Invited Paper: Field Sequential Color Display

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Abstract

With substantial research and modification, the world-wide 1st large-sized 360hz 8K FSC display is accomplished. It features 360 Hz to 480 Hz driving system, fast liquid crystal material evaluation, new algorithm for low color break-up quality, and up to 30% power consumption saving under high brightness application.

Author Keywords

LCD; novel display; Field Sequential Color, Color breakup

1. Introduction

In the modern world, pollution has become more severe than ever. Natural resources are expected to be exhausted in the near future due to the rapid growth of technology. Consequently, the power consumption of domestic electricity products has become a significant concern. Displays, which are among the most popular commercial items, play an important role in our lives. From televisions in buildings to outdoor signage and billboards on the streets, displays serve as crucial interfaces for information transmission to the public. Therefore, reducing the power consumption of displays could contribute positively to environmental protection. Field Sequential Color (FSC) technology is an efficient power-saving display method suitable for high-brightness applications. Given the advantages of this technology, numerous papers and dissertations on FSC have been published, and these will be briefly summarized in this article. However, most of the prior research consists of computational simulations using conventional LCDs that still employ RGB color filters (CF). As a result, the effects of liquid crystal response time and the diffusion of backlight are often overlooked in those experiments.

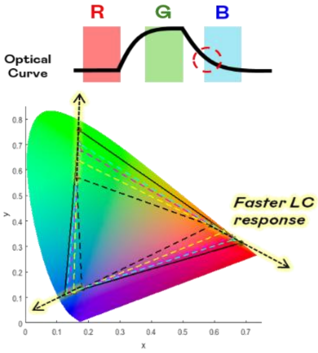

Figure 1. Color saturation performance of FSC would be influenced by the response time of liquid crystal.

In this paper, the FSC display combined with a CF-less cell, RGB BL, and a 480Hz driving system is developed for technology advancement. We can evaluate different CBU improvement algorithms, such as Stencil Algorithm [1] and De-flicker Algorithm [2], in real situations. As shown in Figure 1, the color saturation is substantially influenced by the characteristics of LC, highlighting the importance of LC material evaluation. Moreover, the light profile post-film diffusion of RGB BL in scanning mode impacts color saturation, which will also be discussed in this article.

In addition, we have developed a new CBU improvement algorithm considering the influence of LC RT and diffusion profile. The CBU improvement algorithm is complicated, so an AI model was applied to accelerate processing speed, which could potentially bring the FSC concept to the product level.

2. Prior art for CBU improvement

In conventional Field Sequential Color (FSC) displays, a standard image frame is divided into three sub-frames. Typically, these sub-frames are associated with the primary colors red, green, and blue, emphasizing the principles of RGB 3-field FSC. When the frame rate exceeds the threshold of human visual acuity, approximately 60 Hz, the viewer perceives these three primary colors as a unified, full-color image. However, it is important to note that human vision is not static; when the pupils move, the separate sub-frames of the primary colors are projected onto the different position of retina. This phenomenon can lead to the color breakup (CBU) effect, as illustrated in Figure 2.

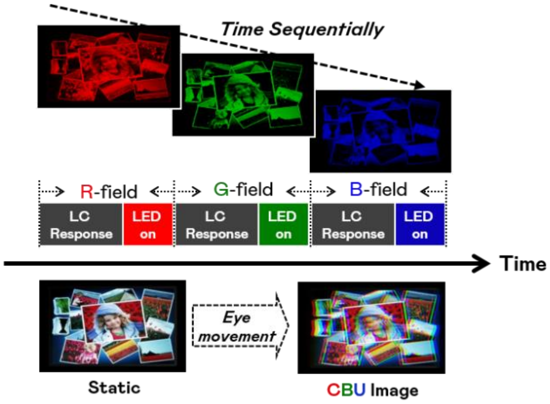

Figure 2. Color breakup (CBU) effect.

To suppress the CBU issue, one of the most straightforward approaches is to increase the frame rate. Projectors can achieve frame rates of over 1000 Hz to mitigate the CBU issue. However, even if the frame rate is enhanced through advanced driving circuit designs, conventional liquid crystal (LC) displays may not respond adequately within the required time frame. Previous research has indicated that a frame rate of 540 Hz significantly reduces the observability of the CBU issue, even when applying a simple RGB 3-field FSC [3]. Nevertheless, frame rate increases are constrained by factors such as resolution, driving system capabilities, and the charging ratio of the LCD driving circuit. Specifically, higher resolutions pose additional challenges to achieving increased frame rates.

Consequently, numerous studies have been conducted to reduce the CBU effect. One approach involves inserting black frames between each primary frame, such as RKGKBK or RGBKKK, as depicted in Figure 3. This six-frame FSC method can effectively

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diminish the CBU effect; however, it necessitates a driving system capable of at least 360 Hz to merge the six sub-frames into a standard 60 Hz color image. A notable downside of this method is the significant reduction in brightness due to the inclusion of dark frames, which negatively impacts the overall efficiency of the FSC display and undermines the power-saving advantages typically associated with this technology.

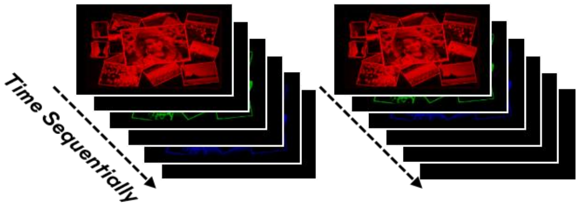


Figure 3. RKGKBK & RGBKKK 6-frame CBU Algorithm.

Another technique, known as the Local Primary Desaturation (LPD) 3-frame algorithm, utilizes new primary colors to construct the image [4]. By selectively displaying a narrower range of the color gamut to composite the necessary colors, this method effectively suppresses the CBU effect, as shown in Figure 4. However, the algorithm's complexity arises from the need to calculate the color gamut coverage for each sub-region and make decisions regarding the appropriate sub-region primary colors. Additionally, maintaining luminous uniformity across regions poses a challenge, as it can lead to light spread and degrade overall color saturation performance.

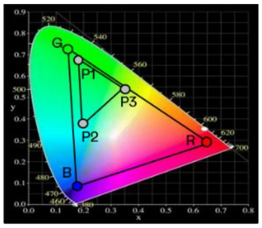


Figure 4. Illustration of LPD 3-field Algorithm indicates sub-region primary colors P1, P2 and P3.

The Stencil algorithm addresses the CBU issue by introducing an additional frame. Unlike other four-frame algorithms, such as the WRGB and RGBG algorithms, the Stencil algorithm employs a low color-saturated field as the first frame, paired with a local dimming system. This approach allows the system to render the desired color for each region, thus producing a blurred image that resembles the target image. The residual color information is then distributed across the second, third, and fourth frames to compensate for the red, green, and blue colors. By minimizing the transmittance of the R, G, and B fields, the CBU effect can be effectively suppressed, as illustrated in Figure 5.

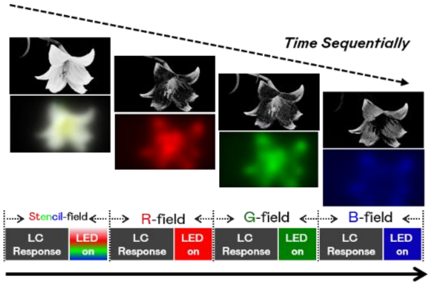


Figure 5. Illustration of resembling target images with Stencil-field for CBU issue improvement.

Despite its strong performance, the Stencil algorithm presents complexities in calculating the blurred backlight profile for the first field, leading to the exploration of the Edge-Stencil algorithm [5]. Human factor experiments have indicated that individuals are more sensitive to perceiving colors along the edges of a moving image. The Edge-Stencil algorithm utilizes an edge detection operator to identify the pixels that should be rendered in the first field and calculates the primary color corresponding to this edge information, as shown in Figure 6. Similar to the Stencil algorithm, the residual color is displayed across the second, third, and fourth fields. By employing the Edge-Stencil method, the FSC technology can effectively utilize global dimming backlighting, simplifying computational calculation resource, as depicted in Figure 7. However, if the target image is vivid and lead to the difficulty to ascertain the primary color, the Edge-Stencil algorithm may not effectively suppress the CBU effect.

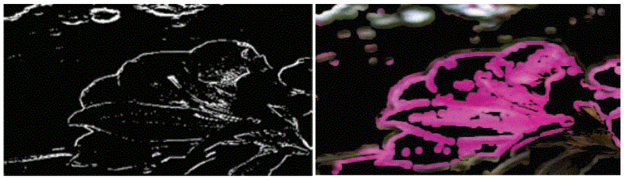


Figure 6. Edge detection and primary color calculation

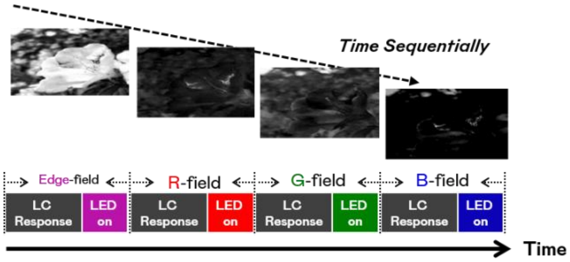


Figure 7. Edge-Stencil Algorithm with global dimming BL.

While the first field of the four-frame algorithm aims to present an image similar to the target to address the CBU effect, it can inadvertently lead to flickering due to the significantly higher brightness levels of the first field compared to the subsequent three fields. To address this issue, the De-Flicker algorithm has been proposed to balance the brightness across all four fields, effectively suppressing the CBU effect while also considering flicker performance within FSC technology.

In this article, we apply the Stencil algorithm as the foundational approach to suppress the CBU effect. We incorporate AI optimization to derive a more accurate backlight local dimming intensity for the Stencil field and the light profile post-film diffusion through the optical film. This allows for the generation of a precise first cell image, from which the residual transmittance of the subsequent three fields of cell and backlight images can be calculated using a similar principle. Furthermore, we account for the behavior of liquid crystals from one field to the next, adjusting the driving voltage to ensure each pixel attains the correct transmittance driven at high frame rates. The Compensation CBU (CCBU) algorithm not only effectively suppresses the CBU issue but also enhances the wide color gamut performance.

3. Design and Spec of Proposed FSC Display

In this section, we introduce the design of the world's first large-sized 360hz 8K FSC display. The display comprises two primary components: a color filter-less (CF-less) cell and a RGB active matrix (AM)-LED direct-lit backlight, with an FGPA to synchronize the panel and BL signal, as depicted in Figure 8.

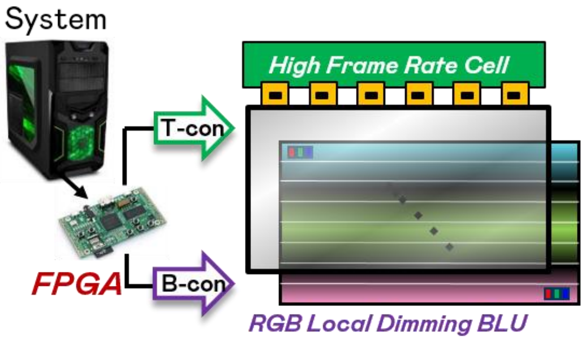


Figure 8. FSC system is composed with CF-less Cell and RGB local-dimming backlight with FGPA synchronization.

We begin with the CF-less panel, which has been fabricated through removing the color filter process, thereby significantly enhancing the transmittance of panel. The cell gap of the panel is designed to be 2.4 micrometers, meeting the requirements for fast response times in liquid crystal (LC) technology.

The RGB AM-LED direct-lit backlight features approximately 2,000 dimming zones specifically designed for the 65-inch display. Each zone incorporates red, green, and blue LEDs that can be controlled independently. This RGB local dimming system is essential for the experimentation and evaluation of the Compensation CBU (CCBU) algorithm. As illustrated in Figure 9, the LEDs are divided into eight scanning sections, enabling each section to synchronize with the LCD timing. The alternating current circuit or integrated circuit controller stabilizes the driving current for the LEDs and adjusts the light-on duty cycle (for example, 20%). These functionalities ensure that the LEDs are activated only after the liquid crystals have been driven to the target tilt angle, which helps maintain excellent color saturation uniformity, as shown in Figure 10.

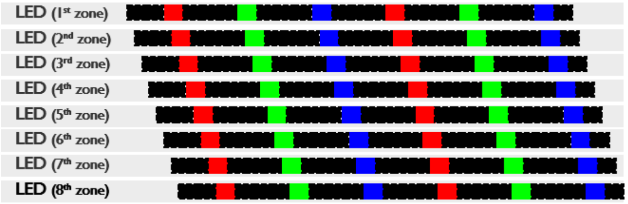


Figure 9. Scanning RGB backlight with light-on duty cycle.

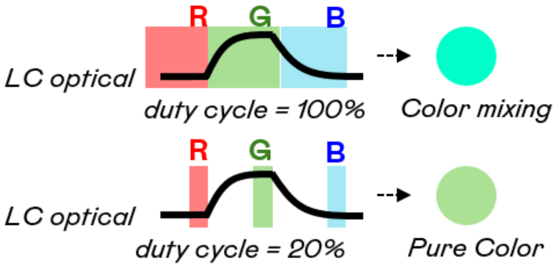
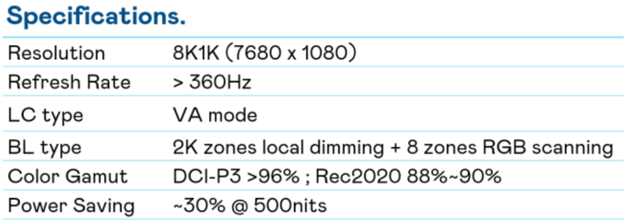


Figure 10. LED duty cycle control is required for better color saturation performance.

An FPGA has been designed to synchronize the timing between the cell and the backlight. The start pulse of the timing controller (T-con) serves as a reference for controlling backlight timing, allowing for precise adjustments of delay timing, duty cycle, and light-on duration to meet picture quality tuning requirements.

Table 1 shows the specifications of AUO's 65-inch FSC display, which features a refresh rate ranging from 360 to 480 Hz, a resolution of 8K by 1K, and color performance achieving over 95% of the DCI-P3 color gamut for random images and 99% for pure colors. Additionally, the display demonstrates a power-saving capability of up to 30% at 500 nits brightness compared to conventional 8K displays.



Specifications.

Resolution	8K1K (7680 x 1080)
Refresh Rate	> 360Hz
LC type	VA mode
BL type	2K zones local dimming + 8 zones RGB scanning
Color Gamut	DCI-P3 >96% ; Rec2020 88%~90%
Power Saving	~30% @ 500nits

Table 1. Specification of AUO 360hz 8K FSC display.

4. Material, BL and Algorithm Evaluation

Most prior researches on the CBU algorithm has been conducted through software simulations. This approach typically involves using a conventional white backlight without scanning and local dimming functionality to sequentially display simulated FSC images using a standard panel. Such simulations can effectively demonstrate the CBU effect for algorithm evaluation.

However, these simulations often overlook critical factors such as the duty cycle of LEDs, the timing associated with different LED scanning zones, the actual light profile post-film diffusion, and the response characteristics of liquid crystals when driven at extremely high frame rates. The rising and falling times of the liquid crystal affect color gamut performance significantly, as illustrated in Figure 11. If the falling time is excessively long, it may result in the incorrect field of light being displayed, thereby impacting color saturation. Consequently, optimizing the liquid crystal's falling time is crucial for achieving improved color gamut performance. At extremely high frame rates, LC may not have enough time to fully rotate to their desired position. Therefore the overdrive function is necessary to compensate for this limitation by driving the LC to the target voltage, ensuring that the correct transmittance is displayed for each pixel.

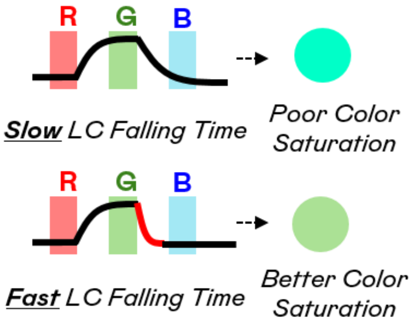


Figure 11. LC Falling time would substantially impact the color saturation performance of FSC.

Moreover, the diffusion characteristics of the backlight film also influence color saturation performance, as depicted in Figure 12.

If the light profile post-film diffusion would inadvertently influence adjacent region, the color from previous fields may incorrectly appear in current fields, adversely affecting the final image color. Therefore, careful consideration of LED dispersion and film design is necessary to mitigate light leakage across different fields.

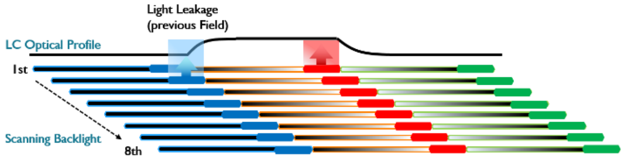


Figure 12. The LED dispersion of BL film would influence the color saturation performance.

Referring to the Stencil Algorithm, the complexity of the first field BL calculation is the main obstacle. It takes too much time to perform the convolution mathematics needed to derive the blurred image profile. To address this, we applied a traditional AI Convolutional Neural Network (CNN) to determine the implicit function from the 2,000 zones of backlight content to the resolution 7680 x 4320 image. With AI, the light profile post-film diffusion image could be derived very fast which satisfies the real-time processing requirements. It could bring the CCBU algorithm concept to the product level. We are currently working on new FPGA for algorithm implementation, which will allow the FSC display to demonstrate video content using the CCBU algorithm. As shown in Figure 13, the CCBU algorithm provides extremely good performance with AUO 65inch 360hz 8K FSC.

Figure 13. AUO 65inch 360hz 8K FSC demonstration.

5. Discussion and Conclusion

In this article, we reviewed the evaluations of FSC development over the past decades. Most of the prior art focused on the simulation of color breakup (CBU) improvement methods, including the 6-field RGBKKK, the 3-field LPD algorithm, the 4-field Stencil algorithm, the Edge-Stencil algorithm, and the De-flicker algorithm.

We applied a realistic FSC display to evaluate new CBU algorithms, not only to address CBU issues but also to consider power consumption and color saturation performance. From our experiments, we realized that the rising and falling characteristics of LC substantially influence color saturation performance. The falling time of LC should be fast enough, depending on the frame rate, to avoid light leakage from subsequent sub-frame colors. The light profile post-film diffusion feature of the RGB BL also needs to be considered in order to achieve better color saturation performance. If the BL film demonstrates severe light diffusion, it would require a smaller LED duty cycle, higher LED current, and faster LC RT, which would impose constraints on FSC design.

After the evaluation, we achieved the world's first large-sized 360Hz 8K FSC display. We designed a CF-less LCD with a low cell gap to meet the high RT LC requirements while maintaining good efficiency through LC material evaluation. We designed a direct-lit RGB BL with high-efficiency LEDs and a stable current-controlled IC for uniform brightness and local dimming functionality. We configured the 360Hz to 480Hz driving system to synchronize the timing of the cell T-con and BL B-con. By controlling LED duty, scanning behavior, and local dimming mapping for the Stencil field and residue field, FSC could provide a high contrast ratio, magnificent color saturation (DCI-P3 95%-99%), an acceptable CBU effect suppressed by the algorithm, and low power consumption performance, up to 30% under high brightness applications.

In addition, new CBU improvement algorithm, the Compensation CBU (CCBU) Algorithm, has been evaluated. This algorithm considers the influence of real-case scenarios, including LC RT, LED duty cycle, and BL light profile post-film diffusion. Given the complexity of BL diffusion approximation and LC rising and falling behavior, we applied an AI model to simplify and accelerate the computational calculations.

With the rapid growth of each component, including faster LC materials, more efficient LEDs, and high-resolution, high-refresh-rate driving systems, AUO has evaluated and showcased the potential of FSC displays. Considering that ESG is becoming an increasingly important topic, we look forward to seeing the application of FSC flourish in the near future.

6. References

[1] Fang-Cheng Lin, Yi-Pai Huang, Ching-Ming Wei, Han-Ping D. Shieh, "Color-breakup suppression and low-power consumption by using the Stencil-FSC method in field-sequential LCDs", Journal of the SID 17/3, (2009).

[2] Kai-Tung Teng, Fang-Cheng Lin, Chi-Wen Chang, Ching-Huan Lin, Y-Pai Huang and Han-Ping D. Shieh, "Reduction of Possible Flicker and Color Breakup using Deflicker-FSC Method for Field-Sequential-Color Displays" SID Digest, (2016).

[3] E.H.A Langendijk et al., "Suppression of color breakup in color-sequential multi-primary projection displays," J. Soc. Info. Display 14, 325-329 (2006).

[4] Yunging Zhang, Fang-Cheng Lin, Erno H. A. Langendijk, "A field-sequential-color display with a local-primary-desaturation backlight scheme," Journal of the SID 19/3, (2011).

[5] Fang-Cheng Lin, Kai-Tung Teng, Chi-Wen Chang, Ching-Huan Lin, Yi-Pai Huang and Han-Ping D. Shieh, "Effective Color Breakup Suppression by a Low-Cost Global Dimming Backlight for Field-Sequential-Color Displays" SID Digest, (2016).