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CORRELATED COLOR TEMPERATURE DETERMINATION FOR LED MODULESUSING A DIGITAL COLOR SENSOR

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Parametrii modulelor LED de putere sunt specificați de cei mai mulți producători la temperatura pe joncțiune (Tj) de 25 °C în timp ce temperatura de operare poate ajunge la 135 °C. Pentru producătorii de aparate de iluminat este important să se specifice temperatura de culoare corelată (CCT) la Tj de operare.

În acestă lucrare se urmăresc calculul temperaturii de culoare corelate (CCT) pentru un modul LED, utilizând semnalele RGB (rosu, verde, albastru) achiziționate de la un colorimetru digital şi deasemena procedura de măsurare cu un dispozitiv prototip. Pentru determinarea CCT a unui modul LED dat, trebuie mai întâi să reprezentăm răspunsul RGB al colorimetrului funcție de componentele tricromatice (X,Y,Z) ale Comisiei Internationale de Iluminat (CIE), utilizănd o sferă de integrare cu spectrofotocolorimetru. Apoi este necesar să se calculeze matricea de corelație între sfera de integrare si colorimetru, pentru determinarea coordonatelor de culoare (x,y) ce pot fi transformate în CCT cu formula lui Mc Camy. Matricea de corelație a fost calculată cu ajutorul a 8 ținte (module LED) și a fost salvată în memoria EEPROM a colorimetrului pentru măsurarea CCT între 3000K și 8000K, după instalarea colorimetrului în dispozitivul prototip ce poate fi utilizat pentru sistemele de calitate din industria iluminatului cu semiconductori (SSL).

White power LED modules parameters are specified by most manufacturers at the junction temperature (Tj) of 25 °C as the operation temperature may rise up to 135 °C. For luminaires manufacturers it is important to specify correlated color temperature (CCT) at the correct operation temperature.

This paper will examine how to calculate CCT of a given LED module using RGB (red, green, blue) signals acquired from a digital colorimeter and also the measurement procedure with a prototype device. In order to determine CCT, the response signals (RGB) must be firstly mapped to the Commission Internationale de l'Eclairage (CIE) tristimulus value (XYZ) by means of an integration sphere with a spectrophotocolorimeter. Then the correlation matrix between integration sphere and colorimeter is calculated, in order to determine colorimeter chromaticity coordonates (x,y) to be converted into a CCT value with Mc Camy's formula CCT. This matrix it was calculated using 8 targets (LED modules) and was saved to colorimeter EEPROM memory to measure CCT from 3000K to 8000K, after colorimeter was installed to the prototype device that can be useful in feedback control and quality systems for solid state lightning (SSL) industry.

Keywords: Correlated Color Temperature, digital colorimeter, tristimulus values (XYZ), chromaticity coordonates (x,y), integration sphere, spectrophotocolorimeter.

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1. Introduction

LED modules is a term as used in order to describe a matrix, surface or an arrangement of individual chip structures on a common substrate who shares same YAG converter and silicon encapsulant. Such LED modules may contain between 2 and 100 chip structures which are wire bonded in series and/or parallel as to get an output power up to 300W with forward voltages ranging between 9V and 100V. During production, the photometric and electrical parameters of the LED modules are measured with a short pulse (10 to100msec) and consequently junction temperature never reaches maximum operation.

The light of LED modules is emmited by solid state electroluminescence, as opposed to incandescent bulbs (which use thermal radiation) or fluorescent tubes. Compared to incandescent lightning, white LED modules produce visible light with reduced heat generation and efficient photon extraction. Most common “white” LED modules convert blue light from a solid state device to an (approximate) white light spectrum using photoluminescence, the same principle used in conventional tubes.

CCT, measured in Kelvin (K), has been used to characterize a near-white (bluish-white, neutral, or reddish white) light source like LED modules. CCT information could be useful in feedback control and quality control systems like the prototype device presented in this paper.

2. Theory

CCT determination

In order to determine CCT for a given LED module using a digital colorimeter, we will first map the sensor response (RGB) to the CIE tristimulus values (XYZ). Then is necessary to calculate colorimeter chromaticity coodonaties (x,y) and finally CCT. The steps as well as the methods used for each transformation are described in Fig. 2.

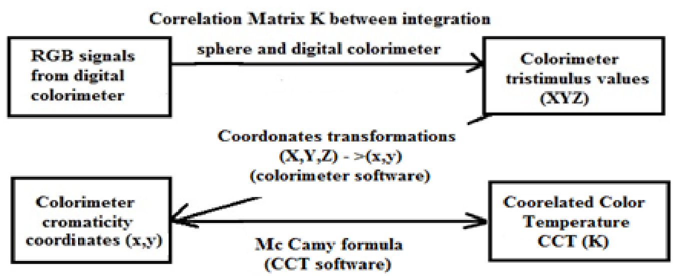

Fig. 2. CCT calculation process overview

Illuminance from integration sphere it will be measured with a luxmeter. The tristimulus value Y represents the illuminance of LED module.

As we can see in the diagram from Figure 2, the first step is to map the RGB sensor response to the CIE tristimulus values (XYZ). This transform is necessary to account for any discrepancies between the spectral response of the sensor and that of the CIE tristimulus value. The two normalized responses are plotted next to each other in Fig. 3.

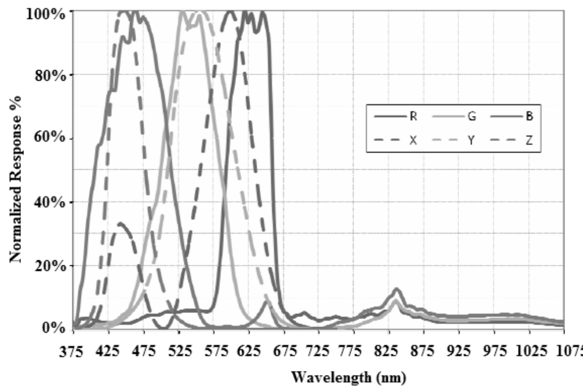

Fig. 3. Digital colorimeter RGB normalized response vs. CIE tristimulus XYZ

The following equations (1-3) can be used to correlate the RGB values from colorimeter and XYZ values from integration sphere. These equations are the result of a correlation matrix K [1].

$$X = (a_{11})\,(R) + (a_{12})\,(G) + (a_{13})\,(B) \tag{1}$$

$$Y = (b_{11})\,(R) + (b_{12})\,(G) + (b_{13})\,(B) \tag{2}$$

$$Z = (c_{11})\,(R) + (c_{12})\,(G) + (c_{13})\,(B) \tag{3}$$

Where $K = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$ is the correlation matrix.

Chromaticity coordonaties (x,y) are based on standard tristimulus values (XYZ). These standards are set by (CIE) [4].

Chromaticity coordinates (x,y) can be calculated with tristimulus values (XYZ) and then the light can be plotted on two-dimensional chromaticity diagram such as the one shown in figure 1, by colorimeter software with (4) and (5) formulas:

$$x = X/(X+Y+Z) \tag{4}$$

$$y = Y/(X+Y+Z) \tag{5}$$

where (x,y) = cromaticity coordinates and (X,Y,Z) = tristimulus values

CCT can be determined using Mc Camy's formula (6) for given a particular x,y chromaticity coordinate [3], with an absolute error of less than 2 degree Kelvin for CCT's in the form:

$$CCT = 449\,n^3 + 3525n^2 + 68253.3n + 5520.33 \qquad (6)$$

where $n = (x - 0.33320)/(0.1858 - y)$

Correlation matrix K determination

Integrating sphere spectrophotocolorimeter it will be used to establish the CIE tristimulus values for LED module. The correlation matrix K can be formulated after XYZ and RGB values are obtained. Once K is determined it can be used to transform the colorimeter response to a set of equivalent values (XYZ) (see (1), (2) and (3) formulas).

3. Experimantal procedure

Measurement equipments used for correlation matrix K determination are the following: an integrating sphere with spectrophotocolorimeter, a digital colorimeter, a luxmeter and a DC power source.

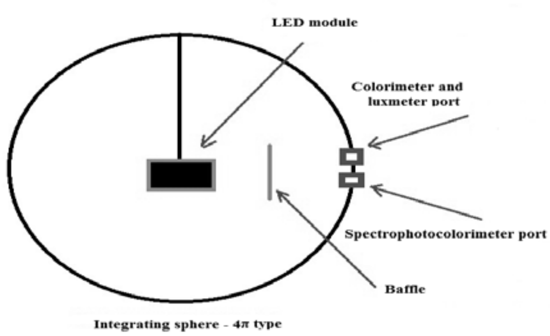

Fig. 4. Integrating sphere with spectrophotocolorimeter

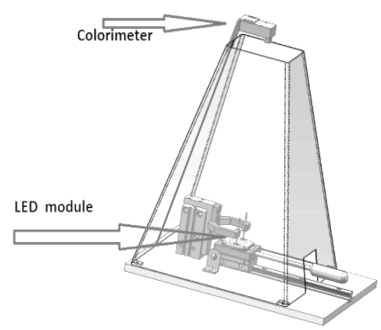

Fig. 5. Prototype device for CCT

Integrating sphere has an input port for spectrophotocolorimeter to aquire CCT and cromaticity coordonates (x,y) and another input port for digital colorimeter to measure RGB signals and for a luxmeter to measure illuminance.

Calculation steps to determine the correlation matrix K are presented below:

a) Data measured from target (T – integrating sphere) and sensor (S – colorimeter):

$$T = \begin{pmatrix} X_1 & X_t \\ Y_1 \ldots & Y_t \\ Z_1 & Z_t \end{pmatrix} \quad S = \begin{pmatrix} X_{ADC1} & X_{ADCt} \\ Y_{ADC1} \ldots & Y_{ADCt} \\ Z_{ADC1} & Z_{ADCt} \end{pmatrix} \tag{7}$$

where t = is the number of targets (the LED modules).

b) Electronic offset:

b1). Electronic offset

ADC values are read out after the sensor it is coverd and saved as $XYZ_{ADCOffset}$:

$$\begin{pmatrix} X_{ADCOffset} \\ Y_{ADCOffset} \\ Z_{ADCOffset} \end{pmatrix}$$

b2). Data from sensor (colorimeter) adjusted with $XYZ_{ADCOffset}$:

$$S' = S - \begin{pmatrix} X_{ADCOffset} \\ Y_{ADCOffset} \\ Z_{ADCOffset} \end{pmatrix}$$

c). Calculate the black-white offset:

c1). Search the min and max values of Sensor data S':

$$\begin{pmatrix} X_{ADCmin} \\ Y_{ADCmin} \\ Z_{ADCmin} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} X_{ADCmax} \\ Y_{ADCmax} \\ Z_{ADCmax} \end{pmatrix}$$

c2). Copy the corresponding values out of Target data T:

$$\begin{pmatrix} X_{min} \\ Y_{min} \\ Z_{min} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} X_{max} \\ Y_{max} \\ Z_{max} \end{pmatrix}$$

c3). Calculate the black-white offset (y – axis intercept) XYZ_{Offset} :

$$\begin{aligned} X_{Offset} &= X_{ADCmin} - \frac{X_{ADCmax} - X_{ADCmin}}{X_{max} - X_{min}} \cdot X_{min} \\ Y_{Offset} &= Y_{ADCmin} - \frac{Y_{ADCmax} - Y_{ADCmin}}{Y_{max} - Y_{min}} \cdot Y_{min} \\ Z_{Offset} &= Z_{ADCmin} - \frac{Z_{ADCmax} - Z_{ADCmin}}{Z_{max} - Z_{min}} \cdot Z_{min} \end{aligned} \tag{8}$$

c4). Adjust Sensor data with XYZ_{Offset}

$$S'' = S' - \begin{pmatrix} X_{Offset} \\ Y_{Offset} \\ Z_{Offset} \end{pmatrix} \quad (9)$$

d). **Calculate the (3,3) correlation matrix K for linear transformation**:

$$K = \left(T \cdot S''^{trans}\right) \cdot \left(S'' \cdot S''^{trans}\right)^{-1} \quad (10)$$

where trans = transpose of matrix and -1 = invers

e). Measurement uncertainties for (x,y) cromaticity coordonates and Y (illuminance):

$$dxy = \sqrt{dx^2 + dy^2} \quad (11)$$

$$dY = \frac{Y_{colorimeter} - Y_{sphere}}{Y_{sphere}} * 100 \quad (12)$$

where (x,y) represents the cromaticity coordonates, (X,Y,Z) are the tristimulus values, Y =L is the illuminance from luxmeter.

4. Result and discussions

Inside integrating sphere it was measured the following parameters of 8 targets (LED modules): cromaticity coordonates (x,y) and CCT from spectrophotocolorimeter, illuminance from luxmeter and RGB signal from colorimeter.

The following coordinates transformation (L,x,y) -> (X,Y,Z) it was applied to sphere integration acquired data (L,x,y):

$$X = \frac{x * L}{y}, \quad Y = L = \text{Illuminance}, \quad Z = \frac{(1 - x - y) * L}{y} \quad (14)$$

where (x,y) represents the cromaticity coordonates, (X,Y,Z) are the tristimulus values, Y =L is the illuminance from luxmeter.

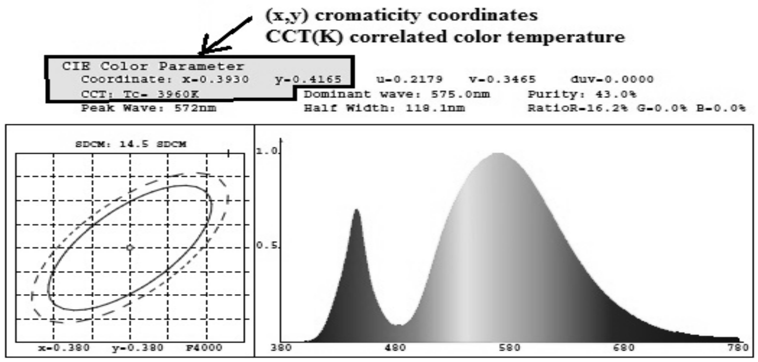

Fig. 6. Example of cromaticity coordonates (x=0.393,y=4165) and CCT =3960K acquired from integration sphere with spectrofotocolorimeter

With these (X,Y,Z) tristimulus values from integration sphere and the RGB signals from colorimeters it was determined the correlation matrix K, using chapter 3 calculation process with (7),(8),(9),(10) and (11) formulas:

$$K = \begin{pmatrix} -2.21000031 & 4.96758367 & -0.81192933 \\ -4.03999198 & 7.16758712 & -1.21982205 \\ -6.95194791 & 7.56599134 & 5.42387898 \end{pmatrix} \qquad (15)$$

This matrix is saved to digital colorimeter EEPROM memory to measure LED module's CCT(K) (from 4000K to 8000K) with prototype device from Fig. 5.

Electronical offfset and black-white offset of colorimeter it was set to zero.

Measurement uncertainties for (x,y) cromaticity coordinates is dxy<0.0028 and for illuminance dY<4.43%.

CCT can be calculated with Mc Camy's formula (6), using colorimeter (x,y) cromaticity coordonates calculated with (1),(2),(3),(4) and (5) formulas.

For example, we have cromaticity coordinates (x,y) = (0.3930, 0.4216) acquired from colorimeter and CCT is calculated below with formula (6):

$$n = \frac{x - x_e}{y - y_e} = 0.258757, \text{ where } x_e = 0.3320,\ y_e = 0.1858$$

then $CCT = 449\,n^3 + 3525n^2 + 68253.3n + 5520.33 = 3982.992$

With integration sphere spectrophotocolorimeter it was measured this CCT = 3960 K, that means the colorimeter value has a difference of 1.933% from sphere.

5. Conclusion

Near-white light of LED modules can characterized with CCT, using RGB color response of a digital colorimeter. CCT it was determined after severel calculation, from (x,y) colorimeter cromaticity coordonates acquired after correlation matrix K.

Correlation matrix K it was calculated using 8 targets (LED modules: 3960K, 4129K, 4684K, 4784K, 4872K, 5217K,6952K, 7824K) and was saved to colorimeter EEPROM memory to measure CCT from 3000K to 8000K, after colorimeter it was installed to the prototype device that can be useful in feedback control and quality systems for SSL industry.

Measurement uncertainties between integration sphere and colorimeter for (x,y) cromaticity coordinates is dxy<0.0028 and illuminance between luxmeter and colorimeter is dY<4.43%.

Correlation matrix K can be calculated with up to 24 targets (LED modules) for narrower range of CCT.

R E F E R E N C E S

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