Adaptive LC/BL Feedback Control in Field Sequential Color LCD Technique for Color Breakup Minimization

Yi-Pai Huang, Ke-Horng Chen, Chun-Ho Chen, Fang-Cheng Lin, and Han-Ping D. Shieh

***Abstract*—A full-color image on field sequential color (FSC) displays is composed of color fields in temporal sequence. With the FSC mechanism, color filters of liquid crystal displays (LCDs) can be removed to heighten the light efficiency and lower the material cost. Color breakup (CBU), however, has appeared intrinsically to degrade visual qualities. A novel gray level determination of liquid crystal and backlight (LC/BL) was proposed to suppress the CBU artifact on FSC-LCDs. Based on the image content in each frame, a dominated color-mixed field was found to minimize the color difference between the CBU and original image. Additionally, the feedback algorithm for the adaptive LC/BL signals was developed and implemented on a 32-inch optically compensated bend (OCB) mode LC panel. According to the evaluation of experiments and observations, the proposed method has been demonstrated to greatly suppress CBU in LCD applications.**

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

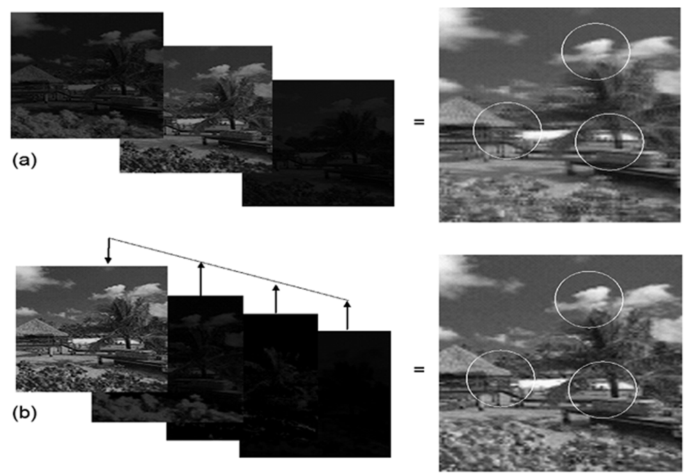

Fig. 1. Color field sequences and simulated CBU images on (a) conventional RGB 3-field and (b) rearranged color FSC displays.

I. Introduction

THE recent development of fast response liquid crystal such as the optically compensated bend (OCB) mode [1] and backlight light sources such as the high efficient light-emitting diodes (LEDs) have enabled liquid crystal displays (LCDs) to perform the field sequential color (FSC) mechanism. By displaying sequential primary red, green, and blue fields faster than the time resolution of human eyes, full color images can be presented without the color filter. In a combination with LED backlights and OCB mode LC panels, FSC-LCDs are now expected to be color LCDs with high light efficiency, low power consumption, and low material cost [2]–[7]. However, it is well known that the most serious issue of FSC displays is the "color breakup (CBU)" artifact [8]–[12]. CBU occurs when there is a relative motion between the object within the imagery and the observer's eyes. Fig. 1(a) shows a simulated CBU image with an RGB color field sequence. The color separation can be perceived (circle marks), resulting in degrading the image quality.

Some researches and experiments were reported to suppress CBU by optimizing the driving method such as field rate increasing [13], [14] and multi-primary color-field insertion [15]. The CBU is expected to be reduced by increasing the field rate. However, this method required a 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 eye-tracking of the brightest field. Less noticeable CBU of five-primary system was produced than that of three-primary (RGB) one [15]. Nevertheless, fast response time of LC for five fields was still required.

In order to suppress the CBU artifact practically, we proposed to concentrate the primary color fields on the dominated color field (D-field) as shown in Fig. 1(b). By rearranging color fields, the intensities of primary colors are lightened and the noticeable field is condensed to a single color-mixed one. Therefore, less color separation and visibility of CBU (circles) as compared with that of conventional RGB 3-field one were expected. An effort was made in order to find the adaptive color of D-field according to the image content in each frame. The algorithm of feedback determination of D-field color and LC/BL signals was studied for the real time application, followed by the implementation on a TV-sized panel and experimental results of CBU evaluation.

D-field feedback control concept contains two important methods and is described in Section II. These two methods are the rearrangement and feedback control methods, which can effectively get optimized BL values for reducing CBU effect. In

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Fig. 2. Simulated CBU images of Lena in three conditions of: (a) none, (b) white, and (c) proposed D-field.

Section III, experimental results demonstrate the performance of the D-field feedback control concept. Finally, a conclusion is made in Section IV.

II. D-Field Feedback Control Concept

A. Rearrangement Method

The rearrangement of LC/BL gray levels on the DRGB color sequence are determined by image content. In the D-field, gray levels of three primary color backlights are set as BL_r, BL_g, and BL_b, respectively. The relation between gray levels and light intensities (gamma curve) is set as a linear proportionality. According to these backlights, the new LC gray levels r', g', b' and d in the red, green, blue, and D-field are represented as (1)–(4)

$$r' = T^{-1}(T(r) - T(d) \times \mathrm{BL}_r) \quad (1)$$

$$g' = T^{-1}(T(g) - T(d) \times \mathrm{BL}_g) \quad (2)$$

$$b' = T^{-1}(T(b) - T(d) \times \mathrm{BL}_b) \quad (3)$$

$$d = T^{-1}\left(\min\left(\frac{T(r)}{\mathrm{BL}_r}, \frac{T(g)}{\mathrm{BL}_g}, \frac{T(b)}{\mathrm{BL}_b}, 1\right)\right) \quad (4)$$

where $T(i)$ is the transfer function from gray level i to transmittance of LC and T^{-1} is the inverse function. This gamma curve between gray levels and less than one of transmittances should be considered to maintain the white balance.

The determination of color backlights of D-field was found to be critical for color breakup reduction. Fig. 2 shows the simulated CBU images of test image, Lena, in three backlight gray level conditions of D-field. The simulated CBU images can be obtained by the superimposition of the shifted 4 color images as shown on top of Fig. 2. We utilized the computing software, MATLAB, to process these image data arrays. Fig. 2(a) shows the CBU image with zero RGB values of D-field (KRGB); in other words, this image represents the perceived one with a conventional RGB 3-field driving. On the contrary, the highest RGB values were applied on the D-field in Fig. 2(b), thus showing the white color in the D-field (WRGB). We summed up the color difference between CBU and original image pixel by pixel as an index, $\Delta\mathrm{E}_{\mathrm{sum}}$, for the evaluation of color separation

$$\Delta\mathrm{E}_{\mathrm{sum}} = \sum_{\mathrm{total\,pixel}} \sqrt{(L_{\mathrm{CBU}} - L_0)^2 + (u'_{\mathrm{CBU}} - u'_0)^2 + (v'_{\mathrm{CBU}} - v'_0)^2}. \quad (5)$$

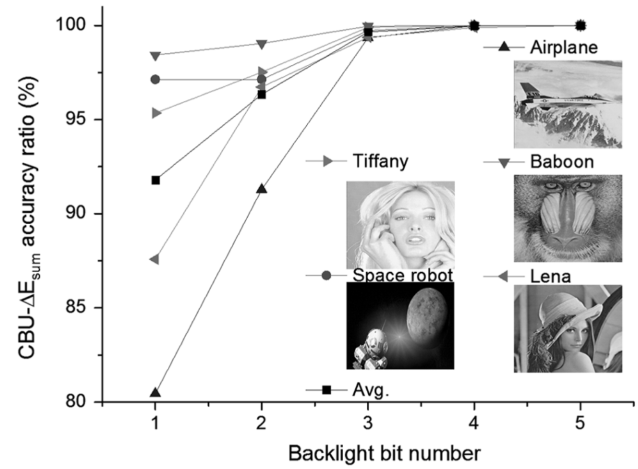

Fig. 3. The relation between color difference and backlight bit number.

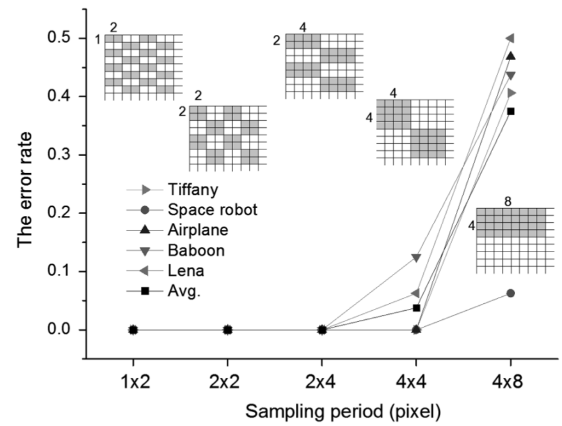

Fig. 4. The relation between the error rate of color difference and sampling period.

In (5), $Lu'v'_{\mathrm{CBU}}$ and $Lu'v'_0$ are color values of CBU and original image in the $Lu'v'$color space. The color backlight determines the distribution of image brightness in color fields. When major intensity of brightness is condensed in the D-field, the primary color fields are discolored. Consequently, less color separation will be perceived. The $\Delta\mathrm{E}_{\mathrm{sum}}$ of DRGB was found to be lower than those of other ones as well as the least CBU in these three images. Therefore, the visibility of CBU can be reasonably minimized when the color backlight for D-field was optimized. Furthermore, the CBU effect could be determined by the index of $\Delta\mathrm{E}_{\mathrm{sum}}$.

B. Feedback Control for Optimized BL Determination

The simplification of color backlight optimization on D-field is necessary in a real time application for the $\Delta\mathrm{E}_{\mathrm{sum}}$ calculation. The more bit number of backlight can obtain the more correct minimum $\Delta\mathrm{E}_{\mathrm{sum}}$. However, the compute loading will grow exponentially with the increase of backlight accuracy. Fig. 3 shows the $\Delta\mathrm{E}_{\mathrm{sum}}$ of five test images are corresponding to the bit number of backlight. In comparison with 1-bit accuracy, these $\Delta\mathrm{E}_{\mathrm{sum}}$ were saturate while the bit number was higher than 3. Therefore, the 3-bit accuracy is set as the modified factor of RGB backlight. Moreover, the resolution of image also determines the complexity of computing. We used several sampling periods, ranging from 1×2 to 4×8 pixels, to lower the resolution of image.

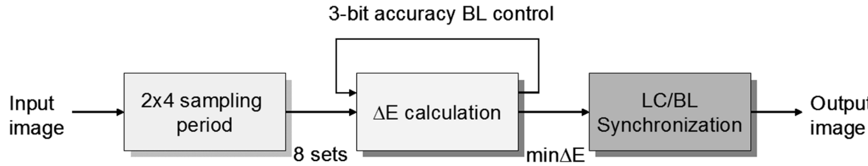

Fig. 5. The concept of optimized BL determination and image processing in a real time application.

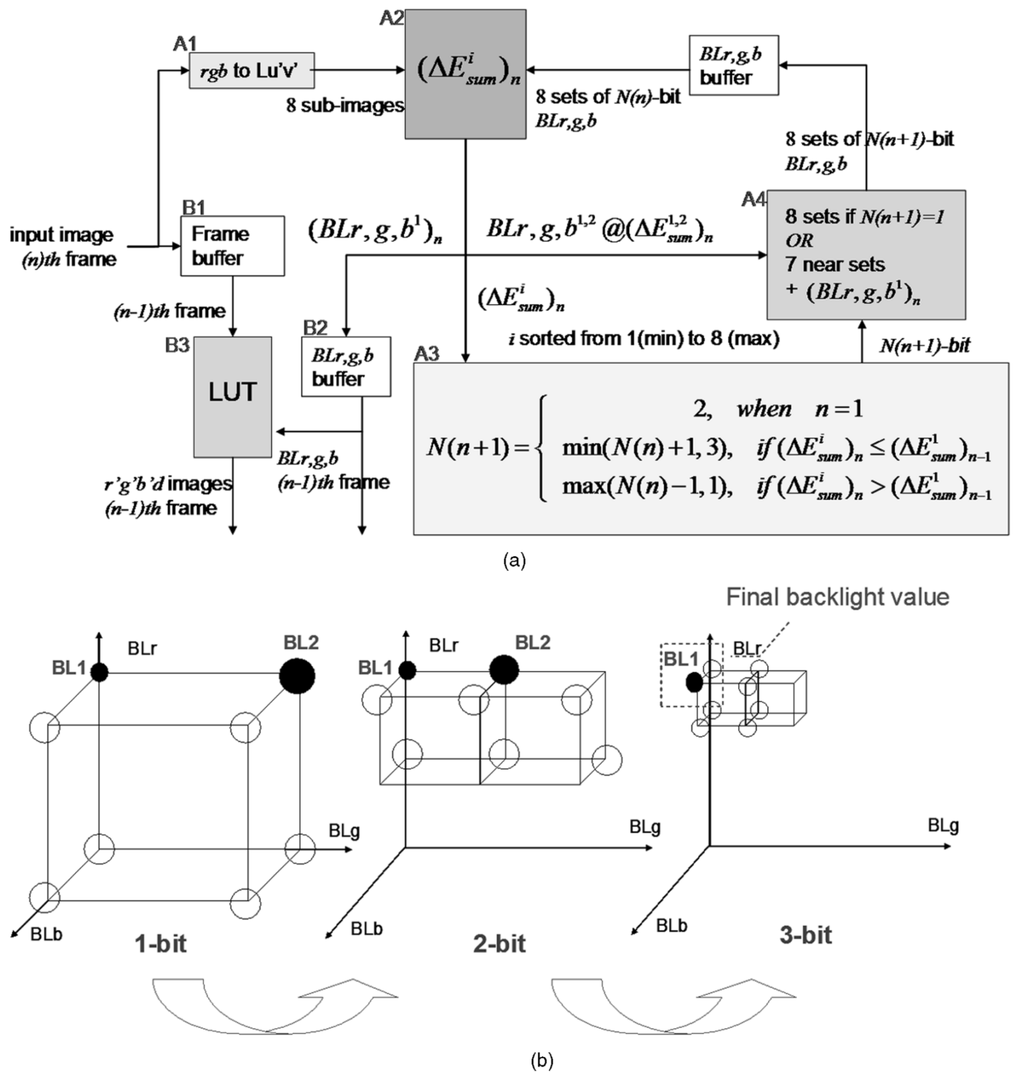

Fig. 6. (a) The flowchart and (b) an example of gray level determination of color backlight are according to the image content and color differences.

For example, four sub-images with the 1/4 resolution can be obtained by the 2×2 sampling. If these four sub-images can replace the original one for the ΔE_{sum} calculation, four different backlight conditions can be examined simultaneously and shorten the step of approach for the minimum ΔE_{sum}. When the RGB backlight condition of sub-image and original image with the minimum ΔE_{sum} are unequal, this sub-image is considered as an error. Fig. 4 shows the relation between the error rate and sampling periods of image. The error rate is defined as the ratio of the number of error to all sub-images. The sampling periods below 2×4 pixels were found without errors in these five test images. Therefore, the 2×4 sampling period was chosen to provide 8 sets of RGB backlight simultaneously for determination of the minimum ΔE_{sum}.

The 2×4 sampling period and the 3-bit accuracy of BL determination were combined for the ΔE_{sum} calculation. The optimized BL in D-field can be obtained by the feedback control of ΔE_{sum} minimization. Fig. 5 presented this concept with the LC/BL synchronization. The gray levels of output image in these DRGB fields were generated according to the optimized BL.

Fig. 6(a) shows the detail flowchart to determinate the gray levels of LC and color BL. First, the image of the nth frame was transferred to the $Lu'v'$ color space as shown in Step (A1). We used 8 sets of 1-bit color backlight and sub-images sampled by 2×4 period to obtain CBU images as shown in Fig. 2. In comparison with the original image, 8 $\text{CBU}-\Delta E_{sum}$ were computed simultaneously in Step (A2). After sorting these ΔE_{sum} and de-

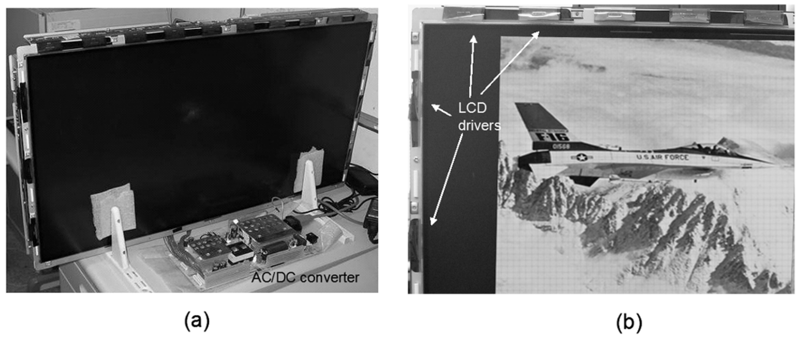

Fig. 7. Photos of (a) system overview and (b) panel taken by a camera with a shutter time of $1/60$ second on the 32” FSC-LCD panel.

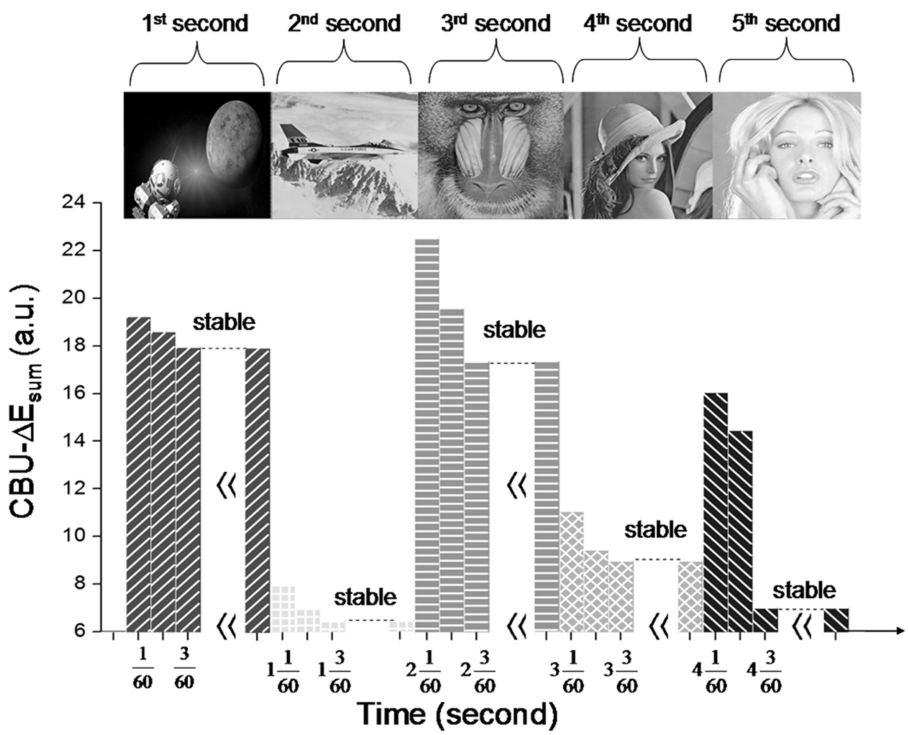

Fig. 8. The variation of color difference ΔEsum with a scrolled speed of one image per second for these test images.

termination of bit number for the next frame in Step (A3), 7 new 2-bit sets of color backlight near 1-bit sets with the minimum two $\Delta E_{\rm sum}$ were considered as well as the set with the minimum $\Delta E_{\rm sum}$ in Step (A4). The total 8 sets of color backlight will be used in Step (A2) by passing through the BL buffer, a signal register for the synchronization between LC and BL.

In an example of Fig. 6(b), the solid circles at 1- and 2-bit sets represent the sets with the minimum two $\Delta E_{\rm sum}$ (BL1 and BL2) as well as hallow circles for other sets with larger $\Delta E_{\rm sum}$. If any $\Delta E_{\rm sum}$ of 2-bit sets is equal or less than those of 1-bit ones, a 3-bit approach as shown at 3-bit set will be applied in Step (A3). On the contrary, if all $\Delta E_{\rm sum}$ of 2-bit sets are larger than those of 1-bit ones, 8 sets of 1-bit color backlight will be computed for the ${\rm CBU}-\Delta E_{\rm sum}$ in the following frame. The bit number accuracy of color backlight is controlled by this feedback for the optimized BL determination. On the other part of flowchart, the LC signal of input image and the color backlight with the minimum ${\rm CBU}-\Delta E_{\rm sum}$ passed through the frame and BL buffer as shown in Steps (B1) and (B2). The synchronal LC and BL signals in Step (B3) were applied to generate new gray levels of LC with the lookup table (LUT) as set in (1)—(4).

III. Experimental Results and Discussion

The proposed method was implemented on a 32” OCB-LC panel of the resolution 1366$\times$768 with the field frequency of 240 Hz. The brightness of a white image can have 400 nits at total power consumption of 50 W. The specifications are shown on Table I. Photos of system overview and this panel are shown in Fig. 7.

Five images in Fig. 3 were scrolled with a speed of one image per second as a test video to verify this CBU reduction method. Fig. 8 shows the ΔEsum variation with time in a frame sequence. During the first three frames of each image, the ΔEsum is confirmed to be decreased and stable by the feedback control of ΔEsum minimization. Thus, the feedback control technique can effectively determine optimized BL values. In addition, the

TABLE I
SPECIFICATIONS

Size	32" OCB
Resolution	1366x768
Brightness	400 nits at white
Power Consumption	50W
Color Gamut	105% of NTSC
Color Depth	24 bits
Field Frequency	240 Hz

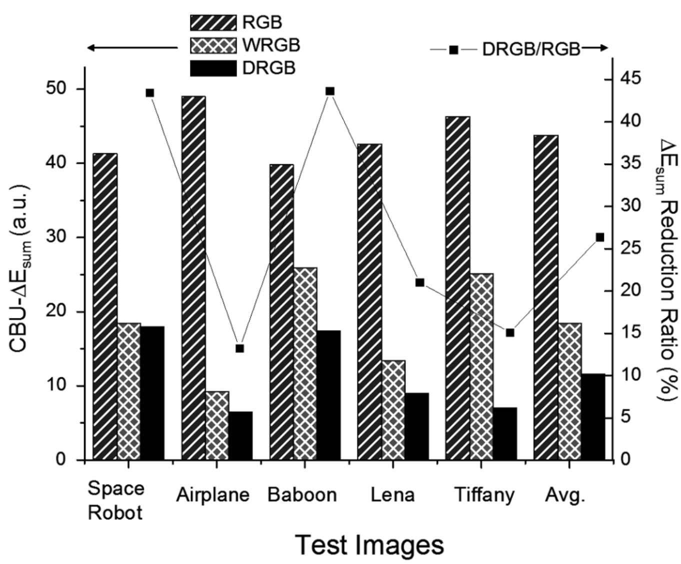

Fig. 9. The ΔEsum comparison of test images with conventional, white, and dominated RGB methods and the ratio of ΔEsum of DRGB to conventional one.

ΔEsum of proposed DRGB method is the lowest in comparison with those of conventional RGB and WRGB ones. This average CBU reduction value is around 25% of conventional one as shown in Fig. 9. According to the evaluation of observations, the CBU artifact as expectation is not noticeable.

Fig. 10 shows the typical CBU and modified images by D-field with the minimum ΔE_{sum}. In the circle marks of Fig. 10, it is obvious that the CBU artifact was greatly reduced in comparison with that of conventional RGB 3-field sequence. The color separation was greatly improved at the edges of Tiffany's face and robot's body. Similarly, the bright and dark sides of mountains in Airplane presented unnoticeable color breakup. The wing of nose in Baboon and the brim of hat in Lena also showed the reduced CBU significantly. The experiment results of perceived images were agreed with the observation.

To further improve the CBU reduction, the proposed method can be extended to determinate the local dimming color backlight in D-field. Currently, the color in D-field is modulated on total backlight (0D-dimming), resulting in still primary colors with high values of gray levels. The color backlight of D-field can be designed along horizontal and vertical segments (2D-dimming) in order to contain more intensity of brightness in D-field and further reduce the CBU artifact. Furthermore, the proposed method can be applied to parallel processing for successive frames with large variations, especially for fast moving images. With the current platform of BL determination on D-field, the optimized value of each frame is obtained after two frame time. In order to determine this value during the same frame time, the parallel architecture of feedback loop can be designed to speed up the processing steps. A real-time CBU reduction becomes realizable for fast moving images.

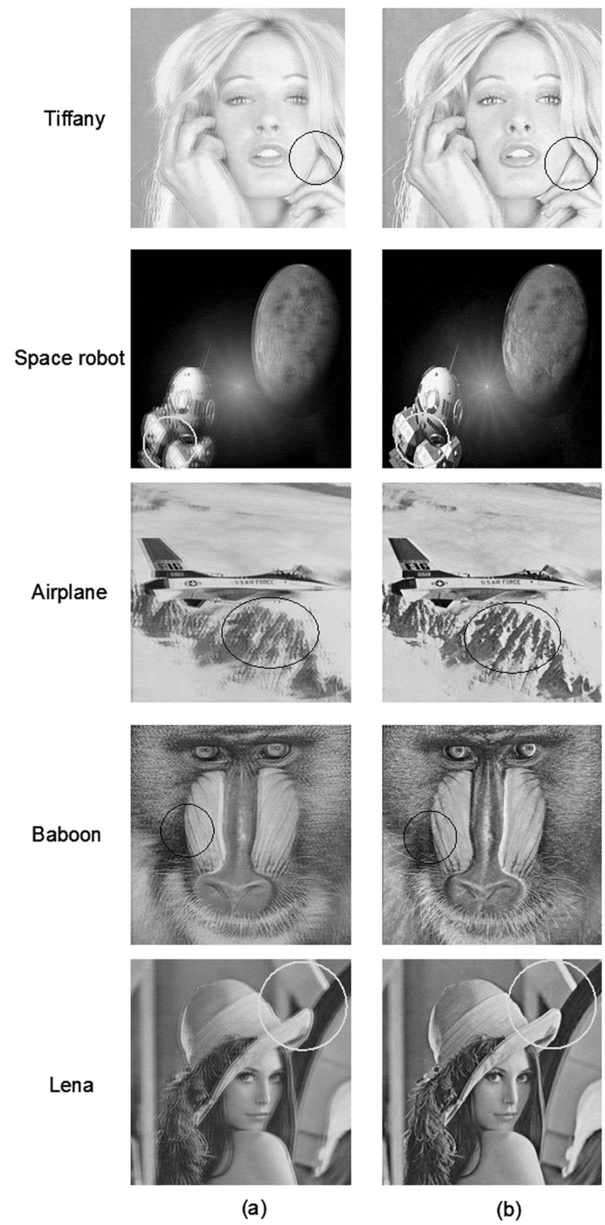

Fig. 10. CBU images with (a) conventional RGB and (b) adaptive DRGB fields.

IV. CONCLUSION

An adaptive feedback control for gray level rearrangement of LC/BL signals to reduce CBU artifact was demonstrated on a 32" FSC-LCD. The color backlight of the D-field with the minimum color difference between CBU images and original ones was proposed to suppress the CBU artifact effectively. According to the image content, the adapted color backlight can concentrate the light intensity on the dominated field and minimize the CBU effect. The 2×4 sampling period of image and

3-bit gray levels of color backlight were applied for the simplification of hardware implementation. The field frequency of 240 Hz, the brightness of 400 nits, and the total power consumption of 50 W were achieved. Most importantly, the 4 fields per frame have been fulfilled compared to the other techniques for reducing CBU effect. With rearranging LC/BL signals dynamically and the proposed feedback algorithm of optimized color backlight, our results successfully demonstrate that the proposed method is a practical way to suppress the CBU in field sequence color LCD applications.

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