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Low Power Consumption Technology for Ultra-High Resolution Mobile Display by Using RGBW System

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SUMMARY Battery life and outdoor visibility are two of the most important features for mobile applications today. It is desirable to achieve both low power consumption and excellent outdoor visibility on the display device at the same time. We have previously reported a new RGBW method to realize low power consumption and high luminance with high image quality. In this paper, the basic concept of a new RGBW calculation utilizing an "Extended HSV color space" model is described, and also its performance, such as low power consumption, color image reproducibility and outdoor visibility is presented. The new method focuses on the luminance-increase ratio by means of a White signal for the display image data, and derives the appropriate RGBW signal and backlight PWM signal for every frame period. This dynamically controlled system solves the problems of conventional RGBW systems, and realizes the same image quality as a corresponding RGB display. In order to quantify its color image reproducibility, a spectroscopic measurement has been completed using the Macbeth Color Chart. In addition, the advantages of high luminance by the new RGBW method is described. The converted tone curve with an RGBW method provides very high luminance, such as 1,000 cd/m^2, and improved outdoor visibility. Finally, a newly developed 4.38-inch full-HD (1,080 × 1,920) 503 ppi prototype LCD utilizing this new RGBW technology is described.

key words: *low power consumption, ultra-high resolution, LCD, mobile display, RGBW*

1. Introduction

In recent years, mobile displays for Smartphone and tablet PC applications have become larger in size and higher in resolution. For example, smartphone resolution has drastically increased from qHD (540 × 960 pixels) to 720HD (720 × 1,280 pixels). Full-HD (1,080 × 1,920 pixels) was launched into the market earlier this year. Tablet PC displays are also moving towards higher resolution than full-HD, such as WQXGA (1,600 × 2,560 pixels). Surprisingly, pixel density is approaching 400 ppi and more. As a result, the display power consumption continues to increase and it has a significant impact on the battery life of the mobile products [1].

For mobile display applications it is important to consider the display visibility in bright sunlight environments. Very high luminance, such as 1,000 cd/m^2, is required for a display to perform well in direct sunlight environments. As a result, the power consumption, especially the backlight portion continues to increase. Therefore, a solution combing both low power consumption and high luminance is urgently needed.

The RGBW pixel arrangement is one of the promising solutions for low power and high luminance [2]–[8]. Several RGBW products have already been launched into the market. However, conventional RGBW technology has image quality problems, such as a color purity degradation caused by both the signal processing itself and the optical illusion called "Simultaneous Contrast" [3]. We have previously reported a new RGBW system to solve the above problems [9]–[14]. We have also previously reported an outdoor visibility improvement using this RGBW system [10], [12].

In this paper, we will describe the performance of the new RGBW system, such as low power consumption, outdoor visibility and color image reproducibility by using the Macbeth color chart. In addition, a newly developed 4.38-inch full-HD (1,080 × 1,920) 503 ppi prototype LCD utilizing this new RGBW technology is described.

2. New RGBW Method

The conversion method from an RGB to an RGBW signal is widely known as Eq. (1). Here (Ri, Gi, Bi) and (Ro, Go, Bo) are digital values of the input and the output data, respectively. The White signal is extracted as the minimum value of the input RGB data.

$$W_o = min(Ri, Gi, Bi) \quad (1)$$

The calculations are performed on the pixel data for the entire display. Usually, for example, for the sRGB color gamut case, the luminance of the White sub-pixel is twice as high as the RGB pixels, because the White sub-pixel has no color filter. As a result, less backlight power consumption is required to maintain the original image luminance.

However, a pixel-by-pixel calculation using Eq. (1) provides luminance enhancement disparity over the screen, because the luminance-increase ratio for each pixel is different and depends on the image data.

For example as shown in Fig. 1, the minimum RGB portion can be replaced by White for the Color 1 area, whereas there is no White component for the Color 2 area which is a saturated color signal. The image deterioration by this luminance disparity has been reported previously [3].

Therefore, the luminance-increase ratio must be considered for the RGBW conversion for each display image. We have developed a new RGBW method, based on an

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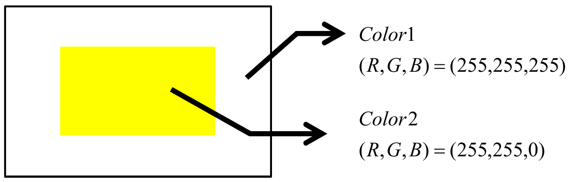


Fig. 1 Yellow window in the white background.

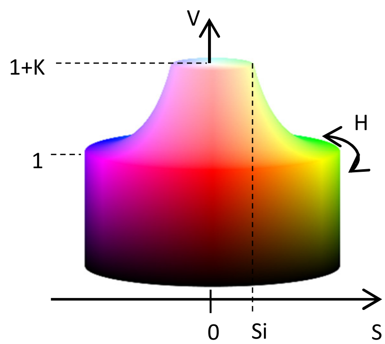


Fig. 2 Extended HSV color space.

extended HSV color space model [9]. This new RGBW method provides a simple way to determine the output White (Wo) and RGB data (Ro, Go, Bo) with an appropriate PWM value for the LED backlight.

The extended HSV color space, as shown in Fig. 2, represents the color and luminance capacity of the RGBW display. The luminance data is plotted via the vertical axis as the V value, the saturation data is plotted via the horizontal axis as the S value and the various colors are plotted via the hue angle as the H value. The H, S and V values are calculated using Eqs. (2), (3) and (4).

$$H = \begin{cases} 60 \cdot \frac{G-B}{Max(R,G,B)-Min(R,G,B)} + 0 \\ \quad If\ Max(R,G,B) = R \\ 60 \cdot \frac{B-R}{Max(R,G,B)-Min(R,G,B)} + 120 \\ \quad If\ Max(R,G,B) = G \\ 60 \cdot \frac{R-G}{Max(R,G,B)-Min(R,G,B)} + 240 \\ \quad If\ Max(R,G,B) = B \end{cases} \tag{2}$$

$$S = \frac{Max(R,G,B) - Min(R,G,B)}{Max(R,G,B)} \tag{3}$$

$$V = Max(R,G,B) \tag{4}$$

By using this HSV color space, we can easily understand that the White sub-pixel approach can be used effectively for the low saturation area, whereas it cannot be used for the high saturation area. As we have reported previously, the brightness value of the low saturation area is expanded by using the White sub-pixel approach, as shown in Fig. 2. This is different from the conventional cylindrical-shaped HSV color space. We call it the "Extended HSV Color Space" for RGBW displays. We can easily estimate the luminance of the RGBW display by using the "Extended HSV color space". Here, K is the ratio of the luminance of the White sub-pixel and that of the RGB sub-pixels as shown in Eq. (5). The RGBW display is potentially (1+K) times higher luminance than the RGB display.

$$k = \frac{Luminance\ of\ W\ pixel}{Luminance\ of\ RGB\ pixels} \tag{5}$$

If we consider the full-white image case, the backlight luminance level is reduced by the inverse of 1+K. The original luminance level is maintained by this calculation.

If we consider images containing saturated colors, we can estimate the luminance-increase ratio by means of the White signal which is the function of the saturation of the input RGB data. Therefore, the maximum luminance-increase ratio (LIR) Z_{max} value is defined as Eq. (6).

$$\begin{aligned} Z_{max} &= 1 + k \quad (0 \le S \le Si) \\ Z_{max} &= f(S) \quad (Si \le S \le 1) \end{aligned} \tag{6}$$

S is the saturation value of the input data. Si is the inflection point on the Extended HSV color space as shown in Fig. 2. This calculation is performed for each input image, and then the optimized RGBW signal and the optimized backlight level are determined as a PWM value by Eq. (7).

$$Backlight\ Level = \frac{1}{Z} \tag{7}$$

Since only one LIR value is calculated for the input image data, luminance enhancement disparity does not exist over the screen. For example, the relative luminance between chromatic and achromatic color is maintained in the RGBW output image. Therefore, color degradation, such as "Simultaneous Contrast", does not occur in this method. Additionally, the backlight level is simply determined as the inverse value of LIR. The output luminance is calculated to maintain the original luminance of the input image. This calculation is performed every frame period, and then the optimized RGBW signal and the backlight level are dynamically controlled in a circuit block as reported previously [9]–[14]. Since the calculation circuits are built into the LCD driver ICs, the data and the command interfaces are the same as a conventional RGB-type LCD.

3. Performances of New RGBW Displays

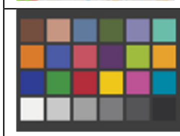
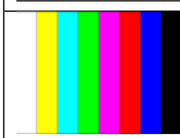
3.1 Backlight Low Power Consumption

Table 1 shows the actual LIR value and the backlight power-saving ratio (%) for several images. Some of them are artificial images such as a map, Macbeth Color Chart and color bars. For these images, the backlight power-saving ratio is small since the image is primarily composed of saturated colors.

On the other hand, for natural images, such as photographs, this new RGBW approach aggressively reduces power consumption. In general, since photographs taken by a digital still camera have very few maximum lightness values, the LIR becomes higher and the backlight power-saving ratio becomes bigger.

We have also obtained significant results in the evaluation of several video images such as movie, TV and gaming.

Table 1 Luminance-increase ratio (LIR) and backlight power-saving ratio results.

	LIR	Power Saving ratio (%)
	1.96	49%
	1.30	23%
	1.16	14%
	1.00	0%
	1.55	35%
	1.96	49%
	1.85	46%

Movie images, especially, were found to have a significant power reduction, because they generally have low lightness and low saturation image data. In any case, very little deterioration has been observed in the RGBW picture quality by comparing it side-by-side with a reference RGB display.

A quantitative comparison has been completed by measuring the color reproducibility as described in the following section.

3.2 Evaluation of Color Image Reproducibility

In order to verify the image quality of a new RGBW display, we have measured the color reproducibility by using a Macbeth Color Chart.

The measurement has been done by using RGB data for Macbeth 24 colors with the conditions of D65 illuminant and 2-degree Standard Observer [15]. This RGBW display has sRGB color gamut with D65 White point and 2.2-gamma. Figure 3 shows the measurement result of a*-b* values for the Macbeth 24 Colors of a new RGBW display, comparing it to the sRGB standard value. Most of the color difference (ΔEab*) between the RGBW and the sRGB standard values were smaller than 3. As this result shows the new RGBW display has excellent color reproducibility and it is compatible to a conventional RGB display which has sRGB color gamut.

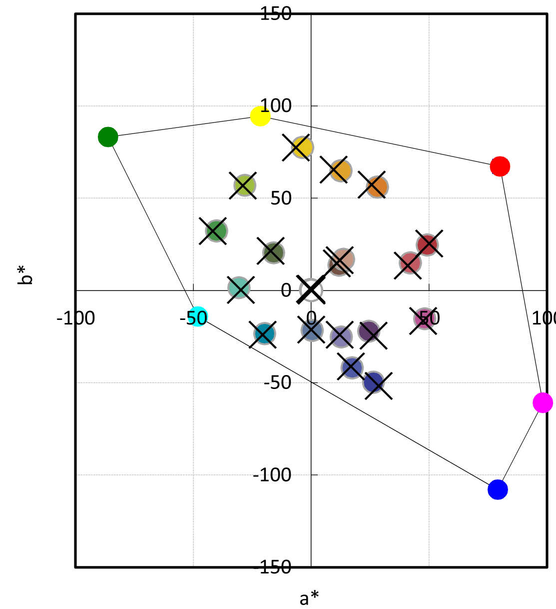


Fig. 3 Measurement result for Macbeth 24 colors.

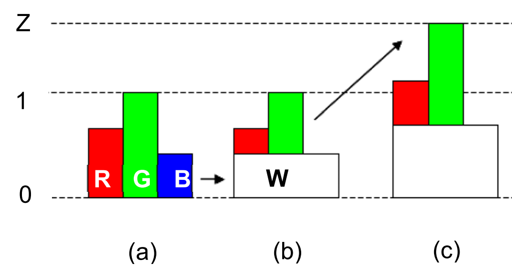


Fig. 4 Luminance improvement method using RGBW. (a) RGB. (b) Conventional RGBW. (c) Luminance enhancement using new RGB (x Z).

3.3 Improvement of Outdoor Visibility

We have developed the method to improve outdoor visibility by using the new RGBW technology with a converted tone curve [10]. When the digital values for input signals are (Ri, Gi, Bi) and the level of the luminancei-increase ratio is Z, the output signals (Ro, Go, Bo, Wo) are defined by Eq. (8). The difference between conventional method and new method is shown in Fig. 4.

In this case, the output luminance is enhanced by the value Z when the backlight control is turned off. As we reported in a former paper [10], [12], the RGBW display potentially has two times higher luminance, such as 1,000 cd/m^2.

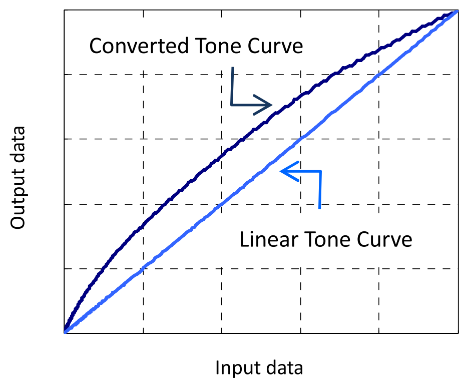


Fig. 5 Tone curve for the dynamic range correction.

$$
\begin{aligned}
R_o &= Z \times R_i - W_o \\
G_o &= Z \times G_i - W_o \\
B_o &= Z \times B_i - W_o \\
W_o &= min\,(Ri, Gi, Bi)
\end{aligned}
\tag{8}
$$

In addition, we have developed a new method, Dynamic Range Correction (DRC), to modify the tone curve as shown in Fig. 5 and enhance the luminance of displayed images [10]. This tone curve correction method can enhance the gray scale luminance.

The outdoor visibility improvement was confirmed by combining the luminance enhancement of the display utilizing the new RGBW technology and the tone curve correction method. We call this "Outdoor mode".

4. Ultra-High Resolution LCD by Using RGBW System

Finally, we will describe the capability of the new RGBW technology for an ultra-high resolution mobile display.

In general, the sub-pixel aperture ratio is dramatically reduced as the pixel density (PPI, pixel per inch) increases. The backlight power consumption also increases and the luminance of the LCD module is limited by both electrical and mechanical reasons. We also need to take into account that the pixel density is limited by the horizontal sub-pixel length in the RGB stripe pixel arrangement which uses a vertical rectangle sub-pixel shape. Figure 6(a) shows the pixel pitch versus display diagonal size for several resolutions. Displays of 500 ppi, such as 4.5-inch full-HD or 6-inch WQXGA, have 50 μm pixel pitches. In this case, the sub-pixel pitch of 12.5 μm is too small to make a RGBW stripe pixel arrangement. The four square sub-pixel arrangement is useful for this purpose, because the sub-pixel pitch become 25 μm. (see Fig. 6(b)).

In this paper, we propose an arrangement of RGBW square sub-pixels to realize an ultra-high resolution 503 ppi display as shown in Table 2. Since the 4.38-inch full-HD (1920 × 1080) RGBW panel has 25.5 μm × 25.5 μm square sub-pixels, high aperture ratio and high transmittance, compatible to lower resolution products has been achieved. The backlight of this ultra-high resolution LCD utilizing new RGBW method realized 40% less power consumption as compared to that of conventional RGB display module. It is estimated that the conventional RGB display with the same diagonal size consumes 500 mW on its backlight portion to achieve the luminance at 350 cd/m^2.

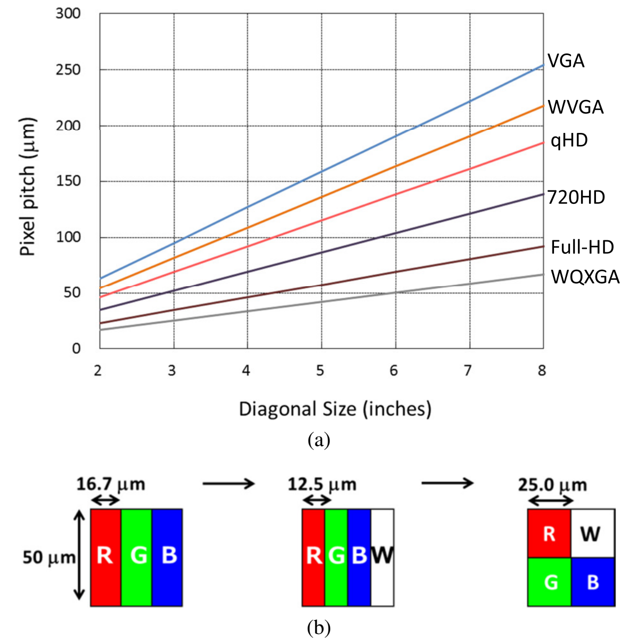


Fig. 6 (a) Pixel density versus display diagonal size.(b) Sub-pixel arrangement for 500 ppi.

Table 2 Ultra-high resolution LCD with RGBW system.

Diagonal Size		4.38 inches
Resolution		1920 x RG/WB x 1080
Pixel Density		503 ppi
Pixel Arrangement		4 square sub-pixels
Color Gamut		72 % (sRGB)
Contrast Ratio		1000 : 1
Viewing Angle (L/R/T/B)		Over 80 deg.
Luminance		350 cd/m^2 (Low Power mode)
		700 cd/m^2 (Outdoor mode)
Backlight	Number of LED	10 LEDs
	Power Consumption	300 mW (Low Power mode)
	@all White image	600 mW (Outdoor mode)

It was also confirmed that the display's outdoor visibility was improved, through both high luminance and converted tone curve as described above. The luminance at the Outdoor mode was 67% higher than that of conventional RGB display with the same backlight power.

Figure 7(a) shows a photograph of the prototype 4.38-inch full-HD LCD with the new RGBW system and Fig. 7(b) shows its magnified image. Since the pixel dots and jagged edges are not perceived at this pixel density, the picture quality approaches that of film photography.

(a)

(b)

Fig. 7 (a) A photo of the prototype 4.38-inch full-HD LCD with RGBW system. (b) A magnified picture of the prototype 4.38-inch full-HD LCD with RGBW system.

5. Conclusion

The new RGBW technology has been successfully developed to save backlight power consumption while maintaining image quality. The power saving ratio of backlight was 40% in average at natural images such as photographs.

The RGBW square sub-pixel arrangement utilizing this new RGBW technology realizes ultra-high resolution over 500 ppi and solves the power consumption issues.

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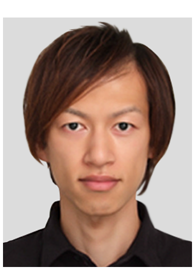

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