System considerations for RGBW OLED displays

Jeffrey P. Spindler
Tukaram K. Hatwar
Michael E. Miller
Andrew D. Arnold
Michael J. Murdoch
Paul J. Kane
John E. Ludwicki
Paula J. Alessi
Steven A. Van Slyke

Abstract — The fabrication of full-color RGBW OLED displays using a white emitter with RGB color filters has been previously described. This paper discusses the effect of several display-system factors on the important RGBW OLED display performance attributes of power consumption, lifetime, and perceived image quality. These display-system factors include the spectrum of the white OLED, the white OLED structure, the color-filter selection, the subpixel aperture ratios, and the pixel arrangement (including sub-sampling).

Keywords — *Organic light-emitting diode, OLED, white, RGBW, power reduction, efficiency.*

1 Introduction

A full-color active-matrix organic light-emitting diode (AMOLED) display, based on a white emitter with an RGB color-filter array, was described previously as a potential lower-cost alternative to AMOLED displays with patterned RGB emitters.[1] The use of a single white emitter simplifies the fabrication of AMOLED displays by eliminating the need to separately deposit three adjacent light-emitting materials (*i.e.*, R, G, and B). This simplification reduces the number of manufacturing steps and eliminates the need for color patterning, which has usually been accomplished with precision shadowmasking. However, RGB displays based on a white emitter are less power efficient than AMOLED displays with patterned RGB emitters because much of the white light that is generated within the device is absorbed by the color filters.

It is well known, however, that natural images contain significant amounts of color that are low in saturation.[2,3] Furthermore, display applications often employ graphic screens with white or near-neutral backgrounds. The fact that much of the content to be displayed is neutral or low in saturation implies that the power efficiency of the display when rendering near-neutral or neutral colors will significantly influence the power consumption of the display. Recently, a white-emitter-based AMOLED display with a red, green, blue, and white (RGBW) pixel format was discussed[4,5] wherein the colors that are near neutral are displayed using an unfiltered white subpixel together with small amounts of light from the RGB filtered subpixels. Importantly, it is possible to employ the RGBW pixel format to significantly increase the power efficiency of the OLED display without decreasing the chrominance of saturated colors. In fact, when operated properly, the color reproduction of the RGBW display is exactly the same as a corresponding RGB display given that the white subpixel may be employed to form metamers to the colors that would be formed on an RGB display having the same color primaries, *i.e.*, stimuli presented on the RGBW display and a corresponding RGB display will have different spectral characteristics, but the stimuli will form a colorimetric match (*i.e.*, have the same CIE 1931 XYZ tristimulus values[6]); and, therefore, the two stimuli will appear similar to an observer with normal color vision, under specified viewing conditions.[7] It was demonstrated that a display of this type requires approximately one-half the power of an analogous white-emitter-based RGB display when rendering natural images. However, a key to enabling the RGBW format is an efficient and stable white emitter.[8]

The RGBW OLED is not the first display to employ an unfiltered white subpixel. LCDs have been described that employ RGBW color subpixels.[9] However, the overall function of an RGBW OLED employing a white emitter with color filters and an RGBW LCD are quite different; and, therefore, the parameters for system optimization differ substantially between these two systems. To understand these differences, it is important to understand light generation and modulation within each system.

In an LCD, the light is generated by a backlight that consumes the vast majority of the power. Controlling the liquid crystals within each subpixel modulates the light that is produced from this backlight to create image information. Because the LCD does not modulate light generation but, instead, only modulates light transmission from the backlight to the observer, the brightest (and highest luminance efficiency) color is achieved when the RGBW LCD is controlled to allow the maximum amount of light to pass through all four subpixels. This fact leads to displays that form their white point with the combination of all four RGBW subpixels, which means that the white subpixel is used to augment the luminance of the RGB subpixels at the expense of color saturation. Many variations of color processing with varying levels of desaturation have been shown, but the typical result is a display with a highly efficient,

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The authors are with Eastman Kodak Co., Research and Development Labs., 1999 Lake Ave., Rochester, NY 14650-2110, U.S.A.; telephone 585/722-0911, fax 585/477-6498, e-mail: jeffrey.spindler@kodak.com.

bright white point that is incapable of rendering bright, fully saturated colors.

In OLED displays, energy is consumed only when a subpixel is active. When the light emitted by a white OLED passes through a color filter, the light is filtered to produce red, green, or blue emission, which reduces the efficiency of the emitted light. However, the light is not filtered significantly when only the white subpixel is illuminated because the light produced by this subpixel does not pass through a color filter. Therefore, in an RGBW OLED display employing RGB color filters, with some subpixels that are not filtered (W), the highest luminous efficiency is achieved when only the unfiltered white subpixels are activated. An optimized display will form its white point using only the white subpixel. Efficiency is improved by replacing the luminance of the RGB subpixels with luminance from the W subpixel wherever possible. This replacement can be accomplished without sacrificing colorimetric accuracy.

Regardless of the technology that is employed, the addition of a fourth color subpixel in any direct-view display technology increases the number of subpixels within each display pixel. This additional subpixel will reduce the pixel aperture ratio (PAR) of a display for any given pixel resolution. The reduction in PAR can reduce the effective luminous efficiency of an LCD because a smaller proportion of the display allows light to pass from the backlight to the observer. In an OLED display, the reduction in PAR affects only lifetime since, for a given display luminance, a smaller PAR translates to the need to drive each subpixel with a higher current density, which negatively impacts the lifetime of an OLED. This effect is a significant factor when evaluating RGBW OLEDs.

In this paper, we discuss the display design parameters that have the largest impact on display power, lifetime, and perceived image quality of RGBW OLED displays.

2 Methods and metrics

To understand the effects that various design parameters have upon display power, lifetime, and perceived image quality, it must be possible to accurately predict these effects. The primary purpose of this section is to generally describe methods and metrics that may be used in the prediction and quantification of these attributes. These methods and metrics will be used to describe and quantify display system interactions throughout the remainder of this paper.

2.1 Power and lifetime estimations

The power and lifetime results are derived using an empirical model that predicts the power consumption and lifetime of a display under specific usage conditions. The inputs to this model are (1) the efficiency and spectral data for each emitter; (2) the drive voltage *vs.* current density characteristics of each emitter; (3) the drive voltage *vs.* aging characteristics of each emitter; (4) the TFT voltage and current characteristics of the display; (5) transmittance properties of the color filters that are used on the display; (6) the transmission properties of any polarizer that might be used on the display; (7) the peak luminance of the display; (8) the target display white point; (9) the emitting area of each color emitter as a percentage of total display area; and (10) the distribution of input code values for a particular application. This model has been validated using performance data from actual displays.

This model may be used to predict the power and lifetime for any particular application. For the purposes of this paper, the distribution of input code values that is applied represents the use of a digital-camera display. This distribution was determined by analyzing a group of more than 13,000 consumer digital camera images that were captured during a period of 9 months by a group of typical users within three U.S. cities.

2.2 Image-quality estimation

To predict perceived image quality, an image processing and display facility was created to allow specific pixel patterns and image-rendering paths to be simulated. The images were judged by groups of observers to ascertain the effect that the simulation parameters (RGBW OLED characteristics) have on perceived image quality.

The simulated OLED images were displayed on a Viewsonic VP2290b LCD monitor having a pixel resolution of 204 dpi. Each simulated OLED image was rendered with 1800 × 1800 LCD pixels, providing a 9-in. square image. When viewed at a distance of 65 in., the image subtended a viewing angle equivalent to viewing a 1.2-in. square portion of an actual OLED display having a resolution of about 125 dpi from a viewing distance of 8.5 in. It should be noted that 125 dpi is a relatively low resolution for a portable display and was selected to be sensitive to artifacts, given that any imaging artifacts that appear at this resolution will be less visible on higher-resolution displays. Within this configuration, each pixel on the simulated OLED was rendered with a grid of at least 12 × 12 LCD pixels, wherein the simulated pixel included a one-pixel black border around each simulated subpixel to represent the inactive area between each subpixel.

For each of the experiments, a group of images containing pictorial, textual, and graphical information was viewed and judged for image quality. The pictorial scenes were selected to include varying degrees of saturated color, areas with and without high spatial frequency information, and facial, as well as scenic, content. The text scenes included black-on-white and white-on-black text, as well as fully saturated red, green, and blue text on a black background. The number of images varied from experiment to experiment and were adjusted based on the sensitivity of the parameter under investigation to scene content differences (*i.e.*, more scenes were included if the effect of the parameter varied significantly as a function of scene content). A group of 20 individuals participated in each experiment. These participants did not judge image quality as an occupation and were required to have corrected or uncorrected far visual acuity of 20/30 or better and normal color vision. Each experiment was conducted in a dark room with the only light being produced by the high-resolution LCD monitor. Participants were seated with a forehead rest to control their viewing distance.

During each experimental comparison, two images were presented on the display, side by side. The participants selected the image having the higher image quality by pressing one of two keys on a numeric keypad. For each scene, the judges compared each experimental variation to all other variations to create a fully populated comparison matrix. The data were analyzed using Thurstone's Law of Comparative Judgment[10] to construct an indirect scale of relative image quality. This analysis allowed the data to be converted to just noticeable differences (JNDs), wherein, one JND is defined to be an image-quality difference that is consistently noticed and rated as higher by 50% of the participants; therefore resulting in a 75/25% split in a paired comparison.

3 Key RGBW systems interactions

Within the following sections, a number of system parameters are discussed that influence the performance of an RGBW OLED display. The reader should recognize that while these parameters are each discussed independently, many of the parameters interact. The ability to predict the impact of each system parameter upon the performance attributes allows one to evaluate a large range of options, selecting the more promising options for prototyping and evaluation.

3.1 Emitter chromaticity and efficiency

The effect of white-emitter chromaticity and efficiency on the power consumption of an RGBW OLED display have been discussed previously.[4,5] Essentially, if the efficiency of the white emitter, expressed in cd/A, is held constant, the average power consumption of the display is minimized when the chromaticity of the white emitter matches the display white point. An equivalent average power consumption can be achieved in displays with white emitters having chromaticity coordinates that are not equal to the chromaticity coordinates of the display white point, but the efficiency of the white emitter must be higher in these displays. Also, these displays will have lower average lifetimes since one or more of the RGB subpixels will be used more frequently in combination with the W subpixel to produce the display white point, increasing the average current density of the colored subpixel(s). As such, a white emitter with high efficiency that matches the display white point is highly desirable; this will generally result in the best power consumption and lifetime performance for the display.

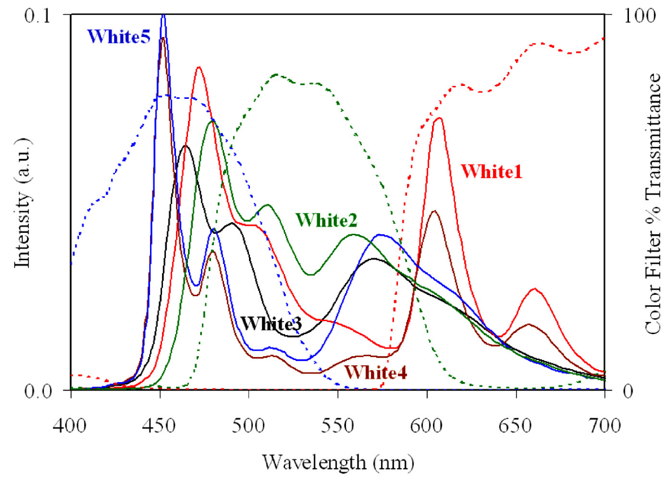

FIGURE 1 — EL Spectra for various white-emitter combinations.

To produce a white emitter with high efficiency and the desired chromaticity coordinates, a white OLED structure with two separate emission layers has been developed. Each emission layer typically contains at least one host and one dopant, and the dopants are selected so that the combined emission from the two layers results in an overall white color. Various combinations of emitters have been recently studied, and the resulting EL spectra can be seen in Fig. 1, along with the spectral transmittance curves for a typical set of LCD color filters. The relative peak heights can be adjusted by optimizing the dopant concentrations and thickness of each emission layer, as previously described.[11] However, the target white color, representing a metameric match to CIE Standard Illuminant D65,[12] cannot be obtained from all emitter combinations.

Table 1 shows the performance of the white-emitter combinations from Fig. 1 for RGB and RGBW displays (2.2-in. diagonal, 15.18 cm^2). Table 1, additionally, shows the experimentally determined luminous efficiency and colorimetric characteristics of the emitter combinations from Fig. 1. In all cases, the target-correlated color temperature for the white point of the display was 6500 K, the luminance was 100 cd/m^2, and the calculations included a circular polarizer with 44% transmittance. Clearly, there are only

TABLE 1 — Performance for various white-emitter combinations. Power values are based on a 2.2-in.-diagonal display driven to 100 cd/m^2 with a 44% polarizer.

White Structure	White Emitter Combination	Efficiency (cd/A)	CIEx	CIEy	RGBW Average Power (mW)	RGB Average Power (mW)
White1	BlueX + RedX	11.3	0.319	0.326	137	280
White2	BlueX + YD3	15.0	0.318	0.434	318	387
White3	BD2 + YD3	11.2	0.314	0.327	137	328
White4	BD3 + RedX	6.2	0.329	0.217	466	566
White5	BD3 + YD3	10.4	0.313	0.281	191	305

two combinations that give low RGBW power consumption (White[1] and White[3]). These are also the only two combinations that are able to achieve a high-efficiency white with chromaticity coordinates very close to the D65 target chromaticity coordinates for the display (x = 0.313, y = 0.329). The chromaticity coordinates and efficiency of the white emitter, as demonstrated in Table 1, as well as the resulting chromaticity coordinates and efficiency of the RGB primaries determine the power consumption of an RGBW display after cascading the white emitter through RGB color filters.

It is important to develop a method to choose the component colors that make up the white OLED emitter. A simple method for making this selection is illustrated in Fig. 2. As shown, the individual emitters can be plotted as a single point on the CIE 1931 x,y chromaticity (or CIE 1976 $u'v'$ uniform chromaticity scale) diagram[6] and connected by a line. If the line intersects the desired white point, the white point can be obtained by the combination of the two emitters by adjusting the relative peak heights. For example, Blue X (actually a blue-green color) in combination with Red X (a pure red) can provide the target D65 white point by adjusting the relative peak heights of these two emitters. Similarly, BD2 and YD3 can be used to attain D65; however, the combination of BD3 (a pure blue emission) with Red X cannot achieve D65 and is a poor candidate for any system using a white emitter with color-filter arrays (in this case, there is insufficient green). Slight changes in chromaticity coordinates may be made by adjusting the thickness of the layers to take advantage of cavity effects; however, these adjustments can only be used to fine tune the emission chromaticity coordinates and cannot be used to correct for major differences in the chromaticity coordinates from the target-display white point. This technique has been experimentally verified, as shown by the many data points (each representing a particular test device that was fabricated) plotted on the CIE 1931 x,y chromaticity diagram in Fig. 2.

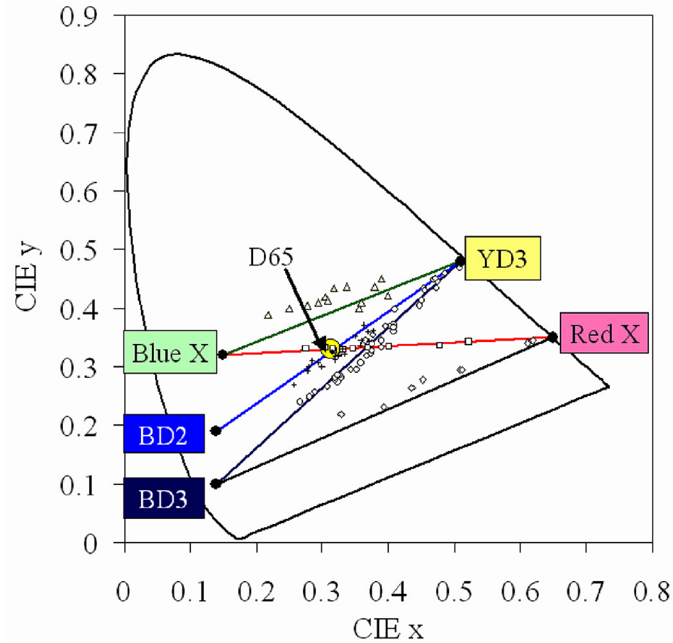

FIGURE 2 — Selecting emitter combinations to achieve D65 white.

3.2 Effects of color conversion

A free parameter within an RGBW system is the proportion of RGB luminance that is allocated to the white subpixel. An algorithm, which converts the incoming RGB signal to drive signals for the RGBW display, controls the proportion. It is important that this algorithm not sacrifice saturation of high luminance colors if image quality is a dominant concern. A preferred algorithm for this process has been described elsewhere[5]; however, a brief summary of its key functions is provided here to aid in the understanding of its effect. This algorithm generally performs the steps of linearizing the input image data to relative intensity, rotating the color of the input RGB image to the RGB intensity of the display primaries, and normalizing the RGB signal to the color of the white subpixel. The minimum of the three R, G, B signals at an individual pixel site is then determined. A proportion, referred to as the white mixing ratio (WMR), is multiplied by this minimum value, and the product is subtracted from the R, G, B signals and added to the white signal. The new RGB values are renormalized to the white point of the display, and finally, a gamma correction is applied based on the luminance characteristics of the display. In performing these operations, the colorimetric accuracy of the image is preserved.

Using this algorithm, any value between 0 and 1.0 might be selected for the WMR without affecting the color rendition (*i.e.*, the display will produce colors that are metameric matches to those produced on a RGB display having the same color primaries). Applying a WMR of 0 produces an image using only the RGB subpixels, while a WMR of 1.0 utilizes the W subpixel as much as possible without affecting the output color. Intermediate values shift varying amounts of energy to the W subpixel.

On average, when the WMR is 1.0, the power required to display a given image on the RGBW display is approximately one-half the power needed to display the same image on the RGB display. This power difference is larger for images with large numbers of pixels that are nearly neutral, and smaller for images with large numbers of pixels that are highly saturated. Reducing the WMR reduces the power savings. Figure 3 shows how the average power varies for a reference RGBW display with different WMRs. Notice that the average power consumption decreases linearly as the WMR is varied from 0.25 to 1.0. This trend would continue for WMRs less than 0.25, as long as there is still a white emitter included in the display. A nonlinearity occurs at a WMR of 0 because this is essentially an RGB display and RGB displays inherently have a larger emitting area. This larger emitting area reduces the peak current densities in the subpixels and lowers the voltage requirements for the display, resulting in the nonlinear behavior near a WMR of 0.0.

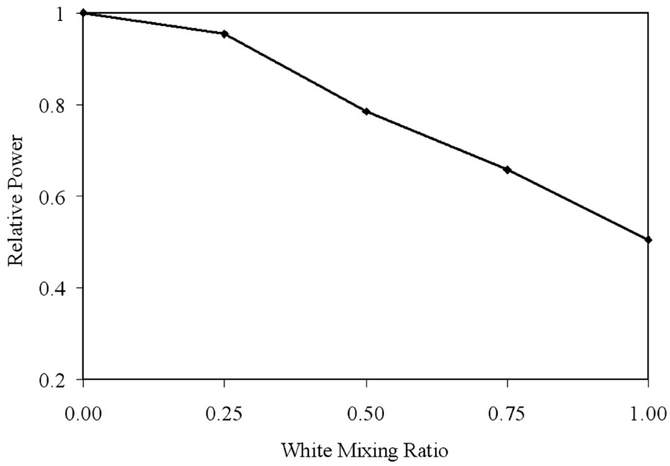

FIGURE 3 — Average power consumption of an RGBW display as a function of WMR relative to the average power consumption of an RGB display.

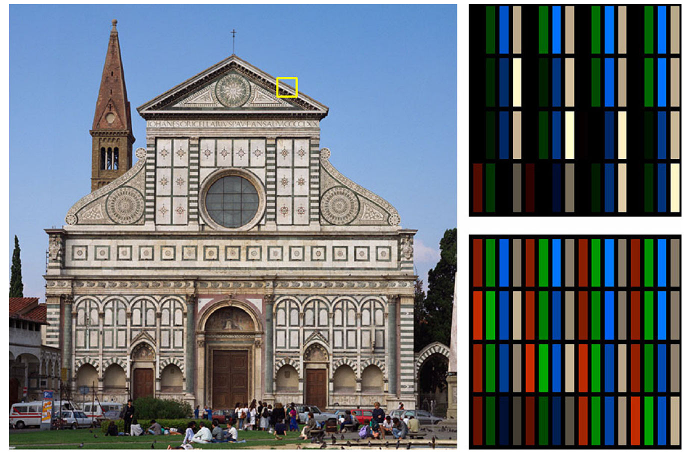

FIGURE 5 — Rendering of a magnified view of a group of RGBW pixels for two renderings from a small portion of an image. The portion is indicated by the yellow square in the photograph. The top-right rendering represents a WMR of 1.0, while the bottom-right rendering represents a WMR of 0.5.

The WMR has a similar effect on the lifetime of the RGBW display. As the WMR increases from 0.25 to 1.0, the average lifetime for an RGBW display increases. Figure 4 shows the effect of WMR on average lifetime. The non-linearity near a WMR of 0.0 is due to the larger emitting area in an RGB display, which reduces the average current density in the subpixels and results in a longer lifetime. At higher WMRs, the effect of the larger PAR is outweighed by the benefits of a more-efficient white emitter.

While a higher WMR provides higher power efficiency, it also influences the perceived image quality of the display as luminance is moved from the RGB to the white subpixel. The source of this effect can be seen in Fig. 5. This figure contains a photograph with a yellow square overlaid upon it. To the right of the photograph are two magnified views of rendered display pixel patterns that could be used to represent the portion of the photograph indicated within the yellow square. Looking at the photograph, one can see that the region from which each of the magnified pixel patterns were extracted contains information that is relatively low in saturation. The two panels on the right were created to represent a RGBW display with a WMR of 1.0 (top) and a RGBW display having a WMR of 0.5 (bottom). The four subpixels (red, green, blue, and white) are all illuminated on the RGBW display when the WMR is 0.5. However, when the WMR is 1.0, the RGBW display produces the majority of the luminance with the white subpixel, produces a significantly smaller proportion of the luminance with two additional color subpixels within each pixel (e.g., G and B), and produces no luminance at the fourth subpixel (R). At low resolutions, the fact that at least one of the subpixels will be black within bright areas of the image can produce the impression that the resulting image is less uniform within some areas compared to the RGBW display having a WMR of 0.5. However, the magnitude of this impression decreases significantly as the resolution of the display is increased.

Image simulations and psychophysical assessments were used to determine the effect of WMR on perceived

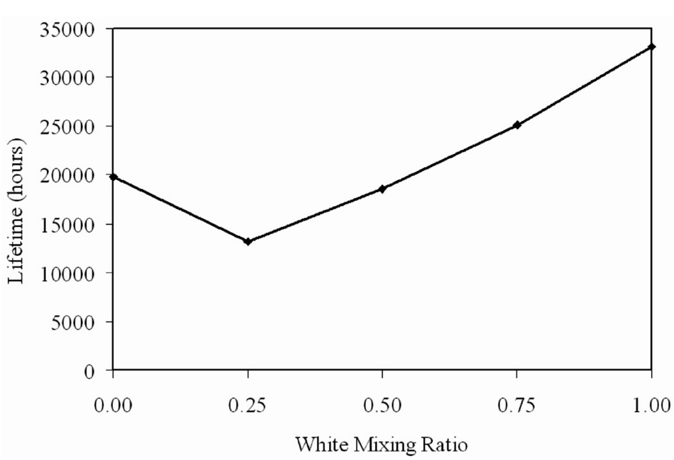

FIGURE 4 — Lifetime of RGBW display having equal SARs as a function of WMR.

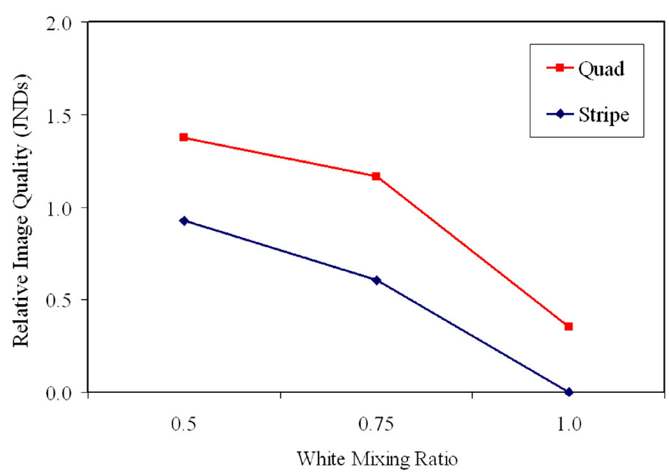

FIGURE 6 — Image quality as a function of WMR for RGBW stripe and quad pixel patterns relative to an RGBW stripe pixel pattern with a WMR of 1.0.

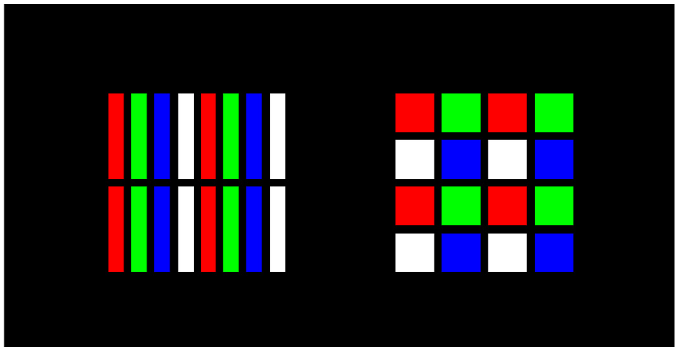

FIGURE 7 — Two potential RGBW pixel patterns: the RGBW stripe on the left and the RGBW quad on the right.

image quality, and the results are shown in Fig. 6 for two typical pixel patterns. As shown in this figure, independent of the pixel pattern, the perceived image quality of the display generally decreases as the WMR is increased from 0.5 to 1.0. However, the decrease in image quality would appear to be slightly more rapid as the WMR is increased to between 0.75 and 1.0 than when the WMR is increased from 0.5 to 0.75. It is also noteworthy that an RGB display having the same pixel resolution would have an image quality of about 0.7 JNDs relative to an image quality value of 0 for the RGBW stripe pixel pattern with a WMR of 1.0. Therefore, the image quality of the RGBW display would appear comparable for the RGB displays for WMRs with less than 0.75 and only a fraction of a JND lower than the RGB display when a WMR of 1.0 is applied. However, the RGBW display is comparable in image quality to the RGB display, regardless of the WMR, and any difference in perceived image quality is likely to be smaller for higher resolution displays.

3.3 Pixel layout

Another display system parameter to consider is the overall pixel layout. Although, many potential pixel patterns have been conceived for RGBW displays,[9,13] the majority of these are derived from either the RGBW striped or quadrilateral (quad) pixel patterns shown in Fig. 7, each of which has advantages and disadvantages. The striped pixel pattern is a simple variant of the common RGB striped pixel pattern that is used in most flat-panel displays. It has the advantages that the individual areas of each of the color emitters may readily be increased or decreased by changing their relative widths without producing misalignment of the subpixels, making the routing of row and column lines in an AMOLED relatively simple. However, to implement this pixel pattern, one-third more column drivers are required than are needed for the traditional RGB display. Further, in an RGBW OLED display with a striped pixel pattern, one-third more power lines might also be required. The quad pixel pattern has the advantage that it requires fewer column drivers and power lines than the RGBW striped pixel pattern, as the vertically aligned subpixels might share column lines. However, RGBW OLED displays constructed with the quad pixel pattern might require twice as many row drivers and capacitor lines. Importantly, it is also often possible to construct quad pixel patterns having a slightly larger PAR than can be constructed using the striped pixel pattern.

In addition to other factors, the selection of a pixel pattern will influence the perceived image quality of the display. Referring again to Fig. 6, one can see that, for the particular condition that was simulated, the RGBW quad pixel pattern is about 0.5 JND higher in image quality than the RGBW striped pixel pattern. It might be noted that this comparison assumed that RGB information was available at each subpixel, taking advantage of the vertical and horizontal offset of subpixels in the quad pattern. Even under this condition, the difference in image quality is relatively small, and other image simulations, the results of which are not shown, demonstrated that when information was not available to take advantage of the vertical offset of the subpixels in the quad pattern, the difference in image quality was, in fact, negligible.

3.4 Spectral shape of the white emitter

An important consideration in any display system is the color gamut, which represents the range of colors that can be produced by the primaries comprising the display system. In an RGBW display based on a white emitter, the color gamut is determined by the combination of the spectrum of the white emitter and the RGB color filters. Figure 8 shows a typical electroluminescent spectrum of a two-peak (broadband) white, as well as an electroluminescent spectrum of a three-peak (peaky) white, along with a typical set of LCD-TV color filters. The broadband spectrum is advantageous in terms of efficiency; however, given that it lacks green and red peaks when it is cascaded with the RGB color-filter transmittances, the resulting RGB primary chromaticity coordinates provide a display having a limited color gamut. The peaky spectrum contains individual blue, green, and red peaks, which align well with the transmission of the individual color filters; however, it is less efficient than the broadband spectrum and therefore will result in a display having higher power consumption. In this particular example, devices fabricated with the peaky emission spectrum require over 50% more power consumption than analogous devices with the broadband spectrum. Figure 9 shows a CIE 1931 x,y chromaticity diagram and the CIE 1976 $u'v'$ uniform chromaticity scale diagram, with the resulting RGB chromaticity coordinates that are produced when the spectrum of the peaky and broadband whites from Fig. 8 are cascaded with the same color-filter transmission spectra. The more commonly used CIE 1931 x,y chromaticity diagram is perceptually nonuniform; therefore, the CIE 1976 $u'v'$ uniform chromaticity scale diagram is included because it provides a representation of a chromaticity diagram that is perceptually more uniform to a human observer. It is apparent that the peaky white spectrum provides a larger color gamut triangle, compared to the broadband white

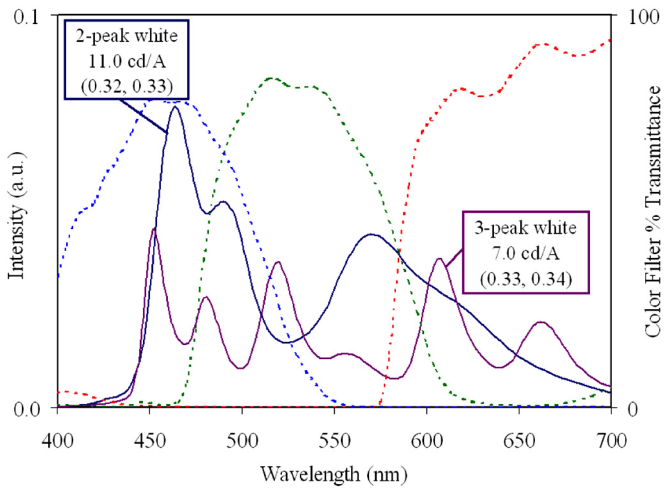

FIGURE 8 — EL Spectra for peaky and broadband white OLEDs.

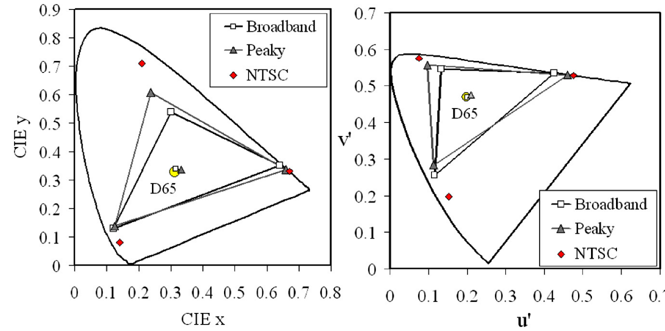

FIGURE 9 — Color gamut for peaky and broadband white OLEDs when cascaded with a standard set of RGB filters. The color gamuts are plotted in both a CIE 1931 *x,y* chromaticity diagram, as shown on the left, and the more perceptually uniform CIE 1976 *u′,v′* uniform chromaticity scale diagram, as shown on the right.

spectrum when used with the same set of RGB color filters. The ratio of the area of the resulting *x,y* color gamut triangles to the area of the *x,y* triangle created using the NTSC primaries for the peaky spectrum is 72%, while it is only 56% for the broadband spectrum. The ratio of the area of the resulting *u′,v′* color gamut triangles to the area of the area of the *u′,v′* triangle created using the NTSC primaries for the peaky spectrum is 67%, while it is only 57% for the broadband spectrum. Clearly, there is a trade-off between power consumption and color gamut and the peaky white emission spectrum would be more desirable if the efficiency was improved.

3.5 Color-filter selection

It is well known that the choice of color filters can significantly influence the power consumption of RGB displays. However, given that much of the light generated by an RGBW display will be generated by the white subpixel and the RGB subpixels are used less frequently, the effect of color-filter selection on average display power is significantly lower for an RGBW display. This is demonstrated in Table 2, which shows the average and peak power consumption for several display configurations. Also shown in this table is the percent change in each of these values. As shown, the relative change in average power consumption of the RGB display for the narrower color filters (color filter 2) is on the order of 34%. However, the corresponding change in average power consumption for the RGBW display is only 12%. Similarly, the change in peak power consumption of the RGBW display is not as great as the RGB display, increasing by only 5% for the RGBW display, compared to 34% for a RGB display. Peak power occurs when an RGB display shows a full screen of white, while peak power occurs when an RGBW display shows a full screen of a secondary color. This is notable because the probability of rendering nearly full screens of very bright, saturated secondary colors is extremely low compared to the frequency of displaying nearly full screens of white.

3.6 SAR optimization for RGBW based on lifetime considerations

When constructing an OLED display, it is possible for each of the color channels of the display to degrade at different rates. For instance, in OLED displays formed from patterned red, green, and blue emitters, it is known that differences in efficiencies of the emitters, the stability of the emitters, and the color of the emitters, relative to the display white point, can produce differences in the rate of aging (*i.e.*, the loss of luminance efficiency) of one color channel compared to a second. If one color channel ages significantly faster than the others, the color balance of the display will change with time, and images displayed using a large fraction of the least stable channel will be significantly lower in luminance than desired. If this differential aging is great enough, the useful lifetime of the display will be dictated by the lifetime of the color channel having the most rapid aging since the color balance of the display will degrade to the point that the display will not be deemed useful. One method of balancing the rate of aging among the color channels is to modify the proportion of the PAR that is devoted to each colored subpixel. In this paper, we refer to the proportion of the PAR that is devoted to each colored subpixel as the subpixel aperture ratio (SAR).

TABLE 2 — Effect of color filters on power consumption of RGB and RGBW OLED displays. Power values are based on a 2.5-in.-diagonal display driven to 200 cd/m^2 with a 44% polarizer.

Color Filter Set	RGB Average Power (mW)	RGB Peak Power (mW)	RGBW with WMR 1.0 Average Power (mW)	RGBW with WMR 1.0 Peak Power (mW)
Color Filter 1	740	3510	450	1560
Color Filter 2	995	4700	502	1640
Percent Change	34%	34%	12%	5%

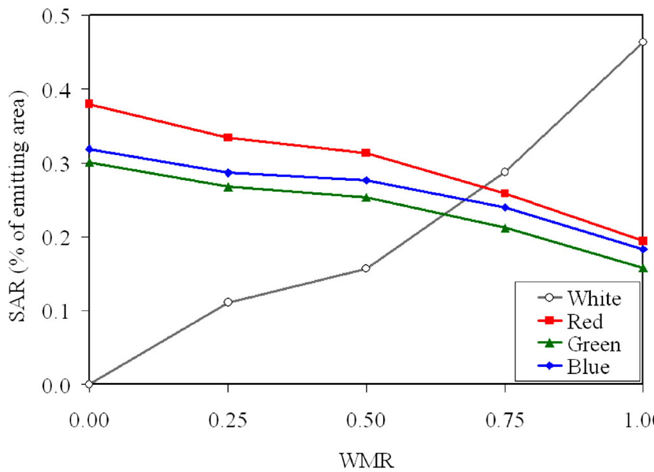

FIGURE 10 — Optimal subpixel aperture ratios for white, red, green, and blue subpixels as a function of WMR.

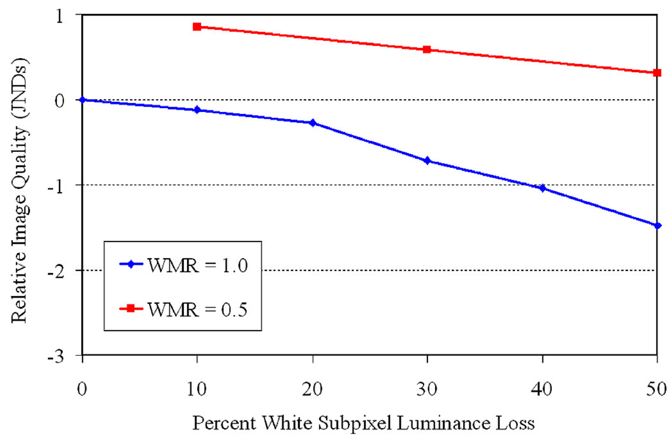

FIGURE 11 — Relative image quality as a function of percent luminance loss of the white subpixel for WMRs of 0.5 and 1.0.

The fact that the efficiencies and stability of the subpixels in an OLED display formed from a single white emitter with color filters will be nearly identical reduces the severity of this problem. However, in RGBW OLED displays, the white subpixel will be significantly higher in efficiency than the red, green, and blue subpixels and, depending on the color-conversion algorithm, may be used much more frequently than the colored subpixels. Therefore, it is desirable to form a white subpixel that has a different SAR than the red, green, and blue subpixels to balance the lifetimes of each subpixel. Since the emitting material in each subpixel is identical (*i.e.,* white), the lifetimes of the subpixels can be approximately balanced – by balancing the SARs to produce the same time-averaged current density for each subpixel. It is important to note that the time-averaged current density must account for the fact that at WMRs of 1.0, some subpixels will be inactive for large portions of time. It should also be noted that, if the white-emitter chromaticity is too far from the display white point, one or more of the colored subpixels will need to be driven to compensate for the chromaticity coordinate of the W subpixel, increasing the frequency of use for this subpixel and, consequently, the desired SAR will be proportionally larger for this channel.

The power and lifetime model discussed previously was used to calculate the luminance of each color subpixel needed to produce a given color on a display based upon the WMR selected. The results of these calculations are shown for a particular display configuration in Fig. 10. As shown in this figure, as the WMR is increased, the SAR to be allocated to the white subpixel increases from 0, when no light is produced by the white subpixel (*i.e.*, WMR of 0), to a value of more than 45 (indicating that 45% of the light emitting area would need to be allocated to the white subpixel) when the WMR is 1. One should also note that even the relatively small difference between the chromaticity coordinates of the white emitter (the BD2 + YD3 combination shown earlier) and the display white point can require the colored subpixels to have different optimal SARs.

Adjusting the SAR values for the subpixels can impact the perceived image quality of the final display. To study the impact of this parameter on perceived image quality, a display having a RGBW striped pixel pattern in which 25% of the active pixel area was devoted to the white subpixel was compared to a display in which 40% of the active pixel area was devoted to the white subpixel. All images were simulated with a WMR of 1.0 using the techniques mentioned earlier. This study demonstrated that increasing the area of the white subpixel relative to the red, green, and blue subpixels improved the apparent uniformity of the resulting images, resulting in an image-quality improvement of about 0.34 JNDs. Given that the experimental error was on the order of 0.2 JNDs, the results would indicate that the SAR of the white subpixel could be increased to improve the lifetime of the display with no (or slightly positive) impact on the perceived image quality.

Because providing a white subpixel with a large SAR may not always be practical, the white subpixel in an RGBW display might be expected to age faster than the red, green, and blue subpixels for displays that are used in imaging applications. To understand the effect of a more rapid loss in white intensity on image quality, various images were simulated in which the luminance output of the white subpixel was adjusted to some proportion of its initial luminance. In this series of images, the color of the white subpixel was assumed to match the white point of the display. The result of this effect upon perceived image quality for WMR values of 0.5 and 1.0 is shown in Fig. 11. As this figure shows, image quality decreases as the relative luminance of the white subpixel is decreased. However, this effect is far from catastrophic. In fact, even when the luminance of the white subpixel is decreased to half its desired value, the display undergoes only about a 1.5 JND loss in perceived image quality when the WMR is 1.0 and only about 0.5 JND loss in perceived image quality when the WMR is 0.5. Therefore, the image quality of RGBW OLED displays is robust against differential aging where the white subpixel ages more rapidly than the red, green, and blue subpixels.

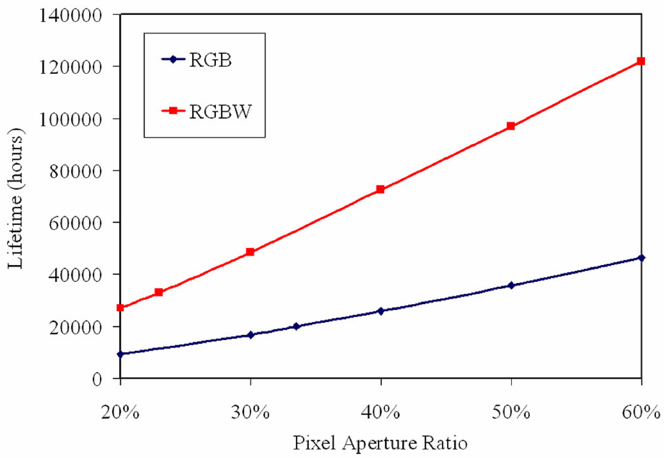

FIGURE 12 — Display lifetime for average use when displaying natural images as a function of pixel aperture ratio.

3.7 Optimized RGBW lifetime and the use of subsampling

It is likely that RGBW OLED displays will have lower PARs than RGB OLED displays of equal resolution because four subpixels will be arranged in the same area that would normally be occupied by three subpixels. As is well known, the reduction of PAR increases the current density required for a given luminance, thereby reducing the lifetime of the display. That said, however, the average current to the display is reduced significantly for RGBW displays, due to the improved efficiency of the unfiltered white subpixel, and this gain in efficiency will offset the loss of PAR to some degree. To understand these effects on lifetime of RGBW and RGB configurations, displays having similar characteristics were modeled and their lifetimes calculated as a function of PAR.

Figure 12 shows the expected average display lifetime to 50% initial luminance for both an RGB and RGBW display as a function of PAR when the SARs are optimized and the RGBW display was driven at a WMR of 1.0. The display simulated was a 2.5-in. QVGA display producing 200 cd/m^2 through a 44% polarizer. The lifetime data measured from a test white emitter device, which used the combination of BD2 + YD3, was one input into the model. The excellent stability of this white emitter, measured at various current densities, is shown in Fig. 13. Using the lifetime data from Fig. 13 (extrapolated to 50% initial luminance at lower current densities), the half-life can be plotted as a function of current density as seen in Fig. 14. This curve is used in the model to predict display lifetime.

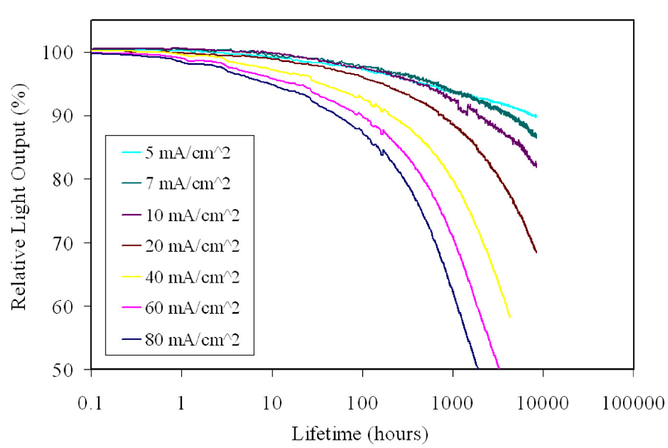

FIGURE 13 — White OLED operational stability at various current densities.

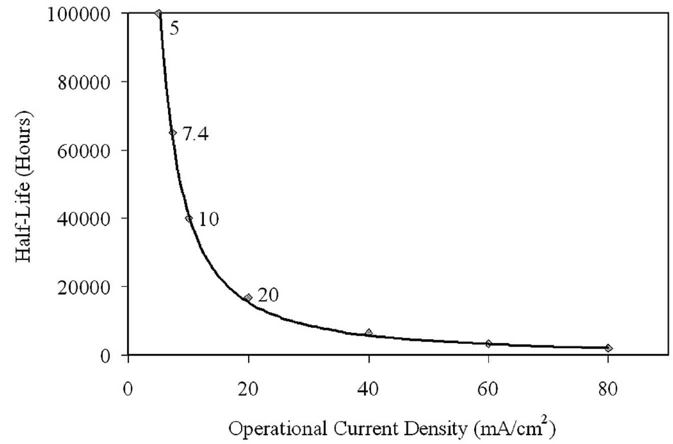

FIGURE 14 — White OLED half-life versus current density.

As Fig. 12 shows, the lifetime of the RGBW display is always higher than the lifetime of the RGB display for imaging applications and PARs between 20 and 60%. This difference results from the increased efficiency as a result of the unfiltered white subpixel. However, depending upon the display configuration and the relevant design constraints, it is likely that the PAR will be significantly lower for the RGBW display compared to the RGB display. For example, if an RGB display is fabricated with a PAR of 40%, a display lifetime of about 26,000 hours is expected. For a similar RGBW display with a smaller PAR (*e.g.*, 30%), a display lifetime of about 48,000 hours is expected. As this example illustrates, the reduction in current density that occurs as a result of the increased efficiency of the unfiltered white subpixel can more than compensate for the loss of lifetime as a result of the reduction in PAR.

While an RGBW display might require the use of more subpixels than an RGB display, it is also possible to construct an RGBW display having the same number of both pixels and subpixels as an equivalent RGB display by subsampling (*i.e.*, reducing the frequency of) certain colors. In particular, blue and red emission contributes a small portion of the total luminance information, and the human eye is relatively insensitive to spatial frequency of these colors; hence, a subsampling configuration where red and blue subpixels are placed at every other pixel results in the same number of subpixels (dots) for both the RGBW (subsampled) and RGB (standard) configurations. Because a reduction in the frequency of the blue and red subpixels can introduce artifacts, whether these artifacts are noticeable is highly dependent upon the subpixel arrangement and the

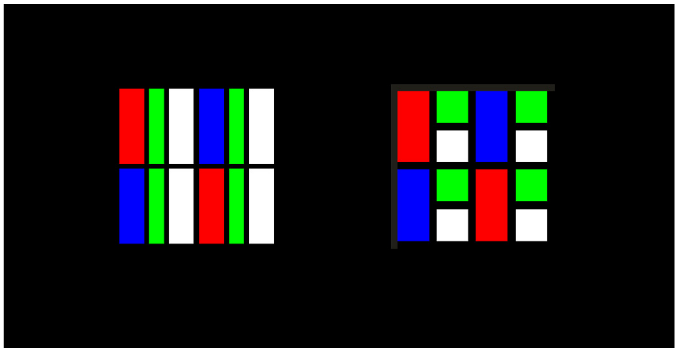

FIGURE 15 — Two potential RGBW subsampled pixel patterns: a derivative of the RGBW stripe is shown on the left and a derivative of the RGBW quad is shown on the right.

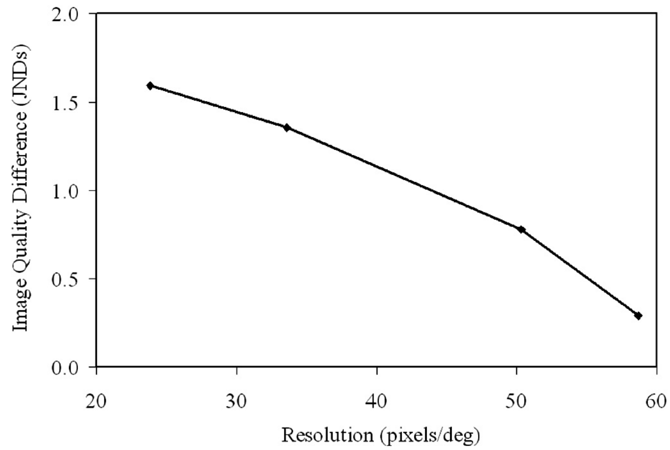

FIGURE 16 — The difference in image quality between the fully sampled and subsampled striped pixel patterns.

resolution of the display. Figure 15 shows two subsampled RGBW pixel patterns (one derived from a striped pattern and one from a quad pattern) that were found to have reduced levels of artifacts compared to others that were investigated.

Figure 16 depicts the image-quality difference, expressed in JNDs, between the RGBW striped pixel pattern shown earlier in Fig. 7 and the subsampled RGBW striped pixel pattern shown in Fig. 15. The image-quality difference in Fig. 16 is plotted as a function of resolution in pixels per degree of visual angle. At lower resolutions (*i.e.*, 24 pixels/deg, which corresponds to a 160-ppi display viewed from a distance of 8.5 in.) the image-quality difference is on the order of 1.6 JNDs. However, as the resolution or viewing distance increases, the image quality difference decreases and crosses the 1 JND line at about 45 pixels/deg (which corresponds to a 160-ppi display viewed from a distance of about 16 in.). Note that at the two highest resolutions, the image-quality difference is less than 1 JND, indicating that fewer than 50% of the observers could reliably select images presented on the subsampled pixel pattern as being lower in quality than the fully sampled RGBW pixel pattern in a side-by-side comparison. Therefore, subsampling may be used on high-resolution displays to reduce the average number of subpixels per pixel, increasing the PAR and further improving the lifetime of RGBW displays with a minimal reduction in image quality. Further, no practical difference in image quality is expected for displays where the resolution approaches 60 pixels/deg (corresponding to, for example, a 160-ppi display viewed from a distance of 21 in.).

4 Summary and conclusions

Many of the display design trade-offs that affect the performance of full-color RGBW OLED displays have been discussed. This paper demonstrates that not only does the RGBW format reduce power consumption to about 50% of that required by the RGB format, it can improve the lifetime of the display, the sensitivity of the power of the display to changes in color filters is reduced, and it can provide comparable image quality to the RGB format. It is also important to consider several parameters when designing an RGBW format OLED display; including the spectrum and white point of the OLED emission, the efficiency and operational stability of the OLED emission, the proportion of RGB luminance that is allocated to the white subpixel, the pixel layout, the color filters, and the subpixel aperture ratios. Each of these parameters can have a significant effect on the power consumption, lifetime, and perceived image quality of the final display and should be optimized to obtain the desired RGBW OLED display performance. Additionally, this paper has discussed the performance of a white OLED formulation that provides superior performance when applied within the RGBW format.

Acknowledgments

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Jeffrey P. Spindler received his B.S. degree in microelectronic engineering from Rochester Institute of Technology in 1993. He worked for Harris Semiconductor for six years in the field of semiconductor device fabrication, where his work involved the research, development, and manufacture of semiconductor devices. He joined Eastman Kodak Research Laboratories in 1999 where his work has centered on organic light-emitting diodes (OLEDs). He has been active in many aspects of OLED-display technology, including research and development of organic device structures, development of active-matrix backplane structures, and development of manufacturing technologies for high-volume OLED-display production.

T. K. Hatwar joined Eastman Kodak Company Research Laboratories in 1985. He received his Ph.D. in physics from the Indian Institute of Technology, Bombay, India, in 1981. He did his postdoctoral work for two years at Texas A&M, Commerce, Texas before joining Eastman Kodak Company. Currently, he is a researcher at the OLED Modules R&D Business Unit where his work is focused on organic light-emitting diode technology. His work involves all phases of OLED technology, from basic research on organic materials, device architectures, and stability improvements to development of manufacturing technologies for high-volume OLED display production. He has worked closely with Kodak's Joint development partners (Sanyo Electric Co. and ULVAC Co. Japan) in developing the world's first 25-in. full-color AMOLED display and later a 15-in. display based on white technology.

Michael E. Miller holds a B.S. and M.S. in industrial and systems engineering from Ohio University and a Ph.D. in industrial in systems engineering from Virginia Polytechnic Institute and State University. His experience includes display research and development at IBM and Eastman Kodak Company. He holds 14 U.S. patents regarding digital camera and display design and has co-authored more than 10 publications on the human factors aspects of visual displays.

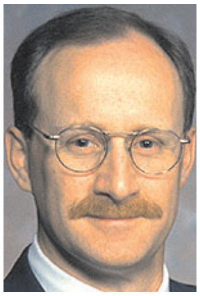
Andrew D. Arnold received his B.S. in electrical engineering from Western New England College and M.S. in electrical engineering from Rochester Institute of Technology. He joined Eastman Kodak in 1973 where he has worked as a project manager and commercialization manager on a wide variety of technical projects. He joined the Research Laboratories in 2001 as the team leader of the OLED Systems Group and has been active in the analysis of OLED system performance.

Michael J. Murdoch received his B.S. in chemical engineering from Cornell University in 1997 and is currently completing a M.S. in computer science at Rochester Institute of Technology, concentrating in computer graphics and image processing. His work at Eastman Kodak Research Laboratories has primarily focused on color imaging science and image quality, including color and performance models of hybrid film-digital systems and emissive display systems.

Paul J. Kane received his M.S. in optics from the University of Rochester. He has been with Eastman Kodak since 1986. His assignments at Kodak have included photographic granularity measurement and modeling, microdensitometry, system image-quality modeling for digital, analog, and hybrid imaging systems, and image quality of electronic displays. His current interests are in image quality, metrology, and image rendering for OLED displays.

John E. Ludwicki received his B.Sc. in electrical engineering from Purdue University (1985), his M.S. in electrical engineering from the Rochester Institute of Technology (1994), and his M.S. in engineering and management from the Massachusetts Institute of Technology (1999). He joined Eastman Kodak Company in 1985, where he has held positions related to various phases of the product development process. He is currently responsible for system engineering and system analysis in support of OLED-display development.

Paula J. Alessi received her B.S. in chemistry from St. John Fisher College and her M.Sc. in color science from Renssalear Polytechnic Institute. She has been with Eastman Kodak Company for 26 years working as a color scientist first in the color film/paper arena, and then her emphasis was on hardcopy/softcopy color appearance matching. Now she works in the digital display imaging arena, specifically for OLED development. She has led color science groups within and outside of Kodak. She has been President of the U.S. national color organization, known as the Inter-Society Color Council. She is the U.S. voting member to CIE Division 1 on Vision and Color. She is currently President of the International Color Association.



Steven A. Van Slyke is a Research Fellow at Eastman Kodak Company. He received his B.A. in chemistry from Ithaca College and M.S. in materials science from Rochester Institute of Technology. He joined Eastman Kodak Research Laboratories in 1979 where his work has centered on organic light-emitting diodes (OLEDs). He has been active in all phases of organic electroluminescence technology, from basic research on organic materials to development of manufacturing technologies for high-volume OLED display production.