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Color Saturation Improvement through the Use of Unequal-Area Color Filters for the RGB-LED-Backlight RGBW LCD

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Abstract

The dependences of color gamut size and power consumption on the area ratio of the neutral and green subpixels for the RGB-LED-backlight RGBW LCD were studied, in which the red- and blue-subpixel areas are the same and represent one-quarter of the pixel aperture area. It was found that the color saturation of the RGBW LCD can be improved through the use of a smaller neutral- and green-subpixel area ratio, at the expense of higher power consumption.

Keywords: RGBW LCD, RGB LED backlight, color filter, color saturation

1. Introduction

The color filters of an LCD absorb backlight and reduce power efficiency. The power efficiency can be significantly improved through the use of the color field sequential (CFS) technology because color filters are not required therein [1, 2]. The color flicker phenomenon occurs in the LCD, however, when the CFS technology is used. The other way of increasing power efficiency is to use the LCD consisting of a neutral subpixel in addition to the red, green, and blue subpixels [3, 4]. The neutral subpixel can do without a color filter. Such LCD is called "red-green-blue-white (RGBW) LCD" by convention. The RGBW LCD has the advantage of higher luminance compared with the equivalent RGB LCD, owing to the high transmittance of its neutral subpixels. It has the disadvantages, however, of lower resolution and a desaturated color appearance.

RGBW LCDs were first proposed for use in mobile displays. There are four equal-area subpixels in a pixel for the RGBW LCD. The resolution problem can be addressed via the proper arrangement of the subpixels, and via image processing [5]. Nowadays, the efficiency of white-light LED (WLED) can be higher than that of CCFL. The RGBW LCD using the WLED backlight is attractive due to its low power consumption, although its color appearance is desaturated due to its neutral subpixels.

The color saturation of the RGBW LCD can be improved through the use of RGB LED as backlight because the color saturation of RGB LED is high. The use of unequal-area color filters for the RGBW LCD using the RGB LED backlight is proposed in this paper to further improve the display color saturation. Two possible layouts of color filters are shown in Fig. 1. The red- and blue-subpixel areas are assumed to be the same and represent one-quarter of the pixel aperture area. The other half-pixel aperture area consists of green and neutral subpixels. The neutral-subpixel area was decreased to improve the display color saturation. The neutral- and green-subpixel area ratio is denoted as a_{ng}.

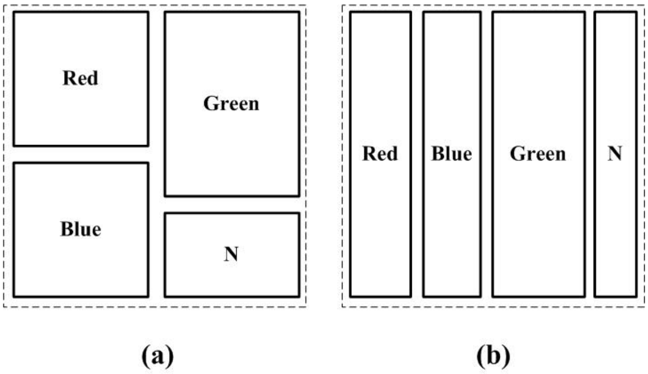

Fig. 1. Two types of unequal-area color filter layouts in a pixel for the proposed RGBW LCD. The neutral filter is denoted as N.

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The dependences of the color gamut size and power consumption on the area ratio a_{ng} were studied.

2. Color Device Model and Numerical Parameters

The color device model of the RGBW display can be represented by a 3×4 chromaticity matrix [6].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b & X_n \\ Y_r & Y_g & Y_b & Y_n \\ Z_r & Z_g & Z_b & Z_n \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ N \end{bmatrix}, \qquad (1)$$

where X_i, Y_i, and Z_i are the maximum tristimulus values of the i primary, and i = r, g, b, and n for the red, green, blue, and neutral primaries, respectively; R, G, B, and N are the normalized linear signals for the red, green, blue, and neutral primaries, respectively; and $0 \leqq R, G, B, N \leqq 1$. In equation (1), the maximum tristimulus values are functions of RGB LED powers. Take P_{er}, P_{eg}, and P_{eb} as the total electrical powers of the red, green, and blue LEDs, respectively. Taking the Y stimulus as an example, the following will be arrived at:

$$Y_i = \frac{K_m \gamma}{\pi A} \frac{A_i}{A_{ep}} \sum_{j=r,g,b} C_j \eta_j P_{ej} \frac{\int S_j(\lambda) F_i(\lambda) \bar{y}(\lambda) d\lambda}{\int S_j(\lambda) d\lambda}, \qquad (2)$$

where i = r, g, b, and n; K_m = 683 lm/watt; γ is the aperture ratio; A is the display area in m^2; A_i is the aperture area of a corresponding subpixel; A_{ep} is the aperture area of a pixel; C_j is the coupling efficiency of the backlight from the corresponding LED to the display output, except for the absorption of the color filters; η_j and $S_j(\lambda)$ are the power conversion efficiency and spectral-power density of the corresponding LED, respectively; $F_i(\lambda)$ is the transmission spectrum of the corresponding color filter; and $F_n(\lambda)$=1 for the neutral subpixels (i.e., neutral subpixels without color filters are assumed). The X and Z stimulus values in terms of the RGB LED powers are the same as in equation (2), except that the color-matching function $\bar{y}(\lambda)$ is replaced by $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$, respectively. The values of P_{er}, P_{eg}, and P_{eb} can be obtained by substituting the functions of the X, Y, and Z stimulus values in terms of P_{er}, P_{eg}, and P_{eb} into equation (1) and applying the white-point condition. The total required electrical power $P_{et}=P_{er}+P_{eg}+P_{eb}$.

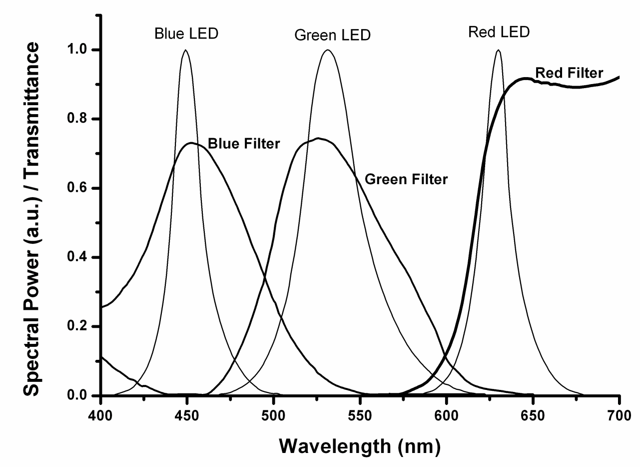

Fig. 2. Spectral-power densities of the RGB LEDs and transmission spectra of the RGB color filters.

The considered spectral-power densities of the RGB LEDs and the transmission spectra of the color filters are shown in Fig. 2, which were taken from [7] and [8], respectively. It was noticed that there was an 11% transmittance at the 440 nm wavelength for the green color filter. The power conversion efficiencies of the red, green, and blue LEDs were 0.298, 0.137, and 0.249, respectively, which were derived from the data sheet given in [7]. The aperture ratio γ of a pixel was assumed to be 0.8. It was also assumed that the luminance L and display area A of the RGBW LCD were 100 cd/m^2 and 1 m^2, respectively. The illuminant D65 white point was used in this paper, which is the white point of the HDTV color standard (ITU-R BT. 709). The coupling efficiency from RGB LEDs to the display output, except for the absorption of the color filters, was assumed to be the unit. Thus, the required electrical power P_{et} shown in the following corresponds to the actually required power of LAP_{et}/C in watts, in which L and A are expressed in 100 cd/m^2 and 1 m^2 units, respectively.

3. Display Color Gamut Size

The display industries usually represent the color gamut of a display with the chromaticity triangle in the CIE xy or $u'v'$ chromaticity diagram. The color gamut of a display, however, 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]. The color gamut of a display was thus represented herein in the CIELAB color space. The color gamut size of a display was represented with a discernible color number instead of a chromaticity triangle area in the following [9]. The discernible color number represents the number of discernible colors as defined based on the calculations using the CIE94 color difference formula in the CIELAB color space. Fig. 3 shows the color gamut of HDTV, in which the discernible color number of the HDTV color gamut was N_{HDTV}=199,491.

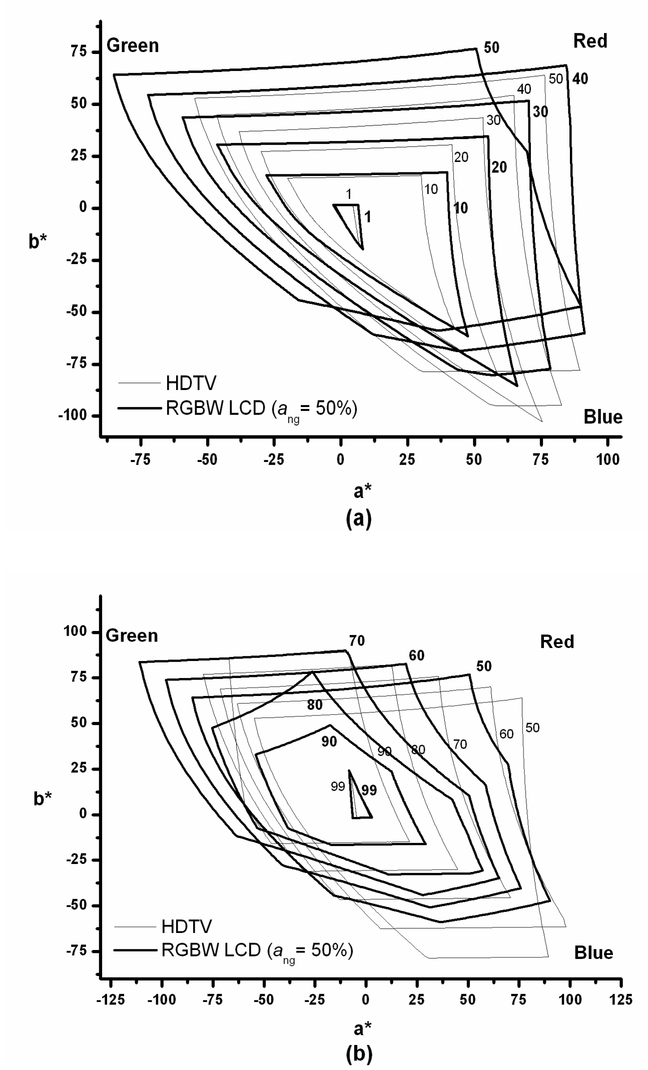

Fig. 3. Color gamut cross-sections of constant lightness (L*) in the CIELAB color space for HDTV and the RGB-LED-backlight RGBW LCD with the area ratio a_{ng}=50%, where (a) $L^* \le 50$ and (b) $L^* \ge 50$. The corresponding values of L* are shown near the boundaries of the cross-sections.

The discernible color number ratio (DCNR) was used to represent the relative gamut size of a display color gamut with respect to the HDTV color gamut [10]. That is:

$$DCNR = \frac{N_d}{N_{HDTV}}, \qquad (3)$$

where N_d is the discernible color number of the display. The part of the display color gamut within the HDTV color gamut is called the “effective display color gamut” because only this part of the display color gamut can be used to reproduce the HDTV colors. To represent the ratio of the HDTV color gamut that can be reproduced by the display, the effective display color number ratio was defined as [10]

$$EDCNR = \frac{N_e}{N_{HDTV}}, \qquad (4)$$

where N_e is the discernible color number of the effective display color gamut (i.e., the number of discernible colors in the HDTV color gamut that can be reproduced by the display).

4. Results and Discussion

For comparison purposes, the conventional RGB-LED-backlight RGB LCD, in which there are no neutral subpixels and the areas of the RGB color filters are the same, will first be considered. The spectral-power densities of RGB LEDs and the transmission spectra of the color filters shown in Fig. 2 were also assumed for the RGB LCD. It was found that the required red, green, and blue LED electrical powers were 6.74, 16.52, and 6.36 watts, respectively; the total RGB LED electrical power was P_{etRGB}=29.62 watts; and the DCNR and EDCNR of the RGB LCD were 133.8 and 100%, respectively.

It is expected that the required electrical powers of the red and blue LEDs will decrease as the area ratio a_{ng} increases owing to the high transmittance of the neutral subpixels, but at the expense of the decrease in display color gamut size. The relation between the required electrical power of the green LED and a_{ng} depends on the following two factors: (1) the green-subpixel area decreases as a_{ng} increases, which results in a higher green LED power requirement; and (2) the green LED light output from the neutral subpixel increases with a_{ng}, which results in a lower green LED power requirement but at the expense of a decrease in display color gamut size. Fig. 4 shows the required electrical powers of RGBW LCD versus the area ratio a_{ng}, 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. It can be seen that all the powers (P_{er}, P_{eg}, and P_{eb}) decrease as a_{ng} increases. The decrease rate of the required green LED power with a_{ng} is less than that of the required red and blue LED powers because of the smaller area of the green subpixel for a larger a_{ng}.

The power-saving ratios $r_s=(P_{etRGB}-P_{et})/P_{etRGB}$ corresponding to Fig. 4 are shown in Fig. 5. The power-saving ratio increases with a_{ng}. The case with a_{ng}=100% corresponds to the RGBW LCD with equal-area color filters, in which 45.6% power can be saved. As the desaturation of the display color also increases with a_{ng}, a compromise has to be made between power consumption and display color saturation.

The light output from the red, green, blue, and neutral subpixels can be called "red," "green," "blue," and "neutral primaries," respectively, although the neutral primary is not independent of the other three primaries. The color of the neutral primary can be produced from the color mixing of the other three primaries. Fig. 6 shows the chromaticity triangles of the red, green, and blue primaries for the cases with a_{ng}=10%, 50%, and 100%, in which the color coordinates of the corresponding neutral primaries are also shown. It can be seen that as the area ratio a_{ng} decreases, the neutral primary changes from whitish to purplish pink because of the higher red and blue LED powers for a smaller area ratio a_{ng}. As the area ratio a_{ng} increases, the color coordinates of the red primary changes slightly, and the saturation of the green and blue primaries increases and decreases, respectively. The change in primary saturation is due to the crosstalk shown in Fig. 2 (e.g., the transmittance of the green color filter is none or zero in the red and blue LED spectra).

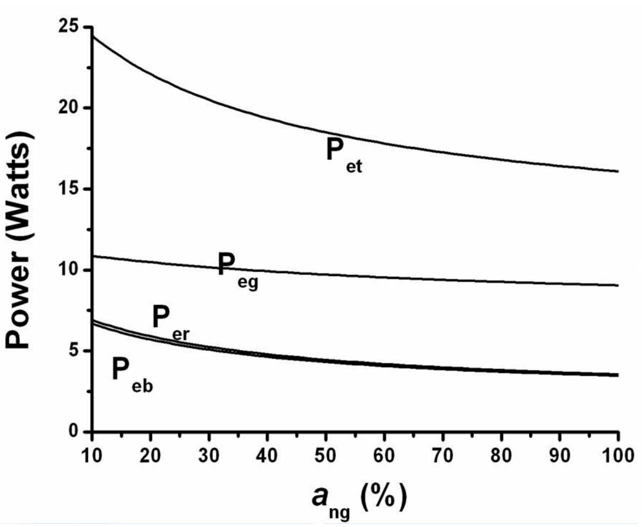

Fig. 4. Red LED power P_{er}, green LED power P_{eg}, blue LED power P_{eb}, and total LED power P_{et} versus area ratio a_{ng}.

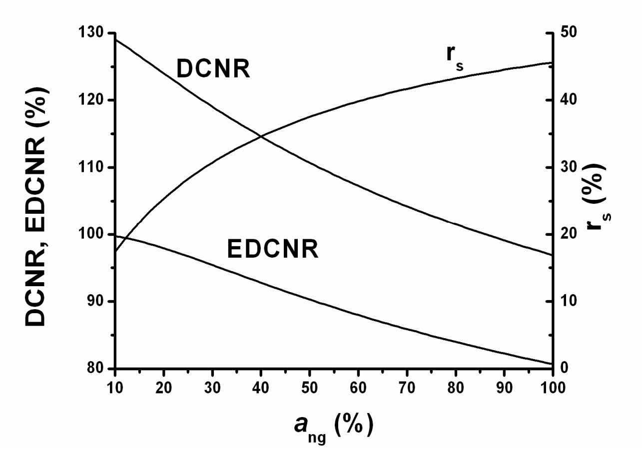

Fig. 5. Power-saving ratio r_s, DCNR, and EDCNR versus area ratio a_{ng}.

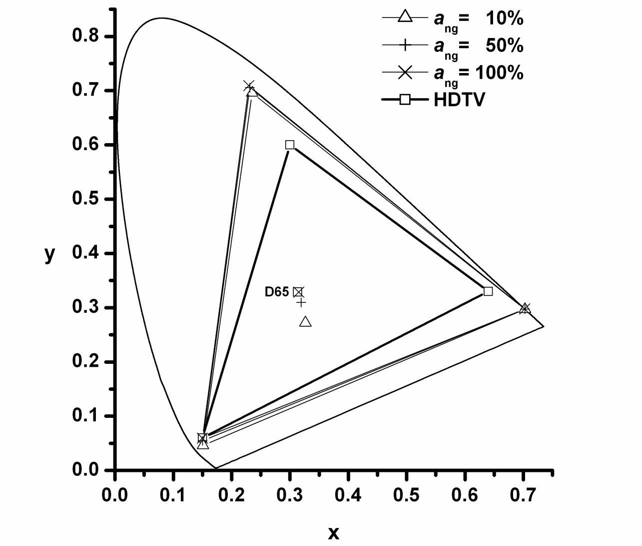

Fig. 6. Chromaticity triangles of the RGBW LCDs with the area ratio a_{ng}=10%, 50%, and 100%, respectively, in which the color coordinates of the corresponding neutral primaries are also shown. The chromaticity triangles of the HDTV color standard (ITU-R BT. 709) and D65 white point are also shown for comparison.

In Fig. 6, it seems that the color gamut of the case with a_{ng}=100% is larger than that of the HDTV color standard. As mentioned previously, however, the chromaticity triangle of a display cannot accurately represent its color gamut. Fig. 5 also shows the corresponding DCNR and EDCNR for the cases shown in Fig. 4. It can be seen therein that DCNR and EDCNR decrease as a_{ng} increases. The color gamut size of the case with a_{ng}=100% is in fact the smallest within the considered value range of a_{ng}. As shown in Fig. 5, DCNR=129.0% and EDCNR=99.7% for the case with a_{ng}=10%; DCNR=110.7% and EDCNR=90.1% for the case with a_{ng}=50%; and DCNR=96.9% and EDCNR=80.7% for the case with a_{ng}=100%.

Both required LED powers and display color gamut size decrease as a_{ng} increases. A design trade-off between display power consumption and color gamut is thus required. Fig. 7 shows the DCNR and EDCNR with respect to the total RGB LED electrical power P_{et}. It can be seen that the increase rates of DCNR and EDCNR with respect to P_{et} decrease as P_{et} increases. The dashed lines shown in Fig. 7 are the tangential lines of DCNR and EDCNR at P_{et}=16.1 watts, which is the smallest required power in the figure and which corresponds to the case with a_{ng}=100%. As shown in this figure, when P_{et} is larger than about 17.5 watts, which corresponds to the case with a_{ng}=65%, the increase rates of DCNR and EDCNR with respect to P_{et} apparently decrease. It is beneficial to choose the case with the required power slightly larger than 17.5 watts considering that the increment of the required power pays for the increments of DCNR and EDCNR. In the following, the case with a_{ng}=50% is taken as a design example, in which P_{et}=18.5 watts and the area ratio of the red, green, blue, and neutral subpixels is 3:4:3:2.

The power-saving ratio r_s of the case with a_{ng}=50% was 37.5% at the expense of 23.1% DCNR and 9.7% EDCNR decrements, compared with the RGB-LED-backlight RGB LCD. Fig. 8 shows the comparison of the color gamuts of the case with a_{ng}=50% and of the RGB LCD, in which the case with a_{ng}=50% was desaturated at high luminance. The case with a_{ng}=50% needs (18.5-16.1)/16.1=14.9% more power than the case with a_{ng}=100%, but its DCNR and EDCNR were improved 13.8 and 10.3%, respectively, compared with the case with a_{ng}=100%. Fig. 9 shows the comparison of the color gamuts of the cases with a_{ng}=50% and 100%, in which the color saturation of the

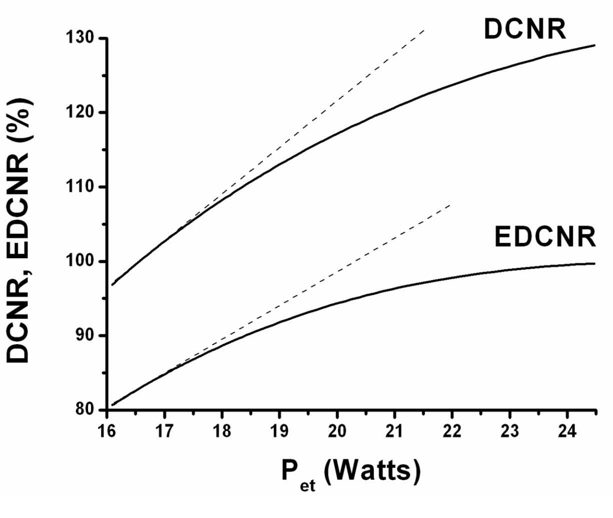

Fig. 7. DCNR and EDCNR with respect to the total RGB LED electrical power P_{et}. The dashed lines are the tangential lines of DCNR and EDCNR at P_{et}=16.1 watts.

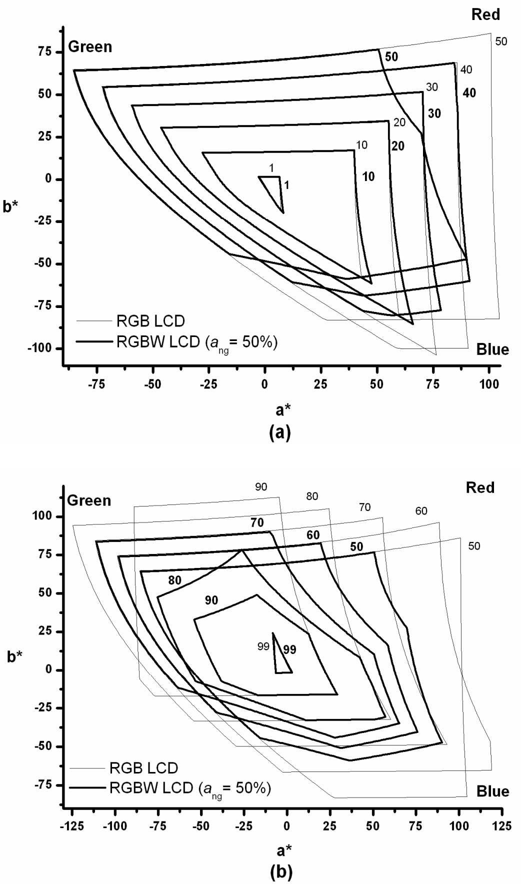

Fig. 8. Color gamut cross-sections of constant lightness (L*) in the CIELAB color space for the RGB-LED-backlight RGB LCD and the RGB-LED-backlight RGBW LCD with the area ratio a_{ng}=50%, where (a) L* ≤ 50 and (b) L* ≥ 50. The corresponding values of L* are shown near the boundaries of the cross-sections.

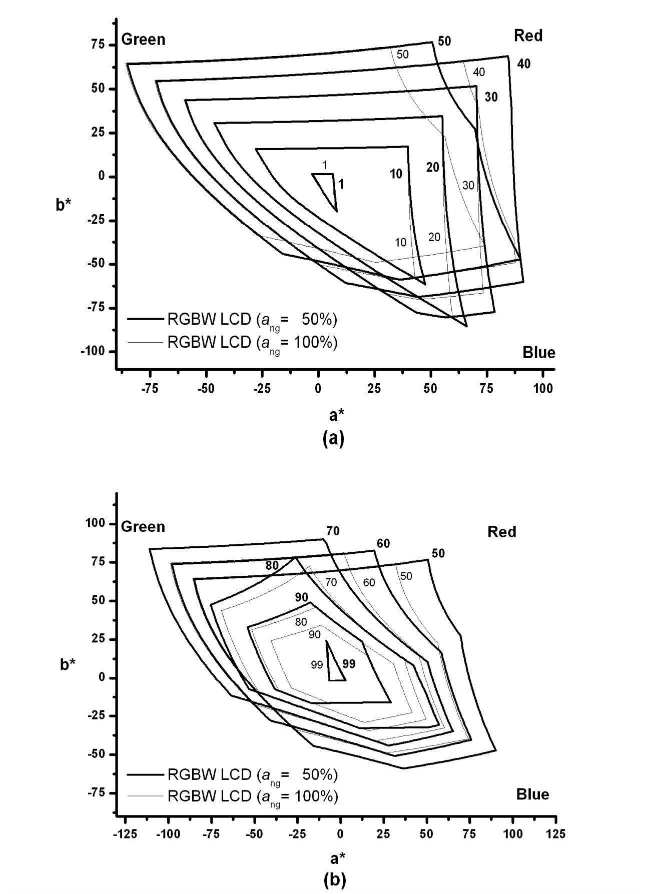

Fig. 9. Color gamut cross-sections of constant lightness (L*) in the CIELAB color space for the RGB-LED-backlight RGBW LCDs with the area ratio a_{ng}=50% and 100%, respectively, where (a) L* ≤ 50 and (b) L* ≥ 50. The corresponding values of L* are shown near the boundaries of the cross-sections.

case with a_{ng}=50% was improved at high luminance. It can be seen in Fig. 9 that the color saturation in the red and blue regions was enhanced for the case with a_{ng}=50%. It was found that if the red-(blue)-subpixel area will be increased instead of the green-subpixel area, the color saturation in the green and blue (red) regions will be enhanced, in which the green- and blue-(red)-subpixel areas are assumed to be the same and represent one-quarter of the pixel aperture area.

The performance of the case with a_{ng}=50% can be evaluated through the comparison of its color gamut and HDTV color gamut shown in Fig. 3. In this figure, the case with a_{ng}=50% is more saturated in green but is less saturated in red and blue compared with HDTV. The desaturated color regions may be improved by further tailoring the red- and blue-subpixel areas and by using the proper LED and filter spectra.

In the case involving the use of a cold-cathode fluorescence lamp (CCFL) or a white LED backlight, the display color is desaturated. The color saturation of the white-light-source-backlight RGBW LCD can also be improved through the use of unequal-area color filters. The dependence of the display color gamut and power consumption on a_{ng} is similar to that in the case where the RGB LED backlight was used.

5. Conclusions

The RGB-LED-backlight RGBW LCD using unequal-area color filters is proposed for the improvement of the display color saturation. The red- and blue-subpixel areas are the same and represent one-quarter of the pixel aperture area. The other half-pixel aperture area consists of green and neutral subpixels. Both the color gamut size and power consumption decrease as the area ratio of the neutral and green subpixels increases. The study results show that high color saturation and power saving can be achieved for the RGBW LCD by properly choosing the area ratio of the neutral and green subpixels. The display color saturation and required power increase as the area ratio of the neutral and green subpixels decreases. Thus, a compromise between display color saturation and power consumption is required. An example shows that the RGBW LCD with a 50% neutral- and green-subpixel area ratio saves 37.5% power compared with the RGB-LED-backlight RGB LCD, but at the expense of 23.1% DCNR and 9.7% EDCNR decrements. The RGBW LCD with a 50% neutral- and green-subpixel area ratio requires 14.9% more power than the RGBW LCD using equal-area color filters, and its DCNR and EDCNR are improved 13.8 and 10.3%, respectively. The comparison of the color gamuts of HDTV and of the RGBW LCD with a 50% neutral- and green-subpixel area ratio revealed that the color appearance of the RGBW LCD is more saturated in the green color region but is less saturated in the red and blue color regions. Further study is required to improve the saturation of the red and blue color regions by tailoring the red- and blue-subpixel areas and by using the proper LED and filter spectra.

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