Color Saturation Improvement by the Use of Unequal-Area Color Filters for the RGBW LCD with RGB LED Backlit

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Abstract

The dependences of color gamut size and power consumption on the area ratio of neutral and green sub-pixels for the RGBW LCD with RGB LED backlit are studied, in which the areas of red and blue sub-pixels are the same and are one quarter of pixel apertu re area. It is found that high color saturation and power saving can be achieved for the proposed RGBW LCD.

1. Introduction

The color filters of LCDs absorb backlit and reduce power efficiency. Power efficiency can be significantly improved by the use of color field sequential (CFS) technology because color filters are not required [1, 2]. However, there is the color flicker phenomenon for the LCD using CFS technology. The other approach to increase power efficiency is to use the LCD comprising a neutral sub-pixel in addition to red, green, and blue sub-pixels [3, 4]. The neutral sub-pixel can be without color filter. Such an LCD is called the RGBW LCD by convention. A RGBW LCD has the advantage of higher luminance compared with the equivalent RGB LCD owing to the high transmittance of its neutral sub-pixels. However, it has the disadvantages of lower resolution and de-saturated color appearance.

RGBW LCDs were first proposed for mobile displays. There are four equal-area sub-pixels in a pixel for a RGBW LCD. The resolution problem can be solved by the properly arrangement of sub-pixels and image processing [5]. Nowadays, the efficiency of white-light LED (WLED) has been higher than that of CCFL. The RGBW LCD using WLED backlit is attractive for its low power consumption though its color appearance is de-saturated due to neutral sub-pixels. The use of RGB LEDs as backlit has been

considered to improve the color saturation of a RGBW LCD [6]. The color gamut of such a display depends on the maximum transmittance of neutral sub-pixels, which is adjusted by the applied voltage on neutral sub-pixels. The color gamut size increases with power consumption and can be larger than the color gamut size of the HDTV color standard (ITU-R BT. 709).

Because the use of neutral sub-pixels deteriorates the display color saturation, this paper proposes the use of unequal-area color filters for the RGBW LCD using RGB LED backlit. Two possible layouts of color filters are shown in figures 1(a) and 1(b). The areas of red and blue sub-pixels are the same and are one quarter of the pixel aperture area. The other half pixel aperture area comprises green and neutral sub-pixels. The area of a neutral sub-pixel is decreased for improving the display color saturation. The area ratio of the neutral sub-pixel and green sub-pixel is denoted as r_a. The dependences of the color gamut size and power consumption on the area ratio r_a are studied.
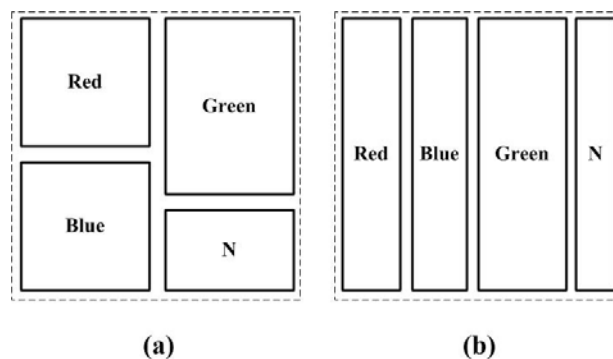

(a)   (b)

Fig. 1. Two types of unequal-area color filter layout in a pixel for the proposed RGBW LCD. Neutral filter is denoted as N.
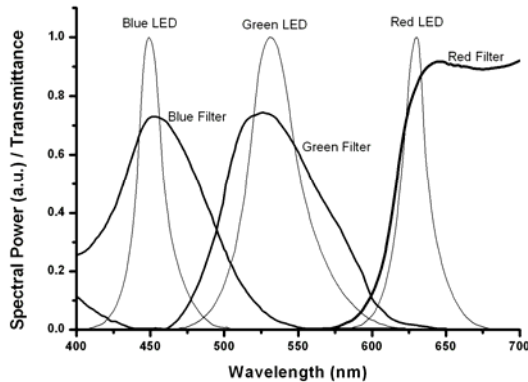
Fig. 2. Spectral power densities of RGB LEDs and transmission spectra of RGB filters.

2. Numerical Parameters

The same display model shown in [6] is taken in this paper. The considered spectral power densities of RGB LEDs and transmission spectra of color filters are shown in figure 2, which are taken from [7] and [8], respectively. It is noticed that there exists 11% transmittance at 440 nm wavelength for the green color filter. The power conversion efficiencies of red, green, and blue LEDs are 0.298, 0.137, and 0.249, respectively, which are derived from the data sheet given in [7]. The aperture ratio of a pixel is taken to be 0.8. We assume that the luminance L and display area A of the RGBW LCD are 100 cd/m^2 and 1 m^2, respectively. The white point D65 defined in HDTV color standard is taken. The coupling efficiency C from the RGB LEDs to the display output except for the absorption of color filters and aperture ratio is assumed to be unit. Thus, the unit electrical power (1 Watt) calculated in the following corresponds to the actual required power of LA/C in unit of Watt, in which L and A are in units of 100 cd/m^2 and 1 m^2, respectively.

Display industries usually represent the color gamut of a display with the chromaticity triangle in the CIE xy chromaticity diagram or CIE $u'v'$ chromaticity diagram. However, the color gamut of a display is a three-dimensional volume in a perceptual color space, e.g., CIELAB. The two-dimensional chromaticity diagrams cannot accurately represent a display color gamut [9]. We represent the color gamut of the considered displays in CIELAB color space. The color gamut size is represented with discernible color number instead of chromaticity triangle area in the following [9]. Discernible color

number represents the number of discernible colors as defined based upon calculations with the CIE94 color difference formula in CIELAB color space. The discernible color number ratio (DCNR) is used to represent the relative gamut size of the display color gamut with respect to the HDTV color gamut [10]. $DCNR = N_d/N_{HDTV}$, where N_d and N_{HDTV} are the discernible color numbers of the display and HDTV color gamuts, respectively. $N_{HDTV} = 199,491$. The part of the display color gamut within the HDTV color gamut is called the effective display color gamut because only this part of display color gamut can be used to reproduce HDTV colors. For representing the ratio of the HDTV color gamut that can be reproduced by the display, we define the effective display color number ratio $EDCNR = N_e/N_{HDTV}$, where N_e is the discernible color number of effective display color gamut, i.e. the number of discernible colors in the HDTV color gamut that can be reproduced by the display.
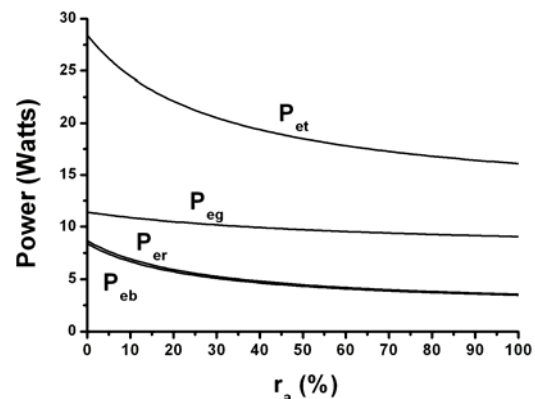

Fig. 3. Red LED power P_{er}, green LED power P_{eg}, blue LED power P_{eb}, and total LED power P_{et} versus the area ratio r_a.
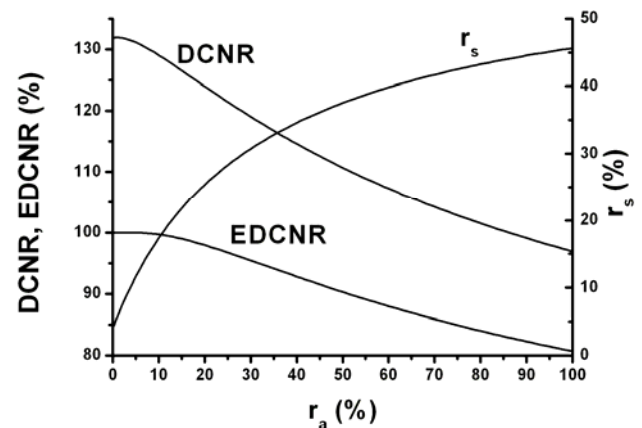

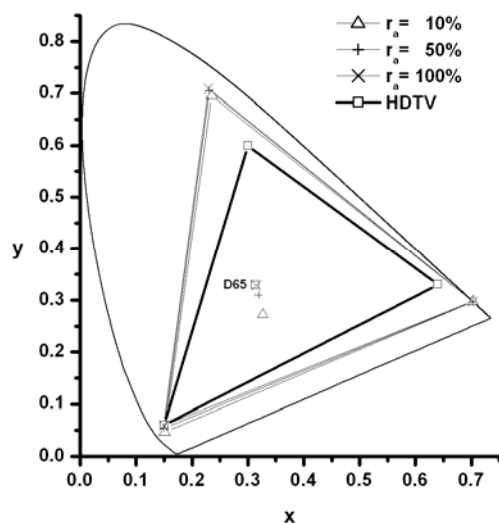**Fig. 4. Power saving ratio r_s, DCNR, and EDCNR versus the area ratio r_a.**

Fig. 5. Chromaticity triangles of the RGBW LCDs with the area ratio r_a= 10%, 50%, and 100%, in which the color coordinates of the corresponding neutral primaries are also shown. Chromaticity triangles of the HDTV color standard (ITU-R BT. 709) and D65 white point are also shown for comparison.

3. Results

For comparison, we first consider the conventional RGB LCD using RGB LED backlit, in which there are no neutral sub-pixels and the areas of RGB color filters are the same. The spectral power densities of RGB LEDs and transmission spectra of color filters shown in figure 2 are also assumed for the conventional RGB LCD. It is found that the required red, green, and blue LED electrical powers are 6.74 Watts, 16.52 Watts, and 6.36 Watts, respectively. The total RGB LED electrical power P_{etRGB}= 29.62 Watts. The DCNR and EDCNR of the RGB LCD are 133.8% and 100%, respectively.

Because of the high transmittance of neutral sub-pixels, it is expected that the required red and blue LED electrical powers decrease as the area ratio r_a increases for the RGBW LCD. But for the green LEDs, their required electrical power increases with r_a because the area of green sub-pixel decreases as r_a increases. Therefore the total required RGB LED electrical power has to be compromised between the decrease of red and blue LED electrical powers and the increase of green LED electrical power. Figure 3 shows the required electrical powers of the RGBW

LCD versus the area ratio r_a, in which the red LED electrical power P_{er}, green LED electrical power P_{eg}, blue LED electrical power P_{eb}, and total RGB LED electrical power P_{et} are shown. The corresponding power saving ratios r_s= $(P_{etRGB} - P_{et})/P_{etRGB}$ are shown in figure 4. We can see that the power saving ratio increases with r_a. The case with r_a= 0% corresponds to the RGB LCD with 1:2:1 area ratio of red, green, and blue sub-pixels, in which 3.99% power can be saved from figure 4. The case with r_a= 100% corresponds to the RGBW LCD with four equal-area sub-pixels, in which 45.6% power can be saved. As the de-saturation of the color appearance also increases with r_a, we has to make a compromise between power saving and display color saturation.

The red, green, blue, and neutral sub-pixels with light output can be called red, green, blue, and neutral primaries, respectively, though the neutral primary is not linearly independent of the other three primaries. The color of the neutral primary can be produced from the color mixing of the other three primaries. Figure 5 shows the chromaticity triangles of red, green, blue, and neutral primaries for the cases with r_a= 10%, 50%, and 100%, in which the color coordinates of the corresponding neutral primaries are also shown. We can see that, as the area ratio r_a decreases, the neutral primary changes from whitish to purplish pink because of higher red and blue LED powers for smaller area ratio. As the area ratio r_a increases, the color coordinates of red primary changes slightly; the saturation of green and blue primaries increases and decreases, respectively. The change of primary saturation is due to the crosstalk shown in figure 2, e.g., the transmittance of green color filter is none zero in the red and blue LED spectra. From figure 5, it seems that the color gamut of the case with r_a= 100% is larger than that of HDTV color standard. However, as is mentioned previously, a chromaticity triangle cannot accurately represent a display color gamut. Figure 4 also shows the corresponding DCNR and EDCNR for the cases shown in figure 3. We can see that DCNR and EDCNR decrease as r_a increases. The color gamut size of the case with r_a= 100% is in fact the smallest in the considered value range of r_a. From figure 4, we have DCNR= 131.3% and EDCNR= 99.98% for the case with r_a= 0%; DCNR= 96.9% and EDCNR= 80.7% for the case with r_a= 100%.

Because the relative gamut sizes DCNR and EDCNR are calculated with respect to the HDTV color gamut, the display color saturation for the case with r_a= 31.6% is still high from figure 4, in which DCNR= 118.3%, EDCNR= 95.0%, and the power

saving ratio r_s= 31.4%. For the RGBW LCD with four equal-area sub-pixels (r_a= 100%), its *DCNR* and *EDCNR* can be increased to 118.2% and 95.0%, respectively, by limiting the maximum transmittance of neutral sub-pixels to be 44.5% through the applied voltage on neutral sub-pixels, but the power saving ratio is decreased from 45.6% to 19.0%. Therefore, it is preferred to use unequal-area color filters for improving the color saturation of RGBW LCDs considering power consumption.

4. Summary

The RGBW LCD using unequal-area color filters and RGB LED backlit is proposed for improving display color saturation. The areas of red and blue sub-pixels are the same and are one quarter of pixel aperture area. The other half pixel aperture area comprises green and neutral sub-pixels. Both the color gamut size and power consumption decrease as the area ratio of neutral and green sub-pixels increases. The results show that high color saturation and power saving can be achieved for such a RGBW LCD by properly choosing the area ratio of neutral and green sub-pixels. An example shows that the RGBW LCD with 31.6% area ratio of neutral and green sub-pixels saves 15.3% more power than the RGBW LCD using equal-area color filters for the same 95.0% *EDCNR*, in which the *EDCNR* of the RGBW LCD using equal-area color filters is increased by limiting the maximum transmittance of neutral sub-pixels to be 44.5% and the *DCNR*s of the two RGBW LCDs are about the same as 118%. For this example of the RGBW LCD using unequal-area color filters, it saves 31.4% power compared with the RGB LCD using equal-area color filters and saves 28.6% power compared with the RGB LCD using 1:2:1 area ratio of red, green, and blue sub-pixels. It is expected that the part of color gamut within HDTV color gamut for the RGBW LCD can be further increased by the use of more proper color filter spectra and matched RGB LEDs.

Acknowledgement

5. References

1. H. Hasebe and S. Kobayashi, *SID '85 Technical Digest*, p. 81 (1985).
2. M. Baba, K. Taira, and H. Okumura, US Patent No. 2002/0122019 A1 (2002).
3. B. W. Lee, C. Park, S. Kim, T. Kim, Y. Yang, J. Oh, J. Choi, M. Hong, D. Sakong, and K. Chung, *SID '03 Technical Digest*, p.1212 (2003).
4. B. W. Lee, K. Song, Y. Yang, C. Park, J. Oh, C. Chai, J. Choi, N. Roh, M. Hong, and K. Chung, *SID '04 Technical Digest*, p.111 (2004).
5. C.-C. Lai and C.-C. Tsai, *IEEE Trans. Consum. Electron.*, **53**, p. 1628 (2007).
6. S. Wen, *SID '09 Technical Digest*, p. 1216 (2009).
7. Technical datasheet DS56, Philips Lumileds Lighting Company, San Jose, California (2008).
8. M. Anandan, *ASID '06 Technical Digest*, p. 130 (2006).
9. S. Wen, *J. Electron. Imag.*, **15**, pp. 043001-1 (2006).
10. S. Wen, *IEEE/LEOS J. Display Techno.l*, **4**, p. 18 (2008).