

## Research Article

# Application of Virtual Display Technology of LCD Backlight Spectrum Optimization Algorithm Based on Linear Programming

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In order to make the color of image display more realistic, optimize the use of energy, and improve the light efficiency of the module through reasonable spectral distribution, this paper proposes a backlight spectral optimization algorithm based on linear programming. With the goal of maximizing the backlight luminous efficiency, the theoretical maximum of the luminous efficiency of the backlight spectrum can be achieved by constructing a linear programming model. The research process is to obtain the optimal distribution of transmittance spectrum by linear programming method on the premise of ensuring the color gamut standard of display system. The results show that the light efficiency can be increased to 335.5 lm/W, while the original light efficiency of the system is less than 150 lm/W. With the goal of maximizing the light efficiency, light sources with narrow bandwidths such as lasers and quantum dot materials can be used to simulate and reconstruct these characteristic wavelengths. There will be easier to approach the ideal optimization spectrum and achieve the theoretical maximum luminous efficiency of 610.8 lm/W.

## 1. Introduction

In recent years, many display devices have been introduced. In particular, the digital flat panel display technology represented by the LCD has been rapid developed [1, 2]. For further improving the effect of the display device and enhancing the performance of the display, the color gamut, as an important indicator of the display quality, will become the focus in the research area of display. At the same time, the polarizer and color filter in the LCD panel structure have a huge impact on the luminous efficiency, which lead to the low light effect. At present, RGB color light source can remove the color filter to improve the luminous efficiency, but there are still some limitations. As the light source of the display, the spectral components contained in the backlight spectrum will directly affect the final color rendering effect. The backlight spectrum is the key to color gamut expansion as well. In this paper, a linear programming-based algorithm is proposed for optimization of the backlight spectrum. Through constructing a linear programming model, the spectrum distribution of the primary colors of

any display and the calculation of the limit value of the light efficiency can be optimized.

The rest of this paper is arranged as follows: Section 2 studies the structure of liquid crystal display and the phenomenon of metamerism; Section 3 illustrates the optimization model of the backlight spectrum; Section 4 reports the analysis of the backlight optimization model. Finally, Section 5 concludes the proposed algorithm and presents several aspects of future work.

## 2. Structure of Liquid Crystal Device and Phenomenon of Metamerism

Since the liquid crystal layer cannot emit the light, the traditional LCD uses a multilayer module for reconstruction of the image by modulating the backlight through diffusers, polarizers, liquid crystal layers, and filters. According to the distribution of the backlight light source, common modules can be divided into two types: edge type and direct type [3, 4]. The schematic diagram of these two structures is shown in Figure 1.

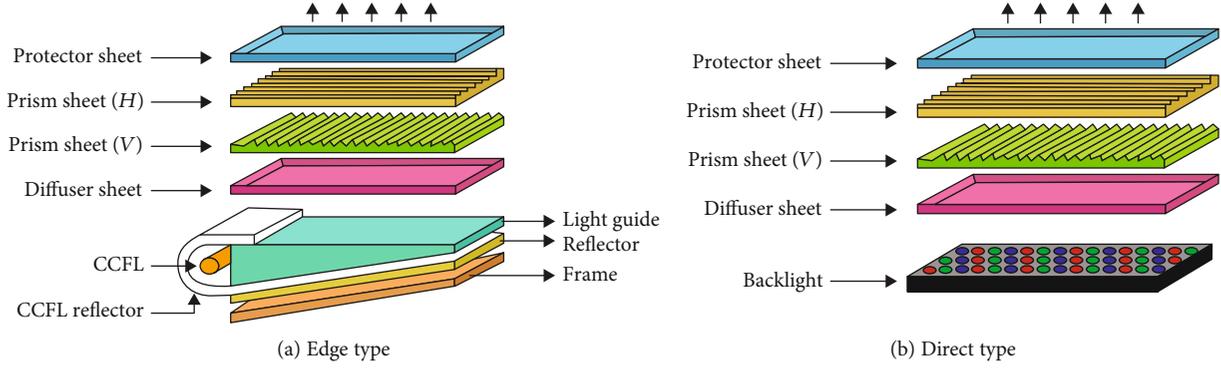


FIGURE 1: Schematic of the LCD module structure.

As for the edge type, the backlight source is placed on the side of the liquid crystal panel. The light guide plate is used for color mixing and can directly couple the light to the liquid crystal panel as the input light energy. However, in the direct type, the light emitted from the backlight is reflected by the reflector. After that, the light is dispersed upward through the diffuser. Eventually, the light can be transmitted from the front side. Taking the direct backlight structure as an example, the basic structure of the module and the transmittance level of each layer are shown in Figure 2. Compared with the direct type, the side type has a lower overall utilization rate of the light energy due to the energy loss of the light guide plate [5, 6].

Because of the multilayer structure of the module, there are only 5% of the light from the direct type module that can be emitted by the screen for forming the final image. This means that the utilization rate of light energy in the LCD system is rather low. To ensure the quality of the reconstructed image, most of the light is absorbed or uniformed by various materials during the layer-by-layer modulation. This phenomenon not only exacerbates the heating problem of the display but also increases the power consumption of the device. Generally, the luminous efficiency (lm/W) is used as an index to measure the electro-optical conversion efficiency of the light source. The luminous efficiency can be calculated as follows:

$$\eta = \frac{k \int_{380}^{780} \Phi(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} \Phi(\lambda) d\lambda}. \quad (1)$$

In which, the coefficient  $k$  represents the maximum optical efficiency, i.e., 683 lm/W, which is also the luminous efficiency value when human watches the yellow-green light (555 nm).  $\Phi(\lambda)$  is the radiance spectral energy distribution of the light source.  $V(\lambda)$  is the light efficiency function of human eyes' optical spectrum. In the LCD system, whether it is a traditional CCFL backlight or a new LED backlight, the luminous efficiency of the device does not exceed 150 lm/W, and the luminous efficiency of the whole system does not exceed 10 lm/W.

The light emitted from the backlight of the flat panel display system is filtered by the module. Under the CIE-1931

XYZ color space, the color is calibrated by its color coordinates  $(x, y)$ . Equation (2) for calibration is given as follows:

$$\begin{cases} X = \int_{380}^{780} \Phi(\lambda) \bar{x}(\lambda) d\lambda, \\ Y = \int_{380}^{780} \Phi(\lambda) \bar{y}(\lambda) d\lambda, \\ Z = \int_{380}^{780} \Phi(\lambda) \bar{z}(\lambda) d\lambda, \\ x = \frac{X}{X + Y + Z}, \\ y = \frac{Y}{X + Y + Z}. \end{cases} \quad (2)$$

In which,  $X$ ,  $Y$ , and  $Z$  represent the tristimulus values of the red, green, and blue channels, respectively.  $\Phi(\lambda)$  is the spectral distribution of the color.  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ , and  $\bar{z}(\lambda)$  are the standard observations of  $X$ ,  $Y$ , and  $Z$ .

Deduced from the integral calculation of the color coordinates, there are infinite possibilities for the color light spectrum distribution that meets the color coordinates. Theoretically, if the color coordinates  $(x, y)$  are the same and have the same brightness, the human eyes cannot distinguish them and will judge these colors as the same color. This phenomenon is also elaborated by Glassman's law [7–9]. In fact, whether in daily life or the industrial production, most of the colors are metameres [10, 11]. This phenomenon is much more common, especially in the industries such as printing, dyes, and painting. Since the actual color perception of the human eye is directly related to the tristimulus value instead of the spectral composition, the optimization of many light sources and spectral analysis can be achieved by using the metamerism. For instance, the metamerism can be used for improving the color accuracy of the multiprimary color display systems [12]. Wyszecki et al. proposed the concept of metamerism black to decompose the spectral reflectance of objects [13]. Cohen et al. proposed an R matrix mathematical model for spectral reconstruction calculations [14, 15]. Similarly, metamerism also provides the possibility to optimize the backlight of liquid crystal displays.

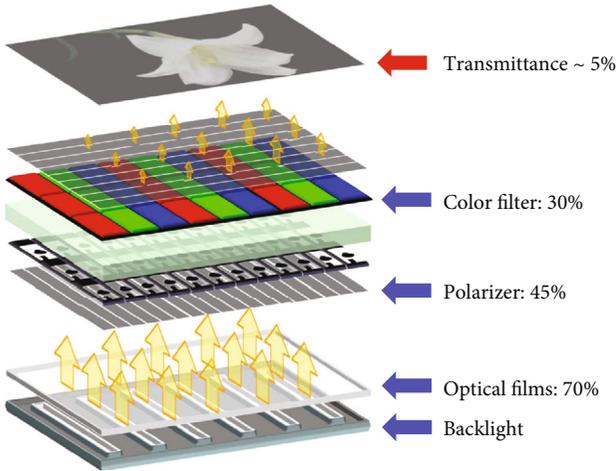


FIGURE 2: Structure of the LCD backlight module and the transmittance of each layer.

The energy consumption of displays is used as another important indicator. In the optimization, the light efficiency of the display is used as a reference indicator to measure the quality of the backlight spectrum, and the high luminous efficiency light source is of great significance for the display. Normally, the power consumption of the general liquid crystal display (LCD) backlight accounts for most of the entire power consumption. Backlight modulation can also be used to improve the luminous efficiency of LCD module, such as flicker backlight technology and scanning backlight technology. Flicker backlight is to make the backlight glow only for a certain period in a frame instead of continuously illuminated. This method can reduce energy consumption but may lead to a decrease in the overall image brightness, which makes the brightness output of the backlight more demanding. Based on the flickering of the backlight, scanning backlight adds the process of controlling the phase of the backlight; that is, lighting up and closing the backlight at the phase when the LCD pixel are completely on and completely off. The advantage of backlight scanning is that the light energy utilization of the backlight is high and can obviously improve the phenomenon of LCD image motion blur, but in order to achieve a constant background light brightness, it is necessary to improve the brightness of the scanned background light. Therefore, the reduction of the power consumption caused by the backlight source is crucial. The utilization of LCDs with higher light efficiency in portable devices can improve the endurance of the device under the same battery capacity which can enhance the practicability and competitiveness of the product.

Besides, the spectral optimization of the display backlight source is also applicable to the field of lighting. In recent years, with the development of cities, the fossil energy has become increasingly tense. The prices of the conventional energy, such as oil and coal, have continued to rise. In particular, international oil prices have reached to the peak leading to an increasingly severe energy supply situation. The sustainable development and utilization of energy has attracted more and more attention. Lighting is one of the main areas

where humans consume energy. Therefore, it is of great significance to achieve energy saving in the lighting field [16]. For alleviating the ever-increasing energy crisis, the “green lighting concept” has been proposed internationally in the early 1990s. The Energy Independence and Security Act of 2007 (EISA2007) signed by the United States specifically requires the inclusion of the “Next Generation Lighting Initiative” (NGLI) [17]. Currently, European and American markets generally adopt the Energy Star (ES) indicator jointly promoted by the US Department of Energy and the US Environmental Protection Agency [18], China, also began to implement the promotion of “green lighting projects” in 1996 [19, 20]. An important step to realize this plan is to develop and promote efficient and energy-saving lighting fixtures. Saving the electricity for lighting, reducing the lighting pollution, and establishing a high-quality, efficient, economical, comfortable, safe, and reliable lighting system are beneficial to the whole system. The high-efficiency lighting source means that the source consumes less energy under the same light output. It is of great significance to save energy and reduce power costs.

Compared with the lighting, the color gamut range should be taken into consideration in the display system while improving the light efficiency. Otherwise, the image quality of the display will be affected due to the decrease in color saturation, which will be harmful to the final quality of the display. By using the metamerism, the simulation and optimization of the spectral distribution of the light source can be achieved with the optimal light efficiency.

### 3. Optimization Model of the Backlight Spectrum

The reconstruction of color images of LCD can be achieved by mixing multiple primary colors. Under the premise of ensuring the color gamut area, the light efficiency of the display should be maximized. The optimized spectrum of each primary color is the basis for the optimized spectrum of the entire backlight. Based on the passive light-emitting principle of LCD, the light of the display received by the viewer is the backlight by passing through the liquid crystal layer and the filter. The absorption of other optical film layers such as polarizers can be treated as a fixed value. In order to achieve a real simulation effect, the spectral distribution of the backlight,  $\Phi_{BL}(\lambda)$ , the transmittance line distribution of the filter,  $T_{CF}(\lambda)$ , and the transmittance distribution of the liquid crystal,  $T_{LC}(\lambda)$ , should be set as unknown parameters. Since these three parameters are unknown, solving the function directly can be very difficult [21]. In order to simplify the process, the optimization of the process can be divided into three steps. Step one is the spectrum optimization of the primary color light. Step two is the spectral synthesis of the display optimization backlight; the final step is the spectral distribution of the color filter transmittance. During the process, the optimized result in each step can be the basis of the next calculation. In the first step of optimization, the transmittance spectrum of the color filter and the liquid crystal can be set as an ideal state, i.e., 100%. Following these three steps, the optimized spectral distribution of the backlight

and the corresponding distribution of the filter and the transmittance spectral of the liquid crystal can be obtained.

**3.1. Spectral Optimization of Primary Colors.** The spectrum optimization of the primary colors is the basis of the display backlight optimization. As for displays that comply with a specific color gamut standard, the color coordinates of each primary color have been determined. Each color coordinate of the primary color is different and vary with each other. Optimizing a certain primary color is equal to optimize the color light spectrum distribution of any known color coordinate. The calculation of color coordinates and light effects can refer to equation (1) and equation (2).  $\bar{w}(\lambda)$  is the white spectrum curve value.  $\Phi(\lambda)$  is the spectral distribution of the color.  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ , and  $\bar{z}(\lambda)$  are the standard observations of  $X$  and  $Y$ . According to the principle of metamerism, there are countless chromatic light spectrum distribution,  $\Phi(\lambda)$ , that satisfy the given color coordinate theoretically. With the goal of maximizing the light efficiency, finding one or more optimized distributions among countless kinds of spectral distributions and improving light efficiency while satisfying the color perception are the task of optimization of primary colors. Using the chromaticity formula, the problem can be transformed into the following mathematical model. Assuming that the function  $\Phi(\lambda)$  satisfies the following equations, we should find  $\Phi(\lambda)$  when  $\eta$  reaches to the maximum.

$$\begin{cases} \bar{w}(\lambda) = \bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda), \\ \int_{380}^{780} \Phi(\lambda)[x\bar{w}(\lambda) - \bar{x}(\lambda)]d\lambda = 0, \\ \int_{380}^{780} \Phi(\lambda)[y\bar{w}(\lambda) - \bar{y}(\lambda)]d\lambda = 0, \end{cases} \quad (3)$$

$$\eta = \frac{k \int_{380}^{780} \Phi(\lambda)\bar{y}(\lambda)d\lambda}{\int_{380}^{780} \Phi(\lambda)d\lambda}. \quad (4)$$

The solution of equation (3) is in the form of a function distribution, which is a functional problem. The tristimulus values,  $x(\lambda)$ ,  $y(\lambda)$ , and  $z(\lambda)$ , are subjective experimental statistical results. There is no recognized analytical formula corresponding to it. In order to simplify the solution process and reduce the difficulty of the solution, the idea of function discretization is used to reconstruct all the function distributions into discrete functions. The integral operation is converted to accumulation operation [22, 23]. Eventually, the problem can be transmitted into a discrete function for a nonlinear programming model. Assuming that the discrete function  $\Phi(\lambda)$  satisfies the following equations, we should find  $\Phi(\lambda)$  when  $\eta$  reaches to the maximum.

$$\begin{cases} \bar{w}(\lambda) = \bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda), \\ \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi(\lambda)[x\bar{w}(\lambda) - \bar{x}(\lambda)] = 0, \\ \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi(\lambda)[y\bar{w}(\lambda) - \bar{y}(\lambda)] = 0, \end{cases} \quad (5)$$

$$\eta = \frac{k \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi(\lambda)\bar{y}(\lambda)}{\sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi(\lambda)}. \quad (6)$$

The discrete functions involved in which all have the same sampling rate. Taking into consideration of the calculation accuracy and time, the sampling interval is set as 1 nm in this paper. In addition, due to the physical meaning of the function, the value of each wavelength in  $\Phi(\lambda)$  is the intensity of the energy distribution. Therefore, the value of  $\Phi(\lambda)$  is non-negative, i.e.,  $\Phi(\lambda) \geq 0$ , ( $380 \text{ nm} \leq \lambda \leq 780 \text{ nm}$ ). Eventually, the nonlinear programming problem takes equation (6) as the objective function, which contains 401 unknown parameters, 2 equality constraints, and 401 inequality constraints.

The nonlinear programming problem is solved by substituting the corresponding constraints and objective functions. After normalization, the solution is the optimal relative spectral power distribution of any color light. In the solving process, it is necessary to substitute the spectral distribution data for satisfying the color coordinates as the initial value. If the initial value is unknown, the approximate color coordinates can be substituted into the calculation. However, the value calculated by the first optimization may not be the best result. The first optimization result can be used as an initial value and then substituted into the mathematical tool for the next round of calculation. The result after two iterations will converge to the final optimal result. The final result maximizes the light efficiency under the premise that the color coordinate is unchanged. Figure 3 shows the optimized results of a certain white light (color coordinates (0.271, 0.234)). Before the optimization, the theoretical luminous efficiency of the original spectral distribution of the illuminator is 237.6 lm/W. After the optimization, the theoretical luminous efficiency is increased to 321.8 lm/W.

Through the optimization, the spectral distribution of the color light represented by any point other than the edge in the tongue diagram of the color gamut in the CIE-1931 XYZ color space can be optimized [24, 25]. Figure 4 shows the optimized contour distribution of the tongue diagram with the maximum light effect. The optimizable range covers the entire tongue-shaped chart color gamut, which provides a basis for the spectrum optimization of the primary colors and the backlight of the display.

**3.2. Synthesis of Backlight Spectrum.** As for traditional displays, the standard of the color gamut provides four sets of color coordinates for the four primary colors, i.e., red, green, blue, and white field. For example, in the NTSC standard (National Television Standards Committee, American Standard Television Broadcast Transmission and Reception Protocol), the color coordinates of red, green, blue, and white are specified as  $(x_r, y_r) = (0.67, 0.33)$ ,  $(x_g, y_g) = (0.21, 0.71)$ ,  $(x_b, y_b) = (0.14, 0.08)$ , and  $(x_w, y_w) = (0.31, 0.316)$ . Briefly, the standard color coordinates of each primary color should be calculated. Then, the aforementioned steps can be used to construct an equivalent nonlinear programming problem. After that, the constructed nonlinear programming problem can be solved. Eventually, the optimal spectral distribution of the light efficiency of each primary color can be obtained. Taking the NTSC standard as an example, the optimized

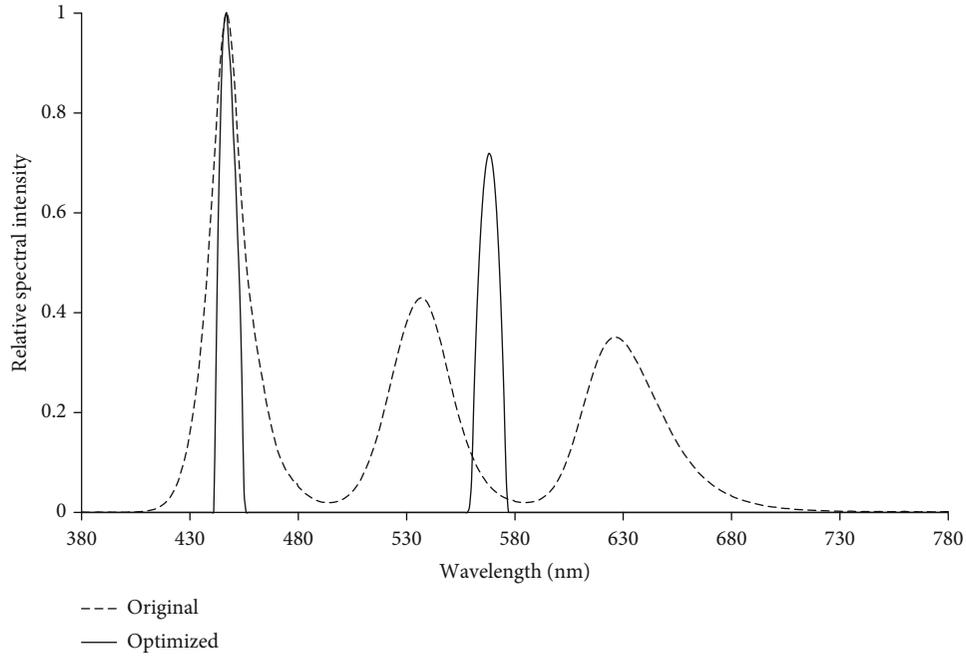


FIGURE 3: The optimized spectral distribution of the white light with color coordinate of (0.271, 0.234).

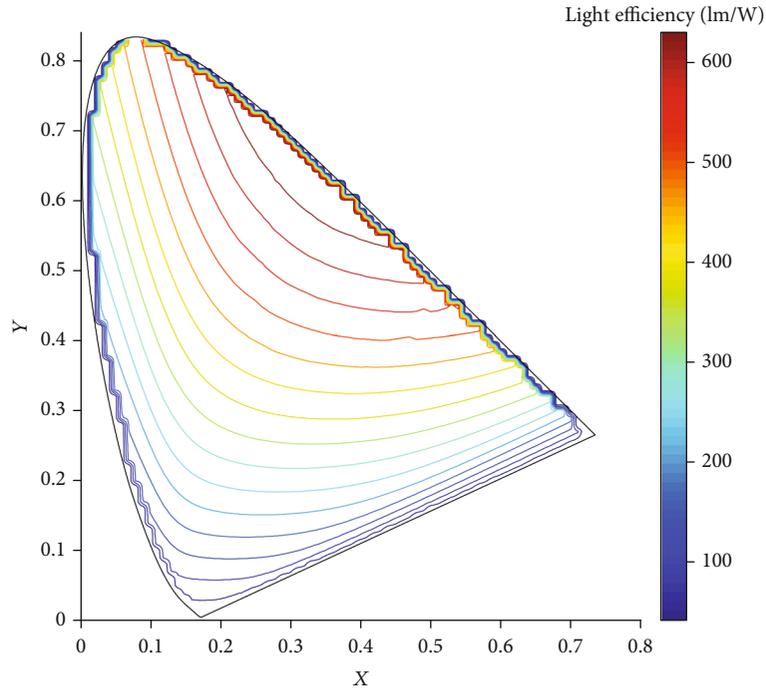


FIGURE 4: The contour map of the maximum light efficiency.

spectral distributions of the three primary colors, i.e.,  $\Phi_r(\lambda)$ ,  $\Phi_g(\lambda)$ , and  $\Phi_b(\lambda)$ , are shown in Figure 5. The theoretical light effects of the three primary colors after the optimization are 330.8 lm/W, 612.9 lm/W, and 101.9 lm/W, respectively.

Since the color coordinates of the white field are also specified in the color gamut standard, the relative intensity of each primary color spectrum needs to be calculated after

obtaining the optimized spectrum of each primary color. To tackle this issue, the synthesized white should be exactly equal to the color coordinates of the white field when the primary colors reach the maximum. Meanwhile, the light intensity of each primary color should be used to maximize the total brightness in the white field. The gain coefficients of the three primary colors of red, green, and blue channels

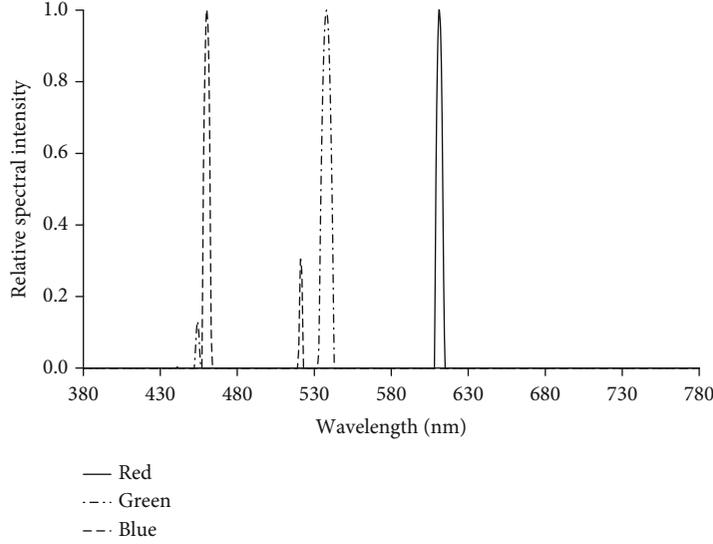


FIGURE 5: The optimized spectral distribution of the red, green, and blue channel under the standard of NTSC.

can be set as  $n_r$ ,  $n_g$ , and  $n_b$ . In order to ensure the white field color coordinates, the intensity coefficient should satisfy the following equations:

$$\begin{cases} [y_g y_b Y_r (x_r - x_w)] n_r + [y_r y_b Y_g (x_g - x_w)] n_g + [y_r y_g Y_b (x_b - x_w)] n_b = 0, \\ [y_g y_b Y_r (y_r - y_w)] n_r + [y_r y_b Y_g (y_g - y_w)] n_g + [y_r y_g Y_b (y_b - y_w)] n_b = 0. \end{cases} \quad (7)$$

In which,  $Y_r$ ,  $Y_g$ , and  $Y_b$  represent the luminous flux of the three primary colors in the optimal spectral distribution of light efficiency, respectively. The expression of these three parameters is given as follows:

$$\begin{cases} Y_r = \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi_r(\lambda) \bar{y}(\lambda) \Delta\lambda, \\ Y_g = \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi_g(\lambda) \bar{y}(\lambda) \Delta\lambda, \\ Y_b = \sum_{\lambda=380\text{nm}}^{780\text{nm}} \Phi_b(\lambda) \bar{y}(\lambda) \Delta\lambda. \end{cases} \quad (8)$$

In which,  $\Delta\lambda = 1 \text{ nm}$ . The total luminous flux,  $Y_w$ , of the white field of the display is expressed as the sum of the luminous fluxes of the three primary colors:

$$Y_w = n_r Y_r + n_g Y_g + n_b Y_b. \quad (9)$$

On the premise that the color temperature of the white field does not deviate and in order to maximize the brightness of the white field, equation (7) can be set as the constraint condition, and equation (9) can be set as the objective function. In order to maximum the solution of equation (9), a linear programming problem can be proposed for solving the gain strength of each primary color. It should be

noted that each gain coefficient is nonnegative, i.e.,  $n_r \geq 0$ ,  $n_g \geq 0$ , and  $n_b \geq 0$ . Besides, the final constructed linear programming problem contains three unknown parameters, two equality constraints, and three inequality constraints. By using some calculation tools,  $n_r$ ,  $n_g$ , and  $n_b$  can be solved. Taking the NTSC standard as an example, the brightness of the white field formed by the combination should be the largest when the white field color coordinates are (0.31, 0.316),  $n_r = 0.8875$ ,  $n_g = 0.5742$ , and  $n_b = 1.0000$ .

After obtaining the spectral intensity gain coefficients of each primary color, the optimized spectra of all primary colors are combined into the display backlight spectrum according to the coefficient ratio. Due to the passive light emitting principle of liquid crystal displays, the backlight of the display should pass through filters for selecting the specific wavelength. Therefore, the final backlight spectrum value at a certain wavelength is the maximum value of the optimized spectrum of all primary colors at that point. The final optimized backlight spectrum  $BL(\lambda)$  is given as follows:

$$BL(\lambda) = \max_{380\text{nm} \leq \lambda \leq 780\text{nm}} (n_r \Phi_r(\lambda), n_g \Phi_g(\lambda), n_b \Phi_b(\lambda)). \quad (10)$$

In which, the optimized backlight spectrum distribution synthesized by the NTSC standard is shown in Figure 6. The theoretical light efficiency of the optimized backlight spectrum is 335.5 lm/W.

**3.3. Spectral Optimization of the Transmittance of the Filter.** Due to the passive light emitting principle of the LCD, the backlight of the display should be selected by passing through filters. A large amount of backlight energy is absorbed by the filter layer causing a low lighting efficiency. Based on the aforementioned principle, the optimization of the transmittance distribution of the filter can also be achieved by constructing a linear programming problem [26, 27]. Assuming that the spectral distribution of the display backlight is  $BL(\lambda)$ , the transmittance distribution functions of the red, green,

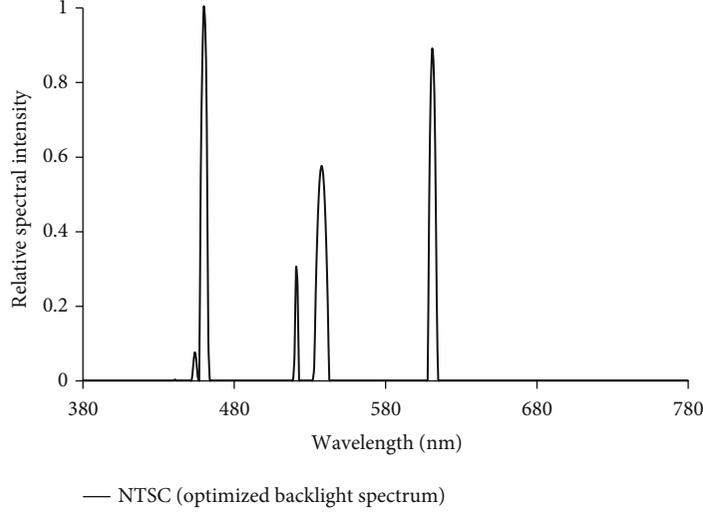


FIGURE 6: The optimized spectral distribution of the backlight under the standard of NTSC.

and blue filters are  $CF_r(\lambda)$ ,  $CF_g(\lambda)$ , and  $CF_b(\lambda)$ , respectively. According to the provision of the color gamut standard, the final color coordinate calculation of the primary color light received by the human eyes meets equation (11) as follows:

$$\bar{w}(\lambda) = \bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda), CF_w(\lambda) = CF_r(\lambda) + CF_g(\lambda) + CF_b(\lambda),$$

$$\begin{cases} x_r = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_r(\lambda)\bar{x}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_r(\lambda)\bar{w}(\lambda)}, & y_r = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_r(\lambda)\bar{y}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_r(\lambda)\bar{w}(\lambda)}, \\ x_g = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_g(\lambda)\bar{x}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_g(\lambda)\bar{w}(\lambda)}, & y_g = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_g(\lambda)\bar{y}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_g(\lambda)\bar{w}(\lambda)}, \\ x_b = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_b(\lambda)\bar{x}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_b(\lambda)\bar{w}(\lambda)}, & y_b = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_b(\lambda)\bar{y}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_b(\lambda)\bar{w}(\lambda)}, \\ x_w = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_w(\lambda)\bar{x}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_w(\lambda)\bar{w}(\lambda)}, & y_w = \frac{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_w(\lambda)\bar{y}(\lambda)}{\sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_w(\lambda)\bar{w}(\lambda)}. \end{cases} \quad (11)$$

Since the backlight is determined, the difference in the transmittance spectrum of the filter will directly determine the luminous efficiency of the display. Therefore, the optimization of the luminous efficiency is equal to the maximization

of the luminous flux. The luminous flux of the brightness of the white field, i.e.,  $Y$ , can be calculated as follows:

$$Y = \sum_{\lambda=380nm}^{780nm} BL(\lambda)CF_w(\lambda)\bar{y}(\lambda). \quad (12)$$

Since there are three independent spectral distributions, each solution contains 401 unknown parameters, if the sampling interval is set as 1 nm. In order to simplify the problem, the three functions can be combined into one function, and this function can be solved by some mathematical tools. The synthesis process is to connect the transmittance distribution functions of the red, green, and blue filters in sequence to form a discrete function, i.e.,  $CF_{all}(m)$ , containing 1203 elements. The synthesis equation (13) is given as follows:

$$CF_{all}(m) = [CF_r(380), \dots, CF_r(780), CF_g(380), \dots, CF_g(780), CF_b(380), \dots, CF_b(780)]. \quad (13)$$

Taking equation (13) as the function to be solved, equation (11) and equation (12) can be transmitted into:

$$A = \begin{bmatrix} BL(380)(\bar{x}(380) - x_r\bar{w}(380)) & \dots & BL(780)(\bar{x}(780) - x_r\bar{w}(780)) & 0 & \dots & 0 & \dots & 0 \\ BL(380)(\bar{y}(380) - y_r\bar{w}(380)) & \dots & BL(780)(\bar{y}(780) - y_r\bar{w}(780)) & 0 & \dots & 0 & \dots & 0 \\ 0 & \dots & 0 & BL(380)(\bar{x}(380) - x_g\bar{w}(380)) & \dots & BL(780)(\bar{x}(780) - x_g\bar{w}(780)) & \dots & 0 \\ 0 & \dots & 0 & BL(380)(\bar{y}(380) - y_g\bar{w}(380)) & \dots & BL(780)(\bar{y}(780) - y_g\bar{w}(780)) & \dots & 0 \\ 0 & \dots & 0 & 0 & \dots & 0 & \dots & BL(380)(\bar{x}(380) - x_b\bar{w}(380)) \dots BL(780)(\bar{x}(780) - x_b\bar{w}(780)) \\ 0 & \dots & 0 & 0 & \dots & 0 & \dots & BL(380)(\bar{y}(380) - y_b\bar{w}(380)) \dots BL(780)(\bar{y}(780) - y_b\bar{w}(780)) \\ BL(380)(\bar{x}(380) - x_w\bar{w}(380)) & \dots & BL(780)(\bar{x}(780) - x_w\bar{w}(780)) & BL(380)(\bar{x}(380) - x_w\bar{w}(380)) & \dots & BL(780)(\bar{x}(780) - x_w\bar{w}(780)) & BL(380)(\bar{x}(380) - x_w\bar{w}(380)) & \dots & BL(780)(\bar{x}(780) - x_w\bar{w}(780)) \\ BL(380)(\bar{y}(380) - y_w\bar{w}(380)) & \dots & BL(780)(\bar{y}(780) - y_w\bar{w}(780)) & BL(380)(\bar{y}(380) - y_w\bar{w}(380)) & \dots & BL(780)(\bar{y}(780) - y_w\bar{w}(780)) & BL(380)(\bar{y}(380) - y_w\bar{w}(380)) & \dots & BL(780)(\bar{y}(780) - y_w\bar{w}(780)) \end{bmatrix}, A \cdot \begin{bmatrix} CF_{all}(1) \\ \dots \\ CF_{all}(1203) \end{bmatrix} = \begin{bmatrix} 0 \\ \dots \\ 0 \end{bmatrix},$$

$$Y = k[BL(380)\bar{y}(380), \dots, BL(780)\bar{y}(780), BL(380)\bar{y}(380), \dots, BL(780)\bar{y}(780), BL(380)\bar{y}(380), \dots, BL(780)\bar{y}(780)] \cdot CF_{all}(m). \quad (14)$$

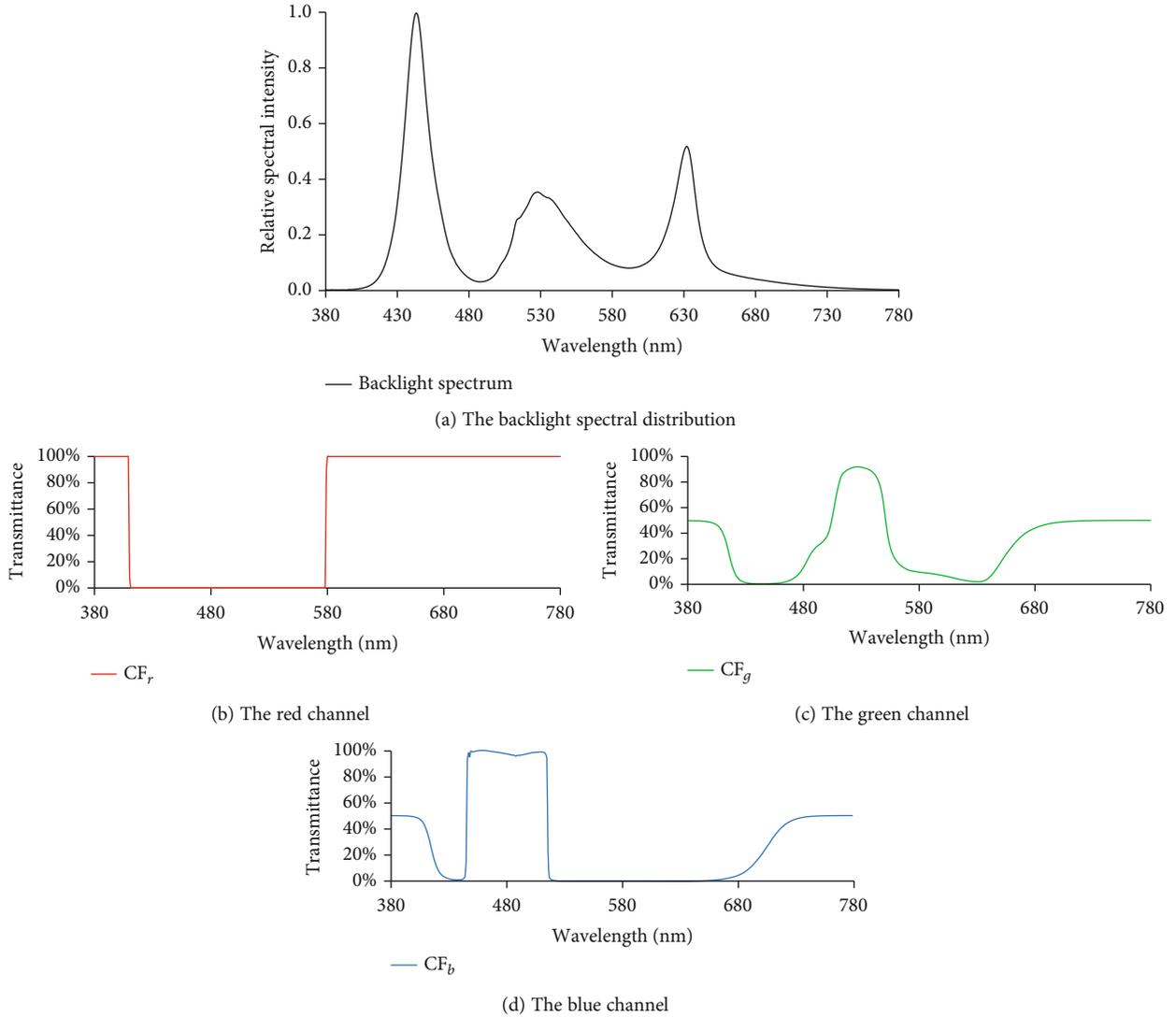


FIGURE 7: The optimization results of transmission spectrum line of the three primary color filter.

In addition, the value of the function  $CF_{all}(m)$  is the transmittance of the material, which should fall in the interval  $(0, 1)$ , i.e.,  $1 \geq CF_{all}(m) \geq 0$  ( $1 \leq m \leq 1023$ ). Finally, the linear programming problem contains 1203 unknown parameters, 8 equality constraints, and 2406 inequality constraints. The optimized distribution of  $CF_{all}(m)$  can be solved. The first to 401th values, the 402th to 802th values, and the 803th to 1203th values of the solution correspond to the red filter, green filter, and blue filter, respectively. By combining these three sets of transmittance spectral distribution and the known backlight, the color coordinates of the three primary colors of the red, green, blue, and white field are all the same, and the light efficiency reaches the maximum.

Through the proposed method, the transmittance optimization spectral distribution of any known backlight of the three primary color filters can be solved. Taking the spectral distribution shown in Figure 7(a) as an example, using NTSC color gamut standard, the abscissa is taken as the

wavelength length, and the ordinate is taken as the relative spectral intensity to calculate the relative intensity of RGB tri-color at the corresponding wavelength. Finally, the transmission spectrum line of the three primary color filters is optimized, and the results are shown in Figures 7(b)–7(d). The final light efficiency is 197.1 lm/W.

If the backlight spectrum is the result shown in Figure 6, the corresponding optimized transmittance distribution of the filter can also be obtained. The result is shown in Figures 8(a)–8(c).

Since the energy of the optimized backlight spectrum shown in Figure 6 is concentrated in some narrow bandwidths, the energy of the backlight can be retained to the maximum if the transmittance of the color filter at the corresponding wavelength is in a high-pass state. The light efficiency of the overall module can reach to the theoretical limit value of 335.5 lm/W. Compared with the common backlight, the loss of the light energy caused by the filter is smaller and easier to achieve.

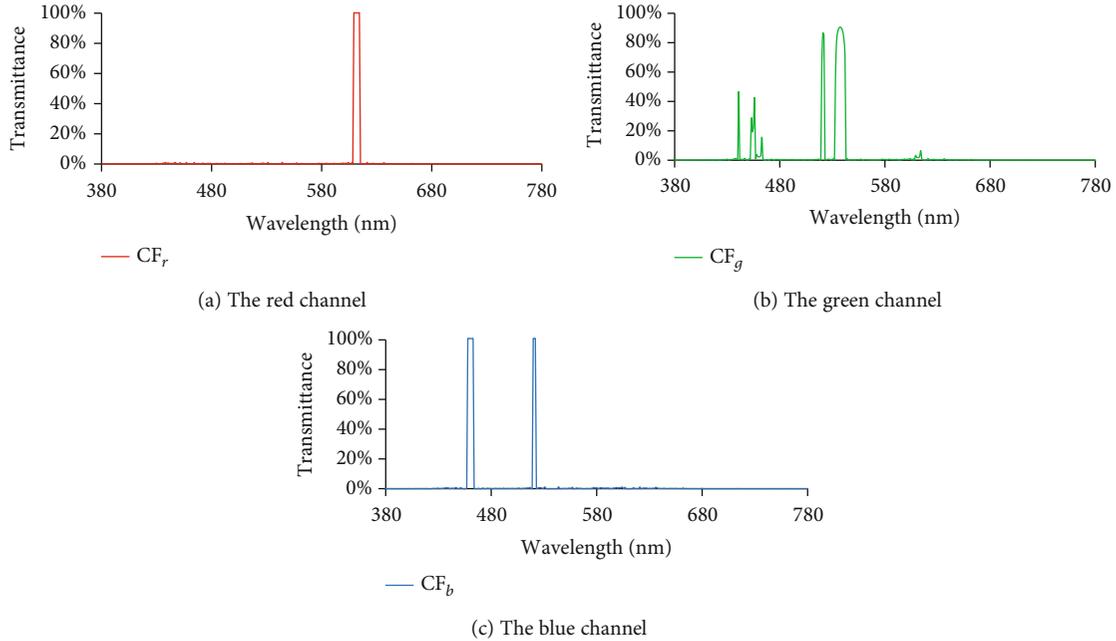


FIGURE 8: The result of filter transmittance lines for optimizing backlight spectrum.

#### 4. Analysis of the Backlight Optimization Model

According to the metamerism in colorimetry, the optimization of any color light spectrum and the LCD backlight spectrum can be achieved by constructing linear programming equations. However, from the simulation results, the spectrum with the theoretical maximum light effect has the characteristic of pulsed distribution. Since the liquid crystal displays is commonly used in the traditional LCD backlight source, the spectrum is difficult to approach the theoretical limit in practical applications. Then, the characteristics of the optimal spectral distribution of monochromatic light will be discussed. Combined with the new quantum dot backlight technology, the optimization of the spectrum in the application of improving the display backlight will also be discussed.

*4.1. Characteristic of Optimization of Primary Colors.* According to the aforementioned algorithm, any color light with known color coordinates can be optimized. Via the simulation of many colored lights, the distribution characteristics of the optimized spectrum of monochromatic light can be found. For a fixed color coordinate, the spectral distribution with the greatest light effect is often concentrated in two segments or a very narrow range, showing a pulse-like distribution. The power of the remaining wavelengths is zero. These wavelengths of zero value mean that they are ineffective or less effective to a given color coordinate. Therefore, the optimized backlight spectrum should avoid letting the power distribute at these wavelengths for reducing the waste of the light energy. The feature of the pulsed distribution simplifies the process of the optimized spectrum. Therefore, the wavelength and the relative intensity of the pulse can be used to determine an optimized spectrum distribution. In Figures 9(a)–9(c), the pulse wavelength and

the relative intensity of the optimized spectrum of three primary colors under the NTSC standard in Figure 5 is annotated, respectively.

It can be seen from Figure 9 that the optimized spectrum for color coordinates (0.67, 0.33) (NTSC standard red) contains a main peak at 611 nm. The optimized spectrum for color coordinates (0.21, 0.71) (NTSC standard green) contains a main peak at 538 nm and a secondary peak at 454 nm, where the intensity is 13.0% of the main peak. The color coordinate (0.14, 0.08) (NTSC standard blue) optimized spectrum contains a main peak at 460 nm and a secondary peak at 521 nm where the intensity is 30.2% of the main peak. These wavelengths of the main peaks are close to the optimization results obtained by Senfar Wen, according to the color difference statistical algorithm [28, 29].

The wavelength positions and relative intensities of the main and secondary peaks of the optimized spectra vary with the color gamut. According to the algorithm discussed above, for any given gamut standard, the characteristic peak position of each primary color can be obtained. In the actual application, the backlight spectrum should be adjusted to the corresponding main and secondary peak positions, and the relative intensity should be maintained to continuously approach the theoretically optimized spectrum. Eventually, the light efficiency of the backlight can be improved when the color gamut is unchanged.

*4.2. Optimization of the Quantum Dots.* As for the optimized spectrum characteristics of the pulsed distribution, the traditional broad spectrum light source is difficult to achieve. In addition to lasers, new quantum dot materials offer great possibilities for approaching the ideal spectrum. As for fitting the ideal backlight, quantum dot materials should be used to meet the wavelength of the primary and secondary peaks in

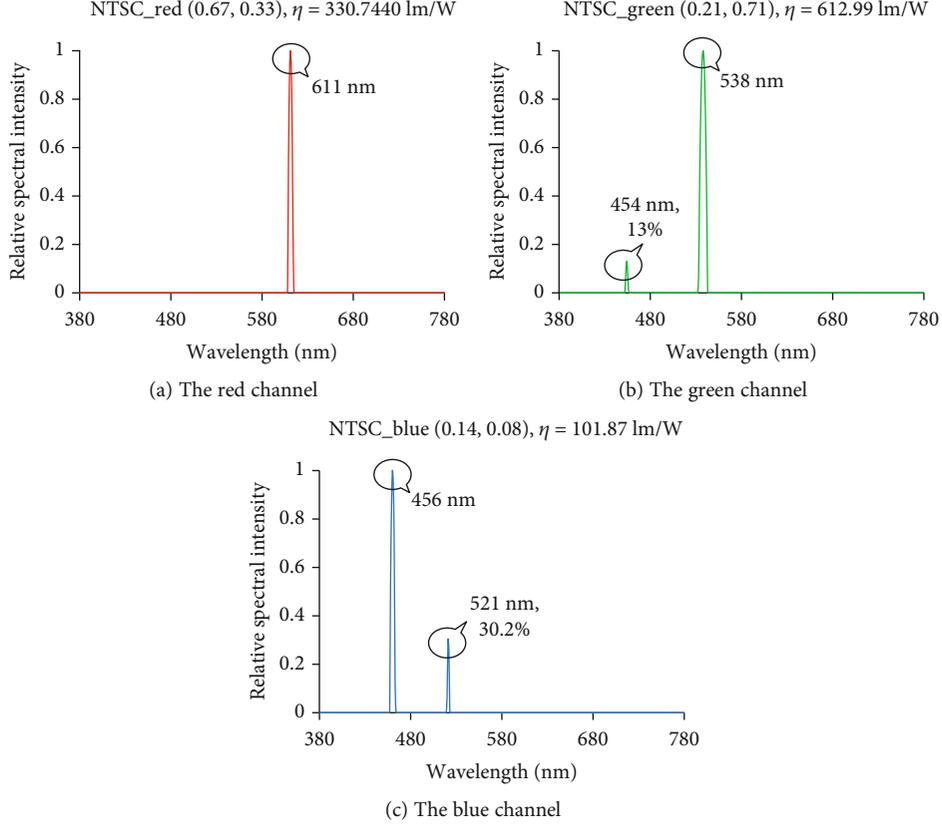


FIGURE 9: The wavelength and relative intensity of the optimized spectral distribution of the NTSC standard.

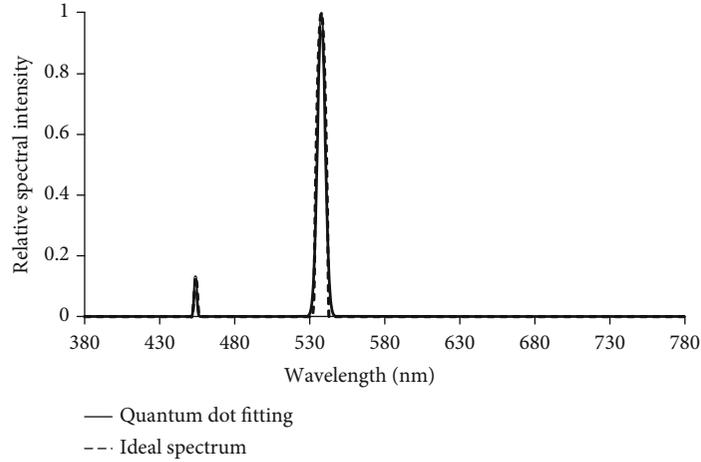


FIGURE 10: The simulation spectrum of the quantum dot backlight.

the optimized spectrum. The relative intensity of each primary color can be controlled by changing the concentration of the quantum dot materials. However, even for quantum dot materials, the spectrum is not strictly in the pulse distribution. In the mathematical model, Gaussian distribution can be used to simulate the spectrum [30, 31]. Equation (15) is given as follows:

$$\Phi_{\text{QD}}(\lambda) = e^{-\ln 2((\lambda - \lambda_p)/d)^2}. \quad (15)$$

In which,  $\lambda_p$  represents the center wavelength of the quantum dot spectrum, and  $d$  represents the half-wave width. In order to study the approximation degree of fitting and optimizing backlight by using quantum dot materials, under the NTSC green standard, the simulation results is shown in Figure 10.

The results show that the position and relative intensity of the main and secondary peaks are consistent with the ideal spectrum. The half-wave width of the main peak is 3 nm, and the secondary peak is 1 nm. The actual color coordinates of

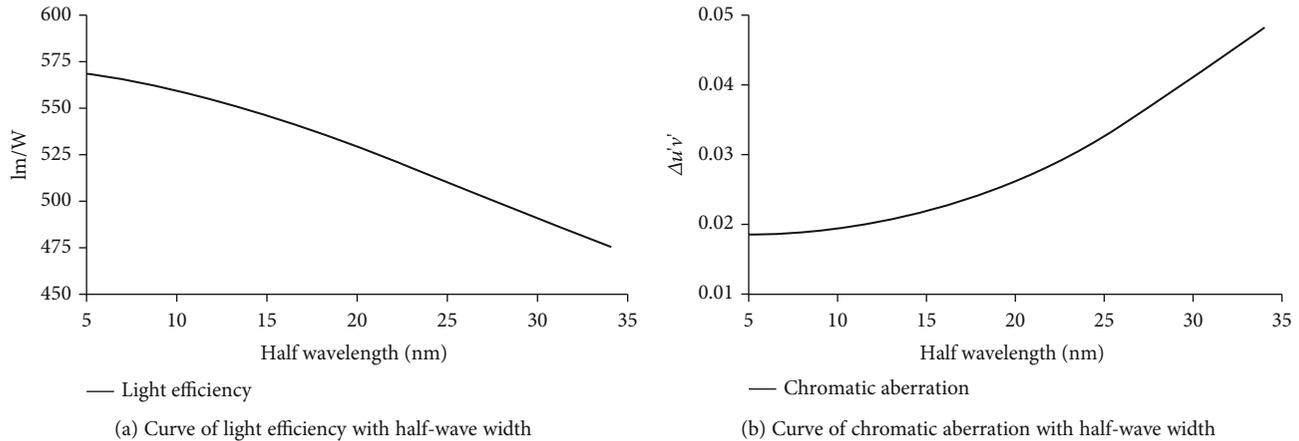


FIGURE 11: The curves of luminous efficiency and chromatic aberration with half-wave width, respectively.

the simulated waveform are (0.21, 0.71), and the luminous efficiency is 610.8 lm/W. The simulated waveform almost coincides with the ideal waveform. The luminous efficiency is improved on the premise that the green color coordinate remains unchanged, showing the importance of the position of the main peak of the spectrum. However, the half-wave width of the actual quantum dot material is wider than the simulation one. The excessively wide spectral distribution will not only generate unnecessary energy consumption but also affect the reproduction of the target color. Figures 11(a) and 11(b) show the variation curves of the luminous efficiency and the chromatic aberration with half-wave width, respectively. The chromatic aberration is characterized by the distance between two color coordinate points, i.e.,  $\Delta u'v'$ , under the CIE-1976  $u'v'$  color space.

It can be seen from Figure 11 that as the half-wave width of the quantum dot material increases, the chromatic aberration of the fitted waveform continues to increase, and the light efficiency continues to decrease. In order to correct the error caused by the half-wave width, it is necessary to further adjust and optimize the primary and secondary positions of the waveform on the basis of the original waveform.

## 5. Conclusion and Future Work

In summary, based on the aforementioned results, using the metamerism of the human visual system, this paper proposes a linear programming-based algorithm for optimization of the backlight spectrum within the range of any given display system color gamut. On the premise of keeping the color gamut of the display system, the maximum theoretical luminous efficiency of the backlight is calculated by the proposed algorithm. The simulation results provide a design reference and characteristic standard for the future low-power display. At the same time, this paper shows that the utilization of narrow-bandwidth light sources such as lasers and quantum dot materials can make it easier to approach the maximum value of theoretical light efficiency. Besides, as the bandwidth of the nonideal backlight source increases, the positions of the primary and secondary peaks of the original optimized waveform may shift. Therefore, the next research can be

focused on optimization of the algorithm by using the specific material. In addition, it needs to be further considered that the Gaussian function spectral distribution characteristics should be combined in the spectral distribution optimization design. At the same time, by reasonably changing some parameters and constraints in the metamerism equation, targeted simulation optimization is realized, and the error is continuously reduced.

## Data Availability

The data in this paper are valid and available from the corresponding author.

## Conflicts of Interest

This paper does not contain any conflict of interest.

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