Performance analysis of PLED based flat panel display with RGBW sub-pixel layout

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ABSTRACT

PLED based flat panel displays with RGBW sub-pixel format utilizing a white emitter as the fourth primary, was analyzed theoretically and experimentally. Instead of the traditional white point characterization method, uniform luminance color space was introduced to characterize the display performance in a more realistic way. In the uniform luminance color space, after the power efficiency of the white emitter exceeds a threshold determined by the green emitter’s efficiency, the RGBW display becomes more energy efficient than the RGB display. To simulate the display performance in different applications, such as computer desktop visualization, or video application, the color usage frequency with Gaussian distribution was adopted. As the color usage frequency distribution gets closer to that in the real images, the full color pixel’s power efficiency of the RGBW display is more and more dependent on the EL performance of the white emitter. With a highly efficient white emitter as W sub-pixel, the RGBW display will be the preferable choice for displaying video information.

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1. Introduction

Organic light emitting diodes (OLEDs) based full color flat panel displays (FPDs) have been successfully commercialized offering superior image qualities, such as wide viewing angles, fast response time, large color gamut, and high contrast, etc. [1–5]. To reproduce a full color pixel, the most common practice is to pattern three individual primary color emission sub-pixels. As the power efficiency of the white OLEDs is continuously pushed higher [6–13], utilizing white OLEDs coupled with transmission color filters to reproduce full color becomes feasible and attractive [14–16]. Though the full color display based on a white emitter possesses the merit of fabrication simplicity, it is at a disadvantage in terms of power efficiency and power consumption, because of the white light absorptions by the color filters [14].

To use the white emitter more efficiently, a white emitter-based display with RGBW sub-pixel layout has emerged as an alternative to RGB sub-pixel technology [3–5]. In RGBW display, the white sub-pixel is added to the traditional three color primaries, i.e. red, green, and blue, to form a full color pixel. Since the nature images consist of bright unsaturated colors and dark saturated colors [5], adding the fourth white sub-pixel appears to be a natural way to better reconstruct real world images. However,
in the application of computer desktop visualization in which bright saturated colors are widely used, adding a white sub-pixel may not be as efficient as in the video application. Moreover, if the size of each sub-pixel is kept the same, adding additional sub-pixel will reduce the display’s resolution. On the contrary, if the display’s resolution is kept the same, the sub-pixel’s size has to be reduced to accommodate the additional sub-pixel. In this work, we present a novel method to characterize the display performance over the whole color space, and we introduce a color usage frequency to simulate real world images. By adjusting the color usage frequency, the advantage of the white sub-pixel can be clearly deduced.

2. Color matching

Since there are three different types of the retinal receptors in human eyes that provide the photopic vision, in principle, any arbitrary color can be reproduced by three primary colors [17]. In a RGB display, any color within the triangle enclosed by the red, green, and blue primary colors can be reproduced (Fig. 1), and the color matching is unique. The following equations give the amount of each primary needed to produce a color at a certain luminance:

\[
\begin{align*}
m_1 &= \left( \frac{1}{\gamma_1} - \frac{1}{\gamma_3} \right) \frac{x}{\gamma_1} - \left( \frac{1}{\gamma_3} - \frac{1}{\gamma_1} \right) \frac{y}{\gamma_1} \cdot m, \\
m_2 &= \left( \frac{1}{\gamma_1} - \frac{1}{\gamma_2} \right) \frac{x}{\gamma_1} + \left( \frac{1}{\gamma_2} - \frac{1}{\gamma_1} \right) \frac{y}{\gamma_1} \cdot m, \\
m_3 &= \left( \frac{1}{\gamma_2} - \frac{1}{\gamma_3} \right) \frac{x}{\gamma_2} + \left( \frac{1}{\gamma_3} - \frac{1}{\gamma_2} \right) \frac{y}{\gamma_2} \cdot m
\end{align*}
\]

(1)

where \(m\) and \((x, y)\) is the amount and chromaticity coordinates of the color to be produced, \(m_1, m_2, m_3\) and \((x_1, y_1), (x_2, y_2), (x_3, y_3)\) are the required amounts and chromaticity coordinates of the three primaries, respectively.

With the additional freedom induced by the fourth primary, the color matching becomes not unique. For example, for a color located inside the triangle enclosed by the green, blue, and white, it could be produced either by red, green, and blue without white, or by green, blue, and white without red. Furthermore, if all the four primaries are used, the solution becomes infinite. To simplify the calculation and take full advantage of the white emitter, we divide the large triangle formed by the primary R, G, and B into three small triangles formed by the primary W with other primaries as illustrated in Fig. 1. Any color will be reproduced by the vertexes of the small triangle where the color is located inside. By this simple color matching scheme, the white emitter is utilized at the maximum rate.

3. Uniform luminance color space

To characterize the display performance, the traditional method is to calculate the efficiency of the display at 200 cd/m² white. However, in a four primary color display with white emitter, characterizing the display at the white point will not be sufficient. For example, if the color coordinates of the white emitter is right at the \(D_{65}\) white position, the display’s efficiency will be equal to that of the white emitter, regardless of the efficiencies of the other three primary colors. To characterize the display in a way close to that under actual operation, we present uniform luminance color space, in which all the color points in the color space have a luminance of 200 cd/m², and we characterize the display’s performance all over the whole color space, not limited only to the white point. The process of characterization is listed in Scheme 1. For every reproducible color point, we calculate the amount of each primary required for the full color pixel to emit 200 cd/m² light at that color point. After all the values are obtained, the average luminance of each primary in the uniform luminance color space is given by the following equations:

\[
m_{R,G,B,W} = \frac{\sum_i m_i}{\sum_i m_{R,G,B,W}}
\]

(2)

where \(i\) is the index of the reproducible colors, and \(m\) is the luminance of each primary.

---

**Fig. 1.** CIE coordinates of R, G, B, and W primaries.

**Scheme 1.**
4. PLED devices

To simulate the display’s performance, we fabricated polymer OLEDs (PLEDs) emitting R, G, B and W lights whose device structures are listed in Table 1. Their current density ($J$)-bias ($V$)-luminance ($L$) characteristics are shown in Fig. 2, and the external quantum efficiency (EQE)-$J$ characteristics are shown in the inset. Detailed descriptions of device making have been reported elsewhere [13,14,18,19]. The CIE chromaticity coordinates of the R, G, B and W primaries for high definition television (HDTV) are also included in Table 1 for comparison [17,20]. Since the chromaticity coordinates of the PLEDs are very close to those of HDTV ones, in the following sections, our calculations will be carried out based on the real electroluminescent (EL) characteristics of the devices and the CIE coordinates of HDTV primary colors.

5. Display structures

To find out the performance of the display based on the fabricated devices, we assume a full color pixel consisting of 3 or 4 sub-pixels in the planar configuration in which the sub-pixels are laid side by side. As mentioned early, adding a fourth sub-pixel will alter the display’s structure. If the size of each sub-pixel is kept the same, the display resolution will lose 25% by adding the fourth sub-pixel. If we keep the display resolution intact, the sub-pixel size has to be reduced by 25% as shown in Fig. 3. In the following calculations comparing the performances between the RGB display and the RGBW display, we will assume the display resolution is the same for both displays. As a result, if the size of the full color pixel is set to 100 $\mu$m x 100 $\mu$m, and each sub-pixel has the same size, the sub-pixel size is 33.3 $\mu$m x 100 $\mu$m for the RGB panel, and 25 $\mu$m x 100 $\mu$m for the RGBW panel. To simplify the calculation, the aperture ratio is set to 100%. The actual luminance of each sub-pixel is first obtained in the uniform luminance color space following the process described in Section 3. Then, the luminous efficiency, the pixel power, and the power efficiency of the full color pixel are calculated based on the performance of the primary color devices shown in Fig. 2.

6. Results

The actual luminance of each sub-pixel in the uniform luminance color space is listed in Table 2 as well as the characteristics of the full color pixel in both the RGB panel and the RGBW panel. As shown, the RGBW display with the luminous efficiency of 8.05 cd/A and the power efficiency

<table>
<thead>
<tr>
<th>Primary</th>
<th>Device structure</th>
<th>CIE</th>
<th>HDTV CIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>ITO/PEDOT:PPS/PVK/PFO:PVBD:Ir(DMFPq)$_2$acac(2%)/PFN/Ba/Al</td>
<td>(0.665, 0.319)</td>
<td>(0.640, 0.330)</td>
</tr>
<tr>
<td>G</td>
<td>ITO/PEDOT:PPS/P-PPV/Ba/Al</td>
<td>(0.368, 0.588)</td>
<td>(0.300, 0.600)</td>
</tr>
<tr>
<td>B</td>
<td>ITO/PEDOT:PPS/PVK/PPF28SOS/Ba/Al</td>
<td>(0.16, 0.08)</td>
<td>(0.150, 0.060)</td>
</tr>
<tr>
<td>W</td>
<td>ITO/PEDOT:PPS/PVK:OXD-7:rirlicr(piq)/Ba/Al</td>
<td>(0.329, 0.362)</td>
<td>(0.313, 0.329)</td>
</tr>
</tbody>
</table>

Fig. 2. Current density ($J$) (solid lines)–operation voltage ($V$)–luminance ($L$) (dot lines) characteristics of R, G, B, and W PLEDs. Inset: external quantum efficiency (EQE)-$J$ characteristics.

Fig. 3. (a) A full color pixel in RGB display. (b) A full color pixel in RGBW display.
of 4.33 lm/W, is more efficient than the RGB one with the luminous efficiency of 6.91 cd/A and the power efficiency of 3.93 lm/W. In addition, it takes less pixel power in the RGBW display (1.45 µW) to produce 200 cd/m² light than that in the RGB displays (1.60 µW). The efficiency improvement and the power consumption reduction are due to the high performance of the white emitter, since the emission of the W sub-pixel accounts for 36% of the full color pixel’s luminance in the uniform luminance color space. At the required luminance of 288 cd/m², the luminous efficiency and the power efficiency of the white emitter are as high as 13.1 cd/A and 6.34 lm/W, respectively. However, if the efficiency of the white emitter is low, the RGBW display may not possess any advantage in terms of power efficiency in comparison with the RGB display. We recalculated the RGBW display’s efficiency by varying the white emitter’s efficiency while fixing the efficiencies of the red, green, and blue emitters. The result shows that only when the white emitter’s efficiency is larger than 4.46 lm/W, the RGBW display becomes more power efficient than the RGB display (Fig. 4a).

In the RGB display, the most used primary color is green, since the human eyes are most sensitive to the green color. Apparently, increasing the green emitter’s efficiency will improve the display’s efficiency. Recently, the power efficiency of the green OLED has reached 102 lm/W at 100 cd/m² [21]. At such high green emitter’s efficiency, without a high efficient white emitter, the RGBW display will not be as power efficient as the RGB display. To find out the minimum efficiency of the W sub-pixel required for the RGBW display to be as efficient as the RGB display, we fixed the efficiencies of the red and the blue emitters, and varied the green emitter’s efficiency to carry out the simulation. The result is plotted in Fig. 4b. The curve illustrates that the white emitter’s efficiency has to keep up with the green emitter’s efficiency to ensure the RGBW display’s power efficiency. For the currently highest green emitter with the power efficiency of 102 lm/W, the white emitter’s efficiency has to reach 8.32 lm/W. It is worth noting that when the green emitter’s efficiency increases from 1 to 25 lm/W, the white emitter’s efficiency has to go from 1.3 to 7.1 lm/W to catch up. However, at the high efficiency region, when the green emitter’s efficiency increases from 25 to 120 lm/W, the white emitter’s efficiency only goes from 7.1 to 8.4 lm/W. It reveals that, in order for the RGB display to be as efficient as the RGBW display, the power efficiency requirement for the green emitter is much higher than the requirement for the white emitter in the RGBW display in order for the RGBW display to be as efficient as the RGB display. The said feature allows for utilizing low efficient green emitter in RGBW display while achieving high display efficiency.

### 7. Color usage frequency

The OLED team in Eastman Kodak Company has sampled more than 13,000 digital images to find out that the

<table>
<thead>
<tr>
<th>Method</th>
<th>Performance</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>W</th>
<th>Full pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB</td>
<td>Areal luminance (cd/m²)</td>
<td>72</td>
<td>110</td>
<td>18</td>
<td>–</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Actual luminance (cd/m²)</td>
<td>217</td>
<td>329</td>
<td>54</td>
<td>–</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Luminous efficiency (cd/A)</td>
<td>8.45</td>
<td>8.25</td>
<td>2.56</td>
<td>–</td>
<td>6.91</td>
</tr>
<tr>
<td></td>
<td>Pixel power (µW)</td>
<td>0.56</td>
<td>0.56</td>
<td>0.48</td>
<td>–</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>Power efficiency (lm/W)</td>
<td>4.05</td>
<td>6.16</td>
<td>1.18</td>
<td>–</td>
<td>3.93</td>
</tr>
<tr>
<td>RGBW</td>
<td>Areal luminance (cd/m²)</td>
<td>57</td>
<td>58</td>
<td>13</td>
<td>72</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Actual luminance (cd/m²)</td>
<td>228</td>
<td>232</td>
<td>52</td>
<td>288</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>Luminous efficiency (cd/A)</td>
<td>8.43</td>
<td>7.69</td>
<td>2.57</td>
<td>13.1</td>
<td>8.05</td>
</tr>
<tr>
<td></td>
<td>Pixel power (µW)</td>
<td>0.44</td>
<td>0.31</td>
<td>0.34</td>
<td>0.36</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>Power efficiency (lm/W)</td>
<td>4.02</td>
<td>5.90</td>
<td>1.19</td>
<td>6.34</td>
<td>4.33</td>
</tr>
</tbody>
</table>

---

Table 2

The characteristics of the full color pixel in both the RGB display and the RGBW display in the uniform luminance color space.

---

**Fig. 4.** (a) The dependence of the full color pixel’s power efficiency in the RGBW display on the white emitter’s power efficiency with fixed R, G, and B sub-pixel’s efficiencies. (b) The minimum efficiency of the W sub-pixel required for the RGBW display to be as efficient as the RGB display at various green sub-pixel’s efficiency.
The most prevalent colors in nature are unsaturated colors around the white point [3]. Lacking their resources, we introduce a color usage frequency \( f \) taking the form of a Gaussian distribution into the uniform luminance color space to simulate the nature colors:

\[
f_i = \exp \left[ -\frac{(x_i - x_W)^2 + (y_i - y_W)^2}{0.043/\alpha} \right]
\]

where \( f_i \) is the color usage frequency, \((x_W, y_W)\) is the CIE coordinates of HDTV white located at \((0.313, 0.329)\), and \( \alpha \) is the normalization non-negative factor defined by the boundary conditions. We use the blue primary usage frequency to set the boundary conditions as follows:

\[
\begin{align*}
    f_W &= 1 \\
    f_B &= 10^{-2} f_W \\
    f_G &= 10 \\
    f_R &= 10 \alpha
\end{align*}
\]

Fig. 5a illustrates the color usage frequency with \( \alpha = 1 \), i.e., \( f_B = 10\% \), while Fig. 5b shows the color usage frequency with \( \alpha = 10 \). As the value of \( \alpha \) increases, the color usage frequency approaches the probability of color usage in nature images [3]. When \( \alpha \) takes the value of the other three primary values, all the reproducible colors have the same probability of usage, which simulates the color usages in the application of computer desktop visualization in which bright saturated colors are widely used. After the color usage frequency is introduced, the average luminance of each primary in the uniform luminance color space is modified into the following equation:

\[
m_{R,G,B,W} = \frac{\sum f_i \times m_{i,R,G,B,W}}{\sum f_i}
\]

The characterizations of a full color pixel in both the RGB and the RGBW displays were carried out in the uniform luminance color space coupled with the color usage frequency. The average luminance of each primary was calculated with different \( \alpha \) value and shown in Fig. 6a. In the RGBW display, the contribution of white emitter grows from 43\% to 67\% of the total luminance as \( \alpha \) increases from 1 to 10, while the contribution of the other three primaries steadily decreases, especially R and B primaries. With \( \alpha \) increasing, the usage frequency of the saturated colors becomes lower. As a result, the average luminance contributions of R, G, and B primaries decrease from 23.5\%, 28.2\%, and 5.3\%, to 8.9\%, 21.7\%, and 2.7\% of the total luminance, respectively, when \( \alpha \) grows from 1 to 10. In the RGB display, G primary makes the most contributions to the total luminance. As \( \alpha \) increases, the average luminance of G primary also increase while the luminance of the other two primaries drop, which means the RGB display mostly depends on the G primary in displaying natural images.

The dependence of a full color pixel’s power efficiency on the color usage frequency in both the RGB and the RGBW displays is shown in Fig. 6b. As revealed in Fig. 6a, when \( \alpha \) is large, the luminance of the RGBW display depends mostly on W sub-pixel. Therefore, the efficiency of the white emitter plays a critical role in the full color pixel’s efficiency. Shown in Fig. 6b, the full color pixel’s power efficiency in the RGBW display increases rapidly with the increase of \( \alpha \). It reaches 6.4 lm/W at \( \alpha = 10 \) from 4.8 lm/W at \( \alpha = 1 \). In the simulation, the white emitter has a high efficiency illustrated in Fig. 2. For comparison, another white emitter with the configuration of ITO/PEDOT:PSS/PVK/PFO-poss/Ir(Bu-ppy)$_3$:(Piq)$_2$Ir(acaF)/Ba/Al was fabricated and utilized as W primary in the RGBW display denoted as RGBW2. Detailed descriptions of device fabrication could be found in Ref. [7]. The EQE-f characteristics of the device are shown in the inset of Fig. 6b. The power efficiency of a full color pixel in the RGBW2 display dependent on \( \alpha \) was as well calculated and plotted in Fig. 6b. For RGBW2 display, although the full color pixel’s power efficiency increases from 3.63 to 3.72 lm/W as \( \alpha \) increases from 1 to 5, it begins to drop thereafter, and falls to 3.65 lm/W when \( \alpha \) reaches 10. The power efficiency’s drop at large \( \alpha \) value is attributed to the low white emitter’s efficiency. Since the full color pixel’s efficiency in the RGBW display is mostly determined by the white emitter’s EL performance at large \( \alpha \) value, the more contribution of the W sub-pixel, the more power consumption of the full color pixel if the white emitter has a low efficiency, which leads to the reduction of the power efficiency. For the RGB display, the full pixel’s power efficiency is not seriously
affected by the color usage frequency. It only changes from 4.09 to 4.45 lm/W as \( a \) goes from 1 to 10. The difference of the full pixel’s power efficiency between the RGBW and the RGB displays becomes larger as \( a \) increases. Thus, by utilizing highly efficient white emitters, the RGBW display will be much more energy efficient than the RGB display for video applications. As the simulation revealed, in the RGBW display, video applications transfer the huge luminance requirements from R, G, and B primaries to W primary. Therefore, if the white emitter has a long lifetime, the RGBW display will have a long lifetime limited only by the white emitter.

8. Summary

In summary, the performances of the flat panel displays utilizing PLEDs with both RGB sub-pixels and RGBW sub-pixels layouts were analyzed theoretically and experimentally. A simple color matching scheme was applied to maximize the usage of the white sub-pixel. Uniform luminance color space was introduced to better characterize the display performance than the traditional single white point characterization. In the uniform luminance color space, the RGBW sub-pixel display will be more energy efficient than the RGB display, when the power efficiency of the white emitter reaches a threshold determined by the green emitter’s efficiency. To simulate the real natural images, the color usage frequency with Gaussian distribution was adopted in the calculation. As the color usage frequency distribution gets closer to that in the real images, the full color pixel’s power efficiency of the RGBW display is more dependent on the EL performance of the white emitter. In order for the RGBW display to be more energy efficient than the RGB display with the same red, green, and blue emitters, a highly efficient white emitter is necessary.

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