Eco-Displays: The Color LCD's Without Color Filters and Polarizers

Yi-Pai Huang, Fang-Cheng Lin, and Han-Ping D. Shieh

***Abstract*—The higher and higher power consumption of LCD-TVs is accompanied by an increase in panel size. By eliminating two of the most power hungry optical components: color filters and polarizers, the stencil-field-sequential-color (Stencil-FSC) with RGBW-LED backlight is applied to LCDs with 120–240 Hz field rates to not only efficiently suppress color breakup but also yield an ultra-low average power consumption. The optical power consumption can be reduced to 13% compared to that of current FSC-LCDs. As a result, a 42-in LCD-TV may only require 9 W optical power consumption.**

***Index Terms*—Color filterless, eco-display, field-sequential color (FSC), polarizer-free, stencil.**

I. Introduction

CLIMATE change is now widely recognized as a major environmental problem. In creating a sustainable world, energy-efficient household electronics should be developed and popularized. For a typical 32-in color liquid crystal display (LCD) panel, color filters and a pair of polarizers are only 30% and 45% in optical throughput, yet with 19% and 10% of the material costs of a panel, respectively [1]. The use of color filters and polarizers, consequently, results in a net optical throughput of about 5%–10% only to yield a front-of-screen image. Can LCDs do without color filters and polarizers but still maintain full-color and high-definition images?

Using three high luminance primary-color (R, G, and B) field images, a field-sequential-color LCD (FSC-LCD) does not require color filters to yield a full-color image by temporal color synthesis. Hence, FSC-LCDs are capable of being high optical throughput, low panel material cost, wide color gamut, and a screen resolution possibly three times higher than that of an LCD with RGB color filters [2]–[4]. However, when the eyes perceive these three high-luminance field images sporadically, a visual artifact called "color breakup" can degrade image clarity [5]–[7]. Increasing the field rate can resolve color breakup, but requires field rates of above 1,000-Hz [8], which is extremely difficult to achieve by today's LCDs. An FSC-LCD was firstly proposed in 1985 by Kobayashi [2], however, color breakup has still not been effectively solved for the past 25 years. Some of the methods like inserting additional primary-color fields (e.g. RGBCY, DRGB) [9], [10] and black fields (RGBKKK) [11] still have limited effects on color breakup reduction for TV-sized applications.

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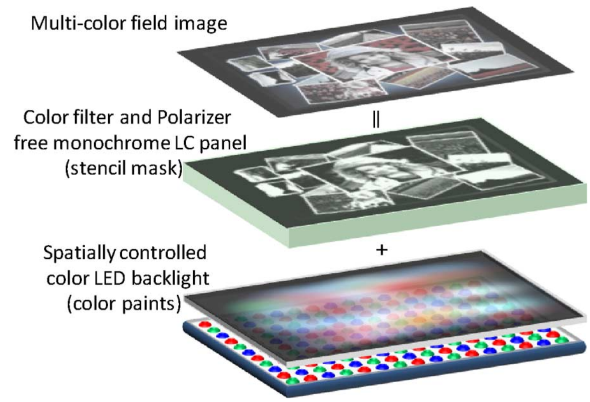

Fig. 1. Stencil-FSC LCD configuration: a locally controllable backlight module (color paints) and a monochrome LC panel (stencil mask).

The proposed Stencil-field-sequential-color (Stencil-FSC) technologies have been reported [12]–[15] to get rid of color filters to successfully suppress color breakup, which enables Eco-LCDs more feasible. In this paper, a high efficiency RGBW-LED backlight system is proposed and a pair of crossed polarizers are further eliminated to make a promising ultra-low power consumption eco-LCD.

II. Stencil-FSC Method

"Stencil graffiti" is a kind of painting arts. The process of stenciling involves applying paint across a stencil (mask) to form an image on a surface. Sometimes multiple stencil layers are used for a single image to add colors or create the illusion of depth. Additionally, in human visual system, the luminance contrast sensitivity function is significantly higher than the chromatic contrast sensitivity functions in both spatial and temporal frequencies. It indicates that the visual system is more sensitive to small image changes in luminance contrast compared to chromatic contrast [16]. Based on stencil concept and the human visual properties, the proposed Stencil-FSC methods incorporate the local-color-backlight-dimming technology on an FSC-LCD [17], [18]. LC panel acts as a monochrome stencil (mask) to form the outline of an image, then the spatially controlled color LED backlight "paints" colors on the mask to yield a multi-color field, as shown in Fig. 1. Consequently, the most image luminance is accumulated at this multi-color field with much lower luminance in residual color-field images. By sequentially displaying these field images, a high-definition and full-color image is generated. Because less primary-light luminance is seen in each field, color breakup is effectively suppressed simultaneously. For more practical applications, the field rate is limited to 240 Hz (4 field-images) or lower for current LCD's. We demonstrate the Stencil-FSC methods at 240 Hz and 180 Hz using commercial OCB (optically compensated bend) or even using multi-domain vertical alignment (MVA), in-plane switching (IPS), and twisted-nematic (TN) LC modes at 120 Hz to effectively suppress color breakup for large-sized TFT-LCDs.

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TABLE I
COMPARISON BETWEEN CONVENTIONAL RGB-FSC AND STENCIL-FSC METHODS

	Conventional RGB-FSC	Stencil-FSC		
		240Hz (4-field)	180Hz (3-field)	120Hz (2-field)
Angular resolution (Divisions/degree)	Full-on	2.45	2.80	5.92
*Spatial BL Resolution (32-inch panel)		34 x 18	38 x 22	80 x 45
Relative Color Breakup (%)	100	58.6	53.3	37.8
#Relative power consumption (%)	100	73	65	33

* Panel size ratio: 16:19; Observing distance: 3 meters. #: Using IEC 62087 as the test video [19]

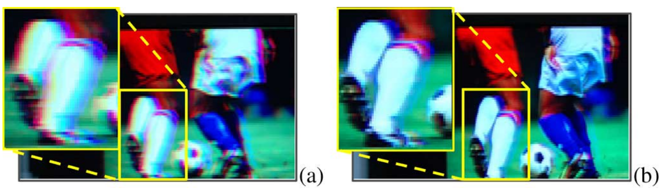

Fig. 2. Captured color breakup images using: (a) conventional RGB-FSC and (b) 180 Hz (3-field) Stencil-FSC method.

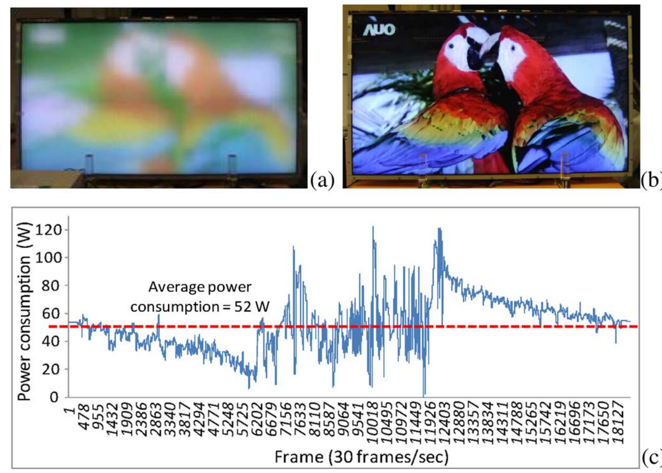

Fig. 3. A 65-in color filter-less FSC-LCD driven by 180 Hz Stencil-FSC, including: (a) locally color controlled backlight image and (b) full displayed image. (c) Power consumption of each frame for the IEC 62087 video [19] with a 52-W average power consumption using the 180 Hz Stencil-FSC method (65% compared to a 65-inch conventional RGB-FSC LCD).

Based on a dual-panel configuration, Stencil-FSC utilizes a high-luminance multi-color image in a color filter-less LCD to suppress color breakup and simultaneous maintain image fidelity. It is a totally different concept compared to the prior color breakup solutions which only utilized single-color field images. The monochrome LC panel is like a mask to form the detail of an image, and the locally controllable RGB-LED backlight is a low resolution backlight panel to control the color and contrast. To optimize the backlight resolution, eighty images from low to high details and monochrome to full-color were analyzed. Due to the viewing quality depends on the panel size and viewing distance, the angular resolution (divisions/degree) was considered. Apparently, the fewer fields need a higher backlight resolution to maintain the image fidelity and yield less color breakup and lower power consumption, as data summarized in Table I. However, higher backlight resolutions cause higher LED material costs and computation complexities.

For 120 Hz (2-field) Stencil-FSC, the color breakup and optical power consumption were reduced to 37.8% and 33%, respectively, compared to those of the conventional RGB-FSC method. Color breakup is almost imperceptible as shown in Fig. 2(b). In addition, 180 Hz Stencil-FSC was implemented on a 65-in color filter-less LCD with 32×24 RGB-LED backlight resolution, as shown in Figs. 3(a) and 3(b). Using the IEC 62087 video [19] according to the average of APLs (average picture levels) curve to evaluate display power consumption, 180 Hz Stencil-FSC (52-Watt in average) averagely reduced power consumption to 65% compared to a 65-in conventional RGB-FSC LCD (80-Watt), as shown in Fig. 3(c).

III. MULTI-PRIMARY LED BACKLIGHT

Power efficiencies of 3-in-1 RGB LEDs are low for image applications. To further reduce the power consumption of Stencil-FSC LCDs, high power efficiency white-light LED (W-LED) is mounted into an RGB-LED as a new multi-primary RGBW-LED set. The intensity part of an image is mainly contributed by a high efficiency W-LED instead of low efficiency RGB-LEDs, thus can further reduce the power consumption.

Using the IEC 62087 video with various efficiencies of W-LEDs, the relative power consumption of 240 Hz and 180 Hz Stencil-FSC methods were further reduced from 73% to 62% and 65% to 51%, respectively, when the 110 lm/W W-LED was added (the efficiencies of R, G, and B LEDs were 25, 50, and 5 lm/W, respectively). Moreover, the relative optical power consumption of 120 Hz Stencil-FSC can be further reduced from 33% to 25% only, i.e., optical efficiency is increased by a factor of 4 compared to that of using the conventional RGB-FSC method.

IV. POLARIZER-FREE LC PANEL

Utilizing an RGBW-LED backlight system on a color filter-less Stencil-FSC LCD, the power consumption is only 25% compared to that of the conventional RGB-FSC method. To be a more efficient eco-LCD, a pair of crossed polarizers which absorb half of the backlight intensity can be eliminated. The selective absorption characteristic of dichroic dye mixed with polymer dispersed LC [20], for example, may be considered as a light modulator. However, the contrast could only reach to 50 which is inadequate for a high quality TV panel. Utilizing Stencil-FSC, the low contrast monochrome LC panel can be in conjunction with a locally controllable LED backlight. Therefore, a high contrast color image can be also rendered.

To determine an acceptable contrast for a polarizer-free LC panel, thirteen images with 120 Hz Stencil-FSC were simulated. Comparing the image difference between various contrasts and an infinity LC panel using the 120 Hz Stencil-FSC method, the average color difference of CIEDE2000 (ΔE_{00}) [21] of each pixel was derived. From a simulation, even the contrast of an LC panel was lower than 60, the average ΔE_{00} was still lower than 0.5 which is undistinguished by the human eyes. Fig. 4 shows an example of a test image-*Harbor*, which is a colorful with high detail image. Reproduced images by 120 Hz Stencil-FSC with an LC panel in contrast ratios of infinity, 1000, 100, 45, and 20

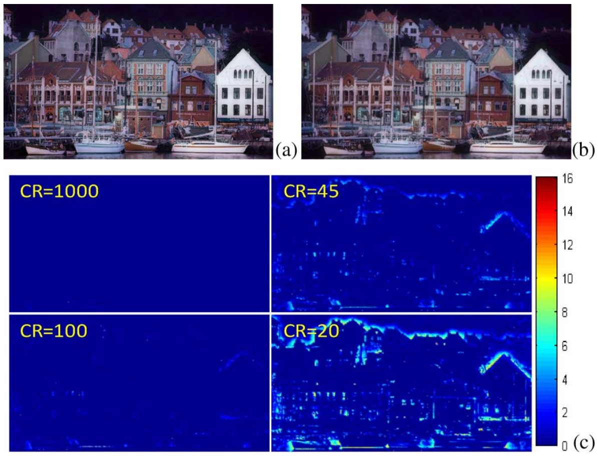

Fig. 4. Comparison of a test image-*Harbor* between the LC panel with (a) infinity contrast, (b) $\mathrm{contrast} = 45$, and (c) CIEDE2000 maps in contrasts of 1000, 100, 45, and 20.

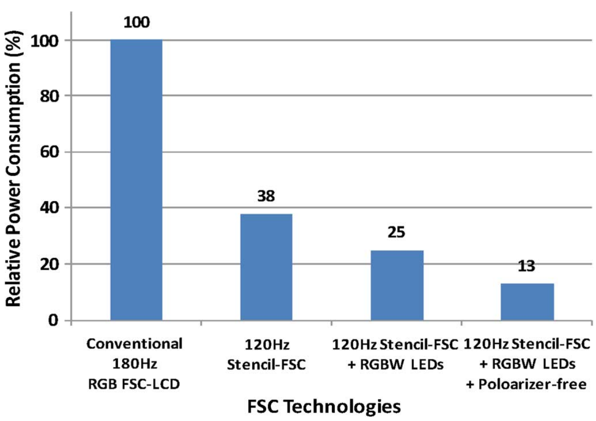

Fig. 5. Power consumption of four different FSC methods.

are shown in Fig. 4. Even contrast ratio was low to 45, 120 Hz Stencil-FSC rendered almost the same image quality as using an infinity LC panel [Fig. 4(b)]. The very slight differences can only be seen by enhancing the color difference map [Fig. 4(c)], indicating that using 120 Hz Stencil-FSC, the contrast of an LC panel is no longer needed to be higher than 60. Consequently, the polarizer-free LC mode is applicable for LCD applications.

Utilizing 120 Hz Stencil-FSC combined with high efficiency RGBW-LEDs and polarizer-free LC mode, the relative optical power consumption was much reduced to 13% of a current FSC-LCD, as shown in Fig. 5. For a mainstream 42-in LCD-TV, for example, the optical power consumption may be less than 9-W only. In contrast, the optical power of a conventional 42-in RGB-FSC LCD and a color-filter LED-backlight LCD is 67 and 200 W, respectively. The worldwide TV shipments are approximate 242 million LCD-TVs in the year of 2010 [22]. A 42-inch Stencil-FSC LCD panel using an RGBW-LED backlight can save as much as 191 W compared to a current LCD-TV with an LED backlight. It is amounted to 46.2 GW power saving by 2010 LCD-TV shipments, equivalent to 9.8 times power capacity of the Fukushima I Nuclear Power Plant which generates a combined power of 4.7 GWe in Japan[1]. Assuming 4-h usage for each LCD-TV per day, the saved power is 1.6 Fukushima I Nuclear Power Plants.

[1]http://en.wikipedia.org/wiki/Fukushima_I_Nuclear_Power_Plant

V. Conclusion

In visual system, the human eye is more sensitive to small image changes in luminance contrast compared to chromatic contrast. Stencil-FSC methods accumulated the most image luminance in a multi-color image and reduced luminance of the residual field-images. A field rate as low as 120 Hz has been demonstrated to successfully suppress color breakup for a high optical efficiency FSC-LCD. To further increase optical efficiency and reduce material cost, an RGBW-LED backlight Stencil-FSC LCD utilized a polarizer-free LC mode dramatically reduced power consumption to 13% compared to a current FSC-LCD. Consequently, a 42-inch LCD-TV may only require 9 W optical power consumption. A low power consumption and lower material cost Stencil-FSC LCD is a promising eco-display, perhaps powered by few sets of batteries or an Ethernet cable. Therefore, we foresee that human beings will enjoy the excitement of multimedia by this eco-display with families and friends and be more environment friendly.

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