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New display concept for realistic reproduction of high-luminance colors

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ABSTRACT

A new display concept for reproduction of high-luminance colors based on a liquid crystal display has been developed using a brighter backlight unit and color mapping algorithms. The new concept is able to display brighter colors close to a peak luminance of a display white than conventional displays so that realistic scene of brighter colors is better reproduced. It may also be one of the future display solutions needed to extend the color gamut in the direction of brighter colors, which is a principal limitation in conventional displays even in high-dynamic range display systems. With the new concept, an xvYCC-(extended-video YCbCr) compatible display can be easily realized.

1. Introduction

Over the past decade, the color gamut of the standard display for the high definition television system and computer displays has been defined by Rec.709 (ITU) and sRGB (IEC) [1,2]. Such displays can reproduce only a portion of all colors visible to humans. To extend beyond this limitation on color gamuts, new wide color-gamut standards such as xvYCC, ITU-R-BT.1361, Adobe-RGB, scRGB and ITU-R.BT.2020 for UHDTV have been published [3–5].

Currently, some wide color gamut displays in the form of multi-primary displays or those using highly saturated primary colors, such as LED and laser displays, are available on the market [6–8]. However, recent technology of the wide color gamut displays focuses mainly on increasing the color purity of the primary colors and the number of display primaries [6,7]. With these efforts, the color gamut can be extended in the direction of more saturated primary colors, as shown in Fig. 1.

Fig. 1 shows only the maximum range of the color-gamut boundaries. In other words, the projected two-dimensional CIE-xy chromaticity diagram represents the color gamut without luminance information. To analyze the color gamut with respect to luminance more accurately, three-dimensional color spaces with an additional luminance or lightness axis are required.

Even though these display types can extend the wide color gamut in the direction of increasing color purity, there are still limitations on the gamut extension in the region of high-luminance colors. The reason for this limitation is that a conventional display reproduces colors by the additive mixture of primary colors. Thus, the reproduction of the high-luminance colors close to the peak luminance of a display white is principally impossible.

Fig. 2 illustrates this limitation in three-dimensional YCbCr color space. The display white with luminance $Y_W = 1$ is optically composed by the mixture of the three primary colors: $Y_W = Y_R + Y_G + Y_B = 0.3 + 0.59 + 0.11$. For that reason, the luminance of all primary colors and other mixed colors cannot possibly exceed the luminance of the display peak white.

However, humans can perceive not only a peak display white but also brighter colors, of which the brightness levels are close to a brightness level of a perceived white. This human-perceptible color gamut is called an optimal illuminant color space, as shown in Fig. 3. This was studied in an article [9].

The brightest gamut range of the optimal illuminant color space is indicated as the red-line in Fig. 3; CIE-L^* = 100 (L^* = 100 is equivalent to $Y = 1$). This range includes many colors with the same luminance of the peak display white, such as yellow, green, and cyan. However, the reproducible color range of the conventional display has only one point of the peak display white at the brightness level of CIE-L^* = 100.

Thus, the chromatic colors having the same luminance as the peak display white cannot be reproduced on the conventional display even though these colors are captured by a camera. These colors are named as "high-luminance chromatic colors" hereafter.

This limitation of high-luminance chromatic colors in relation to the peak display white of the conventional display causes degradation image qualities during high-luminance color reproductions. This often occurs during display on a high dynamic range (HDR) imaging system; for example, to capture and to display the colored illumination on a stage during live music performances (see Fig. 4) or colors of brighter LED-lighting of Christmas trees.

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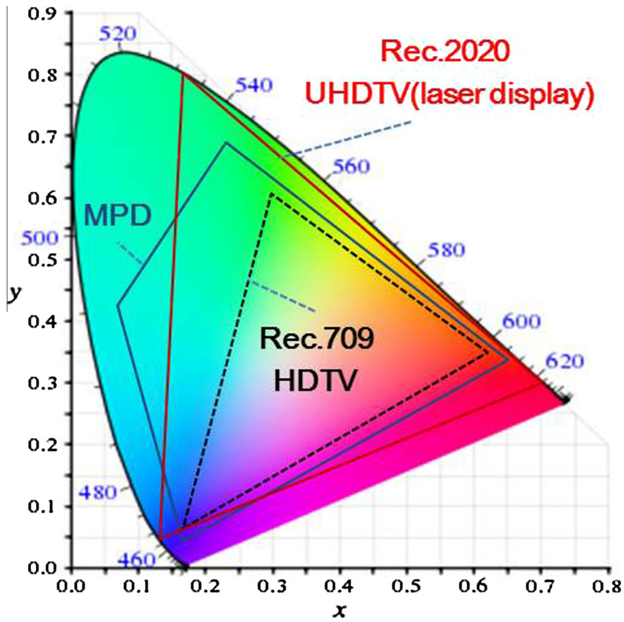

Fig. 1. Multi-primary display (MPD) technology and wide color gamut display using highly saturated primary colors of lasers in comparison with the TV standards (Rec.709 and Rec.2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In such cases, the conventional display usually clips bright colors to boundary colors of the display gamut so that corresponding colors may be desaturated or their luminance may be decreased while maintaining their chroma even in more sophisticated mapping algorithms. This limitation reduces the dynamic range of the original scene and results in a dull-image look to observers. This is one of the reasons of why human observers feel that a live scene is much better than a reproduced image on display. To overcome this problem, a significant research area is HDR imaging in the field of extended-encoding schemes such as LogluvTIff, OpenEXR, scRGB, RGBE, and HDRi [11], and some HDR displays [12] that can reproduce much higher peak luminance than conventional displays. However, HDR displays unfortunately use the same additive mixture reproduction concept as conventional displays; they still cannot reproduce the high-luminance colors close to the peak display white.

To summarize, current displays may need to extend their color gamut in the direction of highly saturated colors in order to realize UHDTV standard Rec.2020 and the dynamic range of displays should be increased to enable HDR imaging. On the other hand, this requires reproducing high-luminance colors closer to a luminance of the peak display white to enable all human-perceptible colors.

With respect to an effective usage of the display color gamut, extending the gamut in the direction of the higher-luminance colors may be much more meaningful than extending the color gamut in the direction of the saturated colors, because the occurrence statistic of high luminance colors is usually much higher than the saturated colors outside of the Rec.709 color gamut.

In Section 2, the concept of the proposed display will be explained in detail. In Section 3, an implementation of the proposed display using a conventional LCD will be described in terms of a standard color reproduction and a color reproduction using the sRGB gamut expansion. In the same section, simulation results of test images for standard color reproduction and experimental results of a subjective image quality assessment for the sRGB gamut-expanding method will be presented. Finally, the paper concludes with the results and a discussion of some future research directions.

2. Display concept

As previously mentioned, the low-luminance color problem in conventional display systems can easily be solved by using high-luminance primary colors; this is realized, for example, by using a brighter backlight in an LCD with an appropriate color-mapping algorithm. This concept is shown in Fig. 5.

The inner "Gamut1" indicates the color gamut of the conventional display. Here, we replace the backlight with one having approximately twice the brightness (w2/w1 = 2). Therefore, the

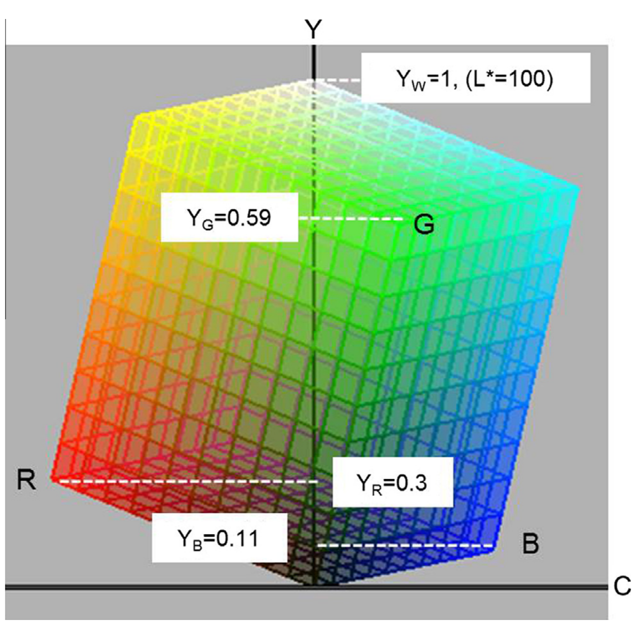

Fig. 2. A typical color gamut of conventional displays in three dimensional YCbCr color space. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

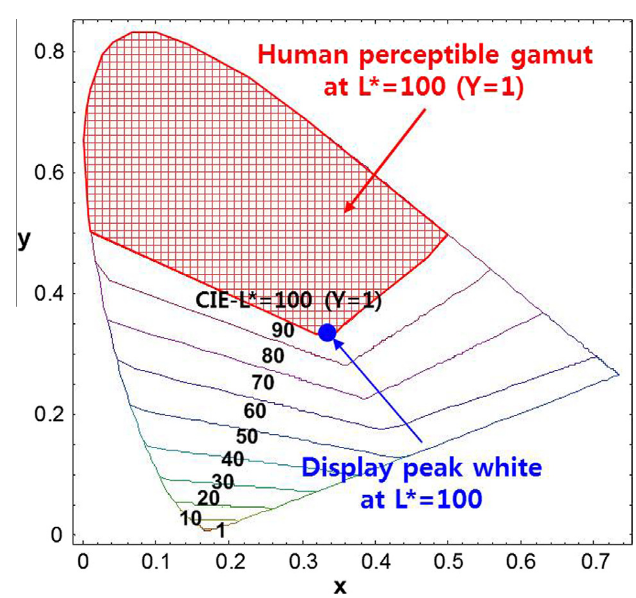

Fig. 3. Optimal illuminant color space: the color gamut of human vision is plotted as a function of the perceived lightness (L^*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)