

**CIE Expert Symposium on LED Light Sources:
- Physical Measurement and Visual and Photobiological Assessment-**

June 7-8, 2004, Tokyo

Monday, June 7

9:00-9:05	Opening		
9:05-9:45	Keynote Paper 1		
	Schanda J	Hungary	Physical and visual requirements for LEDs to be used for future lighting systems
9:45-10:00	Tea Break		
Session I: Vision / Colour Rendering			
10:00-10:30	Invited		
	Bodrogi P.	Hungary	Colour rendering : past, present(2004), and future
10:30-10:50	Sandor N.	Hungary	Visual observation of colour rendering
10:50-11:10	Yaguchi H.	Japan	Categorical color rendering of LED light sources
11:10-11:30	Tea Break		
11:30-11:50	Bodrogi P.	Hungary	Why does the CIE Colour rendering index fail for white RGB LED light sources?
11:50-12:10	Ohno Y.	U.S.A.	Simulation analyses of white LED spectra and color rendering
12:10-12:30	Muray K.	U.S.A.	White LEDs: special characteristics and simple methods to improve their color-rendering
12:30-14:00	Lunch & Poster presentations		
Session II: Vision			
14:00-14:20	Nurmi T.	Finland	The determination of the effective light intensity of LEDs
14:20-14:40	Hagiwara K.	Japan	Visibility of color stimuli using LEDs in driving situations
14:40-15:00	Nakamura H.	Japan	Basic theory for quantifying the effect of illuminance on the conspicuity of recessed-mount LED equipment
15:00-15:30	Tea Break		
Session III: Photobiological Safety			
15:30-16:00	Invited		
	Horak W.	Germany	Photobiological safety issues concerning LEDs-problems and requirements
16:00-16:20	Sliney D.	U.S.A.	Health and safety aspects of LEDs

16:20-16:40	Schulmeister K.	Austria	Eye simulating scheme for a complete characterization of the retinal hazard of LEDs
16:40-17:00	<i>Tea Break</i>		
17:00-17:20	Horak W.	Germany	Prospect for the use of the CIE photobiological lamp safety standard for hazard assessments of “visible” LEDs for general lighting purposes
17:20-17:40	Reidenbach H.	Germany	Results of lab and field trials regarding the eye blink reflex as a safety means for LEDs
17:40-18:00	Pinho P.	Finland	Analysis of photobiological aspects of crop plants growing under high-brightness light –emitting diodes
18:00-18:30	Discussion and Summary		
19:00-21:00	<i>Dinner Cruise (on Japanese style boat-Yakatabune)</i>		

Tuesday, June 8

9:00-9:05	Announceme		
9:05-9:45	Keynote paper 2		
	Mueller G.	U.S.A.	White light from LEDs
9:45-10:00	Tea Break		
Session IV : Measurement (1)			
10:00-10:30	Invited		
	Muray K.	U.S.A.	LED measurements: Current work within CIE
10:30-10:50	Gibbs D.	UK	Improved traceability for LED measurements and the results of a round-robin comparison of LED cluster measurements
10:50-11:10	Schuette J.	Germany	LED transfer standards
11:10-11:30	Tea Break		
11:30-11:50	Mathe G.	Germany	Measurement of averaged LED intensity based on spectroradiometric standards
11:50-12:10	Farkas G.	Hungary	Complex characterization of power LED-s: simultaneous measurement of photometric/radiometric and thermal properties
12:10-12:30	Csuti P.	Hungary	Comparison of the goodness of fit to the function of photometers using real LED spectra
12:30-14:00	Lunch & Poster presentations		
Session V : Measurement (2)			
14:00-14:20	Samedov F.	Turkey	Establishment of temperature-controlled reference LED's and characterization of their optical properties

14:20-14:40	Young R.	U.S.A.	Practical uncertainty budgets for spectral measurements of LEDs
14:40-15:00	Eppeldauer G.	U.S.A.	Development and application issues of a spectrally tunable LED source
15:00-15:20	Zong Y.	U.S.A.	Measurement of total radiant flux of UV LEDs
15:20-15:50	<i>Tea Break</i>		
15:50-16:10	Rattunde R.	Germany	Color and color distribution of signal lamps with LEDs
16:10-16:30	Ikonen E.	Finland	Evaluation of calibration methods of a photometer measuring maritime LED buoy lanterns
16:30-16:50	Ogata F.	Japan	Considerations on optical properties of LEDs for general illumination
16:50-17:10	Pan J.	China	General lighting purpose LEDs, their characteristics and physical measurement
17:10-18:00	Discussion and Summary		

Poster Presentations (for lunch times and breaks)

1	Santos P.	Brazil	Para Museum of Gems
2	Santos P.	Brazil	Assembleia Paraense Night Club
3	Nakano Y.	Japan	Color rendering simulator using multispectral camera and its application to evaluating white LED light sources
4	Nicholson M. and Tutt I.	UK	LED clusters - A bright future!

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Keynote Paper 1 Schanda J	Hungary	Physical and visual requirements for LEDs to be used for future lighting systems
Keynote paper 2 Mueller G.	U.S.A.	White light from LEDs

Physical and visual requirements for LEDs to be used for future lighting system

J Schanda

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Introduction – Development of LEDs

Solid state electrical light generation dates back to the first decades of the 20th Century, when a faint blue glow was observed on SiC crystals under a point contact electrode. By the mid 1930th a second form of electroluminescence was discovered: Destrau invented the ZnS microcrystalline layer based electroluminescent panel. This is a high-voltage device, where field-effects play an important role.

Light emitting diodes became available only in the 1960th, when first the infrared emitting GaAs diode, and then semiconductor diodes, based on III-V compounds, with larger bandwidth and visible light emission became available. By 1974 the efficacy of the LEDs increased above 1 lm/W in green GaP emitters. The next major step was the development of the AlGaAs diodes, when the 10 lm/W barrier was reached at the end of the 1980th. The introduction of GaN based diodes enabled the production of blue and even UV emitting LEDs, and thus the possibility of producing white light with LEDs became a reality (both based on the Red-Green-Blue principle and the now practiced blue/UV+phosphor principle). The luminous efficacy of commercial white LEDs surpassed that of halogen incandescent lamps, and laboratory samples have efficacies comparable to that of fluorescent lamps. At present most manufacturers use for red to yellow LEDs AlInGaP, and for green to UV (and white) InGaN based materials.

The packaging of LEDs went also through a major development, from the simple plastic signal lamp packages to the surface mounted constructions, where for the high power types the development of better heat dissipation technology came into the foreground of interest. This is true both for the single (large) chip constructions, and those with a number of microchips.

Application areas of LEDs

Still the indicators and alphanumeric displays, built using indicator type LEDs, have the largest market share (about 37 %), followed by the IR transmitters (21%). backlighting takes an approximately 17 % share. A rapidly growing segment is the application of signage, the use of LEDs in road-, railway-, water and airway-signaling (about 10 %), followed by another rapidly growing segment, the automotive application (~7 %). Other transportation

applications and decorative lighting have a 5 to 6 % share. A small, but very perspective area is the use of white light LEDs in traditional illuminating engineering applications.

Photometric and colorimetric measurement of LEDs

The new and rapidly growing applications have direct implication on CIE activities: Guidelines for measuring the photometric characteristics of the new LEDs, developed for these applications, is a demanding task.

The Average LED Intensity measuring geometry helped the unification of signal-lamp LED measurement tremendously. With current high intensity LEDs the situation is different, these are already real “lamps”, they can be photometrically evaluated as any other light source. But at the same time the new applications will need new practical photometric measurements, and especially agreed test methods. Just as if a compact fluorescent lamp is used in an outdoor luminaire, one has to take into consideration the influence of the temperature of the environment, the temperature stabilization of the lamp, etc., for the application of LEDs in a billboard one has to consider the stabilization of the LEDs, their temperature dependence, etc. A simple measurement under standard laboratory conditions is meaningless for such applications.

For the fundamental photometric characteristics – my personal impression is – that the only way to get more consistent workshop floor results is the same as practiced in every photometric laboratory of every lamp manufacturer: use secondary standards with the same characteristics as the lamp type to be measured. This the safest way out when the lamp has unusual spatial light distribution characteristics, or the detector colour correction is not perfect. The standardization of these secondary standard lamps has to be the task of well equipped standards developing laboratories.

There are, however, a number of question, where CIE should get involved that are not the actual measurement of the LEDs, but are brought about by the introduction of the LEDs. Colour rendering is certainly a question in the lime-light of many applied lighting engineers, who try to experiment with white LEDs. But there are other issues as well: The spectral distribution of white LED lamps will be for a considerable time different from traditional sources. This unusual spectral power distribution makes the differences using the traditional methods and the more precise methods now available non negligible. In some cases, e.g. discomfort glare evaluation on the road, will need new input to get correct measures.

Outlook on LED application and measurement requirements

In my opinion one of the first big applications of white LEDs will be the car-headlamp. Here still a number of technological problems has to be solved, but with the new sources we are

faced with the possibility to produce quite new light distributions. As CIE was the spear-head at the time the current standards for light distribution were established, it would be high time to start work to get to new prescriptions that can make our roads safer. Questions of visibility of signs – also for colour deficient drivers, glaring of other vehicles headlamps and of traffic signs, better description of sun phantom elimination tests, etc. are all questions that have to be solved.

It is obvious that with increasing efficacy the luminance of the actual sources will increase. This has eye-safety implications, where the geometry of the light distribution will be again different both from that of the traditional LED signal lamps and of that of lasers. Generally, if at all, the possible eye hazard posed by LEDs is basically not different from that of any other source of strong optical radiation. Commonly accepted optical radiation safety standards require a measurement on specified conditions of the source emission (e.g. radiance) followed by a comparison of the result with threshold limits values. These measurement conditions relate to specific potentially hazardous viewing conditions and even physiological features of the eye (e.g. accommodation, pupil size and unintentional eye movements). Therefore, they differ significantly from usually applied optical characterization methods. Due to the growing attention to photobiological safety issues, which is not just limited to LED-lamps, it is increasingly necessary, to provide and configure the required specific measurement techniques as well.

The general purpose use of LEDs in indoor areas might be somewhat farther away. In these applications one needs emitters in the klm range, but in niche applications white LEDs might come very soon. For these applications colour rendering seems to be the most important photometric-colorimetric characteristics, where basically new concepts are needed. As soon as some unification will be introduced in the form, spatial light distribution and base of the LEDs by the different manufacturers, the fundamental photometric measurements will certainly become standardized, enabling the testing laboratories to use unified methods.

Summary

It is not only that LEDs are bright and become brighter and brighter, but also the engineers and scientists who deal with better measuring methods of the LEDs can look into a bright future. There are a number of new and challenging tasks to be solved, starting with the very fundamental measurement of the LED (partial) luminous flux and ending with the development of new concepts for the evaluation of glare, visibility evaluations, etc.

White Light from LEDs

Gerd O. Mueller, Regina Mueller-Mach

Lumileds Lighting

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Light Emitting Diodes have outrun colored light sources efficiency-wise; filtering incandescent to red or even blue is just an energy waste. White light, however, can either be generated by mixing of colored LEDs or by phosphor-conversion of blue or near-UV light from LEDs. Both methods incur losses of the inherently high efficiency of the short wavelength diodes. Both methods do not easily yield continuous spectra resembling blackbody (BB) radiation, and often this is not even wanted. Many display and signaling application are not judged by criteria like color rendering, but all illumination application are. Warm white LUXEON – illumination grade, meaning $R_a > 90$, $R_9 > 60$ – has recently been introduced and sold in large quantities. Spectra deviating very little from black body ones raise the question whether their color rendition properties can be adequately described by the present standard, which states that spiky fluorescent lamp spectra are as good. Examples of actual spectra will be analyzed in comparison to BB ones of the same (Correlated) Color Temperature (CCT) using photometric units and equal luminous flux in order to make the marginal differences more evident.

As discussions about the relevance of comparisons of color rendition with BB (or daylight) of equal CCT seem to be not settled, and the preference of warm white for workplace lighting is under scrutiny, the possibility of phosphor-converted (pc)LEDs with higher color temperature and equally good color properties will be presented.

As luminous efficiency – energy savings – is always at least the second ranking issue in light sources, a discussion based on practical experience of comparative advantages of different types of pcLEDs – blue-pumped-2-phosphor, UV-pumped-3-phosphor - using a broad phosphor portfolio will be presented.

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Colour rendering: past, present(2004), and future

Extended Abstract

CIE Expert Symposium on LED Light Sources: Physical Measurement and Visual and
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Peter Bodrogi

Abstract

This paper reviews the background, the current state of the art, and the emerging future issues related to the colour rendering of light sources. The concept of colour rendering is defined and discussed together with related concepts. Results of past research are summarized. Trends of current experimental work are outlined with emphasis on LED light sources. Possible future theoretical descriptions of colour rendering are shown.

Concept of colour rendering and related concepts

Colour rendering (CR) is defined as "Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant"[1]. The colour rendering index (CRI) calculation method officially introduced in 1974 is described in a CIE publication[2]. CIE first standardized a spectral band method (1948), but in 1961, it was decided to regard the "test sample colour shift" method[2] as the fundamental method for CR appraisal. Besides graphical colour shift vector representations and multi-number rating, it was claimed to derive a single-number CR characterization of each light source. Latter demand resulted in the establishment of the current CIE CRI calculation method.

Besides the concept of CR there are other concepts to describe the more general concept of light source "colour quality"[3] (CQ): colour discrimination capability, "visual clarity", and colour preference or "flattery".

Certain visual tasks require easy *discrimination* among colours (e.g. a wiring task with colour-coded wires). Colour discrimination index (CDI) was defined[4] as the gamut area of eight test colours in the CIE u, v diagram. Another CDI was defined quantifying how well adjacent colours can be discriminated under the test source[5] (similar to the Farnsworth-Munsell 100 hue test).

The concept of "*visual clarity*" is related to the general brightness sensation of the illuminated room or to the "feeling of contrast" (i.e. the perception of large-scale colour differences) between coloured objects under the test source. "Feeling of contrast" was quantified by CIELAB chroma and CIELAB overall colour difference[6]. Although "visual clarity" is not perfectly predicted by CRI, a positive correlation was found between them.

Colour preference (CP) corresponds to the user's "aesthetics" task. The colour preference index (CPI) quantifies the matching of the colour appearance of surface colours to an "ideal" or

"preferred" appearance. Latter is usually different from their appearance under CRI's reference source. CPI was defined by the aid of colour differences between actual and preferred appearance[7].

Past research to improve the CRI

Since the introduction of the CIE CRI calculation method in 1974, several shortcomings of the method have been realized and a number of new colorimetric recommendations (CIELAB and CIELUV colour spaces, new chromatic adaptation transforms, CIECAM97s and CIECAM02 colour appearance models) have been made. By the 1991 Quadrennial Meeting, TC 1-33 (Colour Rendering) was formed and a new CRI calculation method (R96_a) was developed. This was described in the chairman's report[8]. The R96a method contained the following new features compared to the standard method[2]: 1. test samples were taken from the Macbeth ColorChecker chart instead of the Munsell atlas; 2. six reference illuminants - D65, D50, 4200K black body radiator(P4200), P3450, P2950, and P2700 were used instead of the continuous Planckian/daylight illuminant set (see also [9]); 3. CIE chromatic adaptation formula[10] instead of the von Kries transform; 4. both the test lamp and the reference lamp were transformed into D65 chromaticity (as the CIELAB space was tested most thoroughly under D65 illumination); 5. colour differences were quantified in CIELAB.

Current experimental work

There is an infinite number of ways to describe CR but deciding will be the results of visual experiments, especially those results that include the most problematic LED light sources for which the failure of CRI is anecdotic. Author is aware of several current visual experiments in the framework of CIE TC 1-62. These experiments usually concentrate on the visual scaling of perceived colour differences of two identical reflecting samples, between the test and the reference light sources of equal or similar chromaticity, by using double booth experiments ([11-12]). Visual colour difference results were in better correlation with colour appearance model predictions than the conventional CIE CRI[12]. Other experimental possibilities would include direct magnitude estimation of colour appearance or a direct scaling experiment about a kind of "general colour harmony impression" when the observer is merged into the visual environment lit by the test lamp (without any visible reference source).

Possible theoretical descriptions of colour rendering in the future

Colour experts seem to agree that the Bradford chromatic adaptation formula (included in CIECAM97s and its improved versions) is better than the previous chromatic adaptation formulae[11]. Recently, it was also demonstrated that CIECAM based colour difference formulae and uniform colour spaces are also capable to predict both small and large colour differences[13]. Therefore, the use of a CIECAM based colour appearance model to calculate CRI looks a

straightforward idea.

Another issue is the number of reference sources. It is likely that more than one reference source should be used since the "ideal" colour appearance depends on the user's intent of producing "intimate", "office", or "harsh" atmospheres[9,11].

The way of representing the calculated colour differences may also change. Simple averaging of colour differences calculated from a limited number of test-colour samples may be subject to error because, especially the RGB cluster LED lamp spectra, may "interfere" with modern narrow band colorants' spectral reflectances. These narrow-band surface colours will produce large or unaccepted colour differences not predictable by one single average CRI number. It was generally claimed that one single CRI did not provide enough information for the lighting designer[14]. By taking *many* test-colour samples and dividing all colour-difference values by the value of chroma, a smooth function of the hue angle was obtained[14]. (Hue, chroma and lightness shifts may not be visually equally relevant from the point of view of CR.) This function characterized CR properties better than the conventional CRI. Colour Rendering Vector Fields were also defined in uniform colour spaces or NCS colour diagrams[14, 15].

Alternatives may include the use of a categorical CRI[16, 17] calculating the "colour category overlap" between the test and reference sources or a combined colour quality[3] index (CQI) including CRI, CPI, and CDI (see above).

The "test sample colour shift" method[2] is based on the original CR definition supposing that the observer *has the ability* to "imagine" the colour appearance of the surface colours under a reference illuminant and to compare this "expected appearance" with their actual appearance. This implies that there are well-known objects (e.g. skin, leaves, sand, etc.) in the field of view from which the observer knows their "reference appearance". But observers are usually also able to assess CR in a scene with only *partial* knowledge about the reflecting samples (e.g. textile samples in a theatre room). It is likely that it is not the absolute value of the colour differences between the test and the reference source which is visually important but the *relative* shifts of the colours. This is related to a kind of "internal colour harmony" among the surface colours or the deterioration of this harmony when going over to the test source illumination[12]. This can be quantified by a new "colour harmony rendering index" (HRI) calculated from the *relative change* of all distances *among* all test colour samples (author intends to describe HRI in another paper). Going one step further, we might also be able to compute a new CRI based on *colour constancy* theories e.g. those applying bilinear models[18]. This approach needs further theoretical considerations.

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- [2] Commission Internationale de l'Éclairage, Method of Measuring and Specifying Colour

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Visual observation of colour rendering

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Revision of the colour rendering index has a long history (see e.g.¹), but despite of several attempts, no new system has been recommended, due to the fact that lamp manufacturers were unable to agree on the necessary modifications, despite of the fact that the current recommended method relies on outdated methods of calculation^{2,3}. The main reason of not accepting a new method was that there are not enough visual observations that contradict the calculated colour rendering results.

Due to above situation we started systematic visual investigations of colour rendering. Pilot experiment have shown that – in accordance with anecdotic earlier observations – the colour rendering index does not always describe visual colour rendering correctly, especially in case of white LEDs (see CIE TC 1-62 interim report⁴). Early results have been reported at the CIE San Diego Conference⁵, where we compared the colour rendering properties of warm white colour light sources (incandescent lamp, tri-band fluorescent lamp and a Red-Green-Blue cluster set to 2795 K correlated colour temperature). Correlation between different mathematical models and visual observations have shown that no model, neither the official CIE Test Method⁶, nor colour difference calculations based on different colour spaces correlated well with the visual observations, but a model based on a revision of the CIECAM97 model⁷ worked best.

As a next step we selected a series of “cool white” lamps, i.e. lamps with correlated colour temperature near to 4000 K, and tested those in a double booth, comparing the colour difference between the 18 chromatic samples of the MacBeth Color Checcer Chart⁸, illuminated on one side alternatively by a number of test sources (standard-, deluxe-, tri-band-fluorescent fluorescent lamps and LED clusters), and with a filtered incandescent lamp on the other side. (In this Abstract we will restrict ourselves to two fluorescent lamps (cool white and PolyLux) and a Red-Green-Blue LED cluster. The spectral distribution of these sources is shown in **Figure 2**. The incandescent lamp was a cool-reflector type of lamp filtered to approx. 4000 K correlated colour temperature, thus its spectral power distribution deviated already slightly from that of a Planckian radiator, but the colour rendering indices were still in the mid 90 region.

Five to ten young observers with good colour vision and some practice of evaluating colour differences participated in the experiments. Every observer estimated the colour difference between the corresponding test samples in the two booths in two sessions. Table 1 shows the relative visual colour difference estimation if values for all samples have been averaged, the CIE 13.3 General Colour rendering Index and two colour differences based on CIELAB colour difference and using CIECAM02⁹ colour appearance model.

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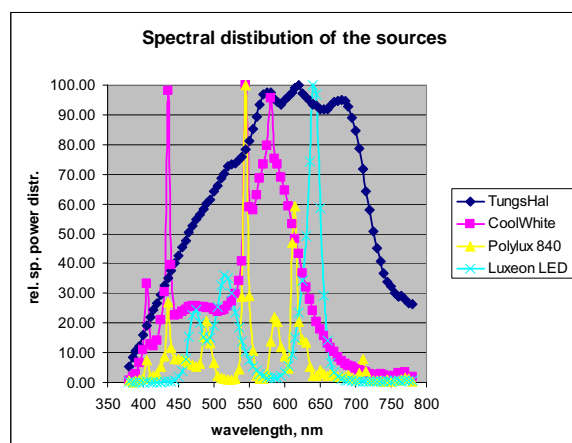


Figure 2: Spectral power distribution of some of the sources tested.

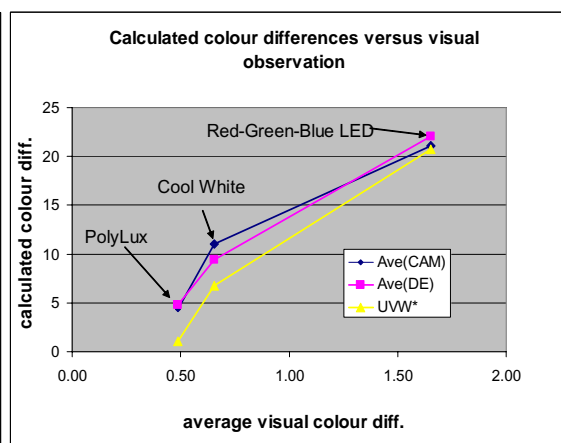


Figure 1: Calculated colour differences versus visually observed colour difference for three sources.

Table 1: Results of the visual evaluation and colorimetric calculations

Type of evaluation	PolyLux fl. lamp	Cool White fl. lamp	R-G-B LED cluster
visual colour diff.	0,49	0,66	1,65
CIE 13.3 Ra	83,9	61,1	5,0
Ave CIELAB ΔE	4,8	9,4	22,1
Ave CIECAM ΔE	4,4	11,1	21,1

For better visualization of the correlation between the visual observation and the different calculated results, we transformed the Ra values into a quasi-colour difference, by calculating $1-0.25 \cdot Ra$, and plotting this together with CIELAB and CIECAM colour differences in Figure 1. As can be seen the 13.3 method (calculation in U^*, V^*, W^* colour space) scales the PolyLux lamp, compared to the LED cluster much better than the CIELAB or CIECAM colour space based colour difference.

Visual colour differences of the single colour samples observed under the LED cluster and the incandescent lamp showed with CIECAM space calculations an extremely good correlation, with a correlation coefficient of 0.89.

In the oral presentation the analysis of further test sources will be presented together with the evaluation of the colour changes of the single test samples.

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Categorical Color Rendering of LED Light Sources

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The CIE color rendering index is not based on the color appearance of the object but on the color differences between the objects under different illuminants. When we need to identify color of the object, however, it becomes important to know how color appearances of the object change according to the change of illuminant. Particularly, use of color names is an important means for communicating color and for recognition of objects. In this study, 292 color chips under five different light sources including fluorescent lamp as simulator of CIE standard illuminant D65 and white LED (blue LED and yellow phosphor type) light sources of four different correlated color temperature; 2800K, 4000K, 5100K and 7500K. Illuminance at the test chip was set to 500 lx for all light sources. We employed 9 subjects. They were asked to sort samples into eleven basic color categories specified by Berlin and Kay¹⁾. Sorting of each color samples under each light source was repeated three times in different experimental sessions. We examined the distributions of color categories in the Munsell Color Space. In order to quantify the category overlap for two different illumination conditions, the evaluation method for the categorical color rendering developed by Yaguchi et al²⁾ was applied in this study. The idea of this evaluation method is similar to percent overlap developed by Boynton, Fargo and Collins³⁾. Assuming the D65 fluorescent illumination as a reference light source, the comparison was made between the color name region obtained from the D65 fluorescent light source condition and those from each of the other four LED light sources. At first, samples sorted into the same color category consistently for all three trials under the D65 fluorescent illumination was selected. Then among these selected samples (let the number be N_{D65}), we count the number (N_s) of samples under each illumination sorted into the same category as in the D65 fluorescent illumination condition consistently for three trials. Also we count the number (N_d) of samples sorted into a different category consistently for three trials. The index of categorical color rendering proposed here was defined as $100(N_s - N_d)/N_{D65}$. The number of samples were accumulated with the results from all of eight subjects. The index of categorical color rendering was calculated for each basic color name shown in Table 1.

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Table 1. Categorical Color Rendering Index for white LED light sources.

Color Name	2800K	4000K	5100K	7500K
red	62.5	72.5	82.5	72.5
green	78.2	81.0	91.1	82.3
yellow	79.5	78.2	84.6	83.3
blue	80.7	86.3	88.8	93.1
pink	45.6	48.3	62.6	59.2
orange	85.1	87.1	75.2	80.2
brown	86.4	85.5	89.6	81.9
purple	75.7	79.0	81.7	88.3
gray	65.7	71.4	80.0	37.1
black	72.2	50.0	72.2	16.7
white	33.3	44.4	61.1	-16.7
Total	75.8	78.6	84.3	80.6

We developed the categorical color rendering index (CCRI) based on color appearance model, CIECAM97s⁴⁾. The present experimental results are applied the CCRI using CIECAM02 instead of CIECAM97s.

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Why does the CIE Colour Rendering Index fail for white RGB LED light sources?

Peter Bodrogi, Peter Csuti, Peter Horváth, János Schanda

Summary. The prediction of white LED colour rendering by the CIE CRI method is problematic. Possible reasons are investigated computationally. An alternative way of colour rendering calculation is presented.

Introduction. Visual experience shows that the prediction of the colour rendering of white LED light sources (especially RGB LED clusters) by the CIE CRI[1] method is problematic. Several reasons were mentioned to explain this problem[2]. In this paper, we would like to computationally examine a possible reason for this problem, namely, the effect of using one single average number calculated from a restricted number of colour differences only. We would also like to present an alternative way of colour difference calculation, the colour harmony rendering index. A comparison of the different colour difference metrics is currently underway.

Computational method. We have computed colour differences between the test source and the reference source in CIELAB by using the six reference sources proposed in the CIE TC 1-33 report[3].

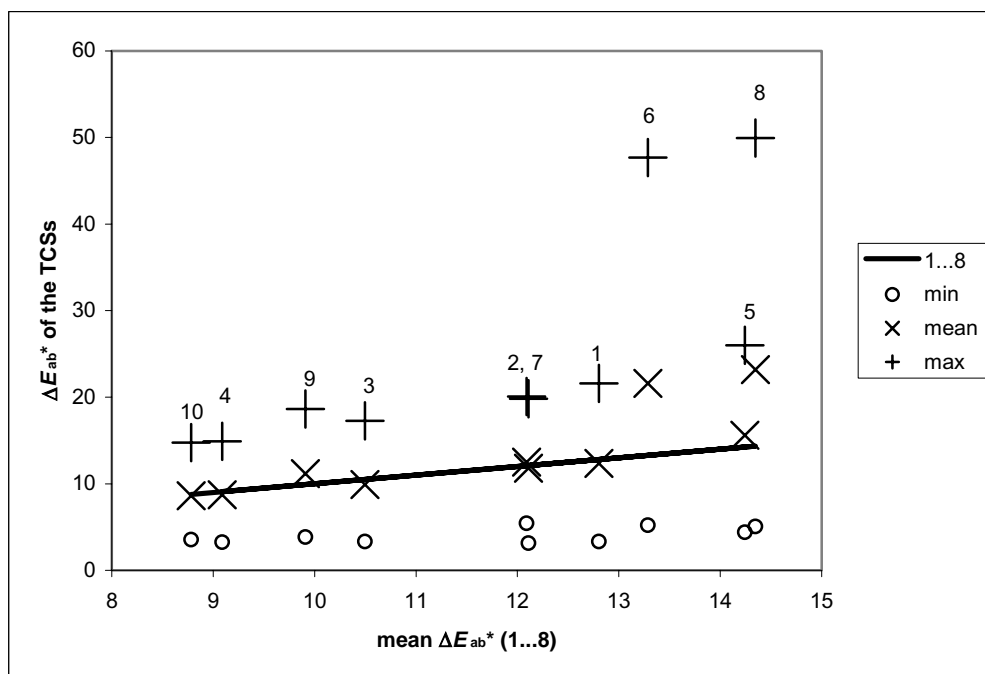
We used 10 test sources (see Table 1) and 34 test-colour samples including CIE TCS 1-14[1], two actual skin colours[3], and the 18 chromatic samples of the MacBeth ColorChecker Chart. Tristimulus values of the test-colour samples illuminated by both the test and the reference illuminants were transformed into CIELAB space for D65 illuminant by using the CIE 1994 chromatic adaptation transform.

Table 1. Test light sources used in the computation

No.	Source	CCT	No.	Source	CCT
1	Osram Lumilux Cool w.	3875	6	Luxeon RGB LED cluster	4008
2	GE Polylux XL	3970	7	Luxeon w. LED with phosphor	7580
3	Osram L.lux de L. Cool w.	3672	8	Luxeon RGB LED cluster	2935
4	Solux Halogen	3953	9	Shark white LED with phosphor	4691
5	Tungsrham Cool w.	4140	10	Tungsrham halogen	2983

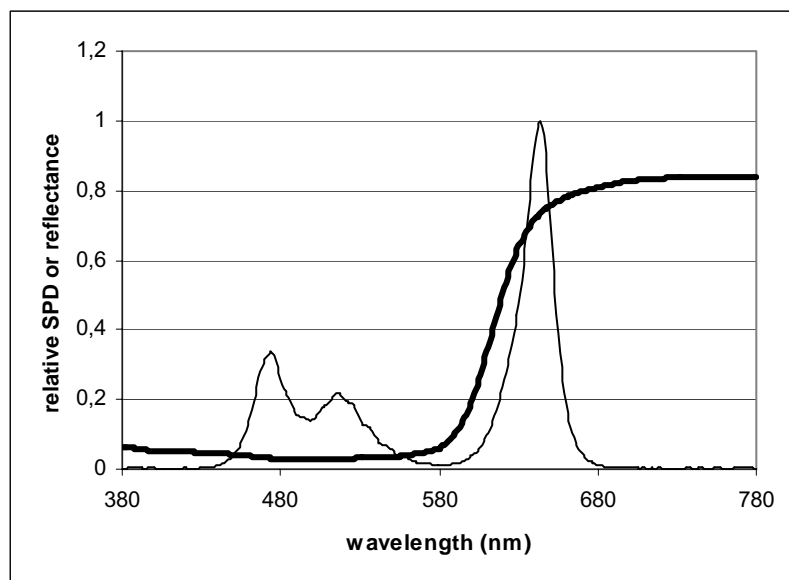
Result and Discussion. The resulting colour differences are shown in Figure 1.

Figure 1. Minimal, mean, and maximal CIELAB colour differences[3] of the test-colour samples, plotted as a function of the mean of the first eight colour differences corresponding to the first 8 CIE TCSs[1]. The numbers above the plus signs (maxima) correspond to the test light sources listed in Table 1. The line shows the mean ΔE_{ab}^* of the first 8 colour differences.



As can be seen from Figure 1, two test sources, No. 6 and No. 8, i.e. the two RGB LED clusters, cannot be well characterized by the mean ΔE_{ab}^* calculated from eight test-colour samples. Both their maxima and mean values are well above those of the other test sources and above the mean ΔE_{ab}^* line. The maximum ΔE_{ab}^* value of test source No. 8 (see the plus sign labelled by 8 in Figure 1) corresponds to CIE TCS #9, a strong red sample. Figure 2 shows its spectral reflectance curve together with the relative SPD of test source No. 8 (an RGB LED cluster). As can be seen from Figure 2, the red peak of the RGB LED cluster is able to **excessively accentuate the strong red** of the CIE TCS #9 test-colour sample. This effect cannot be traced back to other test-colour samples or an average value calculated from them. For RGB LED clusters, TCS #9 is not an exceptional case. Several other colour samples also show large colour differences explained by similar reasons.

Figure 2. Spectral reflectance curve of CIE TCS #9 (thick curve) and relative SPD of the test source No. 8 (RGB LED cluster, thin curve)



Colour harmony rendering index (HRI)

The CIE CRI calculation method[1] is based on colour shifts of test colour samples when illuminated by a reference illuminant and by a test illuminant. But, according to the authors' feeling, the *relative* shifts of the test colours may also be visually relevant when observers appraise CR. This is related to the deterioration of the "internal colour harmony" among the test colour samples under the reference illuminant when going over to the test illuminant[4]. We may quantify this deterioration of "internal colour harmony" by a "colour harmony rendering index" (HRI) calculated from the relative change of all distances among all test colour samples e.g. in the following way:

$$\text{HRI} = 100 - c \sum (|d_{i,\text{test}} - d_{i,\text{ref}}|) \quad (1)$$

In Eq.(1), d_i is the distance between *two* test colour samples under the *test* illuminant or *the same two* test colour samples under the *reference* illuminant, e.g. in a CIECAM based uniform colour space[5]. Index i runs over all possible pairs of test colour samples, and c is a suitable constant. HRI computations for different test sources including LED lamps are currently underway.

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Simulation Analysis of White LED Spectra and Color Rendering

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There has been significant advancement in light-emitting diodes (LEDs). High brightness LEDs are now available in all colors and their efficiency is being improved at a great pace. White LEDs are highly expected for use in general lighting due to a potential of great energy saving. White LEDs are produced either by multi-tip LEDs (e.g., red, green, blue) or by combining phosphors excited by blue or UV LED emission; thus, white LEDs have greater freedom in spectral design than traditional sources that were limited by available phosphors and gas emissions. Thus the spectra of white LEDs can be very different from those of traditional sources, and questions arise on what the spectra of white LEDs should be for best color rendering. The CIE Color Rendering Index (CRI) [1] is currently the only metric available to judge this, but it is known to have deficiencies, especially when used for LEDs [2]. An effort has started in CIE (TC1-62) to develop a new metric for LED light sources.

When considering spectra of light sources for general illumination, another important aspect to consider is luminous efficacy of radiation (lumens per optical watt; hereinafter denoted as LER), which is also determined by the spectrum. LER and color rendering are both important parameters for light sources for general lighting, and these two are generally in trade-off relationship. Based on the CRI, color rendering is best achieved by broadband spectra distributed throughout the visible region, while luminous efficacy is best achieved by a monochromatic radiation at 555 nm. This trade-off relationship is evident in many existing lamps. By studying the CRI, some people are lead to believe that white LED spectra should mimic the spectrum of the sun or blackbody or equal-energy white. While such spectra would give high CRI no doubt, they would suffer from much lower LER. The challenge in creating LEDs for use as illumination sources is to provide the highest possible LER while achieving sufficiently good color rendering. As such, an accurate metric of color rendering is of importance. If the metric is incorrect, energy will be wasted. It should also be noted that the available efficiency of LEDs varies a lot depending on wavelength (e.g., very low efficiency at the 550 nm to 580 nm region). In practical applications, the luminous efficacy of a

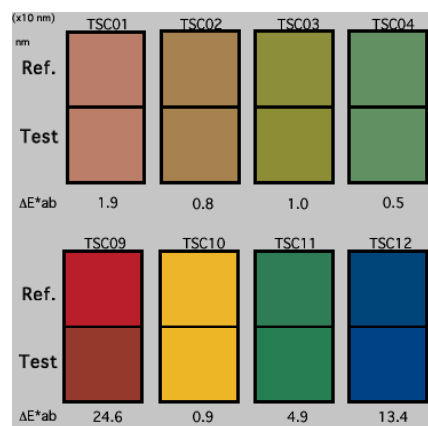


Fig. 1 An example of presentation of the appearance of the color samples of CIE 13.3. (only 8 of the 14 colors are shown.)

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source (lumens per electrical watt) needs to be considered.

To analyze the possible performance of white LEDs and also the problems in CRI, a simulation program has been developed to analyze white LED spectra mainly by multi-chip LEDs in comparison to various conventional sources. To simulate multi-chip LEDs, a mathematical model is used to approximate a single-color LED spectrum at any wavelength and spectral width. The program can simulate 3 or 4-chip white LEDs, and automatically calculates the power ratios of each LED to bring its chromaticity coordinate exactly on the Planckian locus at a given correlated color temperature (CCT). This allows the use of an iterative method to optimize LED spectra for maximizing the CRI or luminous efficacy under given conditions. The program calculates the general and special color rendering indices (R_a , R_1 to R_{14}) as well as the LER (lm/W). The color differences in ΔE^*_{ab} are also evaluated. The program then presents the actual colors of the 14 color samples of CIE 13.3 under the reference illuminant and test illuminant on the computer display, which provides visual impression of the color appearance (Fig.1). The presentation of the colors is achieved by conversion from XYZ (calculated back from CIELAB coordinates) to the display RGB space and applying gamma correction [4]. The data of Macbeth Color Checker are also added in the program to test color samples other than those in CIE 13.3.

By simulating various combinations of 3-chip white LED spectra, the following observations have been made.

- The trade-off relationship between CRI and LER is demonstrated (Fig. 2). Also, maximum CRI does not depend much on CCT.
- Higher CCT can produce slightly lower LER (Fig. 3). This is due to the fact that more blue power is needed for higher CCT while blue emission has very little contribution to lumen.
- 3-chip LED models show acceptable color rendering (up to $R_a=89$), while there may be significant color shift for some saturated color samples other than $R_9 - R_{12}$, which needs to be studied.

4-chip LED model showed excellent color rendering ($R_a=97$, or $\Delta E^*_{ab} < 4.4$). The color shifts of saturated color samples seem to be not significant, but it needs to be verified.

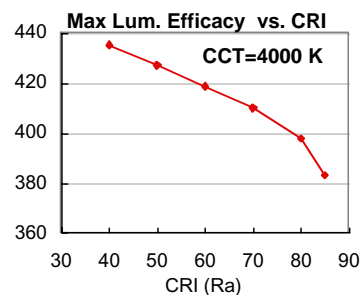
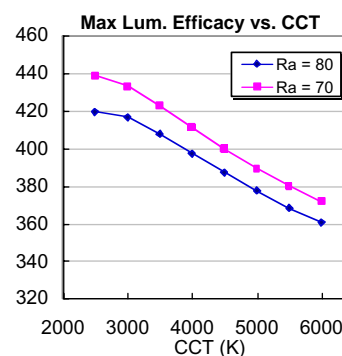


Fig.2 Maximum LER vs. CRI at constant CCT for RGB white LEDs.



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The LER of various source spectra are also compared. For example, a spectrum of D65 cut out in the 400 nm to 700 nm has LER of only 248 lm/W, while 3 or 4-chip white LED spectra ($R_a = 80$ to 97) can produce 350 to 420 lm/W.

Such a metric for color rendering as CRI, if it is accurate, would be a useful tool to design spectra of white LEDs. However, the following problems of CRI have been identified.

- 1) The color rendering of saturated colors ($R_9 - R_{12}$), particularly R_9 , can be very poor while R_a is a decent number. An example: $R_9 = -67$ while $R_a = 82$ (3 chip LED: 460, 530, 600 nm). In this case, R_9 sample appears to be brown. This demonstrates the problem in the selection of the color samples.
- 2) The 2000 K (very reddish) blackbody or daylight spectra at 20,000 K (twilight) gives $R_a = 100$ though colors do not render well. This demonstrates a problem in the definition of the reference source (CCT of the reference source moves with that of test source). Chromatic adaptation is assumed to be too perfect.
- 3) The CRI does not account for the shift in chromaticity coordinates across the Planckian locus well. For example, the chromaticity coordinate of a 3-chip LED (3000 K, $R_a = 85$) is moved from $duv = 0$ to $duv = 0.01$ in the yellow direction. The R_a is still 85 while this color is very yellowish and unacceptable for room lighting. This implies a problem in chromatic adaptation formula.
- 4) The plots of color differences on $W^*U^*V^*$ scale (outdated) indicates significant nonuniformity compared to CIELAB. The distortion is notable particularly in red region.

The CRI should be improved on those aspects. Many of these points were already addressed [3]. Another observation was that the incandescent lamp with neodymium coating showed $R_a = 77$ while this type of lamp is often preferred to normal incandescent lamps ($R_a = 99$). The chroma of red and green samples are shown to be slightly increased. Other references indicate that such feature provides better visual clarity. This implies that color preference should also be considered in addition to color fidelity.

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White LEDs: Special Characteristics and simple method to improve their Color-Rendering

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This paper will show measurement data obtained on white LEDs, particularly on 5 mm single lamps. It will be shown that their spectral power distribution appears different when viewed from different angles. This phenomenon has been observed before, and explanation of this effect can be found in the literature.

CIE has defined a measuring geometry for Average LED Intensity, but has not decided yet on the measuring geometry on (total) luminous flux measurement for LEDs. Some experts favor total immersion (the LED being in the middle of the sphere), others prefer to put the LED near to the wall of the sphere. For white LEDs showing this angle dependent colour change spectral measurement data in the two geometries will be different, while the final user of the LEDs might even utilize further light distributions differing from the above three possibilities. This might become increasingly important as LEDs are now used in luminaires or integrated into such fixtures and used for general illumination. It will become very important to standardize also on such geometries that take the practical use into consideration. We will show results on the spectrum/colour if different portions of the LED is utilized. Also attempts to minimize this effect will be discussed, with special reference to phosphor coating techniques.

Calculation of color rendering index from the spectral power distribution of white LEDs will depend also on the measurement condition, giving a better value when viewed along the geometrical axis than any other viewing condition.

When a cluster of white LEDs are utilized in many applications, this effect may be even more disturbing, especially when reflectors are added to the housing.

A simple method will be described for eliminating the discrepancy between the spectral power distributions along different directions, and improving the color rendering index of white LEDs without changing their phosphor layer and composition.

This technique consists of introducing special glass layers added to the package of a finished lamp, or depositing over the phosphor layer of the chip. The layers can be optimized in respect of their thickness and transmittance. Although such filtered LEDs will have a slightly reduced efficacy, the colour and colour rendering can be increased considerably. Thus e.g. an LED of high

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correlated colour temperature (above 7000 K) can be filtered to a 4400 K emitter that will show a general colour rendering index of about 70.

Examples will be shown, both for spectral distribution dependence on spatial direction and color rendering index change by utilizing different glasses added to the housing.

Problems remaining after this technique was introduced will be discussed; possible other solutions will be mentioned

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Nurmi T.	Finland	The determination of the effective light intensity of LEDs
Hagiwara K.	Japan	Visibility of color stimuli using LEDs in driving situations
Nakamura H.	Japan	Basic theory for quantifying the effect of illuminance on the conspicuity of recessed-mount LED equipment

THE DETERMINATION OF THE EFFECTIVE LIGHT INTENSITY OF LEDs

1. Background

On major part of the flashing light applications on ground, at sea, on aerial navigation or in traffic control, the effective intensity is used as the basis for comparing the flashing lights. Light flash can be described with a parameter that is called the effective light intensity of the flash. The eye does not analyse the momentary changes of the light current during the light pulse, but reacts to the total impression. Because the calculation formulas for effective intensity in use are based on measurements done with incandescent light sources, it was seen relevant to make a limited test series on LED light sources.

2. The experiment setting

A continuously burning and a flashing LED (250ms on/750ms off) were set on the back wall of the test laboratory approximately 10 m from the test person. LEDs were on the eye level when the test person sat on a chair. LEDs were covered with a shade that had a hole of 3mm diameter for making sure that the apparent angle of the light source was less than one arc minute.

It was noticed on the preliminary tests that it was practically impossible to adjust the continuous light as bright as the flashing light, especially if the luminance was much higher than the threshold luminance. It was decided to perform the tests as a threshold measurement to each light source separately.

Several measurement conditions were tested. It was noticed that the best results were obtained in twilight conditions. The test person was put to sit on a closet which had walls made of opaque cloth. Lights were put on both sides of the closet. Otherwise the laboratory was dark. Five measurements/LED was found a suitable number and the result was the average of three measurements where the largest and smallest value were left out.

A opening of 12*6 cm was located on the eye level of the observer. An alternative was a 15*20 cm opening. The front wall of the closet with the opening was approximately 50 cm from the face of the test person.

The test person was first asked to adjust the solid light with a potentiometer so that he/she

was just able to see the LED. When the LED was adjusted this way the electric current was recorded and from earlier luminance measurements the luminance was calculated.

There were 44 test persons. On age group 20-29 years there were 23 persons and on age group 40-49 years 16 persons. The remaining 5 persons were outside these age groups and were accounted for in the combined results. Test persons had a good eyesight either corrected with eyeglasses or without.

3. The test results

The results are calculated as a ratio of luminances L_e/L_0 (which equals I_e/I_0) in which L_e is the luminance of the solid light and L_0 is the maximum luminance of the square pulse.

The results of all test persons measured with the smaller opening: The average of $L_e/L_0 = 0,67$. (Allard $\approx 0,71$, Schmith-Clausen&Blondell-Ray $\approx 0,55$).

The test results from all test persons when the LEDs were viewed from the larger opening: The average of $L_e/L_0 = 0,57$. (Allard $\approx 0,71$, Schmith-Clausen&Blondell-Ray $\approx 0,55$).

There was also differences between different age groups.

4. Conclusion

The measurement results are different when the LEDs were viewed from larger and smaller opening. The average of the results is closer to the computational formula of the Allard formula when viewing from the smaller opening. With larger opening the values are closer to Smith-Clausen and Blondel-Rey-Douglas computational values. In addition when comparing the average measurements of age group of 20-29 year and 40-49 year old it is noticed that on the older age group the ratio of effective luminances is smaller than in the younger group. This difference might be explained by age vision.

Visibility of Color Stimuli using LEDs in Driving Situations

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1. INTRODUCTION

In this study, we examined the visibility of a small cluster of LEDs of different colors lit in various places in the visual field in the situation that simulates driving a car at dusk. Reaction time to detect the stimulus and its categorical color appearance were measured in psychophysical experiments.

2. EXPERIMENT

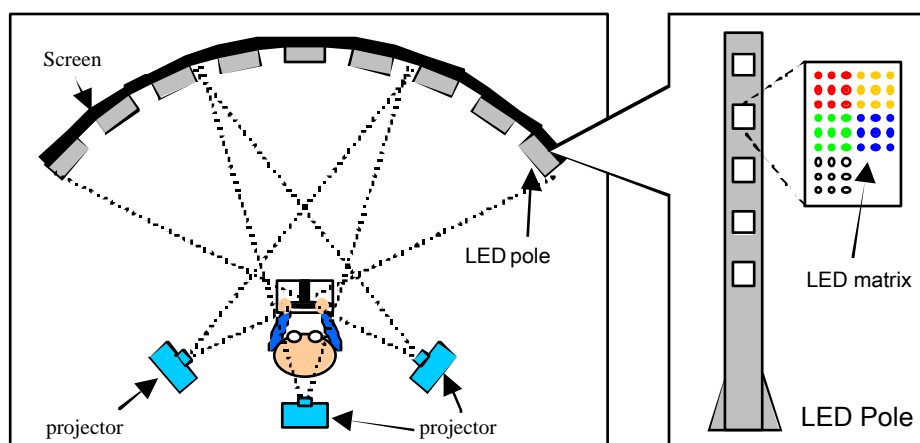


Figure 1. Left: the top view of the experimental apparatus. Right: LED Pole.

The left part of Figure 1 shows the top view of the experimental apparatus, and the insertion in the right indicates the LED pole composed of five LED matrixes of different colors. LED matrix was composed of 3 X 3 dots of red, yellow, green, blue and white LEDs, and they are respectively marked as R, Y, G, B, and W as stimulus codes.

In a background stimulus, three synchronized video movies were projected onto a wide

curved screen in front of the observer. The movies were taken by three DVD cameras placed on the dashboard of a car running on a road with a speed of nearly 40km/h at dusk. Nine LED poles were placed along the screen with an interval of about 13 deg in visual angle.

In an experimental session, the observer was asked to manipulate the steering wheel and foot pedals while freely watching the stimulus movie as if he/she drove the car through the road. From the start of the video movie, one LED matrix lit at one time, and the observer was asked to push the response button when he/she detect the stimulus. After pushing the button, the LED matrix was put off and the observer had to response the direction of the stimulus such as "left", "center", or "right", and its color appearance using 11 basic color names. The LED matrix lit 5 sec as the longest case.

3. RESULTS & SUMMARY

At the present, we obtained the results from two male observers who are in their early twenties. The response of the direction of the light stimulus was used to confirm whether the observer's response was really based on the detection of the LED matrix presented in that trial. Therefore, the responses of the direction were checked by the experimenter in the session and not analyzed here. Reaction time and the categorical color response were analyzed.

Figure 2 indicates the average results of the two observers for R and B stimuli in the categorical color naming. As shown in the figure, "red" response is dominant over the entire range for R stimulus, while "yellow" response appears even in the center. For the B stimulus, "blue" response is obtained in a wide range of the positions of LED pole, however, some "white" or "green" response appear in the positions in periphery. The results of other stimuli, Y and G, showed more unstable color appearance especially in the positions far from the center.

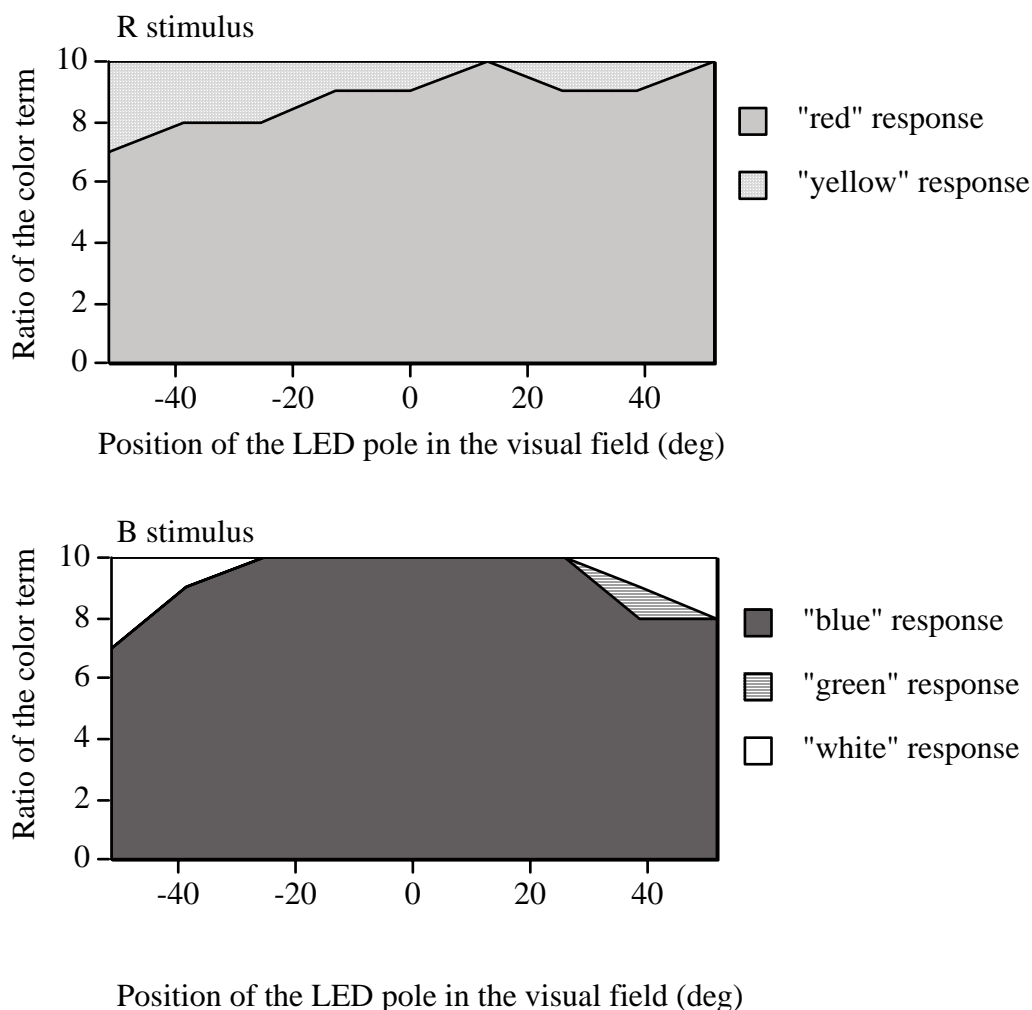


Figure 2. The results of categorical color naming for R (red) and B (blue) stimuli.

Concerning to the property to keep the same categorical color name as that obtained in the center, the B stimulus showed the best performance, and this is consistent with the previous results of color zone maps¹. In the results of the reaction time for detection, slight increase with eccentricity is shown while no significant difference is so far found among different color stimuli. The measurements are being done for other observers and the results will be presented at the symposium.

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Basic Theory for Quantifying the Effect of Illuminance on the Conspicuity of Recessed-mount LEDs Equipment

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1. Introduction

Recessed-mount LEDs equipment has many applications. For example, it can notify people of a direction when installed in the floor of a passage or indicate a boarding position by being installed on a platform of a railway station. The recessed-mount LEDs equipment in such applications needs to have high conspicuity to meet the intended purpose. The conspicuity of recessed-mount LEDs equipment is determined primarily by the luminance contrast and color difference between the equipment and the background object around it. The horizontal illuminance largely affects these two factors.

This paper proposes the method for theoretically obtaining luminance contrast and color difference from a given illuminance level. This method is required as the first step for theoretically predicting conspicuity of recessed-mount LEDs equipment.

2. Method of Obtaining Luminance Contrast

Because the measurements of apparent luminance contrast and color difference, of recessed-mount LEDs equipment (Fig.1), require time and effort, the method of calculating the values is described in this chapter and the next chapter.

(1) The apparent luminance on the surface of recessed-mount LEDs equipment consists of the following components.

- (a) The luminance L_o by the emitted light of the LEDs, equivalent to the luminance measured in a dark room.
- (b) The luminance generated by the light reflected on the LEDs equipment surface. This luminance can be divided into the luminance L_d by the diffused reflection and the luminance L_s by the specular reflection. L_d can be expressed by the following equation (1).

In the equation, q is luminance coefficient, and E is the illuminance on the surface of the LEDs equipment.

$$L_d = q \cdot E \quad (1)$$

Luminance L_s can be expressed by the following equation (2).

In this equation, p is an index indicating the degree of specular reflection, and L_e is the luminance of the objects (lighting fixtures, windows etc) reflecting on the LEDs equipment surface.

$$L_s = p \cdot L_e \quad (2)$$

The apparent luminance L of the LEDs equipment surface is expressed by the following equation (3).

$$L = L_o + L_d + L_s \quad (3)$$

The value L_s does not exist when no object is reflected on the surface.

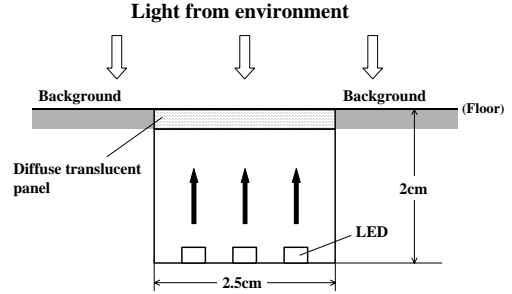


Fig.1 Recessed-mount LEDs Equipment

(2) The luminance L_b of the background object around the LEDs equipment is equivalent to the product of luminance coefficient r_b and horizontal illuminance E_b . The luminance coefficient r_b of a point B can be obtained by measuring the luminance L_b of the point B viewed from the observation point and horizontal illuminance E_b by using the following equation (4).

$$r_b = \frac{L_b}{E_b} \text{ [(cd/m}^2\text{)/lx]} \quad (4)$$

(3) The apparent luminance contrast C was obtained by the following equation (5).

$$C = \frac{L - L_b}{L_b} \quad (5)$$

3. Method of Obtaining Color Difference

The apparent chromaticity (u'_o , v'_o) of recessed-mount LEDs equipment can be obtained from the spectral power distribution $L(\lambda)$ radiated from the LEDs equipment, spectral reflectance distribution $L_r(\lambda)$ of the LEDs equipment, spectral power distribution $P(\lambda)$ of the incident light from the lighting environment into the LEDs equipment, and the ratio (k_1 , k_2) of the light from the own LEDs and luminous quantity from the lighting environment. The equations for obtaining chromaticity are shown below. The range of wavelength required for the integration in equation (6) and (7) is 380nm to 780nm. The values \bar{x} , \bar{y} , \bar{z} are spectral tri-stimulus values.

$$\begin{aligned} X_1 &= \int L(\lambda) \bar{x}(\lambda) d\lambda, \quad Y_1 = \int L(\lambda) \bar{y}(\lambda) d\lambda, \\ Z_1 &= \int L(\lambda) \bar{z}(\lambda) d\lambda \end{aligned} \quad (6)$$

$$\begin{aligned} X_2 &= \int L_r(\lambda) P(\lambda) \bar{x}(\lambda) d\lambda, \quad Y_2 = \int L_r(\lambda) P(\lambda) \bar{y}(\lambda) d\lambda, \\ Z_2 &= \int L_r(\lambda) P(\lambda) \bar{z}(\lambda) d\lambda \end{aligned} \quad (7)$$

$$X = k_1 X_1 + k_2 X_2, \quad Y = k_1 Y_1 + k_2 Y_2, \quad Z = k_1 Z_1 + k_2 Z_2 \quad (8)$$

$$u'_o = \frac{4X}{X + 15Y + 3Z}, \quad v'_o = \frac{9Y}{X + 15Y + 3Z} \quad (9)$$

The chromaticity of a background object (u'_b, v'_b) can be obtained by calculation based on the spectral power distribution of the illuminating light to the object and spectral reflectance distribution of the background object. The color difference ΔE can be obtained from the following equation (10).

$$E = \{(u'_o - u'_b)^2 + (v'_o - v'_b)^2\}^{1/2} \quad (10)$$

4. Conclusion

This paper proposed the theory for obtaining the luminance contrast and color difference of recessed-mount LEDs equipment based on the physical constants such as illuminance. Based on these two values, the theory for obtaining a sensory level of conspicuity needs to be developed. The tasks required for this objective should be done in a near future.

CIE Expert Symposium on LED Light Sources:
- Physical Measurement and Visual and Photobiological Assessment -

Invited Horak W.	Germany	Photobiological safety issues concerning LEDs-problems and requirements
Sliney D.	U.S.A.	Health and safety aspects of LEDs
Schulmeister K.	Austria	Eye simulating scheme for a complete characterization of the retinal hazard of LEDs
Horak W.	Germany	Prospect for the use of the CIE photobiological lamp safety standard for hazard assessments of “visible” LEDs for general lighting purposes
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Photobiological safety issues concerning LEDs - problems and requirements

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LEDs in photobiological safety standards

Since 1993, photobiological safety aspects of LEDs have been covered by the international IEC laser safety standard. Providing the "best available technology", this standard is listed under the "Low Voltage Directive" of the European Community. This means: compliance is necessary to gain a "CE-label" which is mandatory for placing products on the EU market and it has to be documented and declared by the manufacturers of LED products (not device manufacturers) within the EU and for the EU common market on a legal basis. Products with LEDs will only remain free from IEC 60825-1 regulations if the result of the classification is, in accordance with this standard, that the radiation output under all operating conditions during maintenance, service or in the event of failure does not exceed the Class 1 limits. As long as LEDs have only been usable as indicators, signal lamps or for simple remote controls, there have mostly been no real problems with the application of the laser-related limits and safety philosophy. However, due to increased efficiency and simultaneously enlarged application areas, this safety issue raises a growing attention – in general as well as related to the appropriateness of the laser regulations. Mainly initiated by (literally) obvious discrepancies in some application areas (e.g. general lighting), optical radiation safety requirements for incoherent optical sources were established which include also LEDs. The CIE photobiological lamp safety standard was published in 2002.

In any case, by extending the photobiological safety standards upon LEDs a wide group of users gets concerned who mostly neither cared for optical features of these components nor for optical measurements up to now. At present, data sheets usually do not contain information on optical radiation hazards or at least critical device parameters for hazard assessments in any case. Due to the complex physiological/biological fundamentals of optical radiation safety and due to some special features of LEDs it is empirically not really simple to determine the limits according to the standards, and consequently to apply the required measurement procedures – which are significantly different from optical characterization methods usually applied. The main and first questions concerning this LED community are therefore: what requirements are to be followed, who is responsible, what implications are to be expected and how to check them, are the (most convenient) exempt limits exceeded, are actions (which?) necessary, what is the future development? The present contribution tries to provide some answers.

Current and expectable future status of the IEC laser safety standard

Although the lamp safety requirements would be more appropriate in some LED applications, in case of doubt the laser standard takes priority due to the above mentioned higher degree of translation into mandatory legislation for product safety. Initially, the laser hazard-related worst case assumptions led to an significant overestimation of real LED-related hazards and in consequence to some serious revisions of the standard. As a result, compared with the status in 1993, the derived luminous or radiant intensity-limits for one and the same LED after two amendments have now increased by factors of some hundredfolds to even some thousandfolds – in particular cases depending on the emission wavelengths (e.g. color) and the source size. However, since the development has been activated on rather low levels, at least the most convenient Class 1-limits have currently been exceeded by high-power state-of-the-art- devices, especially in the colors blue, greenish-blue and the most important white LED lamps for general lighting. (Since the following Class 1M is mostly not available, these devices would belong to Class 2 (– with similar restrictions as for laser pointers.)

Unfortunately, the whole relaxation-procedure was just a quantitative but not a qualitative improvement. Therefore, the current status is still a (mandatory) classification requirement for (even white light emitting) LED products in general. This still implies an inappropriate discrimination, especially in application areas where the power saving and ecologically beneficial LEDs are in competition with conventional lamps of the same brightness (which have not to be classified on a similar mandatory level). Instead of solving this situation in a general satisfying way, the responsible IEC committee for the laser safety standard, prefers and continues dealing with technical details further on – mainly with a background of an adapted (relaxed) safety philosophy. Therefore, the laser safety standard is far from being unchangeably consolidated and at least the following further LED- related modifications can certainly be expected:

Currently, an "LED-exemption annex" is under preparation - actually in order to avoid needless testing. However, instead of providing limit data which would be comparable with usual LED-data sheets without the necessity of measurements, this annex just provides transformed laser limits in radiance and consequently requires an additional new (and currently unusual) measurement procedure. The main idea is, that by the Law of Conservation of Radiance, all LEDs emitting below the radiance level specified (and preferably already determined by the LED-manufacturer) cannot exceed Class 1 limits regardless of the optics placed in front of them (safety philosophy of Class 1). However, compared with the basic standard, the virtual simplification and limitation of the provided radiance limit set finally results in even more restrictive LED intensities. Therefore, the

practical benefit of this "LED-exemption annex" seems to be limited.

The future amendment 3 for the basic standard is already under preparation, and shall also provide a modified measurement procedure beside some other things. Unfortunately, the implication of this strongly relaxing modification is limited only to devices where thermal retinal hazards dominate, e.g. to ("green to red") LEDs which now have already unreachably high limits. The above mentioned critical device group where photochemical retinal hazards are dominating will not be attached by this change.

Most promising with the project for amendment 3 is a very recent approach to exclude at least LEDs for general lighting, signaling and indicating from the scope of the laser safety standard. This is not a real harmonization on a scientific level but would solve most current problems in a short run. However, the first draft of amendment 3 has not been published yet and – with the background of yearlong experience in such general scope modifications - a commonly simple approval is not really expectable. In the best case, the requirements of the CIE lamp safety standard would remain for LEDs in these application groups. However, the same critical group of devices with dominating photochemical hazards (which includes the phosphor converted white LED) also exceeds the exempt criteria of this standard and needs at least some attention in terms of photobiological hazards.

A main parameter for proper hazard assessment and classification of LEDs is their source size which is usually intermediate in between the extremes of small (or point) sources (lasers) and large extended sources (conventional lamps). In most cases, the applicable limit values as well as the assigned measurement conditions are strongly depending on the angular subtense (size) of the source. First "round robin" comparison tests among several manufacturers and test houses have shown a very large scatter resulting of the standard being prone to misinterpretation. Therefore, a clear guide and instruction for these measurements is absolutely necessary and the IEC committee is currently working on this issue. However, the first draft (for a technical report IEC 60825-13) favors the "beam propagation method", which is common within the laser community and that uses the curvature of the wavefront to determine the size, location and angular subtense of a source. This method should also be applicable to the "non-Gaussian LED-beams". But it is rather unknown, generally uncommon and the related measurement equipment barely available within the LED community so far. First comparisons with geometrical optical LED-source size measurements, which are still required in standards for incoherent sources, even led to surprisingly strong differences - to advantage of the beam propagation method. If these first results are really confirmed scientifically, this fact alone could be a reason to deal with this method in more detail. It is to be expected, that testing, harmonization or proper adaptation of this method will need some more time.

Conclusion

LEDs are included in photobiological safety standards for lasers as well as for incoherent sources in a general way - without application specific limitations. However, the IEC laser standard takes priority in the end, because of its higher degree of translation into mandatory legislation for product safety.

Current photobiological safety standards of any kind provide requirements concerning LEDs which are practically not controllable – due to the lack of mandatory described and proved measurement techniques. Therefore, the impacts can only be assessed by calculations.

The most convenient worst case exempt limits in any standard have already been exceeded by high-power state-of-the-art devices with photochemical retinal hazard potential, including the most interesting white light emitting LED lamps.

Although they are forced by this target, future developments of the laser standard provide no real relaxation for this specific device group.

At least, most promising would be a possible scope modification of the laser standard which would exclude LEDs for general lighting, signaling and indicating from the mandatory classification requirement.

Health and Safety Aspects of LEDs

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More than a decade ago, few would have suggested that the conventional LED could pose any biological effects other than as a visual stimulus. Today—with the development of ultraviolet-emitting LEDs and bright, blue-emitting LEDs—there are reasonable concerns that past assumptions about the total ocular safety of LEDs may not be true in all cases. Recent discoveries of a heretofore unknown photoreceptor system within the ganglion-cell layer of the retina that responds to blue light opens the door to both health applications and potential health hazards. LEDs have largely replaced the miniature tungsten lamps traditionally used as indicating lamps, and higher radiances are now available at shorter, more photobiologically active, wavelengths. LED arrays have replaced many higher-power tungsten lamps used in signaling applications, and once again, higher brightness signals are seen in roadway lighting for signaling and illumination.

LED arrays have also been used to optimize photobiological effects upon the neuro-endocrine system as mediated by the newly discovered ganglion-cell, blue-sensitive photoreceptors in the retina. In the mammalian retina, this photoreceptor array apparently determines the pupillary size and signals the pineal body to suppress melatonin secretion, thus controlling our sleep-wake cycle and seasonal changes due to the length of day, sun position, etc. The most likely chromophore in these special retinal ganglion cells is thought to be melanopsin and this sensory system is not uniform across the retina, but is more sensitive to light emanating from one hemisphere. Since the photobiological action spectrum for these effects peaks near 470 nm and the photobiological action spectrum for photochemically induced retinal injury peaks near 445 nm, blue LEDs must be used carefully in new applications. The photobiological effects must be examined in new applications. An LED emitting near 470 nm can be more than ten times more effective in controlling this new retinal sensor than a white-light source. Since we do not yet know all of the implications of exposing the retina to narrow-band blue light, application engineers and lighting designers need to tread with caution when using LEDs emitting below 500 nm. In the future, there will probably be highly beneficial health applications of these LED wavelengths, but as is true with any physical or chemical agent that elicits strong biological effects, there can be both risks at excessive levels and benefits at physiologically significant

levels of exposure.

In 2002, the CIE published an international standard on the *Photobiological Safety of Lamps and Lamp Systems*, S-009/E:2002. This standard covers potential photobiological hazards associated with ultraviolet radiation emissions and intense visible and infrared radiation from all types of lamps, including LEDs. Certain underlying assumptions were made with regard to viewing conditions and lamp use in this standard that may require a further review with regard to LEDs and LED-arrays. To complicate matters, there is another international safety standard that covers LEDs as well. As an extension to the scope of an international laser product safety standard published by the International Electrotechnical Commission (IEC), Technical Committee TC76 of the IEC included LEDs a decade ago because of the use of LEDs along with diode lasers in optical fiber communications. A European standard, EN 60825-1, requires LED testing to determine compliance with the EN (IEC) standard and many manufacturers have been burdened with added “safety” testing of LEDs as a result. However, virtually every conventional (surface-emitting) LED is perfectly safe to view under any reasonable conditions of use. This was emphasized in a widely circulated statement of the International Electrotechnical Commission (ICNIRP) published in the journal *Health Physics* in 2000. Bright visible LEDs can certainly pose a severe glare source, but not an ocular hazard under conventional and reasonable viewing conditions.

Unfortunately, many of the underlying assumptions in laser safety standards (such as collimated beams) do not apply to sources such as LEDs, and laser safety concepts can mislead LED users to overstate potential retinal hazards. The traditional surface-emitting LED, consisting of a directly visible chip of the order of 1 mm square, most often has a reflecting cup to collect and redirect the radiant emission from the side faces outward to add to the total radiant power output and to increase the radiant intensity. The contributions from the sides can add up to four times the directly visible surface emission, thus when one takes a magnified view of the emitter, one typically sees the central square emitter, sometimes with an apparent black spot in the center (the front electrode), and a surrounding ring of reflected side light. Some devices have a semiconductor chip that is somewhat transparent or translucent, and energy that is emitted in the backward direction from the chip is reflected back and travels through the chip to add to the apparent radiance of the source. From both a theoretical basis and in practical experience, the radiance of the central square surface is not exceeded by the radiance projected from the reflector. The built-in lens of most LEDs complicates any measure of chip radiance, since the source will not appear at a

single source plane. The measure of radiance is very important to assess potential retinal hazards, since retinal irradiance E_r is directly proportional to source radiance L , the square of the diameter of the pupil d_e , and the transmittance τ of the ocular media, i.e., $E_r = 0.27 \cdot L \cdot \tau \cdot d_e^2$. Furthermore, since the Law of Conservation of Radiance prevents the lens or any other optics from increasing the radiance, a measure of the chip radiance provides an upper limit for the hazard regardless of what optics are applied in a final product.

One method to measure radiance without the complexities of the optical lens, has been to cut off the plastic encapsulation lens of the LED at a plane as close to the front electrode as possible without severing the electrode. This “bare LED method” removes the magnification of the chip by the lens and a spot photometer or mask technique could be used to accurately measure the radiance of the chip. Some encapsulating plastic is spared in order to provide an appropriate index matching. The LED lens can be “flattened” through the use of a razor cut and then the lens surface is polished flat. The radiance could also be measured in air at the manufacturing facility; however, because of the altered thermal considerations, the radiance would have to be measured at less than full current, but since the radiance increases linearly with current, this measured radiance could be scaled up to a maximum current value based upon the specifications of the diode. Obviously, the radiance can be greater if operated in short pulse, as opposed to CW, conditions. The manufacturer can plot the radiance as a function of drive current and time in the same way that radiant power as a function of time is currently plotted in specification sheets issued. An added advantage to the manufacturer from specifying radiance is that application notes could be prepared to explain to design engineers how radiance could be used to calculate the maximum irradiance at any focal plane in an actual application such as in illuminators. The source radiance could be used to determine immediately whether the source would be adequate for achieving a given irradiance at some application point. If this advantage were adequately explained and some draft application notes generated, this would be a selling point for encouraging LED manufactures to provide this information.

LEDs offer many new possibilities for light and lighting, signaling and indication, but the designers of new products need to recognize the different potential for photobiological effects. They can be used either for an advantage, or unwittingly pose a possible hazard or adverse health effect. Health and safety standards of the future need to consider this.

Eye simulating scheme for a complete characterization of the retinal hazard of LEDs

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ABSTRACT

For the hazard assessment of optical radiation in the retinal hazard wavelength region of 400 nm to 1400 nm it is necessary to characterize both the power that enters the eye as well as the 'angular subtense of the apparent source' α , which is directly related to the retinal irradiance profile. For a complete hazard assessment, we argue that the complete range of exposure positions within the beam as well as, for each position, the full range of accommodation of the human eye, needs to be considered, to determine both the appropriate α as well as the most hazardous exposure position. Contrary to the current international laser safety standard, for this approach it is not necessary to determine the location of the apparent source. Also, depending on the divergence of the emitted radiation, it is not necessarily the chip which constitutes the apparent source in the sense of the location of accommodation that produces the most hazardous retinal irradiance profile. To obtain the retinal irradiance distributions of all relevant accommodation states and source-to-eye distances, a measurement method using a power detector, a lens and a CCD-camera is introduced, which aims to simulate the imaging by the human eye.

1. APPARENT SOURCE

The dependence of the threshold (MPE or AEL for product classification) for the retinal thermal hazard on the diameter of the retinal irradiance profile (corresponding to the image of the source) is characterised by the 'angular subtense of the apparent source α '. Since for a given beam and a given position of the eye in the beam, the image at the retina depends on the refractive power of the lens, α is defined as the *smallest* angle that can be obtained by accommodation. The location to which the eye accommodates to obtain this minimum angle is then considered as the *location* of the apparent source. Only for bare LED chips (i.e. without focusing optical elements) is the actual chip also the apparent source. A lens cap reduces the divergence of the beam but also moves the chip optically to the back and magnifies it. In the extreme case of a chip being exactly in the focus plane of the lens cap, all rays coming from one point of the source are parallel after passing through the projecting lens and the eye accommodates to infinity to produce the smallest retinal image, a sharp but in respect to the physical object enlarged image. In this rather theoretical case it

can be shown [1] that the location of the apparent source is at infinity and α equals the divergence angle of the beam, at least for all viewing positions within the flash distance. But this is not the case for general sources.

Figure 2 shows images of a LED that were obtained by placing a lens in front of a CDD camera to mimic the imaging of the human eye. While the position of the lens (and therefore of the eye) in the beam was kept constant, the CCD camera was moved to mimic the accommodation properties of the human eye. Figure 2a shows the image of the eye accommodated to image the cap, 2b the magnified chip, 2c some distance behind the chip and 2d results from a relaxed eye, i.e. accommodation to infinity. The power that entered the eye and that is distributed across the image is the same in all cases; however, the angular subtense of the apparent source varies. Currently, there is no standardised way to evaluate the irradiance profile in order to determine α , but the rather high irradiance peaks of 2c and 2d show that, depending on the LED, it is not necessarily the accommodation to image the chip that represents the most hazardous viewing condition. Other images can result in a smaller α .

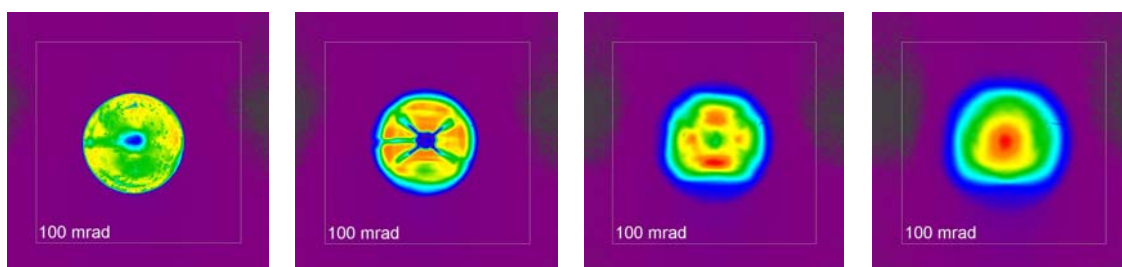


Figure2a

Figure2b

Figure2c

Figure2d

Irradiance distribution of a LED imaged by a lens and a CCD-camera for a distance of 100 mm between the surface of the LED and the lens and for an eye accommodation distances of a) 100 mm b) 128 mm c) 208 mm and d) 6250 mm

3. EYE SIMULATING MEASUREMENT SET-UP

The analysis of images such as shown in figure 2, for a given position in the beam, results in the value of α for that position. For a complete safety analysis it is necessary to analyse the full range of potentially hazardous exposure positions within the beam, as both the power that enters the eye P as well as α depend on the exposure position. The maximum ratio of P/α characterises the most hazardous position. We propose an experimental set-up for this procedure as follows.

First, the power passing through a 7 mm aperture as a function of the distance from the closest accessible point of the source is measured. The eye-simulating imaging system is set-up such that the field of view does not change when the detector is moved back relative to the lens. This is achieved by misplacing the imaging lens relative to a virtual eye so that the eye is assumed to be in the focal plane of the lens. By moving the lens, the position of the eye is varied and for each position, the CCD camera is moved relative to the lens to simulate different accommodation states of the eye.

The focal length f of the lens has to be long enough so that the ratio of f and the diameter of the CCD chip is greater than 100 mrad. The near point of the eye (assumed to be 10 cm) is simulated by placing the CCD-Camera some distance behind the back focal plane of the lens so that the conjugate plane of the CCD-Chip has a distance of 100 mm from the front focal plane. By moving the camera closer to the back focal plane, the irradiance distributions of different accommodation states from 100 mm to infinity (when the CCD Chip is in the focal plane of the lens) can be recorded, while all images are magnified but have the same scaling in respect to the front focal point, as shown in figure 3. This magnification and constant scaling factor is the main advantage of the proposed set-up.

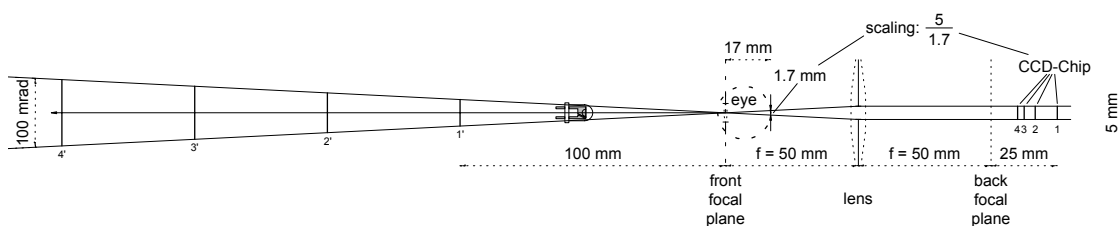


Figure 3: Measurement of the irradiance distribution within 100 mrad for the example of an eye-source distance of 50mm over the entire accommodation range using a lens with a focal length of 50 mm.

As the pupil and the focusing elements of the human eye are virtually located at the front focal plane of the lens, the power passing through the 7 mm aperture of the imaging lens is not equal to the power entering the eye, but this can easily be corrected using the data of the previous power measurement. For a complete safety analysis, not only exposure on-axis but also off-axis, i.e. looking slightly sideways into the LED, need to be considered, i.e. above procedure needs to be applied to somewhat tilted positions of the LEDs as well.

The scheme can also be used for the characterisation of the photochemical retinal hazard, where a certain field of view, as small as 11 mrad is specified. Above setup can be used to determine the amount of power contained with that FOV, which is represented by a certain

area on the CCD-Chip.

4. CONCLUSIONS

The thermal effect of laser or LED radiation on the retina depends on both the power that enters the eye and the irradiance pattern on the retina. It was pointed out that imaging the LED-Chip does not necessarily constitute the worst case accommodation position of the eye. For a complete and accurate hazard evaluation, the irradiance distribution on the retina for all relevant source-to-eye distances and for each distance, the entire accommodation range has to be analysed. For this purpose a new measurement method was developed which allows the measurement of the irradiance distribution on the retina for different source-eye distances and accommodation states while, in accordance with the human eye, the spatial extension on the 'detector' of a specific field of view remains constant (in the eye it remains constant as the image plane remains fixed, in our set-up it remains the same by placing the human eye virtually into the focal plane of the imaging lens).

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Prospect for the use of the CIE photobiological lamp safety standard for hazard assessments of "visible" LEDs for general lighting purposes

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abstract

At least LEDs for general lighting will hopefully be deleted from the scope of the IEC laser safety standard in the next future. In this case, the remaining optical radiation safety requirements for incoherent sources of the CIE "photobiological lamp safety" standard have to be observed. Instead of performing sophisticated measurements, the prospect for the use of this standard for a risk group allocation of "visible" LEDs can be checked by calculations. Thus it appears that for the most colored LEDs the most convenient exempt limits of the standard are already unreachable high – it is unimaginable, that they can be approached in the next future. This does not fully apply for state-of-the-art "blue" LEDs and sometimes also for the most important "white" LEDs for general lighting. Due to their dominating photochemical hazard potential, extensive deliberate long-term direct viewing can be hazardous. However, these high power light sources can be allocated to the "low risk group" by the majority i.e. these LEDs are safe for accidental or occasional viewing, which would supposedly be adequate and therefore sufficient for the unintended direct viewing of general lighting sources.

The theoretical considerations may also deliver focal points for future development of adjusted measurement methods as well as for photobiological safety circles.

introduction

Currently, the optical radiation safety requirements for LED are provided by different standards, due to historical reasons^{1,2/}. The most developed and commonly internationally accepted product safety regulations in this area are now: the CIE standard^{3/} for incoherent sources and the IEC laser safety standard^{4/}. Recently, especially the inappropriateness of the laser safety standard for sources used for general lighting became increasingly obvious and the related classification requirement will hopefully be withdrawn in the next future. The prospect for the use of the remaining CIE standard for hazard assessments of "visible" LEDs will be checked in the following. Beside providing the exposure limits for a hazard

assessment under conditions of use, the CIE standard also requires an allocation of optical sources in risk groups. It would be most convenient if the LEDs met in any case the exempt group criteria.

limit transformation

In order to avoid the effort of practical measurements and nevertheless to receive an impression on the implications on LEDs, an assessment based on geometrical optical calculation was performed. For this, the spectrally weighted radiance limit values per risk group as well as the appropriate measurement conditions had to be considered. Both were transformed in corresponding luminous intensity values which are easy comparable with data sheet values.

The results are presented for a defaulted intermediate range of source sizes in terms of device colors (or "white") rather than in peak-wavelengths.

results

Although posing a dominating photochemical ("blue light") hazard (!), the exempt group limits in the wavelength area from "green" to "red" are unreachable high and do currently not pose any problem for manufacturers and users in any case. However, especially the exempt limits in the "blue" area (just 2.8 cd) and also for "white" LEDs (23 cd) may have already been exceeded by high-power state-of-the-art devices. This most simple exemption approach is not sufficient and according to the CIE standard, modern optoelectronic sources in this wavelength range would therefore presumably belong to the "low risk group". This theoretical result was also confirmed by first practical measurements /5/. Due to the limited acceptance angle for a virtual measurement, the (transformed) low risk group limits become strongly dependant on source size. However, the worst case limits for small white light emitting LEDs are now already at about high 30 cd. I. e. as long as the specified intensity of a phosphor converted white LED is below this limit, the actual source size needs not jet to be considered. For the sake of completeness, it should just be mentioned, that the luminous intensities for the moderate risk group are roughly one order of magnitude higher – and therefore realistically unreachable, especially under consideration of the source sizes

conclusion

A simple transformation of the threshold limit values of the CIE lamp safety standard into corresponding luminous intensities was performed in order to get a first impression on the impact on LEDs for general lighting. Partly the limits itself as well as the consideration of the required measurement procedures lead to a more or less strong dependence of the derived luminous intensity values on the angular subtenses of the sources. These dependencies are different for the eye hazards which have to be considered within the selected range of wavelengths. In consequence, for one and the same device the origin for the applicable most restrictive limits sometimes changes within one risk group – depending on the source size. Practical measurements should care for this behavior. This puzzling overlapping and hazard-crossing of the results is sometimes hardly to be explained by photobiological reasons and should be addressed and possibly harmonized by optical radiation safety committees (e.g. CIE TC 6-55).

The very interesting white light emitting phosphor conversion LEDs for general lighting pose a dominating photochemical hazard due to their strong part of blue light emission. In this case the retinal eye hazard depends on the absorbed energy (dose) rather than the power. Therefore, the expectable exposure duration (within one day) plays an important role for hazard assessments.

Present theoretical consideration as well as first measurements elsewhere indicate that the most simple approach is not always sufficient since the exempt limits for "blue" or (most important for general lighting) "white" LEDs may be exceeded by high-power state-of-the-art-devices. However, for all other colors the exempt limits are unreachable high – unimaginable, that they could be approached in the next future.

Therefore, assessments or even measurements, if any, seem to be necessary for the addressed device group only. If desired, the radiance could be measured by simply averaging over an acceptance angle of 100 mrad, in order to decide whether a certain device could be exempted or not. At this step the actual source size of the emitter does not play any role.

If this measurement or the data sheet indicates, that a certain high-intensity device would exceed the exempt limits, the individual source size should be taken under consideration. If it is not a downright point-type source, in almost all cases, the device can be allocated to the low risk group (safe for accidental or occasional viewing - sufficient for general lighting sources). Generally, less problems occur if the LED-source is as much extended (up to 20 mm diameter) as possible. This is especially valid for high power blue light emitting LEDs. Unfortunately, the low risk group range is comparably narrow (factor of about only 1.3 above

the exempt limits for source dimensions smaller than 2.2 mm) and they may therefore quickly belong even to the "moderate risk group".

Since the exempt group criteria bases on some worst case assumptions (e.g. viewing duration of 10^4 s from a minimum accommodation distance of 20 cm), it should be noted that even if the limits under these conditions would be slightly exceeded, there will be no real hazard at all under most reasonable foreseeable viewing conditions of current general lighting LED sources.

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Results of lab and field trials regarding the eye blink reflex as a safety means for LEDs

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Introduction

The classification of laser products has been done according to the accessible emission levels (AEL) up to now in IEC 60825-1. The AELs are given in terms of power or energy respectively. Hazards are associated in this laser safety philosophy corresponding to the levels of laser radiation. Since in the international standard light emitting diodes (LED) are included whenever the word "laser" is used the classification rules are valid for LEDs too. In the case of laser class 2 the continuous wave (CW) power is limited to 1 mW in the visible part of the spectrum and the IEC-Standard assumes that eye protection is normally afforded by aversion responses including the blink reflex.

Since this provides adequate eye protection under reasonably foreseeable conditions of operation the respective laser products including LEDs belonging to laser class 2 are treated as safe for the human eye.

In addition this strategy has been responsible for several regulations for the prevention of accidents, where human aversion in terms of the blink reflex has been regarded to protect against a person's overexposure from bright light within 250 ms. This time duration has been chosen as a time base for class 2 and 2M lasers, i. e. it was actually agreed that the eye blink reflex as a "property of the human eye to close the lid due to an intense light stimulus limits any further exposure within 0.25 s". This is to say that it is the blink reflex which has been used synonymous for aversion responses to protect against laser class 2 irradiation since about 20 years or even more in the relevant written regulations at the work place and in the respective instructions for users.

Method

In 1999 it has been published [1] that between 12.7 % and about 20 % showed no blink

reflex when they have been irradiated with a commercially available photo flash light.

These findings influenced the decision not to regard the blink reflex as a physiological means to protect the human eye from an overexposure due to incoherent optical radiation in a regulation for the prevention of industrial accidents in Germany. The results concerning the lack of the blink reflex in more than 10 % initiated a research project on the "examination of laser classification with regard to the eye blink reflex" which has been funded by the Federal Institute for Occupational Safety and Health (FIOSH, BAuA) affiliated to the Federal Ministry of Economics and Labour (BMWA), Germany. The final report of this research project has been published in the meantime [2].

Goal of our research project has been to review the safety philosophy concerning lasers of class 2 based mainly on the existence of the eye blink reflex. When exposing test persons with laser light an overexposure had to be avoided under all circumstances staying below the maximum permissible exposure (MPE).

To gain dependencies of the eye blink reflex on physical parameters like output power, exposure duration, wavelength and physiological parameters of test persons like age, sex and so on, it has been necessary to do some laboratory work in advance to greater field studies.

For laser exposures we used diode-laser modules at 670 and 635 nm, furthermore a He:Ne-Laser at 632.8 nm and a diode pumped frequency doubled Nd-Vanadat-laser at 532 nm.

Besides that we used several ultra bright LEDs for irradiation with the dominant wavelengths at 468 nm and 615 nm to cover the whole visible spectrum. For the use in laboratory and field studies we constructed an apparatus which allowed to undertake our test persons a controlled exposure with different wavelengths. Figure 1 shows a schematic set-up of the test apparatus, where the laser module has been replaced by ultra bright LEDs too. Fig. 2 shows the location of applied laser and LED devices and the respective power in comparison to the different laser classes according to IEC 60825-1 (2001 and 1993). The investigations have been done in field trials with 3 different lasers with a power of 0.8 mW at a wavelength of 670 nm, 635 nm, and 532 nm and 2 LEDs with a power of 1.8 mW (correction factor $C_6 = 13$) and 7.1 mW ($C_6 = 66,7$) at a dominant wavelength of 615 nm or 468 nm, respectively (cf. Fig. 2, marked points d,e for LEDs). In addition we have investigated the blink reflex reaction with a white light LED with an output power of 0.59 mW at a distance of 100 mm.

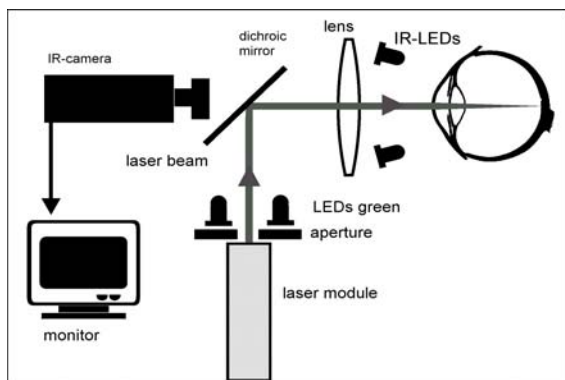


FIG. 1. Schematic set-up of the blink reflex apparatus

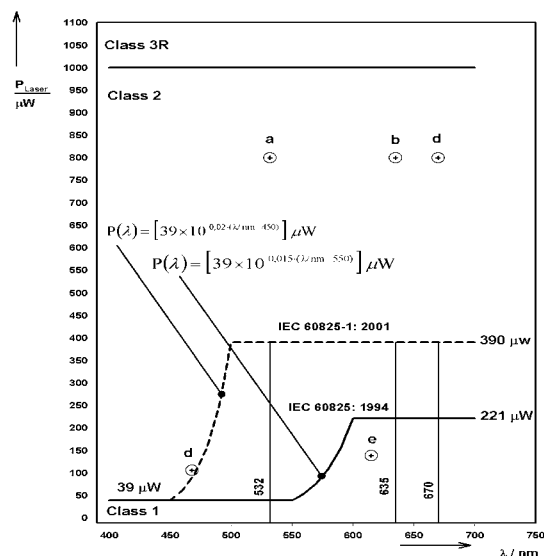


FIG. 2. Output power of the investigated laser and LED devices and classification regions according to IEC 60825-1:2001 and 1993

Results

In lab and field trials we have irradiated volunteers with a laser beam (0.8 mW, 250 ms exposure time) from a specially designed ophthalmologic apparatus in order to stimulate the blink reflex.

A total of 556 (laser: 503, LED: 53) volunteers have been irradiated in our laboratory tests. From these only 15.83 % showed a blink reflex (laser: 15.5 %, LED: 18.9 %).

In the field trials 690 volunteers have been irradiated with a laser beam and 208 with LED. The respective numbers for the blink reflex frequency were 15.7 % at 670 nm, 17.2 % at 635 nm, and 22.4 % at 532 nm. The results for the LEDs are given in Tab. 1 [3].

Table 1. Wavelength dependence in the field trials with LEDs

wavelength/nm	number of volunteers	blink reflex	
		number	%
615	14	2	14.3 ± 7.1
468	194	48	24.7 ± 0.6

In total 1454 volunteers took part in our experiments but only 264 reacted with an eye blink reflex when exposed with either lasers or LEDs giving a result of 18.16 % (± 0.07).

Discussion

As far as a wavelength dependency of the eye blink reflex is concerned one could say that

there is a weak correlation to the spectral visibility of the human eye. To gain more information about that, more persons should be tested with more wavelengths especially at the point of the maximum visibility of light and below 532 nm in the blue region. The tests we performed with blue LEDs showed that the eye blink reflex is as well triggered by non coherent sources, but the results are not directly comparable to those gained with lasers, as the emission of LEDs is not a collimated beam, resulting in larger spot sizes on the retina and being dependent on the diameter of the test persons pupil, i. e. on the ambient illumination conditions. Nevertheless up to now the investigations with LEDs have shown the blink reflex is stimulated via LED-irradiation not only at 615 nm (red) but in the blue region of the spectrum (468 nm) as well.

The relatively small number of blink reflex cases claim for a modification of the safety rules concerning laser class 2 products in the International Standard, i. e. the definition of the laser class should be changed and active protective aversion reactions should be implemented in the safety instructions in the user's guide.

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Analysis of Photobiological Aspects of Crop Plants Growing Under High-brightness Light-emitting Diodes

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Introduction

Light-emitting diode (LED) has definitely become one of the most interesting and challenging topics in lighting field. That interest arises mainly from the fact that their well known physical and electrical robustness, compact size and a more efficient use of electrical energy compared with the most common light sources used nowadays. Potential developments in LEDs technology for lighting applications are still underway. Those developments may forecast great changes in lighting field and the way we define lighting today.

Controlled environment

The use of LEDs as a light source for crop plants growth in controlled environment applications (e.g. greenhouses) has some advantages. In addition to the compactness and efficient energy conversion of LEDs, the output spectral characteristic can be considered as an extra asset for applications as a light source for controlled environments. This is so, because monochromatic LEDs have the advantage of having spectral characteristics that closely matches with the absorption peaks of the chlorophyll molecules. The discussion is still open in relation to the most effective way of achieving an appropriate and healthy growth of the plants. The spectrum composed by different wavelength pulses of radiation, as it happens with the use of high-brightness monochromatic LEDs, originate photobiological changes on the plant that need to be considered carefully. Controlled environment comes as an additional factor, which may influence the photosynthetic response of the plant, leading to photobiological alterations.

Photobiological aspects

Plants are using photosynthesis in order to convert the energy from light into chemical energy of organic molecules. "Light" as an energetic source in form of electromagnetic radiation has an important role in this process. This importance can be evaluated in terms of quantity and quality. The last one is generally referred to the spectral output of the light source and its correlation with the relative quantum efficiency (RQE) curve of the plant (Barnes, 1993). This curve measures the average plant photosynthetic response for different radiation wavelength between 360 to 760nm. From a brief inspection of the curve it is possible to observe that the main peak responses are to red light (600-700 nm) and in a smaller proportion or efficiency, to blue light (400-500 nm). It has been found that red LED radiation supplemented with blue light results in a better growth of the plant comparing to pure red LED radiation (Yorio, 2000). Nevertheless the maximal growth of the plant was not yet achieved. Tests with red and blue LEDs with different peak wavelengths have been proposed (Yorio, 2000) in order to find out the response of the plant to the blue light.

Plants have photoreceptor molecules that absorb light in broadband spectrum. They react to light quality and to the photon irradiance spectrum of the light source that are exposed, in different ways. For that reason it makes sense to have a more comprehensive approach to the effects that other radiation wavelength pulses have on the growth of the plant. For example, it has been known that plants have also photoreceptors, which are sensitive to wavelengths in the region of blue/ultraviolet-A and ultraviolet-B. The different groups of blue/UV-A photoreceptors existing in the plants have important effects for the development of the plant such as germination, stem extension, leaf expansion, root growth and phototropism (Aphalo, 2001). Thus, it will be interesting to know in which way the growth of the plant will be affected if a combination of different wavelength pulses is used.

Objectives

Despite of the successive good achievements obtained by the combination of high-brightness red and blue LEDs for plant growth (Bula, 1991 and Yanagi, 1996a,b), there is still space for improvements. One of the objectives of our paper is to analyse and understand which are the advantages and drawbacks of using a different wavelength radiation pulses combinations for plant illumination. The goal is to have an approach of what can be attained in a practical experimentation, having in mind that the final result should be a healthier plant with improved morphology and growth capabilities. In our paper will be also included a comprehensive analysis of what has been done in this field and what are the

expectancies for the future.

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CIE Expert Symposium on LED Light Sources:
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Invited Muray K.	U.S.A.	LED measurements: Current work within CIE
Gibbs D.	UK	Improved traceability for LED measurements and the results of a round-robin comparison of LED cluster measurements
Schuette J.	Germany	LED transfer standards
Mathe G.	Germany	Measurement of averaged LED intensity based on spectroradiometric standards
Farkas G.	Hungary	Complex characterization of power LED-s: simultaneous measurement of photometric/radiometric and thermal properties
Csuti P.	Hungary	Comparison of the goodness of fit to the function of photometers using real LED spectra

LED Measurements: Current work within CIE

Kathleen Muray / INPHORA Inc

Abstract

LED Measurement technique was not defined or standardized till the late nineties. Most of the light-source manufacturers used well-known methods before to characterize their products and the users got more-less understandable catalogues listing the usual quantities; it was possible to select the desired properties of the light sources by comparing different catalogues.

Unfortunately this was not the case for selecting LEDs based on different manufacturers' characterization in their catalogues. The problem became more acute as higher and higher brightness LEDs were developed and more colors became available, allowing a wide range of applications.

As it is well known by now, solution of the discrepancies was to standardize LED measurement methods. The first attempt in this direction was made within CIE Division 2; a Technical Committee was formed and finally resulted in the CIE recommendations how to measure LEDs; this work is published in the CIE **Report #127**.

The above-mentioned publication was only the beginning; it was considering all aspects of LED measurements, defining the problems related to measure each quantity reproducibly and how to reduce measurement uncertainties.

Most frequently used quantity for LED characterization is the Luminous/Radiant Intensity; however this quantity is the most difficult to measure. As it is described in the report, due to the many different type of LED packages and mis-orientation of the optical and mechanical axis of the lamp make it very difficult to determine the exact "distance" of the actual source of light from the detector.

In order to achieve reproducibility a new definition was needed for LED intensity:

Averaged LED Intensity came to life; here the actual measurement distance is fixed from the tip of the lamp measured along the mechanical axis to the center of the 1cm² area of the aperture in front of the detector. The character used for this quantity is $I_{LED A}$ or $I_{LED B}$, expressed in Candelas or Watts/steradian.

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A and **B** are the two distances fixed:

316 mm for CIE Condition A, and 100 mm for CIE condition B.

This arrangement if followed exactly was leading to reproducible measurements within different laboratories.

Besides the geometrical conditions the type of photometers used needed to be looked into; the most accurate values can be expected when the photometer has a perfect $V(\lambda)$ response for photometric values or flat response for radiometric values.

Evaluation of the goodness of the match of the detector-response with respect of the $V(\lambda)$ response was evaluated by the previously recommended method, determining the f_1' value and trying to obtain detectors with the lowest available commercially ($f_1' < 1.5\%$ was considered as best).

In case of photometers with higher f_1' value ($< 4\%-5\%$) good measurements still can be performed if substitution method is applied; for this type of measurements calibrated standards of the same type of LED lamps are needed as the test LEDs. They need to have the same spectral power distribution and most importantly the same spatial power distribution.

Two new Technical committees, **CIE TC2-45** and **CIE-TC2-46** were formed shortly after publication of the #127 Report.

CIE-TC2-46's purpose was to make it a standard the Averaged LED Intensity measurement method; at present they are finalizing the format.

CIE TC2-45 was formed to update the recommendations in CIE report "127 according to new developments in the LED manufacturing and to new research results in their evaluation method. At present the forth and final draft is available for comments and hopefully soon agreed upon by the members of the committee.

There will be several major conclusions in the upgraded report; with the availability of high efficiency blue and even UV LEDs, it was important to re-evaluate the meaning of the f_1' number; there may be necessary to introduce a different type of definition which could be more useful at the two ends of the $V(\lambda)$ curve; since the f_1' was developed for the broad

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spectrum type of light sources, the narrow-band blue LEDs and red LEDs may not be well served by detectors with even the lowest f_1 detectors.

Total flux measurement of LEDs before were performed in small integrating spheres; without very careful substitution method application it was not possible to obtain values, which agreed between different laboratories. In the new recommendations it is considered very carefully what is needed by the newest applications; one single “total flux” value is not enough. In most cases only a portion of radiation needs to be considered, which exits from the LED lamp into a given solid angle. Recommendations are describing how to measure such “partial flux” values; this new technique may require the introduction of new definition for LED partial flux. The report describes how the integrating sphere should be constructed, and how the LED should be positioned inside, at the wall or outside of the sphere.

More specific recommendations are described how to measure spectral distribution of the LEDs. It is known for some time that LEDs (chips as well as lamps) show variation in their spectral power distribution along spatial directions. This problem is more pronounced in the case of white LEDs where phosphor coating is applied over the blue chip. Therefore it is very important to obtain the spectral data with given geometrical arrangements; it should be measured either by illuminating the entrance optic of the spectrometer similarly arranged as in the case of CIE condition A or B as described for ILED measurements, or under other stated conditions; on the other hand if the LED is inserted into an integrating sphere an averaged spectral power distribution along different spatial directions will be the result. Most importantly the measurement condition needs to be clearly stated.

Since more LEDs are available on the market and more applications are developed daily, many of them require clusters of LED lamps, or large number of chips allowing the user to put them into different type of housings. In many cases the chips are left on the substrate grown with sophisticated integrated semiconductor technology to the customer's specifications. These specialized units have unique requirements for testing; until most recently there was no standardized way to evaluate them and specify them. With the growing number of manufacturers and users of such devices, it was necessary to broaden the involvement of the CIE in LED measurements. Several new TC-s were formed during the last two years to help in standardizing these aspects of measurements. **CIE-TC2-50** is working along these considerations to recommend measurement techniques for LED clusters with respect of applications. **CIE-TC1-62** Looks at the Color-Rendering of white LED light sources by investigating through visual experiments their color rendering

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properties and to test the applicability of the CIE color rendering index to white LEDs

Finally, the high brightness LEDs needed to be studied from an other point of view: how safe are they at different circumstances and in different applications. For many years this problem was not considered because the light output was so low that according to studies mostly conducted on lasers they were far below the level where they could do any harm. Lately it became more important to establish more realistic limits for those quantities which are important for the biomedical community applicable directly to LEDs and determine test methods how to measure them. The newest Technical Committee **TC2-58** was established only a year ago, it is in Division 6, in order to work closely with those specialists together who are directly involved with photo-biological effects

TC2-58 will come up with recommendations for measurement of LED Radiance and Luminance, taking particular account of the specific requirements for evaluation of photo biological safety

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Improved Traceability for LED Measurements and the Results of a Round-Robin Comparison of LED Cluster Measurements.

David Gibbs

National Physical Laboratory, UK

LEDs and LED clusters are attractive alternative to traditional incandescent sources for a number of applications, such as transport signalling, due to their extended service life, higher luminous efficacy, improved mechanical performance and reliability. However, the introduction of LED clusters into signalling applications has raised a number of measurement and specification issues. Some of these issues are similar to those of single LEDs, such as the relatively narrow spectral distribution and the effect of temperature on the output characteristics. Other measurement issues are due to the characteristics of the clusters, such as pixilation and uniformity of signal luminance, phantom/swamping effects of solar illuminance and luminous intensity distribution. It these issues that have led to the establishment of a Focussed Interest Group (FIG) under the Optical Radiation Measurement Club in the UK to consider the measurement issues related to LED Clusters. The membership of the FIG comprises LED suppliers, LED light source manufacturers, optical radiation measurement equipment and service providers, and lighting designers and practitioners.

The members of the LED clusters FIG have undertaken a round-robin comparison of measurements on railway signals formed of clusters of LEDs. The purpose of the round-robin was to gauge the level of agreement between laboratories at various positions within the measurement dissemination chain, and to investigate potential sources of systematic error in LED cluster measurement. Five different LED artefacts were used during the exercise, covering a range of colours, spatial distribution and mechanical construction. Although general instructions were provided on the operation of the artefacts, the participants were requested to use their normal operating procedures and equipment for the measurements. The facilities used by the participants include a range of technologies, such as scanning monochromator and diode array spectroradiometers, photometers, goniophotometers, and photoelectric colorimeters.

As a member of the LED Clusters FIG, the Optical radiation Measurement Group at the National Physical Laboratory, UK, were invited to participate in the round-robin exercise. The NPL have recently developed a range of facilities to improve the traceability for the

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measurement of LEDs and LED clusters in UK. These facilities, which can be used to measure the photometric, colorimetric, spectroradiometric, spatial and temporal characteristics of LED sources, were used for the round-robin exercise.

This poster will present the results of the round-robin exercise together with a description of the facilities that have been developed at NPL for the measurement of LEDs and LED light sources.

LED transfer standards

Jens Schuette

Abstract:

Today a global network of multiple suppliers and manufacturers is involved in the fabrication of a product. Therefore standardization and qualification of components is an essential issue. LEDs are used in increasing numbers by many industries in varied applications. Accurate, adequate and traceable measurements are required to characterize light emitting diodes. Comparisons have shown that huge differences in measured values between different manufacturers can be found. To overcome this a technical report was set-up in 1997. CIE 127 "Measurement of LEDs" defines a useful guideline in this context.

To benefit from CIE 127-1997 traceable LED transfer standards are needed. The aim is to create a short- and longterm stable, easy to handle reference-LED. Ambient influences such as temperature should be compensated and measurement uncertainties have to be minimized.

In 1999 EBT Optronic, a company of SLI Miniature Lighting, established a calibration laboratory for optical measurands. It was world-wide the first laboratory in the private sector that was accredited in accordance with EN 45001 for calibration of "Averaged LED Intensity" $I_{LED A}$ and $I_{LED B}$. Based on 5 years of practical experience in manufacturing and calibration of Averaged LED Intensity transfer standards the presentation will focus on the following topics:

Spectral, spatial and thermal characteristics of LEDs.

Considerations for choosing an LED as reference

Design and operation of intensity references

Generation of secondary standards

Alignment and calibration

Measurement uncertainty

Measurement of Averaged LED Intensity BASEd on SPECTRoradiometric standards

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Over the past years the demand for LED measurement equipment has experienced a powerful growth. The requirement for low-uncertainty measurement of averaged LED intensity (ILED, A, ILED, B) imply a well-defined and stable calibration of the whole measuring system. The use of light sources providing a broad spectral range (for instance pre-selected and seasoned halogen lamps) to determine the spectral response functions of spectroradiometers is an established procedure. However, for the absolute calibration LED standards are used. They are calibrated by the corresponding national photometry laboratories (NIST, etc.). This ensures the traceability of photometric quantities of LEDs to national standards.

These LED standards provide the basis for absolute calibration in a straightforward way. Nevertheless modern temperature-stabilized LEDs are complex optical elements based on semiconductor technology. Degradation effects may occur, both during operation and storing. In addition, fabrication tolerances affecting the long term behaviour cannot be completely excluded.

For these reasons it is useful to verify the LED-based photometric calibration with another one. It should be based on standards with different modes of operation and having been characterized in a different way. For instance, a controlled and stabilized halogen lamp with known absolute spectral power distribution (radiant power and irradiance) can serve as a tool to monitor the consistency of both calibration strategies.

In order to achieve low measurement uncertainty not only the standards but also each component of the measurement equipment has to fulfil certain requirements. Spectroradiometers have turned out to serve as reliable tools to evaluate photometric and radiometric properties of light sources. Since the level of the measurement signal of the used standards may differ by several orders of magnitude, a good linearity of the

spectrometer detector and a low and stable dark current is essential.

Instead of the typical $V(\lambda)$ based detector a special optical probe is used as an input optics for the spectroradiometer. As an essential feature this input optics has to provide a very good lateral homogeneity. For fibre based spectroradiometers integrating spheres can fulfil this requirement.

Integrating spheres transform incoming light into a diffuse and spatially homogeneous radiation: An ideal integrating sphere provides a cosine-like angular radiation distribution at each position of the sphere wall. The exit port of the sphere should ideally show the same response pattern. Diffusers in front of the input port can enhance the formation of a cosine-like radiation distribution. Figure 1 shows the lateral response of a suitable optical probe based on an integrating sphere.

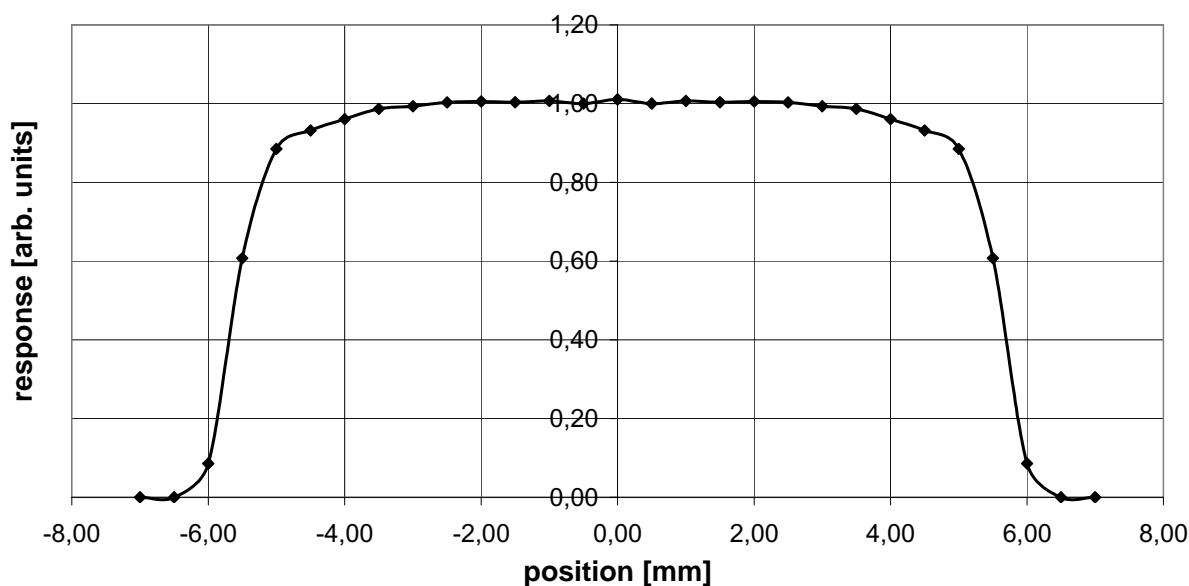


Figure 1

For point-like sources irradiance and illuminance depend on the inverse square of the distance. The same applies to the measured partial flux gathered by the input port of an integrating sphere (provided that the solid angle defined by the aperture of the input port and the distance to the source is small compared to unity). Therefore a precise knowledge of

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distances and diameters is essential to achieve absolute radiometric and photometric data of low uncertainty.

Integrating spheres used as launching optics for spectroradiometers and providing above-mentioned properties can be calibrated to irradiance and coupled with an ILED, A or ILED, B aperture tube. Photometric measurements of LED standards in an ILED-B configuration [1] agree surprisingly well with the values provided by the corresponding national laboratories. Deviations in averaged LED intensity are typically less than 2.5 %.

Complex characterization of power LED-s: simultaneous measurement of photometric/radiometric and thermal properties

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In case of power LED-s used as light sources, thermal issues are important. Although light conversion efficiency of these devices is rather high, 65-70% of the supplied electrical power heats up the LED, that results in junction temperature rise of 25-50 °C, depending on the thermal resistance of the device and its enclosure. Thus, besides reaching high efficiency and meeting photometric targets, the proper thermal management of the power LED devices is gaining importance. Since the power of LED-s used in lighting is 1 to 10 Watts, severe overheating problems may occur and like in case of any semiconductor device, this overheating may destroy the device which otherwise would have an infinite lifetime. In other words, the junction-to-case / junction-to-ambient thermal resistance (or in general, thermal impedance) must be kept at minimum in order to minimize the temperature rise at the light emitting region of an LED device, ensuring its expected lifetime and reliability. In addition to that, the good thermal management is also a key factor in maintaining stability of the photometric / colorimetric properties of power LEDs.

The need for a combined photometric/radiometric/thermal characterization of LED devices originates also from the standard device characterization procedures of the semiconductor industry. In case of semiconductor devices, besides their electrical characteristics thermal parameters such as junction-to-case thermal resistance are important parameters. The same applies for the light emitting diodes, for LEDs. In case of conventional semiconductor devices the total electrical power supplied to the device is dissipated in form of heat, while in case of LED-s about 30-35% of the power is converted to light. Thus, thermal characterization of LEDs cannot be completed properly without knowing the energy flux emitted as light (radiometric flux), that is why radiometric characterization of a LED device is a pre-requisite for its thermal characterization as a semiconductor device.

In case of photometry/radiometry of LEDs the stabilized temperature of the PN junction is required – the measurement takes place in equilibrium. Upon completing the measurement,

when switching off the LED, its cooling transient starts – this can be recorded by thermal transient testers [1] used for thermal characterization. Thus, the two measurements – photometric/radiometric measurements in thermal and electrical steady-state and thermal characterization based on recording of thermal transients – inherently complement one-another.

Our team proposes a combined LED characterization station based on this principle. A trial setup, such as shown in Figure 1 was built and used for the measurement of a 1W red LED [2]. As the figure suggests, any standard photometric/radiometric measurement setup can be completed with a usual thermal transient setup such that the two measurements can be carried out in series: we can record a switching-off transient after the photometric-radiometric measurements are completed. In our experiment the device under test was measured with 60, 75, 150 and 300 mA bias current and the identified optical power was subtracted from the electrical one when evaluating the obtained thermal transient curves – all shown in Figure 2. From the corrected thermal transient curves the so called *structure functions* [3] can be identified – these are thermal capacitance / thermal resistance maps of the junction-to-ambient heat-conduction path. From these one can easily build accurate thermal models of a LED device [4] (see Figure 3) to be used e.g. in board-level thermal simulation or in electro-thermal simulation.

The full paper will deal with the details of the proposed new measurement setup, the definition of the thermal resistance of high power LED devices and details of the evaluation of the results of the combined photometric/radiometric/thermal measurements including generation of multi-domain compact models of LED devices.

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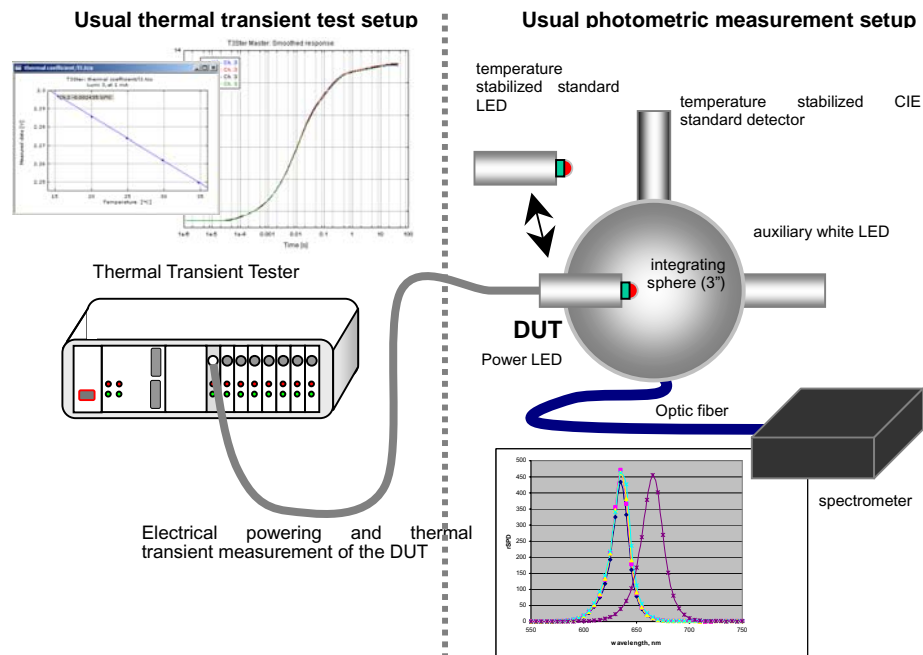
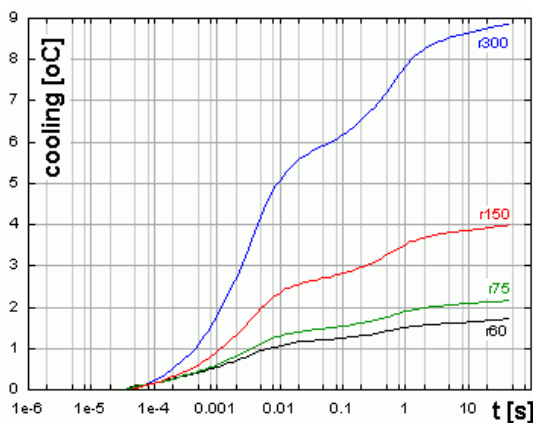


Figure 1: A trial setup for the combined photometric/radiometric and thermal measurement of power LED devices



I_{bias} [mA]	60	75	150	300
P_{opt} [W]	0.046	0.056	0.106	0.205
P_{el} [W]	0.1233	0.1575	0.3435	0.792
η	0.37	0.35	0.31	0.26

Figure 2: Cooling curves of a 1W power LED, obtained at different bias currents, the electrical power supplied to the device, the radiated optical power identified with the measurement setup shown in Figure 1 and the device efficiency

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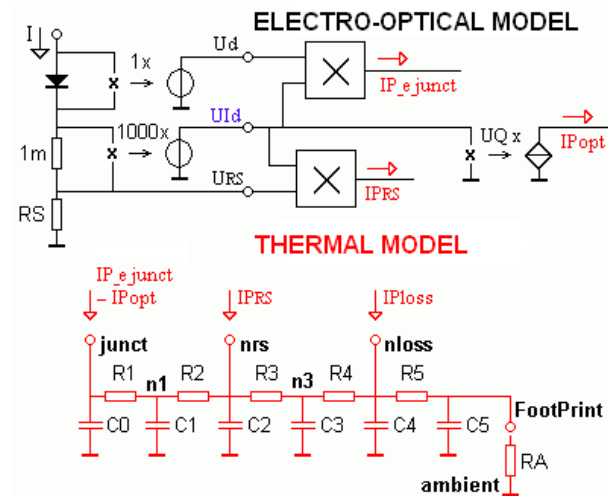


Figure 3: Multi-domain compact LED model, where the thermal RC model was created using the structure function method 0

Comparison of the goodness of fit to the $v(\lambda)$ function of photometers using real led spectra

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abstract

The $V(\lambda)$ correction of the detectors used in photometers is approached by filtering. The classification of those detectors is possible with the f_1' number published in the CIE publication No 53. It was shown that this f_1' number is not necessarily a good descriptor of the goodness of fit to the $V(\lambda)$ function if the measured source is a narrowband source, like a single colour LED, because the spectral mismatch errors can be very large even if the f_1' value is small, and even the measuring error of a photometer with a detector with a small f_1' value could be larger than that of a photometer with a detector with a larger f_1' value. In the draft version of the CIE TC 2-45 report there are further recommendations instead of the f_1' . In those recommendations mathematically modelled LED spectra are used. In this report we compare the three indexes expressing the goodness of fit to the $V(\lambda)$ function with the help of an additional index, which is the calculated real measurement error.

The f_1' index is an error definition, which is based on the summation of the absolute differences of the normalized relative spectral responsivity of the detector and of the $V(\lambda)$ function, the CIE spectral luminous efficiency function for a photopic observer. The error function itself is often called the colour mismatch error. The detectors are normally calibrated using a tungsten filament lamp set to the CIE standard Illuminant A. The elimination of the colour mismatch error is possible only if the spectral power distribution of the measured source is known. This correction is called the spectral mismatch correction. For measuring white LEDs if the source and detector spectral distribution is not known, and thus the application of the spectral mismatch correction is not possible, it has been recommended to use photometers with an f_1' error value less than 3.0 %. According to our calculations this will contribute to the measurement errors of the photometric quantity by not more than 2.0 %.

When measuring a single colour LED the spectral mismatch error can be very large even if the f_1' is small. Therefore the $f_{1,LED}$ index has been introduced and recommended to evaluate photometers for measuring single-colour LEDs. At the present moment two definitions are in the CIE draft technical report, one by Yoshi Ohno and one by Kathleen Murray. In those proposals there are calculated spectral mismatch correction factors using mathematically modelled LED spectra. The LED spectra models have peak wavelengths ranging from 400

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nm to 700 nm at 10 nm intervals and 20 nm spectral widths. In the first definition the $f_{1,LED}$ is calculated taken the largest spectral mismatch correction factor from the range 450 nm to 650 nm. In the second proposal the average spectral mismatch correction factor from the whole visible spectral region is used to calculate the $f_{1,LED}$ index. As an additional index we calculated several versions of the real measurement error.

In this report we use the spectra of real $V(\lambda)$ fitted detectors and of real single colour LEDs. The real measurement error has been calculated for each pair of detector and LED. The f_1' and the two $f_{1,LED}$ error definitions have been rated with the results of the real error calculations. Up to now 14 real detectors and 6 different types of LEDs have been analysed, but we collect further detector and LED spectra and will report at the meeting using the results of many more input data. We are working also towards a further goodness of fit definition.

We will show also that there are differences if the artificial LED spectra are used, and when real LED spectra are taken into consideration. The conclusion of that report will show which index has the best correlation with the calculated real measurement errors using the spectra of the real LEDs.

Keywords: goodness of fit, spectral mismatch, single-colour LED, error definition.

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ESTABLISHMENT OF TEMPERATURE-CONTROLLED REFERENCE LED's AND CHARACTERIZATION OF THEIR OPTICAL PROPERTIES

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ABSTRACT

Light Emitting Diode's (LED) have been widely used in industry applications particularly in opto-electronic technology. LED's, as semiconductor devices, emit optical radiation generally in the visible range, and particularly at red, yellow and green lines. Therefore LEDs find wide applications in signal lights and traffic safety systems for transmitting the visually required information. There are different measurement techniques in order to characterize radiometric, photometric and colorimetric properties of LEDs.

We have established specially designed measurement systems in order to measure and calibrate light emitting diodes. LEDs are attached to a purpose built holder that has five degrees of freedom. The holder has a thermoelectrical cooler based temperature controlled unit which keeps the temperature of LED stable between 15° and 30° with an uncertainty of 0,01°C. The electrical properties of LEDs are measured by using the four-pole-technique in which two lines for LED supply current and two for measuring the voltage. In order to obtain high stability in bias, LEDs are operated with current stabilized (10^{-5}) DC power supply. Current is measured across calibrated shunt resistance using a calibrated digital voltmeter (DVM) having 8½-digit resolution. A software program in LabView is developed in order to operate and simultaneously measure the photometric properties of LEDs.

The optical properties of each LED are determined by measuring accurately radiometric, photometric and colorimetric quantities. Effective peak wavelength, spectral power distributions and chromaticity coordinates are measured using a reference spectrophotometer on photometrical bench system under standard geometry of 0/45 and

calculated between 380 and 780 nm wavelength range. In order to determine the color parameters, a BaSO₄ coated diffuse reflectance standard is used.

The photometric properties of sources like luminous intensity (cd), illuminance (lx) and luminance (cd/m²) are realized accurately with established system. In the measurements, reference photometer head is used as a detection element. The photometer head consists of a silicon photodiode, $V(\lambda)$ -corrected filter and a precision aperture of 100 mm² area. Both photometer and LED are located on the same optical axis and the alignment of the system is performed using a precision telescope and a laser diode. The distance between source and photometer is measured precisely with a HP5529A model laser interferometer having resolution of ± 1.7 ppm. The luminous intensity measurements are carried out according to CIE (Commission Internationale de l'Eclairage) standard conditions. Alternatively, the spatial intensity distribution parameters, which is the luminous intensity dependence on the direction (θ, φ) and are very important for LEDs, are measured on angular basis. To rotate LEDs in vertical and horizontal positions, two goniometers are employed in the system. The same system is also used to measure luminance and illuminance. In luminance and its homogeneity measurements, a reference luminance meter in a step motor controlled two-dimensional translation stages are used.

Keywords: LED, Photometry, Radiometry, Color, Measurement, System

Practical Uncertainty Budgets for Spectral Measurements of LEDs

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Christopher MacLellan, Optronix Laboratories, Inc.

Abstract:

LEDs are used in many applications, ranging from signalling to ambient lighting to displays. Specifications and tolerances are used in the selection of LEDs and these, in turn, are achieved by actual measurements. Uncertainties associated with measurements of LEDs are extremely important, since they define practical limits on specification and quality control expectations. They can also establish whether differences in values between measurements are the result of expected variations or discrepancies in measurement technique, ensuring the litigation is kept to a minimum.

The essentials of uncertainty calculation can be found in the Guide to the Expression of Uncertainty in Measurement (GUM). Unfortunately, most people have not read this document and some that have find it incomprehensible. Several conferences and symposia have addressed the measurement and calculation of uncertainty, but confusion persists. Some confusion stems from the mathematical content of the subject, but most comes when translating a general document, e.g. the GUM, into a specific set of tests aimed at providing values for a specific measurement. Common questions that arise are:

- What components of uncertainty are significant?
- How are they determined?
- How can the result be verified?

To some extent experience is essential to answer these questions. However, by choosing specific quantities, device under test and equipment we can illustrate the process by example. The quantities are LED measurements of CIE Condition B averaged LED luminous intensity and luminous flux. The device under test is a temperature regulated LED and the equipment used is a commercial CCD spectroradiometer. Using a spectral irradiance standard in conjunction with limiting apertures of precisely known area allows calibration and measurement of both parameters. Spectroradiometer measurements are traceable to the NIST spectral irradiance scale. This particular LED was chosen because it also has an independent NIST traceable calibration via another path and can provide

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verification of measurements.

For values of both total luminous flux and CIE Condition B averaged LED luminous intensity there are two independent traceability paths to NIST, as illustrated in Figure 1.

Figure 1 illustrates the traceability of each path to NIST for CIE Condition B averaged LED luminous intensity. A similar figure would apply to values of luminous flux.

For each path:

- The significant components of uncertainty are identified
- Measurement techniques for obtaining uncertainty values are described with actual results
- uncertainty budgets for the measurements are constructed.

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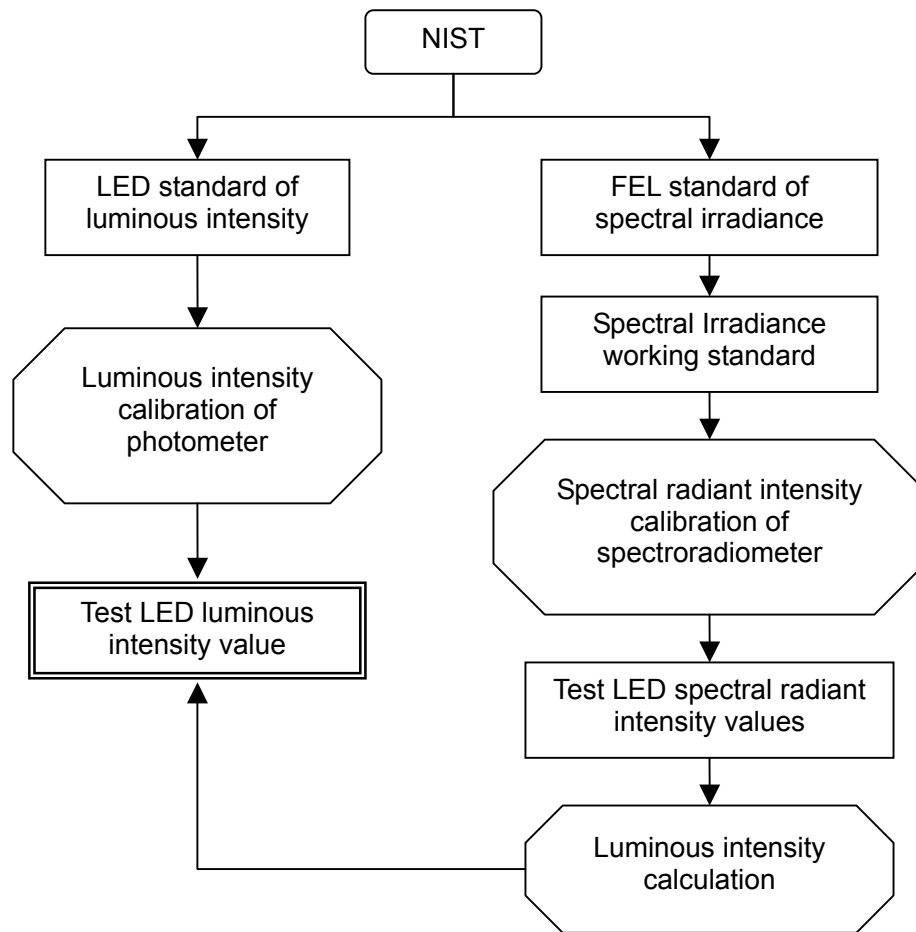


Figure 0. The two paths to CIE Condition B averaged LED luminous intensity values for this study. For clarity, CIE Condition B averaged LED luminous intensity has been abbreviated to “luminous intensity” in this figure.

By illustrating measurement uncertainties in this way, important parameters associated with measurement technique and equipment are revealed. Also, the uncertainty budgets may be used as an example for others using the same types of measurement systems.

Development and application issues of a spectrally tunable LED source

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A spectrally tunable solid-state source based on Light Emitting Diodes (LEDs) is being developed at the National Institute of Standards and Technology (NIST) to mimic the spectral distributions of different light sources. The tunable source is to be utilized in calibrations of photometers, colorimeters, and spectroradiometers to reduce the measurement uncertainty in certain colorimetric, photometric, and radiometric applications. Details of the tunable source, LED characterizations, different source-distribution realizations, and application issues are discussed in this paper.

As photometers and tristimulus colorimeters do not have the same (ideal) spectral responsivities as the standardized color matching functions, the measurement uncertainty increases when the spectral distribution of a test source is different than the distribution of the traditional source used for calibration. For example, the errors of a colorimeter that measures display colors can be very large when it is calibrated against an incandescent standard lamp [1]. If a source distribution equal (or similar) to the distribution of the (test) source is produced by the tunable source then the tunable source can be used as a transfer source (but not a reference standard) to propagate calibrations from a reference photometer or colorimeter to a test photometer or colorimeter with a minimum increase in the measurement uncertainty. Also, the tunable source can be used as a calibration (reference standard) source for spectroradiometers, especially in the ultraviolet and blue region, where traditional tungsten sources do not have sufficient radiant power. A spectrally optimized calibration source can calibrate accurately both colorimeters and spectroradiometers for various applications.

A prototype tunable source has been built using an integrating sphere. Temperature-controlled LED holders and different model LEDs — with different spectral peaks and distributions — are mounted onto the sphere. High resolution and stable voltage-to-current converters independently control the feeding current of the large number

of LEDs. A ten-channel LED driver has been realized which is now being extended to 64 channels. The large number of channels helps facilitate matching of fine structure in target source spectral distributions. A calibrated spectroradiometer integrated with the system measures the spectral distribution of the sphere source. The system has been characterized for radiometric stability as function of time, LED drive current, and temperature.

The tunable source can be used for both illuminance and luminance mode measurements. The expectation from the performance of the tunable source is less demanding in illuminance mode where the source works like a point source. In this case, both the photo/colorimeters and the spectrograph measure the uniform irradiance from the source at a certain distance. In luminance measurement mode, a spectrally and spatially uniform exit port radiance is needed. When the tunable source is used as a transfer (not a standard) source, high stability is required in both measurement modes only for the duration of a substitution measurement. High long-term stability will be needed from the tunable source if it is used as a standard source to calibrate photometers, colorimeters, or spectroradiometers.

A large number of LEDs have been purchased and their spectral power distribution and radiometric stability were measured in order to select the most suitable types and pieces for the tunable source. The LEDs were seasoned to minimize their time-dependent changes during applications. After seasoning, the LEDs were characterized. Luminance and chromaticity coordinates of red, blue, and green LEDs were measured versus drive-current [2]. The LED aging measurements included intensity and dominant wavelength changes versus time. Temperature dependent measurements were made on red, blue, yellow, and white LEDs between 5 °C and 48 °C. The forward voltage was measured versus temperature at a constant drive-current of 20 mA. The temperature coefficients of the forward voltages, luminous intensities, and dominant wavelengths were determined for the four types of LEDs. The spectral distribution measurements were made at five different temperatures.

Different target source-distributions for LCD and CRT displays are realized using an optimization method. A program calculates the difference of the total-LED distribution and the target source distribution at each wavelength. The equality is obtained from a large number of iterations where the individual LED currents are increased or decreased in small steps. The individual LED currents are obtained from the optimization. The integral-sum of the differences at each wavelength shows the quality of the realized spectral match.

The realized spectral distribution of the tunable source, in spite of the optimization, can be different than the target distribution. The deviations are caused by limitations in the availability of LEDs with the appropriate peak spectral distributions, their finite spectral bandwidths, as well as temperature differences, LED aging, and the non-linearity of the LED spectral power distribution versus feeding current. When these differences are small and slowly varying, a second optimization program can be applied that further reduces the difference between the target and the source spectra.

The real evaluation of the realized (optimized) source distribution is to use it for calibration of colorimeters. According to our calculations, the chromaticity coordinates obtained with the tunable source calibration will be about one order of magnitude more accurate than those obtained using a traditional Standard Illuminant A source.

References:

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Measurement of Total Radiant Flux of UV LEDs

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National Institute of Standards and Technology, USA

High-efficiency deep-blue LEDs and ultraviolet (UV) LEDs are being developed as the light source for white LEDs utilizing multiple phosphors for better control of spectra and color rendering characteristics. The high power UV LEDs are also developed for such applications as material decontamination, air purifying, and bioanalysis. Thus, there is an increasing need for accurate measurement of the total radiant flux (watt) and efficiency of such LEDs in the deep-blue to UV region. NIST has already established a calibration facility for the total luminous flux (lumen) of LEDs using our 2.5 m integrating sphere [1]. The current absolute integrating sphere calibration method employed cannot be used for radiant flux measurement in the UV region or even at the deep blue region where the photometer signal is very low and the uncertainty is too high. Total radiant flux measurements can be realized by radiometric measurements with a goniophotometer or by measurements of total spectral radiant flux (W/nm). However, these facilities are yet to be established at NIST. To accommodate the urgent need in the industry for calibration of such UV and deep-blue LEDs, we have established alternative methods for calibration of UV LEDs using our 2.5 m integrating sphere facility. We have implemented two different methods, which allow us to cross-check and verify the accuracy of each method.

The first method is a source-based method as depicted in Fig. 1. This method employs a spectroradiometer and a spectral irradiance reference lamp as an external source, and

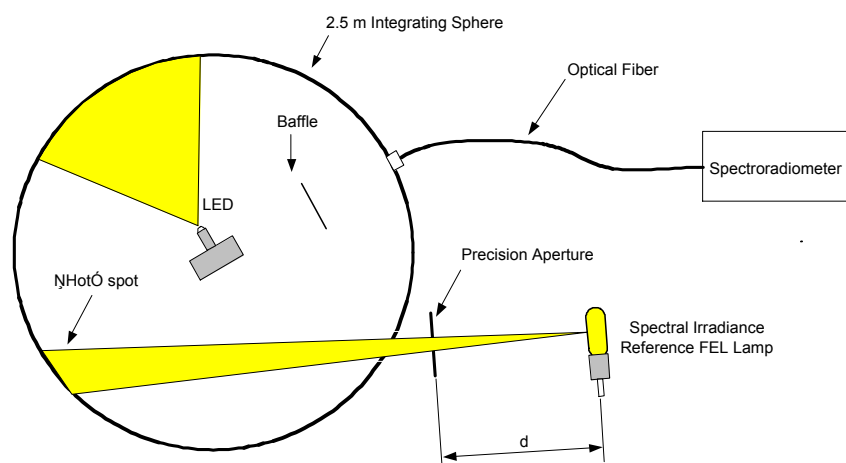


Fig. 1 System setup using the source-based method

enables absolute measurements of total spectral radiant flux. The same principles of the

Absolute Integrating Sphere method [2] for the luminous flux measurement at NIST is used but applied spectrally. The total sphere system (spectroradiometer and the integrating sphere) is calibrated against the spectral radiant flux of the beam introduced from the external source. The spectral flux of the beam is determined from the spectral irradiance at the aperture plane and the area of the aperture. The corrections, necessary for the absolute sphere method, are made spectrally for the spatial nonuniformity of sphere response and incident angular dependence of the sphere responsivity. Series of spatial mapping measurements were conducted spectrally using the spectroradiometer. Since the flux from an LED is relatively low and due to the large size of our sphere, we need an instrument with a very high sensitivity. We used an array spectroradiometer employing a back-illuminated CCD array, which gives sufficient s/n ratio for radiant flux down to 10 mW. The stray light is another issue. We used a blue-violet bandpass filter (~355 nm to 459 nm), which removes radiation of unnecessary spectral region before entering the spectroradiometer, and avoids significant stray light errors in the UV region. The linearity of the instrument has been tested in various conditions. We found that the cosine-response of the fiber input of the spectroradiometer on the sphere wall is extremely important. The surface-ground quartz we first used had regular transmittance component, which caused serious errors. We now use teflon diffuser solving this problem.

The second method is a detector-based method as depicted in Fig.2. This method employs a radiometric detector (silicon photodiode) to measure the output of the sphere. In this method, the spectral responsivity (radiant power responsivity) of the total integrating sphere system (ampere per watt) is calibrated using monochromatic radiation at many wavelengths produced by a tunable laser directed through a fiber into a small integrating sphere (5 cm diameter). The small integrating sphere produces near-Lambertian radiation. We used a portable version of the NIST Spectral Irradiance and Radiance Calibration Uniform Source (SIRCUS) [3] that covered wavelengths from 360 nm to 510 nm. The radiant flux introduced into the sphere is determined by measuring the irradiance at the aperture plane using a reference detector calibrated for spectral irradiance responsivity using the NIST Spectral Calibration Facility (SCF). A product of the irradiance (average irradiance over the aperture plane) and the aperture area gives the radiant flux (watt) of the beam introduced for each wavelength. We applied the same corrections (as used in the first method) for the spatial nonuniformity and incident angle dependence of the sphere responsivity. The cosine correction of the detector for the sphere is critical just as with the first method. One disadvantage of the detector-based method is that the relative spectral power distribution (rSPD) of the test LED must be measured. The uncertainty dependence on the rSPD is sensitive to the slope of the spectral responsivity of the sphere system.

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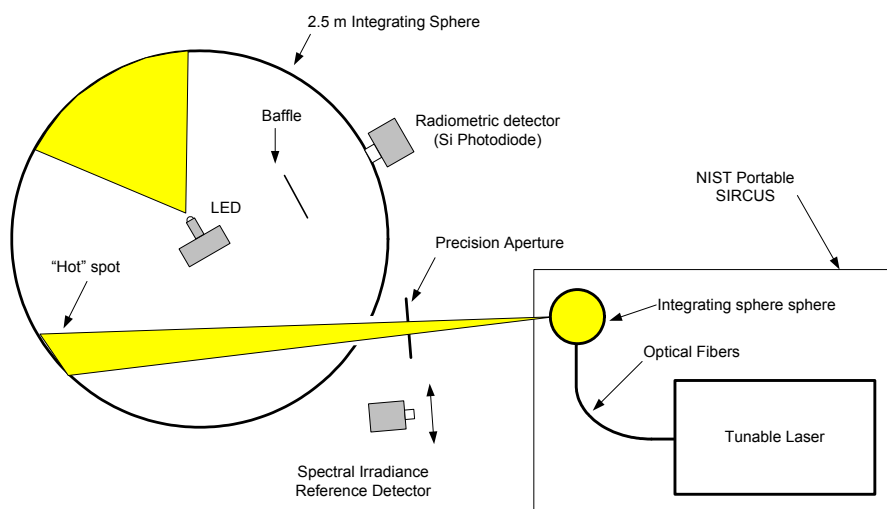


Fig. 2 System setup using the detector-based method

Several UV and deep-blue LEDs with peak wavelengths 375 nm and 390 nm have been measured using the two methods and the results are compared. Some blue LEDs with 425 nm to 430 nm peak wavelengths have also been measured for using the first method and the luminous flux is obtained, which are compared with our luminous flux measurement using the normal procedures [1]. These results, as well as data of characterization of the sphere system for the two methods, will be presented.

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Color and Color Distribution of Signal Lamps with LEDs

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Introduction

In various ECE regulations of automotive lighting or other directions special requirements are given for the color of the light emitted by signal lamps. These requirements are generally stated as areas within the CIE color diagram, limited by geometrical functions of the chromaticity coordinates x , y , or z . Conventional signals usually emit uniform color, so that it has been sufficient to measure the color of the emitted light in one direction, generally at HV. Signal lamps with coated bulbs, reflectors or front lenses nowadays may show a dependence of the emitted color from the direction. Therefore, it has been recommended to measure the color into all directions of the photometric grid, and even in the whole visibility range. These tasks require colorimeters which are able to do fast, reliable and accurate measurements, often in combination with goniophotometers.

This paper deals with the instrumentation which allows fast and reliable measurements of color distribution of any light source, including LEDs. Accuracy, measurement uncertainty, and the limitations for low level intensities are discussed. A practical method for evaluation of color distributions is demonstrated. A method discussed in CIE division 2 describing the performance of colorimeters is applied and it will be shown, how performance parameters of the colorimeters can be used to estimate the uncertainty of color measurements.

Especially the use of tristimulus colorimeters with filtered Si-photoelements, whose spectral sensitivities are adapted to the CIE color matching functions, will be discussed. The paper will show the relation of the f_1 parameters known from photometers to measurement deviations, and will point out the strong correlation between f_1 and the measurement uncertainties, if the adaptation to the color matching functions is good.

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Evaluation of calibration methods of a photometer measuring maritime LED buoy lanterns

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A photometer used for on-line product testing of light emitting diode (LED) buoy lanterns was calibrated for illuminance responsivity using two different methods [1]. The first method is based on absolute calibration of the photometer with CIE standard illuminant A light source, combined with spectral correction factors calculated from measured spectral responsivity of the photometer and relative spectra of the LED lanterns. The second method is based on direct comparison with a characterized reference photometer using the LED lanterns as light sources. The resulting correction factors for the calibrated photometer differ by +0.6 %, +0.4 %, -1.0 %, and +0.2 %, for green, yellow, red, and white LEDs. The expanded uncertainties of the first and second methods are 0.9 % and 1.0 %, respectively.

Overall it seems that the first method has several advantages. Absolute level of the reference illuminance is achieved by using a standard lamp with uniform intensity distribution and broad emission spectrum. This bypasses the difficulties arising from the geometrical and spatial properties with the LED sources and provides more stable repeatability. Only one calibration, using CIE standard illuminant A, is needed annually to calibrate the absolute illuminance responsivity level. If new LED types are taken into use, the only additional measurement needed is the measurement of the relative spectrum of the LED to calculate a new spectral correction factor. The second method requires full calibration of the photometer and spectral characterization of the lantern each time a new LED type is taken into use. Thus, the first method requires more work during the first calibration, but further maintenance and upgrading of the measurement system is easier.

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Considerations on Optical Properties of LEDs for General Illumination

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(Teknologue Co., Ltd.)

In order to characterize optical properties of LEDs, various optical values, both quantitative and qualitative have been nominated and measured. At an early stage of LED application, as amount of light output emitted from LED was so small and color of LED light was nearly monochromatic, LEDs were mainly used as indicators and/or display uses, and optical properties basing on these uses were measured and used for LED evaluation. Items of optical properties at that time were for examples, luminous intensity, luminance, peak wavelength, dominant wavelength, length of half width, color (chromaticity coordinates) and so on.

Recently, as light output of LEDs has been becoming gradually increased and white light LEDs have been developed and led into actual market, LEDs are expected to be applied to general illumination, ranking among conventional light sources, such as incandescent lamps, fluorescent lamps, HID lamps and so on. To use for general illumination, other optical properties than those for indicator uses and/or display uses have been often required.

As for conventional light sources for general illumination, needed applicable optical properties for general illumination have been measured and their results are easily introduced in technical data and/or catalogue of conventional lamp makers. The items are total luminous flux, spatial candle power distribution, color rendering indices, correlated color temperature, and so on. Most lighting designers can obtain actual value of these optical properties necessary to design actual lighted environment through lamp manufacturers' catalogues however, in case of applying LEDs to general illumination, they can not obtain necessary detailed optical characteristics data for designing lighted environment from LED manufacturer's catalogues nor their technical data.

As size, shape, construction of sources, energy conversion process, electrical characteristics of LEDs are largely different from those of conventional light sources, and as actual luminaries may also be largely different, items and contents of necessary optical

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properties will not be just the same as the conventional light sources.

Through these background, proper items and contents of optical properties of LEDs for general illumination have been considered and several proposals including concepts for measuring are introduced hereinafter.

General Lighting Purpose LEDs , Their Characteristics and Physical Measurement

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The development, production and application of LEDs have increased tremendously in recent years. After the blue LEDs were invented, and higher power and efficiency LEDs were developed, the LED light sources are expected to be most widely applied in general lighting purposes in this new century.

The government of China began her industrialization plan for general lighting purpose LEDs in June 2003. More and more manufacturers begin to pay their attentions on general lighting purpose LEDs in China. So, this new industry is developing rapidly. The quality assessment for general lighting purpose LEDs becomes more important and usual. But the problem is that the test reports for the same LED lamp, from different manufacturers, different laboratories or different business companies, are different. The reasons for these different test results are as the followings:

The semiconductor industry (the original chip manufacturers for general lighting purpose LEDs) and general lighting industry have their different understandings and assessment methods for the LEDs;

The general lighting purpose LEDs, especially phosphor-converted LEDs and tri-band LEDs, have their special characteristics which are different from traditional single-colored LEDs;

Using the different test conditions and different instrumentation is the third error source;

In this paper, some existed and possibly-imaged LED light sources for general lighting purposes are described. Their common characteristics in light, radiation and color, electronics are analyzed. The application purposes and assessment parameters in physics and psychophysics are discussed.

A combined, complete test system, widely applied in China, for general lighting purpose LEDs, is introduced in this paper. This test system includes a goniophotometer, an air-conditioned sphere-photometer and a spectroradiometer, a constant current DC power supply and electrical meters.

The test methods, calibrations and final uncertainties are discussed. The discussion also includes the existing CIE standards and publications on which this test system mainly base.

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The typical test report of a general lighting purpose LED lamp is shown in details.
Experiments demonstrate a satisfied reproducibility of this test system for general lighting LEDs.

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Santos P.	Brazil	Para Museum of Gems
Santos P.	Brazil	Assembleia Paraense Night Club
Nakano Y.	Japan	Color rendering simulator using multispectral camera and its application to evaluating white LED light sources
Nicholson M. and Tutt I.	UK	LED clusters - A bright future!

Pará Museum of Gems

It has amethysts, tourmalines and diamonds coming from several regions in Pará, Rondonia, Tocantins and other countries in the Panamazon region. Pieces over 500 millions years old, and a collection of gold samples, extracted from the mineral province of Carajás. The journey begins with an overview on the cultural history built by the first Amazon people and it ends with a recent jewel production of Pará.

At first, the purpose was to use the optical fiber technology in this work, but after the preliminary studies, I ran into the initial high cost for the implementation of the project, because we had to light 24 display windows and some of them had more than 20 specific points to be lit. Besides the legends, we also considered that for some situations, we'd have to use MHR 100 metallic steam lights or BLV 150w or similar, which is very expensive and would have to be changed every 5000 Hs, because although the lamp lasts 10.000 Hs, its dichroic reflector lasts a little more than 5000hs. Looking for another alternative for the project, I remembered the evolution I could notice on the LEDS and Super Leds in the last International Light Fair in Frankfurt. Then I began to research and together with Brazilian companies, I succeeded in developing equipments, controls and supply drivers can be dimmerized. Exactly at that moment, I decided to try to use the LED technology. I knew about the difficulties I would find because till then, no company in the world had ever developed any equipment that used a Led as an effectively light emitter. I had some information about its application as a marker. But I knew that if I succeeded, this would be undoubtedly a milestone in the application and development of LED technology.

What did we take into account? Limiting points for the Project.

In this work, there were very specific parameters, out of which we highlight the team of designers formed of gemologists, museum specialists and architects didn't give in.

- Validation of the material displayed, producing the brightness and sparkling necessary for the appropriate appreciation of the people.
- Smaller incidence or absence of maintenance, avoiding contamination or disruption of security due to eventual openings of the display windows in order to change the lights.
- Minimum working temperature to avoid damages to the constructive material of the displays and archaeological objects.
- Minimum power consumption following the government recommendations.
- Absence of electromagnetic radiation (UV and IR) that might alter the original features of the material displayed.
- Great flexibility for adjustment, light blow opening, dimmerization, and color corrections without changing the equipments.
- Minimum dimensions so that they fit into the spaces provided.
- Easy assembly and installation.
- Concerning all the previous features, produce the expected and necessary atmosphere for the adequate validation of the public toward the material displayed.
- And low costs for the establishment and maintenance.

Main Differentials of this Project

The LED-based equipments proposed for this work bring some constructive and functional features that have never been seen so far. They are as follow:

- Minimum dimensions so that they can fit into any available place without problems (see pictures attached).
- Light emitting spots from a single LED in white color for each equipment
- Minimum power consumption 1W for every light point.
- High quality constructive materials, aluminum items with anodized completion, and colimator with optical acrylic.

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- Orbital articulation with great manipulation and easy adjustment.
- Minimum working temperature: 35°C.
- Complete absence of harmful radiation like ultraviolet and infrared.
- Lifetime over 50.000 hs, or for 6-hour use approximately 20 years.
- The equipments accept a great variety of color correcting filters, reducers and diffusion devices for the light blows.

In the end, we had a properly lit museum, where it is possible to see the delicate sparkling effect of a diamond, the bright colors of an Indian crown or the rugged texture of a centennial ceramics.

Finally, we emphasize that this is the first installation in the world which has these characteristics, completely built by Brazilian companies, and it certainly will become a world standard for this kind of application.

Assembly



Os Resultados



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Assembléia Paraense Night Club

Assembléia Paraense, a social club in Belém, Pará (Brazil), which has over 16 thousand associates, had its night club reformed and it serves as a place for shows, presentations and music (discotheque). I was invited to develop a luminotechnical Project for this amusement center. I decide to use the LED technology in some points like floor lights and details in the ramps and the stage, providing a High Tech futurist feature. Because the equipments operate on low tension of 12V, they were connected to a set of batteries so that in a casual shortage of power, there would be a way to show the emergency exit. Besides, we would have as an additional gain the low consumption per unit, and the minimum maintenance concerning the life period of the LED around 30.000 Hs.

The new night club has been equipped with almost 500 LED's (MARKERlight and BACKlight) in the colors blue, green and red in their 2.500m². The blue color was used to mark the walking bridge. The green color was used as light sources on the floor showing the parts of access, and the lights were connected sequentially, producing a movement for the lights. The green color was used for the stage and the dancing hall. This is the biggest framework with LED in the North/Northeast of the country.

Outcomes



Color rendering simulator using multispectral camera and its application to evaluating white LED light sources

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Color rendering is one of a key feature to develop commercial white LED light sources. To develop white LED light sources having good color rendering property, its spectral power distribution must be controlled. It is time-consuming and costs much, however, to make actual light sources having various spectral power distribution using LEDs in order to test its color rendering performance. In this study, we proposed a system of color rendering simulator that can simulate color rendering property of light sources having arbitral spectral power distribution. We applied this system to evaluate color rendering feature of white LED light sources.

Following procedure shows how color rendering was simulated.

1. Estimate spectral reflectance distribution pixel by pixel using a multispectral camera.
2. Calculate X, Y, Z tristimulus values using spectral reflectance data obtained from the multispectral camera and spectral power distribution of simulating light source.
3. Display an image on CRT screen that was properly calibrated so that tristimulus values were correctly reproduced.

The multispectral camera was composed of infrared absorbing filters (HOYA HA-50, Kenko IRC65L), a liquid crystal tunable filter (CRI VIS1-50-LC-20) and a cooled monochromatic CCD camera (Mutoh CV-04II). Figure 1 shows spectral sensitivity functions of the system. Infrared absorbing filters play an important roll that eliminates sensitivities in infrared region because CCD has certain sensitivity and liquid crystal tunable filter has certain transmittance in this region. Liquid crystal tunable filter (LCTF) is an electronic device that can adjust peak wavelength of its spectral transmittance distribution. We used 10 peak wavelengths from 425 to 650 nm at intervals of 25 nm. Bandwidth of the filter was about 50 nm.

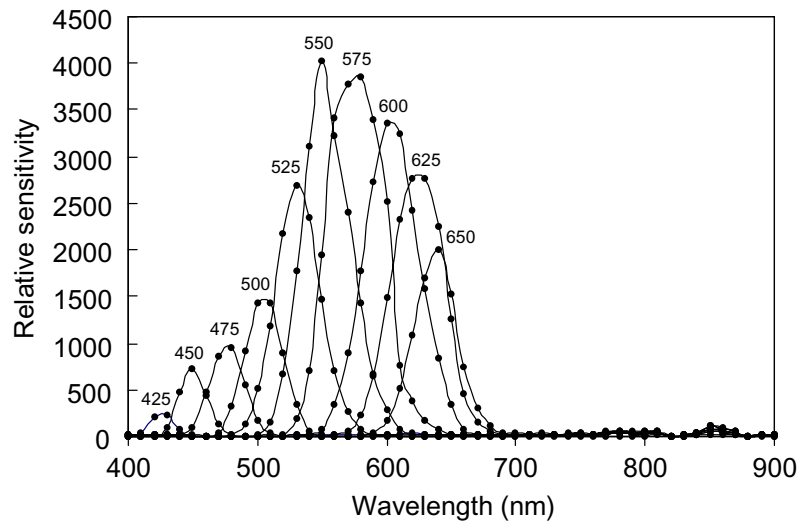


Figure 1. Spectral sensitivity functions of multispectral camera used in this study.

Estimation of spectral reflectance distribution was performed in the following way. We took 10 camera images by changing peak wavelength of LCTF for a same sample scene using the multispectral camera. Reference white, that has higher reflectance than 0.9 in whole visible spectrum region, was placed on the scene, and a reflectance at a certain pixel was calculated as

$$R(\lambda) = \frac{\text{pixel data in the image with peak wavelength of } \lambda}{\text{pixel data at reference white in the image with peak wavelength of } \lambda} \quad (1)$$

Figure 2 shows an example of estimated spectral reflectance distribution. Filled circles with solid line show measured spectral reflectance using spectrophotometer (GRETAG spectrolino). Open triangles show estimated spectral reflectance using Equation 1. Estimated spectral reflectance shows broader shape than actual spectral reflectance in general because spectral sensitivity functions of the multispectral camera have broad bandwidth as shown in Figure 1. We used Equation 2 to modify this deviation.

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$$\begin{pmatrix} R'_{425} \\ R'_{450} \\ R'_{475} \\ \vdots \\ R'_{625} \\ R'_{650} \end{pmatrix} = \begin{pmatrix} 0.8 & 0 & & & & \\ -0.5 & 1.8 & -0.5 & & & \\ & -0.5 & 1.8 & -0.5 & & \\ & & \ddots & \ddots & \ddots & \\ & 0 & & -0.5 & 1.8 & -0.5 \\ & & & 0 & 0.8 & \end{pmatrix} \begin{pmatrix} R_{425} \\ R_{450} \\ R_{475} \\ \vdots \\ R_{625} \\ R_{650} \end{pmatrix} \quad (2)$$

R_{425} , R_{450} , etc. represent estimated spectral reflectance using Equation 1, and R'_{425} , R'_{450} , etc. represent modified spectral reflectance. Open diamonds in Figure 2 shows the modified spectral reflectance, and they are closer to measured reflectance than open triangles. To interpolate and extrapolate the modified spectral reflectance, seven Gaussian functions peaked at 420, 460, 500, 540, 580, 620, 660 nm with 80 nm bandwidth were linearly combined to fit to the data. Dotted line shows the combined function and we used this function to calculate tristimulus values to be reproduced.

Test images were reproduced on a CRT screen so that tristimulus values on the screen match with those calculated from spectral reflectance of every pixel and spectral power distribution of a simulating light source. We compared tristimulus values between actual scene under known light source and those of the simulated CRT image by measuring them using a spectroradiometer (Photo Research PR-650), and confirmed that the match was fairly good.

Finally, we simulated LED light sources using this color rendering simulator. Figure 3 shows spectral power distributions of two kinds of white LED light sources. They have exactly the same chromaticity coordinates and illuminance, but simulated images were quite different. Red colors looked darker and yellow colors looked brighter when the image was simulated under the white LED that composed of blue LED and yellow phosphor, while red colors looked brighter and yellow colors looked darker and reddish under the white LED that composed of red, green and blue LEDs.

Using this color rendering simulator, we simulated several combinations of commercial LEDs to make white light sources. We will report the results on color rendering evaluation of the light sources in terms of semantic differential method.

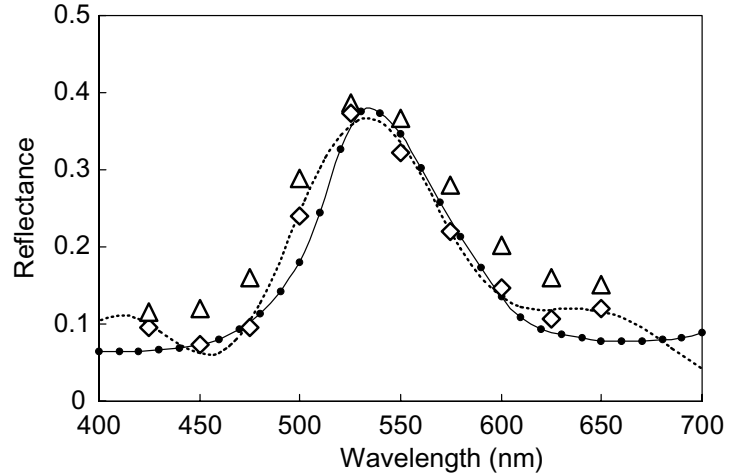


Figure 2. An example for estimation of spectral reflectance. Filled circles with solid line: measured spectral reflectance, open triangles: estimated reflectance, open diamonds: modified reflectance, dotted line: least square fit of Gaussian functions to the modified reflectance.

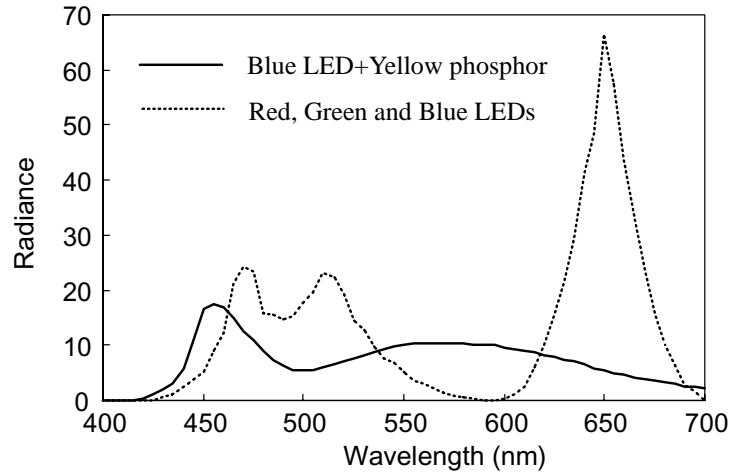


Figure 3. Spectral power distributions of two kinds of white LEDs.

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LED Clusters - A Brighter Future!

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Abstract for Presentation Poster - CIE Symposium, Tokyo, June 2004

The Research and Development Department of the General Lighthouse Authorities (GLA's) of UK and Ireland is based on the Isle of Wight and carries out lighting research to improve marine aids to navigation (AtoN's).

Flashing light beacons used in marine AtoN's are, in effect, pulsed light projectors. LED's provide good colour rendering, rectangular pulse shape, high efficiency and reduced maintenance costs. It follows therefore, that traditional incandescent lamps with focussing optics are being superseded in many areas by LED multiple light sources (LED clusters). However, problems have been encountered when comparing the performance of traditional beacons and 'LED cluster' beacons, not least in the area of photometry.

Recent work undertaken by the GLA's R&D Department includes the implementation of a zero-length photometry light range for goniophotometric measurements of marine AtoN beacons. This complements the existing outdoor, long-distance light range that has been in operation since 1957. Although designed for small beacons, the zero-length system provides a shorter light-path length whilst retaining the long effective measurement distance required for such beacons. A short path length and optical gain from the curved mirror enables low-gain (fast) photometer amplifiers to be utilised giving a fast measurement capability required for pulsed LED's.

Photometric measurements carried out on LED light sources may be subject to considerable spectral error. To account for this, spectral correction of the photometric result is carried out using current recommended methods. However, the uncertainties associated with this correction process can be quite large, especially since the stepping monochromators used are too slow to measure pulses of light. Improved methods of spectroradiometry alongside existing goniometric methods are being developed.

The ability of an LED to provide a near rectangular pulse of light may be of use in determining effective intensity. The two most commonly used methods of calculating effective intensity are those of Blondel-Rey and Schmidt-Clausen. These methods agree when applied to rectangular pulses. Therefore, it seems reasonable that a device that produces such a pulse may be used as a transfer standard for effective intensity by both methods. However, the minimum photometric distance required for LED's is often difficult to determine. Treating the LED as a projector and applying the 'Walsh' formula for crossover distance may provide a means of calculating such minima.