Research about evaluating the spectrum of WOLED

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■ Abstract

White organic LED spectrum for lighting and displaying should be designed for high luminous efficiency as well as good chromaticity coordinate, pleasant correlated color temperature and color rendering. A program based on Matlab was made to make these calculations convenient. The chromaticity coordinate and luminous efficiency was calculated according to the CIE 1931 colorimetric system, while the correlated color temperature(CCT) was calculated based on CIE 1960 UCS diagram. The color rendering characteristics were evaluated according to the CIE Color Rendering Index (CRI), using Ra, Ri and △E from the 14 color samples defined in CIE13.3.

Key word: WOLED, CRI, CCT, Luminous efficacy of radiation

1. Introduction

Interest in next-generation displays and lighting technologies has stimulated research on organic light-emitting devices (OLED). Especially, white-emitting OLED(WOLED)have led to significant improvements in efficiency, targeting light source and backlights for full color displays or even ones combined with color filters. Since white light by OLED is realized by dozens of structures with different materials, questions arise on how the spectra of white OLEDs should be designed for good light source or full-color displays. Appropriate white color and good color rendering performance have to be the main direction. Color rendering, as well as luminous efficacy are the two most important criteria. Color rendering is a property of a light source that shows how natural the colors of objects look under the given illumination. If color rendering is poor, the light source will not be useful for general lighting. Besides color rendering, luminous efficacy, the spectrum of WOLED, CCT are also important characteristics. Since color rendering and efficacy are generally in the trade-off relationship, the spectra of white-light OLEDs need to be designed to meet requirements in both aspects. Besides this, to measure and compare these WOLEDs with different structures and materials efficiently also becomes a problem for laboratory researchers. In this paper , a small program based on Matlab was made to calculate characteristics of WOLED including the color rendering index, luminous efficacy, the spectral distribution, correlated color temperature, chromaticity coordinate and the R,G,B coordinate through color filters.

2. Results

For laboratory use, the program code itself should be easily read and understand, so that different users can used it freely and add in new functions according to their experiments' needs. Matlab fits all our desires. Besides these, it can also provide powerful graphic interface, which makes

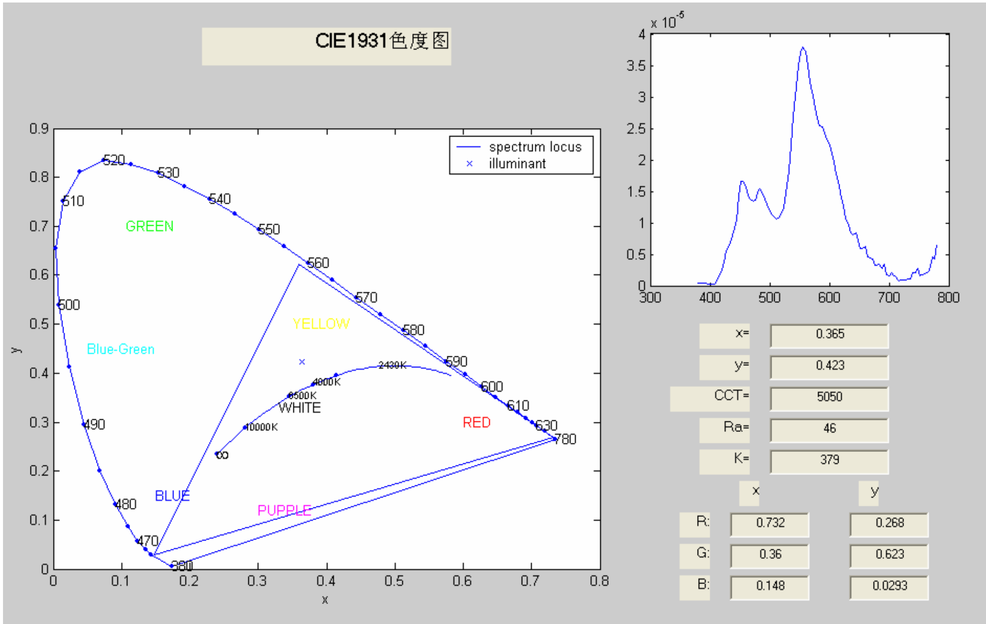

Figure 1

our comparisons more intuitionistic. See Figure 1.

As is shown above, this program contains 6 characteristics of white light: the color rendering index(CRI), correlated color temperature(CCT), luminous efficacy, light coordinate, spectral distribution curve, and the final R, G, B coordinates through color filters.

2.1. CIE color coordinate

For white OLED, the first characteristic should be considered is its color coordinate, which, as everyone knows, should be around (0.33, 0.33). The procedure for the calculation is, first, to sample the correlated spectral distribution data $S(\lambda)$ with a sampling interval of 5nm in this report. Then, calculate the tristimulus values(X, Y, Z) of CIE1931 color system according to the spectral distribution data measured above by

$$X = \kappa \sum_{\lambda} \varphi(\lambda) \bar{x}(\lambda) \Delta\lambda \text{ --------------(1)}$$

$$Y = \kappa \sum_{\lambda} \varphi(\lambda) \bar{y}(\lambda) \Delta\lambda \text{ --------------(2)}$$

$$Z = \kappa \sum_{\lambda} \varphi(\lambda) \bar{z}(\lambda) \Delta\lambda \text{ --------------(3)}$$

$$\kappa = \frac{100}{\sum_{\lambda} \varphi(\lambda) \bar{y}(\lambda) \Delta\lambda} \text{ ----------------(4)}$$

$(\Delta\lambda = 5\text{nm})$

,where $S(\lambda) = \varphi(\lambda)$ for light source.

The chromaticity coordinates(x, y) for white light is obtained by

$$x = \frac{X}{X+Y+Z} \text{ ---------------------(5)}$$

$$y = \frac{Y}{X+Y+Z} \text{ ---------------------(6)}$$

So, any light emitting from WOLED can be expressed by the chromaticity coordinate (x, y) on the CIE1931(x, y) chromaticity diagram on program interface, as shown in Figure 2.

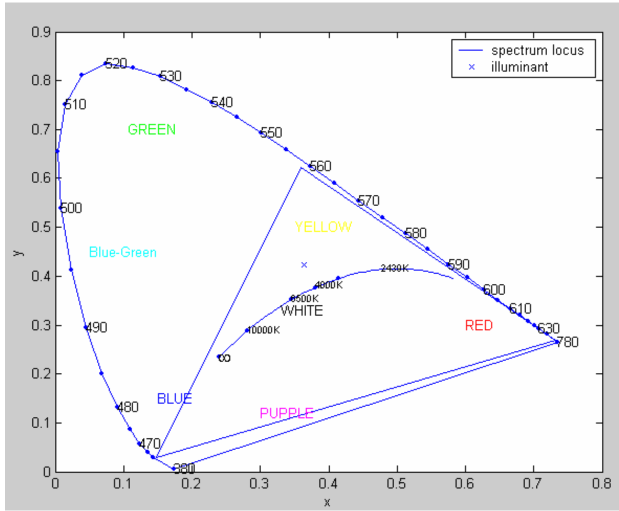

Figure 2

2.2. Luminous efficacy of radiation

The luminous efficacy of radiation, K, (ratio of luminous flux to radiant flux) is determined by the spectral distribution $S(\lambda)$ of the source as given by

$$K = \frac{K_m \sum_{\lambda} V(\lambda)S(\lambda)\Delta\lambda}{\sum_{\lambda} S(\lambda)\Delta\lambda} \text{ ----------------(7)}$$

, where K_m = 683 [lm/W].

2.3. Correlated color temperature (CCT)

Correlated color temperature(CCT) is the temperature of the blackbody whose perceived color most resembles that of the light source in question. Due to the nonlinearity of the x, y diagram, the iso-CCT lines are not perpendicular to the Planckian locus on the x, y diagram. To calculate CCT, CIE 1960 UCS is used, where the iso-CCT lines are perpendicular to the Planckian locus by definition. The u, v chromaticity coordinate is transferred from x, y chromaticity by

$$u = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3}$$

-----------------------(8)

$$v = \frac{6Y}{X+15Y+3Z} = \frac{6y}{-2x+12y+3}$$

-----------------------(9)

Because of the limitation of data base, method of interpolation is used to calculate CCT, see Figure 3.

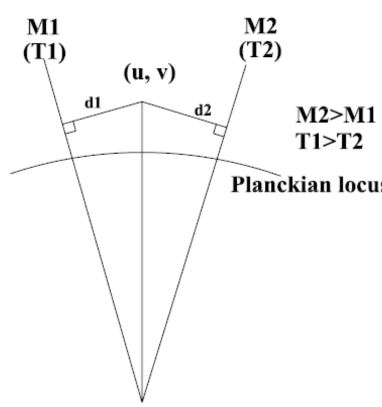

Figure 3

In Figure 3, point (u, v) is between two isotherms with unit of mired. The CCT of light source is given by

$$T_{C48} \approx 10^6 \Big/ \left[M_1 + \frac{(M_2 - M_1) \times d_1}{d_1 + d_2} \right]$$ -----------------(10)

As the two isotherms are based on the international practical temperature scale in 1948, expression is made below, to change into the international practical temperature scale in 1968,

$$T_c = \frac{1.4388}{1.4380} \times T_{c48}$$ --------------(11)

2.4. Color rendering index (CRI)

Color rendering index of a light source is evaluated by comparing the appearance of various object colors under illumination by the given light source with that under reference illumination, day light for CCT>5000K and Planckian radiation for CCT<5000K. The smaller the color differences of the object colors are the better the color rendering is.

The procedure for the calculation can be divided into 6 steps. First, to select the right reference illumination by comparing the color difference ΔC of the given illumination (u_k, v_k) and the reference illumination (u_r, v_r), with 5.4×10^{-3} by

$$\Delta C = \left[(u_k - u_r)^2 + (v_k - v_r)^2 \right]^{\frac{1}{2}}$$ -------------------(12)

ΔC should be less than 5.4×10^{-3}.

The second step is to calculate the color differences ΔE_i (on the 1964 W*U*V* uniform color space-now obsolete) of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination.

$$\Delta E_i = \sqrt{(U^*_{r,i} - U^*_{k,i})^2 + (V^*_{r,i} - V^*_{k,i})^2 + (W^*_{r,i} - W^*_{k,i})^2}$$ --------------------(13)

Where $W^*_{r,i}$, $W^*_{k,i}$, $U^*_{r,i}$, $U^*_{k,i}$, $V^*_{r,i}$, $V^*_{k,i}$ are the test illumination and reference illumination coordinates under 1964 W*U*V* uniform color space. It should be noticed that the von Kries chromatic adaptation transformation is considered in this step.

The third but the last step is to calculate R_a. The first eight samples are medium saturated colors, and the last six are highly saturated colors (red, yellow, green, and blue), complexion, and leaf green. For each color sample, the special color rendering index is obtained by

$$R_i = 100 - 4.6 \triangle E_i$$ ---------------------(14)

This gives the evaluation of color rendering for each particular color. The General Color Rendering Index Ra is given as the average of the first eight color samples:

$$R_a = \frac{1}{8} \sum_{i=1}^{8} R_i$$ --------------------(15)

The source of perfect color rendering (color difference is zero) is 100. So the better the color rendering is, the closer it is to 100. The CRI is often referred to R_a.

2.5. R, G, B chromaticity coordinates

In case of full-color display, it is important to evaluate the R, G, B chromaticity coordinates after the white light go through color filters. This function is achieved by

$$X_i = \kappa \sum_{\lambda} \varphi(\lambda) \bar{x}(\lambda) f_i(\lambda) \Delta\lambda$$ -------------------------(16)

$$Y_i = \kappa \sum_{\lambda} \varphi(\lambda) \bar{y}(\lambda) f_i(\lambda) \Delta\lambda$$ -------------------------(17)

$$Z_i = \kappa \sum_{\lambda} \varphi(\lambda) \bar{z}(\lambda) f_i(\lambda) \Delta\lambda$$ -------------------------(18)

$$\kappa = \frac{100}{\sum_{\lambda} \varphi(\lambda) \bar{y}(\lambda) \Delta\lambda}$$ ------------------------(19)

$$x_i = \frac{X_i}{X_i + Y_i + Z_i} \qquad \text{------------------------(20)}$$

$$y_i = \frac{Y_i}{X_i + Y_i + Z_i} \qquad \text{------------------------(21)}$$

$$z_i = \frac{Z_i}{X_i + Y_i + Z_i} \qquad \text{------------------------(22)}$$

Where $f_i(\lambda)$ is the filter index with a sampling interval of 5nm.

3. Conclusion

In this report, six major characteristics of white-light OLED are calculated and expressed on the program interface with spectral distribution curve. From this interface, every WOLED sample can be analysed very soon as well as we measured the spectral distribution. And then, other WOLED samples can be compared with and shown in both curves mentioned above, while the number of compared samples are not limited and each sample is identified with different color. See Figure 3. This program can be a very helpful tool for our researchers to analyse and decide the research direction on structure or material.

And for now, our further work will be concentrated on simulating 2-peak, 3-peak or even 4-peak white light and from its appearance on the other characteristics mentioned above, we can decide which form of spectrum peak can be wroth trying.

4. Acknowledgements

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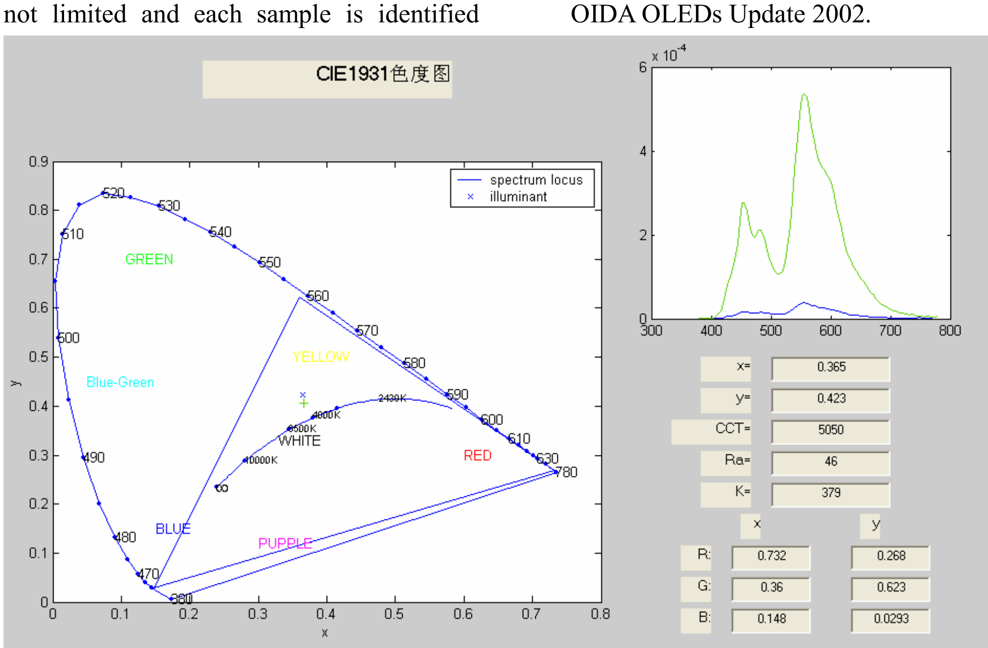

Figure 4