D-FSC algorithm.

III. PSEUDO ZERO-DIMENSION DIMMING TECHNIQUE IN FSC-LCD FOR POWER SAVING

The principle of the proposed dynamic backlight is to reduce the backlight of an image and compensate for the reduction by improving the gray level of the image so as to obtain an image without distortion and lower power consumption. Equation (5) denotes the backlight brightness using the 2-D dimming technique. L_a denotes the backlight brightness without the 2-D dimming technique, whereas L_b denotes the resulting luminance with the dimming factor as K if the image position is at (x,y).

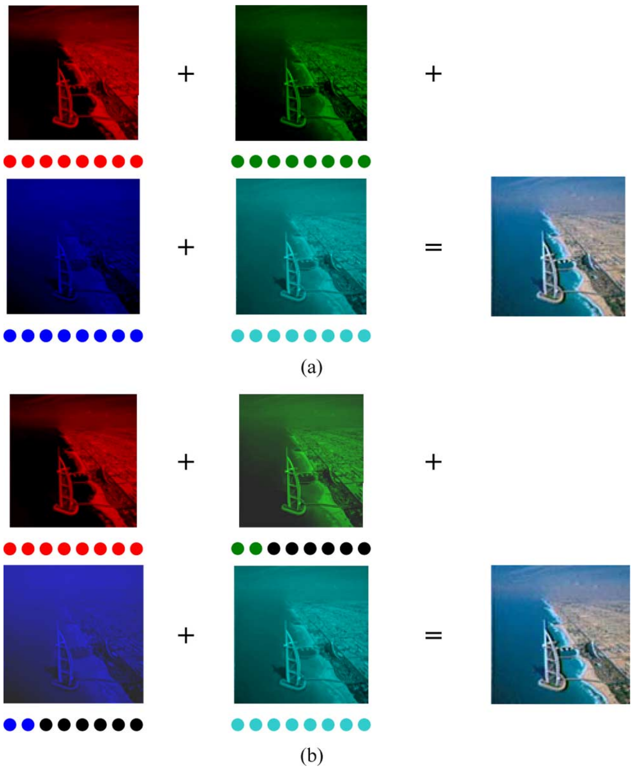
$$L_a(x,y)=L_b(x,y)^{*}K(x,y). \qquad (5)$$

For example, as most LCD panels need to use 12 CCFL tubes, a 32-in TV with an LCD panel will be used to demonstrate the case of the fully local dimming technique. It can only be drawn up into 12 blocks in the 1-D dimming technique. Additionally, the major problem of the CCFL is that the turn on/off speed is not sufficiently fast. Constant usage of the switching speed will negatively affect the working performance and longevity of the CCFL. Fortunately, the implementation of 0-D to 2-D LED dimming technique in the LED backlight is easy. For example, 1152 LEDs (48^{*24}) are arranged in a matrix in the experiment using the 32-in TV [Fig. 4(a)]. The actual video image for 0-D dimming combined with the D-FSC technique is shown in Figs. 10 and 11 for the RGBC pattern and the RGBY pattern, respectively. The image in Fig. 10 can obtain significant power reduction through the 0-D dimming technique; however, the image in Fig. 11 cannot obtain any power reduction, which poses a serious problem in the 0-D dimming technology. Most of the actual 0-D dimming technique cases are similar to Fig. 11(b), wherein the gray level of the frame data is too high after the backlight is reduced, leaving no room left for the video signal



(a) (b)

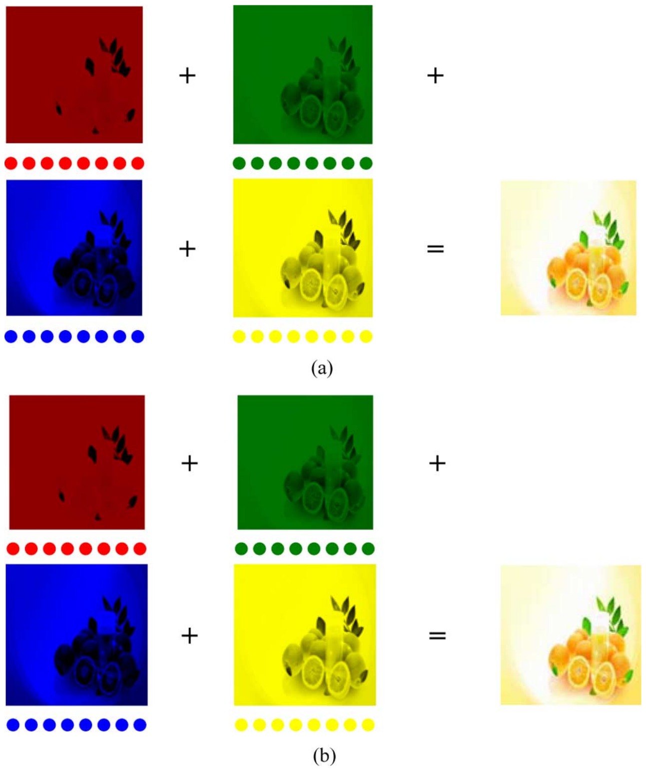
Fig. 9. (a) 1 × 1 LED backlight unit is divided into 4 × 4 small blocks to further enhance the performance of the D-FSC technique by the spatial method. (b) The cyan, yellow, magenta, and white blocks denote the $RGBC$, RGBY, RGBM, and $\mathrm{RGBW}_{\min}$ patterns, respectively.



(a)

(b)

Fig. 10. (a) The RGBC pattern without the 0-D dimming technique. (b) The RGBC pattern with the 0-D dimming technique.



(a)

(b)

Fig. 11. (a) The $RGBY$ pattern without the 0-D dimming technique. (b) The RGBY pattern with the 0-D dimming technique.

to be adjusted upward. This results in the failure of the dynamic backlight technique, as well as the power-saving technique.

Thus, the 2-D dimming technology is used to deal with cases similar to that in Fig. 11. The experimental result is shown in Fig. 12. In this case, the panel is divided into 4×4 blocks. The number (1–8) on each small block of the picture represents power consumption (number 8 means that $K = 8/8 = 1$ and the number 1 means that $K = 1/8$). The aforementioned methods need one more DRAM buffer to store the adjusted NEW GRAY value for each sub-frame, as well as delay one more frame time to output the current scene. The hardware requirement is more complex than the experiment platform. However, the proposed pseudo 0-D dimming technique can play an important role in reducing power consumption.

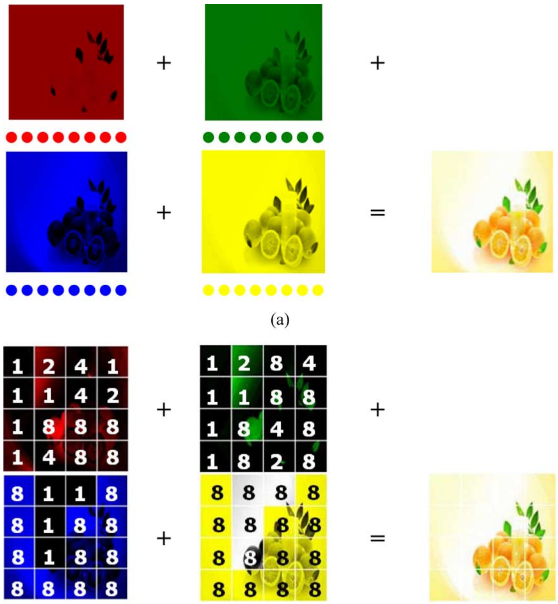
The proposed pseudo 0-D dimming technique needs some modifications in the original system architecture to further achieve a power-saving performance. For example, the original $\mathrm{RGBW}_{\min}$ equations are modified as (6)–(9). If the value of $\mathrm{LC}_{\min}$ is greater than the threshold value, then the value of $\mathrm{LC}_{\min}$ is only limited to the threshold value to ensure correct operation of the dimming algorithm.

$$R = \min(T^{-1}(T(r) - T(D)), \mathrm{threshold}) \tag{6}$$

$$G = \min(T^{-1}(T(g) - T(D)), \mathrm{threshold}) \tag{7}$$

$$B = \min(T^{-1}(T(b) - T(D)), \mathrm{threshold}) \tag{8}$$

$$D = T^{-1}\left(\min\left(\begin{array}{c} T(r \times 2), T(g \times 2), \\ T(b \times 2), \mathrm{threshold} \times 2, 1 \end{array}\right)\right). \tag{9}$$



(a)

(b)

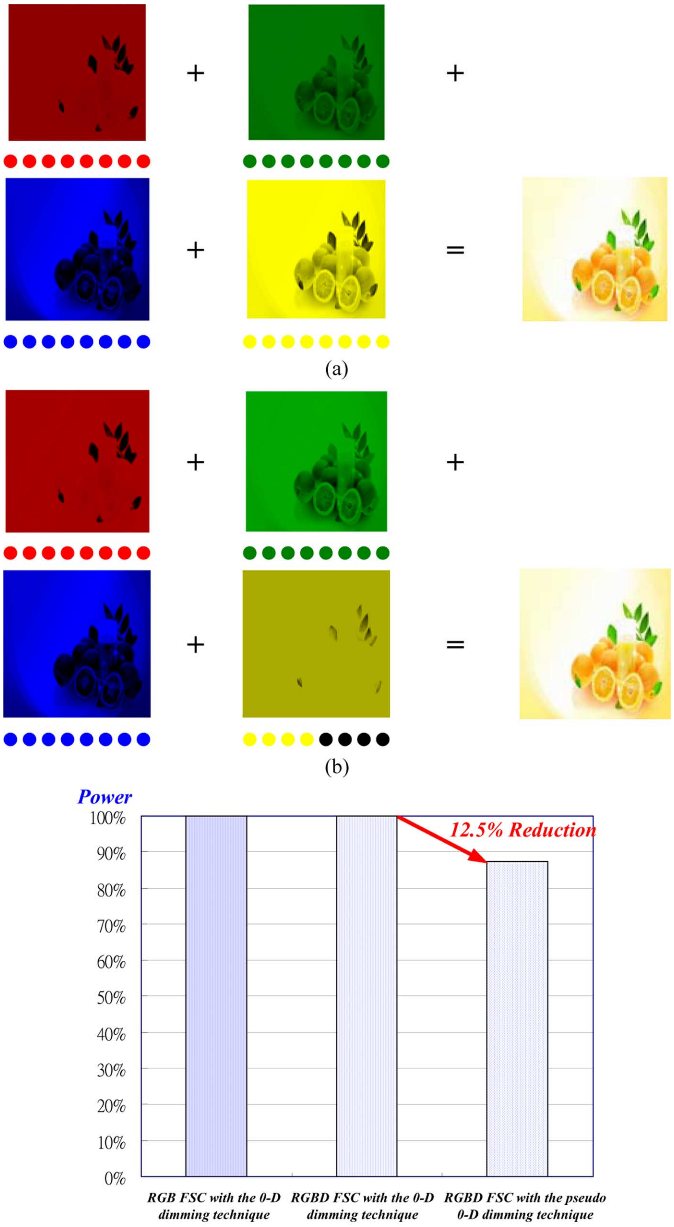
Fig. 12. (a) RGBY FSC pattern with the 0-D dimming technique. (b) RGBY FSC pattern with the 2-D dimming technique.

TABLE IV
ALGORITHM OF THE $\mathrm{RGBW}_{\min}$ PATTERN IN THE PSEUDO 0-D DIMMING TECHNIQUE

	Conventional RGB	RGBW$_{min}$	RGBW$_{min}$ +0 D Dimming
Red	LC$_R$	LC$_R$-LC$_{min}$	LC$_R$-LC$_{min}$
Green	LC$_G$	LC$_G$-LC$_{min}$	LC$_G$-LC$_{min}$
Blue	LC$_B$	LC$_B$-LC$_{min}$	LC$_B$-LC$_{min}$
White	-	LC$_{min}$ (min of RGB)	LC$_{min}$ (min of RGB and Threshold) × 2

The proposed algorithm can guarantee that the gray level of the D sub-frame does not contain a gray level value that exceeds the permitted value. For example, the threshold value is set to 85 (Table IV). Then, the gray level of the D sub-frame is raised twice (i.e., 170); simultaneously, the backlight brightness of the D sub-frame is changed to 1/2 to save power. The new algorithm effectively reduces power consumption using the pseudo 0-D dimming technique.

Fig. 13 shows the experimental result with the pseudo 0-D dimming technique. This research uses the pseudo 0-D technique, which can avoid high gray level in the D sub-frame, to implement the new dimming technology for 0-D power- saving. In conventional 0-D dimming, the dimming technique is applied to the whole panel; however, it exhibits its limitation in certain high-brightness spots. The power-saving performance will, therefore, be limited. In the proposed pseudo 0-D technique, the power percentages for red, green, and blue backlights are expressed as BL_R, BL_G, and BL_B, respectively, compared with conventional design. In this case, BL_R, BL_G, and BL_B are equal to 100%. Meanwhile, the power percentage of the D-frame backlight is BL_D and is equal to 50%. The total power percentage, which equals 87.5%, can be expressed as (10). As shown in Fig. 13(a) and (b), conventional 0-D dimming cannot have good power reduction; on the other hand, the proposed method can improve power consumption by approximately 12.5%. In other words, all images produced by the pseudo 0-D technique can have at least 12.5% power reduction in backlights. Fig. 13(c) depicts the power comparison between three FSC methods with and without the pseudo 0-D dimming technique



(a)

(b)

(c)

Fig. 13. (a) RGBY pattern without the 0-D dimming technique. (b) RGBY pattern with the pseudo 0-D dimming technique. (c) Bar chart for power consumption of different 0-D dimming technique for backlight module.

$$\text{Power} = (BL_R + BL_G + BL_B + BL_D) \times \frac{1}{\text{number\_of\_subframes}}. \qquad (10)$$

IV. RE-DIMMING IMPROVEMENT TECHNIQUE

To further decrease power consumption, the pseudo 0-D dimming technique can be iterated for the second power reduction,

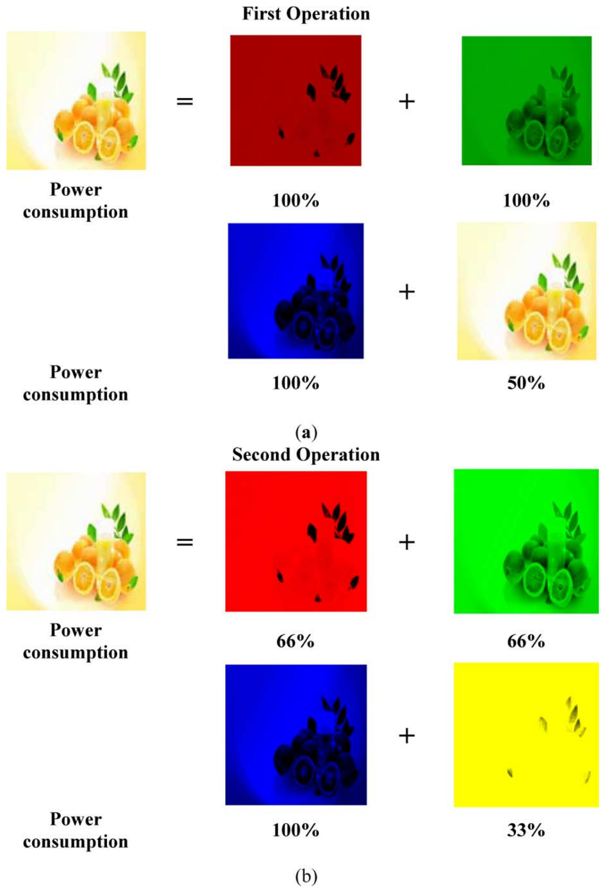


Fig. 14. (a) First pseudo 0-D dimming operation similar to Fig. 13(b). (b) Second operation that can have re-dimming improvement compared to conventional 0-D dimming technique.

known as the re-dimming improvement. According to (6)–(8), the gray level of the red, green, and blue sub-frames is effectively reduced due to the first implementation of the pseudo 0-D dimming technique. Obviously, the second operation will not be limited by a high-brightness image because of the results of the first operation. Power consumption can thus be greatly reduced by subsequent 0-D dimming (i.e., the re-dimming technique). Fig. 14 describes the detailed operation results. At this time, the values of BL_R, BL_G, BL_B, and BL_D are 66%, 66%, 100%, and 33%, respectively. The power percentage of the proposed method is 66.25% compared with the conventional design.

Fig. 14 shows the result of the re-dimming improvement. The range of the K factor in (5) is extended to conveniently explain the re-dimming improvement. Although it may cause image distortion, it can be compensated by the dithering technique. Fig. 14(a) shows the result of the first operation, which is pseudo 0-D dimming. In Fig. 14(b), the red and green sub-frames have a K factor of 0.66, whereas the blue sub-frame has a K factor of 1.0. In addition, the yellow sub-frame has a K factor of 0.33. After the power calculation, not only can the power consumption be reduced by about 33%, the color breakup effect suppression can also be maintained effectively due to the D-FSC technique with the dynamic forth sub-frame. In summary, the pseudo 0-D dimming technique can reduce the power consumption of conventional 0-D dimming to save power. The re-dimming operation can be applied not only on the fourth sub-frame, but also on the first three sub-frames to get a better power reduction and high efficiency (Fig. 15).

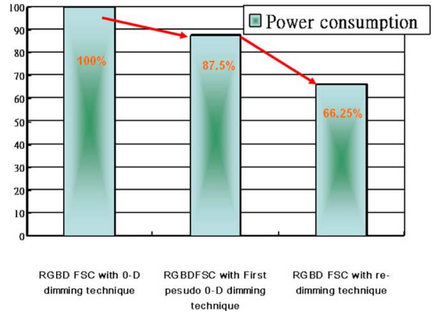


Fig. 15. Bar chart for power consumption of different 0-D dimming techniques for backlight module.

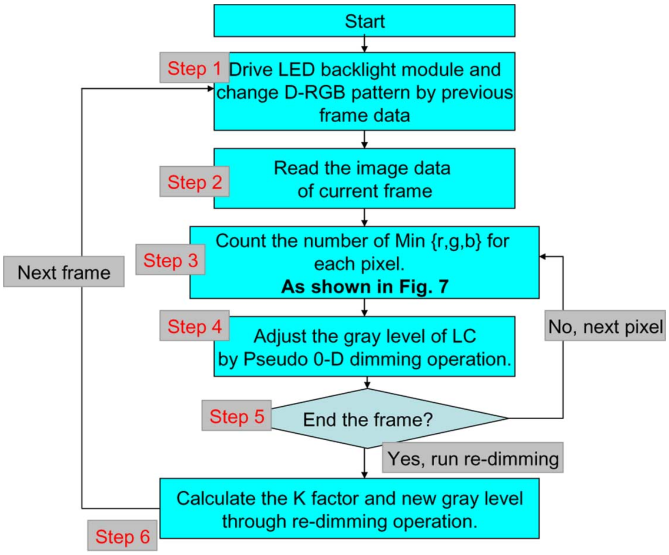
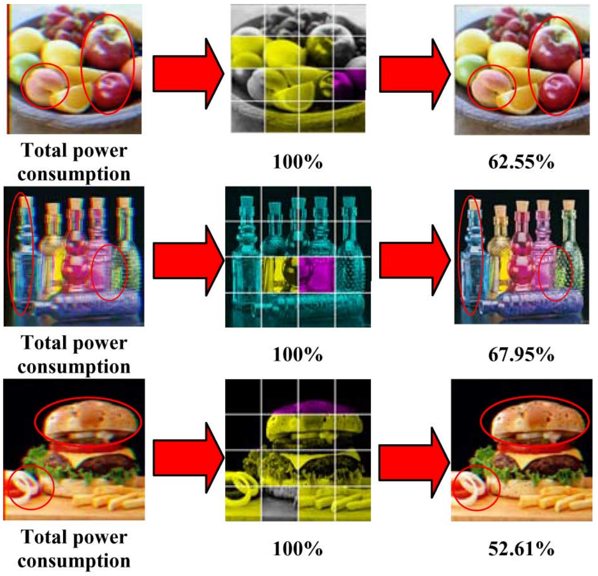


Fig. 16. Flowchart for the image processor.

Fig. 16 shows the controlling flowchart of the generalization of the FSC technique in Section II and the pseudo 0-D dimming technique in Section III. In Step 2, the system reads image data into memory. Step 3 is used to select the correct D-RGB pattern, of which the procedure is described in detail in Section II and Figs. 7 and 8. In Steps 4–5, all new gray level values of one frame are calculated by the pseudo 0-D dimming technique system. The system then runs the re-dimming operation to get the K factor and new gray level once more. Finally, the calculated data are set to the backlight module for LED driving, and the correct D-FSC pattern for the next frame is selected (Step 1).

Finally, each 2-D block can be regarded as a smaller 0-D block. As a result, the pseudo 0-D dimming technique can be applied on the 2-D dimming condition. Fig. 17(a) shows three images that need to obtain independent D-RGB pattern assignments for each small block due to the critical CBU effect and the high power consumption. Thus, the LCD panel is divided into 4×4 blocks, where each block has its own independent D-RGB pattern [Fig. 17(b)]. Each 2-D block can select its own optimum D-RGB pattern to further reduce the CBU effect [Fig. 9(b)] and adjust the luminance of the backlight to reduce power consumption through the pseudo 0-D re-dimming technique alone. As a result, Fig. 17(c) shows the revised images. Note that the



(a) (b) (c)

Fig. 17. (a) Original images exhibit critical CBU effect and high power consumption. (b) FSC backlight pattern arrangement of the D-frame for each block in a divided 4×4 panel. (c) Display image results after the proposed technique was applied.

on-screen CBU phenomenon, which is highlighted by a red line in Fig. 17(a), has been effectively reduced.

On the other hand, the total power consumption also exhibited obvious reduction. In fact, if the LCD panel can be divided into many small blocks, the power-saving and CBU-suppression performance will be greatly reduced. Define the power consumption of 2-D dimming mode to $Power$. In addition, the power consumption of each 2-D block denotes $P(x,y)$, which is expressed as (10). The coordinates (x,y) denote the horizontal and vertical positions on the LCD [see Fig. 9(a)]. The power consumption of the 2-D dimming mode can be calculated as (11), and the result exhibits a power consumption of 52.61% [see Fig. 17(c)].

$$\text{Power} = \frac{\sum P(x,y)}{\text{number\_of\_blocks}}. \tag{11}$$

V. CONCLUSION

Based on real-time image data, the pseudo 0-D LED dimming technique is proposed to further reduce power dissipation in the D-FSC technique, which can intelligently select an adequate color sequence. Expensive hardware is particularly needed in a conventional 2-D LED dimming technique used to obtain high-contrast images in low-power. The pseudo 0-D dimming technique can effectively reduce power consumption in the D-FSC algorithm that utilizes the dynamic D-FSC technique in temporal and spatial domains to suppress the CBU effect without greatly increasing frame rate. Experimental results show the CBU suppression can be improved substantially and the power dissipation can be reduced by at least 12.5%. Power consumption can also be further reduced through the re-dimming improvement in the proposed pseudo 0-D dimming technique; that is, power saving can be improved with a satisfactory CBU suppression performance.

REFERENCES

[1] T. Uchida, K. Saitoh, T. Miyasita, and M. Suzuki, "Field sequential full color LCD without color filter for AMLCD," in *Proc. 17th IDRC*, 1997, pp. 37–40.

[2] F. Yamada, H. Nakamura, Y. Sakaguchi, and Y. Taira, "Sequential-color LCD based on OCB with an LED backlight," *J. Soc. Inf. Display*, vol. 10, pp. 81–85, 2002.

[3] T. Fukami, "New driving method for field sequential color LCDs using OCB mode," in *IDW'06*, 2006, pp. 1617–1620.

[4] F. Yamada, H. Nakamura, Y. Sakaguchi, and Y. Taira, "Color sequential LCD based on OCB with an LED backlight," in *SID Symp. Dig. Tech Papers*, 2000, vol. 31, pp. 1180–1183.

[5] P. C. Baron, "Saccadic color breakup in field sequential color displays: An overview," in *ADEAC 2006*, pp. 138–143.

[6] H. Nakamura, K. Miwa, and K. Sueoka, "Modified drive method for OCB LCD," in *Proc. 17th IDRC*, 1997, pp. L66–69.

[7] S.-C. Chen, S.-P. Yan, Y.-K. Cheng, F.-C. Lin, C.-M. Wei, Y.-P. Huang, and H.-P. D. Shieh, "A human visual model for color break-up artifact in design field-sequential color LCDs," in *IDMC 2007*, pp. 872–875.

[8] S.-P. Yan, Y.-K. Cheng, F.-C. Lin, C.-M. Wei, Y.-P. Huang, and H.-P. D. Shieh, "A visual model of color break-up for design field-sequential LCDs," in *SID Symp. Dig. Tech. Papers*, 2007, vol. 38, pp. 338–341.

[9] 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.

[10] Miettinen, R. Näsänen, and J. Häkkinen, "Effects of saccade length and target luminance on the refresh frequency threshold for the visibility of color break-up," *J. Display Technol.*, vol. 4, no. 1, pp. 81–85, Mar. 2008.

[11] J. B. Eichenlaub, "Develop and preliminary evaluation of field sequential LCD free of color breakup," in *SID Symp. Dig. Tech Papers 25*, 1994, pp. 293–296.

[12] K. Sekiya, T. Miyashita, and T. Uchida, "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.

[13] C. H. B. Elliott, S. Han, M. H. Im, M. Higgins, P. Higgins, M. Hong, N.-S. Roh, C. Park, and K. Chung, "Co-optimization of color AMLCD subpixel architecture and rendering algorithms," in *SID Symp. Dig.*, 2002, vol. 31, pp. 172–175.

[14] E. H. A. Langendijk, S. Swinkels, D. Eliav, and M. en-Chorin, "Suppression of color breakup in color-sequential multi-primary projection displays," *J. Soc. Inf. Display*, vol. 14, pp. 325–329, 2006.

[15] H. Sugiura, H. Kaneko, S. Kagawa, M. Ozawa, H. Tanizoe, H. Katou, T. Kimura, and H. Ueno, "Six-Primary-Color 23-in WXGA LCD using six-color LEDs," in *SID Symp. Dig.*, 2005, vol. 34, pp. 1124–1127.

[16] L. D. Silverstein, "ST color: Hybrid spatial-temporal color synthesis for enhanced display image quality," in *SID Symp. Dig.*, 2005, vol. 34, pp. 1112–1115.

[17] N. Koma and T. Uchida, "A new field-sequential-color LCD without moving-object color break-up," *J. Soc. Inf.. Display*, vol. 11, pp. 413–417, 2003.

[18] 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.*, no. 3, pp. 290–295, Sep. 2008.

[19] P. J. Bos and K. R. Koehler, "The pi-cell: A fast liquid-crystal optical-switching device," *Mol. Cryst. Liq. Cryst.*, vol. 113, pp. 329–339, 1984.

[20] M. B. Chorin, "Improving LCD TV color using multi-primary technology," in *FPD Int. Forum*, Yokohama, 2005, Paper PC2–2.

[21] K. Endo, "New mobile technologies creating a host of new mobile equipment," in *FPD Int. Forum*, Yokohama, 2005, Paper B1–4.

[22] A. Konno, Y. Yamamoto, and T. Inuzuka, "RGB color control system for LED backlights in IPS-LCD TVs," in *SID Symp. Dig.*, 2005, vol. 34, pp. 1380–1383.

[23] W. Cheng, "Power minimization of LED backlight in a color sequential display," in *SID Symp. Dig.*, 2005, vol. 34, pp. 1384–1387.

[24] F.-C. Lin, Y.-P. Huang, C.-M. Wei, H.-P. D. Shieh, C.-C. Tsai, and W.-C. Tai, "Stencil-FSC method for color break-up suppression and low power consumption in field-sequential LCDs," in *SID Symp. Dig. Tech Papers*, 2008, vol. 39, pp. 1108–1111.

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

[26] C.-H. Chen, K.-H. Chen, Y.-P. Huang, H.-P. D. Shieh, and M.-T. Ho, "Gray level redistribution in field sequential color LCD technique for color breakup reduction," in *SID Symp. Dig. Tech. Papers*, 2008, vol. 39, pp. 1096–1099.

[27] Y.-T. Hsu, F.-C. Lin, C.-H. Chen, Y.-P. Huang, and H.-P. D. Shieh, "Drive and control circuitry of OCB field-sequential color LCD with high data rate," in *IDMC 2007*, pp. 435–438.

[28] L. Y. Liao, F. C. Lin, Y. P. Huang, H. P. D. Shieh, and S. C. Yeh, "A real-time liquid crystal signal compensation method for high dynamic range LCD," in *IDW 2007*, pp. 1–1.

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