Color Filter-Less LCDs in Achieving High Contrast and Low Power Consumption by Stencil Field-Sequential-Color Method

Fang-Cheng Lin, Yi-Pai Huang, Ching-Ming Wei, and Han-Ping D. Shieh, *Fellow, IEEE*

***Abstract*—The field-sequential-color liquid crystal display (FSC-LCD) without a color filter enables high light efficiency, wide color gamut, and low material cost. However, the visual defect of color breakup (CBU) is perceived when relative velocities exist between the screen image and the human eye. We proposed the Stencil-FSC method with a 240-Hz field rate to make CBU imperceptible. Given the Stencil-FSC method, the hardware parameters were optimized to reduce hardware complexity while maintaining sufficient suppression of CBU. After implementing Stencil-FSC on a 32-in FSC-LCD, the image contrast ratio was shown to be ten times more than that of a conventional CCFL LCD, and the average power consumption was reduced to less than 35 W—a 67% savings in power consumption.**

***Index Terms*—Color breakup (CBU), field-sequential color (FSC), low power consumption, stencil.**

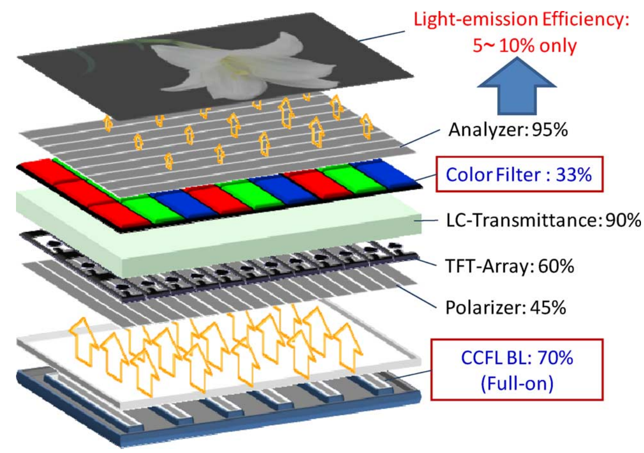

Fig. 1. Low light-emission efficiency in a CCFL backlight (BL) LCD attributed to the transmittance of each optical component.

I. Introduction

LIQUID crystal displays (LCDs) are widely used in small mobile devices, car navigation systems, notebooks, monitors, and TVs. The high number of applications can be attributed to several features, including high resolution, high brightness, light weight, and thin profile. However, LCDs have traditionally suffered from low power efficiency and an imperfect black level. A traditional active-matrix LC-TV system is generally illuminated using a constant full-on backlight which consists of conventional cold cathode fluorescence lamps (CCFLs). The generated light propagates through an optical stack comprised of two sets of polarizers, color filters, and diffusers. In each of these components, substantial proportions of light are scattered and absorbed. Overall, approximately $5 \sim 10\%$ of light generated by the backlight reaches the front-of-screen image (Fig. 1).

A high light efficiency field-sequential-color (FSC) LCD without a color filter was proposed to reduce power consumption [1], [2]. By rapidly displaying red (R), green (G), and blue (B) field-images time-sequentially, a full-color image was created by temporal color synthesis, as illustrated in Fig. 2. To prevent luminance flicker, the three-primary color system required a minimum refresh rate of 180 Hz. Consequently, fast response light-emitting diodes (LEDs) were applied to LCD backlight systems to replace conventional CCFLs. Without a color filter, FSC-LCDs are prized for many characteristics, such as high light efficiency, wide color gamut, low material cost, three times the possible screen resolution, and other features, when compared with LCDs with color filters.

However, FSC-LCDs still face an inherent visual artifact, color breakup (CBU), which occurs when relative velocities exist between the screen object and the human eye. This may occur during both smooth motion pursuit (eye velocity is slower than 90 deg/s) and particularly saccadic movement (eye velocity is faster than 90 deg/s) [3]–[6]. During eye movements, the separated R, G, and B sub-pixels of an image degrade image quality and cause viewer discomfort, as shown in Fig. 3. Once the CBU issue is overcome, a low power consumption and high image quality LCD becomes feasible.

CBU suppression has been implemented on digital light processing (DLP) projectors by inserting additional mono-color fields [7] or increasing the field rate to 540 Hz or more [8]. Hence, most traditional CBU solutions for FSC-LCDs involved either inserting additional mono-color fields or increasing the field rate [9]–[13]. Although LED backlights can be switched very rapidly, LC response time prevented the implementation of many of the above methods in large-sized FSC-LCDs.

In light of the above, we thus propose an alternative method we termed the “Stencil Field-Sequential-Color” (Stencil-FSC)

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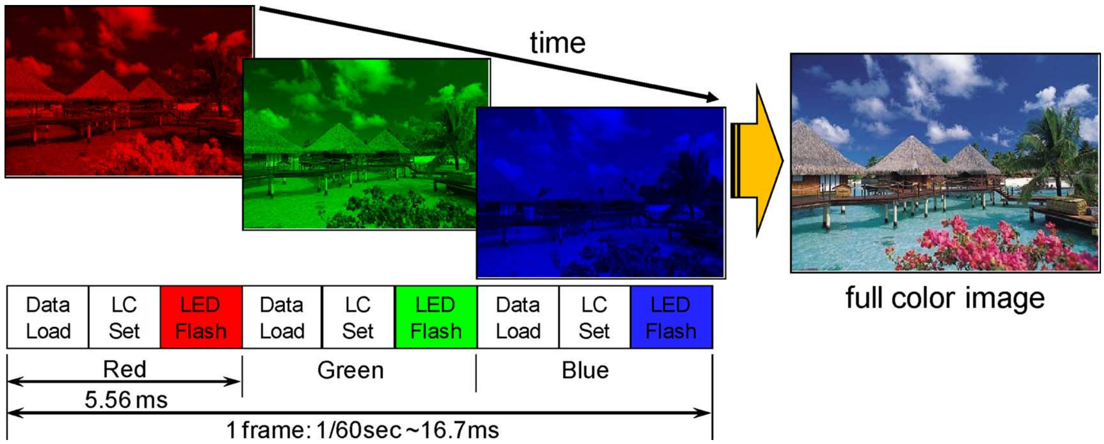


Fig. 2. FSC-LCD mechanism: A color image is created by rapidly flashing the display primaries in time- sequence.

(a) Target image (b) CBU image

Fig. 3. (a) Target image, *Lily* and (b) FSC display color breakup phenomenon (orange dotted circle).

method to suppress CBU. Stencil-FSC can be implemented on an FSC-LCD TV by using a conventional OCB-LC mode [14], [15] because a low field rate of 240 Hz (four sub-frames) is used. In addition, Stencil-FSC utilizes a "multi-color" field in a single sub-frame image to suppress CBU, which is much different from previous CBU reduction methods. In this paper, we first describe the concept and algorithm of Stencil-FSC. Hardware parameters are then optimized using simulations of the Stencil-FSC method. CBU reductions from field rate increases and from Stencil-FSC are then compared via simulations. Finally, the experimental results from implementing Stencil-FSC on an FSC-LCD are discussed.

II. Stencil FSC Method

A. Concept

CBU is perceived because three high luminance primary-color images cannot be projected onto the retina at the same position, when eye gaze sweeps across the screen. When R, G, and B image intensities are reduced, the CBU phenomenon caused by smooth pursuit (in dynamic videos) or saccadic movement (in static pictures) is noticeably suppressed even though the three images are projected onto the retina separately. Therefore, using this concept, instead of "mono-color" images, a "multi-color" image was used in the 1st-field to display high luminance and rough color; the other three dimmer primary-color fields were then used to only modify color details (Fig. 4). Combining these four field-images, a vivid color image with less perceptible CBU was created on an FSC-LCD. Using a "multi-color" image in a color filter-less LCD to suppress CBU is unprecedented in FSC-related technologies. We named the method Stencil Field-Sequential-Color or Stencil-FSC because its process was similar to "stencil" painting.

Local color-backlight dimming technology [16]–[19] was utilized to produce a multi-color image on a color filter-less FSC-LCD. An LC-TV with a local backlight control comprised the superposition of two displays with different spatial resolutions: a low resolution LED array backlight and a high resolution LC panel [20]. The backlight module displayed a low resolution color image, and the color filter-less LC cell preserved high resolution monochrome image details. In applying the Stencil-FSC method to suppress CBU, there were two main features that necessitated local color-backlight diming technology: high image contrast ratio and low power consumption when compared to conventional LCDs and traditional FSC-LCDs.

The Stencil-FSC algorithm is derived and shown in Fig. 5. Using local color-backlight dimming technology, a set of three primary-color backlight signals was obtained using a color-backlight determination method (BL_R, BL_G, and BL_B) [21]. Accordingly, the corresponding LC compensation transmittances were determinate (T_R, T_G, *and* T_B). In this paper, the image was evenly divided into non-overlapping rectangles corresponding to the number of backlight divisions. We directly averaged the all three primary-color pixel values that subtended the rectangular region in front of each given backlight division independently as color-backlight signals (BL_R^o, BL_G^o, BL_B^o). The detailed local color-backlight dimming algorithm is illustrated in Fig. 6 and explained in Section II-B.

B. Backlight Intensity Distribution

After determining color-backlight signals, the crosstalk between LED backlight divisions was considered when compensating LC signals [22]–[24]. Convolving the backlight signal with the point spread function (PSF) of each backlight division is a traditional method for obtaining backlight intensity distribution. A broader PSF results in visible crosstalk and produces a blurrier backlight image. When convolution is used, computational complexity makes real-time demonstrations prohibitively difficult. To reduce computational complexity, we utilized the Discrete Fourier Transformation (DFT) and a Gaussian low pass filter (GLPF) to simulate three primary color-backlight intensity

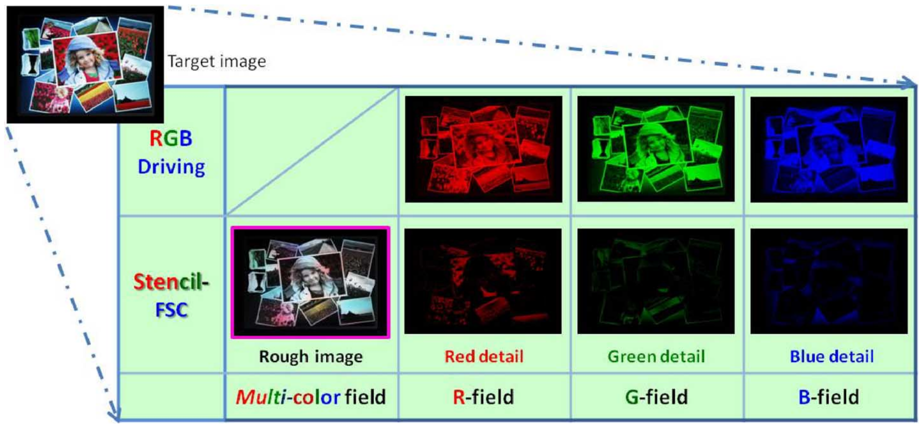


Fig. 4. Target image (*Girl* © Microsoft, http://www.microsoft.com/surface/index.html) and field images using the conventional FSC-LCD and Stencil-FSC method.

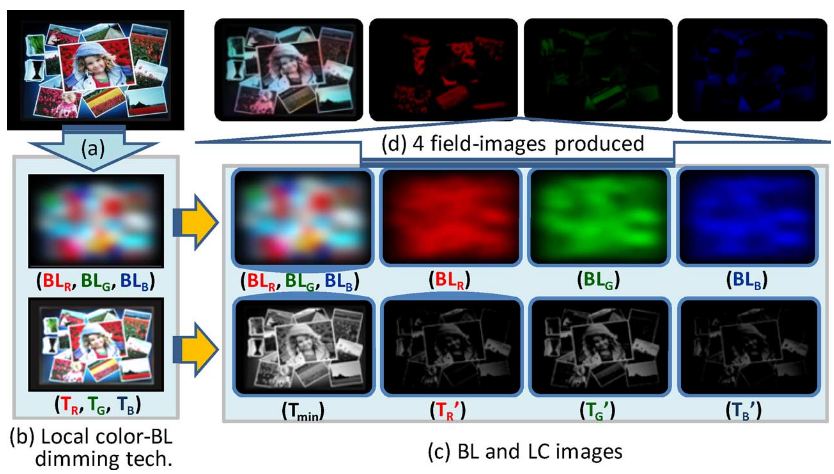


Fig. 5. Stencil-FSC algorithm processing. (a) Input image. (b) Local color-backlight dimming technology. (c) Backlight and LC images produced. (d) Four field-images produced.

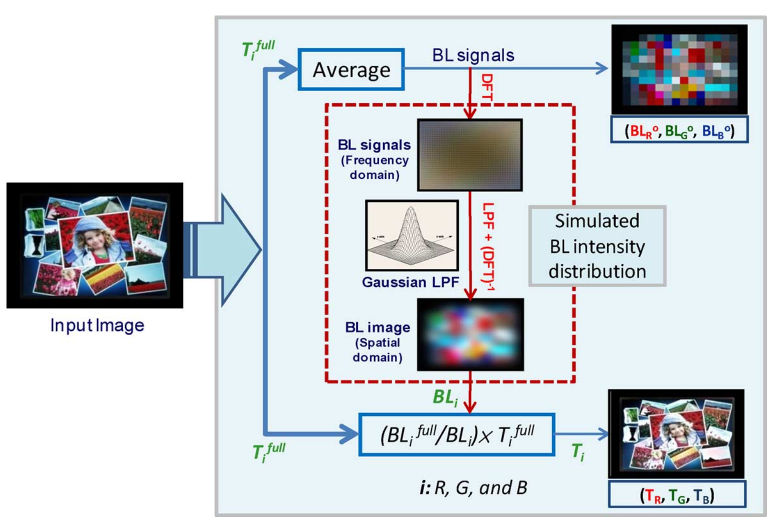


Fig. 6. Processing of local color-backlight dimming algorithm.

distributions (BL_R, BL_G, and BL_B), as illustrated in Fig. 6. First, the color backlight signals of each backlight division were determined (BL^o_R, BL^o_G, *and* BL^o_B). Second, the DFT process transferred the backlight signals from the spatial domain to the frequency domain. When utilizing a GLPF, the high frequency information (the boundary area) was filtered out. Finally, a light spread backlight image was simulated by using the inverse of the DFT process (BL_R, BL_G, and BL_B). Let $H(u, v)$ denote

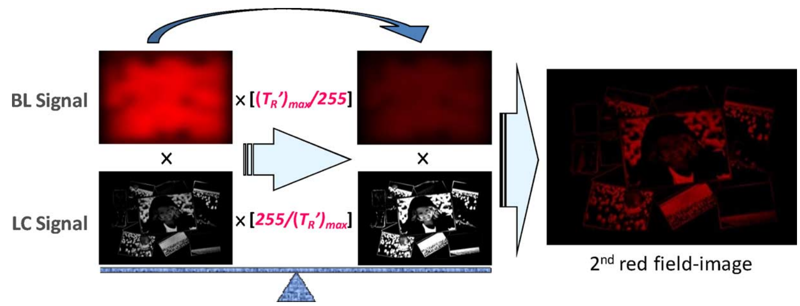


Fig. 7. Taking the red signal as an example, like a seesaw concept, enhancing LC signals by multiplying a ratio of $255/(\mathrm{T'}_R)_{\max}$ and reducing BL signals by multiplying a ratio of $(\mathrm{T'}_R)_{\max}/255$, the same luminance 2nd red field-image was produced.

the Gaussian filter in the frequency domain, and its function is given in (1)

$$H(u,v) = e^{-D^2(u,v)/2{D_0}^2} \quad (1)$$

where $D(u,v)$ is the distance from the Fourier transform origin and D_o is the cutoff frequency. The (u,v) represents the position in the frequency domain [25]. Moreover, D_o is directly related to backlight spread. For example, a smaller D_o value allows lower frequency content and results in a blurrier backlight image. Therefore, we can simulate the backlight intensity distribution in arbitrary PSFs by controlling D_o.

C. Production of Four Field-Images

After obtaining the backlight intensity distribution (BL_i) by using the DFT and a GLPF, the LC transmittance values of R, G, and B sub-frames, T_R, T_G, and T_B, were compensated for by using (2), where I_i^{full} and I_i denote image luminance; BL_i^{full} and BL_i denote intensities of the traditional full-on backlight and blurred backlight images while using local color-backlight dimming technology. Then, $T_{\min}$ was calculated by taking the minimum transmittance value across T_R, T_G, and T_B for each LC pixel to generate the LC signal for the first sub-frame. The new LC signals for the R, G, and B sub-frames, T'_R, T'_G, and T'_B, were determined using (3)

$$I_i^{full} = I_i \Rightarrow BL_i^{full} \times T_i^{full} = BL_i \times T_i \quad i = R,G,B$$
$$\Rightarrow \begin{bmatrix} T_R \\ T_G \\ T_B \end{bmatrix} = \begin{bmatrix} \frac{BL_R^{full}}{BL_R} & 0 & 0 \\ 0 & \frac{BL_G^{full}}{BL_G} & 0 \\ 0 & 0 & \frac{BL_B^{full}}{BL_B} \end{bmatrix} \begin{bmatrix} T_R^{full} \\ T_G^{full} \\ T_B^{full} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} T'_R \\ T'_G \\ T'_B \end{bmatrix} = \begin{bmatrix} T_R \\ T_G \\ T_B \end{bmatrix} - T_{\min}, \text{ where } T_{\min} = \min(T_R, T_G, T_B). \quad (3)$$

Once the backlight and LC signals were determined, the three primary-color backlight signals (BL_R, BL_G, and BL_B) and the minimum LC signal $(T_{\min})$ were combined to display high luminance with rough color information in the first sub-frame image. Likewise, combining the BL_R with T'_R, BL_G with T'_G, and BL_B with T'_B, created three other primary-color images as shown in Fig. 5 (sections c and d). Displaying these four sub-frame images at 240 Hz generated a vivid color image. This allowed the image energy to be concentrated in the first field, thus reducing the intensities of the red, green, and blue fields which ultimately suppressed CBU. Additionally, a clipping effect was observed while local-dimming technology was used. When backlight signals were excessively low, the LC compensation signals would exceed 255 (for 8-bit signal). Therefore, the high-dynamic-range display system could not show the signal correctly, thus the "clipping effect" became perceivable [26]. Using the Stencil-FSC method, each primary color had two sub-frames displaying its luminance and color (the multi-color field and the primary-color field); therefore, the clipping effect was not obvious. Accordingly, the Stencil-FSC method also increased the dynamic contrast and lowered power consumption because local color-backlight dimming technology was used.

D. Further Power Reduction

LC image intensities were low in Fig. 5(c), implying that LC signals could be enhanced to reduce backlight signals and simultaneously lower power consumption. Red, green, and blue residual LC signals were enhanced by multiplying by a factor of $255/(T'_i)_{\max}$, and each backlight division signal was reduced by multiplying by a factor of $(T'_i)_{\max}/255$ to preserve prior luminance (Fig. 7). The i denotes the R, G, and B index and $(T'_i)_{\max}$ denotes the maximum LC signal in each field-image. By recalculating backlight and LC signals, power consumption was further reduced using the same image luminance.

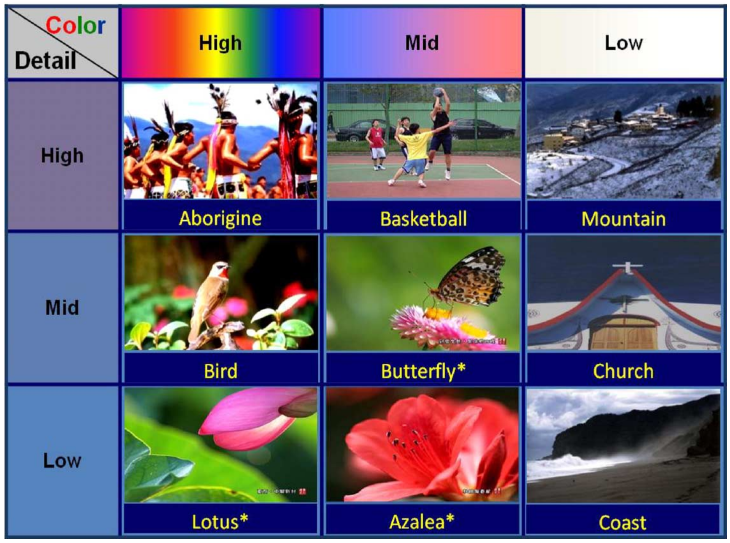
III. Optimization of the Stencil-FSC Method

In CBU suppression and hardware implementation, two parameters were optimized to suppress CBU more efficiently: the number of backlight divisions and the cutoff frequency (D_o) of the GLPF. Nine images with different levels of detail and color complexity as shown in Table I were chosen as test images. To simulate a relative velocity between the screen object and the human eyes, a CBU image was produced by composing the four field-images with 60 total pixel shifts which is equivalent to a velocity of about 180 cm/s [see Fig. 3(b)].

A. Relative CBU Value for CBU Evaluation

The color difference index was defined in the CIELAB color coordinate ($\Delta\mathrm{E}^*_{\mathrm{ab}}$ given in (4) [27]. By summing up the color difference between the original image and the CBU image ($\Sigma\Delta\mathrm{E}^*_{\mathrm{ab}}$), CBU was evaluated. A lower $\Sigma\Delta\mathrm{E}^*_{\mathrm{ab}}$ corresponded to less CBU. Using the Stencil-FSC method, the

TABLE I
NINE TEST IMAGES WITH DIFFERENT LEVELS OF COLOR AND DETAIL COMPLEXITY. (∗: TAKEN BY JACKY LEE, http://jac3158.com/blog)



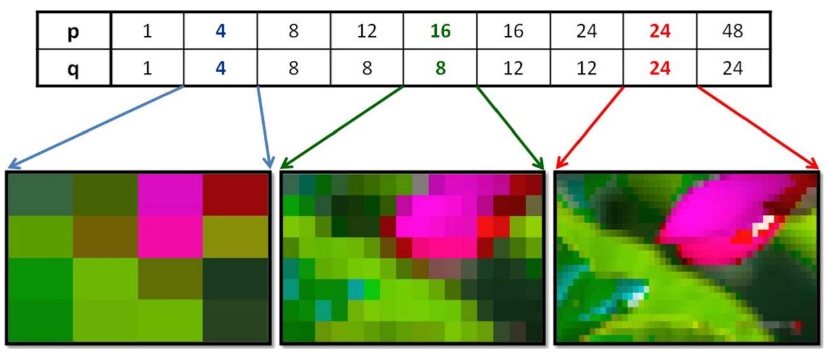


Fig. 8. Simulation backlight division combinations with three corresponding backlight signals for the test image_*Lotus*. (p is the column number and q is the row number).

relative $CBU_{\max}$ index was defined as the ratio of total color difference between $p \times q$ backlight division and the maximum total color difference as shown in (5), where p and q were the numbers of column and row backlight divisions. A smaller *relative* $CBU_{\max}$ denotes less CBU in its backlight divisions.

$$\Delta E^*_{\text{ab}} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (4)$$

$$\text{relative } CBU_{\max} \equiv \frac{\sum \Delta E^*_{\text{ab}}(\text{Target, Stencil})_{p*q}}{\max\left[\sum \Delta E^*_{\text{ab}}(\text{Target, Stencil})_{p*q}\right]} \times 100\%$$
$$p, q: \text{division number.} \quad (5)$$

B. Optimization for Point Spread Function (PSF) and Backlight Divisions

Typically, a greater number of backlight divisions suppresses CBU more effectively. On the other hand, a greater number of backlight divisions uses more IC drivers and results in greater hardware computational complexity. To help determine the optimal arrangement of backlight divisions, nine different configurations were formed by variable subdividing the total set of LEDs in an existing backlight (48 horizontal $\times$ 24 vertical) (Fig. 8). In addition, the PSF was also optimized using different backlight division combinations. As mentioned in Section II-B, PSF is directly related to D_o in the frequency domain. Therefore, 0.001, 0.003, 0.005, 0.007, and 0.010 were five D_o values used in each backlight division combination to get the minimum total color difference ($\Sigma\Delta \text{E}^*_{\text{ab}}$).

The nine test images, as shown in Table I, were used to test the number of backlight divisions vs. D_o values which caused the minimum $\Sigma\Delta \text{E}^*_{\text{ab}}$ and is shown in Fig. 9. The number of backlight divisions vs. *relative* $CBU_{\max}$ is shown in Fig. 10. In Fig. 9, a larger number of divisions using a larger D_o value can get the minimum $\Sigma\Delta \text{E}^*_{\text{ab}}$. Therefore, when the number of divisions is larger, the PSF became more localized. From Fig. 10, as the number of backlight divisions increases, *relative* $CBU_{\max}$ decreases till 24×12 backlight divisions when $\text{CBU}_{\max}$ effect becomes invisible. When taking into account CBU suppression and hardware implementation, $24 \times 12 \sim 24 \times 24$ might be the optimal number of backlight divisions.

C. Simulations of CBU Suppression

Comparing the D_o value and optimized number of backlight divisions, we chose $D_o = 0.010$ and 24×24 backlight divisions as the optimized combination to simulate CBU suppression. Comparing the total color difference caused by Stencil-FSC and

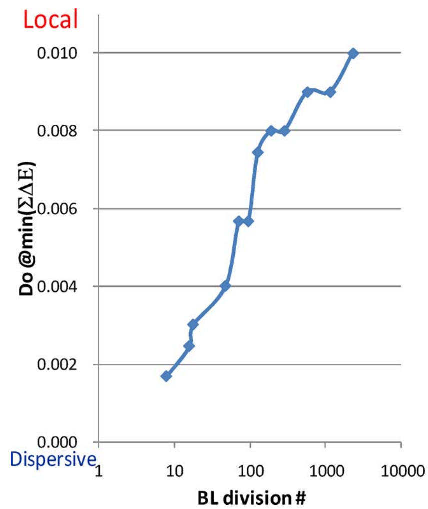


Fig. 9. Relation between the number of backlight divisions and the D_0 value when creating minimum $\Sigma\Delta \mathrm{E}^*_{\mathrm{ab}}$.

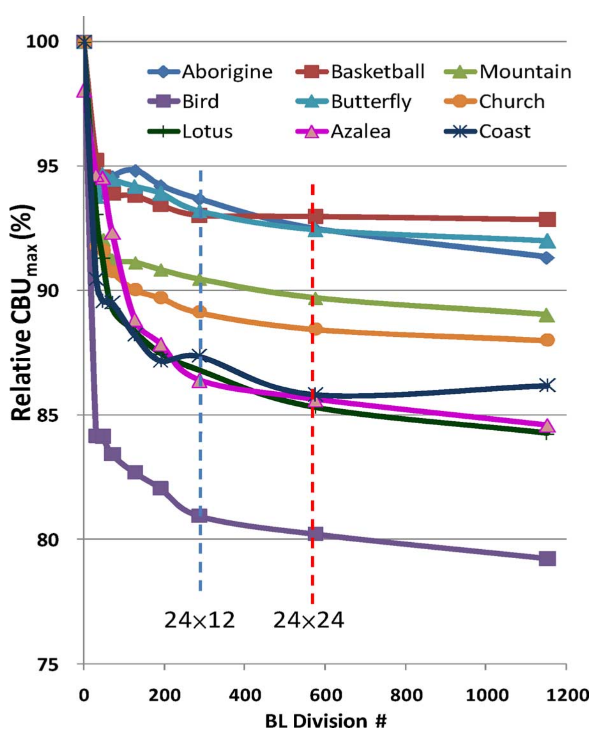


Fig. 10. Relation between the number of backlight divisions and the relative $\Sigma\Delta \mathrm{E}^*_{\mathrm{ab}}$ ratio caused by CBU in the nine test images.

conventional RGB-driving, *relative* $\mathrm{CBU_{RGB}}$ was defined in (6) to evaluate what percentage of CBU, caused by the conventional RGB-driving, was suppressed. According to Fig. 11, Stencil-FSC suppressed CBU by $14 \sim 66\%$ when related to RGB-driving, and the average *relative* CBU_{RGB} was 47% for the nine test images.

$$relative\ CBU_{\mathrm{RGB}} \equiv \frac{(\sum \Delta E^*_{\mathrm{ab}})_{\mathrm{Stencil-FSC}}}{(\sum \Delta E^*_{\mathrm{ab}})_{\mathrm{RGB-driving}}} \times 100\%. \quad (6)$$

D. Comparison of CBU Suppression Using Different Driving Methods

CBU suppression using Stencil-FSC was also compared to double (360 Hz) and triple (540 Hz) driving field rates methods. $\Sigma\Delta \mathrm{E}^*_{\mathrm{ab}}$ of the nine test images using these three methods were calculated and then divided by $\Sigma\Delta \mathrm{E}^*_{\mathrm{ab}}$ of RGB-driving (*relative* CBU_{RGB}). The average *relative* CBU_{RGB} values using 360 Hz, 540 Hz, and Stencil-FSC were 76.6%, 59.8%, and 47.2%, respectively, and are illustrated in Fig. 12. In conclusion, the Stencil-FSC method was more effective than increasing the field rate, when CBU suppression and hardware implementation were considered.

IV. Experiments on a 32-Inch FSC-LCD

The Stencil-FSC method was implemented on a 32-inch OCB-mode FSC-LCD with 1366×768 image resolution. The backlight module was composed of 1152 (48×24) LEDs [28]. To capture the CBU image, a digital still camera (Fujifilm-F50) was set up 2 m from the FSC-LCD on a moving stage with a horizontal velocity of 200 cm/sec to simulate eye movement (about 53 deg/sec). The camera exposure time was 1/60 s. Two pictures, *Girl* and *Lily*, were used as test images. In Fig. 13(a), the first sub-frame photo presents a multi-color image with high luminance and rough color information. The red, green, and blue residuals in the remaining fields completed a full color image. This allowed the image energy to focus in the 1st-field, and reduce the red, green, and blue field intensities and suppressed CBU. The experimental CBU photos in Figs. 14 and 15 demonstrate the Stencil-FSC method suppresses CBU effectively. In addition, by utilizing a locally controlled RGB-LED backlight, the dynamic contrast ratio (CR) of *Girl* was enhanced to 6,544:1 at 35 Watts power consumption. For the other high CR image, *Lily*, the CR was also enhanced to 26 335:1 using only 28 W. As a result, using the Stencil-FSC method, not only was CBU suppressed, but also reached high contrast with low power consumption in a 32-in FSC-LCD TV. The contrast ratio (CR), power consumption (P), CBU, and color gamut (NTSC ratio) of the three 32-in LCDs (commercial IPS-CCFL, conventional RGB driving FSC, and Stencil-FSC) displaying two test images were measured and are shown in Table II.

V. Discussion

The response time of OCB-mode liquid crystal needs to be less than 2 ms to make a 240 Hz field rate feasible. However, the OCB-mode LCD has not been extensively used in the display industry. We are working on methods to further reduce the Stencil-FSC field rate from 240 Hz (4-field) to 120 Hz (2-field). The 2-field method utilizes a high resolution LC panel and a low resolution RGB-LED backlight system to generate two field images, a red-blue field and a green-blue field. By sequentially displaying these two field images at 120 Hz, a full color image can be generated. Therefore, current commercial LC modes, such as twisted nematic (TN), multi-domain vertical alignment (MVA), or in-plane switching (IPS), can be used for a high light efficiency color filter-less LCD by the proposed Stencil-FSC to reduce power consumption and panel material cost.

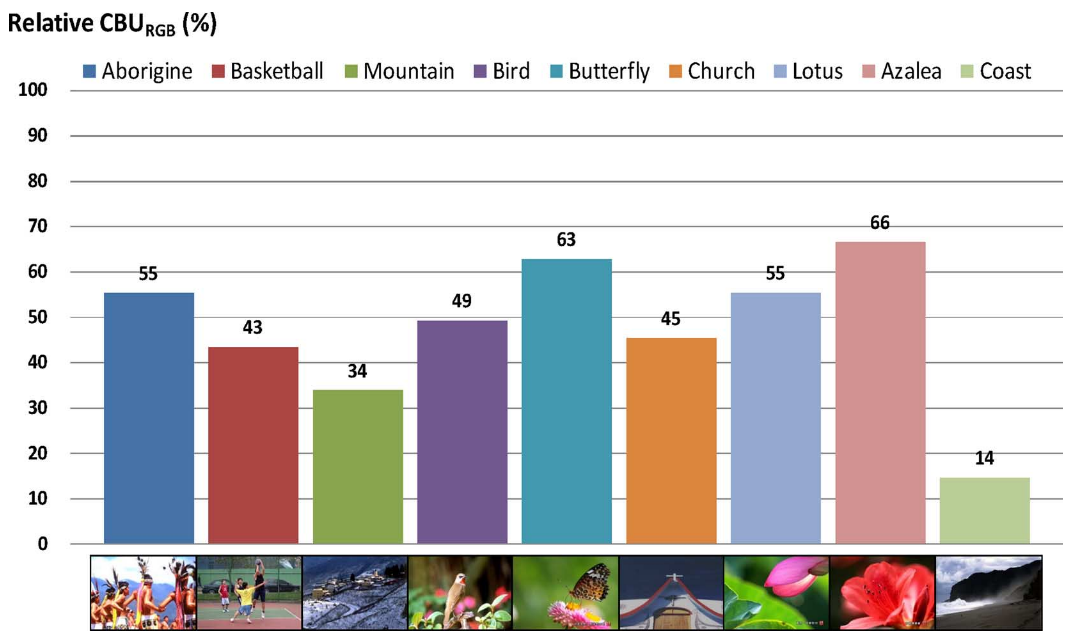


Fig. 11. Total color difference ratio by using Stencil-FSC to RGB-driving in the nine test images.

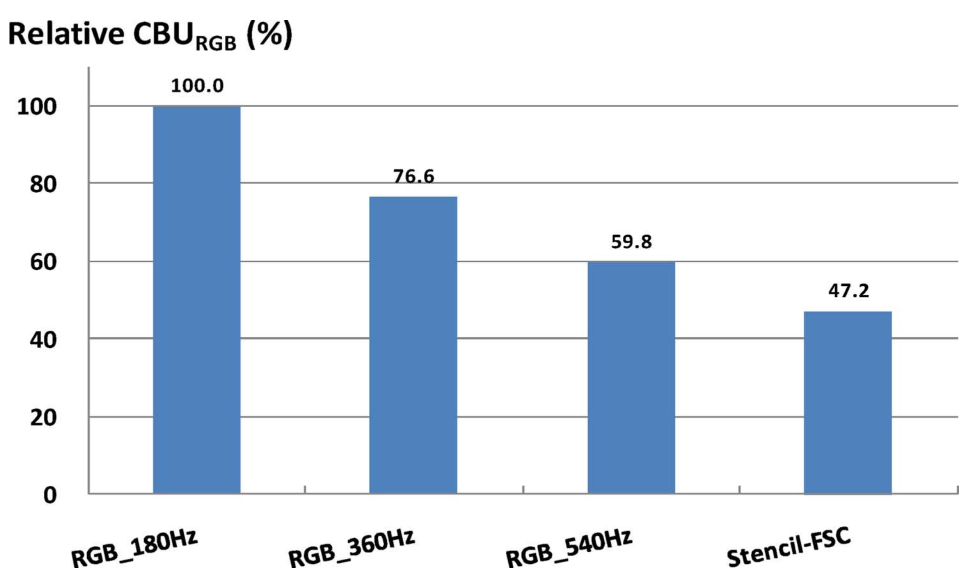
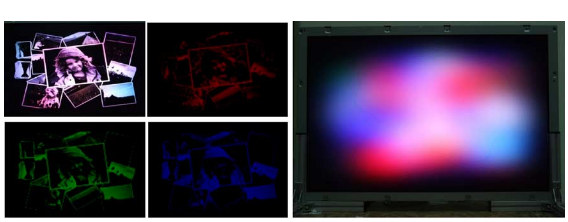


Fig. 12. Comparison of the average *relative* $\mathrm{CBU}_{\mathrm{RGB}}$ using 180, 360, and 540 Hz RGB-driving, and the Stencil-FSC method in the nine test images.



(a) Four sub-frame images (b) backlight image

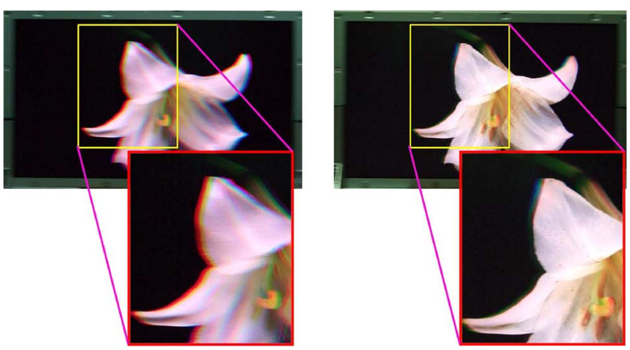
Fig. 13. (a) Four sub-frames demo photos of *Girl* (©2007 Microsoft Corporation) on a 32-inch FSC-LCD using the Stencil-FSC method. (b) Backlight image on a Stencil-FSC LCD.

VI. Conclusion

The FSC-LCD has high potential for lower power consumption. However, a visual defect, color breakup (CBU), remains an issue. We proposed the Stencil-FSC method to suppress the CBU phenomenon using a multi-color field image instead of a conventional single-color field. The RGB-LED based backlight module was treated as a low resolution panel. Using color local-dimming technology, the low resolution color image created by the LED backlight enabled the generation of a full color RGB image on a color filter-less LCD with an increased contrast ratio and color gamut. The multi-color sub-image provided high luminance and rough color content in the first field; the intensities of three other primary-color sub-images were greatly reduced and can effectively suppress CBU caused by smooth pursuit (in dynamic videos) and saccadic movement (in static pictures). In order to balance hardware complexity and CBU suppression, the number of backlight divisions can be reduced to 24×24, using a 0.010 cutoff frequency for the Gaussian low

(a) Conventional FSC-LCD (b) Stencil-FSC method

Fig. 14. CBU experimental results for *Girl* using the (a) conventional FSC-LCD and (b) the Stencil-FSC method.



(a) Conventional FSC-LCD (b) Stencil-FSC method

Fig. 15. CBU experimental results for *Lily* using the (a) conventional FSC-LCD and (b) the Stencil-FSC method.

TABLE II
COMPARISON OF THREE 32-INCH LCDS OF IPS-CCFL, CONVENTIONAL FSC, AND STENCIL-FSC METHOD DISPLAYING TWO TEST IMAGES_*GIRL* AND *LILY*

		IPS-CCFL	OCB-mode FSC (Conventional RGB-driving)	Stencil-FSC
Girl	CR	692 : 1	442:1	6,544:1
	P (W)	105	67	35
	CBU	--------	Fig. 14(a)	Fig. 14(b)
Lily	CR	766 : 1	512 : 1	26,335 : 1
	P (W)	105	67	28
	CBU	--------	Fig. 15(a)	Fig. 15(b)
Color Gamut* (% of NTSC)		72 %	114 %	114 %
➢ Power consumption of a 32” conventional LED-based TV: ~180W (*: The maximum NTSC ability of the LCD)				

pass filter. CBU was suppressed by more than 50% to be almost imperceptible. The Stencil-FSC method was implemented on a 32-inch FSC-LCD TV to yield a high dynamic contrast of 26,000:1, power consumption of less than 35 Watts, and a wide color gamut of 114% NTSC. Among the most important finding is that Stencil-FSC successfully suppressed CBU in an OCB-LC panel with a limited response time (240 Hz). Using the Stencil-FSC method, a color filter-less LCD TV has been successfully realized and demonstrated. These results suggest that the Stencil-FSC LCD has strong potential for future “Green Eco-Display” LCD-TV applications.

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