Chapter 1

Introduction and Objective

Preface

Over the 70 years, displays were developed from cathode ray tube (CRT) to flat panel display, such as traditional transmissive-type liquid crystal display (LCD), plasma display panel (PDP) and even reflective LCD. The tendency of revolution is the lower weight and volume, the more colorful image, the higher image saving, and the more flexible substrate than before. Reflective LCD has been gradually used as mobile information display devices in terms of flexibility, weight and power consumption [1]. However, the image quality of reflective LCD is highly relevan upon the lighting, which is widely varied due to the spectral power distribution (SPD) at different environment.

Unlike the traditional transmissive-type LCD, whose color performance is mainly determined by the luminance of backlight and color filter, the optical characteristics of reflective display are highly relevant to the surrounding environment. That is to say, color rendering performances of the reflective LCD is acutely affected by the spectrum of the ambient light, which exhibits huge variations under different environmental conditions. Therefore, to comprehend the fundamental color theory, the base terminology of color will be mentioned in the first section. Then, chapter 1-2 will refer to the color variance of color object under the different light sources with the same chromaticity but different spectra. The concept in chapter 1-2 will be extended afterwards to reflective display, so chapter 1-3 will discuss the comparison of transmissive-type and reflective type LCDs. Finally, the main objective will be given in the last section.

1.1 Color Rendering Performances

Some fundamental expressions to represent the color performance are mentioned in this section. Before discussing the terminology of the fundamental color appearance, color sensations of human eyes are firstly introduced.

Optical information includes the luminance and color. The luminance sensation of environment is mainly decided by the photopic vision, and some formulas are used to predict the luminance sensation of human eyes ([3] Chapter 1.2). In addition to the luminance signals, color appearance is an important issue as well. The theme of color appearance is determined by the relative response from three kinds of cone cell in retina of human eyes. The three types of cones are referred to as L, M, and S cones, as shown in Fig. 1-1. [2] These names are referred to long, middle, and short wavelength sensitive cones, respectively. Therefore, human eyes can be regarded as a photoreceptor of visual light with four color filters based on different luminance and wavelength. [3]

There are countless colors in our daily life. It is hard to distinguish how dark is called navy blue or how light is referred to sky blue. Therefore, a precise method to evaluate color performance of an object is essential for color appearance

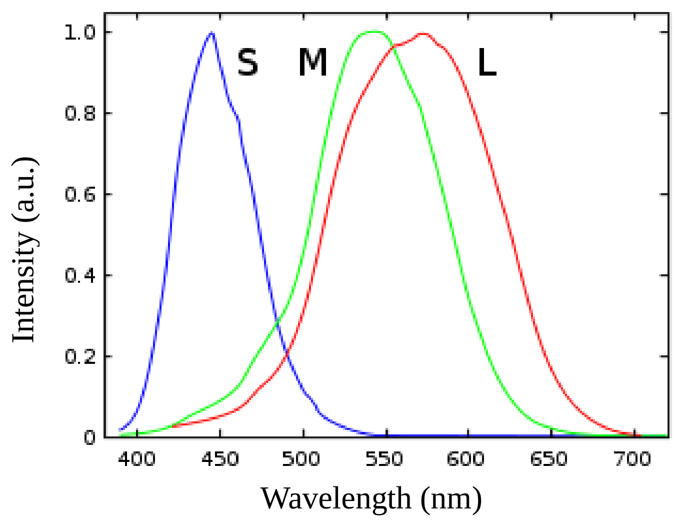

Fig. 1-1 Normalized responsivity spectra of human cone cells, S, M, and L cones

characterization. A problem in color rendering performance of color chips will occur under different lighting. When an object is viewed under illuminants of different spectral distributions, the perceived color remains approximately constant because of "color constancy". However, color appearance differs slightly from one illuminant to another because of the imperfect color constancy. The effect of different illuminants (from sun light to indoor illuminants) on the color appearance of object color is called "color rendering", and the color rendering for a light source is called "color rendering property". Moreover, Commission Internationale de I'Eclairage (CIE) compared the color appearance of object color under test light (For example: incandescent light) and reference light (For example: D65 light source) in 1974, and they estimated the level of appearance identity from both sources. The standard to evaluate the color rendering property is the "Color Rendering Index (CRI)". In this study, the concept of CRI is used to evaluate the color appearance of different lighting sources. Besides, different lighting sources are used to investigate the relation of the spectrum of light source and the reflective LCD.

1.2 Definition of "Equal White"

Color rendering performance of standard color chips will changed under different lightings even though these light sources have the same white point on chromaticity diagram. Therefore, the definition of the same white is discussed in this section.

Color attributed by human eyes is determined by combination of the SPD of light source, the reflectivity of the object color, and the color matching function as shown in Fig. 1-2. Because color matching functions are fixed under normal situation, color perceived by eyes is determined mainly by the spectrum of light source and reflectivity of object color. For the same object, spectra of source lightings become a key issue for color rendering performance. However, color render performance is relative to the consequence of product instead of the only spectrum of light source. Hence, different light source may induce the same color performance for the same reflectance and color matching function. Two light sources with the same white point (Which means "chromaticity coordinate" or "correlated color temperature (CCT)"), as shown in Fig. 1-3, illuminate to two same sets of color balloons. [4] It appears that two sets of the same color balloons have entirely different color performance under

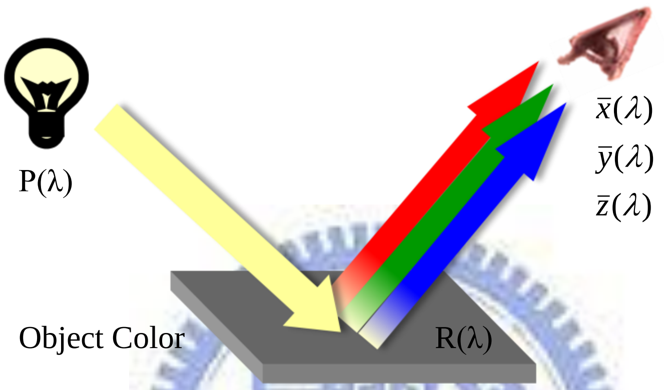

Fig. 1-2 Color induced from light source to human eyes

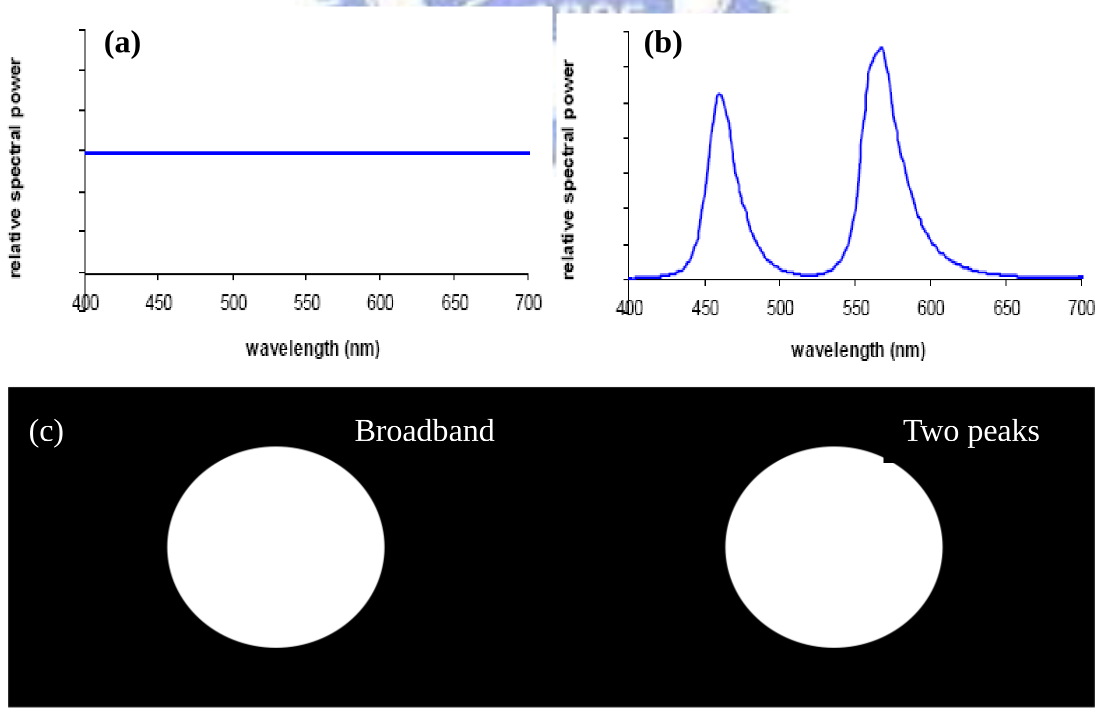

Fig. 1-3 Two light sources with the same white point (a) Broadband spectrum (b) Two peaks spectrum (c) Two sources seen by human eyes

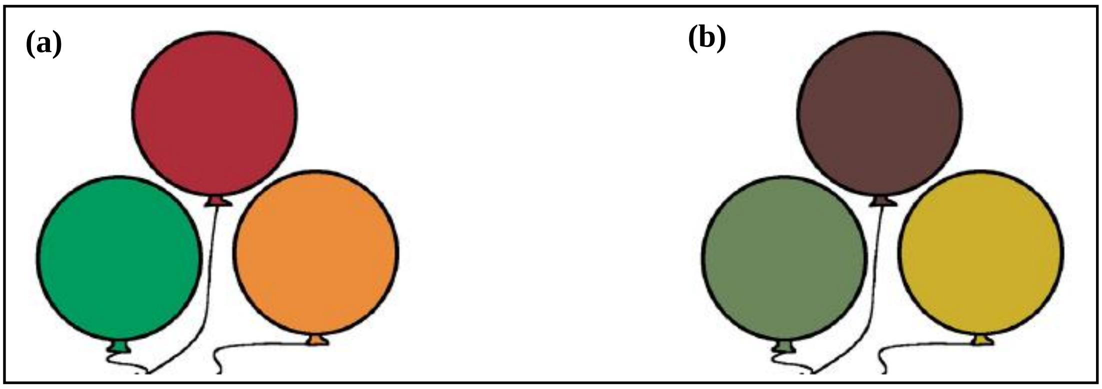

Fig. 1-4 Red, green, and orange color balloons under two different spectra of source lightings with the same whit point

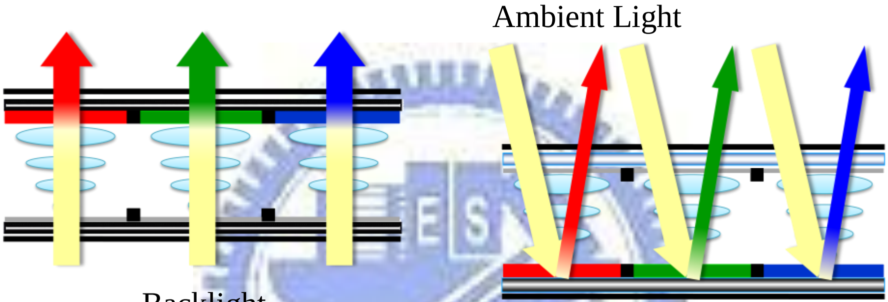

Fig. 1-5 The sketch of transmissive (Left) and reflective (Right) type LCDs

the two light sources with the same white point as shown in Fig. 1-4. Afterwards, two questions are derived from the concept of color shift issue in the previous description.

1. What if these color balloons are substituted into display, especially the reflective one?
2. Will the color shift phenomenon recuer to the reflective displays?

To explain why the reflective LCD was selected as the test platform in this thesis, next section will be the comparison of transmissive and reflectivetype LCDs

1.3 Transmissive and Reflective Type Displays

LC based displays can be separated into two parts, first one is the transmissive type LCDs, and the other is reflective type LCDs, as shown in Fig. 1-5. Both side emitting type and directly view type backlight systems of transmissive LCDs come with built-in backlight. Therefore, color performance of this kind of LCDs is mainly decided by the fixed built-in backlight and color filter, and it will waste power to turn on the backlight.

Nevertheless, color performance of reflective type LCDs rely on the environmental light, for example, the outdoor sun light or indoor cold cathode fluorescent lamp (CCFL). For this reason, it is much more sensitive to environmental light source but at the same time the character of needless backlight will save more power compared with transmissive type LCDs. Color performance of conventional transmissive type LCD mainly depends on the backlight and color filter subject to specific spectrum, so it is less sensitive to the environmental lightings. However, while the light source reflective type LCD is unconstant, so the chromaticity diagram will vary from different light sources. The input red image of display should be altered to orangey red as the input light source changed from high CCT of D65 light source to yellowish illuminant A. For this reason, we use two reflective display samples as a platform to test the effect of changed light sources on reflective displays, one is Cholesteric LC (Ch-LC) RGB color strips, and the other is the mobile transflective display. This relative information will be introduced in chapter 4.

1.4 Objective

In this study, the effect of various environmental lights on the reflective LCDs is discussed. Chapter 2 is the principle we of this essay, and chapter 3 is the fundamental standards of measurement. To make short of the matter, the evaluation standard of CCT for lightings may induce some problems on the color rendering property of light sources. Two light sources with the same CCT but different spectra may cause different color rendering performances. That is the main reason why CRI is used in lightings. However, CRI is not adequate enough when the light source are short bandwidth, such as light emitting diodes (LEDs) of popular environmental lightings. A new standard based on concept of CRI is used to solve the problem. Afterwards, the introduction of experimental setup and the result is given in chapter 4. The used Ch-LC test color strips and a transflective mobile display will be introduced in chapter 4, as well. Besides, narrow band and broadband spectra of light sources will be compared. Finally, chapter 5 is the discussion and conclusions.

A scheme is offered at the end of this chapter to illustrate the whole story of the thesis, as shown in Fig. 1-6. Higher color gamut and higher color rendering performance are the key issue in this study. In addition, it can be separated into three parts to discuss. One is the category of the reflective display, another is the variety of the light sources which can be classified according to the spectra, and the other is the evaluation standards to evaluate the color rendering performance.

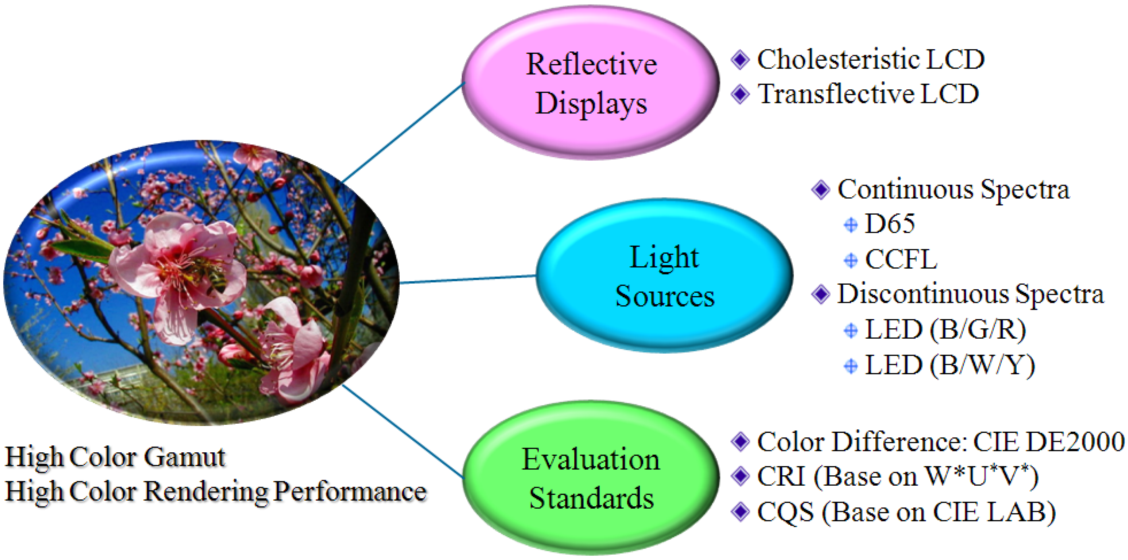

Fig. 1-6 Scheme of the thesis between images and the light sources for reflective displays in this research

Chapter 2

Principles

2.1 Color System

Color plays an essential role in our daily life. However, there are countless colors in our environment, so we often have difficulties in expressing color appearances. For instance, it is hard to describe the sky blue or the navy blue into details to others and distinguish how dark is the blue which is called navy blue. Especially for academic research, the qualitative description to recognize different color samples is very important. Therefore, the characterization of color became a key issue in colorimetry. Color specification needs a popularly accepted way to describe an attribute color, and the qualitative values are called "color specification values."

Table 1-1 Comparison between color appearance system and color mixing system

Color Systems	Color Appearance	Color Mixing
Category	Perceived color	Psychophysical color
Principle	Color appearance of standard color chips	Color mixing of light
Object of expression	Color of object	Color of light
Typical specification	Munsell	CIE
Specification Values	Color appearance values(e.g. hue, lightness, chroma)	Colorimetric values(e.g. tristimulus values)
Process for Color Expression	Visual color matching with standard color chips	Converting color stimulus functions into psychophysical values by color matching function

Color systems comprise "color appearance" and "color mixing". [5] Color appearance system is developed on the base of color perception, but is defined in terms of standard object color (for example, color chips) under specified condition. However, color mixing system is based on mixing chromatic light, which is used to match color to a reference one in a color mixing experiment. Both color appearance system and color mixing system are compared in table 1-1 and will be further introducing in the following.

2.1.1 Color Appearance System (Munsell Color System)

Color appearance system is based on subjective psychophysical perception, and the subject color is called perceived color. Perceived color usually includes the texture of the surface, the distance between object and detector, and the environmental conditions (For instance, the reflected and the transmitted condition), etc. We do not pay attention to distinguish the surface color of reflected light and transmitted color of transmission. Color appearance is the main topic in this section.

One thousand different color chips are classified by some orders in color appearance system. These classification methods are "Hue", "Lightness", and "Chroma", respectively. Some names of red, green, blue, etc., different kinds of colors, are called hue. On the other hand, there are different levels of brightness and shade. For instance, one red hue can be classified into bright-red or dark-red. Therefore, these color chips are categorized by relative brightness and darkness, which means lightness. Moreover, the same lightness of red chips can still be discriminated from each other. Some red chips are vivid, and some are dull even though they have the same hue and lightness. Therefore, another classification which differs from lightness is called chroma.

Munsell color system is the most commonly used color appearance system, which is developed by an American artist, Albert Munsell in 1905, and the scale was improved by the Colorimetry Committee of the Optical Society of America (OSA) in 1930. Munsell color system uses cylindrical coordinate to configure the color chips. As shown in Fig. 2-1, Munsell color tree shows the fundamental classification principles of Munsell color system. [6] Every page stands for different hues called Munsell hue (H), the radial direction represents saturation or Munsell chroma (C), and vertical axis shows the lightness of Munsell value (V). Besides, white, grey, and black colors are called achromatic color, and the color having hue is called chromatic color. Achromatic colors are arranged from V=0 (ideal black) to V=10 (ideal white).

Munsell color system is adopted by the Japanese Industrial Standards (JIS), and JIS set up color chips by the method of Munsell color system. Two kinds of color chips are obtainable, one with glossy surface and the other with matte surface. Chips of both types are made in the interval of H=2.5, V=1, and C=2. The glossy surface type has 1300 chips, and the matte surface has 1900 chips.

The inconvenience of Munsell color system is the limited numbers of chips, and

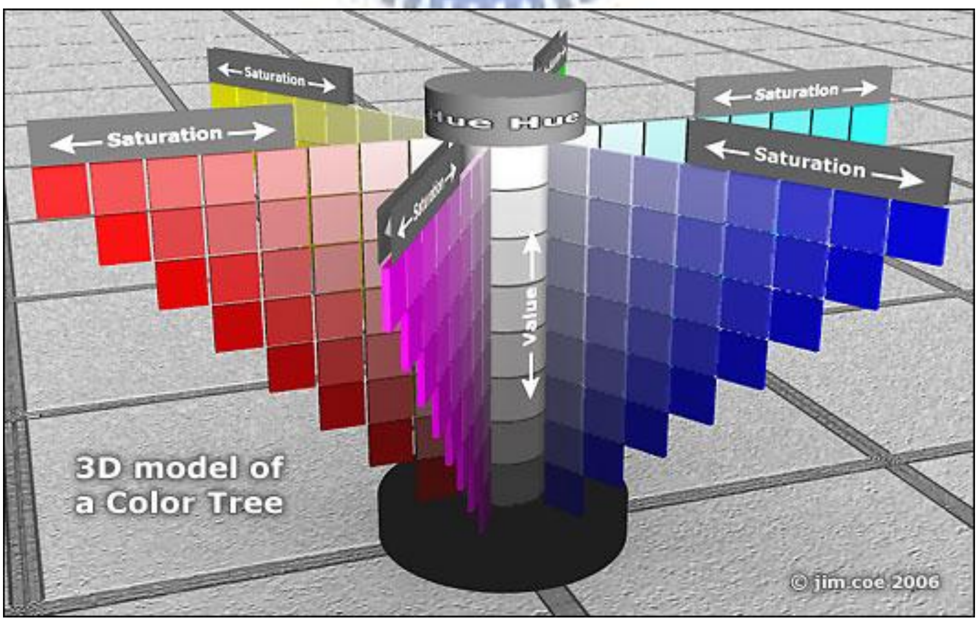

Fig. 2-1 Munsell color tree

it will induce the mismatch between the color chip and test color specimen. Therefore, the Munsell notation of the specimen needs to be evaluated by interpolating between neighboring chips to infer the Munsell value. However, the accuracy of Munsell value will be degraded in the interpolating method. Furthermore, to obtain the Munsell notation outside the region covered by the chips, the extrapolation will be used, but the precision of resulting value will be lowered under the extrapolation.

2.1.2Color Mixing System (CIE Color System)

We often deal with color without considering factors such as surround and surface texture in a color mixing system. Thus, the simplest attribute of perception is involved, and it is called color sensation. A color viewed through a dark aperture can be regarded as color sensation, and this kind of color is called color stimulus. Color mixing system is developed on the base of color stimulus, and it often uses three values to express the color stimulus, hence it is called trichromatic system. The three color stimuli are specified by the amount of three reference stimuli, usually red, green, and blue, and the spectral distribution of color stimulus is known as color stimulus function. Furthermore, tristimulus values are combined with color matching function and psychological spectral response of human eyes. That is why these values are thought of psychophysical values.

Random tristimulus values can be determined with the fixed color matching function, but it can still be changed with different color matching function. To solve the problem, CIE set up standard color matching functions in 1931 based on two principles. The first principle is that assigned reference stimuli [R], [G], and [B] are monochromatic lights with wavelength $\lambda_R = 700.0nm$, $\lambda_G = 546.1nm$ and $\lambda_B = 435.8nm$, respectively. The second principle is that the basic stimulus is the white color stimulus of equi-energy spectrum, and the amounts of reference stimuli

[R], [G], and [B] are in the ratio of 1.0000:4.5907:0.0601.That is to say, the equi-energy white light of 1.0000+4.5907+0.0601=5.6508 lm can match the reference stimuli [R], [G], and [B] with the ratio of 1.0000:4.5907:0.0601, and the color matching functions $\bar{r}(\lambda), \bar{g}(\lambda)$ and $\bar{b}(\lambda)$ referenced by the average data of Guild and Wright are shown is Fig. 2-2. Thus, the color can be matched by using reference stimulus. In normal trivial case, monochromatic light is too saturated to match the combination of reference tristimulus. For this reason, [R] is added into [F_λ] to lower the saturation, as shown in Equation 2-1.

$$[F_\lambda] + R[R] = G[G] + B[B] \quad (2\text{-}1)$$

Grassmann's Law can transform the equation into the following form

$$[F_\lambda] = -R[R] + G[G] + B[B] \quad (2\text{-}2)$$

The negative –R term is the reason which induces the partially negative value in color matching function. The color matching equation can be regarded as vector equation in 3-dimensional space with vector components [R], [G] and [B], as shown in Fig. 2-3. However, it is inconvenient to describe color [F] in three-dimensional diagram. Therefore, the intersection point (r, g, b) of vector [F] and unit plane

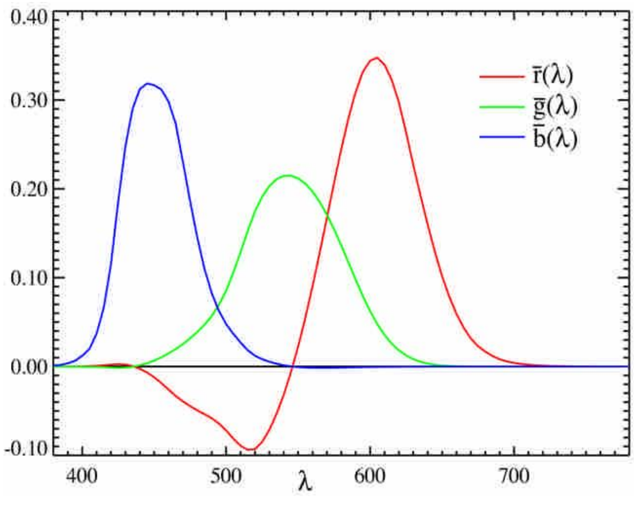

Fig. 2-2 Color matching functions $\bar{r}(\lambda), \bar{g}(\lambda)$ and $\bar{b}(\lambda)$ of CIE RGB color specification system

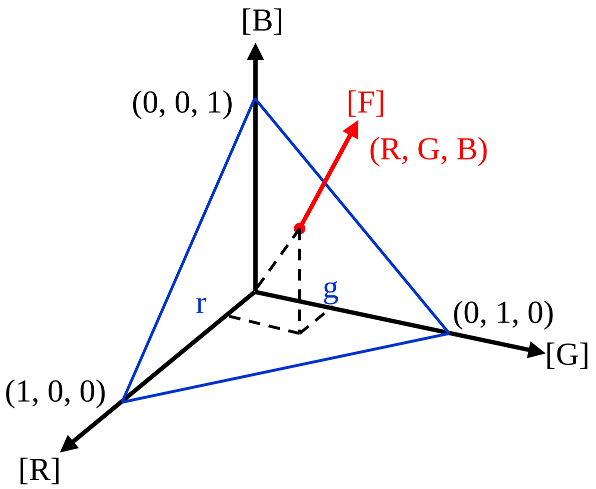

Fig. 2-3 Three-dimensional expression diagram of color [F]

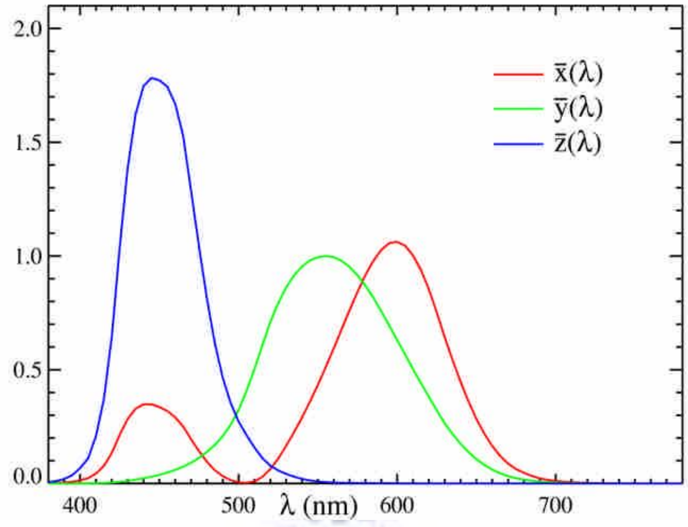

Fig. 2-4 Color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ of CIE XYZ color specification system

R+G+B=1 is used to expressed color [F], and (r, g, b) can be calculated by formula 2-3, and it is noted that r+g+b=1

$$r=R/(R+G+B)$$
$$g=G/(R+G+B) \qquad (2\text{-}3)$$
$$b=B/(R+G+B)$$

In the time of calculating tristimulus values manually, partially negative value of color matching functions in RGB color system will make the calculation much more complicated. To solve the problem of negative matching function, CIE set up a new reference stimuli [X], [Y], and [Z] in 1931, and the color matching is revised as shown in Fig. 2-4. Owing to the non-uniform distribution of cone cell in human eyes, XYZ color system can be separated into "CIE 2° Colorimetric System" and "CIE 10° Colorimetric System".

Tristimulus X, Y and Z of a color stimulus $\phi(\lambda)$ can be derived by calculating R, G, and B firstly and utilizing a transformation to change RGB into XYZ. Nevertheless, in general, tristimulus values are calculated by color matching functions $\bar{x}(\lambda), \bar{y}(\lambda)$ and $\bar{z}(\lambda)$, as shown in Equation 2-4

$$\begin{aligned} X &= k\int_{vis}\phi(\lambda)\cdot\bar{x}(\lambda)d\lambda \\ Y &= k\int_{vis}\phi(\lambda)\cdot\bar{y}(\lambda)d\lambda \\ Z &= k\int_{vis}\phi(\lambda)\cdot\bar{z}(\lambda)d\lambda \end{aligned} \tag{2-4}$$

where, k is a constant, and the integral is taken in the visible light region. In addition, color stimulus $\phi(\lambda)$ is mainly determined by the spectrum of light source P(λ) and the reflectivity spectrum of reflective color object R(λ). Therefore, previous formula can be changed into the next form

$$\begin{aligned} X &= k\int_{vis}R(\lambda)\cdot P(\lambda)\cdot\bar{x}(\lambda)d\lambda \\ Y &= k\int_{vis}R(\lambda)\cdot P(\lambda)\cdot\bar{y}(\lambda)d\lambda \\ Z &= k\int_{vis}R(\lambda)\cdot P(\lambda)\cdot\bar{z}(\lambda)d\lambda \end{aligned} \tag{2-5}$$

where the constant k is defined as

$$k = 100/\int_{vis}P(\lambda)\cdot\bar{y}(\lambda)d\lambda \tag{2-6}$$

The constant is selected such that the tristimulus value Y equals to 100 for a perfect reflecting object.

As described in RGB system, the chromaticity diagram (x, y) are established by the intersection of color vector (X, Y, Z) and unit plane X+Y+Z=1 as follows

$$x=X/(X+Y+Z)$$

$$y=Y/(X+Y+Z) \tag{2-7}$$

Many color systems based on XYZ color system were developed on different purpose. For instance, CIE $U^*V^*W^*$ color space in 1964, $L^*u^*v^*$ and $L^*a^*b^*$ color spaces in 1976, and many others systems based on $L^*a^*b^*$ color space. [7]

2.2 Color Difference

To quantify the variation of two stimuli, color difference formula is defined to express Euclidean distance between the coordinates for the two stimuli. According to different color spaces, color differences have various formulas with the similar form. Color difference correlates closely with lightness, chroma, hue angle, and hue difference, and the correlates of certain perceived attributes of color and color difference can be calculated in CIELAB or CIELUV color space. [3, 5] The expression in terms of a CIELAB ΔE^*_{ab}, which can be calculated by using Equation 2-8.

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{2-8}$$

where three terms in the equation is defined as

$$\Delta L^* = L^*_1 - L^*_2$$

$$\Delta a^* = a^*_1 - a^*_2 \tag{2-9}$$

$$\Delta b^* = b^*_1 - b^*_2$$

Color difference can still be expressed in the viewpoint of lightness, chroma, and hue difference as illuminated in Equation 2-10 by using the combination of Equation

2-8 and 2-11

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2]^{1/2} \qquad (2\text{-}10)$$

$$\Delta H^*_{ab} = [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2]^{1/2} \qquad (2\text{-}11)$$

To improve the uniformity of color difference measurements, modifications to CIELAB ΔE^*_{ab} equation have been made upon various empirical data. The CIE has evaluated such equations, and the available visual data, recommending a new color difference equation for industrial use. This system for color difference measurement is called CIE 1994 (ΔL^* ΔC^*_{ab} ΔH^*_{ab}) color difference model with the symbol ΔE^*_{94} and abbreviation CIE94. In addition, CIE 94 has a standard form of color difference as shown in Equation 2-14, and the standard viewing conditions are defined as Equation 2-15.

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*}{k_H S_H}\right)^2} \qquad (2\text{-}12)$$

$$S_L = 1$$

$$S_C = 1 + 0.045 C^*_{ab} \qquad (2\text{-}13)$$

$$S_H = 1 + 0.015 C^*_{ab}$$

Numerous color difference systems with different coefficient k and S are developed under the foundation of Equation 2-14. The parametric factors, k_L, k_C, and k_H are used to adjust the relative weighting of the lightness, chroma, and hue components, respectively, of color difference for various viewing conditions and application that depart from the CIE 94 reference conditions which defines all k values equal to 1. On the other hand, the weighting functions S_L, S_C, and S_H are used to improve the perceptual uniformity of CIELAB.

Except for the CIE94, CIE has established the CIE DE2000 color difference equation that extends the concept of CIE 94 with further complexity. [8] While the CIE DE2000 equation certainly performs better than CIE94 for some data, its added complexity is probably not justified for most practical applications.

CIEDE2000 color difference (ΔE_{00}) is modified from CIE94 ΔE^{*}_{ab} as introduced in chapter 2.2, but an extra term ΔR is added to correct the nonuniformity of the discrimination ellipses in $a^{*}b^{*}$ diagram. [8, 9] The ΔE_{00} formula is expressed as Equation 2-14, and the calculation method of constant is expressed in the range of Equation 2-15 to Equation 2-29.

$$\begin{aligned}\Delta E^{*}_{00} &= \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + \Delta R} \\ &= \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}\end{aligned} \tag{2-14}$$

$$\Delta L' = L'_1 - L'_2 = L^{*}_1 - L^{*}_2 \tag{2-15}$$

$$\Delta C' = C'_1 - C'_2 \tag{2-16}$$

$$\Delta H' = 2C^{*} \sin\left(\frac{\Delta h'}{2}\right) \tag{2-17}$$

$$S_L = 1 + \frac{0.015(\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}} \tag{2-18}$$

$$S_C = 1 + 0.045\,\bar{C}' \tag{2-19}$$

$$S_H = 1 + 0.015\,\bar{C}' T \tag{2-20}$$

$$R_T = -\sin(2\Delta\theta) R_C \tag{2-21}$$

$$C' = \sqrt{a'^2 + b'^2} \tag{2-22}$$

$$a' = (1 + G)a^{*} \tag{2-23}$$

$$b' = b^{*} \tag{2-24}$$

$$G = 0.5\left(1 - \sqrt{\frac{\overline{C}_{ab}^{*7}}{\overline{C}_{ab}^{*7} + 25^7}}\right) \tag{2-25}$$

$$\left|\Delta h' = h_1' - h_2' = \tan^{-1}(b_1'/a_1') - \tan^{-1}(b_2'/a_2')\right| \le 180^\circ \tag{2-26}$$

$$\begin{aligned} T = {} & 1 - 0.17\cos(\overline{h}' - 30^\circ) + 0.24\cos(2\overline{h}') \\ & + 0.32\cos(3\overline{h}' + 6^\circ) - 0.20\cos(4\overline{h}' - 63^\circ) \end{aligned} \tag{2-27}$$

$$\Delta\theta = 30\exp\{-[(\overline{h}' - 275^\circ)/25]^2\} \tag{2-28}$$

$$R_C = 2\sqrt{\frac{\overline{C}'^7}{\overline{C}'^7 + 25^7}} \tag{2-29}$$

where k_L, k_C, and k_H are parametric factors k. These parametric factors account for the influence of specific experimental conditions on perceived color difference, and they are adjusted according to different viewing parameters such as textures, backgrounds, separations, etc. Generally, these values are assumed to 1 to simplify the condition. S_L, S_C, and S_H are weighting functions S. These weighting functions can improve the perceptual uniformity of *a* b** diagram. In addition, the R_T function play an essential role to improve the performance of color difference equation for fitting chromatic differences in blue region.

Whole story should be stated from the original *a* b** diagram. Luo and Riggprepared over 600 pairs of samples close to the color centers to do psychophysical experiments. Then, the color discrimination ellipses are generated as Fig. 2-5. Three evident trends can be obtained from the Fig. 2-5:

(1)Ellipses close to neutral colors are the smallest;

(2)Ellipses are larger and longer when chroma is increased;

(3)Most ellipses point towards the neutral point except for those in the blue region as the blue square in Fig. 2-5.

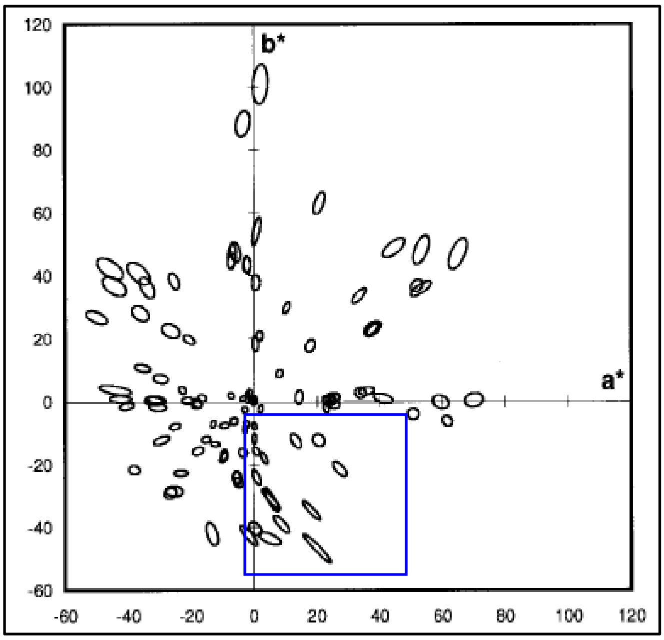

Fig. 2-5 Luo and Rigg experimental color discrimination ellipses plotted in *a* b** diagram

Afterwards, weighting functions S are used to make the discrimination ellipses to have the constant color difference, and the Rotation function R_T function is used to rotate the ellipses in the blue region point toward to the center.

2.3 Color Rendering Index (CRI)

As mentions in Chapter 1-3, the effect of various lightings on the reflective displays is the key issue in this study. Therefore, the standard of estimation for light sources is significant. In the past, the chromaticity coordinate or the CCT (T_c), which is derived from the corresponding absolute temperature on the Planckian locus, is used to characterize a quantified color property. Nevertheless, the imperfect effect of color constancy is hard to describe by using the chromaticity coordinate or the T_c. To solve the problem, color rendering index (CRI) is used to evaluate the level of keeping the color constancy between two light sources. CRI is recommended by CIE to express numerically the degree of matching of color appearance under a test light source with the color appearance under a reference illuminant, and the following will be descriptions of the reference illuminant and color sample.

In principle, T_c of test source should be equal to the T_c of reference illuminant. To do into details, when the T_c of test source is lower than 5000 K, a black-body radiator is used, on the other hand, when the T_c of test source is 5000 K or higher, a CIE daylight illuminant is used. In general, in either case, the reference illuminant used in the evaluation is one whose T_c is equal to that of the test source. For special purpose, a standard CIE illuminant or any other illuminant can still be adopted in the CRI measurement. Therefore, D65 of standard CIE illuminant is used in our experiment.

Except for the reference illuminant, these color samples used in the CRI measurement are designated as well. In normal situation, 14 color chips, as shown in Fig. 2-6, are chosen to compute CIE CRI, and they can be separated into two groups. Test colors 1-8 are corresponding to the V/C in the range of 6/4 to 6/8 for Munsell notations. These colors with medium lightness and saturation represent average object colors, so they are used to obtain an average color rendering index, known as General Color Rendering Index, for ordinary lightings. Test colors numbered 9-14 are used to obtain special color rendering indices and representative of important object colors.

Fig. 2-6 14 test color samples used in computation of CRI

Reference colors 9-12 are representations of high saturation colors, such as red, yellow, green, and blue colors, respectively. In addition, reference colors 13 and 14 standards for the skin color of white Caucasian people and the color of a typical green leaf, respectively. Sometimes, another color samples can be selected for specific purpose, such as the 15th test sample adopted by Japanese Industrial Standards (JIS) standards for the average face color of Japanese women.

For the computation of color difference, the following colorimetric values U^*, V^* and W^* according to the CIE 1964 uniform color space are used.

$$W^* = 25Y^{1/3} - 17$$

$$U^* = 13W^*(u - u_n) \qquad (2\text{-}30)$$

$$V^* = 13W^*(v - v_n)$$

where, u and v represent the chromaticity coordinates in the CIE 1960 UCS chromaticity diagram, and can be calculated from the tristimulus values X,Y and Z or the chromaticity coordinates x and y according Equation 2-31.

$$u = 4X/(X+15Y+3Z)$$

$$= 4x/(-2x+12y+3) \qquad (2\text{-}31)$$

$$v = 6Y/(X+15Y+3Z)$$

$$= 6y/(-2x+12y+3)$$

In general, the chromaticity coordinates of reference illuminant and test light source are different, but the color shift induced by the variance of chromaticity coordinates can be compensated by color adaption. Therefore, a series of correcting formulas are used to revise the color difference formula. The corrected formulas can express the chromaticity values U^*, V^* and W^* separately as shown in Equation 2-32.

$$W^*_{r,i} = 25(Y_{r,i})^{1/3} - 17$$

$$U^*_{r,i} = 13W^*_{r,i}(u_{r,i} - u_r)$$

$$V^*_{r,i} = 13W^*_{r,i}(v_{r,i} - v_r) \qquad (2\text{-}32)$$

$$W^*_{k,i} = 25(Y_{k,i})^{1/3} - 17$$

$$U^*_{k,i} = 13W^*_{k,i}(u_{k,i} - u_k)$$

$$V^*_{k,i} = 13W^*_{k,i}(v_{k,i} - v_k)$$

where the subscript r and k represent the reference illumination and test lighting, respectively, and subscript i standards for different test color samples. In addition, the tristimulus values $X_{r,t}$, $Y_{r,t}$ and $Z_{r,t}$, as well as $X_{k,t}$, $Y_{k,t}$ and $Z_{k,t}$, can be computed from the spectral distributions $S_r(\lambda)$ and $S_k(\lambda)$, where i=1,2,…,15. The color difference ΔE_i (i=1,2,…,15) according to the CIE1964 uniform color space are obtained from these values in accordance with Equation 2-33.

$$\Delta E_i = \{(U^*_{r,i} - U^*_{k,i})^2 + (V^*_{r,i} - V^*_{k,i})^2 + (W^*_{r,i} - W^*_{k,i})^2\}^{1/2} \qquad (2\text{-}33)$$

The special color rendering indices R_i for each test color are obtained by

$$R_i = 100 - 4.6\Delta E_i \qquad (2\text{-}34)$$

The coefficient 4.6 in Equation 2-20 was introduced by CIE so that the general color render index R_a, which is an average value of special color rendering indices for test colors 1-8, of warm white fluorescent lamp would be R_a=50 and is obtained by the following formula.

$$R_a = (\sum_{i=1}^{8} R_i)/8 \qquad (2\text{-})$$

From a theoretical point of view, there are several improvements that could make a progress on calculating the CIE color rendering index. For instance, a better chromatic adaption transform could be incorporated. However, such progress would cause changes in ratings that have become well established in practice so, to data, the

CIE has not recommended any changes.

2.4 Interaction of Reflectance and Illumination in Generating Color Return

Interaction between the spectra of light source and reflectance is the key point of discussion. Hence, the interaction which would result in stimulus of illumination, reflectance, and transmittance is discussed in this section. [10]

The spectral stimulus that confront human observers under most natural conditions are products of the reflectance of surface, the spectrum of the illuminant, and the transmittance of the intervening medium, as illustrated in Fig. 2-6. The spectral distribution of light in any stimulus necessarily conflates the contribution of these three factors as in the perception luminance. In Fig.2-7, a surface with a given reflectance efficiency function, which is illustrated as a simple sine wave, is illuminated by equiluminant spectra whose configuration is the same(1), the opposite(2), shifted toward long(3), and shifted toward short(4) wavelength comparative to the surface's reflectance. For comparison, the dashed line in the

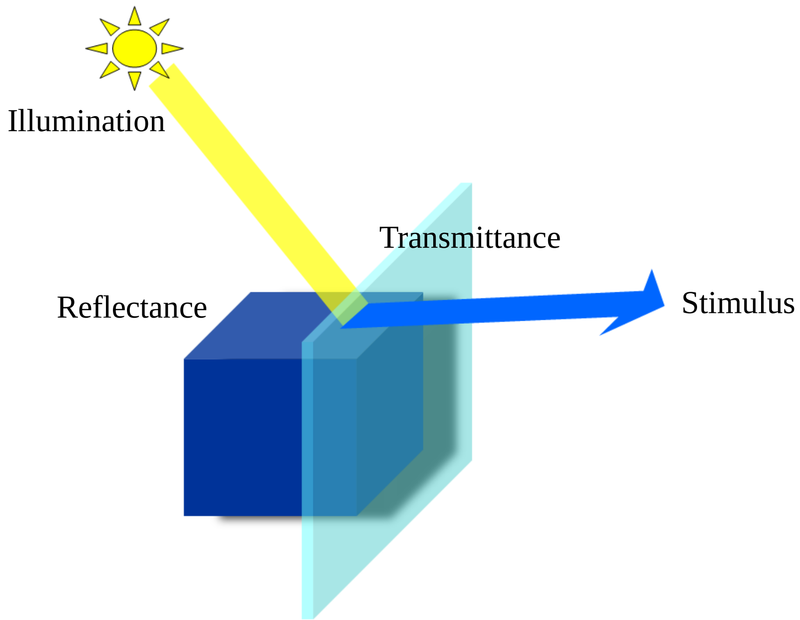

Fig. 2-6 Inevitable conflation of illumination, reflectance, and transmittance in the generation of spectral returns that elicit color sensations

diagram of illumination represents a white illuminant comprising a uniform distribution of wavelengths; for the sake of simplicity, the transmittance is assumed to be uniform. Note that the spectral returns given by the product of reflectance and the illuminants vary systematically relative to the return generated by the surface under the white light with uniform spectrum. The rules in Fig. 2-7 can be summarized as followings, and the effect is considered relative to the same surface under equally intense illuminant whose power is uniformly distributed:

1. A surface is illuminated by a spectrum which is similar to the reflectance of surface (as in graph 1 of Fig. 2-7): The intensity of the return from the surface is increased,

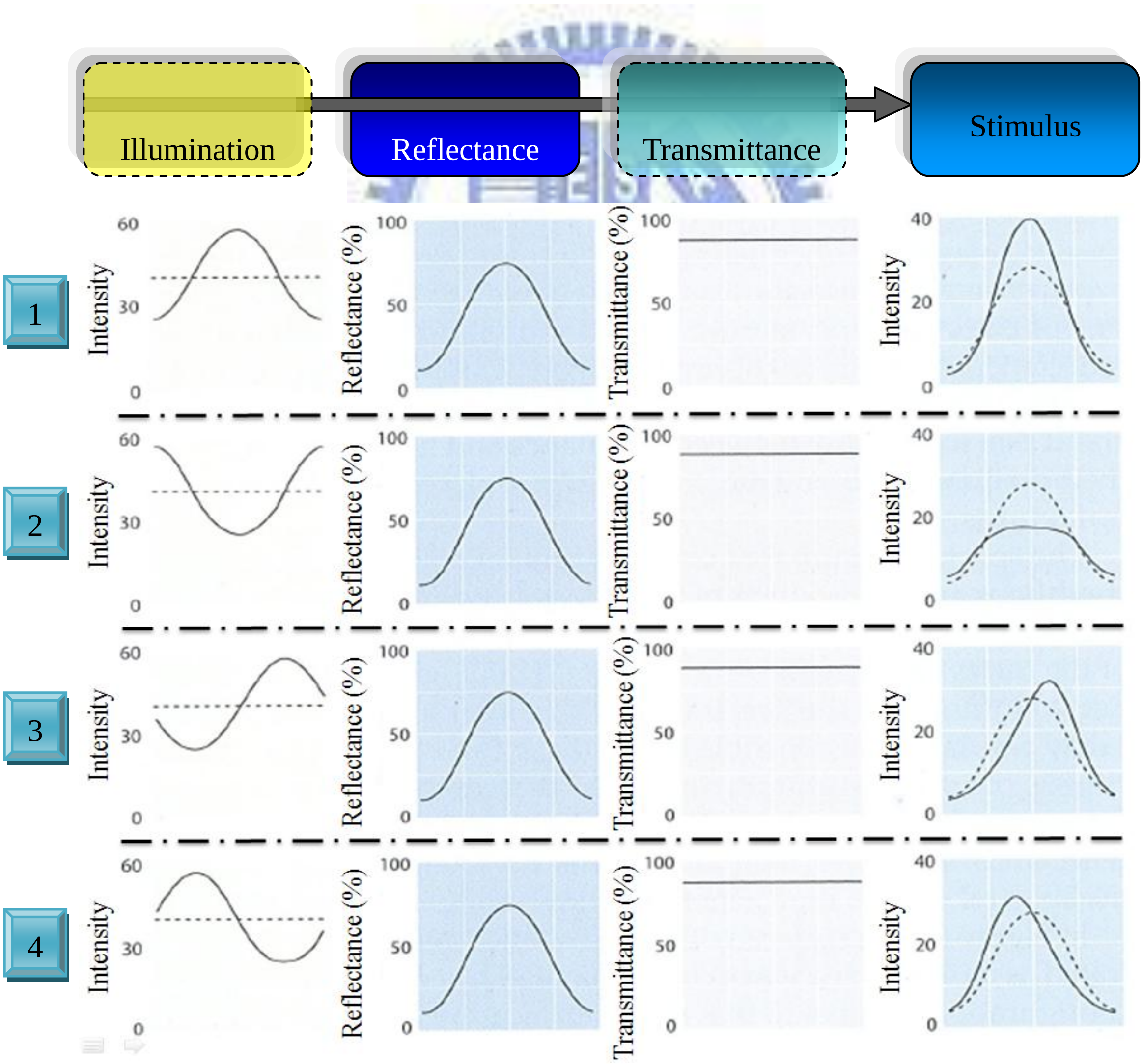

Fig. 2-7 The typical result of the interaction of reflectance, illumination, and transmittance in four cases

whereas the width of the distribution narrows. However, the location of the peak of the distribution is not much changed.

2. A surface is illuminated by a spectrum which is opposite to the reflectance of surface (as in graph 2 of Fig. 2-7): The intensity of return from the surface is decreased, whereas the width of the distribution broadens and flattens. Again, the location of the peak of the distribution is not much changed.

3. A surface is illuminated by a spectrum which is neither the same nor opposite in the reflectance of surface (as in graph 3 and 4 of Fig. 2-7): the power and width of the return are affected to an intermediate degree. Nevertheless, the location of the peaks of the power distribution in the spectral return becomes less relative to return from the same surface under white light illumination compared with graph 1 and 2. In other words, the spectral return shifts along the x-axis in the direction of te spectral profile of the illuminant.

In brief, all these effects are influenced by the width of the spectral distribution of the illuminant and the reflectance of the surface. In other words, the narrower the distributions of power in the illuminant relative to the reflectance efficiency function of the surface, the greater are all the effect described above.

Because these several rules describe the way spectral returns from surfaces must always be affected by different illuminants, they define the universal experience of observers with the relationship between reflectance, illuminants, and the spectra they generate. If spectral stimuli elicit percepts as a result of visual experience with the typical provenance of spectral returns, then when observer is presented with any stimulus, the colors that are perceived should accord with the predictions determined by these empirical relationships.

Chapter 3

Evaluation Standards

3.1Why Choose Lab Color Space

As the statement in Chapter 2.1.2, two essential color spaces coexist in the area of colorimetry. They are $L^*a^*b^*$ and $L^*u^*v^*$ color spaces, respectively. Why $L^*a^*b^*$ color space was chosen in this thesis instead of the $L^*u^*v^*$ color space?

CIE recommended $L^*a^*b^*$ and $L^*u^*v^*$ color spaces to calculate color performance. Furthermore, both of them have their own advantages, for example, $L^*a^*b^*$ has the comparatively uniform color space and it is capable of expressing the character of color constancy regardless of illumination, and straight lines in $L^*u^*v^*$ chromaticity diagram can readily express additive color mixture. Therefore, CIE $L^*a^*b^*$ is widely used in most color analyses, but CIE $L^*u^*v^*$ is commonly used in industrial fields that depends on the additive mixing of light, such as in color TVs, video monitors, etc.

In this study, $L^*a^*b^*$ color space was chosen as the chief color system in this study. In addition, the experiment confronted some problems when using $L^*a^*b^*$ color space, so an improved method brought up by Wendy Davis and Yoshi Ohno, which will be discussed in the next chapter in detail.[11]

To complete the contents of Chapter 2.2, color difference ΔE^*_{uv} , which is based on CIELUV color space, between two stimuli of (L^*_1, u^*_1, v^*_1) and (L^*_2, u^*_2, v^*_2) is introduced as Equation 3-1.

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \qquad (3\text{-}1)$$

where

$$\Delta L^* = L_1^* - L_2^*$$
$$\Delta u^* = u_1^* - u_2^* \qquad (3\text{-}2)$$
$$\Delta v^* = v_1^* - v_2^*$$

CIELAB and CIELUV have been widely used, mainly because it is relatively easy to relate colors as seen with positions on the diagram. The ΔE values are calculations of the distance between the standard and sample in these spaces. They are used for industries concerned with subtractive mixture (surface colorant) and additive mixture of colored light (TV), respectively. [12] While CIELAB color space was designed with a goal of having color differences be perceptually uniform throughout the space, which means a ΔE^*_{ab} of 1.0 for a pair of red stimuli is perceived to be equal in magnitude to a ΔE^*_{ab} of 1.0 for a pair of gray stimuli. However, this goal was not strictly achieved. Hence, color difference CIEDE2000 (ΔE_{00}) was developed to solve the problem, as introduced in the previous chapter.

3.2 Problems of CRI

Even though CRI is a comparatively commonly used index on evaluating the color appearance before, it still confronts by some problems on facing the more and more popular light source of light emitting diodes (LEDs), especially for the wavelength of red-band [13].

Two 3-in-1 RGB LED models having the same R_a value of 80 and CCT value of 3300K but different spectra as shown in Fig. 3-1. The dominant wavelength of 3-LED-1 are 457/540/605 nm, and the dominant wavelength of 3-LED-2 are

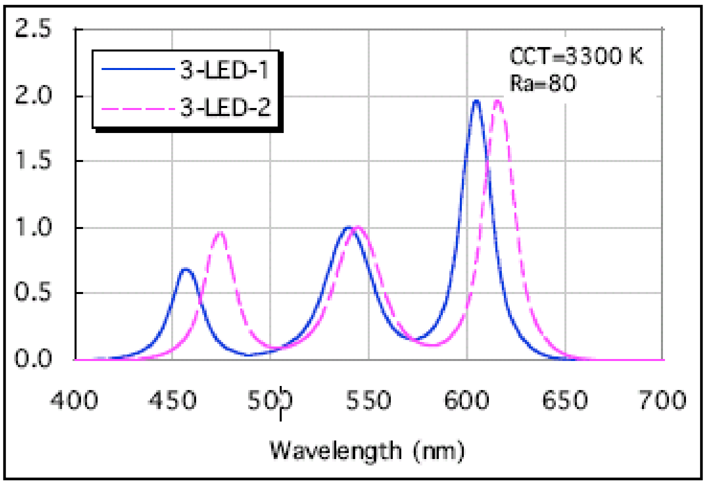

Fig. 3-1 The SPDs of the two 3-chip LED models both having *R*a=80 at 3300 K

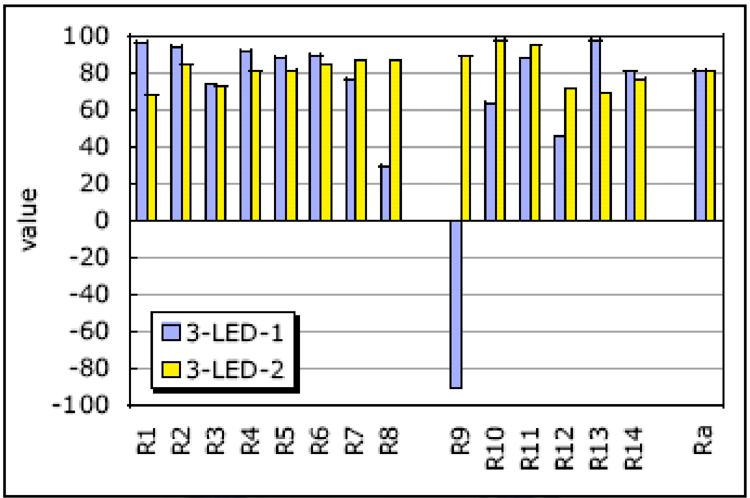

Fig. 3-2 Special CRI (R_1 to R_{14}) of the two 3-chip white LED models with the spectra of Fig. 3-1

474/545/616 nm. In addition, the shift of blue waveband is the largest, and the green waveband is the smallest. The special CRI, R_1 to R_{14}, of these 3-chip LED models are shown in Fig. 3-2. Both models have the same R_a value of 80, but 3-LED-1 exhibits very poor rendering of red (appearing brown) and $R_{9\text{-}12}$ only 27, whereas, 3-LED-2 exhibits good rendering of all the four saturated colors as well as the medium saturated colors. This is a case where the sources having the same *R*a can exhibit very different color rendering performance. This demonstrates that R_a is not trustable to judge the color rendering of 3-chip white LEDs and possibly also for conventional light sources with a few narrowband peaks.

Then, is $R_{9\text{-}12}$ a good indicator? Since saturated colors have sharp changes in spectral reflectance curves, $R_{9\text{-}12}$ may causes some irregular results with SPDs having large valleys between peaks in the spectral distribution curve. As a simple test, all the sample spectral reflectance data are shifted from –20 nm to +20 nm to examine the sensitivity of the results to small changes of color samples as shown in Fig. 3-3. As expected, $R_{9\text{-}12}$ is very sensitive to the wavelength shift of the samples while R_a is fairly stable. This means that, even if $R_{9\text{-}12}$ is good, color rendering of some other saturated colors (For instance, orange, purple, etc.) may not be accurately rendered (hue will shift).

There is always a contradiction between any kinds of CRI (For instance, R_a and $R_{9\text{-}12}$) values and color rendering performances. Therefore, National Institute of Standards and Technology (NIST) framed another evaluation standard which is named of "Color Quality Scale (CQS)". The principle of calculation is similar to the CRI, so CQS is denominated to differentiate from the CRI. Except for the CRI,

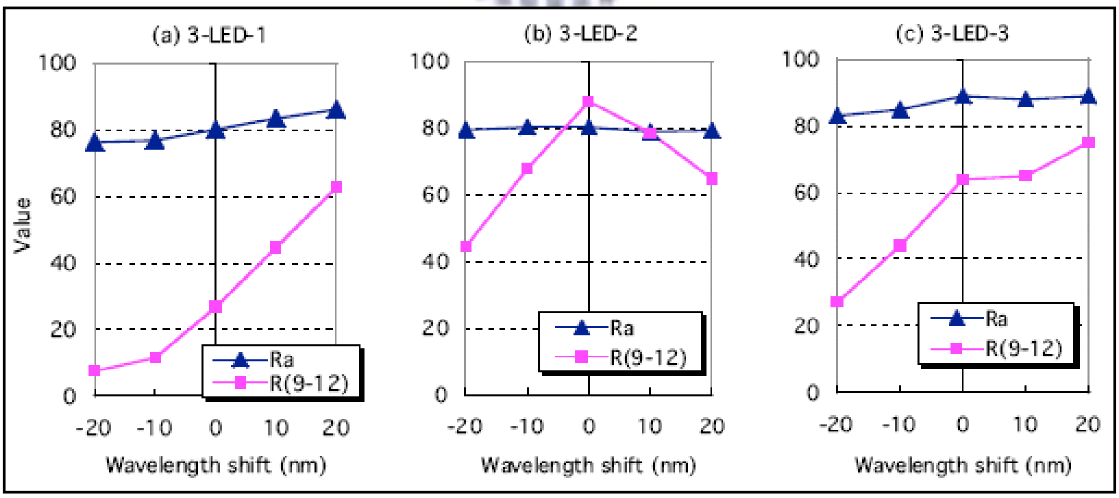

Fig. 3-3 The changes of R_a and $R_{9\text{-}12}$ of 3-chip white LED models when the wavelengths of the sample spectral reflectance data are shifted

fundamental concept of color difference is an essential element in this study as well, so CIEDE2000 (ΔE_{00}), which will be introduced in chapter 3.3, is chosen to judge the color difference.

3.3 Color Quality Scale (CQS)

Rather than an entirely re-invention, CQS is developed from the fundamental method of CRI, which is maintained and modified. The most significant change is to involve a deviation away from definition of color rendering. Rather than evaluate only color fidelity, this improved method is intended to evaluate overall color quality of light sources and is appropriately named Color Quality Scale (CQS) to avoid confusion with the CRI. [11] The altered contents of CQS are itemized as following.

1. New Test Color Chips:

One of the most serious problems of CRI is that some color rendering performances of saturated colors can be very poor even though R_a is good. For this reason, 15 high chromatic saturation colors spanning the entire hue circle are chosen to replace the 8 color chips in CRI. All are currently available Munsell samples of the following hue value/chroma: 7.5 P 4 / 10, 10 PB 4 / 10, 5 PB 4 / 12, 7.5 B 5 / 10, 10 BG 6 / 8, 2.5 BG 6 / 10, 2.5 G 6 / 12, 7.5 GY 7 / 10, 2.5 GY 8 / 10, 5 Y 8.5 /12, 10 YR 7 / 12, 5 YR 7 / 12, 10 R 6 / 12, 5 R 4 / 14, and 7.5 RP 4 / 12. These color chips are exhibited in in Fig. 3-4.

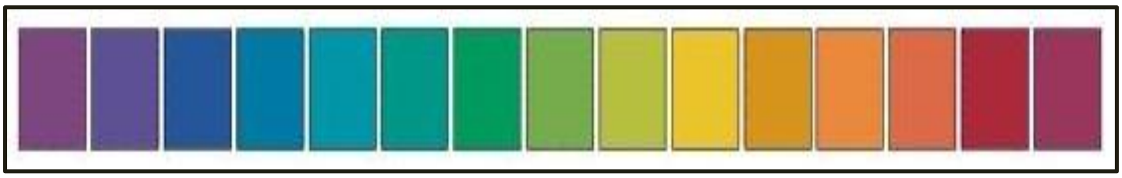

Fig. 3-4 15 Color chips used in Color Quality Scale (CQS)

2. Different Color System:

The $W^*U^*V^*$ color system used in CRI is obsolete because of the nonuniform color space. Color differences would be extremely exaggerated in the red region and suppressed in yellow and blue regions. CIE 1976 L*a*b*, which is abbreviated to CIELAB, is currently recommended by CIE and is widely used in many applications. In the CQS, the W*U*V* color space is replaced by the CIELAB for evaluating the color difference under the test and reference light sources.

3. Use of Root-Mean-Square (RMS):

Color difference is calculated by arithmetic average in CRI. However, arithmetic average may induce the good CQS score for a lamp, even when it renders one or two samples poorly. This kind of situation would be serious especially for the SPDs with narrowband spectra, for instance, the LEDs. The root-mean-square (RMS) is used to emphasize the influence of hue shift. The RMS formula of color difference for the 15 samples is shown as following.

$$\Delta E_{RMS} = \sqrt{\frac{1}{15}\sum_{i=1}^{15}\Delta E^2} \tag{3-3}$$

4. New CCT factor:

In CRI method, the CCT of reference source is matched to that of the test source. Hence, the CRI score is perfect for any CCT. In actual case, color rendering is degraded at extremely high or low CCTs. A set of temporary correct factors, which are based on the color gamut of 15 samples under the reference source for various CCTs, is developed because of the incomplete understanding on chromatic adaption, as shown in Table 3-1. Color rendering performance of reference source is assumed that it will degrade as the gamut area is decreased. The multiplication factors are the

Table 3-1 The color gamut of the 15 samples under reference sources with various CCT and the multiplication factors for each CCT.

CCT(K)	Gamut Area	Multiplication Factor
1000	2645	0.32
1500	5424	0.65
2000	6902	0.83
2500	7676	0.93
2856	7987	0.97
3000	8075	0.98
3500	8268	1.00
4000	8347	1.00
5000	8341	1.00
6000	8274	1.00
6500	8211	1.00
7000	8151	0.99
8000	8040	0.98
9000	7947	0.97
10000	7868	0.96
15000	7620	0.93
20000	7945	0.91

relative gamut area normalized at 6500K. In addition, certain CCT ranges are given the multiplication factors, which are lower than 1, to keep the CQS score lower than 100.

5. New Scaling Factors:

Currently, a new scaling factor (equals to 3.01) is chosen to make the average score of CQS for the CIE standard lamps (F1 through F12) be equal to the average score of the current CRI R_a (=75.1) as shown in Equation 3-4.

$$R_{CQS} = 100 - 3.01\Delta E_i \qquad (3\text{-}4)$$

6. Conversion to transform CRI into the range of 0-100:

Negative CRI values for some lamps are always confusing. Because the range of 0-100 would be better comprehended by users, keeping in the range of 0-100 is much more significant than the linearity for a color rendering scale. An equation of transformation is introduced to make sure the CQS values would be hold in the scope of 0-100, as shown in Equation 3-5.

$$R_{out} = 10 * \ln[\exp(R_{in}/10) + 1] \quad (3\text{-}5)$$

Where the R_{in} is the input value and the R_{out} is the output value of the conversion. The function (dash line) can transform the original CQS values (solid line) lower than 20 into the range of 0-100, as shown in Fig. 3-5.

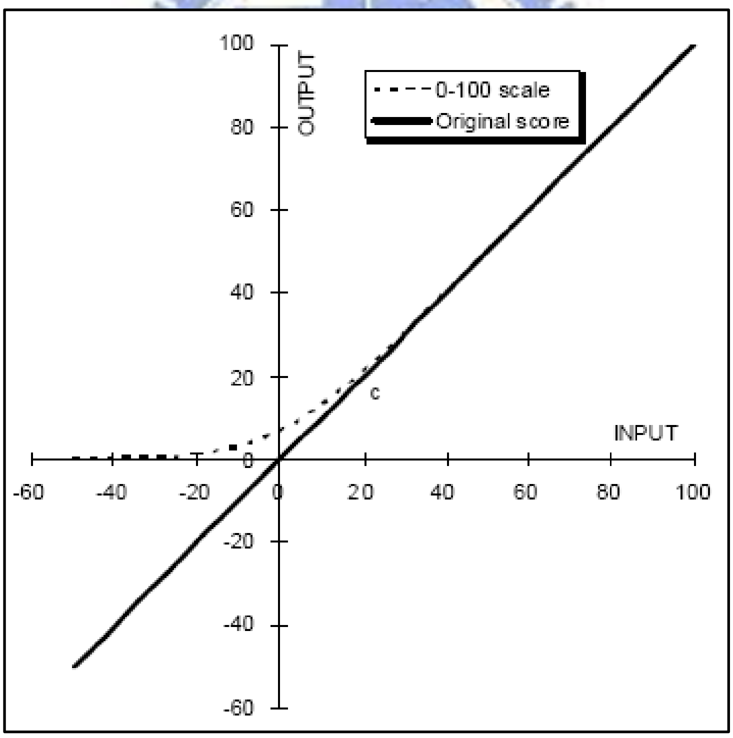

Fig. 3-5 The 0-100 scale function (- -) used to convert original scores (—)

Chapter 4

Experiment & Discussions

4.1 From Luminance to Illuminance

Luminance is the density of luminous intensity in a given direction and a given solid angle. Therefore, it is measured in the unit of cd/m^2. In addition, luminance is often used to characterize the emission from a diffuse light source. It indicates how much luminous power should be received by a detector when viewing the surface from a particular angle, which means the luminous power illuminated by the source per area and solid angle.

Illuminance means the photons which fall within a unit area of a given surface. It is measured in the unit of lux, or $lumens/m^2$. Illuminance is often used in lighting applications to measure the amount of light reaching an object such as a wall or a detector. The illuminance will decrease as the total area illuminated is increased even with the constant luminance intensity of the light source.

In brief, luminance is used to characterize the light source itself, and illuminance is used to specify the object reflected from the ambient light. Hence, this concept was used in this study to differentiate the color performance of the light source and the perceived color of reflective LCD. To evaluate the color performance of the light source, the evaluation standard for a reflective LCD is an essential issue especially for the LED.

LED became more and more popular with the time of energy saving because of the character of merit of thin body and low power consumption. Nevertheless, the narrowband-spectrum character of LED will easily lead to the mismatch between the spectra of the light source and the reflectivity of the display. The key issue in this thesis is induced by the description above. Two main targets are "Bring an evaluation standard into the area of the reflective LCD for the light source" and "Verify that the spectrum of light source has the essential impact on the reflective LCD and find a proper spectral recipe for the display." After the clarification of the topic, the next section is the introduction of the test platforms.

4.2 Two test platforms

Two displays were used as the test platform of the relation between the spectrum of the light source and the reflective display. They are the Cholesteric LC (Ch-LC) color strips and the commercially available transflective display, respectively. The following is the introduction of these two platforms.

4.2.1 Ch-LC Color Strips

The first test platform is the Ch-LC color strips made by the inkjet printing (IJP) process. Various colors can be formed by changed pitch of the LC, which means the reflective waveband is determined by the refractive index and pitch of LC. On the other hand, the reflective waveband of the Ch-LC can be varied by different chiral doping recipe of LC. The formula of reflective waveband is expressed in Equation 4-1 and Fig. 4-1.

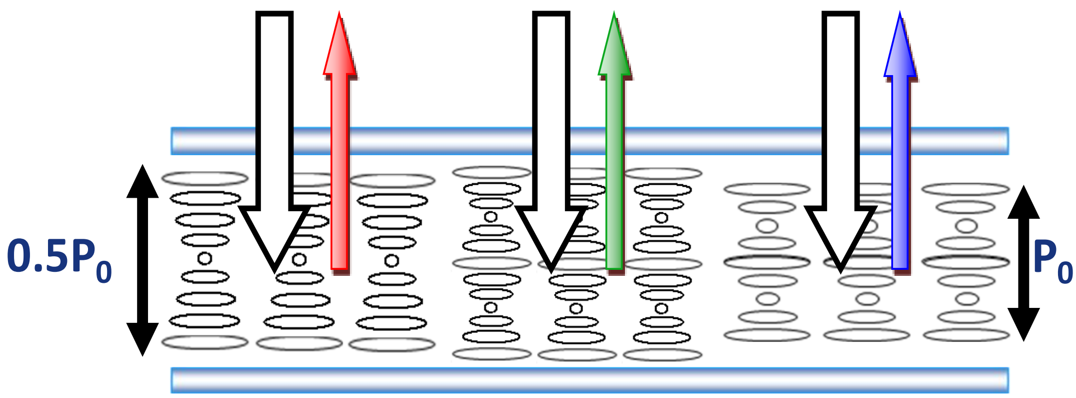

Fig. 4-1 Color formation diagram of Cholesteric LC

$$\lambda = P_{0\lambda} \cdot n_{LC} \tag{4-1}$$

There are three main color shift issues in the topic of Ch-LC as following: (1) Incident angle; (2) Viewing angle; (3) Spectrum. The previous two issues, which are expressed in Fig. 4-2, can be interpreted by Equation 4-1, but the spectrum problem had never been concerned before. Hence, the impact of the various spectra of light sources became a key issue in this study.

Different color perceived in the color strips of the thesis was manufactured by the IJP process without any color filter. In addition, this sample was made including the rubbing process instead of the scattering form as the large area billboard display made by Magink [14]. Hence, the color shift induced by various viewing angle, which exhibited highly color shift phenomenon especially for red color bar as shown in Fig. 4-3, is much more serious than the Magink's reflective Ch-LCD. To eliminate the color shift induced by viewing angle, perpendicular measuring angle was adopted. This Ch-LC color strips sample was used to verify that different spectra of light sources would lead to color various levels of color shift under these lightings.

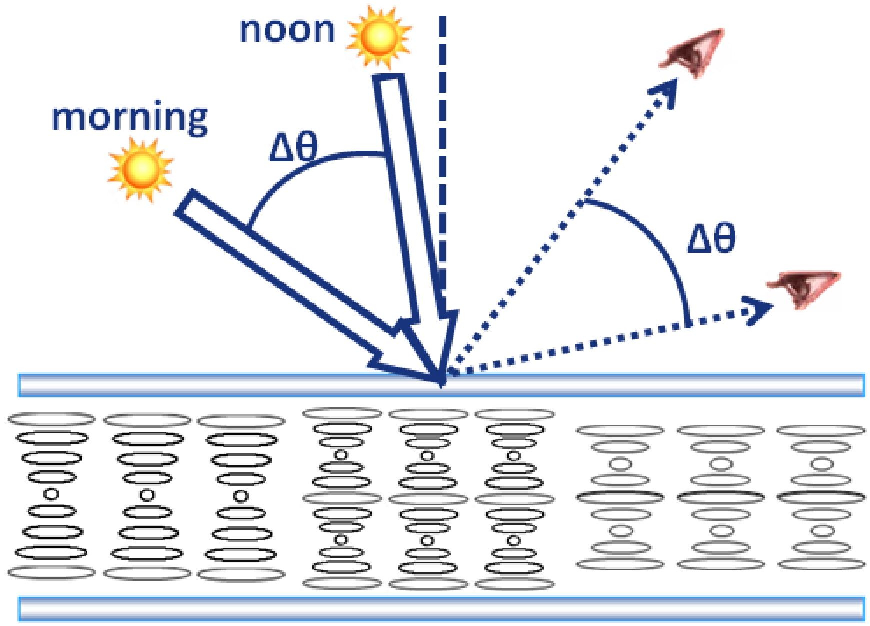

Fig. 4-2 Color shift issues of Ch-LC: The left hand side is the different incident angle of light source; the right hand side is the various viewing

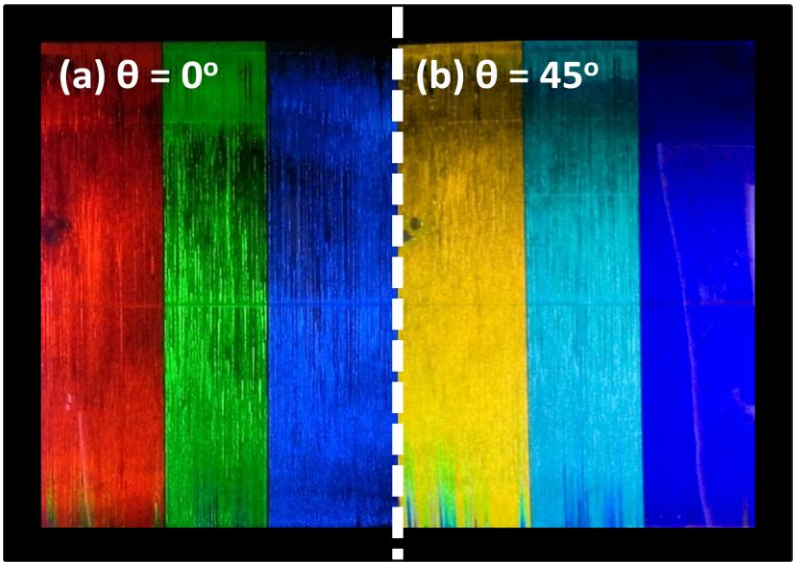

Fig. 4-3 Cholesteric LC R/G/B color strips in the normal and 45° viewing angle

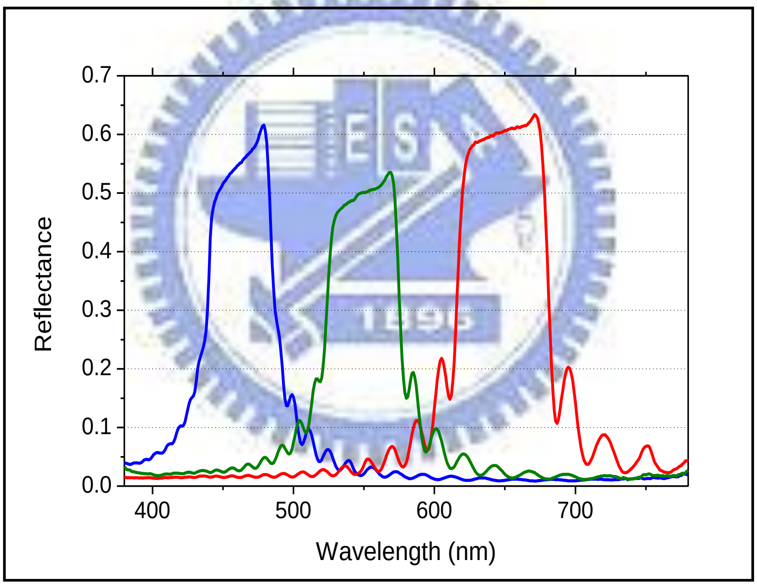

Fig. 4-4 Reflectance for the Ch-LCD sample of red, green, and blue color strips

Fig. 4-4 shows the reflectance of each color strip, and it can be used to compare with the spectra of light sources. In addition, the Ch-LC test sample in a dark room, where the incident lighting was fixed at 0.6 meter and 45° respect to the normal direction. In addition, the spectro-radiometer was in front of the sample, and the distance between the sample and spectro-radiometer is 1 meter, as shown in Fig. 4-5. After the setup is finished, we can use the computer to control the spectro-radiometer.

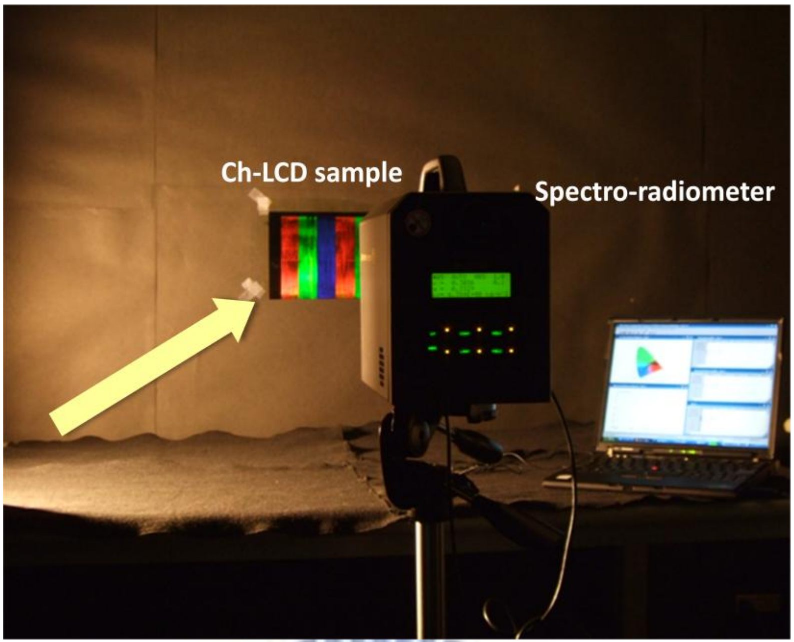

Fig. 4-5 Experimental setup: (1) Ch-LC color strips; (2) Spectro-radiometer; (3) Light source (30°); (4) Software

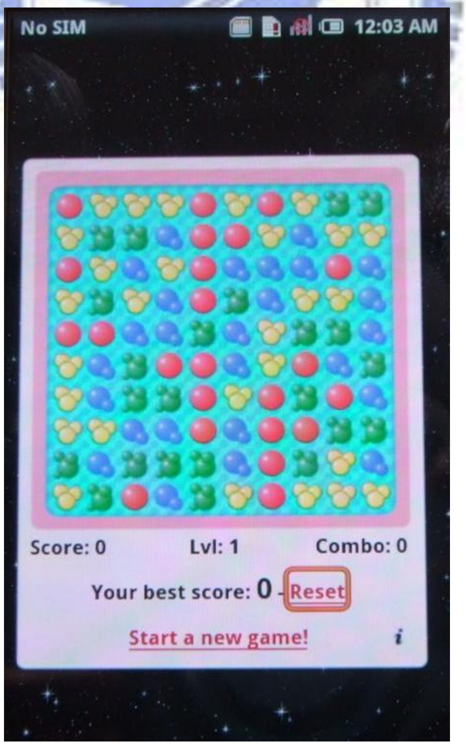

Fig. 4-6 Commercially available transflective panel of mobile phone

4.2.2 Transflective LCD

Except for the experimental test sample, a transflective panel of cell phone, as shown in Fig. 4-6, was used to ensure that the impact of spectra can exactly occur even for the commercially available display.

To evaluate the color performance of every light source in this thesis, 8 color chips used in CRI [Chapter 2.3] and 15 color chips used in CQS [Chapter 3.3] were reproduced on the panel of cell phone. A characteristic matrix was adopted to connect the digital signal R/G/B and tristimulus X/Y/Z. The tristimulus values were derived as the reference light source (D65) illuminated to the color chip first, and then the characteristic matrix was used to calculate the relative digital value. After this procedure, these color chips can be reproduced on the transflective panel. After that, the light sources illuminated to this sample to compare the color rendering performances are introduced in the next section.

4.3 Light Source Groups

This experiment was separated into two parts; the first part used two light sources with similar CCT to verify the color shift induced by varied spectra, and two set of light sources was designed to evaluate the color rendering performances further in the second part.

A set of Ch-LC color strips in this study was provided by ITRI (Industrial Technology Research Institute), Taiwan and illuminated by two commercially available lighting sources, where source 1 was 3-in-1 RGB LED cluster and source 2 was white LED with YAG phosphor plus U30 light tube [15-17]. To make the CCT of these two light sources close to each other, U30 light tube was added to white LED with YAG phosphor. Therefore, two different spectra of light sources with similar CCT can be achieved, as shown in Fig. 4-7.

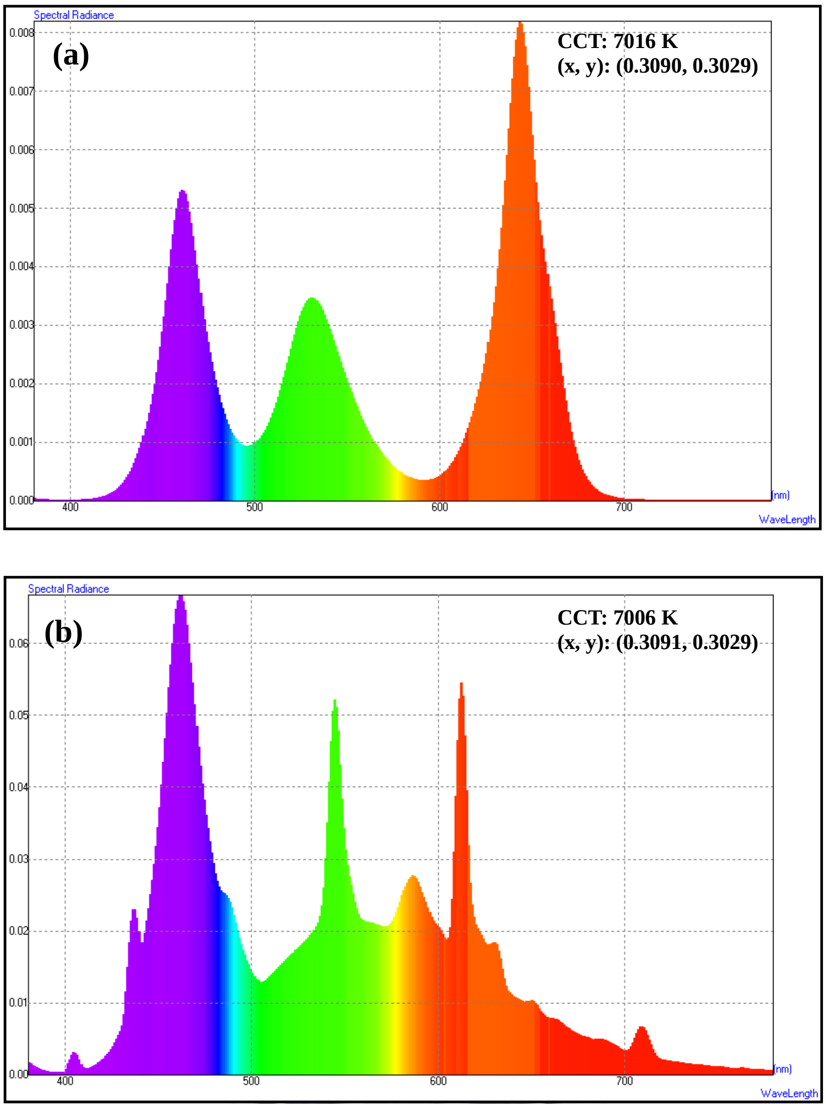

Fig. 4-7 The spectrums of different light sources: (a) 3-in-1 RGB LED cluster; (b) white LED with YAG phosphor plus U30 light tube

3-in-1 RGB LED cluster was selected as test light 1 which has three dominant narrowband peaks: 460nm, 530nm, and 640nm. In addition, white LED with YAG phosphor plus U30 light tube were selected as test light 2. LED with YAG phosphor mainly contributed to the wavelengths in blue and yellow region, where U30 light tube was introduced to resemble the white point with test light 1 and lead to the irregular valleys in the SPD.

The second set of light sources was classified into D65-group and CCFL-group.

Both groups had three kinds of light sources; they are the D65/CCFL of continuous spectrum, the combination of blue/green/red LEDs, and the combination of blue/white/yellow LEDs, respectively. D65 and CCFL were the light tubes in the

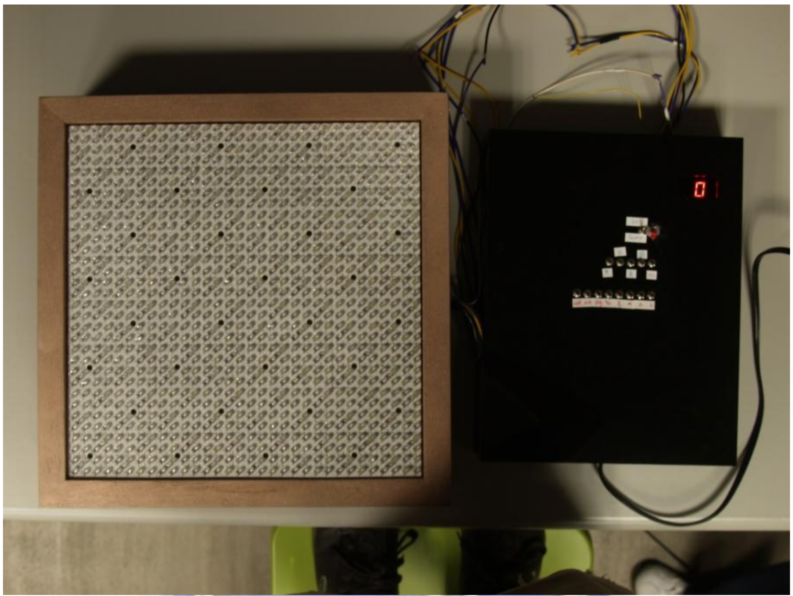

Fig. 4-8 LED cluster combined with R/G/B/Y/W LEDs

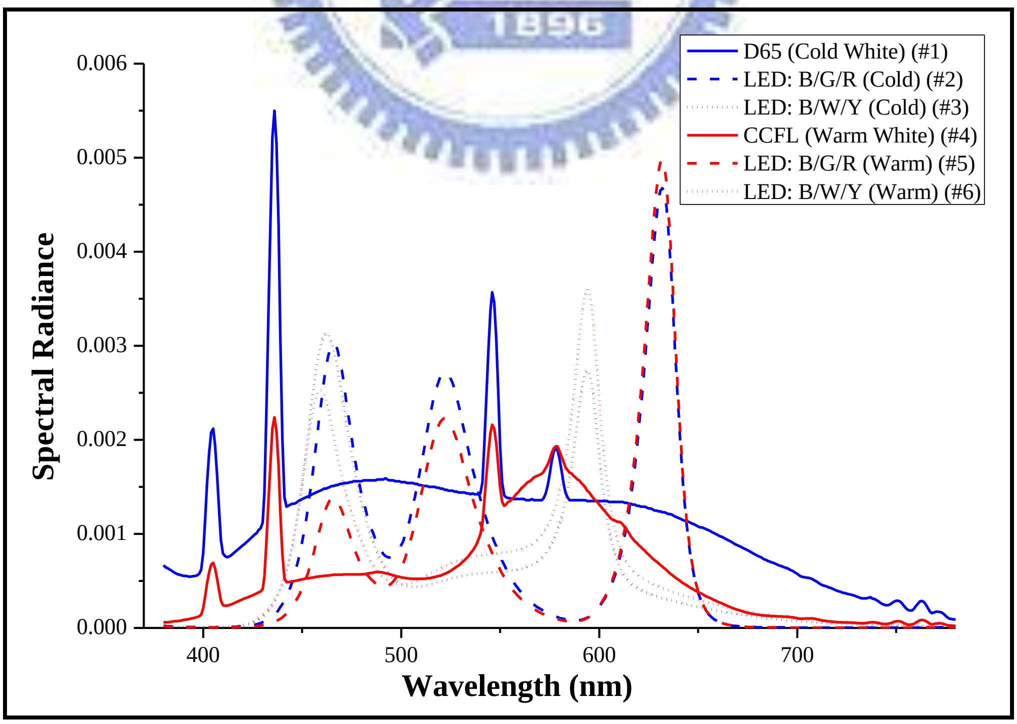

Fig. 4-9 Spectra of light sources: Blue line is for D65-groups; Red line is for CCFL-groups

lighting booth from Colorpilot Info-Tech Corporation [15], and the combination of LED clusters as shown in Fig. 4-8, which utilize PWM to establish different weighting of R/G/B/Y/W LEDs to constitute various spectra of light sources.

The spectra of all light sources were exhibited in Fig.4-9. The blue curve standards for D65-group, and the red curve stands for CCFL-group. In addition, solid line represents the D65/ CCFL, dash line represents the combination of B/G/R, and the dash and dot line represents the combination of B/W.Y. Besides, the CCT of D65-group was around 6700K, and the CCT of CCFL-group was around 4100K.

4.4 Experimental Result and Discussions

In the first part of the experiment, color performances of the Ch-LC color strips were shown in Fig. 4-10. The red strip of the three color bars suffered from the strongest yellowish effect.

With different SPDs of illumination, the color differences in R, G, and B color were 50.36, 30.55, and 13.83, respectively. It is noted that red color has the largest

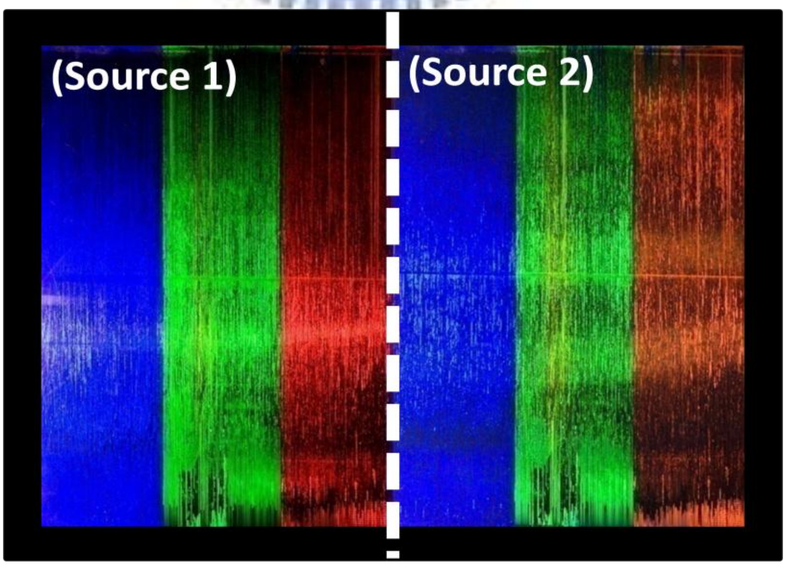

Fig. 4-10 Ch-LC color strips under the test source 1(3-in-1 RGB LED cluster) and test source 2(White LED plus U30 light tube)

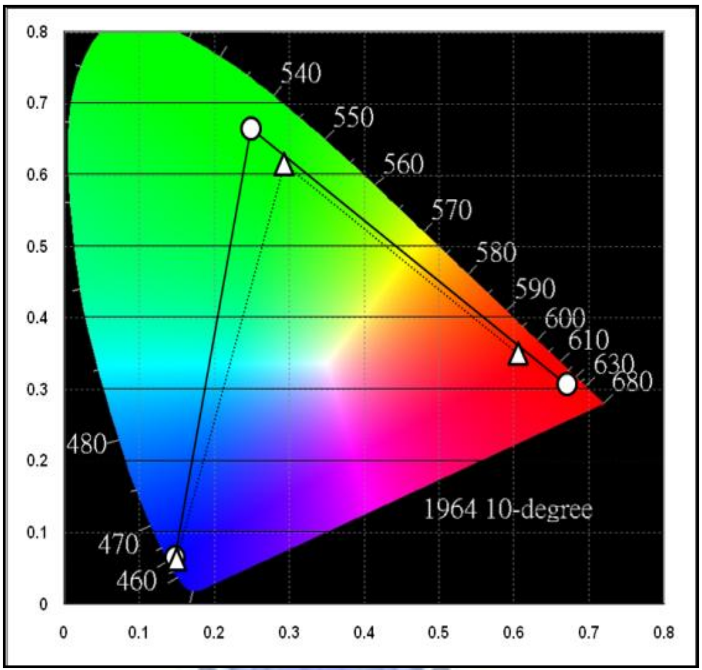

Fig. 4-11 Chromaticity of two different light sources: 3-in-1 LED cluster (○); white LED with YAG phosphor plus U30 (Δ)

color shift, as shown in Fig. 4-11. The results were in close agreement with the perception of human eyes. The spectral matching diagrams were plotted in Fig. 4-12 to compare the discrepancy of the spectra of the light source and the reflectance. The reflectance of red, green, and blue color-bars comparatively fit within the peak of the 3-in-1 RGB LED cluster. Furthermore, the spectra of the two test light sources had the relative peaks on green and blue regions. However, red bands of test light 1 and 2 have the entirely different curves. In other words, the reflective wavelength is not a monochromatic light; the spectrum of incident light does not certainly have the whole region of the reflective wavelength range. Therefore, the reflective light may have the various chromaticities even though the incident lights have the same white point.

Three main points can be derived from these two diagrams:

(1) The reflectance spectrum comparatively fit in with the peak of the 3-in-1 RGB LED cluster.

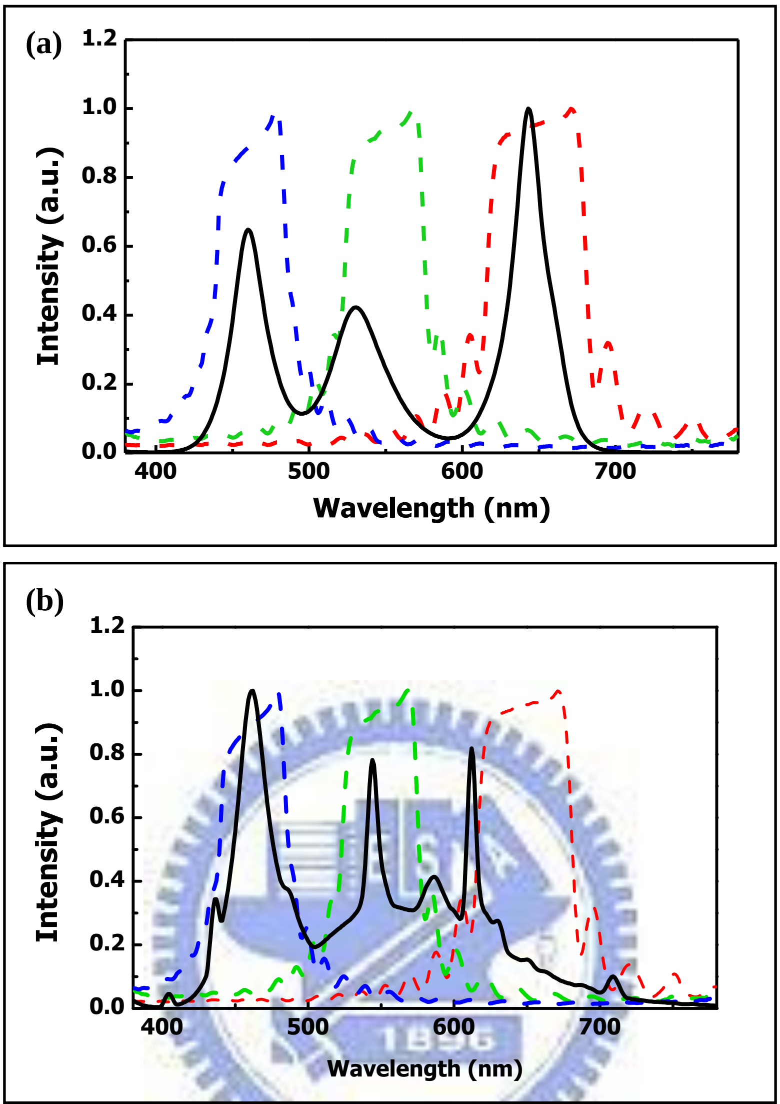

Fig. 4-12 Spectral matching diagrams of two test sources: (a) 3-in-1 RGB LED cluster; (b) White LED with YAG phosphor plus U30 light tube

(2) The spectra of two test light sources had the relative peaks in green and blue regions.

(3) Red bands of light source 1 and 2 had the entirely different curves under the reflectance of red color bar.

The interference can be deduced from the discussions: The more that spectra of reflectance and light source can match to each other, the better color reproduction of reflective light you can achieve. Besides, mismatched waveband will induce more color difference.

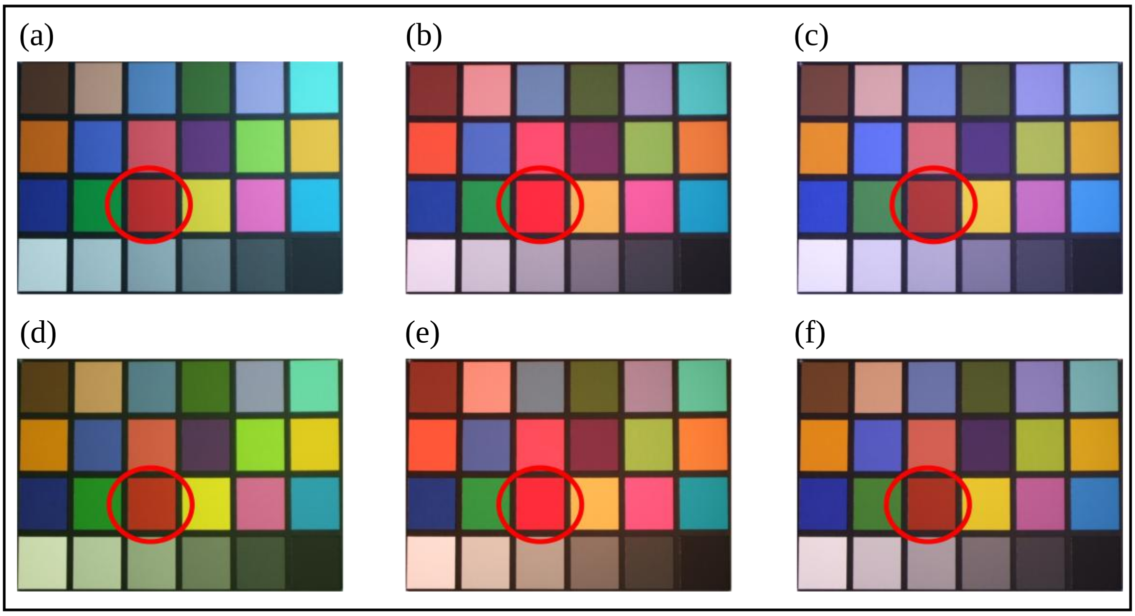

Fig. 4-13 Six test sources illuminated on the colorful dolls: (a) ~ (c) were D65-group; (d) ~ (f) were CCFL-group

After the initial proof of the color difference induced by the various spectra, the platform was transflective panel was used to reproduce the color chips to apply the evaluation standard of color rendering performance. Color checker were illuminated by six test light sources in this part of the experiment, as shown in Fig. 4-13. The cold white group of sources illuminated to the dolls in figure (a) to (c), and the warm white group of sources illuminated to the dolls in figure (d) to (f). It is notable that color performances would be different even with the same CCT of lights. This color shift phenomenon should occur as the color checker is changed into the transflective panel. To confirm the color shift effect would occur to the transflective panel, these light sources illuminated to the color with the same digital value R/G/B, as shown in Fig.4-14. In Fig. 4-14, (a) to (c) are illuminated by D65 (cold)/LED: B/G/R (cold)/LED: B/W/Y (cold) and (d) to (f) are illuminated by CCFL(warm)/LED: B/G/R (warm)/LED: B/W/Y (warm), respectively. The simple test can corroborate the color shift effect induced by not only CCT, but also spectrum,

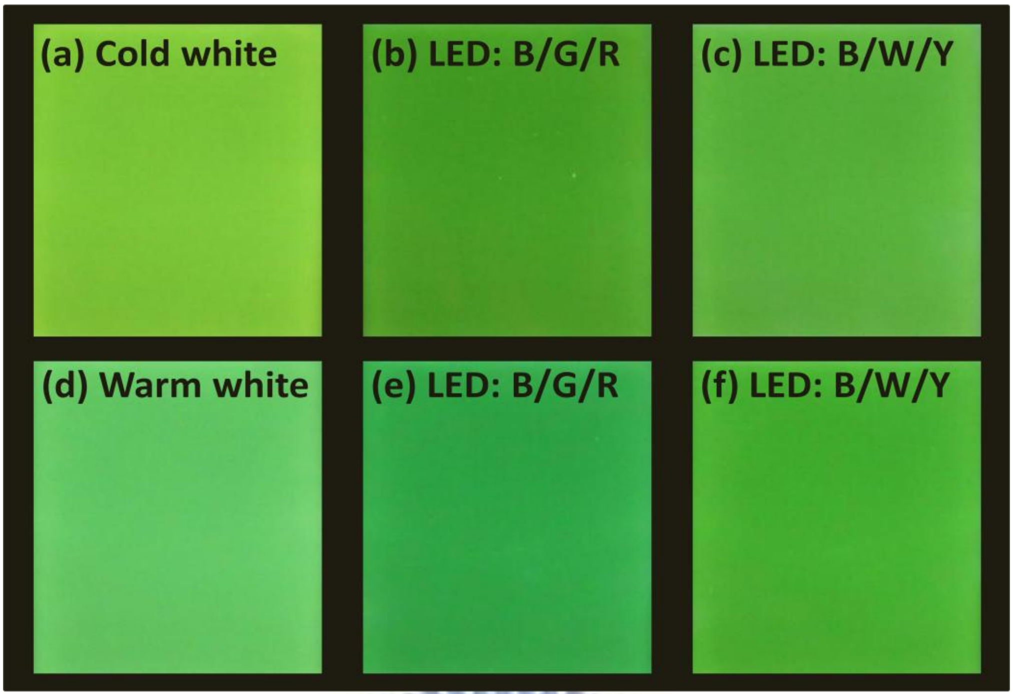

Fig. 4-14 Six test sources illuminated on the same green chip: (a) ~ (c) were D65-group; (d) ~ (f) were CCFL-group

Hence, the special CRI (R_1 to R_8), general CRI (R_a), and CQS were utilized to evaluate the color rendering of these sources. Table 4-1 summarizes the results from the measurements of these test sources, and it shows the general CRI-R_a, special CRI-R_1~R_8, and the other key parameters, such as illuminance (In the unit of "lux") and CCT.

A detailed analysis of the general and 8 special CRIs calculated for 5+1 (D65 was for reference) of the tested spectra was exhibited in Fig. 4-15 (a) and (b). As expected, higher level of spectral mismatch would lead to color shift or lower color rendering performance. The former four of the special CRIs showed extra low color rendering performances under source #3, as shown in Fig. 4-16. Take the third color chip (R_3) for example; light source #3 of R_3 had the lowest special CRI (=-333.39), and the spectral reflectance of the third chip had the most diversity form the spectrum of B/W/Y LED combination, as shown in (c) diagram of Fig. 4-16.

Table 4-1 Summarized results for 6 various spectra of sourced used in visual tests

	D65 #1	**LED (B/G/R: 60/49/91) #2**	**LED (B/W/Y: 28/37/65) #3**	**CCFL #4**	**LED (B/G/R: 28/41/96) #5**	**LED (B/W/Y: 3/39/71) #6**
lux	161	187	164	162	161	176
CCT	6734	6753	6783	4130	4135	4104
CRI		68.01	-105.34	-7.85	15.81	-27.20
x	0.3092	0.3068	0.3179	0.3803	0.3786	0.3624
y	0.3254	0.3372	0.2712	0.3952	0.3882	0.3199
R_a		68.01	-105.34	-7.85	15.81	-27.20
R_1		42.29	-109.71	-14.08	33.66	-24.97
R_2		54.71	-200.35	-47.18	-14.76	-34.18
R_3		53.89	-333.39	-89.11	-80.12	-51.12
R_4		65.38	-181.75	-27.56	4.90	-44.13
R_5		75.90	-53.82	18.88	41.30	-27.69
R_6		84.03	20.08	32.19	24.66	-18.54
R_7		84.75	17.91	35.15	47.94	-9.91
R_8		83.11	-1.68	28.95	68.87	-7.09
CQS		99.28	99.75	98.59	26.39	98.98

However, the CQS values for each test light source had comparatively stable value. At least the CQS value can perfectly controlled the evaluated level of color rendering in the range of 0-100, unlike the unstable values of CRI, which may be extra low and indirect sense for human cognition. It is notable that CQS had the smallest value as being under the test light #5. To investigate how does spectrum affect the color rendering performance, spectra of the highest (=99.75) and the lowest (=26.39) CQS values of sources were compared in the same diagram of Fig. 4-17 (a) and (b). Compared to test source #3, the spectral range covered by source #5 had a

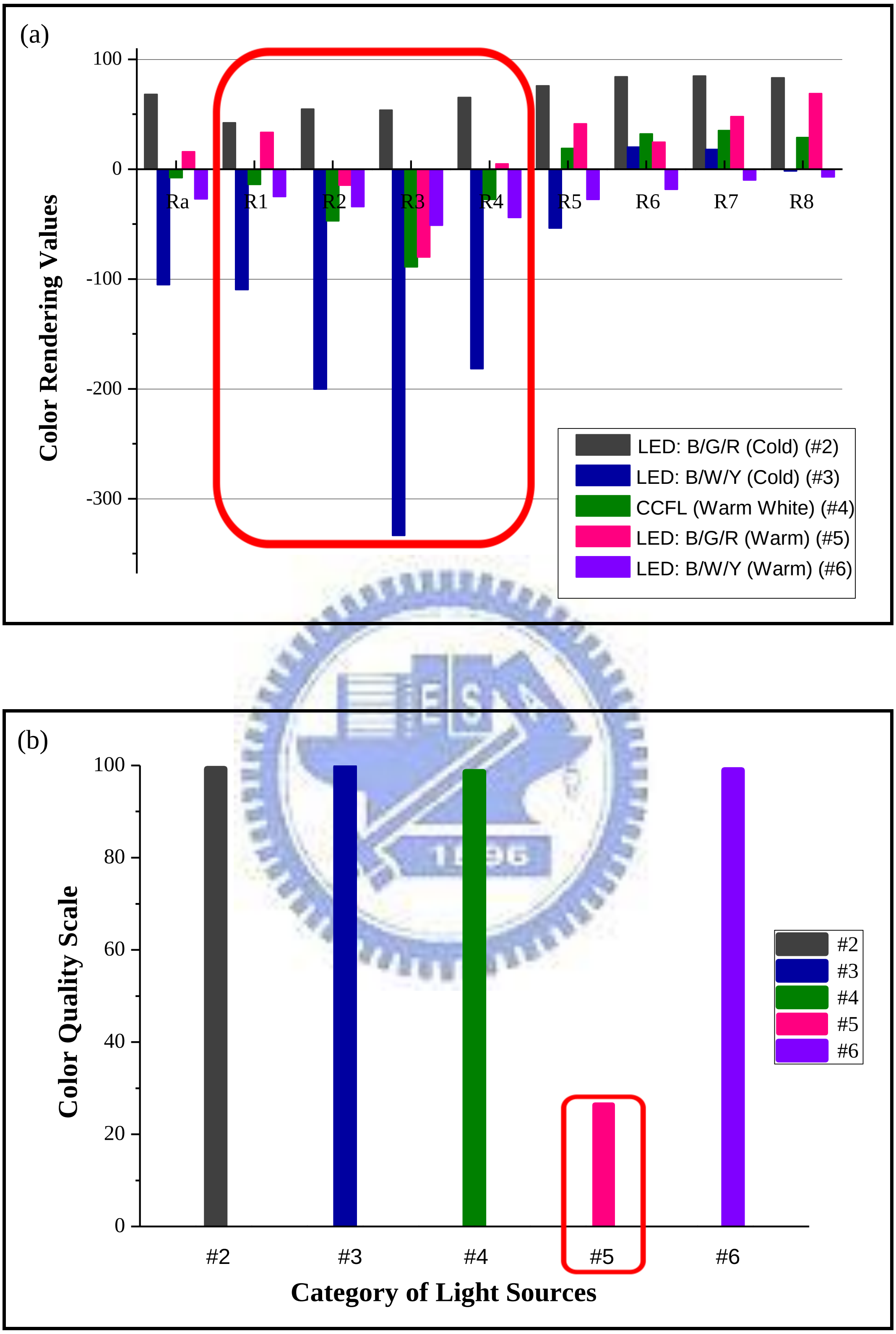

Fig. 4-15 Color rendering performances for the 5+1 light sources: (a) Color Rendering Values; (b) Color Quality Scales

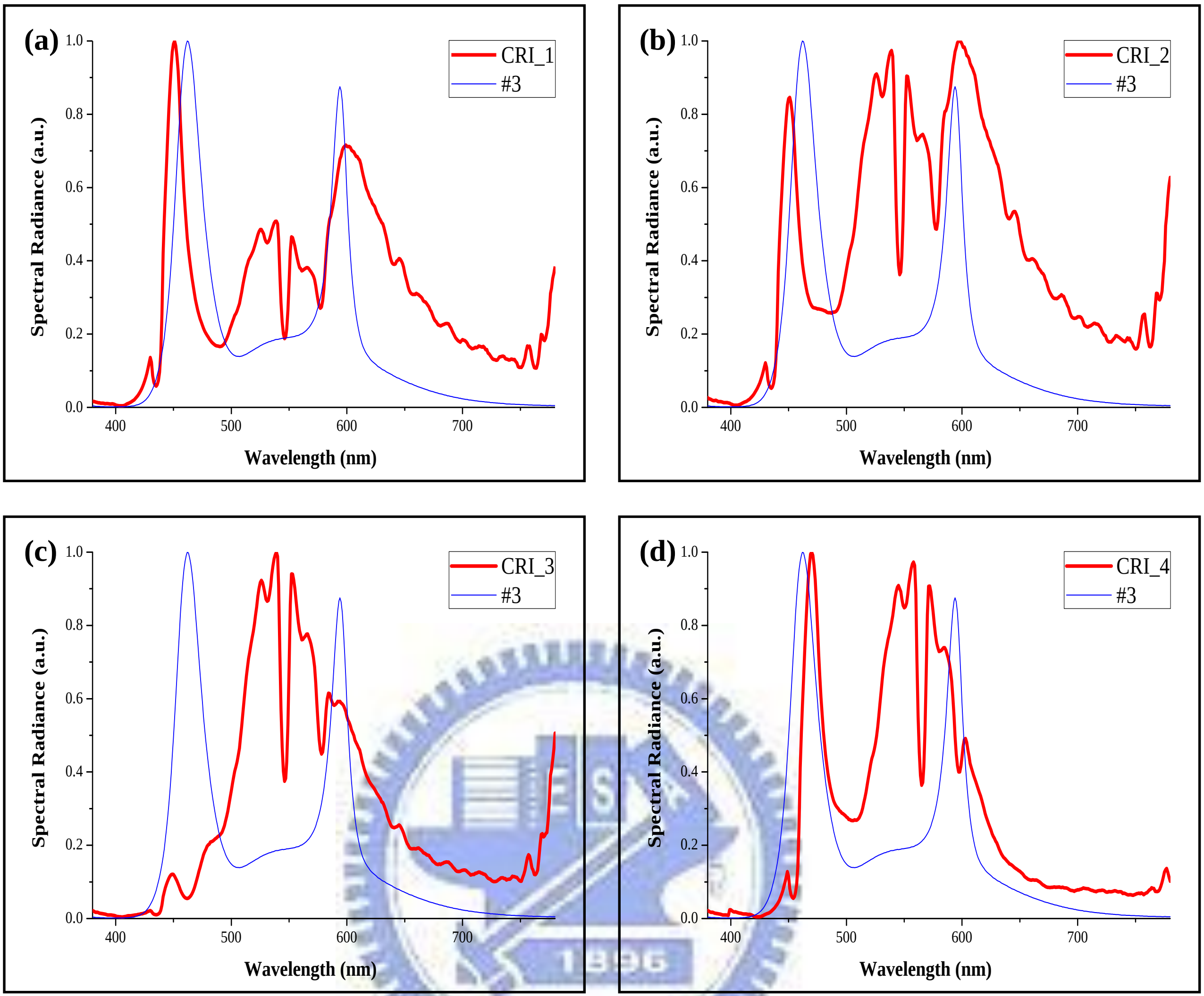

Fig. 4-16 The spectral matching diagram of reflectance **(**CRI_1~4: (a) ~ (d)**)** and test source #3

wide variety from sample color 1 to 15 of CQS. In the range around 450 nm, the source #5 had quite low weighting of the whole spectrum. On the other hand, the source #3 can almost contain the low waveband of reflectance. Hence, test source #3 had relatively higher CQS values than #5 had. This result can further improve that the matching level of light source and the reflectance can highly affect the color rendering performance. You can observe the color rendering by compare the color difference of each CQS sample, as shown in Table 4-2.The color difference of each CQS sample under source #5 almost higher than source #3 had. No wonder the source #5 has much

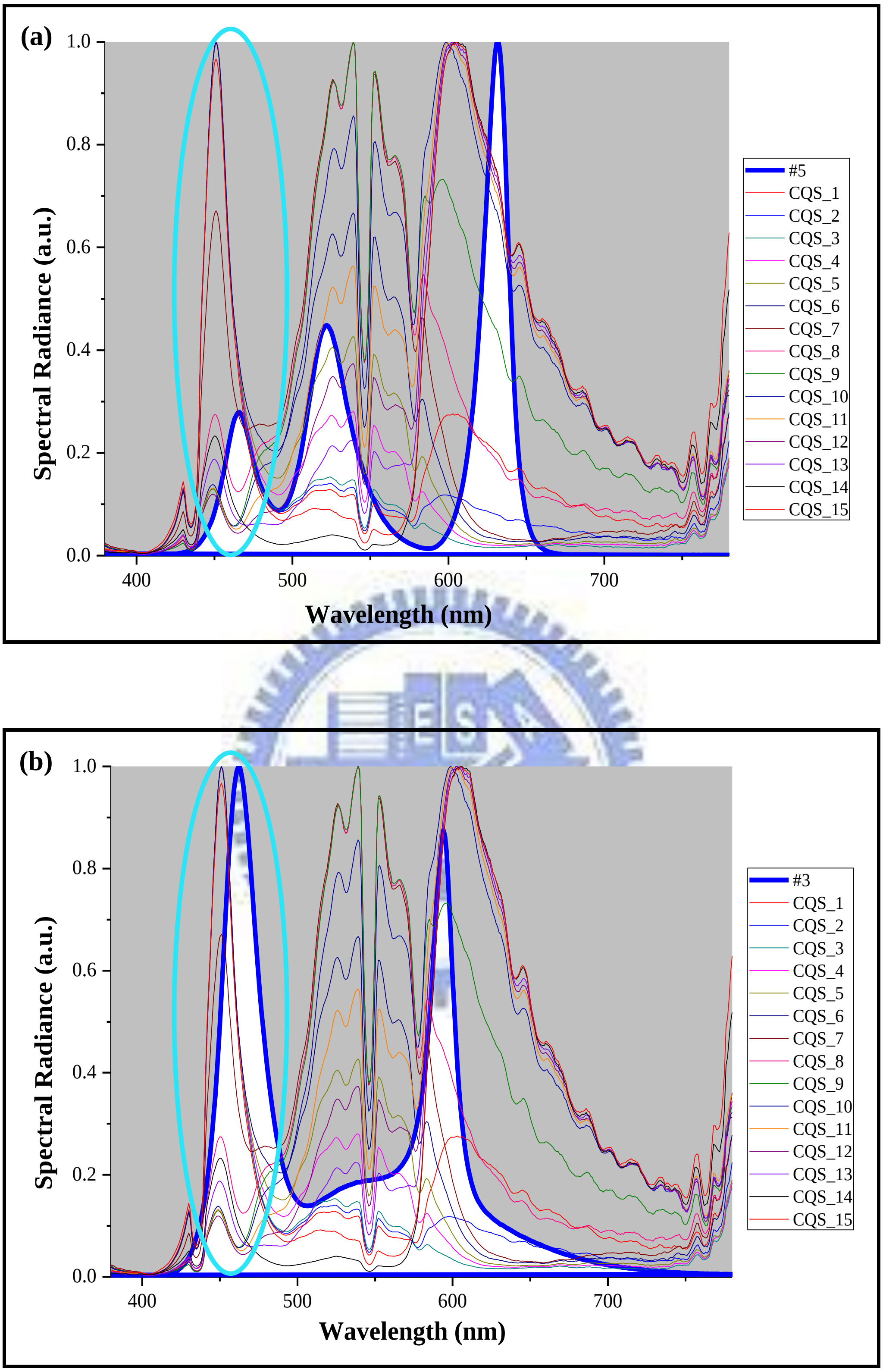

Fig. 4-17 Spectral matching diagrams of the source #5/#3 for the CQS color samples in (a)/ (b)

lower CQS value than #3 has. For deep thinking, the R/G/B color filter of reflective display determines the reflectance of it. Therefore, the spectral matching level of the color filter and light source should be concerned for the reflective displays. In addition, the R/G/B LED cluster of light source, which can highly match the color filter, should have the higher color gamut because of the higher saturated color performance of the LED.

Table 4-2 Color differences of CQS color sample for source #5 and source #3

#5 (ΔE_{00})	**CQS_1**	**CQS_2**	**CQS_3**	**CQS_4**	**CQS_5**	**CQS_6**	**CQS_7**	**CQS_8**
	4.9211	4.0672	2.4428	5.6296	7.1346	6.4725	3.6367	1.7489
	CQS_9	**CQS_10**	**CQS_11**	**CQS_12**	**CQS_13**	**CQS_14**	**CQS_15**	
	1.3002	0.9357	0.3236	0.3897	1.072	2.419	5.6807	
#3 (ΔE_{00})	**CQS_1**	**CQS_2**	**CQS_3**	**CQS_4**	**CQS_5**	**CQS_6**	**CQS_7**	**CQS_8**
	0.2493	0.2007	0.3257	0.3642	0.3763	0.2176	0.2873	0.0983
	CQS_9	**CQS_10**	**CQS_11**	**CQS_12**	**CQS_13**	**CQS_14**	**CQS_15**	1
	0.1117	0.236	0.2649	0.1903	0.3213	0.2057	0.2385	

Chapter 5

Conclusions & Prospect of Future

We verified that not only CCT or chromaticity diagram but also spectrum of light source would affect the color rendering performance of the reflective display. On the other hand, different SPDs of light sources contribute the change of color performance. Before investigating the problem of color shift issue of reflective displays, the merits of light sources for the reflective display is quite essential to evaluate color rendering performances. In this paper, we introduced the concept of the “Color Rendering Index” as well as “Color Quality Scale” to gauge the level of color render performances.

LED-based lighting is a good option for reflective displays in terms of higher color gamut. Take the experiment of Ch-LC color strips for example; the color gamuts, as shown in Fig. 4-10, in test light 1 and 2 were 91.30% and 66.59% NTSC, respectively. Compared with 72% NTSC under conventional CCFL, reflective display illuminated by multi-chip cluster LED light source enabled the comparable color gamut, as the typical transmission-type LCD. LED-based lighting offered a higher NTSC than normal CCFL lighting. Therefore, a tunable LED lighting is an effective way to improve the color quality and provide a correction scheme for reflective displays. The color reflected from the reflective display is composed of the R/G/B color filters of display. Therefore, the R/G/B LED cluster can provide a wider range of color gamut than continuous spectra or B/W/Y LED cluster of light sources. Nevertheless, LED has a significant problem of red-shift [13], and will become a key issue for reflective displays while using LEDs to be the light sources.

In our experiment, CQS had relatively stable values than the special CRI (R_1~ R_8) and general CRI. The real color chips used in CRI may not exactly be reproduced because of the limited color gamut of the display. It resulted in the incorrect and indirectly sense of physical meaning for color rendering performance. Therefore, CQS was a comparatively proper standard especially for the LED-based reflective displays.

In the future, a look up table, which can characterize the environmental light source, is expected to be sorted. Firstly, specific CCT of light sources should be dependent on different purposes. Then, plenty of light sources with identical CCT should be searched. Finally, the color difference or CQS of these sources can be calculated after measurement, and a light source recipe for the reflective display can be acquired. Not just the structure of reflective display should be focused in the days to come. The research topics of reflective display should add "the design of light source especially for large size reflective display", "the evaluation and estimation of color rendering performances of various light sources", etc. The importance of evaluation of color performance and source design will be highlighted frequently in the hereafter.

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