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LED-based metameric light sources: Rendering the colours of objects and other colour quality criteria

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Solid-state white light sources based on multiple light emitting diodes (LEDs) have three features that make them radically different from other sources of electrically generated light. These are the narrowband spectra of the individual LEDs, the possibility of controlling the light output of the individual LEDs and the limited stability of the LED's colour. These features make it possible to achieve a set of solid-state white light sources that are metameric to a selected reference light source. A computational method to optimise the intensities of narrowband LEDs to obtain these metameric light sources is proposed. The appearance of object colours under these metameric light sources differs and can be used to satisfy users' requests according to the various aspects of colour quality required, without altering the visual appearance of the light source.

1. Introduction

Solid-state lighting technology based on multi-chip light emitting diodes (LEDs) is now emerging as a cost-competitive, energy-efficient alternative to conventional electric lighting.[1] A few aspects of narrowband LED light sources make them different from other sources of electrically generated light and are important for the evaluation of colour rendering. These aspects are the narrowband spectra of the LEDs, the controllability of light output and the limited stability of the colour of LEDs.

The narrowband spectra of LEDs used in lighting raise some doubt about the usefulness of a common metric used by the lighting industry to represent the colour rendering properties of electrically generated light sources. The colour rendering problems of white LEDs are being investigated by the International Commission on Illumination (CIE), with a future plan to develop a new metric.[2]

There are now more than 10 indices suggested for the evaluation of one or more aspects of colour appearance under illumination provided by sources of electrically generated light. Guo and Houser[3] reviewed nine of these indices. Several new indices have been suggested since.[4–7] Colour rendering index (CRI) is the most common metric.[8] CRI describes one aspect of a light source, i.e. CRI describes the colour appearance of a set of reflective test colour samples under the test light source compared to a reference light source. To calculate the CRI, the colour differences of a set of selected 14 Munsell colour samples[9] when illuminated by a reference illuminant and by the given illuminatant are determined. Then, the special CRI for each colour sample and the general CRI, taken as the average of the first eight colour samples, are calculated. A poor correlation between visual evaluation of white LEDs and the general CRI has been reported.[10–14] The conclusion of the CIE is that the CRI is

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generally not applicable for predicting the rank order of light sources for colour rendering if the set of light sources to be evaluated includes white LEDs.[2]

The colour discrimination index suggested by Thornton evaluates another aspect of colour appearance under illumination provided by sources of electrically generated light.[15] It is useful for predicting how well one can discriminate between differences in hue. The flattery index suggested by Judd[16] evaluates the degree to which an artificial illuminant succeeds in flattering people and objects viewed under it. The colour-rendering capacity describes the maximum possible number of different colours that can be displayed by a given illuminant.[17] Worthey[4] suggested a 3×3 'rendering matrix' to estimate systematic colour shifts when one illuminant is replaced by another. The elements of this matrix quantify the gain or loss of redness and greenness and the gain or loss of blueness and yellowness. A colour rendering approach based on the number of rendered colours from an extended colour palette (1269 Munsell samples) has been suggested by Žukauskas *et al*.[5,6] The rendered colours are defined as those whose chromaticity shifts are within three radii of the MacAdam ellipses. As a figure of merit for the overall assessment of colour rendering properties of an illuminant, the number of rendered colours measured as a percentage of the total number of the test samples is used.

Almost all these procedures for colour rendering evaluation are based on the calculation of the colour rendering of either a set of selected multiple colour samples or of a gamut of colours. Then, the result can be used to evaluate the colour rendering of a single colour. This is correct when the spectrum of the electrically generated light is more or less continuous. However, the uneven spectra of LED light sources make it difficult to account for the colour differences that occur with many different colour samples. Sharp gradients 0073 in the spectral reflectance curves of saturated colours cause some irregular results, with the spectra of LED light sources having large valleys between peaks in the spectral distribution curve.[18] For example, a saturated red can appear brown under an LED light source and have negative special CRI (−90), although the general CRI value is good (80).[18]

Controllability is another property of LED light sources based on multi-chip LEDs. LED light sources have a unique property compared to other light sources – they allow a wide degree of control over the spectrum of the light emitted. This property is based on changing the light output of individual LEDs, so that the LED light source can be metameric with reference light source. Since the chromaticity of the multi-chip LED light source illuminant can be made to exactly match the reference illuminant for a standard observer, no adaptive colour shift needs to be taken into account. That can eliminate errors of comparison of the colour appearances of objects under the test illuminant as opposed to the reference illuminant. It should be noted that due to the inter-observer variability of colour matching, the matching for a standard observer will not always match for a particular real observer and LED-type spectra enhance this effect.

Furthermore, this property allows selecting one LED light source from a few metameric LED light sources to optimise the colour appearance of selected objects. This allows estimation and optimisation of a specific colour appearance for coloured objects selected by users of the illuminant. Some customers prefer to be able to distinguish certain colours easily; others prefer colours to be saturated, and so on. For example, the preferred colour of the human complexion differs considerably from the average actual colour by being redder and more saturated, and the preferred colour for butter is less saturated than its actual colour.[19] In an operating theatre, a suitable colour temperature of the LED light can be set depending on the site of the operation e.g., brain surgery, thoracic surgery, celiac surgery and orthopaedic surgery.[20]

Another property of LED light sources that make them different from other sources of electrically generated light is the limited stability of their colour. It is the result of changes in the parameters of LEDs over time, due to environmental conditions, such as ambient temperature and humidity.[21] The possibility of controlling the light output of individual LEDs inside a multi-chip LED light source can be used to ensure the stability of colours. This depends on the chosen method of powering the LEDs.

The goal of this paper is to suggest a method for choosing the parameters of LEDs, so that a set of multi-chip LED light sources that are metameric to a given reference light source can be identified. An algorithm that implements the method is suggested. The algorithm is tested on a few examples of metameric light sources composed of two sets of four LEDs. The different colour rendering properties of metameric light sources are shown. This method can also be used to design the feedback circuits to power LED light sources with guaranteed colour stability.

2. Method

The aim of the simulation was to estimate the parameters of a set of white LED light sources metameric to a reference white light source and to perform comparisons between the colours of objects under these illuminants. In other words, our goal is to manipulate the spectral composition of multi-chip white LED light sources without altering the visual appearance of the light source itself, and to estimate the changes in the colours of objects.

The chromaticity coordinates (x, y) of a multi-chip LED light source, defined by the chromaticity coordinates of individual LEDs (x_i, y_i) are:

$$x = \sum_{i=1}^{n} x_i \frac{r_i}{y_i} \Big/ \sum_{i=1}^{n} \frac{r_i}{y_i}; \quad y = 1 \Big/ \sum_{i=1}^{n} \frac{r_i}{y_i}; \quad \sum_{i=1}^{n} r_i = 1, \tag{1}$$

where r_i is the relative luminous intensity of the individual LEDs and n the number of types of LEDs used in the multi-chip light source.

The relative luminous intensity r_i of individual LEDs can be estimated from Equation (1) and defined by:

$$\begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ 1 & 1 & 1 \end{pmatrix}^{-1} \times \left[\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} - \sum_{i=4}^{n} r_i \begin{pmatrix} a_i \\ b_i \\ 1 \end{pmatrix} \right], \tag{2}$$

where $a_i = \dfrac{x - x_i}{y_i}$, $b_i = \dfrac{y}{y_i}$ and r_i is any number in the range $0 \leq r_i < 1$ for $n > 3$.

Based on the statement that (x, y) are the chromaticity coordinates of the reference light source, a set of white LED light sources metameric to a reference white light source can be defined. If a white LED light source consists of three types of narrow-band LED $(n = 3)$, then there cannot be more than one set of LED luminous intensities that will make the white LED light source metameric to a reference light source. If at least one LED's luminous intensity has a negative value, a light source that is metameric to a reference light source does not exist. If a white LED light source consists of more than three types of LED $(n > 3)$, then more than one light source can be metameric to the reference light source.

The relative spectral power distribution of a white LED light source metameric to a reference light source can be expressed by the relative spectral power distributions of the LEDs:

$$S(\lambda) = \sum_{i=1}^{n} r_i S'_i(\lambda), \tag{3}$$

where $S'_i(\lambda) = S_i(\lambda)/\int_{380}^{780} \bar{y}(\lambda)\, S_i(\lambda)\, \mathrm{d}\lambda$ is the relative spectral power distribution of the LEDs, $S_i(\lambda)$ the spectral power distribution of the LEDs and $\bar{y}(\lambda)$ the colour matching function.

The algorithm showing the proposed methodology for estimating the parameters of a white LED light source metameric to a reference light source is shown in Figure 1.

A user selects the reference light source, the types of LEDs for the white light source and the criterion of colour rendering. The types of the reference light and the LEDs can be selected from databases of spectral power distribution of reference light sources and LEDs. Calculations of relative luminous intensity of LEDs are performed using Equation (2). The chromaticity coordinates (x, y) of the reference light and the LEDs are obtained from the spectral power distributions of the reference light and the LEDs. If the user selects more than three types of LEDs for the light source, then the relative luminous intensity of the fourth, fifth, etc. type of LEDs is changed from 0 to 1 by a fixed step. For every step, the calculations of relative luminous intensities of LEDs are performed. Relative luminous intensities of LEDs and the spectral power distributions of the LEDs are used to calculate the spectral power distribution of the white LED light source (Equation (3)). This spectral power distribution, the spectral power distribution of the reference light and the spectral reflectance factors of Munsell samples or real objects are used to calculate an index of colour rendering or some other aspect of light source colour quality like colour preference. The user's request is satisfied if the index of colour quality corresponds to the user's criterion value of that index.

3. Results of simulation

The aim of the simulation was to illustrate the applicability of the method. The proposed algorithm was used to create a computer program. We show the results of the simulation for a set of white LED light sources metameric to two reference light sources and composed of two sets of LEDs. The first set of LEDs was based on commercially available high power LEDs with the peak wavelengths of 641 nm (red), 598 nm (amber), 521 nm (green) and 447 nm (blue). The second set of LEDs was based on commercially available high power LEDs with the peak wavelengths of 598 nm (amber), 521 nm (green), 465 nm (cyan) and 447 nm (blue). The two reference light sources were a commercially available fluorescent lamp, F20T12/65, 6500 K, MacBeth Lighting ('DAY' source in the text below) and an incandescent lamp, 75Q/CL/RP ('A' source in the text below).

The luminous intensities of the LEDs were calculated by Equation (2) for each set of LEDs. As an example, the relative luminous intensities of the LEDs were calculated for five metameric white LED light sources. The results of these calculations are given in Table 1.

Using the relative luminous intensities of the LEDs given in Table 1, the spectral power distribution of the white LED light source was calculated by Equation (3). Figure 2 shows the relative spectral power distribution of white LED light sources and the reference DAY and A light sources. Figure 2(a) and (c) shows the relative spectral power distribution of three white LED light sources (1, 3 and 5

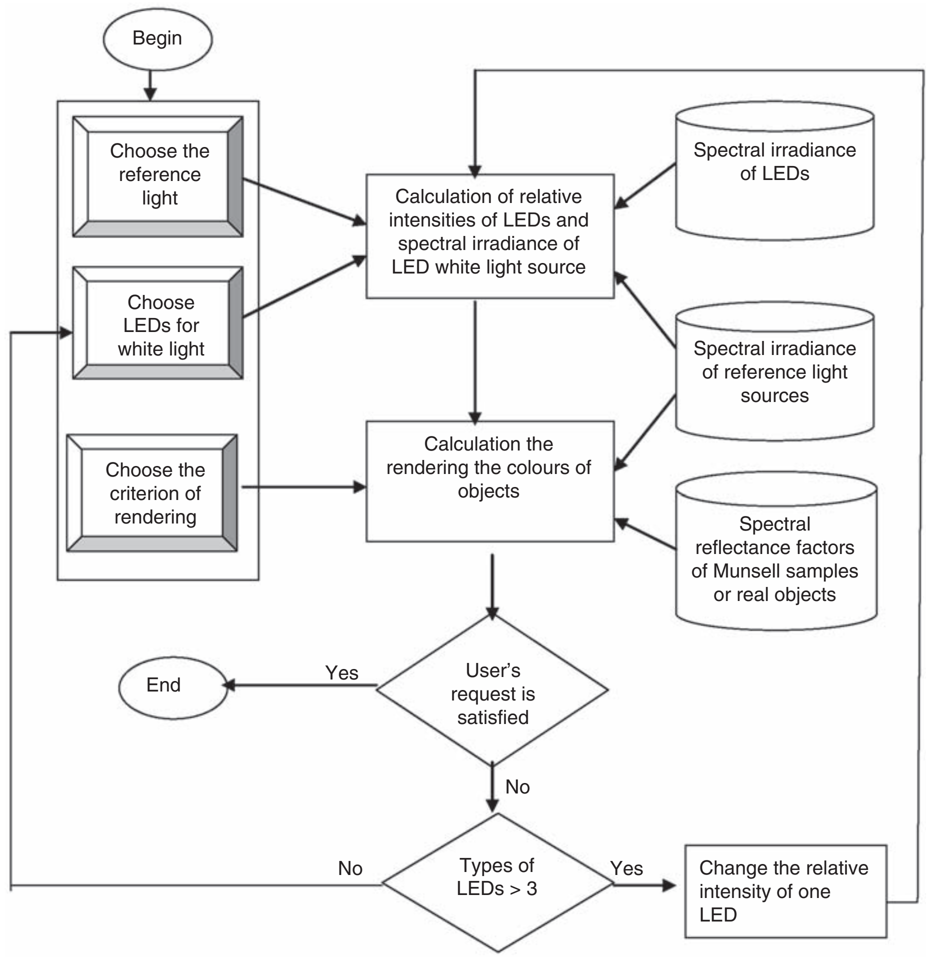

Figure 1 Algorithm for estimating the parameters of a white LED light source

Table 1 Relative luminous intensity (%) of LEDs

	White LED light sources metameric to DAY light source					White LED light sources metameric to A light source				
First set of LEDs	1	2	3	4	5	1	2	3	4	5
R (641 nm)	23.8	18.3	12.9	7.5	2.0	37.5	29.2	20.9	12.6	4.3
A (598 nm)	1.4	10.1	18.9	27.5	36.3	1.8	15.1	28.4	41.7	55
G (521 nm)	70.8	67.6	64.2	60.9	57.6	59.8	54.8	49.8	44.7	39.7
B (447 nm)	4.0	4.0	4.0	4.1	4.1	0.9	0.9	0.9	1.0	1.0
Second set of LEDs	1	2	3	4	5	1	2	3	4	5
A (598 nm)	39.5	40.1	40.7	41.3	41.9	61.9	62.1	62.2	62.4	62.5
G (521 nm)	56.3	55.0	53.7	52.3	51.0	37.0	36.6	36.3	35.9	35.6
C (465 nm)	0.1	1.7	3.4	5.0	6.7	0.2	0.6	1	1.4	1.9
B (447 nm)	4.1	3.2	2.2	1.4	0.4	0.9	0.7	0.5	0.3	0.0

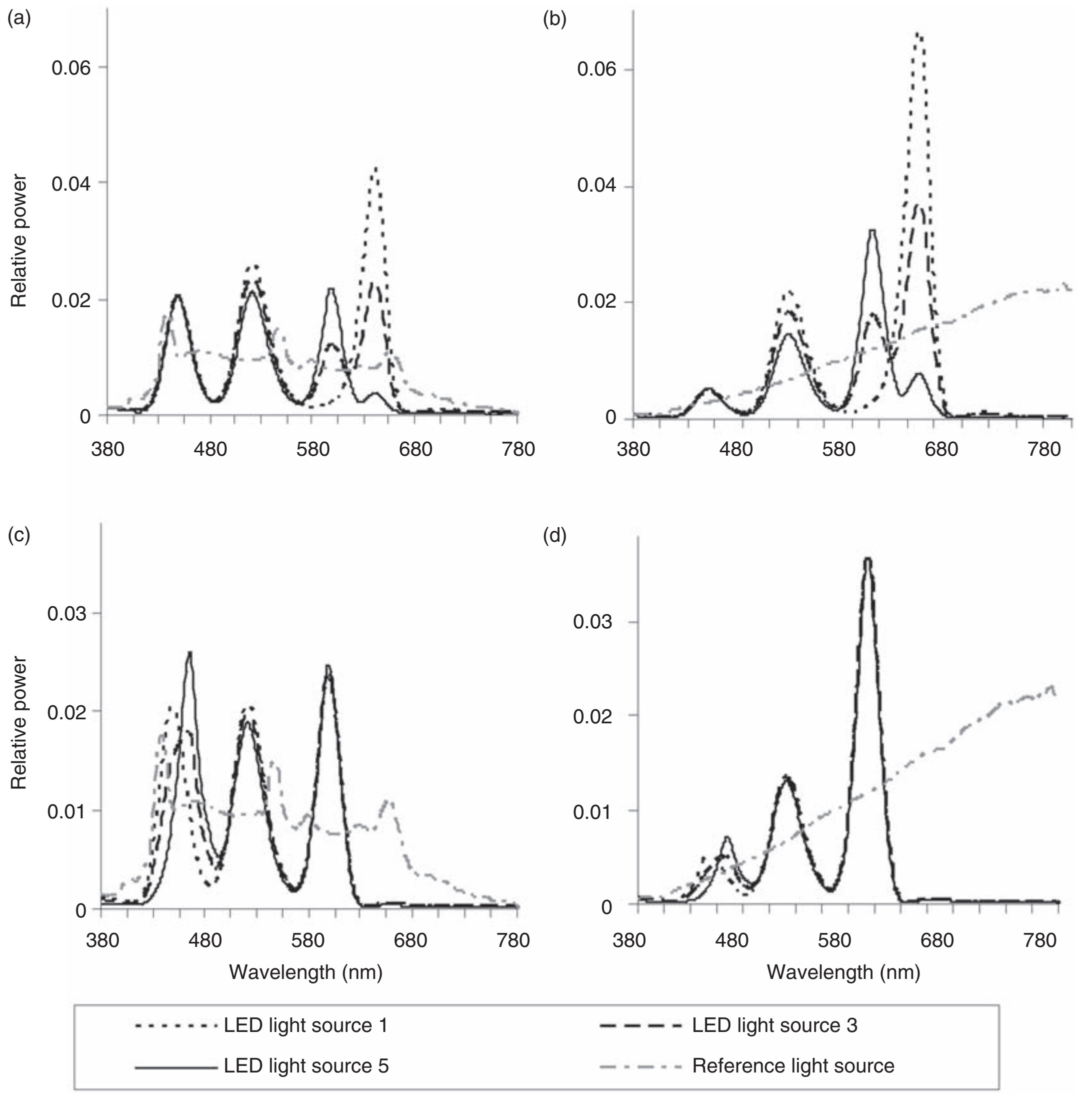

Figure 2 The relative spectral power distribution of the metameric LED and reference white light sources calculated by Equation (3): (a) relative spectral power distribution of three metameric white LED sources composed from the first set of LEDs and the relative spectral power distribution of the reference DAY light source; (b) relative spectral power distribution of three metameric white LED sources composed from the first set of LEDs and the relative spectral power distribution of the reference A light source; (c) and (d) are the same as (a) and (b) but for the second set of LEDs, respectively

from Table 1) metameric to the reference DAY light source and based on the first set and the second set of LEDs, respectively. The same is shown in Figure 2(b) and (d) only for the reference A light source.

What can be learned from Figure 2 is that for the first set of LEDs, the metamerism of light sources is mainly achieved by changing the spectral power distribution of the red and amber LEDs, and for the second set of LEDs by changing the spectral power distribution of the blue and cyan LEDs. The change of the spectral power distribution of the green LED is not significant.

To illustrate the colour changes under metameric LED and reference white light sources, the colour coordinates of Munsell colour samples under these illuminations were calculated. The reflectance spectra of glossy Munsell colour samples were used.[22] Figure 3 shows the colour coordinates in CIELAB space of 40 Munsell colour samples of value 6 (the same value as that used in the CIE method for the estimation of the general CRI[8]), chroma 6 (the average quantity used in the CIE method) and hue increased by 2.5 (hue increment of Munsell colour samples[9]). Every panel in Figure 3 shows the CIELAB a^*–b^* values of 40 Munsell colour samples under metameric illumination provided by 3 white LED light sources and the reference light source. Figure 3(a) shows the colour coordinates of the colour samples under illumination provided by metameric DAY and white LED sources based on the first set of LEDs; (b) – under illumination provided by metameric A and white LED sources based on the first set of LEDs; (c) – under illumination provided by metameric DAY and white LED sources based on the second set of LEDs; and (d) – under illumination provided by metameric A and white LED sources based on the second set of LEDs.

It can be concluded from Figure 3(a) and (b) that the increase in the luminous intensity of the amber LED and the decrease in the

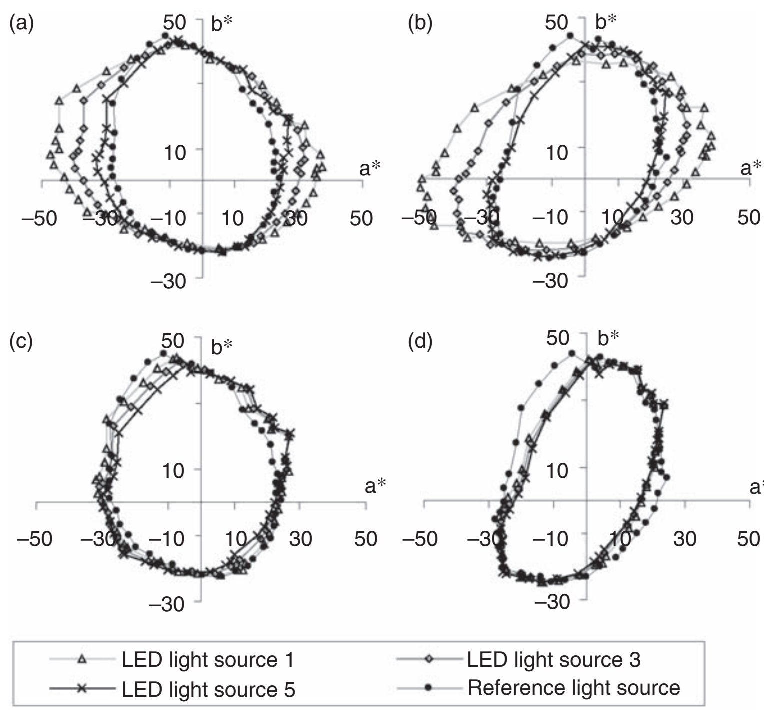

Figure 3 Colour coordinates in CIELAB space of 40 Munsell 6/6 (value 6, chroma 6) samples: (a) and (c) illuminated by the metameric DAY and three white LED light sources; (b) and (d) illuminated by the metameric A and three white LED light sources. (a) and (b) white LED light sources based on the first set of LEDs; (c) and (d) white LED light sources based on the second set of LEDs

luminous intensity of the red LED reduce the reproducible colour gamut area so the illuminated scene will appear duller. The illuminated scene can be made more saturated or duller without changing the visual appearance of the light source itself. These data are consistent with the reports that the lack of a red component shrinks the reproducible colour gamut and makes the illuminated scene look dull.[18] The saturation of colour samples increases along the red-green axis (the axis a^* in the CIELAB colour space) more than along the yellow-blue axis (the axis b^* in the CIELAB colour space). Under the reference DAY and A light sources, the illuminated scene appears duller than under illumination by the metameric white LED light sources based on the first set of LEDs, i.e. in the case of the first set of LEDs the size of colour gamut increases. On the other hand, illumination by the white LED light sources based on the second set of LEDs (Figure 3(b,d)) essentially does not change the size of colour gamut. In the case of illumination by the white LED light sources based on the second set of LEDs metameric to the A light source (Figure 3(d)), the illuminated scene is even slightly duller than under illumination by the A light source.

Four metrics, namely CRI,[8] the colour discrimination index,[15] the flattery index[16] and the number of rendered colours[5] were used to evaluate the colour quality of the metameric white LED light sources based on the first and second sets of LEDs metameric to the DAY or A light sources.[23] The increase in relative luminous intensity of the red LED of the metameric light sources reduces CRI, the flattery index and the number of rendered colours, but enlarges the colour discrimination index. Thus, increasing the relative luminous intensity of a red LED reduces the naturalness of the appearance of natural colours, preference of colours and number of rendered colours but increases the colour saturation.

4. Conclusions

The basic idea behind this study was that white light sources based on multi-chip LEDs can be used to satisfy users' requests according to different aspects of colour quality without altering the visual appearance of the light source (i.e. the reference white). The metric of light source colour quality depends on what particular aspect the users of the light source focus on.

A method to estimate the relative luminous intensities of individual LEDs to obtain a set of metameric light sources has been developed. This shows that the appearance of object colours under these light sources differ. The first step is to select the luminous intensities of the individual LEDs of the light source, so that it will be metameric to the reference light source. Only the CIE 1931 chromaticity coordinates (x, y) of the reference light source and the LEDs are required for this calculation. The second step is to calculate a certain colour quality metric by considering the objects under the LED light source and the reference light source. In this case, the spectra of the LED light source and the reference light source are used. In addition, the reflectance spectra of glossy Munsell colour samples or of real objects chosen by a customer can be used. The results of such calculations do not disagree with the results obtained by psychophysical experiments.[24–26]

The stability of parameters is an important problem for LED light sources. It has been shown that small amplitude and wavelength shifts in LED light output can cause perceptible colour differences in LED light sources.[21,27] Monitoring the light output of LEDs and stabilising their light output by feedback[28] are not enough to ensure the stability of colour appearance under LED light sources. Therefore, a method of stabilisation using the chromaticity coordinates (x, y) of LED light sources is required. The colour shift can be minimised by monitoring the chromaticity coordinates (x, y) of LEDs, calculating the luminous intensity of LEDs by Equation (2) and regulating the power supply in a feedback circuit.

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