A Field Sequential Color LCD Based on Color Fields Arrangement for Color Breakup and Flicker Reduction

Chun-Ho Chen, Fang-Cheng Lin, Ya-Ting Hsu, Yi-Pai Huang, and Han-Ping D. Shieh, *Fellow, IEEE*

***Abstract*—The field sequential color (FSC) mechanism can effectively generate multi-primary color fields in temporal sequence to form a full-color image. Color breakup (CBU), however, has appeared intrinsically in conventional FSC displays to degrade visual qualities. A novel CBU suppression method, color fields arrangement (CFA), was proposed to eliminate the artifacts for FSC liquid crystal displays (LCDs). The modified order of consecutive color fields results in superimposed color images on a retina without CBU. Additionally, the 4-CFA method with a field rate of 240 Hz was found to avoid the flicker phenomenon on static images. The proposed method was successfully implemented on a 5.6-in optically compensated bend (OCB) LC panel. Our results confirm that the visibility of CBU artifacts can be reduced as the evaluation of dynamic and static models.**

***Index Terms*—Color breakup (CBU), field sequential color (FSC), flicker.**

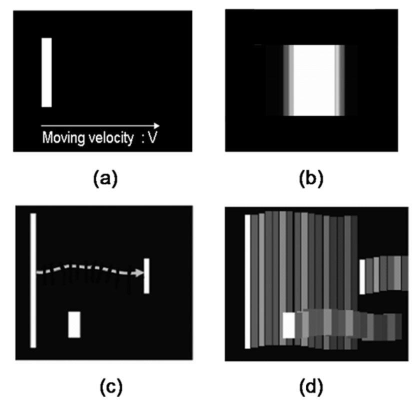

Fig. 1. (a) A moving white bar image; (b) perceived CBU image; (c) a still image with path of a saccade; and (d) observed CBU during or just after the saccade [9].

I. INTRODUCTION

SINCE the last decade of the 20th century, display technologies have been progressing rapidly. A liquid crystal display (LCD) is the most dominated display device due to the desired features of thin format, compact size, light weight, and high image quality. The liquid crystal (LC) does not emit light itself; therefore, the LCD equipped with an illuminator called a backlight system disposed at the rear surface thereof. Thus, the amount of light from the backlight which transmits through the color filter built in pixel structures of the LC panel is controlled in order to realize full color images. However, only one third of light from the backlight is transmitted, resulting in a poor optical efficiency of the light usage. This drawback can be alleviated by using the field sequential color (FSC) mechanism that was known as one trail of the color displays in the mid-20th century. According to the recent development of fast response LC such as the optically compensated bend (OCB) mode [1], [2] and backlight light sources such as the high efficient light-emitting diodes (LEDs), LCDs have enabled the reintroduction of the FSC mechanism. By displaying sequential primary red, green, and blue sub-images faster than the time resolution of human eyes, full color images can be observed without a requirement of the color filter. In a combination with LED backlights and OCB mode LC panels, FSC-LCDs are now expected as future color LCDs with high light efficiency, low power consumption, and low material cost [3]–[5].

It is well known that the most serious issue of FSC displays is the "color breakup (CBU)" artifact [6]–[8]. CBU occurs when there is a relative motion between the object within the imagery and the observer's eyes. When the color object is moved by a certain motion vector as shown in Fig. 1(a), eyes are tracking the same motion vector smoothly. The perceived CBU image is called a dynamic CBU as shown in Fig. 1(b). For static images, the eyes may induce the saccade movement and then perceive a static CBU along the motion direction. Figs. 1(c) and (d), [9] show that an original still image seems to be broken into three color fields along the motion direction at the instant of saccade eye movement.

Aiming at the CBU reduction, many researches and experiments were reported to optimize the driving method. These proposals can be categorized as field rate increasing [10], multi-primary color-field insertion [11], and motion compensation [12]. The CBU is expected to be reduced by increasing the field rate. However, this method required a double or higher field rate of color sequence, which was not practical in the current LCD system. In a multi-primary color fields of RGBYC (Y for yellow, C for cyan), the perceived CBU was determined by the order of color sequence and the tracking of the brightest field. Less CBU of five-primary system was produced than that of three-primary (RGB) one. Nevertheless, fast image fields and fast response time of LC were still required. By the motion compensation, RGB sub-images were displayed at different points along the

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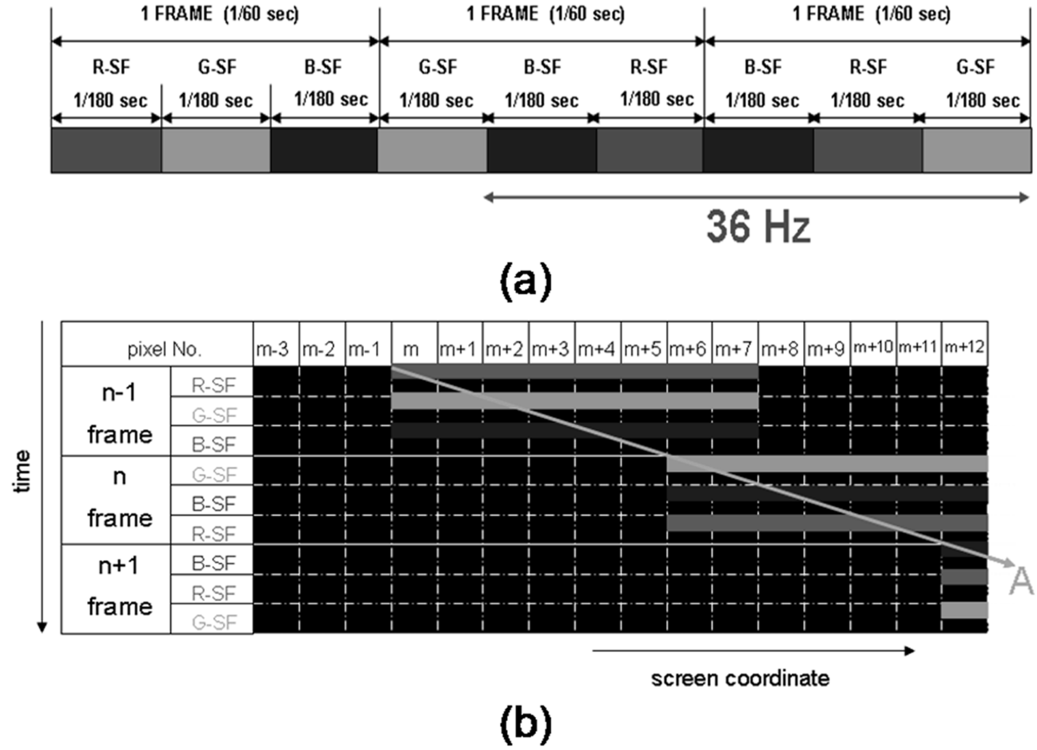

Fig. 2. (a) Color fields of RGB, GBR, and BRG in three consecutive frames. (b) Relation between time and location of motional image.

moving speed of object. As eyes tracked the moving object, these sub-images were focused in the same point on the retina, therefore, CBU was not observed. However, most video contents are too complicate to take into account all motion vectors in a real situation. This driving method is simply effective in particular cases.

In this paper, we proposed an effective method, color field arrangement (CFA), to reduce the CBU of FSC-LCDs. According to the relation between time and location of motional image, the adequate color field orders of three consecutive frames were found to compensate with each primary color. The CBU mechanism and perceived images on the retina were simulated when eyes followed the motional image. In addition, the flicker phenomenon, which occurred in both temporal variation of the luminance (brightness) and chromaticity (color) [13], has been considered and prevented. A 4-CFA method with repeats on color fields was proposed to suppress the flicker phenomenon and still perform to eliminate the CBU. This proposed method has been implemented and verified on a 5.6-in OCB-LCD. Finally, a comparison of the CBU perception with conventional and the CFA method was shown. The physical evaluation of dynamic and static CBU with eyes tracing has also been measured.

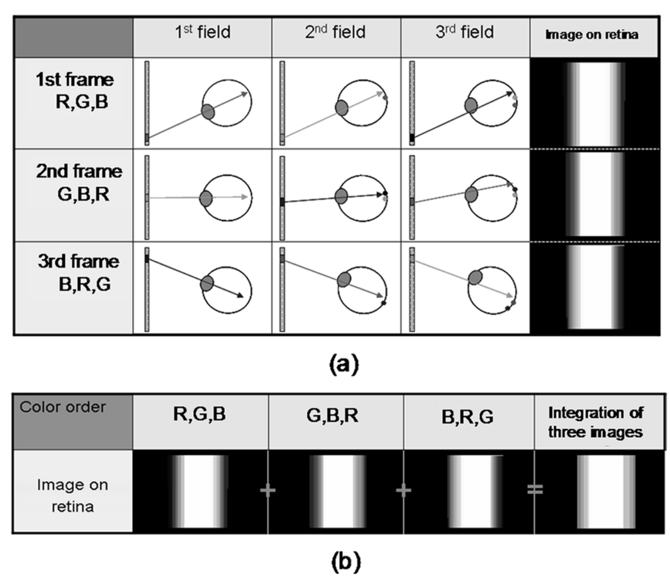

Fig. 3. (a) Mechanisms of the color breakup when eyes follow the motional image. (b) An integrated image in three consecutive frames with the CFA method.

II. Proposed CBU Reduction Method

A. Color Fields Arrangement Method

The two dimension time and location diagram was analyzed in order to determine an integration image of consecutive frames on FSC-LCDs [10]. The fields of primary colors are respectively displayed in Fig. 2. When the observer views a moving image, the viewpoint follows the shift of the image, as indicates by the arrow A. Consequently, the observer recognizes a CBU image as rainbow color in Fig. 3(a). The outline portion of image is determined by the order arrangement of color fields. Two other frame images with the color fields arrangement (CFA) were obtained. The integration of three consecutive frames is shown in Fig. 3(b). The image on a retina will be compensated as a gray level image because of the viewpoint through the same ratio of each primary color. Consequently, the observer recognizes a non-CBU image with these color fields.

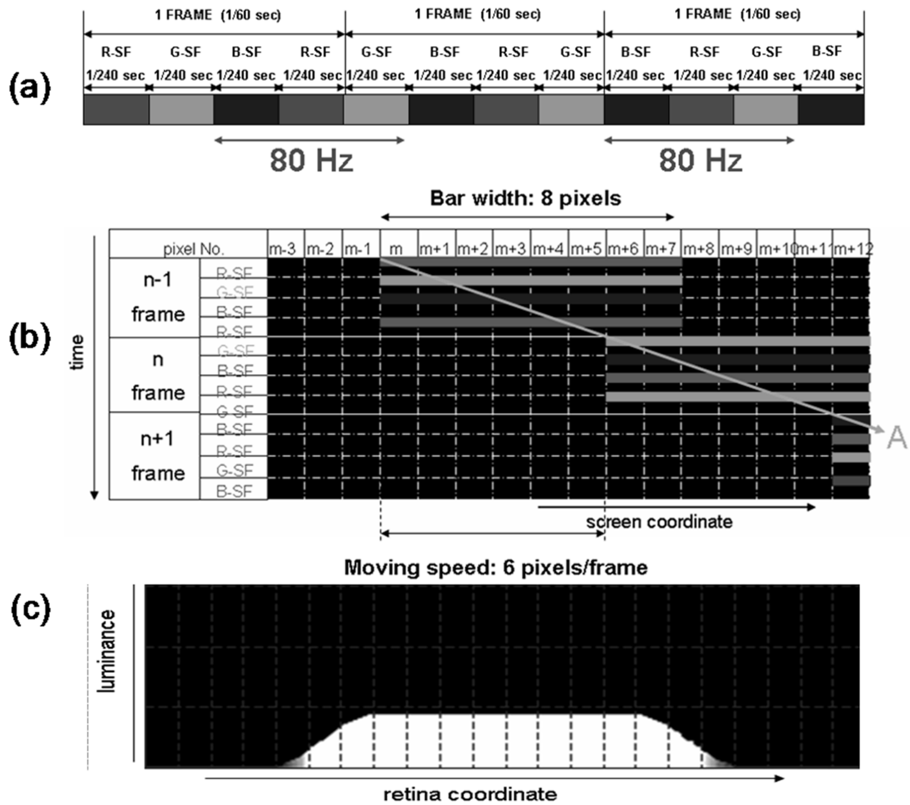

Fig. 4. (a) Color fields of RGBR, GBRG, and BRGB in three consecutive frames, (b) the relation between time and location of motional white bar with width of 8 pixels and velocity of 6 pixels/frame, and (c) the simulation image on retina with the 4-CFA method when eyes follow the image.

TABLE I
LOWEST FIELD FREQUENCY THAT PRODUCES INVISIBLE FLICKER FOR EACH COLOR

	R	G	B
Frequency (Hz)	30	50	35

Although the CFA method can avoid the CBU of dynamic images, a flicker phenomenon will be an issue for the CFA method. Because the human eye is more sensitive to green color, the lowest field frequency for green color to perceive invisible flicker is 50 Hz as shown in Table I [14]. However, the green field appeared at the first and third fields in straight two frames. The green field frequency of 36 Hz in this worst case would be lower than the invisible condition. In order to suppress the flicker phenomenon, we proposed to insert a fourth color field to speed up the field frequency.

B. 4-CFA Method With Repeating Color Orders

The color fields with orders of RGBR, GRBG, and BRGB in three consecutive frames were proposed in the 4-CFA method. The color of the fourth field repeated the one of the first field as shown in Fig. 4(a). The motional image and simulation result of a moving image of white bar are shown in Figs. 4(b) and (c). The margin of perceived image is blurred due to differences in brightness but without color separations. In addition, the flicker phenomenon should be suppressed because of the color field frequency of 80 Hz, higher than the invisible condition of 50 Hz.

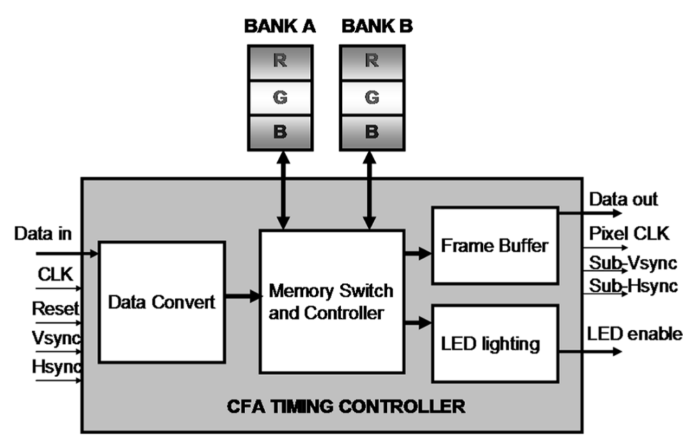

Fig. 5. The block diagram of the FSC controller.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Implementation of FSC Controller

A timing controller, which is designed to convert the image data to a desired format in response to the timing signal, is a key component in an FSC system. The block diagram of the controller is shown in Fig. 5. This controller consists of the data convert, frame buffer, memory switch, and LED lighting unit. A graphic card is used to convert the input video rate to 60 Hz in advance. These 24-bit RGB input signals are stored

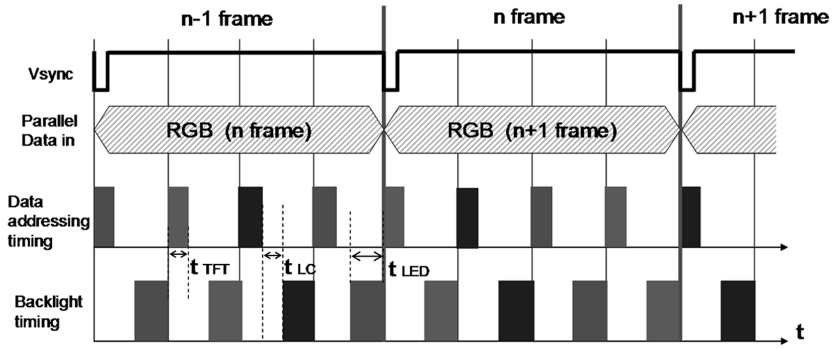

Fig. 6. Timing chart of the 4-CFA FSC-LCD.

into monochromatic red, green, blue data separately in the data convert unit. The function of the memory switch unit is to access the consecutive frame data alternately between two banks of SDRAM. As one is on reading operation, the other one is on writing operation. To avoid conflicts of the consecutive frame data during the operation, a frame buffer is as a register to translate the data into LCD drivers. At the same time, an LED timing unit determines the enable signals for LED drivers to switch corresponding LEDs on.

A 5.6-in OCB-LCD with QVGA resolution was used as a prototype to evaluate the properties of CBU and flicker phenomenon. The response time of OCB mode LC cell $(\mathrm{t_{LC}})$ and the data addressing time $(\mathrm{t_{TFT}})$ were about 1.0 and 1.2 ms in this study. For a field frequency of 240 Hz, the illumination time of LEDs $(\mathrm{t_{LED}})$ about 1.9 ms was obtained as shown in Fig. 6. The backlight intensity of first and fourth fields was modified to meet the criterion of white balance. From the observation, there was no flicker phenomenon as we predicted. The videos of the prototype with 3- and 4-CFA are available on ftp://fpd:fpd@140.113.165.213:518.

B. Physical Evaluation of CBU

The evaluation works of CBU were done by a camera-tracking experiment. The perception of CBU was evaluated to verify the proposed CBU reduction method. The motion image in Fig. 1(a) was used as a test pattern to compare the image quality with the conventional and proposed methods. A stage with a high-speed camera, Phantom V5.1 by Vision Research, Inc. [15], was set up on a track and adjusted the velocity by a computer interface. In order to simulate the shift of the observer's viewpoint, we synchronized the moving velocity of the bar on the image and the camera on the track. The exposition time of camera was set to 1/20 second to integrate three consecutive frames while a frame frequency was 60 Hz. The experimental results of perceived images are agreed with the observation as shown in Fig. 7. The CBU is eliminated in the 4-CFA method with a blurring margin as predicted in Fig. 4(c). On the contrary, the conventional CBU was obvious for multi-color. Considering the moving velocities, the CBU widths are proportional to the velocities of objects on a motional image. Similarly, the blurring margin of fast-motional image became wider in the 4-CFA method. Fig. 7 shows the comparison results with bar widths of 15 and 30 pixels. The widths of CBU and blurring margin were independent to bar widths in both driving methods. Moreover, cyan and yellow bars were tested in the 4-CFA method as shown in Fig. 8. Images with

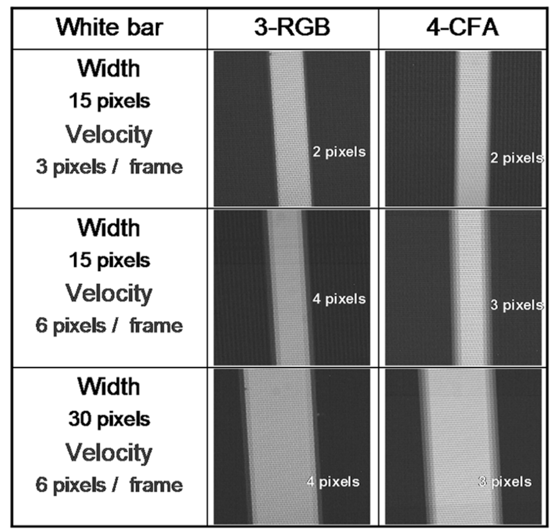

Fig. 7. Photos of a moving white bar, which were taken by a tracing camera, with bar widths of 15 and 30 pixels, velocities of 3 and 6 pixels/frame.

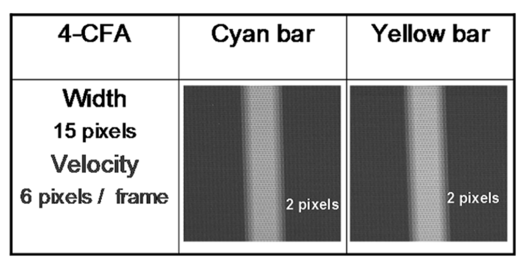

Fig. 8. Photos of moving cyan and yellow bars, which were taken by a tracing camera, with bar width of 15 pixels and velocity of 6 pixels/frame.

narrower and blurring margins were obtained simultaneously. Comparatively, field rate increasing [10], one of previous CBU reducing methods, could narrow the CBU width but not blur the margin at the same time. On the contrary, the intensity of color separation could be lightened but the CBU width could not be narrowed by multi-primary-color insertion method [11]. From the evaluation results, the color-field orders of 4-CFA is concluded as the practical method to eliminate the CBU phenomenon.

C. Discussion of Static CBU

In order to evaluate accurately the image qualities, the static CBU should be considered. The static CBU occurs when abrupt perturbation produces the saccadic movement. This movement

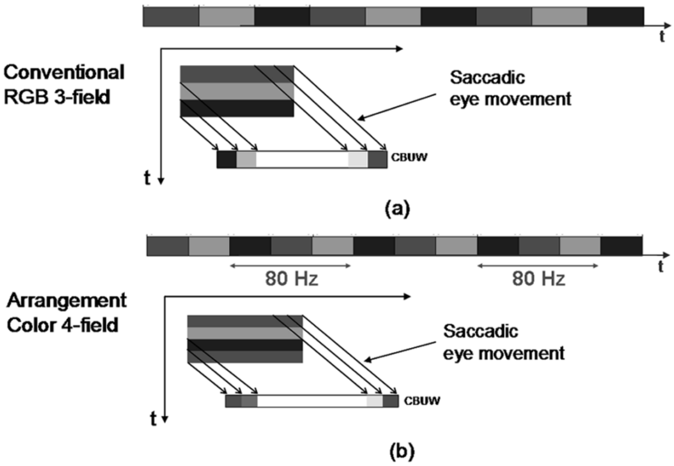

Fig. 9. Mechanism of static CBU with (a) conventional and (b) CFA methods.

gives a retina broken color sequence which is easily experienced while rotating the head or eyes. Therefore, the effective way to reduce this artifact is to increase the sequential frequency. For the still image, the field frequency of 4-CFA in three consecutive frames is 240 Hz as shown in Fig. 9. Comparing the static CBU with the conventional and 4-CFA methods, the field frequency of 4-CFA is 1.3 times faster than that of the conventional one, resulting the slighter static CBU width. The results of our evaluation supported that the proposed 4-CFA method can reduce the visibility of CBU artifacts.

IV. Conclusion

The FSC-LCD is desirable for its high optical efficiency, low power consumption, and low cost. However, the color breakup is significantly observed on FSC-LCDs. We have proposed a novel CBU suppression method, 4-color field arrangement (4-CFA) method, to eliminate the artifacts for FSC-LCDs. A 5.6-in prototype FSC-LCD was built and confirmed experimentally on the CBU suppression. According to the velocity of the moving bar, a synchronized high-speed camera system was to substitute for the movement of eyes tracking. In comparison with the conventional 3-field RGB driving method, the margin of image was blurred without the CBU in the 4-CFA method. The physical evaluation results of perceived images on static and dynamic CBU are agreed with the prediction. Among the investigated field sequential color methods, the 4-CFA method is concluded as the practical method to suppress the CBU for FSC-LCDs.

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