行政院國家科學委員會專題研究計畫 成果報告

適用於廣色域顯示器的色差公式之研究
研究成果報告(精簡版)

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中 華 民 國 98 年 11 月 08 日

行政院國家科學委員會補助專題研究計畫成果報告

適用於廣色域顯示器的色差公式之研究

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成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

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中　華　民　國　98　年　10　月　31　日

中文摘要

推導色差公式需要由心理物理實驗所測量的色彩辨別橢圓。本計畫使用一台由紅綠藍發光二極體背光的液晶顯示器進行實驗，使得在心理物理實驗中能顯示高飽和度色塊，以測量高飽和色彩的辨別橢圓，並得以研究適用於廣色域顯示器的色差公式。由於實驗需要小於色差0.05（以CIEDE2000為單位)的色塊，本計畫提出一種空間信號抖動方法，使得實驗所用的顯示器之位元數得以等效地增加。顯示器的紅綠藍信號為24位元(單原色信號為8位元)。本計畫定義一個含有9個像素的超像素，加在這9個像素的紅綠藍信號可以依據需要而不同。如果此超像素的視角小於1分弧度，由於人眼的敏銳度限制，人眼不能分辨此超像素中的9個像素之細節。利用這個特性，本計畫可以對於一單原色產生256×9= 2304個亮度階，也就是相當於有11位元的單原色信號，或33位元的紅綠藍信號。使用這個空間信號抖動方法，本計畫對17位觀察者進行心理物理實驗。測量數據與文獻中原始的MacAdam橢圓做比對，結果是相符的。本計畫顯示高飽和度色彩辨別橢圓的測量結果，其色彩飽和度超越文獻中的數據。實驗結果顯示CIEDE2000色差公式不僅在高色彩飽和度區域不精確，在中色彩飽和度區域也不夠精確。因此，需要發展新版的色差公式，使得人眼視覺對所感知的色差差異之描述能更精確。

關鍵字：色差公式，色彩辨別橢圓，廣色域顯示器。

Abstract

The derivation of color difference formula requires the chromaticity discrimination ellipses measured from psychophysical experiment. We use a wide-color-gamut (WCG) LCD backlit with RGB LEDs for displaying high saturation color patches in the psychophysical experiment so that the chromaticity discrimination ellipses of high saturation colors can be measured and the color difference formula for high saturation color can be studied. Because the color patches with less than 0.05 color difference in unit of CIEDE2000 are required in the experiment, we propose a spatial-dithering method for the WCG LCD so that the bit depth of the LCD can be effectively improved. The RGB signal of the WCG LCD in the experiment is 24-bit (8 bits for each primary signal). For the WCG LCD, we define a super-pixel comprising 9 pixels. The applied RGB signals of the 9 pixels can be different and are given as required. If the viewing angle of the super pixel is less than 1 minute of arc, the details of the 9 pixels cannot be observed owing to the visual acuity of human eye. By utilizing this property, we are able to generate 256×9=2304 levels for a primary, which effectively corresponds to 11-bit primary signal or 33-bit RGB signal. Psychophysical experiment with 17 observers is taken by the use of this spatial-dithering method. The experimental results are checked with the original MacAdam ellipses in literature and the agreement is well. The chromaticity discrimination ellipses with color saturation beyond the color saturation of measured data sets in literatures are shown. Experimental result shows that CIEDE2000 is not an accurate color difference formula not only in high color saturation region but also in medium color saturation region. Therefore, the development of new version of color difference formula is necessary so that the perceptual color difference of human vision can be more accurately described.

Keyword: color difference formula, chromaticity discrimination ellipse, wide-color-gamut display

1. Introduction

The displays with larger color gamut are able to show more colorful and attractive images. The color gamut of a display can be expanded by the use of high saturation primaries. Owing to the advance of display technologies, wide-color-gamut (WCG) displays have been realized but are not yet popular. The liquid crystal display backlit with RGB light emitting diodes (LEDs) and the laser projection displays are two examples. The color gamuts of both displays can be larger than that of NTSC and HDTV (ITU-R BT. 709) color standards [1]. Nowadays, video programs are recorded according to HDTV specification. Primary color coordinates of WCG displays are much different from that of HDTV primaries. Color processing is required for the video programs shown on WCG displays so that the color hue shift due to primary changes can be corrected or preferred color appearance can be achieved.

Because CIE color coordinate system is a non-uniform color space, the metric for measuring the color difference between two color points is an important issue. The metric is called the color difference formula, which is a basic tool for color science and technology. In color processing, the calculation of the color difference between two color points is frequently encountered. CIE has published three versions of color difference formulas in 1976, 1995, and 2000 [2-4]. Color difference formula can be obtained by fitting chromaticity discrimination ellipses to a mathematical formula [2, 5]. The chromaticity discrimination ellipses are measured from psychophysical experiment, in which a group of observers are asked to indentify whether testing color patches are the same as a reference color patch or not [2]. From the data collected from the psychophysical experiment, the chromaticity discrimination ellipse centered at the color coordinates of the reference color patch can be calculated by statistical method. The color patches were usually prepared with a set of color chips, which are made of tiles and textiles for examples, so that their color appearance can be stable under a given illumination [5]. The pigments of the color chips are usually not fluorescent and not highly saturated. Therefore, they do not include high saturation colors in nature including the colors of butterfly wings and fluorescent light. Visible LED is made of band gap material and the bandwidth of its emission spectrum is narrow and highly saturated. Thus, current CIE color difference formulas may not be suitable for calculating the color difference between two high saturation colors that can be shown by wide-color-gamut displays.

Cathode-ray tube (CRT) displays have been used as the experimental apparatus for displaying color patches in psychophysical experiments [5-8]. In this paper, we use a WCG LCD backlit with RGB LEDs for displaying color patches of high saturation in the psychophysical experiment so that chromaticity discrimination ellipses can be measured and the color difference formula for high saturation color can be derived. However, the color patches with tiny color difference are required in such an experiment. In [5-8], the signal processing in CRT is analog and the required color patches can be displayed by careful tuning signal voltages. Nowadays, the signal processing in LCDs is digital and the displayed color patches are limited by the bit depth. We propose a spatial-dithering method for the WCG LCD to show the color patches with tiny color difference. The RGB signal of the WCG LCD is 24-bit (8 bits for each primary signal). For the WCG LCD, we define a super pixel comprising 9 pixels. The applied RGB signals of the 9 pixels can be different and are given as required. Because the visual acuity of human eye is 1 minute of arc, if the viewing angle of the super-pixel is less than 1 minute of arc, the details of the 9 pixels cannot be observed. Thus, we are able to generate more than 256 levels for a primary by the use of super pixels. Psychophysical experiments with 17 observers are taken by the use of this spatial-dithering method. The experimental results have been checked with original MacAdam ellipses [2]. The chromaticity discrimination ellipses of the high saturation color points near primary color coordinates are also measured for deriving the color difference formula for high saturation colors.

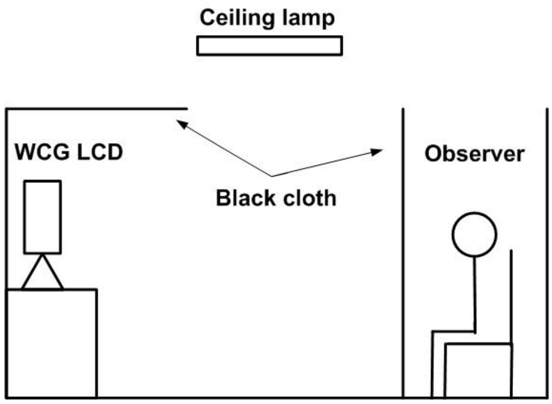

Figure 1: Side view of experimental setup.

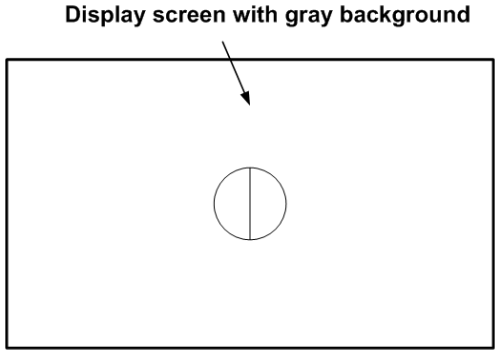

Figure 2: Color patches for psychophysical experiment. In screen center, the left and right half circles are reference and test color patches, respectively.

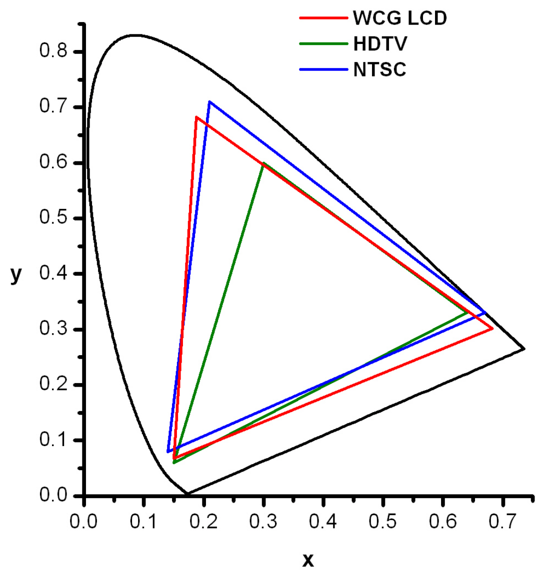

Figure 3: Chromaticity triangle of the WCG LCD, in which the chromaticity triangles of HDTV and NTSC are also shown for comparison.

2. Experimental Setup

Figure 1 shows the side views of the experimental setup. The setup is surrounded by black cloth for avoiding the reflection of surrounding environment lighting from the display screen. The observer views screen through an aperture of 20 cm ×10 cm on the black cloth facing the screen. The distance between the observer and screen is 2 m so that the viewing angle extended from the observer to the color patches shown on screen is 2° and the viewing angle extended from the observer to a super-pixel defined by spatial-dithering method is less than 1 minute of arc. The color patches are shown in Fig. 2, in which the diameter of the color patches is 3.49 cm and the left and right half circles are reference and test color patches, respectively. Seventeen observers are asked to change the color coordinates of the test color so that the test and reference colors are just discernible. From a set of just discernible color coordinates corresponding to a reference color, the chromaticity discrimination ellipse can be calculated by the statistical method given in [2].

RGB-LED backlit View Sonic VLED221wm is used as the WCG LCD, in which its screen diagonal length is 22 inches, resolution is 1680×1050, horizontal and vertical viewing angles are 170° and 160°, respectively. Figure 3 shows the chromaticity triangle of the display, in which the chromaticity triangles of HDTV and NTSC are also shown for comparison. Room temperature is kept within 24°C and 26°C. The warm up time of the display is 1.5 hours. The display is characterized with the spectrophotometer Photo Research PR-670. 3D-LUT is taken as the color device model of the display. In addition, each displayed color patch is measured and checked with PR-670.

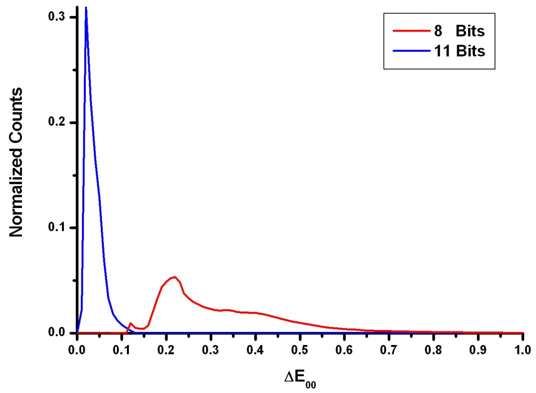

Figure 4: The maximum color difference statistics for the palette of the WCG LCD with 24-bit signals, in which the case with effective 33-bit signals is also shown. The number of counts is normalized so that the area under each curve is unit.

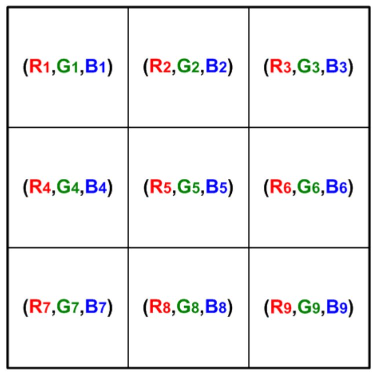

Figure 5: A super-pixel of the spatial-dithering method.

3. Spatial-Dithering Method

There are 2^{24}= 16,777,216 colors in the palette of the display with 24-bit RGB signal (8 bits per color channel). Figure 4 shows the maximum color-difference statistics for the palette of the WCG LCD with 24-bit RGB signal, in which the number of counts is normalized so that the area under each curve is unit. For a given signal of (*R*, *G*, *B*), in which the values of *R*, *G*, and *B* are from 0 to 2^8-1, the maximum color difference in unit of ΔE_{00} (CIEDE2000) among neighboring signals shown in Fig. 4 is defined as

$$\Delta E_{\max} = Max\{\Delta E(R,G,B;R+1,G,B), \Delta E(R,G,B;R,G+1,B), \Delta E(R,G,B;R,G,B+1)\}, \quad (1)$$

where $Max\{\}$ is the maximum function; and $\Delta E(R_1,G_1,B_1;R_2,G_2,B_2)$ is defined as the color difference between the signals of (R_1,G_1,B_1) and (R_2,G_2,B_2). In Eq.(1), only the neighboring signals of larger than unit digital count are taken into account so that the maximum color differences of two neighboring signals are not calculated in duplicate. We can see that the maximum color differences of all signals among their neighboring signals as defined in Eq.(1) are almost less than unit color difference. However, such color differences are not small enough for measuring chromaticity discrimination ellipses that will be shown in the next section. Therefore the display of more bit depth is required for measuring chromaticity discrimination ellipses. Figure 4 also shows the case with 33-bit RGB signal (11 bits per color channel), in which the maximum color differences of all signals among their neighboring signals defined in Eq.(1) are almost less than 0.2 and the color difference is small enough for measuring chromaticity discrimination ellipses. The proposed spatial-dithering method is used to improve the effective bit depth of the display.

We define a super-pixel comprising 9 pixels arranged as is shown in Fig. 5 so that we are able to show a RGB signal with ($R+r/9$, $G+g/9$, $B+b/9$), in which R, G, B , r, g, and b are integers; $0 \leqq R, G, B <$ 255; $0< r, g, b< 9$. Taking the case with R= 50, G= 100, B= 150, r= 2, g=4, and b= 6 as an example, in each super-pixel, we may randomly assign the red signals of the 9 pixels so that they comprise two 51 and seven 50, the green signals of the 9 pixels so that they comprise four 101 and five 100, and the blue signals of the 9 pixels so that they comprise six 151 and three 150. If the viewing angle of the super-pixel is less than 1 minute of arc, the details of the 9 pixels cannot be observed owing to the visual acuity of human eye. By utilizing this property, we are able to generate 256×9= 2304 levels for a primary, which effectively corresponds to 11-bit primary signal or 33-bit RGB signal.

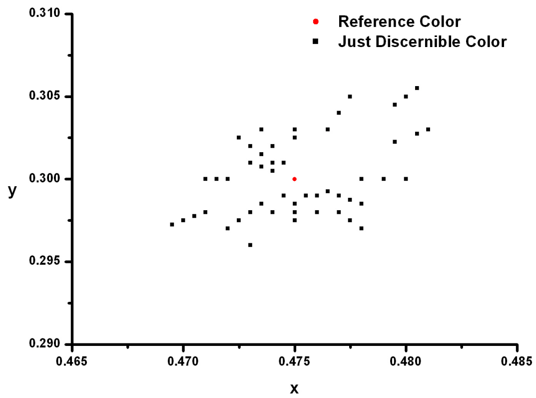

Figure 6: Distribution of the just discernible color coordinates of 17 observers for the red reference color at (x,y)= (0.475,0.3).

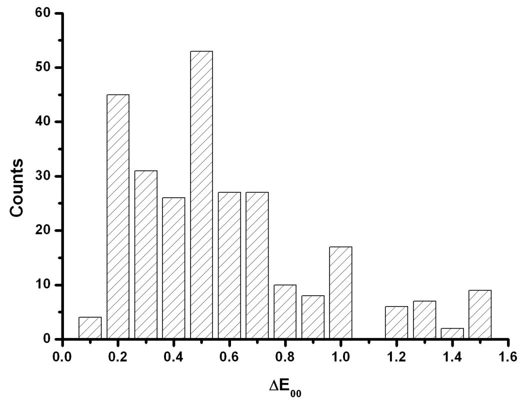

Figure 7: Statistics of the color difference of the just discernible colors shown in Fig. 6 and the reference color at (x,y)= (0.475,0.3).

4. Results

For a given reference color, test color patches are prepared along the lines crossing the reference color coordinates. The slant angles of the lines with respect to positive horizontal axis (x axis) are in step of 22.5° from 0° to 337.5°. Figure 6 also shows the distribution of the just discernible color coordinates for the 17 observers, in which the reference color coordinates are (x,y)= (0.475,0.3). The statistics of the color differences (in unit of ΔE_{00}) between the just discernible colors and reference color for the cases shown in Fig. 6 are shown in Fig. 7. From Fig. 7, we can see that the color differences vary from 0.1 to 1.5. Thus, it requires the color difference between successive test color patches to be at least less than 0.05. From Fig. 4, we can see that the display with 33-bit RGB signal is required for this psychophysical experiment. The use of spatial-dithering method is necessary for the display with only 24-bit RGB signal.

Figure 8 shows seven chromaticity discrimination ellipses measured from the psychophysical experiment, in which the ellipses are enlarged tenfold so that they can be clearly shown. In Fig. 8, there are four checking chromaticity discrimination ellipses, in which their reference color coordinates are chosen to be the same as four reference colors of original MacAdam ellipses [2]. According to

MacAdam's experimental condition, the luminance of the four checking chromaticity discrimination ellipses are set to be 48 cd/m^2; the gray background color is set be the illuminant C with 24 cd/m^2. The corresponding MacAdam ellipses are also shown by dashed ellipses in Fig. 8 for comparison. We can see that the four checking chromaticity discrimination ellipses measured from our experiments are about the same as the MacAdam ellipses. The slight differences between the chromaticity discrimination ellipses and MacAdam ellipses may be due to the observer factor, room lighting, and other viewing conditions.

The other three chromaticity discrimination ellipses near red, green, and blue primaries color coordinates in Fig. 8 show the examples of high saturation reference colors. The luminance of the red, green, and blue chromaticity discrimination ellipses are set to be 40 cd/m^2, 48 cd/m^2, and 20 cd/m^2, respectively, because of the limitation of primary luminance. The gray background color is the same as the four checking chromaticity discrimination ellipses. The size of chromaticity discrimination ellipse increases with color saturation in literatures [3-5]. However, from Fig. 8, we can see that the red and blue ellipses are slightly smaller than the red and blue checking chromaticity discrimination ellipses, respectively. This result shows the dependence of chromaticity discrimination ellipse on luminance [9]. It is noticed that the color saturation of the three measured chromaticity discrimination ellipses are well beyond the color saturation of four data sets studied in [9].

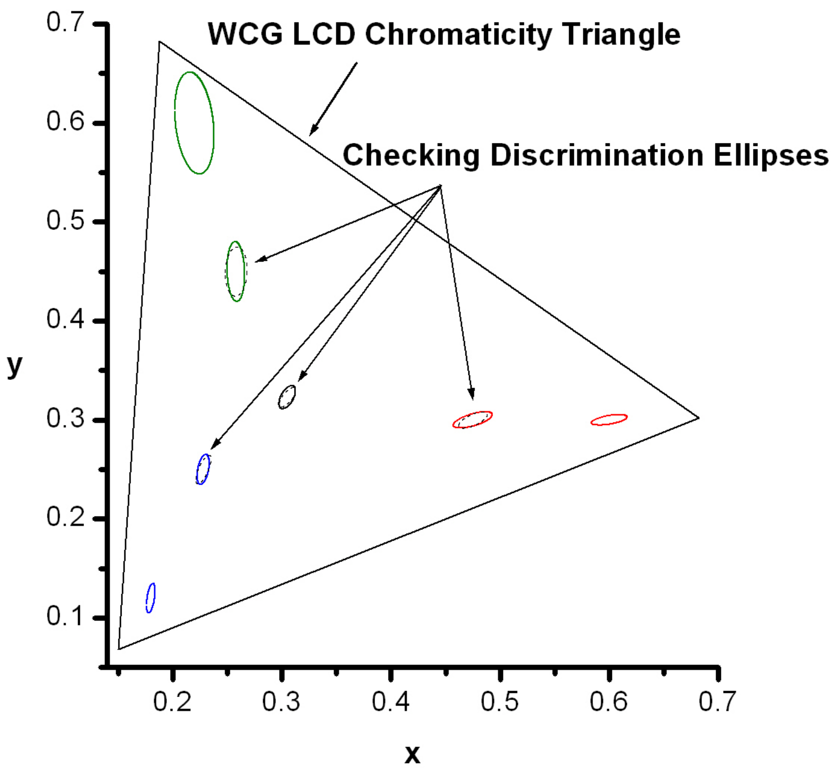

Figure 8: Chromaticity discrimination ellipses measured from psychophysical experiment, in which the ellipses are enlarged tenfold so that they can be clearly shown. The corresponding MacAdam ellipses are shown by dashed ellipses for comparison, which are also enlarged tenfold. The experimental conditions should be referred to the text in this paper.

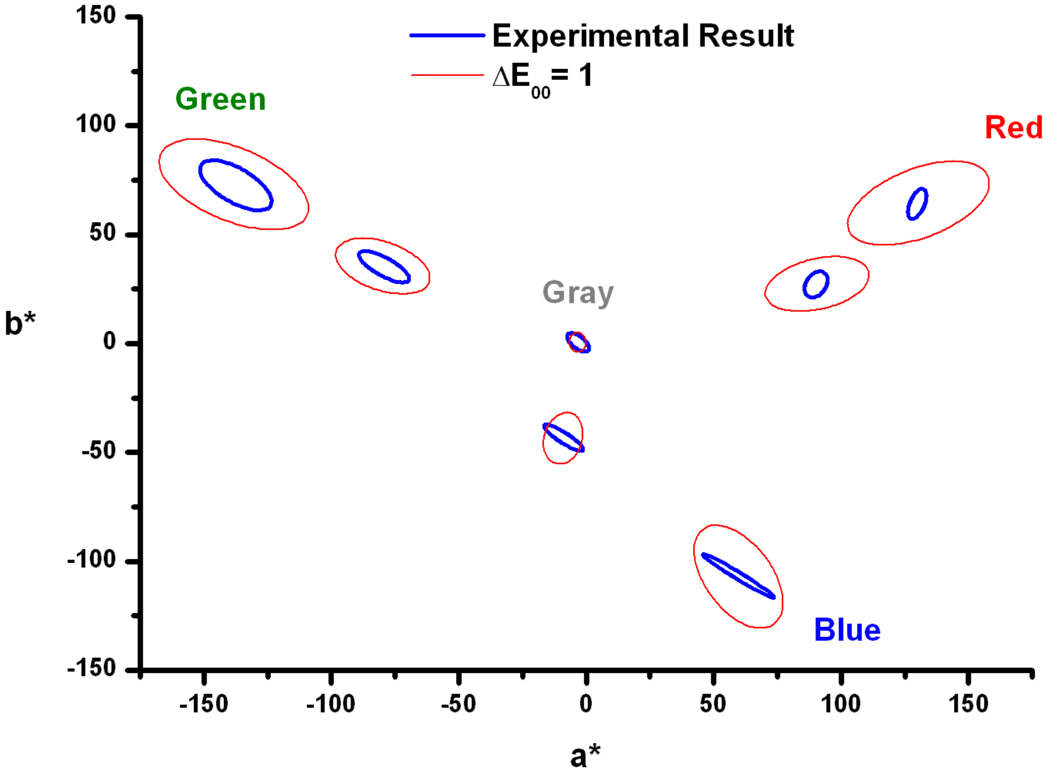

Figure 9: Measured chromaticity discrimination ellipses for the cases shown in Fig.8, in which the ellipses are represented in CIELAB and are enlarged fourfold so that they can be clearly shown. The corresponding ellipses with $\Delta E_{00} = 1$ are shown in red lines for comparison, which are also enlarged fourfold.

Figure 9 shows the measured chromaticity discrimination ellipses for the cases shown in Fig.8, in which the ellipses are represented in CIELAB and are enlarged fourfold so that they can be clearly shown. The corresponding ellipses with $\Delta E_{00} = 1$ are shown in red lines for comparison. We can see that the gray chromaticity discrimination ellipse with $\Delta E_{00}=1$ is nearly circular and the lengths of its axes are close to that of the measured corresponding chromaticity discrimination ellipse. However, the axis lengths of other six chromaticity discrimination ellipse with $\Delta E_{00}=1$ are longer than that of corresponding measured ellipses. It is noticed that the orientations of the chromaticity discrimination ellipses with $\Delta E_{00}=1$ are very different from that of corresponding measured ellipses in red and blue regions. Experimental result shows that CIEDE2000 is not an accurate color difference formula not only in high color saturation region but also in medium color saturation region.

5. Conclusions

A WCG LCD backlit with RGB LEDs is used as the apparatus for displaying high saturation color patches in the psychophysical experiment so that the chromaticity discrimination ellipses of high saturation colors can be measured and the color difference formula for high saturation color can be studied. Because the color patches with less than 0.05 color difference in unit of CIEDE2000 are required in the experiment, we propose a spatial-dithering method for the WCG LCD so that the bit depth of the LCD can be effectively improved. The RGB signal of the WCG LCD in the experiment is 24-bit (8 bits for each primary signal). For the WCG LCD, we define a super-pixel comprising 9 pixels. The applied RGB signals of the 9 pixels can be different and are given as required. If the viewing angle of the super pixel is less than 1 minute of arc, the details of the 9 pixels cannot be observed owing to the visual acuity of human eye. By utilizing this property, we are able to generate 256×9=2304 levels for a primary, which effectively corresponds to 11-bit primary signal or 33-bit RGB signal. Psychophysical experiment with 17 observers is taken by the use of this spatial-dithering method. Four checking chromaticity discrimination ellipses in red, green, blue, and gray regions, respectively, are shown. The results well agree with the original MacAdam ellipses shown in literature. The chromaticity discrimination ellipses of the high saturation color points near primary color coordinates are also shown. The color saturation of the measured chromaticity discrimination ellipses are well beyond the color saturation of measured data sets in literatures. Experimental result shows that CIEDE2000 is not an accurate color difference formula not only in high color saturation region but also in medium color saturation region. Therefore, the development of more accurate color difference formula is necessary. The collection of more experimental data is undertaken for further investigation and the results will be published elsewhere.

6. References

[1] International Telecommunication Union, *Parameter values for the HDTV standards for production and international programme exchange*, Revision 2, ITU Recommendation ITU-R BT.709, Geneva (1995).

[2] G. Wyszecki and W. S. Stiles, *Color Science*, 7th ed., John Wiley & Sons, New York (1982).

[3] Commission Internationale de l’Eclairage (CIE), *Industrial colour-difference evaluation*, CIE Publication No. 116, Vienna (1995).

[4] Commission Internationale de l’Eclairage (CIE), *Improvement to Industrial colour-difference evaluation*, CIE Publication No. 114-2001, Vienna (2001).

[5] M. R. Luo, G. Cui, and B. Rigg,” The development of the CIE 2000 colour-difference formula: CIEDE2000,” Col Res Appl, **26**, 340-350 (2001).

[6] M. Melgosa, M. M. Pérez, A. El Moraghi, and E. Hita,” Color discrimination results from a CRT device: influence of luminance,” Col Res. Appl., **24**, 38-44 (1999).

[7] J. H. Xin, C. C. Lam, and M. R. Luo,” Evaluation of the crispening effect using CRT-displayed colour samples,” Col Res. Appl., **29**, 374-380 (2004).

[8] R.-C. Wu, R. H. Wardman, and M. R. Luo,” A comparison of lightness contrast effects in CRT and surface colours,” Col Res. Appl., **30**, 13-20 (2005).

[9] R. W. Pridmore and M. Melgosa,” Effect of luminance of samples on color discrimination ellipses: analysis and prediction of data,” Col Res. Appl., **30**, 186-197 (2005).

行政院國家科學委員會補助團隊參與國際學術組織會議報告

98 年 6 月 10 日

報告人姓名	溫盛發	服務機構	中華大學	職稱	教授
會議正式名稱	中文：資訊顯示器學會 2009 國際學術會議				
	英文：Society for Information Display (SID) 2009 International Symposium				
會議時間	自 96 年 5 月 31 日至 96 年 6 月 5 日	地點（國、州、城市）	美國，德州，San Antonio (聖安東尼)		

報告內容應包括下列各項：

一、參加會議經過

二、與會心得

三、考察參觀活動（無是項活動者省略）

四、建議事項

五、其他

一、參加會議經過

國際最著名的顯示器學術組織 SID 今年在德州 San Antonio 的 Henry B. Gonzalez 會議中心舉辦。今年受到經濟不景氣與 H1N1 新流感的影響，參與人數比往年少一些。根據大會所提供的資料，今年 SID2009 約有 685 篇論文投稿，共接受發表約 493 篇論文，其中口頭報告論文 292 篇與壁報論文 201 篇。前六發表論文國家分別是：韓國(27%)，台灣(22%)，美國(19%)，日本(15%)，歐洲(10%)，與中國(4%)，各國發表論文的比例與去年差不多。這個排序與各國在顯示器產業的影響力大致符合。美國雖然沒有量產消費性顯示器的產業，但在技術授權與原物料提供上，影響力舉足輕重。由於韓台日中發表論文佔了 68%，加上大陸在美國的留學生，東方人在會場中應該至少佔 70%。韓日大廠的員工身穿一式服裝，成群結隊，很是可觀。往年會議的主角其實是國際知名大公司，如韓國的 Samsung，日本的 Sony，與荷蘭的 Philips 等。耀眼的成果多來自這些大公司，這也反應出顯示器技術的現實。也就是這些大公司的資源充沛，比較有能力負擔新技術開發成本。學術界的資源不如大公司，研究成果自然沒有大公司出色。可以這樣說，學術界的研究成果主要在點的突破，大公司的研究成果除了點也能做線的突破，最終是落實到產品，由大公司做全面性的成果收割。除了論文報告，會議同時舉行廠商展覽(Exhibition)，今年受到經濟不景氣的影響，日本的 Sony 以及台灣的友達與奇美都沒參展，展覽會場不如往年盛況。而今年學術會議的主角則是 Samsung，往年的其他主角如 Sony 與 Philips 則較不顯眼。在學界方面，則以交通大學顯示科技研究所發表的論文最多，為台灣爭光。不過重點是這些研究成果要能落實到顯示器產業，使得將來友達與奇美能如 Samsung 一樣，成為技術上的領導者。

本屆論文最重要的特色分為三類：OLED TV，電子紙，與立體顯示器。會議同時所舉行的廠商展覽會除了這三類顯示器，另外受到 Window 7 的影響，有多家廠商展示觸控式螢幕。展示攤位面積最大的是 Samsung，在整個展覽會場中，Samsung 表現出其在顯示器技術的龍頭地位。Samsung 的攤位擺滿最新產品，與各種概念性原型機。其中 Samsung 也展示其薄型 LCD，並在論文報告中說明其薄型 LCD 的設計概念。不過會場中最令人印象深刻是 Samsung 展示的一台約 22 吋的透明 AMOLED，如同好萊塢電影「關鍵報告」的透明顯示器一樣，只是少了觸控功能而已。各國參展廠商都展示電子紙，所顯示的效果比去年好一些，對比度與解析度都有加強，電子紙的普及化將會實現。展覽會所展示使用的顯示器最新技術，都是論文發表會與學術期刊中的熱門題目。也就是新技術一經發表，立刻被大公司應用於原型機，而且將來也很有機會進入產品線量產。這種顯示技術熱門的程度，說明開發新技術刻不容緩。稍有懈怠，在學術上落伍，在產業上不是喪失商機，便是將來要付出鉅額權利金。

一般學術會議的口頭報告，報告人當場能回答問題的時間很有限。從 SID2007 開始，有一創新的安排以彌補這缺陷。論文發表當天的議程結束後，大會提供大型場地，舉行一個小時的 Author Interview。每位報告人一個攤位，使報告人與聽眾能直接面對面討論問題。另外，有些報告人在口頭報告中沒時間展示的軟硬體，便在其攤位上展示給觀眾看。由於同一個 Symposium Section 的報告人共用同一區的攤位，Author Interview 的場地也提供同一個 Symposium Section 的報告人之間有近距離的互動與認識機會。

本人在 6 月 4 日下午做壁報論文展示，題目是 Color Gamut and Power Consumption of a RGBW LCD using RGB LED Backlight。由於具有省電的優點，RGBW LCD 原被提出應用於 mobile display，如手機螢幕。一般 mobile display 使用白光 LED 為背光源，其色彩飽和度較差。本論文研究使用 RGB LED 作為其背光源，發現會比使用白光 LED 為背光源省電，同時色彩飽和度可以調整。論文的結論是使用 RGB LED 為背光源的 RGBW LCD 可以有三個工作模式，一是省電模式，色彩飽和度比 HDTV 稍差，可省 45.9%電功率；一是標準模式，色彩飽和度比 HDTV 相當，可省 20%電功率；三是高色彩飽和度模式，色彩飽和度比 HDTV 佳，不省電。在壁報論文展示現場，

對這篇論文感興趣者相當多，值得一提的是 Samsung 的 Fundamental Technology Group 1 LCD Division 的首席研究員 Bonghyun You 深感興趣，仔細詢問論文細節。發表壁報論文的好處是，透過現場展示在壁報上的論文內容，作者可以直接跟與會人士做更深入的討論，溝通效果要比口頭報告與大會安排的 Author Interview 的效果好。

二、與會心得

2000 年以來，平面顯示器的發展出乎意料的快速。以本人對中大尺寸 LCD 顯示器的觀察，第一波熱潮的動力是幾年前的電腦監視器換機潮，第二波動力是正在進行中的家庭電視機換機潮。未來第三波動力的來源是多樣化的，例如高色彩飽和度顯示器(如 OLED TV 與使用 RGB LED 背光的 LCD)，電子紙，薄型電視，觸控式螢幕，與立體顯示器等。儘管家庭電視機換機潮將在這幾年完成，第三波的動力將是推向特殊應用市場。例如高色彩飽和度顯示器提供前所未有的視覺經驗，電子紙取代報紙書籍，薄型電視作為壁掛電視(Wall TV)，觸控式螢幕用於互動顯示器。立體顯示器看似還早，不過其國際標準已在制訂中，若制訂完成將加速立體顯示器進入消費者市場的進度。這一波波的成長動力將支持平面顯示器未來十年以上持續的發展。不過在世界各大公司以大量資源的努力下，其中主要的關鍵技術近期幾年內應會被陸續開發出來。由會議中 Samsung 所發表的論文觀察，Samsung 顯示出主導高色彩飽和度顯示器與立體顯示器國際規格的雄心，Samsung 具體提出一些技術方案，未來若 Samsung 如願以償，將不利台灣顯示器產業與其競爭。因此開發主要關鍵技術競賽所剩的時間不多，台灣產官學界短時間內應挹注更多資源，以免在競賽中落後。否則不是產業喪失商機，便是將來要付出鉅額權利金，損失難以估計。

三、建議事項

1. 鑑於上述與會心得，台灣產官學界應設法投入更多資源，加強顯示器技術開發。

2. 本人在會議報告論文中所提出的多重工作模式顯示器的概念，值得國內相關業者參考。

四 、攜回資料名稱及內容

1. 會議論文集。

P-34: Color Gamut and Power Consumption of a RGBW LCD using RGB LED Backlight

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Abstract

The relation of color gamut and power consumption of a RGBW LCD using RGB LED backlight is studied. The result shows that the display can be operated in high color saturation mode, normal mode (20% power saving), and power saving mode (45.9% power saving). The color saturation in normal mode is about the same as that of ITU-R BT. 709 specification.

1. Introduction

Owing to the efficiency improvement and cost down of visible LEDs, the LCD monitors using RGB LED backlight have been commercially available. Although color field sequential technology is able to significantly reduce power consumption, the color flicker phenomenon has not yet been completely solved [1,2]. Therefore, the use of RGB color filters is necessary for the LCD monitors using RGB LED backlight. The power consumptions of the LCDs using CCFL backlight and RGB LED backlight are about on the same level nowadays. However, the efficiencies of RGB LEDs are still evolving rapidly. Visible LEDs are semiconductor band gap materials, in which their spectral bandwidths are narrow and color saturations are high. The LCDs using RGB LED backlight also have the advantage of wide color gamut owing to the high saturation primaries.

Power consumption is a critical issue for mobile displays because of the limited capacity of battery. Because the efficiency of white-light LED (WLED) is higher than that of CCFL and RGB LEDs, it is popularly used in mobile displays. However, it has the disadvantage of less saturated primaries and, therefore, it is not used as the backlight of LCD monitors. The primary saturation of the LCDs using WLED backlight can be improved by the use of narrowband color filters but its effective luminous efficiency is reduced. The other method to improve primary saturation is to use the WLED of warm color temperature but its effective luminous efficiency is also reduced.

RGBW LCDs were proposed for mobile displays [3,4]. There are four equal-area sub-pixels in a pixel for a RGBW LCD. Three of the sub-pixels comprise red, green, and blue color filters, respectively. The fourth sub-pixel is without color filter and is called the white or neutral sub-pixel. 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. A RGBW LCD has the advantage of higher luminance compared with the equivalent RGB LCD owing to the high transmittance of neutral sub-pixels. However, it has the disadvantages of lower resolution and de-saturated color appearance. The resolution problem can be solved by the properly arrangement of sub-pixels and image processing [5]. In this paper, we consider the RGBW LCDs using RGB LED backlight. The size of color gamut is improved for the RGBW LCDs using RGB LED backlight compared with the case using WLED backlight. The relation of the color gamut size and power consumption is numerically studied.

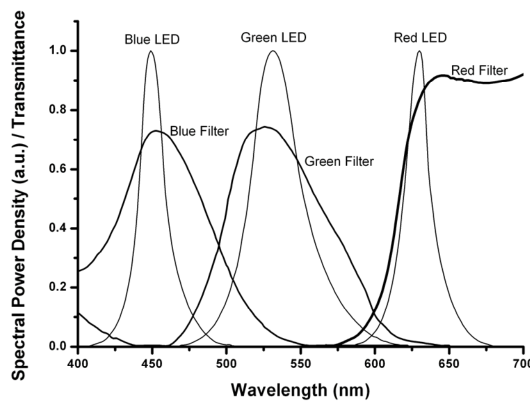

Fig. 1: Spectral power densities of RGB LEDs and transmission spectra of RGB filters.

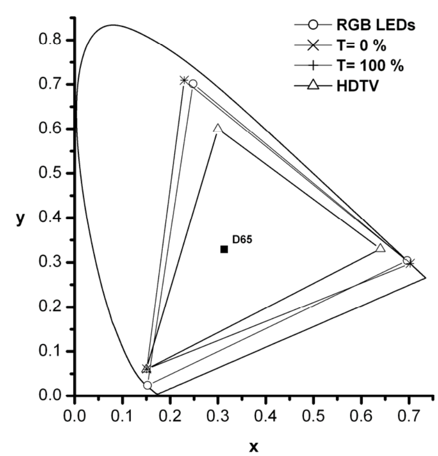

Fig. 2: The chromaticity triangle of RGB LEDs and the chromaticity triangles of RGBW LCDs, in which the cases with the maximum transmittance of neutral sub-pixels *T*= 0% and 100% are shown for RGBW LCDs. Chromaticity triangles of the HDTV color standard (ITU-R BT. 709) and D65 white point are also shown for comparison.

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2. Color Device Model

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

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b & TX_n \\ Y_r & Y_g & Y_b & TY_n \\ Z_r & Z_g & Z_b & TZ_n \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ N \end{bmatrix}, \quad (1)$$

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 red, green, blue, and neutral primaries, respectively; T is the maximum transmittance of neutral sub-pixels and $0 \leqq T \leqq 1$; R, G, B, and N are the normalized linear signals for red, green, blue, and neutral primaries, respectively, and $0 \leqq R, G, B, N \leqq 1$. The factor T is used to limit the light output from neutral sub-pixels for adjusting the color gamut size and power consumption for a given white luminance value Y_w. The factor T can be controlled by the applied voltages of neutral sub-pixels.

In Eq.(1), the maximum tristimulus values are functions of RGB LED powers. We take P_{er}, P_{eg}, and P_{eb} as the total electrical powers of red, green, and blue LEDs, respectively. Taking Y stimulus as an example, we have

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

where i= r, g, b, and n; K_m= 683 lm/Watt; γ is the aperture ratio; m= 4 for the display with four primaries; A is the display area in unit of m^2; C_j, η_j and $S_j(\lambda)$ are the coupling efficiency to the display output except for the absorption of color filters, 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 neutral sub-pixels. The X and Z stimulus values in terms of RGB LED powers are the same as Eq.(2) except that the color matching function $\bar{y}(\lambda)$ is replaced by $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$, respectively. We can solve for P_{er}, P_{eg}, and P_{eb} by substituting the functions of X, Y, and Z stimulus values in terms of P_{er}, P_{eg}, and P_{eb} into Eq.(1), and applying the white point condition. The total required electrical power P_{et}= P_{er} + P_{eg} + P_{eb}. The white point of HDTV color standard (ITU-R BT. 709) is illuminant D65, which is also assumed in this paper.

The spectral power densities of RGB LEDs and transmission spectra of color filters assumed in this paper are shown in Fig. 1. The LED spectral power densities and filter transmission spectra are taken from [7] and [8], respectively. Figure 2 shows the chromaticity triangle of RGB LEDs and the chromaticity triangles of RGBW LCDs, in which the cases with T= 0% and 100% are shown for RGBW LCDs. Chromaticity triangles of HDTV and D65 white point are also shown for comparison. It is noticed that the color coordinates of RGBW primaries depend on T because P_{er}, P_{eg}, and P_{eb} change with T. However, the dependence is slight as is shown in Fig. 2. The red and green primaries are more saturated than the red and green LEDs because the filtering effect of color filters.

3. Display Color Gamut Size

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. For example, the color gamut of RGBW LCDs changes with the maximum transmittance T as is shown later but this fact cannot be shown in Fig. 2. Thus, we represent the color gamut of the considered display in CIELAB color space. The color gamut size is represented with discernible color number instead of chromaticity triangle area in the following [9,10]. Discernible color number represents the number of discernible colors as defined based upon calculations with the CIE94 color difference formula in CIELAB color space.

Color gamut of a RGBW LCD is calculated from Eq.(1) [6]. We take the discernible color number ratio (DCNR) 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.

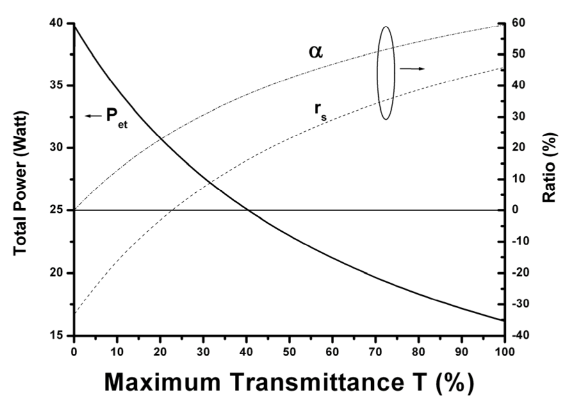

Fig. 3: Total electrical power P_{et}, power saving ratio r_s, and neutral luminance ratio α versus the maximum transmittance of neutral sub-pixels.

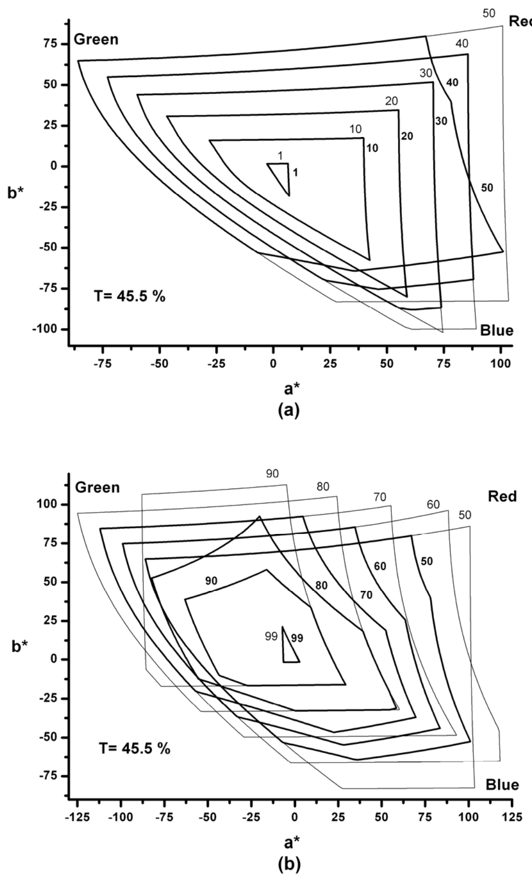

Fig. 4: Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the RGBW LCD with the maximum transmittance of neutral sub-pixels *T*= 45.5%, where (a) L* ≤ 50, and (b) L* ≥ 50. The corresponding values of L* are shown near the boundaries of the cross-sections. The case for the equivalent RGB LCD is also shown in thin lines for comparison.

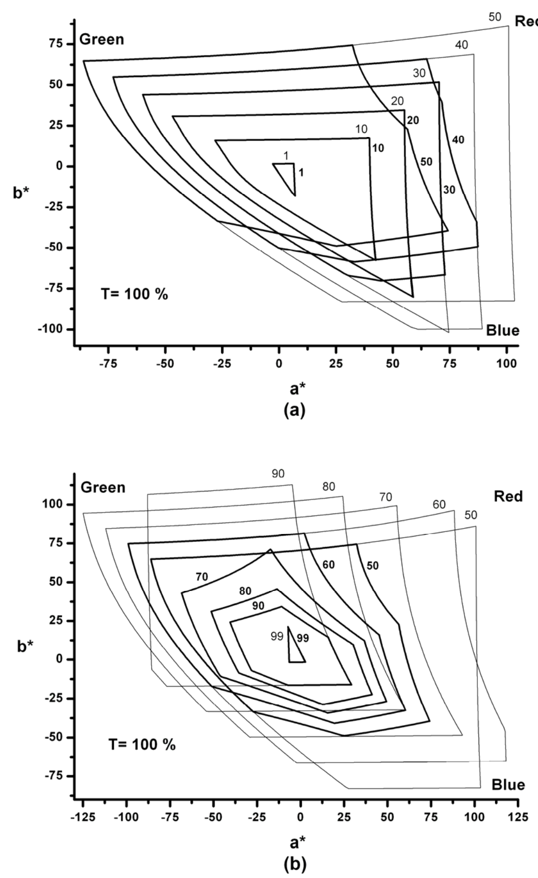

Fig. 5: Color gamut cross-sections of constant lightness (L*) in CIELAB color space for the RGBW LCD with the maximum transmittance of neutral sub-pixels *T* = 100%, where (a) L* ≤ 50, and (b) L* ≥ 50. The corresponding values of L* are shown near the boundaries of the cross-sections. The case for the equivalent RGB LCD is also shown in thin lines for comparison.

4. Results

In the following we assume Y_w= 100 cd/m^2; A = 1 m^2; γ = 0.8; C_i = 1 for i= r, g, and b; η_r= 0.298, η_g= 0.137, and η_b= 0.249, which are derived from the data sheet given in [7]. Figure 3 shows total power P_{et}, power saving ratio r_s, and neutral luminance ratio α versus the maximum transmittance T. The power saving ratio r_s= (P_{etRGB} - P_{et})/P_{etRGB}, where P_{etRGB} is the total power for the equivalent RGB LCD. The neutral luminance ratio $\alpha = TY_n / Y_w$, which represents the contribution of white luminance from neutral primary. One can see that power is not saved for T< 23% because the factor m= 3 in Eq.(2) for the RGB LCD. For the case with T= 100%, r_s= 45.9% and α = 59.5%. Although power can be saved about a half when T= 100%, the neutral luminance contributes about 60%. For this case, the color appearance will be significantly de-saturated because the luminance values of RGB primaries decrease as the luminance value of neutral primary increases under the requirement of white luminance. This effect can be clearly observed from the display color gamut represented in CIELAB color space.

Figures 4 and 5 show the color gamut cross-sections of constant lightness (L*) in CIELAB color space for the RGBW LCDs with T = 45.5% and 100%, respectively. The case for the RGB LCD is also shown in thin lines for comparison. For the case with T = 45.5%, r_s= 20% and α =40%. From Fig. 4, we can see the de-saturation in red, green, and blue color regions for the lightness L* larger than 40, 70, and 20, respectively. From Fig. 5, we can see the de-saturation in red, green, and blue color regions for the lightness L* larger than 30, 60, and 20, respectively. Because the maximum luminance value of blue primary is the smallest among RGB primaries under white point condition, the color saturation in blue region is reduced the most significant when the luminance value of neutral primary increases. The maximum luminance value of green primary is the largest among RGB primaries. The color saturation in green region is reduced the least when the luminance value of neutral primary increases. However, if the color saturations of RGB primaries are high enough in the absence of neutral primary, the color appearance of the de-saturated display may be still acceptable.

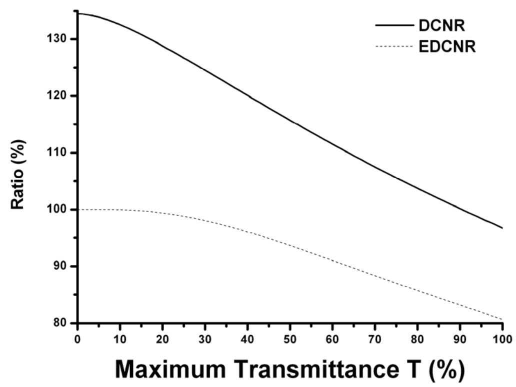

Fig. 6: *DCNR* and *EDCNR* versus the maximum transmittance of neutral sub-pixels.

Figure 6 shows *DCNR* and *EDCNR* versus the maximum transmittance *T*. From this figure, *DCNR*= 117.5% and *EDCNR*= 94.7% for the case with *T* = 45.5%; *DCNR*= 96.8% and *EDCNR*= 80.6% for the case with *T* = 100%. Because the relative gamut sizes *DCNR* and *EDCNR* are calculated with respect to the color gamut of HDTV, the color de-saturation of the case with *T* = 45.5% is acceptable, but may not be acceptable for the case with *T* = 100%. Therefore, the use of proper image processing technique to improve the color appearance of images is required.

For the considered RGBW display, a possible application scenario is to design the display that can be operated in three modes. The first is high color saturation mode: the maximum transmittance *T* is set to be 23%, in which *DCNR*= 127.6% and *EDCNR*= 99.1%. The power consumption of this mode is the same as that of the equivalent RGB display, in which *DCNR*= 133.7% and *EDCNR*= 100.0%. For the high color saturation mode, the color saturation of the display is less than that of the equivalent RGB display but is still higher than that of HDTV considering the larger *DCNR* and about the same *EDCNR*. The second is normal mode: the maximum transmittance *T* is set to be 23%, in which 20% power can be saved and the color saturation is about the same as that of HDTV considering the larger *DCNR* and the slightly smaller *EDCNR*. The third is power saving mode: the maximum transmittance *T* is set to be 100%, in which 45.9% power can be saved at the expense of smaller color gamut.

5. Conclusions

The relation of the color gamut size and power consumption of a RGBW LCD using RGB LED backlight is numerically studied. There are red, green, blue, and neutral sub-pixels in a pixel for the RGBW LCD. The maximum transmittance of neutral pixels is controlled by applied voltages for adjusting color gamut size and power consumption for a given white luminance. The results show that 0%, 20%, and 45.9% power can be saved with the maximum transmittance *T*= 23%, 45.5%, and 100%, respectively, compared with the equivalent RGB LCD. The color gamut size decreases as the maximum transmittance increases. It is found that the display can be operated in three modes: high color saturation mode (*T*= 23%), normal mode (*T*= 45.5%), and power saving mode (*T*= 100%). The color saturation of the display in high color saturation mode is higher than that of HDTV. The color saturation of the display in normal mode is about the same as that of HDTV. The color saturation of the display in power saving mode is less than as that of HDTV. Further optimization of LED spectral power densities and color filter spectra may improve the color saturation of the case with *T* = 100%.

Acknowledgment

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References

[1]H. Hasebe and S. Kobayashi," A full-color field sequential LCD using modulated backlight," SID 85 Digest, pp. 81-82, 1985.

[2]M. Baba, K. Taira, and H. Okumura," Field-sequential color display unit and display method," UP 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, "TFT-LCD with RGBW Color System," SID 03 Digest, pp.1212-1215, 2003.

[4]B. W. Lee, K. Song, Y. Yang, C. Park, J. Oh, C. Chai, J. Choi, N. Roh, M. Hong, and K. Chung, "Implementation of RGBW Color System in TFT-LCDs," SID 04 Digest, pp.111-113, 2004.

[5]C.-C. Lai and C.-C. Tsai, "A modified stripe-RGBW TFT-LCD with image-processing engine for mobile phone displays," IEEE Trans. Consum. Electron., vol. 53, pp. 1628-1633, 2007.

[6]S. Wen, "Design of relative primary luminances for four-primary displays," Displays, vol. 26, pp. 171-176, 2005.

[7]Technical datasheet DS56, Philips Lumileds Lighting Company, San Jose, California, 2008.

[8]M. Anandan," LED Backlight: Enhancement of picture quality on LCD screen," Proc. Of ASID'06, pp. 130-134, 2006.

[9]S. Wen," Display gamut comparison with number of discernible colors," J. Electron. Imag, vol. 15, pp. 043001-1- 0043001-8, 2006.

[10] S. Wen," Representations of relative display gamut size," to appear in IEEE/LEOS J. Display Technol, vol. 4, pp. 18-23, 2008.