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Analysis and design of the color wheel in digital light processing system

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Abstract

Colorimetric characters are very important to the optical engine, the kernel of the projector. The equations to calculate the colorimetric characters of the color wheel in optical engine are proposed. They are proven by measurements and the calculation results. Based on this theory, the sensitivity of the spectral transmittance of the color filters to the chromaticity coordinates is analyzed. A conclusion on the color filters of the color wheel which is useful to the tolerance control is drawn. Finally, a color wheel system is designed by using the theory. The design can satisfy the specific of the original color wheel well.

Keywords: Color wheel; DLP; Colorimetry; Projection display

1. Introduction

Projection display based on digital light processing (DLP) technology has grown up rapidly over past few years. This technology, especially single chip DLP projection, has been widely used to offer high contrast, high brightness and sharp images for home and business application [1]. The kernel of the single chip DLP projector, named optical engine (OE), is composed of light source, color wheel, integrator rod, digital micro-mirror device (DMD) chip and projection lens. Many companies and research teams have contributed a lot to achieve a better optical efficiency [2]. However, as we known, the research work on the colorimetric character of the color wheel has not been reported yet. In this paper, the equations to analyze the colorimetric character for the single-chip DLP OE are proposed. These equations, to our knowledge, have not been reported before. They are proven by following experimental measurements and calculations. Then these equations are used to analyze the sensitivity of the spectral transmittance of the color filters to the chromaticity coordinates of the primary colors. Finally, a color wheel system is designed and the results of coating design are given.

2. Theory

The color wheel in the OE is composed of color filters, high-speed motor and some corresponding controlling circuits. The color wheel mostly used in the single chip DLP OE has six color filter sectors. They are red, green, blue, red, green and blue, individually. When the high-speed motor rolls, three primary display colors (red, green and blue) are created sequentially. At the same time, they are modulated by DMD sequentially and projected to the screen by the projection lens.

After the light passes through the color filter, the primary color we get can be described by following equations [3].

$$X = \sum S(\lambda)\tau(\lambda)\bar{x}(\lambda)\Delta\lambda, \quad x = \frac{X}{X+Y+Z},$$
$$Y = \sum S(\lambda)\tau(\lambda)\bar{y}(\lambda)\Delta\lambda, \quad y = \frac{Y}{X+Y+Z},$$

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$$Z = \sum S(\lambda)\tau(\lambda)\bar{z}(\lambda)\Delta\lambda, z = \frac{Z}{X+Y+Z},$$
$$x + y + z = 1,$$

In Eq. (1), X, Y and Z, are tristimulus values of the primary color, respectively. $\bar{x}(\lambda), \bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are CIE1931 standard colorimetric observer. x, y and z are CIE1931 chromaticity coordinates, respectively. $\Delta\lambda$ is the interval of the wavelength. $S(\lambda)$ is relative spectral power distribution of the source. $\tau(\lambda)$ is the spectral transmittance of the color filter. These two parameters can be obtained by measurements.

On the base of colorimetric principles and the working process described above, the equations for the color wheel in the OE are deduced as below [3]:

$$X = X_R T_R + X_G T_G + X_B T_B,$$
$$Y = Y_R T_R + Y_G T_G + Y_B T_B,$$
$$Z = Z_R T_R + Z_G T_G + Z_B T_B. \quad (2)$$

In this equation, X, Y and Z are tristimulus values of the mixed color to be displayed. While X_i, Y_i and Z_i ($i = R$, G, B) are tristimulus values of the primary display colors, respectively. T_i is the actual modulation time for each primary color when the color wheel rolls 360°. When the tristimulus values of the mixed color are obtained, the colorimetric characters of the mixed color such as the chromaticity coordinates and the correlated color temperature (CCT) will be calculated easily.

3. Measurements and calculations

The OE of the Amoisonic RPTV Model DL52HWT is used during the measurements. The engine uses the OSRAM 120W UHP arc lamp as its light source. The relative spectral power distribution of the source and the spectral transmittance of the color filters of the color wheel were measured by the OCEAN–SD2000 fiber spectrometer and the WFZ-25A ultra violet-visible spectrometer, respectively. The results are shown in Fig. 1.

According to Fig. 1, the chromaticity coordinates of the primary colors are calculated from the Eq. (1). The results are shown in Table 1 and Fig. 2.

Fig. 2 uses the CIE1931 standard colorimetric system. Every point in the figure corresponds to a chromaticity coordinate of one color. The vertexes of the triangle are the primary color point. The area of the triangle means the amount of the color composed of these three primary colors with different proportion. Since the television is produced for Chinese market, the PAL standard which is using in China currently should be paid more attention. In Fig. 2, the color triangle of the OE includes that of the PAL totally.

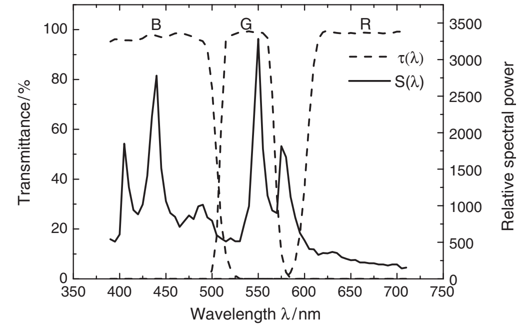

Fig. 1. Relative spectral power distribution of the source and the spectral transmittance of the color filters of the color wheel.

From the curve of the relative spectral power distribution in Fig. 1, the power of the waveband 450–500 and 500–575 nm which is blue and green, respectively, is so much stronger than that of the waveband 600–700 nm which is red. This power distribution of the light source makes the white field have a higher CCT. If we want to get a white field with lower CCT suitable for display, the modulation time for the blue and green colors in the OE has to be decreased. This is realized with the method of circuit control [4]. More modulation time is decreased; the white field has lower CCT. Therefore, the CCT is the highest value when DMD is always in the state of modulation. In this state, the modulation time of the primary color is totally decided by the angle of the color filter sectors and the speed of the motor. Since the speed of the motor is constant, the modulation time T_i in Eq. (2) is proportional to the angle of the color filter sectors. The angles of the red, green and blue color filter sectors are 75°, 55°and 50°, respectively. After calculation by using Eqs. (1) and (2), the CIE1931XYZ chromaticity coordinate of the white field is (0.252329, 0.304805), and the CCT of the white field is 12201 K. Considering the errors of the measurements and the precision of the arithmetic used to calculate the CCT of the white field, this result agrees well with the specification 12000 K which is provided by the manufacture [5]. Therefore, the equations deduced in Section 2 can be proven. At the same time, we believe that it is absolutely feasible if these equations are used to make some analysis and design in the following section.

4. Analysis and design

In this section, the sensitivity of the spectral transmittance of the color filters to the chromaticity coordinates of the primary colors will be analyzed firstly. For a spectral transmittance curve, we define $\Delta\lambda$ as the difference between the start–stop wavelengths of the band-pass and the corresponding cut-off wave-