Full-Color AMOLED with RGBW Pixel Pattern

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Abstract

A full-color AMOLED display with an RGBW color filter pattern has been fabricated. Displays with this format require about ½ the power of analogous RGB displays. RGBW and RGB 2.16-inch diagonal displays with average power consumptions of 180 mW and 340 mW, respectively, are demonstrated for a set of standard digital still camera images at a luminance of 100 cd/m². In both cases, a white-emitting AMOLED is used as the light source. The higher efficiency of the RGBW format results because a large fraction of a typical image can be represented as white, and the white sub-pixel in an RGBW AMOLED display is highly efficient because of the absence of any color filter. RGBW and RGB AMOLED displays have the same color gamut and, aside from the power consumption difference, are indistinguishable.

1. Introduction

High-performance, direct-view full-color AMOLED displays were first demonstrated in 2000 [1] and commercialized in 2002 [2]. Others have also demonstrated full-color displays on both polycrystalline [3] and amorphous [4] Si active matrix substrates in both top-emitting and bottom-emitting formats. All of these displays used precision shadow masking to define the red, green and blue emitters. Issues with manufacturing yield and scalability to large substrate sizes when applying shadow-masking techniques, however, have prompted the investigation of other methods to produce color. A 15-inch diagonal, full-color AMOLED based on white emission and color filters was demonstrated in 2002 [5]. Although this format does not require precision shadow masking, it suffers from the absorption of emitted light by the color filters. It is attractive, however, for several reasons in addition to the avoidance of the precision masks. These include: 1) the reduction in the number of manufacturing steps (one or two emitting-layer depositions, rather than three separate depositions), 2) more uniform degradation of the emission (red, green and blue emitters often degrade at different rates), and most importantly, 3) it is enabled by the high-efficiency, stable white OLED formulations that have recently been demonstrated [6]. However, even with these high-efficiency white emitters, it is difficult to envision full-color OLED displays using RGB color filters that are as efficient as displays fabricated with direct-patterned emitters. This is a consequence of the fact that as much as 80% of the white light generated within the display is absorbed by the filters. The efficiency can be increased substantially with an RGBW format in which, in addition to the standard RGB sub-pixels, a white-emitting sub-pixel is included within each pixel. With this structure, the emission from the white sub-pixels within the display is unattenuated. For imaging applications, this is highly beneficial because the three color channels are highly correlated in an RGB system. In other words, all three sub-pixels usually emit. Thus, many colors may be created by replacing the appropriate combination of R, G, and B luminance with unfiltered white. Because of the prevalence of near-neutral colors, the highly efficient white emitter is used frequently, leading directly to a reduction in power consumption in comparison to the RGB format.

RGBW AMLCD displays have recently been demonstrated [7] that are brighter than analogous RGB displays. Like the RGBW AMOLED, the unfiltered white emission leads to a higher display efficiency. In both the RGBW AMLCD and the RGBW AMOLED, the use of an additional white sub-pixel results in a reduction in the emissive area. In the RGBW AMLCD, this leads to lower red, green, and blue display luminance for a given backlight luminance and, consequently, a reduction in gamut because high-luminance saturated colors are lost. In the case of the RGBW AMOLED displays, no loss in gamut is incurred because the display luminance level is dependent on the current supplied to the sub-pixels. For example, to display the same areal luminance saturated red, the same current level is supplied to the red sub-pixels in the RGBW and RGB formats. The sub-pixel current density (and, consequently, the sub-pixel luminance) will be higher for RGBW; however, the pixel (and display) luminance is the same.

For the common two-transistor AMOLED, the power consumption is determined by the total current supplied to the display and the drive voltage applied across the drive TFT and OLED structures. Typically, the voltage is held constant; hence, the power consumption is directly proportional to the drive current supplied to the emitting structures. The power consumption is, therefore, dependent on the frequency of use of the highly efficient unfiltered white pixel. To this end, a lower power consumption compared to RGB will be observed for display applications with a high probability of unsaturated image content—typical for consumer imaging applications—and equivalent power consumption to RGB will occur with images containing predominantly highly saturated colors.

An RGBW AMOLED display has been fabricated and compared directly to an RGB AMOLED of the same size. For test images representative of images captured by digital still cameras, the

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RGBW display requires approximately ½ the power of the RGB display operated at the same luminance level.

2. Experimental

2.1 White OLED Structure

The white-emitting OLED layer structure is shown in Figure 1. Emission from blue and yellow zones within the multi-layer structure combines to provide a white emission that can be filtered appropriately to provide R, G, B and W emission from the display. Details of the fabrication of white OLEDs are discussed in detail elsewhere [6].

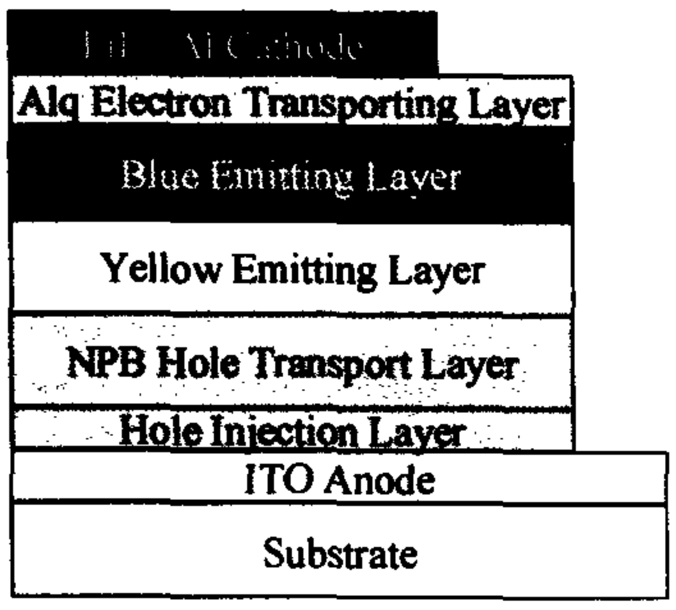

Figure 1. White OLED structure.

2.2 RGB and RGBW Display Formats

RGB and RGBW displays with the same dot count were fabricated by adjusting the location of the sub-pixels, as shown in Figures 2 and 3, respectively. In both cases, the column count (data) was 528, the row count (scan) was 220 and the pixels were arranged in a stripe pattern. For the RGB display, the panel configuration was 176 (RGB) x 220 and the RGBW display was 132 (RGBW) x 220. For both configurations, the diagonal dimension was 2.16 inches. The display aspect ratio was 4:5, and images were displayed in both portrait and landscape orientations.

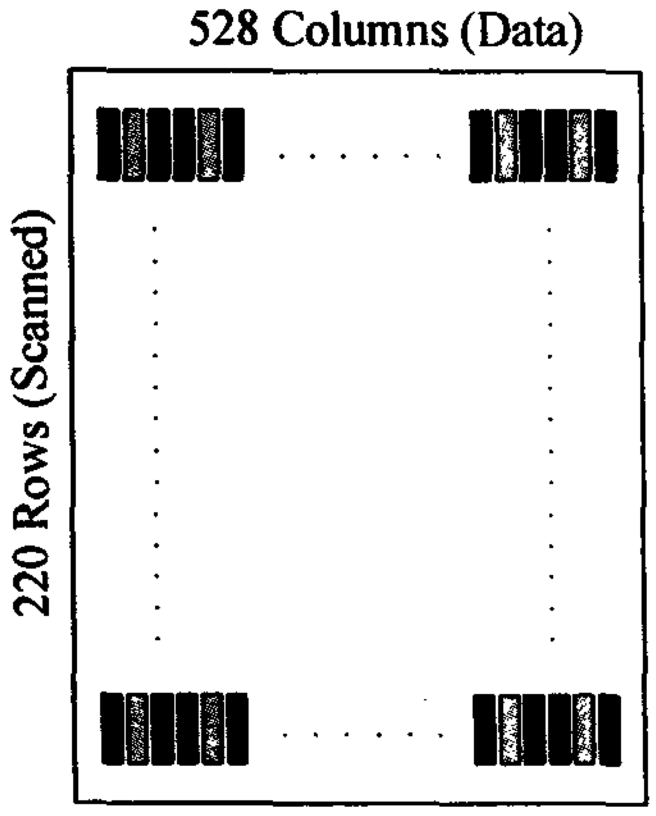

Figure 2. Display format for RGB.

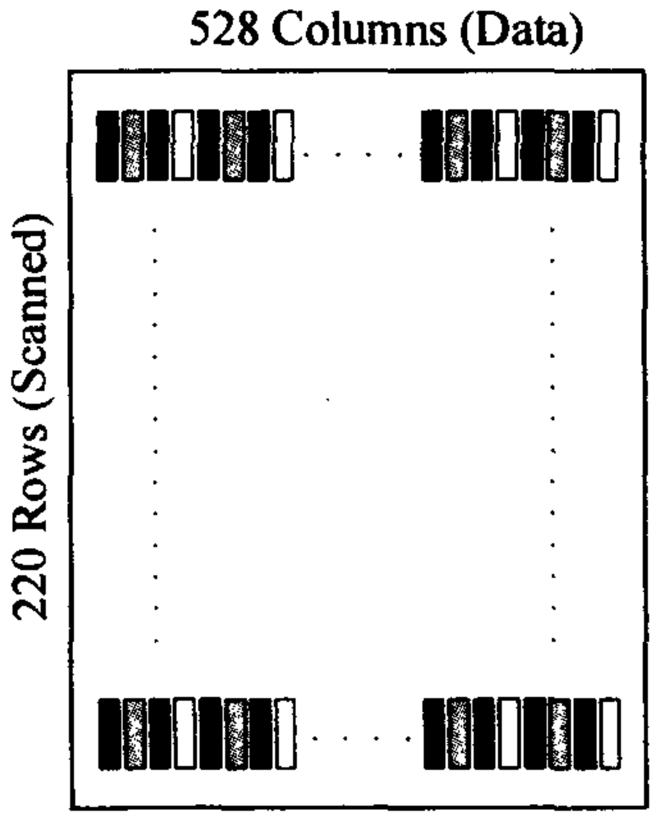

Figure 3. Display format for RGBW.

2.3 RGB to RGBW Conversion

The test images, originating in gamma-encoded sRGB color space, were transformed to OLED RGB intensity, or relative luminance factor. For the RGB AMOLED, the RGB intensity was transformed through the measured OLED gamma lookup table to the appropriate drive TFT gate voltage. For the RGBW display, the RGB intensity was converted to RGBW intensity by a white replacement algorithm and similarly transformed. This algorithm computes RGBW intensity by removing the neutral luminance from the R, G and B channels and replacing it with W. To account for a W sub-pixel that is a different color than the target display white point (D65), a normalization is performed on the RGB intensity such that equal amounts of R, G, and B produces a color of the same chromaticity as the W sub-pixel. The W intensity value is the minimum of the three normalized RGB intensities (RnGnBn). This W value is subtracted from each of the RnGnBn intensities, and the result is renormalized using the inverse of the previous normalization, resulting in the modified RGB intensity, R'G'B'. The R'G'B'W intensity combination is then transformed to the TFT gate voltage used to drive the display. This algorithm is illustrated in Figure 4. For the RGBW test images, the pixel count was reduced from 176 to 132 in the column direction by one-dimensional spatial filtering to avoid aliasing artifacts, followed by subsampling.

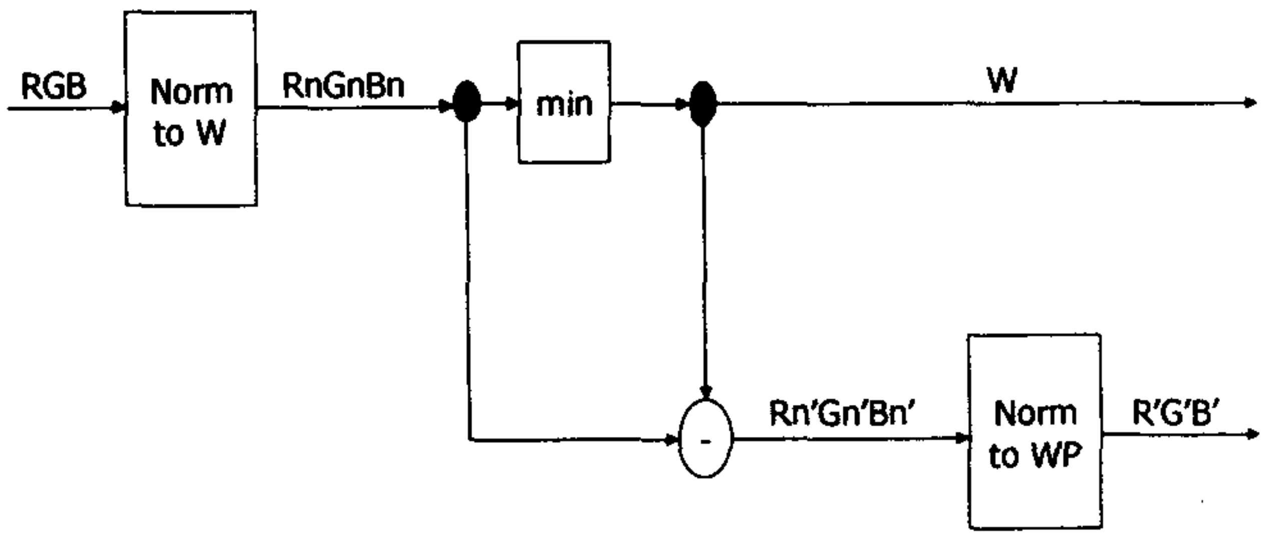

Figure 4. RGB-RGBW white replacement algorithm.

2.4 Display Characterization

The white points for both the RGB and RGBW AMOLED displays were adjusted to D65 at a luminance of 100 cd/m^2, after passing through a circular polarizer with 44% transmittance (i.e., 227 cd/m^2 before the polarizer). For the RGB display, the R, G, and B sub-pixels were all activated to achieve D65 white. For the RGBW display, the white sub-pixel was operated primarily and because it was slightly yellow relative to D65, enough blue luminance was added from the blue sub-pixel to attain D65. On each display, a sequence of images representative of those obtained with digital still cameras was displayed and, for each image, the current was measured and the power calculated, based on a drive voltage of 13 V (corresponding to the voltage applied across the drive transistor and OLED structures).

3. Results and Discussion

The emission spectrum of the white emitter used in this work is shown in Figure 5, and the corresponding 1931 CIE chromaticity diagram with R, G, and B points achieved after filtration is shown in Figure 6. Also shown are the white point of the unfiltered emitter (0.361, 0.380) and the D65 (0.3127, 0.3290) white point. Any color within each of the sub-triangles shown can be created by the appropriate combination of primary colors with the white. For example, any color in sub-triangle RGW can be attained by operating the R, G, and W sub-pixels (B is not required). It is useful to mention that all points within this color triangle will use the white sub-pixel, except for the R and G primaries and the colors along the line connecting R and G. The chromaticity and efficiencies of the R, G, B and W sub-pixels are shown in Table 1. It is clear that the white emission is highly efficient, a consequence of the lack of any color filter. Also the white emission is yellowish in comparison to D65, which means that blue emission must be added to attain the panel D65 white point. As shown, the blue efficiency is much lower than the white efficiency, and this leads to the correct conclusion that it is important to attain the white point with the white emitter for lowest power consumption.

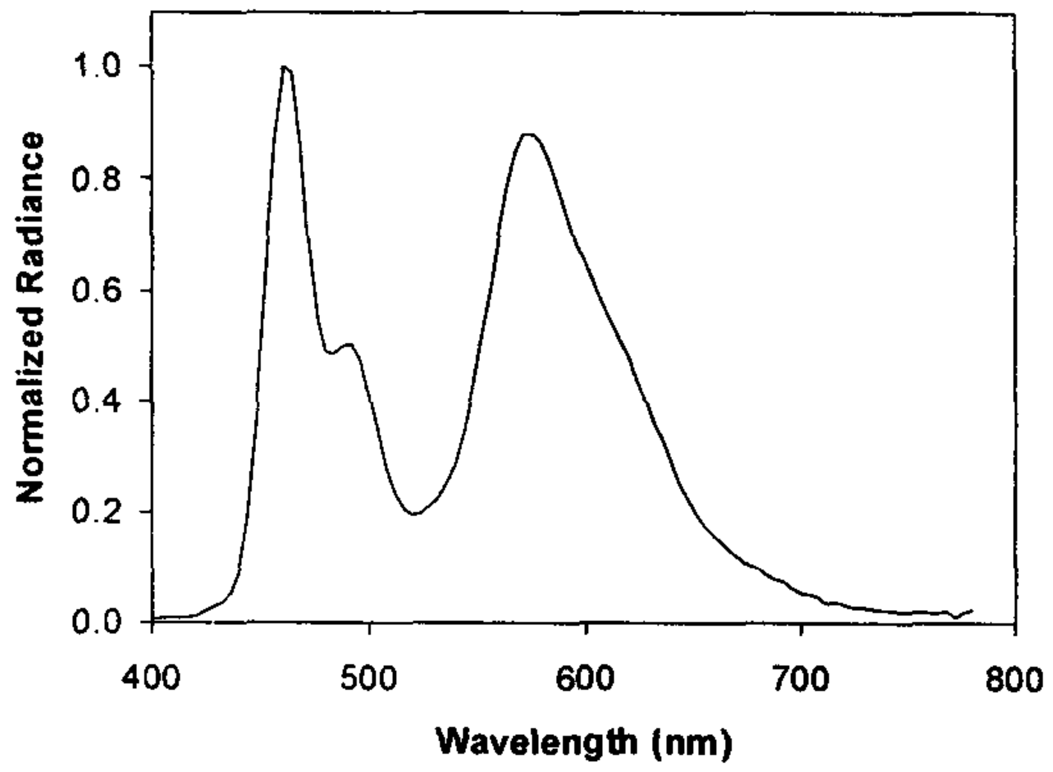

Figure 5. White emission spectrum.

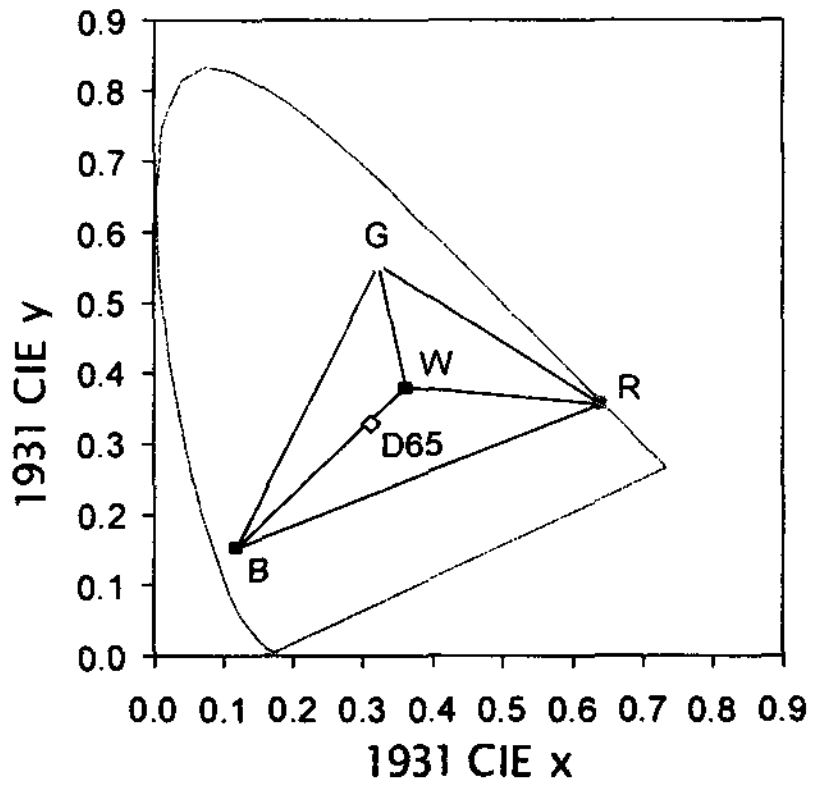

Figure 6. R, G, B and unfiltered W chromaticity. Also indicated is the D65 white point.

	R	G	B	W
CIE x	0.641	0.323	0.119	0.361
CIE y	0.357	0.554	0.153	0.380
cd/A	2.63	6.60	1.14	12.48

Table 1. 1931 CIE x,y coordinates and luminous efficiency of the AMOLED panels.

Figure 7 shows the power consumption for the RGBW and RGB AMOLED displays for various images. On average, under identical luminance conditions, the power consumption required for the RGBW display is approximately ½ the power consumption of the RGB display. For this image set, the RGBW and RGB average power consumptions are 180 mW and 340 mW, respectively. This is in agreement with modeling results based on 13,000 digital camera images and is indicative of the fact that saturated colors are relatively rare in most scenes. Clearly, images with large amounts of white content displayed using an RGBW format will require much less than ½ the power of an RGB format, as a consequence of the highly efficient white channel,

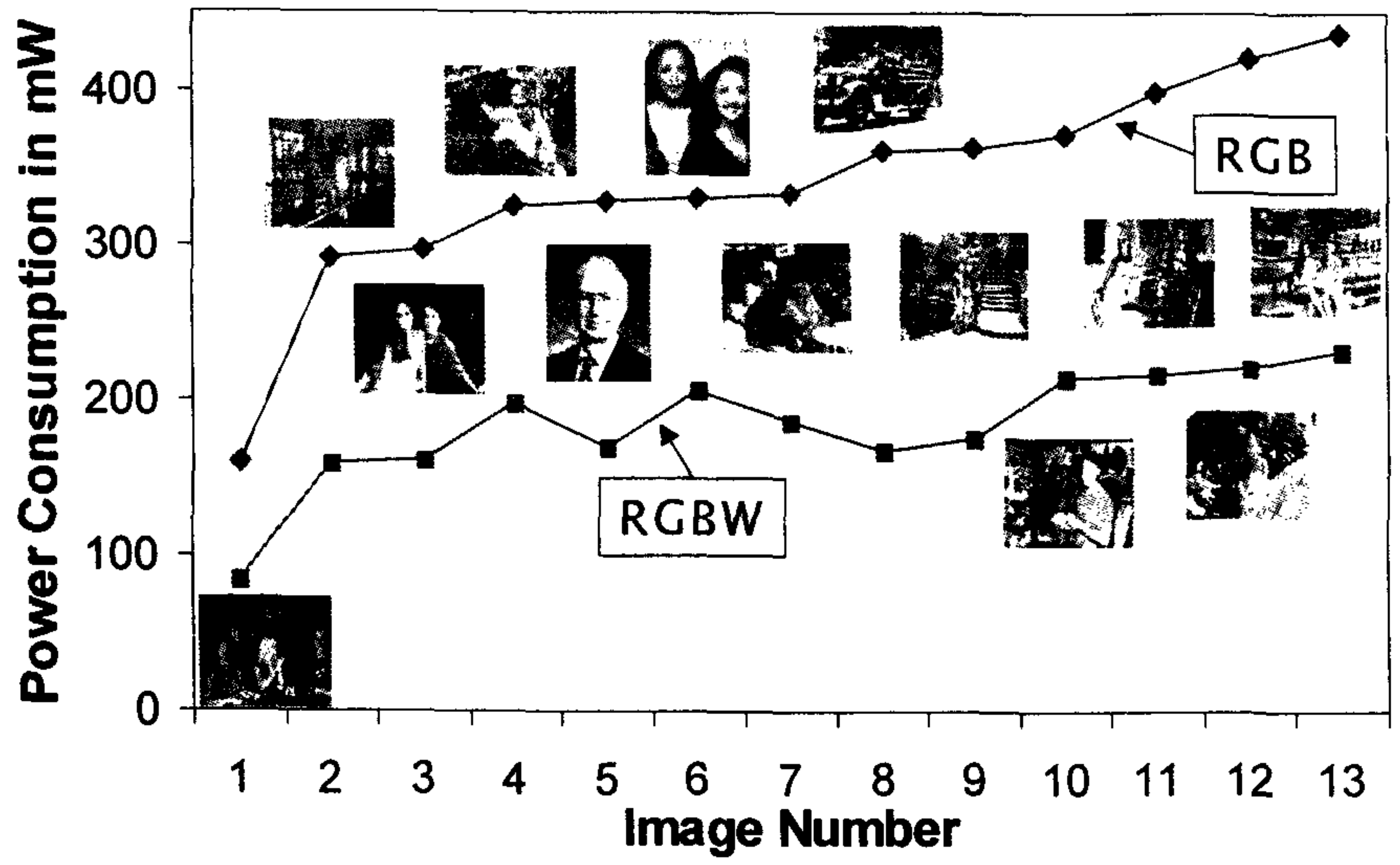

Figure 7. Power consumption of RGB and RGBW displays for various images.

whereas scenes with large amounts of saturated color will be much closer in power consumption.

Figure 8 shows a side-by-side comparison of the RGBW and RGB displays. In the case of the RGBW display, the lower resolution is clearly observed as horizontal lines, however, the luminance and gamut appears the same. It is expected that RGBW displays with the same number of pixels (25% more sub-pixels) will appear to be equal or higher in image quality than RGB displays.

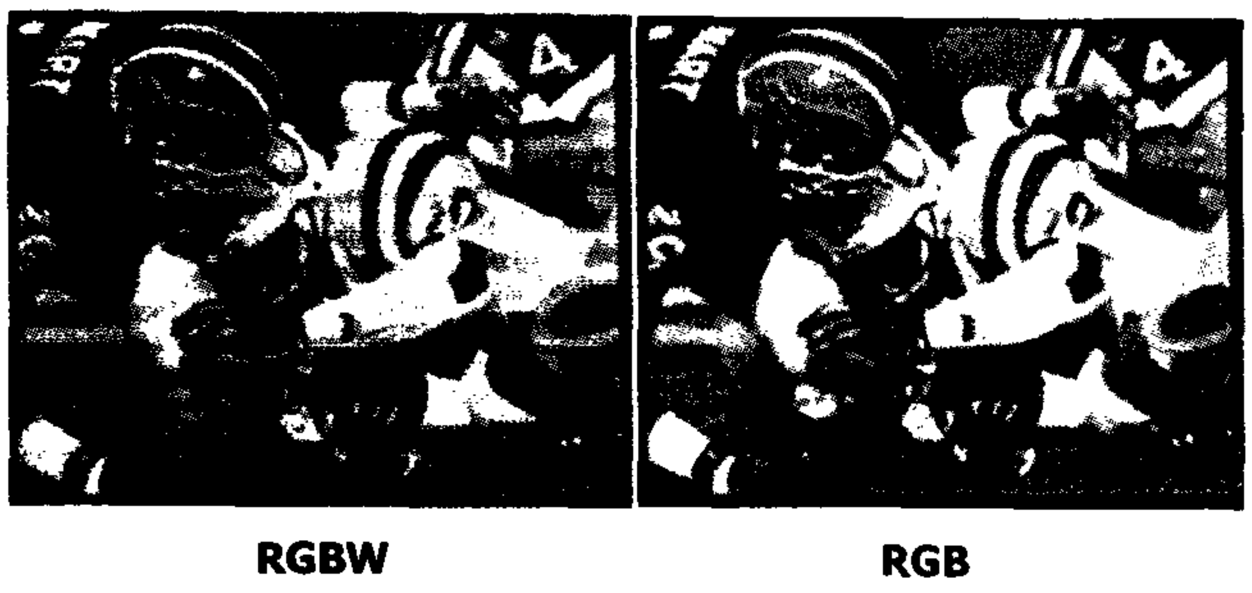
RGBW RGB

Figure 8. Images from RGBW and RGB displays.

4. Conclusions

An AMOLED RGBW display has been fabricated and requires approximately ½ the power compared to the RGB format. Other display characteristics (luminance, gamut) are the same for both RGB and RGBW displays.

5. Acknowledgements

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6. References

[1] G. Rajeswaran, M. Boroson, S. Barry, T. K. Hatwar, K. B. Kahen, K. Yoneda, R. Yokoyama, N. Komiya, H. Kanno and T. Takahashi, SID '00 Digest, 974 (2000).

[2] KODAK EASYSHARE LS633 Zoom Digital Camera.

[3] T. Sasaoka, M. Sekiya, A. Yumoto, J. Yamada, T. Hirano, Y. Iwase, T. Yamada, T. Ishibashi, T. Mori, M. Asano, S. Tamura and T. Urabe, SID '01 Digest, 384 (2001).

[4] T. Tsujimura et al., SID '03 Digest, 6 (2003).

[5] K. Mameno et al., Proc. 8th Int. Conf. Electron. Mater. **275** (2002).

[6] T. K. Hatwar, J. P. Spindler, M. L. Ricks, R.H. Young, Y. Hamada, N. Saito, K. Mameno, R. Nishikawa, H. Takahashi and G. Rajeswaran, SPIE **5214**, 233 (2003).

[7] B. Lee, C. Park, S. Kim, T. Kim, Y. Yang, J. Oh, J. Choi, M. Hong, D. Sakong, K. Chung, S. Lee and C. Kim, SID '03 Digest, 1215 (2003).