ISSN 1392 – 1215 ELECTRONICS AND ELECTRICAL ENGINEERING 2009. No. 7(95)
ELEKTRONIKA IR ELEKTROTECHNIKA

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ELEKTRONIKA

# Rating the Colour Quality of the Solid-state White Light Lamps

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## Introduction

Solid-state lighting technology based on multichip light emitting diodes (LED) offer many advantages: possibility to implement a full light colour control, better light quality and higher efficiency [1]. Evaluation of the colour quality of such light sources by general colour rendering index (CRI) is not correct as band of the LED emission spectra is narrow. To develop a new metric the International Commission on Illumination (CIE) [2] addresses the problem the evaluation of colour quality of white LED.

There are more than ten indices suggested how to evaluate different aspects of colour appearance under artificial illumination. Gua and Houser reviewed the nine indices [3]. A few new indices have been suggested later [4, 5]. Aim of our work is to compare existing indices for evaluation of colour quality of LED based white light sources.

The most common metric is CRI [6] which characterizes how natural objects are appeared under changes of illuminants. Another measure of colour quality – a gamut area index (GAI) [7], is applicable for predicting how well one can discriminate differences in chromaticity. The flattery index (FI) suggested by Judd [8] evaluates the degree to which an artificial illumination 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 illumination [9]. The 3_3 "rendering matrix" suggested by Worthey [4] estimates the gain or loss of redness and greenness and gain or loss of blueness and yellowness when one illumination is replaced by another. The evaluation of colour quality, suggested by Žukauskas et al. [5] is based on the number of rendered colours (NRC) from an extended colour palette.

In this article we presented evaluation of colour quality of LED based white light lamps (WLL) by applying four metrics, namely CRI, GAI, FI, and NRC as well as analysis of the relations between these metrics. The motives to choose CRI, GAI, and FI are that they are concerned with the main aspects of colour appearance that are important to persons, namely, appearance of natural colours, colour discrimination capability, and preference of coloured objects. All these metrics are based on calculations of the colour quality indices for selected colour samples (from 8 to 10). The NRC was chosen as it evaluates the colour quality on all gamuts of colours.

## Method

Evaluation of the colour quality of the WLL was performed under WLL metameric to chosen reference sources based on two sets of LED. The first set of LED involves four commercially available high power LED with the peak wavelengths of 641 nm (red), 598 nm (amber), 521 nm (green), and 447 nm (blue). The second one involves four high power LED with the peak wavelengths of 598 nm (amber), 521 nm (green), 465 nm (blue-green) and 447 nm (blue). As reference light sources were chosen the fluorescent lamp F20T12/65, 6500 K, Macbet Lighting (DAY source in the text bellow) and incandescent lamp 75Q/CL/RP (A source bellow). Five variants of WLL, metameric to reference DAY source and five variants, metameric to reference A source were composed from each set of LED. The flux intensities of LED were calculated by using special computer program.

Relative LED flux powers for the WLL metameric to reference DAY and A sources are presented in the Table 1 and Table 2.

**Table 1.** Relative LED flux powers for WLL metameric to DAY source

| | WLL number, relative power | | | | |
|---|---|---|---|---|---|
| First set of LED | **1** | **2** | **3** | **4** | **5** |
| R (641 nm) | 0.238 | 0.183 | 0.129 | 0.075 | 0.02 |
| A (598 nm) | 0.014 | 0.101 | 0.188 | 0.275 | 0.363 |
| G (521 nm) | 0.708 | 0.675 | 0.642 | 0.609 | 0.576 |
| B (447 nm) | 0.04 | 0.04 | 0.04 | 0.041 | 0.041 |
| Second set of LED | **1** | **2** | **3** | **4** | **5** |
| A (598 nm) | 0.395 | 0.401 | 0.407 | 0.413 | 0.419 |
| G (521 nm) | 0.563 | 0.55 | 0.537 | 0.523 | 0.51 |
| BG (465 nm) | 0 | 0.017 | 0.034 | 0.05 | 0.067 |
| B (447 nm) | 0.041 | 0.032 | 0.027 | 0.013 | 0.004 |

**Table 2.** Relative LED flux powers for the WLL metameric to A source

| First set of LED | WLL number, relative power | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| R (641 nm) | 0.375 | 0.292 | 0.209 | 0.126 | 0.043 |
| A (598 nm) | 0.018 | 0.151 | 0.284 | 0.417 | 0.549 |
| G (521 nm) | 0.598 | 0.548 | 0.498 | 0.447 | 0.397 |
| B (447 nm) | 0.009 | 0.009 | 0.009 | 0.01 | 0.01 |
| Second set of LED | **1** | **2** | **3** | **4** | **5** |
| A (598 nm) | 0.619 | 0.621 | 0.622 | 0.624 | 0.625 |
| G (521 nm) | 0.37 | 0.366 | 0.363 | 0.359 | 0.356 |
| BG (465 nm) | 0.001 | 0.006 | 0.01 | 0.014 | 0.018 |
| B (447 nm) | 0.009 | 0.007 | 0.005 | 0.003 | 0 |

Relative spectral power distribution of the first and fifth WLL based on first set of LED metameric to reference DAY and A sources are presented in Fig. 1 a) and b) respectively, while relative spectral power distribution of the first and fifth WLL based on second set of LED metameric to reference DAY and A sources are presented in Fig. 2 a) and b) respectively.

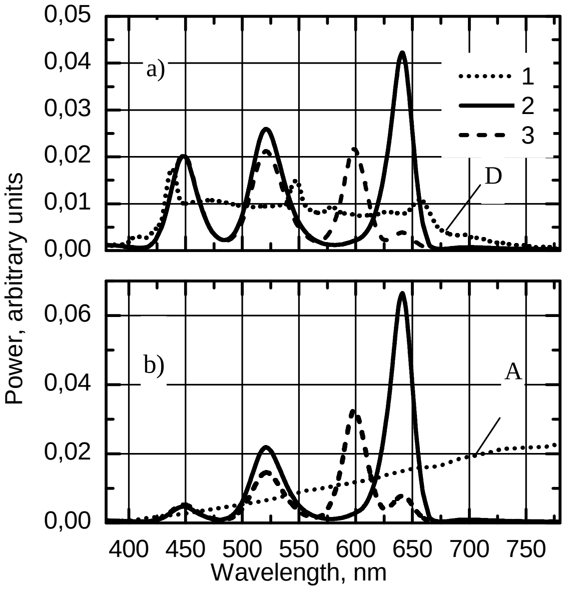


**Fig. 1.** Spectral power distribution of reference and metameric WLL based on first set of LED: **a)** for the reference DAY source; **b)** for the reference A source: 1 – spectral power distribution of the reference (A –reference A source, D –reference DAY) sources; 2 – spectral power distribution of the first source; 3 – spectral power distribution of the fifth source

The CRI has been calculated as the average colour shift of selected eight Munsell samples under replacing of a reference light source by the metameric WLL [6]. The reflectance spectra of glossy Munsell colour samples were applied for calculations [10].

The calculation of FI is similar to the CRI except that the average colour shift has been evaluated between colours of ten Munsell samples viewed under the illumination of LED based white light and the preferred colours of these test samples viewed under the illumination of reference source [8].

GAI was defined by the area of the polygon formed by the points of the eight Munsell samples in the *u*, *v* colour plane. These samples are the same as for calculation of the CRI [7]. For analysis, the gamut area of the DAY light is scaled to 100 points and defined as GAI.

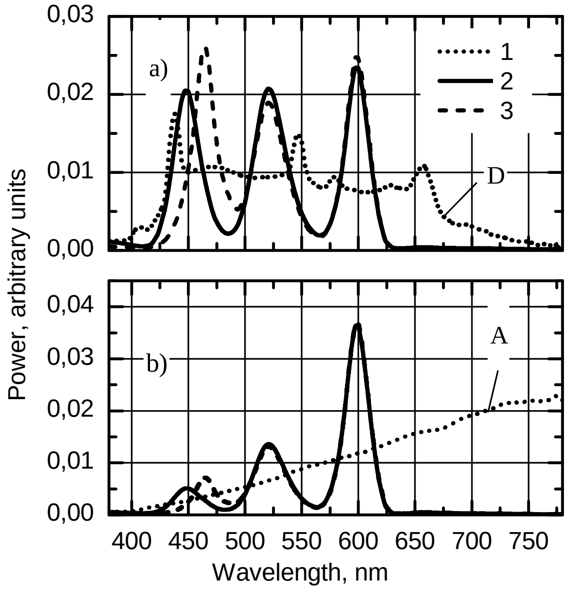


**Fig. 2.** Spectral power distribution of reference and metameric WLL based on second set of LED: a) for the reference DAY source; b) for the reference A type source: 1 – spectral power distribution of the reference (A – reference A, D – reference D) sources; 2 – spectral power distribution of the first source; 3 – spectral power distribution of the fifth source

The CIE 1960 (*u*, *v*) chromaticity coordinates were applied for the CRI, FI, and GAI calculations. The distances between colour points in this colour plane have a good match with the subjective colour discrimination.

NRC was calculated in percents with respect to the entire 1269 samples of Munsell palette. The rendered colours defined as the colours that shift of its coordinates between the conditions when illuminated by a reference illuminant and by the LED illumination only within the MacAdam ellipsoid in 3-D space [5]. They [11] are the experimentally determined colours that are indistinguishable by human vision.

## Results

The results of CRI, FI, GAI, and NRC calculations for WLL metameric to reference DAY and A sources and based on two sets of LED are presented in Fig. 3 and Fig 4. Fig. 3 presents indices for five WLL based on the first set of LED metameric to reference DAY source (Fig. 3a), and metameric to reference A sources (Fig. 3b) versus the relative LED flux intensity, which is defined as ratio (R-A)/(R+A), where R and A are the relative flux intensities of red and amber LED respectively. The flux intensities of these LED were selected, as the metamerism of light sources is mainly achieved by varying the flux intensities of the red and amber LED. Variations of the green LED flux intensities are negligible (see Fig. 1).

Fig. 4 a) and b) presents colour quality indices for five WLL based on the second set of LED metameric to reference DAY, and A sources respectively, as a function of the relative LED flux intensity, which is defined as ratio (B-GB)/(B+GB), where B and GB are the relative flux intensity of blue and blue-green LED respectively, as the metamerism of WLL is mainly achieved by varying the flux intensities of the blue and blue-green LED.

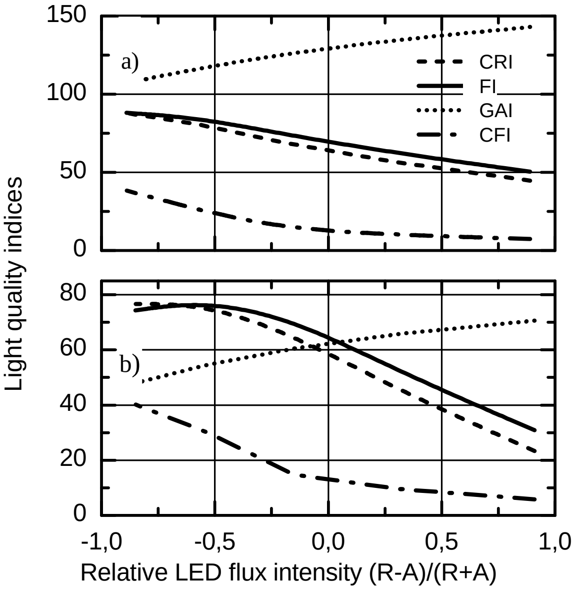


**Fig. 3.** Colour quality indices for five WLL composed from the first set: a) metameric to reference DAY source; b) metameric to reference A source

As seen from Fig. 3 and Fig. 4, the manipulation of the spectral composition of multi-chip WLL, without altering the visual appearance of the lighted environment (metameric WLL), changes the colour quality evaluation indices. For WLL composed from the first set of LED, an increase of the red LED flux intensity and a decrease of the amber one flux intensity reduce the CRI, FI and NRC, and boost the GAI. That is true both for the LED WLL metameric to DAY source (Fig. 3a) and for those metameric to A source (Fig. 3b). On the other hand, an increase of the blue LED flux intensity and a decrease of the blue-green LED flux intensity enlarge all indices in small amount for WLL composed from second set of LED. This is true for the WLL metameric to reference DAY sources (Fig. 4a) as well for the sources metameric to reference A source (Fig. 4b).

The experiments on CRI and GAI of different phosphor- based light sources also show that for the several light sources CRI are low and GAI are high or vice versa [12].

Analysing graphs, presented in Fig. 3 and Fig. 4, we also concluded that the difference between the CRI and the FI is small for the WLL metameric to reference DAY as well as to A sources based on both set of LED. There is difference between CRI and NRC but the tendency of changes of CRI and NRC is similar (correlation coefficient $r > 0.86$) for all situations.

The value of CRI equal to 100 points means that all samples illuminated by a light source in test would appear to have the same colour as illuminated by a reference source. The CRI decrease when the flux intensity of red LED increase for the WLL composed from first set of LED and the flux intensity of blue LED decrease for the WLL composed from second set of LED for the both reference light sources. As a result the appearance of natural colours severe decrease as the flux intensity of red LED increase for the WLL composed from first set of LED, and little increase when the intensity of blue LED increase for the WLL composed from second set of LED.

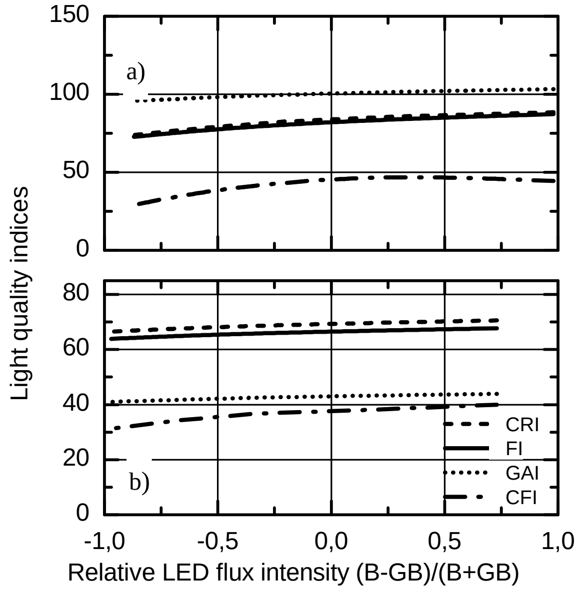


**Fig. 4.** Colour quality indices for five WLL composed from the second set: a) metameric to reference DAY source; b) metameric to reference A source

The GAI of 100 points is selected for the reference DAY type light source. The rising of the red LED flux intensity increase the GAI over 100 for the LED white sources composed from first set of LED and metameric to the reference DAY type light source (Fig 3a). Thus the colour discrimination capability under illumination of WLL is higher compared with one under illumination of reference DAY source.

For the reference A source value of the calculated GAI is 52. Fig. 3b) shows that the increasing the red LED flux intensity also boosts the GAI for the WLL composed from first set of LED and metameric to the reference A source. For a flux intensity of red LED near to zero the colour discrimination capability is less than for A source, and became higher when red LED flux intensity grows.

For the second set of LED increasing of a flux intensity of blue LED improves the colour discriminability insignificantly for the LED white light lamps metameric to DAY and A type light sources (Fig. 4a and b).

## Conclusions

A manipulation on the spectral composition of multi-chip WLL without altering the visual appearance of the lighted environment can change an appearance of object's colour. More appreciable changes in colour appearance occur when a flux intensity of LED with the peak wavelengths in a long wave range is changing.

The increase of an intensity of the red LED reduces

CRI, FI and NRC, but enlarges GAI, i.e. an increasing of intensity of a red LED flux reduces the appearance of natural colours, preference of colours and number of rendered colours but increases the colour discriminability.

As the CRI, FI and NRC consider only one of colour appearance aspect, there is no significant difference between the CRI and FI, and a tendency of a changing CRI and NRC for the WLL. As GAI is the measure of another aspect of colour appearance (the colour discriminability), then a tendency of a changing GAI and CRI can be different.


### Acknowledgment

This study was supported by Lithuanian State Science and Studies Foundation.


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Received 2009 04 01



**V. Viliūnas, H. Vaitkevičius, Z. Bliznikas, K. Breivė. Rating the Colour Quality of the Solid-state White Light Lamps // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 7(95). – P. 29–32.**

The colour rendering index (CRI), the flattery index (FI), the gamut area index (GAI), and the number of rendered colours (NRC) are estimated for the gamut of metameric Solid- state white light lamps based on two sets of multi-chips light emitting diodes (LED). It is shown that the manipulating on the spectral composition of multi-chips LED white light lamps without altering the visual appearance of the lighted environment makes the colour rendering indices to change. This is more evidence if the intensities of LEDs are changing for LEDs' with the peak wavelengths in a long wave range than for LEDs' with the peak wavelengths in a short wave range. The increase of the intensity of the red LED in the metameric LED lamps reduces CRI, FI and NRC, and enlarges GAI. There is no obvious difference between the CRI and FI and tendency of changing CRI and NRC in the metameric LED light sources. Ill. 4, bibl. 12 (in English, summaries in English, Russian and Lithuanian).

**В. Вилюнас, Г. Вайткевичюс, З. Близникас, К. Брейве. Исследование качества цветопередачи полупроводниковых ламп белого цвета // Электроника и электротехника. – Каунас: Технология, 2009. – № 7(95). – С. 29–32.**

Представлены результаты исследования качества цветопередачи (ЦП) полупроводниковых ламп, образованных из четырех групп светодиодов с разными длинами волн излучаемого потока. Эти лампы являются метамерными либо излучению дневного света (тип D), либо излучению полного излучателя (тип A). Для оценки качества ЦП использовались расчетные величины общего индекса цветопередачи (*англ*. CRI), индекса предпочтения (*англ*. FI), индекса области гаммы цветов (*англ*. GAI) и число воспроизведенных без искажений цветов (*англ*. NRC). Установлено, что подбором соотношения потоков групп можно образовать большое число метамерных источников с разными параметрами ЦП. На качество ЦП сильнее влияет взаимное соотношение потоков длиноволнового диапазона. Полученные результаты имеют практическую ценность для проектировки и конструирования полупроводниковых источников белого света. Ил. 4, библ. 12 (на английском языке; рефераты на английском, русском и литовском яз.).

**V. Viliūnas, H. Vaitkevičius, Z. Bliznikas, K. Breivė. Puslaidininkinių baltosios šviesos lempų spalvinės kokybės tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2009. – Nr. 7(95). – P. 29–32.**

Pateikti baltosios šviesos lempų, sudarytų iš keturių skirtingų bangos ilgių šviesos diodų grupių, spalvinės kokybės (SK) tyrimo rezultatai. Tiriamosios lempos yra metamerinės dienos (tipas D) arba visiškojo spinduolio (tipas A) šviesos šaltiniams. SK vertinta apskaičiavus šiuos parametrus: spalvinės atgavos (*angl.* CRI), spalvų patrauklumo (*angl.* FI), spalvių gamos ploto (*angl*. GAI) indeksus bei neiškraipytai atkurtų spalvų skaičių (*angl.* NRC). Nustatyta, kad, keičiant diodų grupių srautų tarpusavio santykį, galima sudaryti daug metamerinių lempų su skirtingais SK parametrais. Didesnę santykinę įtaką SK vertėms turi srautai, kurių bangos ilgiai yra ilgųjų bangų ruože. Gauti rezultatai yra naudingi projektuojant ir konstruojant praktinius puslaidininkinius baltosios šviesos šaltinius. Il. 4, bibl. 12 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).