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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

MEASUREMENT OF LEDS

CIE 127:2007
2nd edition

UDC:	53.085.342	Descriptor:	Light sources, indicating devices
	535.24		Photometry
	621.3.032.32		Light-emitting elements

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are :

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organisations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

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1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen L?ndern zu sein.
2. Grundnormen und Verfahren der Me?technik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorg?ngen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu ver?ffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Tagungen werden alle vier Jahre abgehalten, in der die Arbeiten der Divisionen überprüft und berichtet und neue Pl?ne für die Zukunft ausgearbeitet werden. Die CIE wird als h?chste Autorit?t für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterh?lt sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 2-45 of Division 2 "Physical Measurement of Light and Radiation" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 2-45 de la Division 2 "Mesures physiques de la lumière et des radiations" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

Dieser Technische Bericht ist vom CIE Technischen Komitee 2-45 der Division 2 "Physikalische Messungen von Licht und Strahlung" ausgearbeitet und vom Vorstand der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, da? das Dokument eine Empfehlung und keine Vorschrift ist. Die neuesten CIE-Tagungsberichte oder das CIE NEWS sollten im Hinblick auf m?gliche sp?tere ?nderungen zu Rate gezogen werden.

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The following members of the TC 2-45 "Measurement of LEDs" took part in the preparation of this report. The committee comes under Division 2 "Physical Measurement of Light and Radiation". This present publication replaces CIE 127-1997 “ Measurement of LEDs ” .

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MEASUREMENT OF LEDS

SUMMARY

This report is an update of the previously published CIE Technical Report CIE 127-1997.

There are significant differences between LEDs and other light sources which made it necessary for the CIE to introduce new quantities for their characterization with precisely defined measurement conditions. New quantities introduced here are "Averaged LED Intensity" and "Partial LED Flux".

The report describes in detail the measurement conditions for ALI (Averaged LED Intensity), Total and Partial LED Flux and Spectral Power Distribution. It is shown that measurements by substitution method using LED standards can be simpler; however it is important to compare similar coloured LEDs or use colour correction on the measurement results. The standard LEDs need to be calibrated by National Metrology Laboratories or a laboratory traceable to National Metrology Laboratories.

MESURE DES DIODES ELECTROLUMINESCENTES (LED)

RESUME

Ce rapport est une actualisation du rapport technique CIE 127-1997 publié antérieurement par la CIE. Il y existe des différences significatives entre les LED et les autres sources de lumière qui ont nécessité, pour la CIE, l'introduction de nouvelles grandeurs avec des conditions de mesure précisément définies pour leur caractérisation. Les nouvelles grandeurs définies ici sont "l'intensité moyennée d'une LED" et "le flux partiel d'une LED".

Le rapport décrit en détail les conditions de mesure de l’intensité moyennée d’une l "ALI" (Averaged LED Intensity), le flux total et le flux partiel d'une LED, et la distribution spectrale de puissance. Il est montré que les mesures par une méthode de substitution utilisant une LED étalon peuvent être plus simples; cependant il est important de comparer des LED de couleur similaire ou d'appliquer une correction de couleur aux résultats des mesures. Les LED étalons doivent être étalonnées par un laboratoire national de métrologie ou un laboratoire tra?able à un laboratoire national de métrologie.

MESSUNG VON LEDS

ZUSAMMENFASSUNG

Dieser Technische Bericht ist eine Aktualisierung des früher publizierten Technischen Berichtes der CIE der Nummer 127-1997.

Es gibt signifikante Unterschiede zwischen LEDs und anderen Lichtquellen; diese erfordern von der CIE die Einführung neuer Gr??en zur Charakterisierung von LEDs unter genau festgelegten Messbedingungen. Die hier neu eingeführten Gr??en sind die "mittlere LED-Lichtst?rke" und der "LED-Teillichtstrom". Dieser Technische Bericht beschreibt im Detail die Messbedingungen für die "mittlere LED-Lichtst?rke", den "LED-Teillichtstrom", den LED-Gesamtlichtstrom und die spektrale Strahlungsverteilung von LEDs. Es wird gezeigt, dass Messungen nach der Substitutionsmethode unter Verwendung von LED-Normalen einfacher sein k?nnen; hierbei ist es wichtig, LEDs ?hnlicher Farbe zu vergleichen oder aber die Messergebnisse bezüglich spektraler Fehlanpassung zu korrigieren. Die LED-Normale müssen bei den jeweiligen Nationalen Metrologischen Instituten oder einem Labor, das rückführbar ist auf die Nationalen Metrologischen Institute, kalibriert werden.

1. INTRODUCTION

This report is a revision of CIE 127-1997 (Measurement of LEDs) and supersedes it. CIE 127 was produced before high power LEDs became commonly available. Since CIE 127 was published, there has been much progress in the development of the LEDs, especially of high power LEDs in a wide range of colours including white, there have been many changes in common practice in measurement of LEDs, and also some new knowledge has become available. This revision reflects such changes, and updates the recommendations for more reproducible and improved measurements of LEDs.

1.1 Scope

Semiconductor devices which emit optical radiation can be divided into two distinct groups, luminescent diodes, usually known as Light Emitting Diodes or LEDs, and laser diodes. The present report is concerned only with the first group, LEDs. This report deals with measurement of individual LEDs only and does not cover clusters or arrays of LEDs, fixtures using LEDs, nor large area surface emitters such as organic light emitting diodes (OLEDs). This report covers measurement of photometric, radiometric, and colorimetric quantities of LEDs, to be performed in calibrating laboratories; it does not cover measurement procedures in production lines which require other considerations. It is the responsibility of the manufacturers and users to ensure that, after obtaining well characterised working standards from their laboratory, the test set-up used for production control will measure the defined quantities properly. The production line measurement recommendations will be dealt with in another report. The deviations from laboratory measurement conditions and possible sources of error have to be carefully examined when the test equipment is designed and installed.

1.2 Terminology

Strictly speaking, the term LED should only be applied to those diodes that emit visible light. Those which emit radiation in the near infrared should, more correctly, be called IREDs (Infrared Emitting Diodes). In general, however, both groups of diodes are widely referred to as LEDs and, since most of the measurement techniques and characterisations are common for the two groups, the term LED is used throughout this report to cover both types. This also applies to diodes emitting ultraviolet (UV) radiation. The sections relating to photometric and colorimetric quantities clearly apply only to those devices emitting visible light, but if there is any confusion this will be made clear at the appropriate point.

Several terms not defined in the CIE Vocabulary are used in this document as:

x Averaged LED Intensity;

x Partial LED Flux.

Please see document for exact definitions.

1.3 Purpose of the report

LEDs are produced in enormous quantities and in a wide range of different types to meet the very different specifications of a variety of applications. When a wide range of different types of LEDs is measured, the multi-dimensional properties of the emitted optical radiation must be considered during a measurement, not only in relation to the emitting diode but also as they affect the receiving detector. The range of possible influences on the result of a measurement is considerable and the related measurement uncertainty becomes correspondingly high. The low level of the radiant power emitted by some LEDs can limit the resolution of the spectral and spatial distribution measurements; in order to increase the signal of the detector, it has become common practice to measure, for example, the luminous intensity of LEDs at relatively short distances at a fairly large solid angle of the radiation coming from the LED. In this case LEDs are not measured as a point source and measured results vary depending on the geometrical conditions used. To minimize such variation of results, this report standardizes such geometrical conditions so that measured values can be comparable and reproducible among different users.

Definitions of the various radiometric, photometric and colorimetric quantities used to characterise the performance of LEDs have been collected and presented here in a way that is intended to show some of the limiting conditions that apply during a measurement. Recommendations are given for new CIE standard measurement conditions that can be used to specify the properties of LEDs.

LEDs that emit visible radiation are widely used in applications where information has to be conveyed to the human eye or for illumination purposes. This report, therefore, deals with the characterisation of the emitted radiant power not only in terms of radiometric quantities, but also, where applicable, in terms of photometric and colorimetric quantities. Whether radiometric or photometric quantities are involved, they should always be measured using the appropriate SI units.

Measurements for characterising LEDs are usually carried out using a DC current power supply and operating under steady state conditions. The assumption is made that there is thermal equilibrium. If the power supply is changed to multiplexed or modulated mode, even if it is adjusted to give the LED under test the same effective electrical power consumption, the values measured are averaged in time and the characteristics of the LEDs can be changed significantly. The reasons for this and the possible effect on the results are discussed.

This report is based on the experience and views of the members of CIE Technical Committee TC 2-34 and later its continuation, TC 2-45, but it can only represent the state of knowledge and development in the field at the time of publication. This is a field where production and measurement techniques are changing rapidly, and it is quite likely that future developments may render some aspects of the present report obsolete. Should it prove to be necessary, it is hoped that the report can be revised from time to time in order to incorporate the results of new developments, for example the introduction of new LEDs at shorter wavelengths, higher light output levels, etc. to keep the document current.

1.4 Categories of LED measurement

LED measurements can be divided into two categories:

1.4.1 Laboratory measurements

Most of the manufacturers and large-scale users of LEDs first characterise the products in a sophisticated laboratory. For each different type of LED, working standards are then prepared for production quality control.

1.4.2 Bulk testing

Bulk testing is used for production control or for checking the quality of incoming units. The test set-up has to be made to operate at high speed in order to cope with large numbers of units, and thus, often simplified or modified from standard measurement conditions. Such simplified or modified measurement conditions for production control may be used as long as the measured results are correlated to the results of laboratory measurements.

Where such routine measurements of LEDs are carried out outside a laboratory, it is of primary importance to obtain stable, calibrated standard LEDs with the same spatial and spectral characteristics as those of the LEDs to be tested, thus ensuring that, as far as possible, measurements can be made on the basis of a simple, direct substitution between similar kinds of devices.

2. PROPERTIES OF LEDS

2.1 Optical properties of LEDs

The radiation from a LED can be characterised by radiometric and spectroradiometric quantities. If the LED emits visible radiation, then photometric and colorimetric quantities are also required to quantify its effect on the human eye. Consequently, radiometric, spectroradiometric, photometric and colorimetric quantities with their related units may all have to be used to characterise the optical radiation emitted by a LED.

Note that for every radiometric quantity there is a photometric analogue (CIE, 1983). The only difference is that, for the radiometric quantity, the radiation is evaluated in power units while for photometric quantities the radiation is weighted by a spectral luminous efficiency function, generally $V(\lambda)$, and multiplied by K_m (= 683 lm/W). To avoid unnecessary repetition, throughout this report, wherever the comments made apply equally to radiometric and photometric quantities, reference is made only to the photometric quantities. If the measurements to be made relate to a radiometric quantity, then the photometric term can be replaced by the radiometric equivalent.

Characterisation of the optical properties of LEDs should be based upon the same methods and techniques as those formulated for other types of light sources. Definitions of the various photometric, radiometric and colorimetric quantities involved are given in the International Lighting Vocabulary (CIE, 1987a). The basic concepts in colorimetry are described in CIE publications (CIE, 1983; CIE, 2004). A fuller and more general treatment of the measurement of optical radiation and colour can be found, e.g., in references (Grum and Bartelson, 1980; Wyszecki and Stiles, 1982).

There are hundreds of different types of LEDs available on the market, differing not only in their spectral distribution but also in the spatial distribution of the radiation emitted, ranging from quasi-Lambertian characteristics to a nearly collimated beam with all the possible variations in between. It is also reasonable to apply some of the quantities normally used to describe the radiation from luminaires to characterise the radiation from LEDs.

2.1.1 Spatial distribution

The optical radiation produced by a LED is generated by a semiconductor chip mounted in some form of package. The package protects the chip during operation, incorporates the electrical contacts and supports it for handling. It should be noted that the packaging frequently changes the spectral and spatial distribution of the radiant power emitted from the chip by providing built-in reflectors or lenses and sometimes scattering material, coloured filters or a fluorescent layer. A selection of some of the different spatial distributions of luminous intensity found in LEDs is presented schematically in Fig. 1, showing the considerable variety that can be found and the associated difficulties of defining a uniform method of measurement and characterisation.

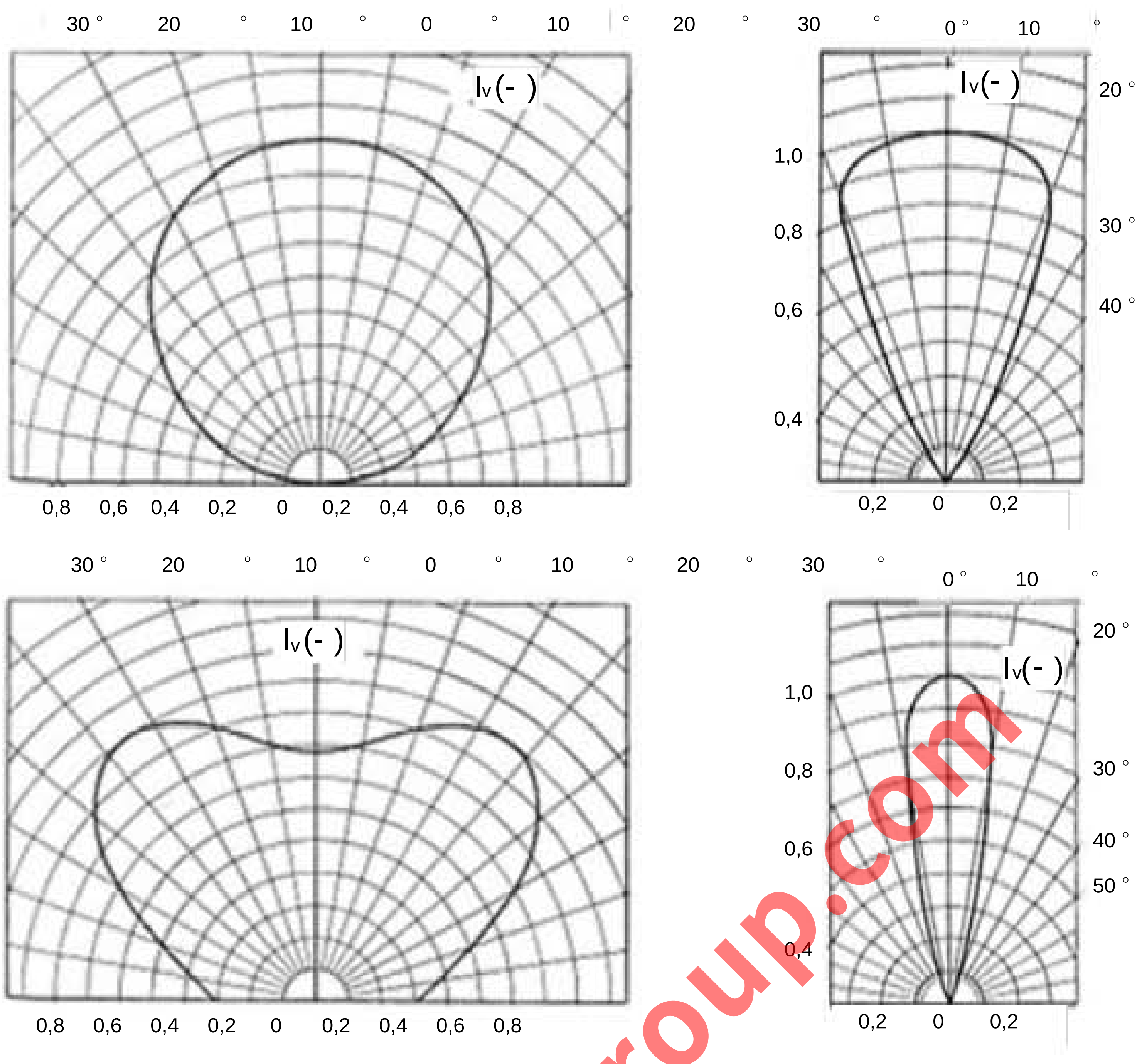


Fig. 1. Some typical spatial distributions of the luminous intensity emitted by a selection of different LEDs. The distributions have been plotted with the maximum values normalised to unity.

2.1.2 Spectral distribution

The spectral distribution of the optical radiation emitted by LEDs is characteristic of these devices and differs in various aspects from that of other sources of optical radiation. Spectral distribution of typical single-colour LEDs is neither monochromatic (as emitted by lasers) nor broad-band (as found with incandescent lamps), but something between the two (quasi-monochromatic), with a spectral bandwidth of some tens of nanometres. Typical relative spectral distributions of LEDs for the visible region are shown in Fig. 2. Note that radiant efficiency of LEDs varies largely depending on their peak wavelength.

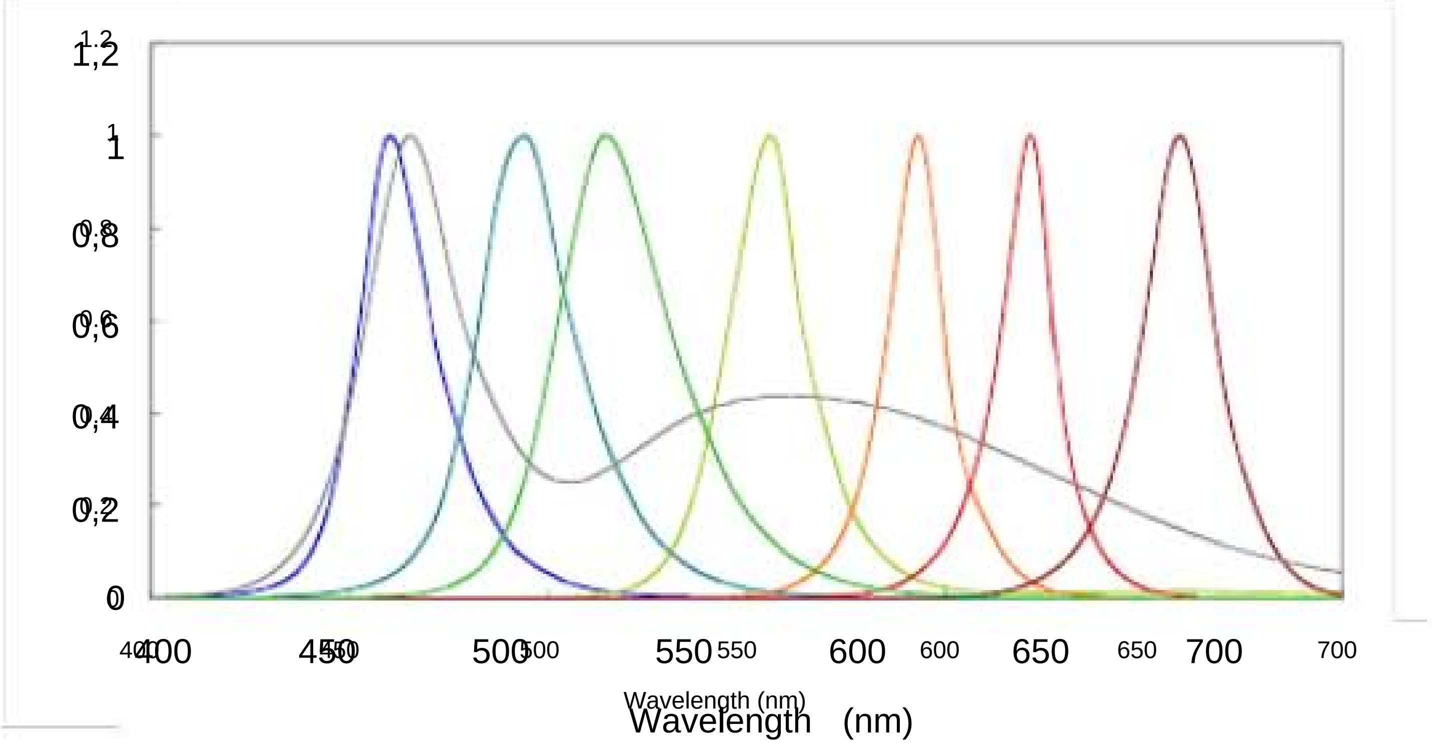


Fig. 2. Relative spectral power distributions of a series of typical LEDs.

2.1.3 Area of emittance

The small packages used for LEDs offer a large variety of sizes and shapes for the light-emitting surface. The area of emittance is characterised by its shape, size and the pattern of the luminance across it. The luminance of the whole light-emitting surface is an averaged value of the luminance distribution over the emitting area. Typically, the luminance is a maximum in the centre of the exiting light beam with significantly lower values at the edges; however there are significantly different distributions in such applications as LED lamps.

In some applications, LEDs are used under conditions where the distance between the exit window of the package and the detector is relatively short so that the light-emitting surface acts as an extended area and the light source can no longer be treated as a point source. In this situation, the ratio of the illuminances produced at different distances no longer obeys the inverse square law and the radiation pattern depends on the distance from the emitter. This is described as the "near-field" condition. For further reading on the "near-field" condition, see reference (Goure and Massot, 1982).

In contrast, "far-field" condition exists when the size of the emitting area is small enough, compared to the measurement distance that the inverse square law is valid, or when the radiation pattern is already independent of the distance from the emitter. The concepts of the "near-field" and "far-field" conditions are discussed in Section 4.

2.2 Electrical characteristics

2.2.1 Electrical operating conditions

LEDs are normally operated with DC power applied in a forward bias direction and at a constant current I_F associated with a certain voltage (forward voltage) V_F, which is measured across the contacts of the LED. For accurate measurements, separate contacts for supplying current to the LED and for measuring the voltage (four-pole sockets) are recommended. They are essential for operation at the higher currents which are typical of the single shot or multiplexed modes. The electrical power P consumed by the LED is calculated from

$$P = V_F \quad I_F \quad (1)$$

At low currents, the radiant power (luminous flux) rises at a rate higher than that of the electrical power (start-up range). At high currents, the slope becomes flatter (saturation area), which is mainly caused by heating of the LED chip. Under normal operating conditions (between the start up range and the saturation area), the optical radiation emitted by LEDs is linearly correlated with the electrical current. Thus operation at constant current is recommended for measurements intended to characterise the properties of LEDs.

In many traditional light sources, a strong correlation is found between the luminous flux emitted and the electrical power consumed. This is not so for LEDs. At constant current the forward voltage of a LED decreases with increase of ambient temperatures. Adjusting the electrical operating conditions only to stabilize the power consumed by a LED will change the chip temperature, thus affecting the voltage drop across the LED. For this reason, stabilization of the electrical power only is not recommended as a means for improving the stability of the radiant output of a LED.

2.2.2 Operation of reference standards

The apparatus used to measure LED characteristics should be calibrated with LED reference standards that have been specially selected and prepared. They should be operated at a constant current with the temperature of the chip maintained at a constant value. When a supplementary heating system is used to control the temperature of the chip, the LED can be stabilised using the temperature dependent forward voltage as an indicator to be maintained at a specified value.

The LEDs used as reference standards can be specially manufactured by incorporating a separate resistor or transistor mounted inside the package of the LED to optimise the thermal contact between heater and chip. Fig. 3 shows the schematics of such a reference standard. This operating procedure is strongly recommended for all reference standard LEDs.

The calibration of primary reference standards should be performed by a national metrological institute (NMI) or a laboratory traceable to NMI. A precise description of the measurement technique and a statement of uncertainty should be given with each calibrated standard LED. The NMI to which the calibration is traceable should also be identified.

The reference standard LED mounted in a specially designed package should be a LED typical of the kind to be tested. The chosen LED has to be pre-selected and "seasoned" (i.e. burnt-in), typically for 500 hours at the ratings which are used later during operation. Accelerated seasoning at higher currents is not recommended. It is important that the LED selected for use as a standard shall have spectral and spatial power distributions which correspond as closely as possible to those of the LEDs to be tested. The package should incorporate a thermostat for keeping the reference standard LED at a predetermined temperature and provide a constant current setting, to ensure a constant optical output.

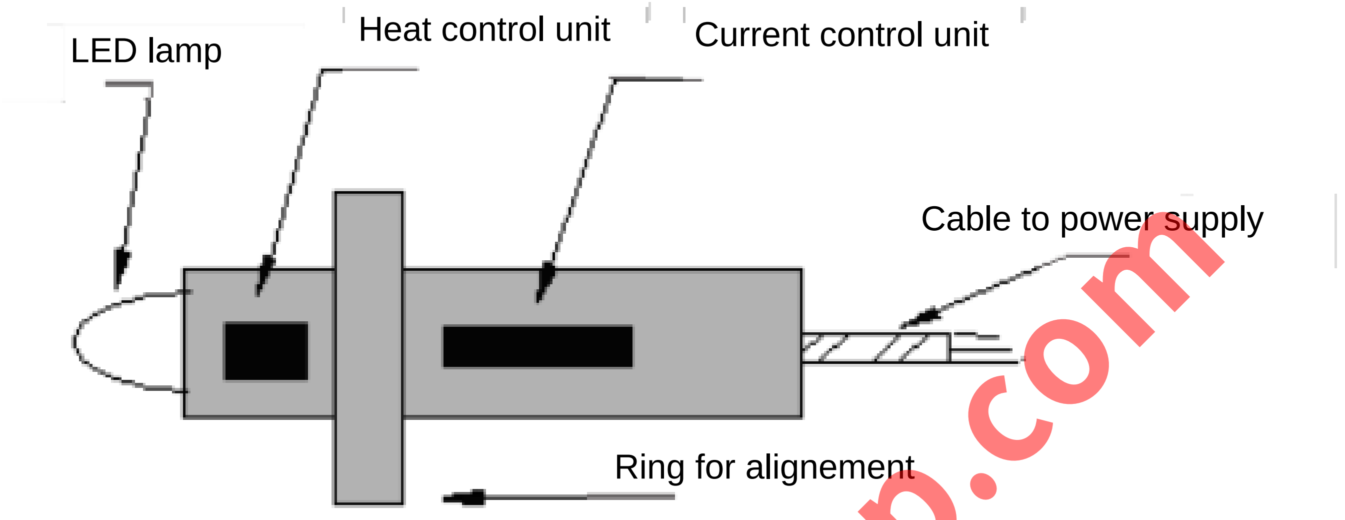


Fig. 3. Schematic diagram of a temperature stabilised standard LED.

2.2.3 Time dependent operation

In many applications, LEDs are operated under non-steady-state conditions such as modulated current, single shot or multiplexed mode. Since the output characteristics of the LED are affected by these operating conditions, it is important to identify the mode of operation when reporting data characterising the properties of LEDs.

2.2.3.1 Modulated current

An increase in current causes an increase of both the luminous output and the chip temperature, which in turn affects the luminous output. In the case of modulated current operation, the chip temperature will also fluctuate so that the average output will be different from that obtained with steady state operation at a constant current of the same mean value. Thus, the radiant efficiency h_e, which is the ratio of the radiant power $)_e$ to the electrical input power P, is a function of the average current, even if the LED is operating well within the normal working region between start-up and saturation levels.

2.2.3.2 Pulsed operation

During production control, the measurements made to characterise the properties of each LED are often carried out as single-shot operations within a fraction of a second and at current levels approximating those typically used under steady state conditions. For most LEDs the heat capacity and the heat conducting properties of the chip and package is too large for the temperature of the chip to reach the value of steady state operation in such a short time. Such operation thus modifies the values obtained for the LED characteristics. Fortunately, these values from a single-shot operation are strongly correlated to the values for steady state operation. The true characteristics can be calculated once the correlation for the particular type of LED has been determined by a few supplementary measurements.

2.2.3.3 Multiplexed operation

In multiplexed mode a high current is repeatedly switched on and off for a short time, the time averaged value of which is equal to the normal operating DC current. As in the case of single-shot operation, the correlation has to be established between the ratio of light output to current under multiplexed operation and the ratio of light output to current under steady state DC operation, and this can again be established by a few supplementary measurements.

The present report is restricted to a discussion of constant current operation but the electrical measurement methods suggested for this case can be extended to other conditions with appropriate adjustments. The optical part of the measurement system is unchanged, but care must be taken to ensure that the photo detector and the photocurrent measuring device average the light linearly.

2.2.4 Forward voltage

The value of the forward voltage depends on the semiconductor material of the LED, with variations of up to a factor of five for the different types available. At the usual working point, with the current set to 20 mA, typical values between 1,2 V for IREDs and 6,5 V for blue LEDs are found. The voltage V_F of an individual LED also depends on the current I_F and on the junction temperature T_C of the semiconductor, which can be substituted by the chip temperature T_C as a first approximation.

$$V_F = V_F\left(T_C, I_F\right) \quad (2)$$

The total derivative dV_F separates the two influences.

$$\mathrm{d}V_F = \frac{\partial V_F}{\partial I_F}\,\mathrm{d}I_F + \frac{\partial V_F}{\partial T_C}\,\mathrm{d}T_C \quad (3)$$

2.2.4.1 Forward voltage dependence on current

Under stabilised temperature conditions, the relationship between the forward voltage of a LED and the current follows a well established pattern common to all semiconductor diodes. In the normal working region, between the start-up and saturation levels, there is a close approximation to a linear relationship with a slope given by

$$\frac{\partial V_F}{\partial I_F} \approx 10 \ \text{[V/A]} \qquad (4)$$

If the LED is operated at a working point corresponding to a current I_{F0} with a related forward voltage V_{F0} and a differential resistance at that point given by

$$R_{F0} = \frac{\Delta V_{F0}}{\Delta I_{F0}} \quad (5)$$

then the current-voltage characteristics can be approximated by

$$V_F(I_F) = R_{F0}\,I_{F0}\,\log\left(b\,\frac{I_F}{I_{F0}} + 1\right) \quad (6)$$

where

$$b = \exp\left(\frac{V_{F0}}{R_{F0}\,I_{F0}}\right) \quad (7)$$

In Fig. 4, the relationship between the forward voltage of a LED and the current is shown at a single working point, corresponding to V_{F0} = 2 V and I_{F0} = 20 mA, for four different values of the differential resistance.

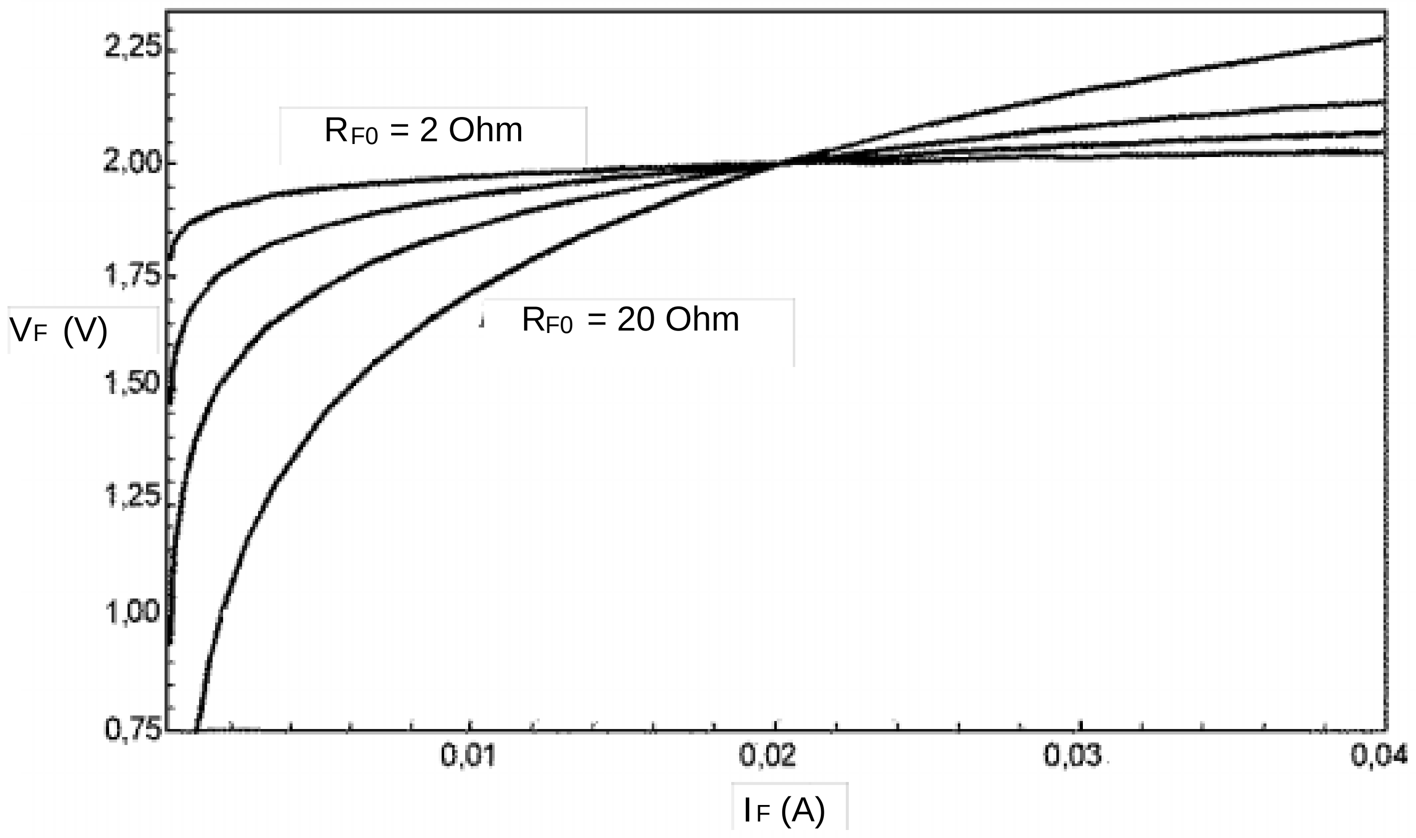


Fig. 4. Relationship between forward voltage and current for a typical LED at a working point corresponding to V_{F0} = 2 V and I_{F0} = 0,02 A shown for different values of R_{F0}.

2.2.4.2 Forward voltage dependence on temperature

For most LEDs, when operating at normal ambient temperatures, typical values for the temperature coefficient of the forward voltage at a constant current are found to be in the range

$$\frac{wV_F}{wT_C} \mid (1{,}5 \text{ to } 2{,}5) \quad [\mathrm{m\,V/K}] \quad (8)$$

2.2.5 Ambient temperature

Unless otherwise specified, an ambient temperature of T_{amb} = 25oC is assumed for LED characterisation. Because of the power consumed in the LED chip, the chip temperature T_C rises after the power has been turned on and stabilises later at a value $T_{Chip} > T_{amb}$. The rate of the temperature change depends on the level of the power input and the heat capacity and thermal resistance of the LED package. After thermal equilibrium has been reached, the value of T_{Chip} is governed by the heat transfer to the surroundings, which takes place mainly via the LED substrate (in case of older constructions via the leads of the LED). As a consequence, the thermal properties of the electrical contacts used to supply the LED and the length of the wires between chip and heat sink can significantly effect the measurement.

The temperature of the LED chip will be more or less unchanged if it is operated under short, single-shot conditions, but a small rise in temperature is usually found during constant current operation. Temperature effects that occur in the case of modulated or multiplexed operation are discussed in Section 2.2.3.1 above.

2.3 Influence of temperature on the radiation

2.3.1 Shift of peak wavelength with temperature

Constant current and a temperature-stabilised voltage will result in constant consumption of electrical power by the LED. It should be noted, however, that stabilising the power without controlling the temperature will result in quite different operating conditions. The relative spectral distribution of the emitted radiation will be affected in two ways. On the one hand there will be a slight change in the shape of the distribution and on the other hand, as the temperature rises, the whole spectral distribution might shift significantly, for GaAsP based LEDs in the direction of longer wavelengths and for GaInN based LEDs (thus e.g. for blue LEDs), the shift is toward shorter wavelengths. For a typical LED, this shift is about

$$\frac{\mathrm{w}O_{p}}{\mathrm{w}T_{C}} \mid (0{,}1 \text{ to } 0{,}3) \quad [\mathrm{nm/K}] \qquad (9)$$

2.3.2 Effects of temperature on efficiency and efficacy

Small temperature changes have very little effect on the radiant efficiency of a LED. The luminous efficacy of LEDs emitting green light is also fairly constant because the peak wavelength of the spectral distribution is close to the maximum of the $V(O)$ function. The luminous efficacy of a coloured LED with a peak wavelength on the slopes of the $V(O)$ function is much more seriously affected by a shift in the spectral distribution. The luminous efficacy of LEDs emitting red or blue light can, therefore, change significantly by relatively small temperature changes. Since the spectral distribution of a LED depends on both the power consumed and the temperature of the chip, stabilisation of current and temperature offers the best way of controlling the operating conditions and maintaining a constant spectral distribution.

2.4 roduction tolerances

Some of the most important quantities used to characterise the optical radiation from LEDs are related to a specific direction. It is, therefore, important to align the LEDs precisely for these measurements. Unfortunately, there are two axes of rotation about the forward direction; one is based on the package and the other is based on the spatial distribution of the emitted radiation. These two axes seldom coincide. The area of emittance, which can vary in shape, size and structure, often has no well-defined limiting aperture, so that it may be difficult to establish the exact location of the light centre. Taken together with typical production tolerances, this results in angular and positional alignment difficulties and leads to increased measurement uncertainty.

Fig. 5 illustrates a LED for which the geometric axis of the package and the optical axis of the emitted light do not coincide. In production testing there is not usually enough time to set the LED in the measuring jig in such a way that the luminous intensity is measured in the direction of the optical axis. In selecting LEDs for standards it is important to use only those LEDs where the optical and geometric axes coincide.

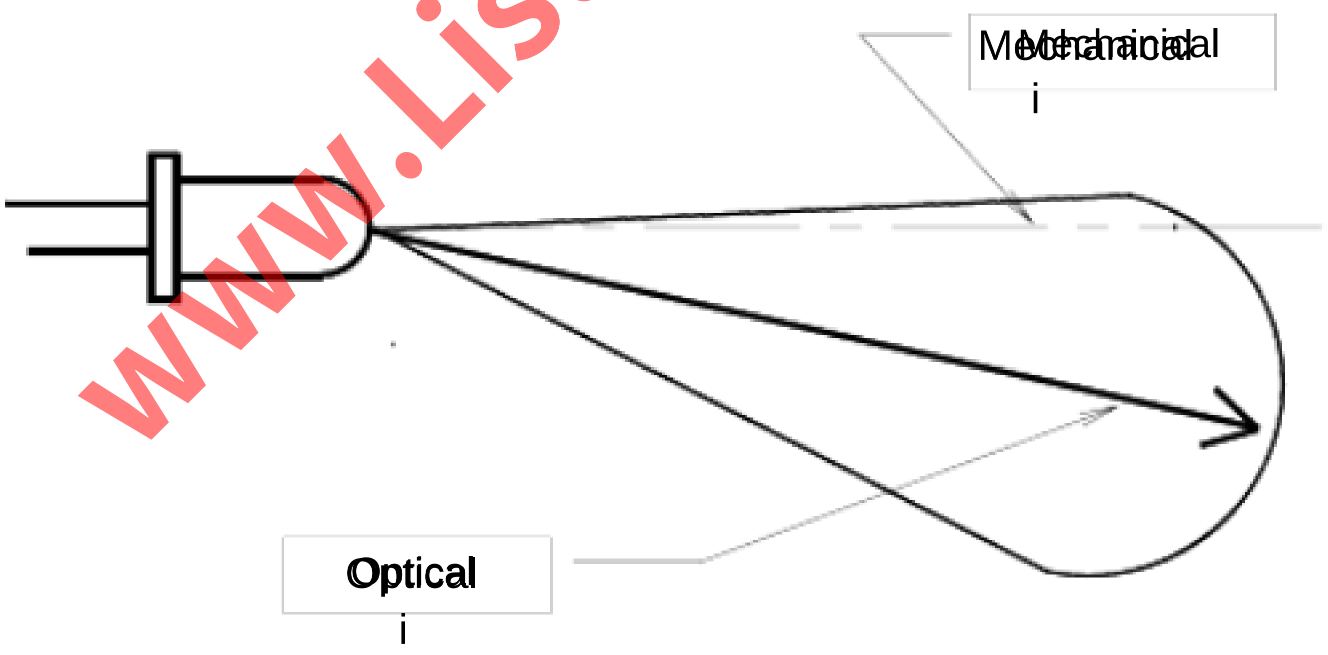


Fig. 5. A LED whose mechanical and optical axes point in different directions.

3. PROPERTIES OF THE PHOTOMETER / RADIOMETER

For measurement of LEDs, a photometer or a radiometer, and/or a spectroradiometer is used depending on whether radiometric or photometric quantities or both are to be measured. Spectroradiometric measurements are described in Section 7. A photometer or a radiometer for LED measurements typically consists of a detector, a filter, an entrance aperture, and an electronic circuit to amplify and measure the detector output. For general requirements of standard photometers, refer to ref. (CIE, to be published a). Some specific information and requirements relevant to LED measurements are described below.

3.1 Detectors

Silicon photodiodes are typically used to construct photometers and radiometers for LED measurements. Silicon photodiodes are sensitive from ultraviolet to near infrared regions to about 1100 nm, with a peak responsivity at about 900 nm. Silicon photodiodes typically have linear response over several decades of input radiant flux and have nearly negligible temperature dependence of responsivity in the visible region. Note that filters have higher temperature dependence of their transmittance.

3.2 Angular and spatial responsivity of photometers / radiometers

A photometer and a radiometer for measurement of Averaged LED luminous/radiant intensity do not require cosine response because light is incident from a narrow angle. They need to have uniform responsivity only over the range of angles at which the radiation from a test LED can be incident on the photometer or radiometer. Therefore, cosine correction is generally not required in the front surface of a photometer or a radiometer for intensity measurement; however a diffuser can be used to realize a light-sensitive area that is larger than the detector’s light-sensitive area (It should be noted, that the short distance to the source requires a significantly larger light-sensitive area of the detector than the front aperture of the photometer). On the other hand, a photometer / radiometer used with an integrating sphere for luminous flux or radiant flux measurement requires good cosine correction.

For measurements of "Averaged LED Intensity" (see Section 4.3) the responsivity across the entrance aperture of the photometer / radiometer should be uniform, to ensure that all the radiation reaching the entrance aperture is measured with the same weight. Some LEDs have a narrow beam angle or irregular intensity distributions that can create non-uniform illuminance distributions within the aperture. If the responsivity across the entrance aperture is not uniform, it can cause significant errors in measured Averaged LED Intensity, particularly in CIE-B geometry, for such LEDs. A photometer with a good spatial uniformity can often be constructed by using a non-diffuser type photometer (CIE, to published a) (it requires a large-area photodiode), or by using a small integrating sphere as an input optic. Diffusers (such as opal glass) are also often used for this purpose, particularly when a smaller photodiode is to be used. It is generally more difficult to achieve good spatial uniformity by using a diffuser. A careful design and selection of diffuser materials are required to achieve sufficiently good spatial uniformity.

3.3 Spectral responsivity of the photometers / radiometers

The spectral responsivity $s(\lambda)$ of a photometer / radiometer can be expressed by an absolute factor s_0 and a relative function $s_r(\lambda)$ with

$$s(\lambda) = s_0 \cdot s_r(\lambda) \quad (10)$$

For recommendations on the procedure for determining the spectral responsivity of optical radiation detectors see reference (CIE, 1984a).

If the detector is irradiated by radiation having the spectral distribution $X(\lambda)$, the photocurrent i can be calculated from

$$i = X_0 s_0 \int^{\infty} s_r(\lambda) S(\lambda) \, d(\lambda) \quad (11)$$

Here $X(\lambda) = X_0 \cdot S(\lambda)$, where X_0 is the normalisation factor and $S(\lambda)$ is the relative spectral distribution. $X(\lambda)$ represents whichever photometric or radiometric quantity is to be measured.

The relative spectral responsivity of a photometer should approximate as closely as possible $V(\lambda)$, the CIE spectral luminous efficiency function for photopic vision (CIE, 1983). The relative spectral responsivity of a radiometer should be as flat as possible over the specified spectral range.

3.3.1 Photometer to measure white LEDs

Commercially available photometers are usually classified according to their f_1' number (CIE, 1987b). The f_1' is recommended for measurement of white LEDs. Unless the spectral mismatch correction is always applied (as described in Section 5.2), it is recommended that a photometer used to measure white LEDs have an f_1' value < 3,0 %. The f_1' is defined as

$$f_1' = \frac{\int \left| s^*(\lambda)_{\mathrm{rel}} - V(\lambda) \right| d\lambda}{\int V(\lambda) d\lambda} \quad (12)$$

where $s^*(\lambda)_{\mathrm{rel}}$ is the normalized relative spectral responsivity of the detector:

$$s^*(\lambda)_{\mathrm{rel}} = s(\lambda)_{\mathrm{rel}} \frac{\int S(\lambda)_A V(\lambda) d\lambda}{\int S(\lambda)_A s(\lambda)_{\mathrm{rel}} d\lambda} \quad (13)$$

$S(\lambda)_A$ is the relative spectral distribution of CIE standard Illuminant A. The latter is included to take into account the fact that photometers are normally calibrated using a tungsten filament lamp set to the distribution temperature of CIE standard Illuminant A. Errors for white LEDs will be minimized if f_1' is small, but uncertainty still needs to be properly evaluated.

If photometers used for LED measurements do not meet these recommendations of f_1', the use of such photometers should be limited to strict substitution (comparison of the same type of standard and test LEDs having the same colour), or such photometers be furnished with individually measured relative spectral responsivity data so that a spectral mismatch correction (see Section 5.2) can be applied.

3.3.2 Photometer to measure coloured (non-white) LEDs

In the case of single-colour LEDs, the spectral mismatch errors can be very large even if f_1' is reasonably small, due to the fact that some LED spectra are peaking at the wings of the $V(\lambda)$ function where the deviation makes little effects on f_1' but can cause large errors.

Determination of a better and more useful number for the goodness of the fit to the $V(\lambda)$ function for LEDs is beyond the scope of this report. [From preliminary results it seems that one number similar to f_1' is not sufficient to evaluate the accuracy of photometers for measurements of all of different colour types of LEDs; instead maybe as many as 4 numbers are needed (Csuti et al., to be published).]

For photometers to measure single colour LEDs, it is recommended that the relative spectral responsivity of photometer be supplied, with examples shown how to apply correction for spectral mismatch errors and how to evaluate the measurement uncertainties of the measured photometric quantity of a given coloured LED.

4. QUANTITIES DEFINING SPATIAL RELATIONS

4.1 Normalisation factor and relative spatial distribution

In general, the luminous intensity $I(\theta, \varphi)$ depends on the direction (θ, φ) and this dependence is called the spatial intensity distribution. It should be noted that measurements of luminous intensity, including those required to map the spatial distribution, must be made over a very small element of solid angle $d\Omega$ and this requires a detector where the diameter of the input aperture and the diameter of the source are small compared to the distance from the source. If the absolute value of the intensity $I(\theta, \varphi)$ is measured in a specified reference direction corresponding to $\theta = \theta_0$ and $\varphi = \varphi_0$ and denoted by $I_{00} = I(\theta_0, \varphi_0)$, then this can be used as a normalising factor and a relative spatial intensity distribution $\Gamma(\theta, \varphi)$ defined. The spatial intensity distribution $I(\theta, \varphi)$ can be expressed as

$$I\ (T,\ I) = I_{00} \cdot G(T,\ I) \quad (14)$$

which can be rewritten as

$$G(T, I) \quad \frac{I(T, I)}{I_{00}} \quad (15)$$

For a spatial intensity distribution there is no dependence on angle I at angles $T = 0$ and $T = S$. Consequently, the value in the direction $T = 0$ is the one usually preferred for normalisation, making $I_{00} = I(T = 0)$.

The simplest form of the function $G(T, I)$ is

$$G(T) = G \quad (16)$$

where G is a constant. This represents the spherical spatial distribution of a totally isotropic point source.

Another spatial distribution that is easily expressed mathematically is the Lambertian distribution. With T measured as the angle between the direction considered and the perpendicular to the surface, the spatial distribution for all values of I is given by

$$G(T) \quad G_0 \left|\cos T\right| \quad (17)$$

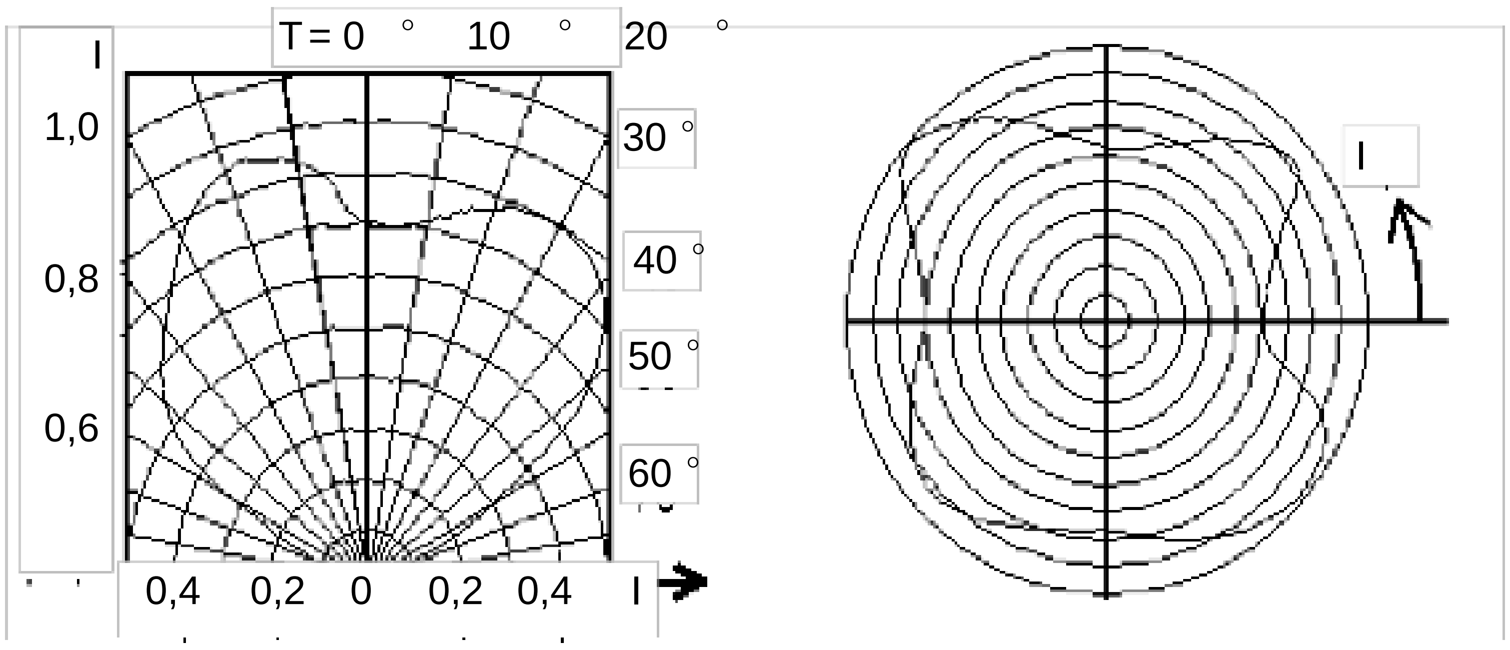
where the range of angles is limited to a hemisphere with $0 \ d\ T\ d\ S / 2$. This spatial distribution is normally used as a reference.

It is not possible to express most practical spatial distributions in terms of a simple mathematical function, but symmetrical spatial distributions are often characterized by specifying the angles corresponding to 50 % and 10 % of the maximum value (CIE, 1987b). It should be noted that, for structured intensity distribution curves, there may be more than one angle that produces the 50 % or the 10 % value. When this method is used, it is recommended that the first angles for such intensity values starting from 0° (measured from direction of mechanical axis) be reported.

The majority of LEDs are designed to provide a distribution with the maximum intensity in the direction $T = 0$, but this is not always the case and for some LEDs the construction of the device gives a significantly lower value in the direction of the geometrical axis than for some off-axis angles. One of the examples in Fig. 1 shows this effect.

Sometimes, because of production tolerances, even if the LED is mounted in a cylindrical package, the mechanical axis of the package (which is used to align the LED in the measurement apparatus) and the optical axis (which is the axis of rotational symmetry of the spatial distribution) may have slightly different directions (see Fig. 5). The measurement procedure must take account of the influence that this could have on the results.

By no means all production LEDs have a spatial distribution that shows perfect axial symmetry. Fig. 6 shows two common forms of asymmetric spatial distribution that are sometimes found in LEDs and can lead to alignment problems. The spatial distribution of the LED depicted in Fig. 6a shows a small minimum in the direction of the package axis ($T = 0°$), and a maximum in an off-axis direction. Fig. 6b shows $I(I)$ plotted at constant T for a LED in which the non-circular shape of the intensity distribution indicates the departure from rotational symmetry.



(a) (b)

Fig. 6. Two frequently occurring non-symmetrical intensity distributions: (a) the optical axis is off the geometric one, (b) the spatial intensity distribution is non axial symmetric.

4.2 Measurement of directional quantities

4.2.1 Luminous intensity

Luminous intensity is defined as the quotient of the luminous flux d I v leaving the source and propagated in the element of solid angle d : containing the given direction, by the element of solid angle.

$$I \quad dI_v / d: \quad (18)$$

Although this may appear, at first sight, to be simply a question of making a measurement of the luminous flux per solid angle in a given direction, in reality the situation is often far more complex. The concept of luminous intensity requires the assumption of a point source, or at least a source small enough for its dimensions to be negligible compared to the distance between source and detector and, in principle at least, there is also a requirement that the measurement should be made over a very small element of solid angle.

Many LEDs have a relatively extended area of emittance (see Section 2.1.3) which, at the short distances at which they are often measured, may be too large to be treated as a point source. In addition, the package of LEDs often has a lens and shifts the effective centre of emission.

4.2.2 Illuminance

The illuminance $E_v(T, I)$, produced at a distance d from a source in a direction (T, I) on an element of surface normal to that direction, is related to the luminous intensity $I_v(T, I)$, in that direction by the equation

$$E_v(T, I) = I_v(T, I) / d^2 \quad (19)$$

provided again that the distance is large enough for the source to behave effectively as a point source and that the angle subtended by the detector is at least small enough for the illuminance to be effectively uniform. Eq. 19 is known as the "inverse square law", but it can be rewritten as

$$I_v(T, I) = E_v(T, I) \quad d^2 \quad (20)$$

This is the basis of all practical measurements of luminous intensity. The quantity actually measured is the illuminance at the surface of a photometer and the intensity is then calculated on the basis of Eq. 20 by multiplying the illuminance by the square of the distance from the source.

For accurate measurements of luminous intensity, however, not only must the relative size of the source and the angle subtended by the detector be small, but it is also important to be able to measure the exact distance between the source and the photometer. Since the actual location of the effective light centre of a LED can be difficult to determine due to its lens or total diffusivity, distances are often measured from an arbitrary location on the LED package.

4.2.3 Location of the effective emitting surface

If the measurement distance is large enough, the actual position of the reference point shouldn't matter very much, but because of the large variety of different types of LEDs available, no simple general rule can be laid down to determine the minimum safe distance for accurate measurement (see CIE, 1987c). This is the reason that CIE recommends the use of the concept of "Averaged LED Intensity" (Section 4.3).

4.2.4 "Near-field" and "far-field" measurement conditions

If a true luminous intensity is to be measured, the size of the emitting area of the source and of the receiving surface of the photometer must be small enough to be insignificant compared to the distance between the two. In this situation, the inverse square law will be obeyed and the illuminance E_V at the surface of the detector will be given by $E_V = I_V / d^2$ (Eq. 19) where I_V is the luminous intensity of the source in the given direction and d the distance between the light centre of the source and the detector. This is sometimes referred to as the "far-field" condition.

In many applications, however, measurements are made on LEDs at relatively short distances, where either the relative size of the source is too great for it to be treated as a point source or the angle subtended by the detector at the source becomes too large. This is known as the "near-field" condition. The inverse square law can no longer be applied and the illuminance measured by the detector becomes critically dependent on the exact measurement conditions.

4.3 Averaged LED Intensity

In manufacturers' literature, one of the parameters most commonly quoted as a measure of the directional output of a LED is luminous intensity. Unfortunately, in many cases, the term is incorrectly used and the quantity measured is not really a true intensity as defined in Section 4.2.1.

The actual procedure employed is to make a measurement of the flux incident on a detector at a measured distance from the LED and to calculate the solid angle by dividing the area of the detector by the distance squared. Because these measurements are commonly made at relatively short distances, the emitting area of the LED could, in many cases, be large enough compared to the distance from the detector to act as an extended area rather than as a point source. This is the situation known as the "near-field condition" as described above. It is also possible, if the detector is too close to the source, that the value of the true luminous intensity may vary as viewed from different parts of the detector surface.

In situations of this kind, which are very common in the real world of LED measurement, the quantity measured is not intensity in the traditional sense but represents a form of Averaged LED Intensity; averaged that is for the various individual elements that make up the extended area of the emitting surface of the LED as well as over the different parts of the detector surface. Unfortunately, this distinction is not just a quibble over the exact wording of a definition. There is a real problem because, in this situation, the results of the measurements and the applicability of the measured values are critically dependent on the exact conditions under which the measurement has been made. This makes it very important to agree and define a precise measurement geometry that can be applied to a wide range of LEDs in order to allow a true comparison between different products and, equally important, between similar products from different manufacturers.

In an attempt to offer a solution to this problem, the CIE has decided to recommend the adoption of a new term, specific to LED measurements, to describe the quantity measured under such "near-field" conditions and to define two standard measurement geometries associated with it. The two measurement geometries are based on current practice in the industry and on views expressed by both manufacturers and users of LEDs.

The new term is called the Averaged LED Intensity. (Averaged LED luminous intensity or Averaged LED radiant intensity).

The measurement geometries are designated as CIE Standard Conditions A and B for the measurement of LEDs. For Averaged LED Intensities determined under these conditions the symbols $I_{LED\ A}$ and $I_{LED\ B}$ are recommended. They can be used for either radiometric or photometric quantities (e.g. $I_{LED\ A\ e}$, $I_{LED\ B\ v}$).

Both conditions involve the use of a detector with a circular entrance aperture having an area of 100 mm^2 (corresponding to a diameter of about 11,3 mm). The LED should be positioned facing the detector and aligned so that the mechanical axis of the LED passes through the centre of the detector aperture. It is the distance between LED and detector that constitutes the difference between conditions A and B. The distances are:

for CIE Standard Condition A: 316 mm, and

for CIE Standard Condition B: 100 mm.

In both cases the distance is measured from the front tip of the LED to the plane of the entrance aperture of the photometer or radiometer.

If the detector has been calibrated for illuminance, the Averaged LED luminous intensity can then be calculated from the relation

$$I_{LED\ v} = E_v\ d^2 \quad (21)$$

where E_v is the average illuminance in lx measured by the detector and d the distance, expressed in metres. For Condition A, d = 0,316 m and for Condition B, d = 0,100 m.

These conditions correspond to solid angles of view of 0,001 sr for Condition A and 0,01 sr for Condition B, but the actual dimensions are as important as the angles in ensuring consistent results. The equivalent full plane angles are approximately 2° for Condition A and 6,5° for Condition B.

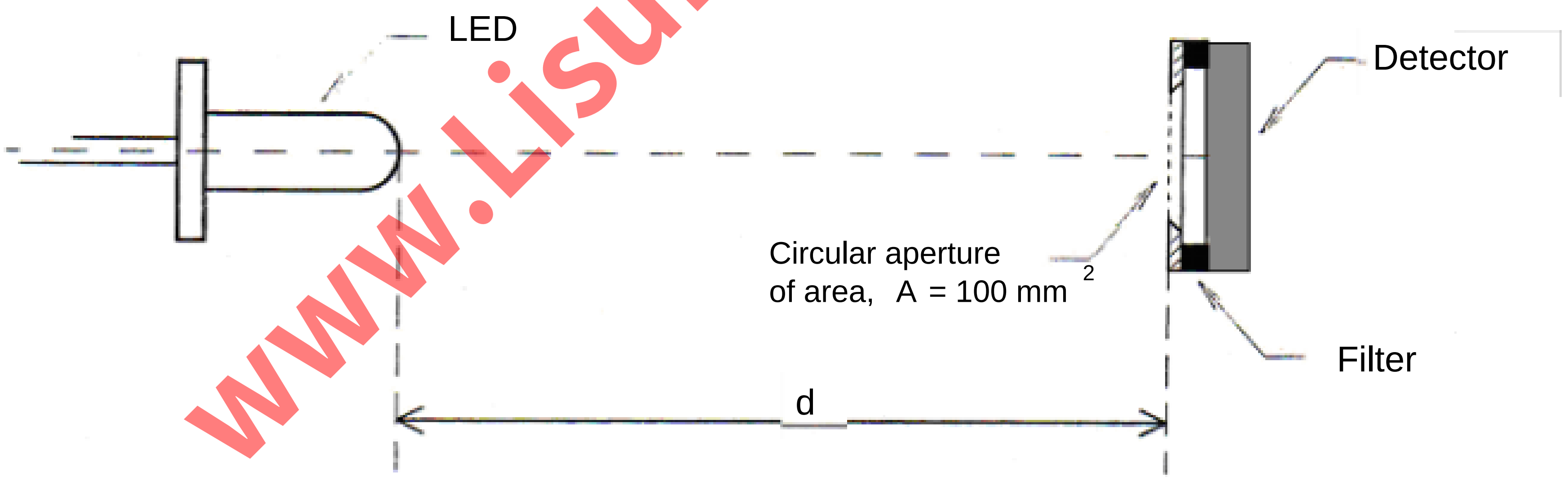


Fig. 7. Schematic diagram of CIE Standard Conditions for the measurement of Averaged LED Intensity. Distance d = 316 mm for Condition A, d = 100 mm for Condition B.

4.4. Measurement of spatial and directional properties

It is desirable that the LEDs selected for use as working standards should have a relative spatial distribution of intensity similar to that of the test LEDs to be measured. For luminous flux measurements using an integrating sphere, use of standard LEDs having similar beam characteristics will minimize spatial non-uniformity errors of the integrating sphere. For intensity measurements, this requirement is not so critical, but the use of standard LEDs having similar beam characteristics will help reduce stray light errors (errors due to light entering the photometer not directly from the source). Standard LEDs for intensity measurements should be selected such that the optical axis of the beam is approximately on the mechanical axis and the spatial distribution around the center axis (within ± ~10°) is smooth and fairly constant so that alignment error will not cause large measurement uncertainties. Thus LEDs having a very narrow beam or having some structures in intensity distribution curves should be avoided. A measurement to check these spatial intensity distribution characteristics should be carried out as a first step in selecting suitable standard LEDs. If the laboratory is equipped with a goniophotometer, it should be used to perform a direct measurement of the spatial distribution of intensity. The best arrangement is to position the front tip of the LED at the centre of the goniophotometer and measure the radiation from as large distance as the instrument will allow.

In laboratories where a goniophotometer is not available, a simple test would be to illuminate a white sheet of paper with the LEDs and compare the beam pattern visually.

5. MEASUREMENT OF AVERAGED LED INTENSITY

5.1 Substitution method

A test LED is calibrated in comparison with a reference LED of the same type (similar spectral distribution). The reference LED must have been calibrated for the same geometry (CIE Condition A or Condition B) as the test LED is to be measured.

The Averaged LED Intensity I_{LED} [cd] of the test LED is obtained by

$$I_{\mathrm{LED,\,test}} = \frac{y_{\mathrm{test}}}{y_{\mathrm{ref}}} I_{\mathrm{LED,\,ref}} \quad (22)$$

where $I_{\mathrm{LED,\,ref}}$ and $I_{\mathrm{LED,\,test}}$ are the Averaged LED Intensity of the reference LED and the test LED, respectively. y_{ref} and y_{test} are the photometer signals for the reference LED and for the test LED, respectively.

With such a strict substitution method, there is no need for spectral mismatch correction and the measurement is most simple. However, if many different types of test LEDs are measured, many different types of standard LEDs are needed. (Also, there will still be some spectral mismatch errors due to small difference in spectral distribution between the reference LED and test LED, which should be evaluated as an uncertainty component.)

5.1.1 Substitution with fewer standards

In many cases, there are too many different types (colours) of LEDs to be measured and so many standard LEDs cannot be maintained. In such cases, the method described in Section 5.2 is acceptable. In this method, it is recommended that calibrated standard LEDs (traceable to a national standardizing laboratory) of several colours of interest are measured using the user's set up and the results are compared to verify the uncertainties of measurements.

5.2 Applying spectral mismatch correction

This method requires the knowledge of relative spectral responsivity of the photometer head. The photometer head is calibrated with standard LEDs of a certain colour (e.g., green or white), and test LEDs of any other colours are measured with spectral mismatch correction applied as below.

$$I_{\mathrm{LED,\,test}} = F \cdot \frac{y_{\mathrm{test}}}{y_{\mathrm{ref}}} I_{\mathrm{LED,\,ref}} \quad (23)$$

Here F is the spectral mismatch correction factor calculated for each test LED as given by

$$F = \frac{\int S_{\mathrm{t}}(\lambda) V(\lambda)\,\mathrm{d}\lambda}{\int S_{\mathrm{r}}(\lambda) V(\lambda)\,\mathrm{d}\lambda} \cdot \frac{\int S_{\mathrm{r}}(\lambda) s_{\mathrm{rel}}(\lambda)\,\mathrm{d}\lambda}{\int S_{\mathrm{t}}(\lambda) s_{\mathrm{rel}}(\lambda)\,\mathrm{d}\lambda} \quad (24)$$

where

S_t(O) is the relative spectral distribution of the test LED;

S_r(O) is the relative spectral distribution of the reference LED;

s_{rel} (O) is the relative spectral responsivity of the photometer head, and

V(O) is the CIE spectral luminous efficiency function of the photopic vision.

The correction factor F is a multiplier to the measured signal of the photometer head for the test LED.

5.3 Use of a spectroradiometer

A spectroradiometer may be used in place of the photometer head for Averaged LED Intensity measurements if the spectroradiometer is appropriately designed for the LED measurements. See Section 7.4.1.1.

5.4 Detector-referenced method

Rather than using standard LEDs to calibrate the photometer head, one can use a photometer as a reference standard (called a reference photometer), as is common practice in general photometry. Selected high-quality photometers are stable over a long period of time. A photometer head having the required aperture for Averaged LED Intensity is calibrated for illuminance responsivity [A/lx] for a reference source spectrum (typically, CIE Standard Illuminant A) at the distances corresponding to CIE Condition A and CIE Condition B geometry. The responsivities for CIE Condition A and B can be slightly different due to near-field effects. Such calibration of a photometer head may be available from a NMI, and also, it can be performed by users by calibrating the photometer head against a standard LED traceable to a NMI. When the photometer head is placed at the exact distance d (316 mm or 100 mm for CIE Condition A or B geometry), the photometer head can measure the Averaged LED Intensity of the test LED directly by

$$I_{\mathrm{LED\ A}} \quad F \quad d^2 \frac{y}{s_{\mathrm{LED\ A}}}; \quad d = 0{,}316\ [\mathrm{m}] \qquad (25)$$

or

$$I_{\mathrm{LED\ B}} \quad F \quad d^2 \frac{y}{s_{\mathrm{LED\ B}}}; \quad d = 0{,}100\ [\mathrm{m}] \qquad (26)$$

where y is the signal of the photometer head, $s_{\mathrm{LED\ A}}$ and $s_{\mathrm{LED\ B}}$ are illuminance responsivities of the photometer head for CIE Condition A and Condition B, respectively, and F is the spectral mismatch correction factor.

The spectral mismatch correction factor F is calculated according to Eq. 24. The difference of this method from the method described in Section 5.2 is that, in this detector-referenced method the scale is maintained on the photometer head. The responsivity is maintained for only one reference source, and LEDs are always measured with spectral mismatch correction applied. The relative spectral responsivity of the photometer head must be known for this method, as well as the relative spectral power distributions of the test LEDs. The photometer head should be recalibrated periodically to maintain a required uncertainty.

When this method is applied, it is recommended that calibrated standard LEDs (traceable to a NMI) of several colours of interest are measured using the user’s set up and compare the results to verify the uncertainties of measurements for LEDs of various colours.

6. MEASUREMENT OF LUMINOUS FLUX

6.1 Measured quantities

The term, total flux, means all the flux emitted from the source, therefore, the total flux integrated over all the directions (4 S steradian solid angle). However, this is not always the important quantity that the application of a particular LED requires. In some cases, the concept of partial flux radiated into a certain solid angle is needed, ignoring the flux in unintended directions (for example, backwards). Therefore, in addition to total luminous flux, a new quantity, "Partial LED Flux" is introduced for LED measurements.

6.1.1 Total luminous flux

Total luminous flux is the fundamental quantity for a light source. It is defined as the cumulative luminous flux of a light source for the solid angle 4 S steradian. The symbol of total luminous flux is) or $)_v$ and the unit is lumen. It is defined as the integral of luminous intensity over the entire full solid angle from the source,

$$? \quad 3^{I\ d:} \quad (27)$$

or, the integral of illuminance from the source over the entire area of a closed imaginary surface surrounding the light source,

$$? \quad 3^{E\ dA} \quad (28)$$

The total luminous flux of a LED, therefore, should include all the flux emitted from a LED including backward flux.

6.1.2 Partial LED Flux

Partial LED Flux is a quantity used for specific applications of LEDs. It is defined as the flux leaving the LED and propagating within a given cone angle (centered from the LED's mechanical axis) that is determined by a circular aperture of 50 mm diameter and the distance measured from the tip of LED. Fig. 8 illustrates this definition. Distance d is set for a desired cone angle x ° as given by

$$d \quad \frac{25}{\tan\frac{x}{2}} > \text{mm} \; @(29)$$

where 0 d x d 180 °

The symbol for this quantity is $)_{\text{LED, } x}$, with the value of x being the cone angle (diameter) in degrees. For example, $)_{\text{LED, } 180}$, corresponds to the flux emitted in the front half hemisphere (forward flux) in which case d = 0. Any flux emitted in the directions other than in the given cone angle is ignored.

The reference point of the LED is the tip of the enclosure of the LED, though it is not the effective center of light emission, because it can be easily identified for any type of LED while the effective center of emission is difficult to determine and sometimes unknown. It is chosen for simplicity and reproducibility of measurement. The diameter of the aperture (50 mm) is fixed in order to achieve reproducibility in measurement. (Measurement results would vary if apertures of different sizes were used for the same cone angle.) This is not a real partial flux defined in the far field; rather, it is called "Partial LED Flux", a quantity that can be used for practical measurement of LEDs with simple instrumentation and reproducible results.

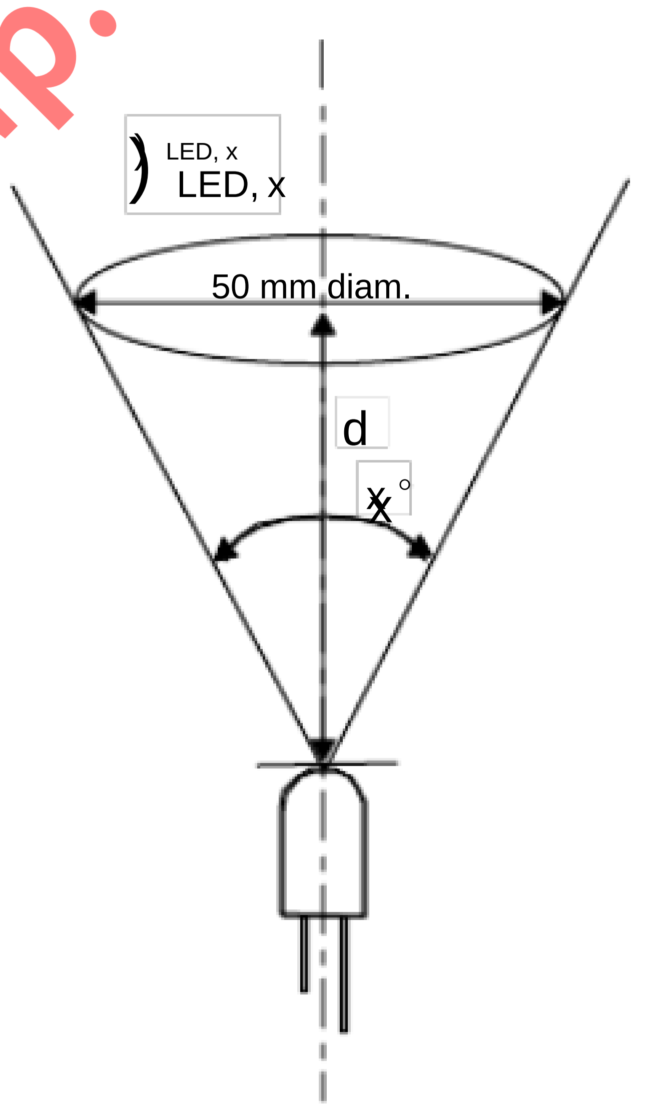


Fig. 8. Partial LED Flux.

It is recommended that total luminous flux (Section 6.1.1) is used as much as possible. Partial LED Flux is used only when total luminous flux does not satisfy the need for a given application. When Partial LED Flux is used, it is recommended that such full angles as 40 °, 60 90 ° and120 ° are used as much as possible. Use of many different angles would make data comparison difficult. Also, it is preferable that the angle be chosen such that most of the main beam flux from the LED is contained in that solid angle. Such a condition will make the measurement less sensitive to LED alignment errors and the errors in distance and aperture diameter.

In a production environment, Partial LED Flux may be measured in a modified geometry (smaller diameter of the aperture), in which case, the measured results can be equalized or corrected to the values under the defined condition (50 mm aperture) based on correlation of results between the two geometries for given type of LED, with an additional uncertainty taken into account.

6.2 Methods of flux measurement

For measurement of total luminous flux, goniophotometers or integrating spheres are used. For measurement of Partial LED Flux, integrating spheres are commonly used.

6.2.1 Goniophotometer method

6.2.1.1 Total luminous flux measurement

A goniophotometer is a device to measure the luminous intensity of the source (or illuminance from the source at a given distance) in many different directions from the source. Compared with the sphere method, the goniophotometer method is theoretically free from errors due to differences in intensity distribution of the light source under test. It does not require total luminous flux standards. Instead, it requires longer time for measurement of each sample.

By measuring the luminous intensity distribution $I(\theta,\phi)$ of the source, the total luminous flux is obtained by

$$\Phi = \int_0^{2\pi}\int_0^{\pi} I(\theta,\phi)\sin\theta\, d\theta\, d\phi \qquad (30)$$

A goniophotometer can be configured such that the illuminance distribution $E(\theta,\phi)$ is measured over an imaginary spherical surface with radius r [m], rather than measuring luminous intensity. In this case, the total luminous flux is given by

$$\Phi = r^2\int_0^{2\pi}\int_0^{\pi} E(\theta,\phi)\sin\theta\, d\theta\, d\phi \qquad (31)$$

By the definition given in Eq. 31 the location of the light source in the imaginary sphere does not matter, Therefore, theoretically, the alignment of light source (LED) is not relevant to the measured total luminous flux, though the light source is normally placed at the center of rotation of the photometer.

The angle intervals of measurement should be carefully chosen depending on the sharpness of the beam pattern of the LED. In reality LEDs are not point sources and they have non-uniform light distribution. The measurement distance (radius of rotation of photometer) should be set long enough (typically 300 mm or longer) so that errors in distance measurement (including error in position of photometer reference plane) (when Eq. 31 is used) or errors in LED alignment (when Eq. 30 is used) will be negligible. If a goniophotometer is also designed to measure Averaged LED Intensity, distance r can be chosen as those for Conditions A and B (100 mm or 316 mm). It should be noted that the angular resolution under these conditions is fairly low (due to the relatively large solid angle in which flux is measured).

The photometer head of the goniophotometer should meet the spectral responsivity requirement given in Section 3.3. The calibration of the photometer head (and spectral mismatch correction) should follow the recommendation for Averaged LED Intensity measurement (Section 5). The instrument also requires careful shielding of ambient light and reflected light within the instrument.

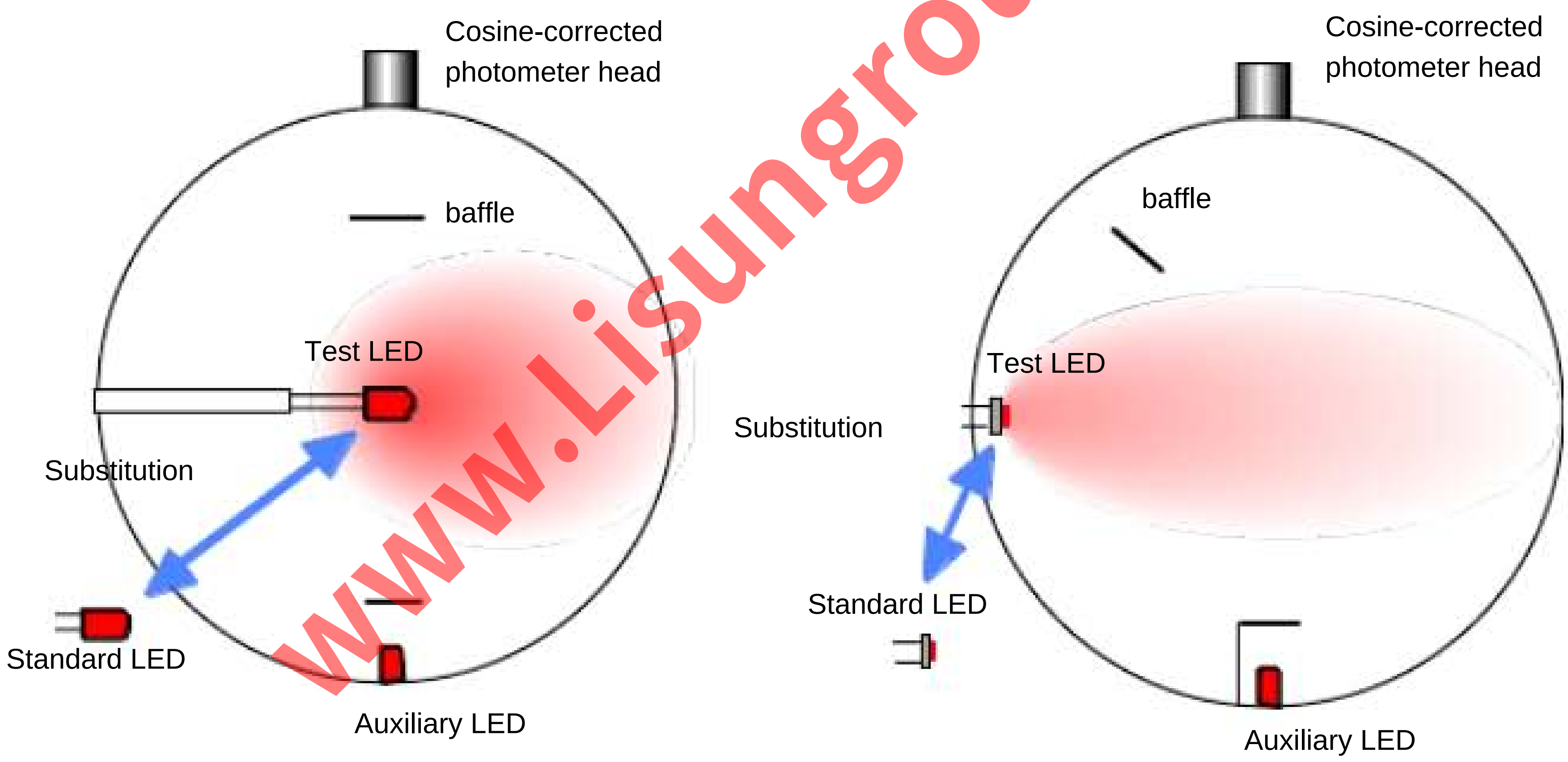
The range of angular scan must cover the entire solid angle to which the test LED emits light. Note that some LEDs have significant amount of backward emission even though they have a narrow beam pattern in forward direction. Such backward emission must be included for total luminous flux. Note that some goniophotometers can scan only the front hemisphere, in which case, any backward emission is ignored, leading to some error in total luminous flux.

6.2.2 Integrating sphere method

6.2.2.1 Total luminous flux measurement

A simpler way to measure the total luminous flux of a LED is to use an integrating sphere photometer. It is a device to perform spatial integration of flux optically, thus the total luminous flux can be measured with one fixed photometer head and measurement can be instant. An integrating sphere photometer is calibrated with a total luminous flux standard. A test light source is measured by comparison to a standard source having similar spatial and spectral distributions. Therefore, this method requires standard LEDs calibrated for total luminous flux. Compared with goniophotometer, measurement is fast, but it is liable to errors when the spatial intensity distributions of test LED and standard LED are dissimilar. This type of error is difficult to correct, so the error should be minimized by using well-designed sphere geometry and similar type of standard LEDs as the test LED.

Fig. 9 shows recommended sphere geometries for total luminous flux measurement of LEDs. Geometry (a) is recommended for all types of LEDs including those having a narrow beam profile or those having broad and backward emissions. This sphere geometry provides good spatial uniformity of responsivity over the sphere wall and is less sensitive to the differences in spatial intensity distribution of a LED. Under the old practice, a test LED was mounted on the sphere wall, which is generally not recommended for total flux measurement, due to the loss of backward emission. However geometry (b) is acceptable for LEDs having no backward emission. This geometry has an advantage that the test LED can be easily mounted on the sphere wall. Note that 5 mm epoxy type LEDs can have significant amount of backward emission and, therefore, should use geometry (a). High-power LEDs having a large heat sink and no backward emission can be measured with geometry (b) where only the LED head is inserted into the sphere and the large heat sink stays outside the sphere.



(a) (b)

Fig. 9. Recommended sphere geometries for LED total luminous flux.
(a) for all type of LEDs, (b) for LEDs with no backward emission

For either geometry, a minimum diameter of 20 cm is recommended for the sphere. Spheres of 20 cm to 50 cm diameter are commonly used for LED measurement. The larger the sphere, the less are errors for spatial nonuniformity (due to relatively smaller size of the baffle) and the sensitivity to self-absorption is less, but the signal is also less. High-power LEDs (e.g., > 1 W consumed electrical power) can be measured in a large integrating sphere (e.g., a 2 m sphere used for measurement of traditional lamps), in which the whole unit of the LED and heat sink can be mounted in the center of the sphere in geometry (a).

The sphere must be equipped with an auxiliary LED (CIE, 1989). Self-absorption measurement must be done unless the test and standard LEDs are of the same type and size (strict substitution), or unless the sphere size is so large that the self-absorption by a LED is negligible. Self-absorption may be different for different colours of LEDs, depending on the sphere characteristics. It is best to use an auxiliary LED having similar colour as the test LED if the differences are found to be significant.

An interior coating reflectance of 90% to 98% is preferred, depending on the sphere size and usage of the sphere. The higher the reflectance, the higher the signal obtained, and the less the errors associated with LED intensity distribution variations. However, with higher reflectance, the sphere responsivity is more sensitive to self-absorption effects, long-term drift and spectral power distribution differences. The size of the baffle should be as small as possible to shield the photometer from direct illumination from reference and test LEDs of the largest size measured.

In either geometry (a) or (b), it is important that the photometer head has a good cosine response and good $V(\lambda)$ match. The spectral responsivity requirements (Section 3.3) apply to the total sphere system (photometer head + the integrating sphere). See Section 6.2.3.3 for spectral mismatch correction methods. If spectral mismatch errors are not corrected, strict substitution (Section 6.2.3.1) should be performed, where test LEDs are compared with standard LEDs of the same type (nearly the same spectral distribution). Care must be taken, if LEDs are measured, which are able to generate fluorescence in the sphere. The error can be significant when the LED peak wavelength is in the wings of $V(\lambda)$ (e.g., deep blue LEDs) and fluorescence occurs in the green region where the value of $V(\lambda)$ is high, in which case, the effect of fluorescence is magnified in the measured luminous flux.

6.2.2.2 Partial LED Flux measurement

An integrating sphere photometer with a geometry depicted in Fig. 10 is recommended for Partial LED Flux measurement. The sphere has an opening, to which a precision aperture (50 mm diameter) is attached. The reference plane (the plane containing the knife edge) should be placed to be flush with the inner surface of the sphere (to allow full cone angle up to $x = 180°$). The area of the aperture must be measured with a stated uncertainty, since it directly affects the uncertainty of Partial LED Flux measurement. It is recommended that the size of the sphere be 20 cm or larger in diameter. A relatively high reflectance coating (95% to 98%) is preferred for higher signal and better spatial uniformity of sphere responsivity, considering a loss of effective reflectance of the sphere due to the large opening. The distance d (from the tip of the LED to the reference plane of the aperture) is determined for a given full cone angle $x°$, according to Eq. 29.

The baffle is placed about half way between the photometer head and the opening, and it should be smallest possible but large enough to shield the photometer (light sensitive area) from the entire opening of the aperture.

Self-absorption measurement will not be needed if the test LED is small and is placed far from the opening (e.g., $x = 60°$). However, self-absorption measurement may be needed if the test LED (including its mount) is large and/or it is placed close to or at the opening (e.g., $d = 0$, $x = 180°$).

The area around the test LED and the opening must be shielded from ambient light, and care should be taken so that only direct light from the test LED can enter the opening, without any stray light or reflections from other objects around the LED.

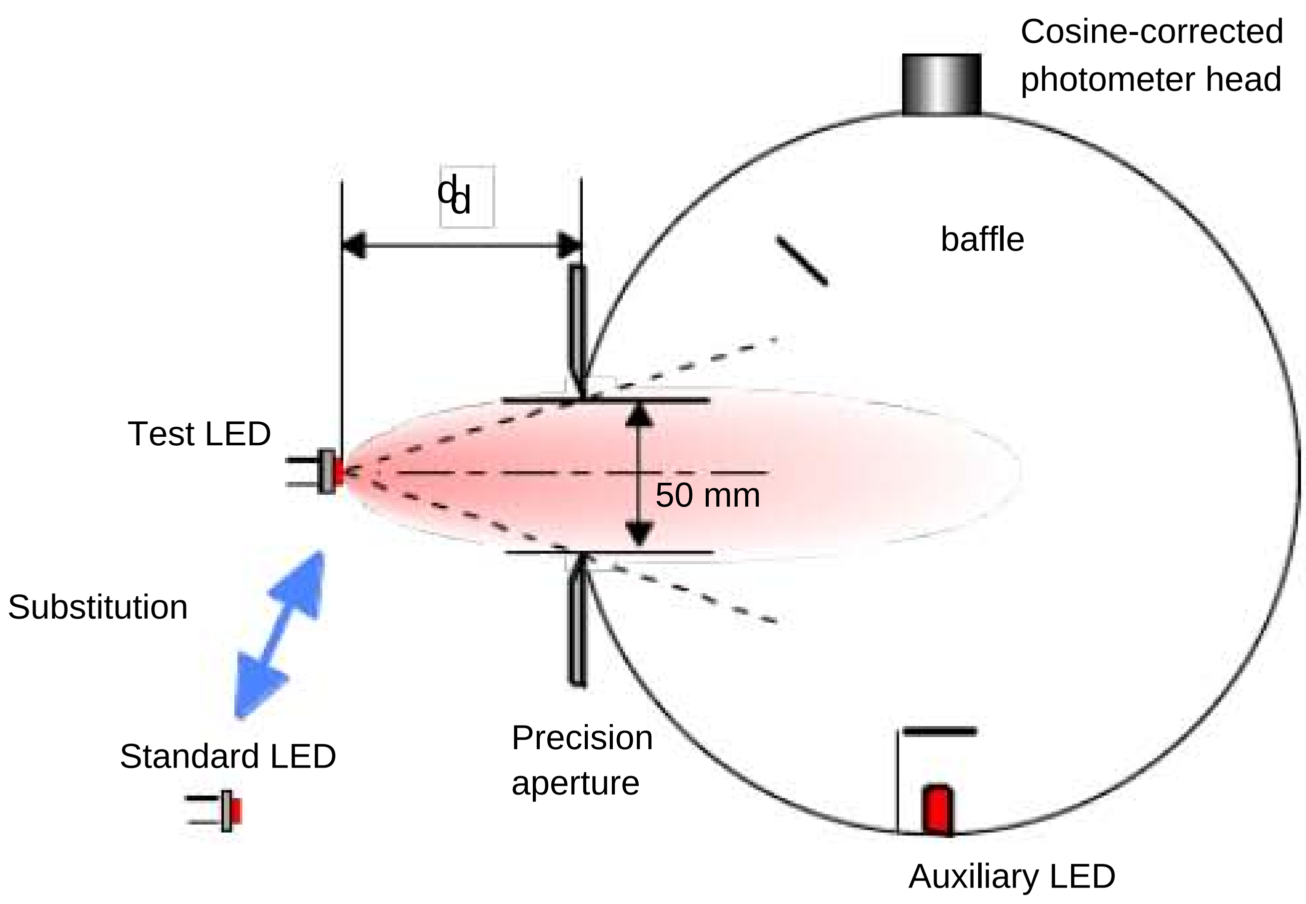


Fig. 10. Recommended sphere geometry for Partial LED Flux measurement.

The test LED is measured in substitution with a standard LED of the same type. Use of standard LEDs having similar spatial intensity distribution is recommended, as it will cancel out or reduce many sources of errors such as stray light, distance d, and aperture area A. See Section 6.2.3 for the use of standard LEDs and spectral mismatch corrections.

6.2.3 Methods for sphere calibration and correction

6.2.3.1 Strict substitution

When a test LED of a certain colour (spectral distribution) is to be measured, the integrating sphere photometer is calibrated against a standard LED of the same colour (or nearly the same spectral distribution). When measuring a test LED of another colour, the sphere photometer is calibrated against another standard LED of the same colour. With such a strict substitution method, there is no need for spectral mismatch correction, and the measurement is most simple. However, if many different types (colours) of test LED are measured, many different standard LEDs are needed. (Also, note that, even in such strict substitution, the spectral mismatch errors will not be zero due to small differences in spectral distribution between the reference and test LEDs, and such errors should be evaluated as an uncertainty component). Auxiliary lamps should be used to determine the self absorption for those cases where the test LEDs differ from the standard LED, as the colour and spatial distribution is immaterial: during operating the auxiliary LED the LED under test is switched off. Important is that the two are different, i.e. their absorption differs.

Substitution with fewer standards

In many cases, there are too many different types (colours) of LEDs to be measured and so many standard LEDs cannot be maintained. In such cases, the method described in Section 6.2.3.2 is recommended. In this case, it is recommended that calibrated standard LEDs (traceable to a NMI) of several colours are measured using the user’s set up and to compare the results to verify the agreement of the results within the stated uncertainties for each colour of LED.

6.2.3.2 Applying spectral mismatch correction

If the relative spectral responsivity of the integrating sphere photometer is known, the sphere photometer is calibrated with standard LEDs of a certain colour (green, white, etc.), then the test LEDs of whatever colour are measured with spectral mismatch correction applied. The relative spectral distribution of the test LED must be measured if not known. The spectral mismatch correction factor F is calculated by Eq. 24, with $s_{\mathrm{rel}}(\lambda)$ replaced by

$$s_{\mathrm{rel}}(O) \quad s_{\mathrm{ph,\,rel}}(O)\ \ T_{\mathrm{rel}}(O) \qquad (32)$$

where $s_{\mathrm{ph,\,rel}}(O)$ is the relative spectral responsivity of the photometer head, and $T_{\mathrm{rel}}(O)$ the relative spectral throughput of the integrating sphere.

P

Measurement of relative spectral throughput

The relative spectral throughput $T_{\mathrm{rel}}(O)$ of an integrating sphere can be measured using the following methods:

1) For total flux measurement in integrating spheres, first, measure the spectral distribution of a reference tungsten lamp outside the sphere, with a spectroradiometer. Measure in several different directions to check that the lamp has spatially uniform spectral distribution. The spectroradiometer must be in irradiance mode and must have good cosine-correction. Then, operate the lamp in the sphere and measure the spectral distribution at a detector port (with direct light shielded) using the same spectroradiometer. The ratio of the measured spectral distribution inside the sphere to the data outside the sphere will give the relative spectral throughput of the sphere.
2) Using integrating spheres for Partial LED Flux measurement, introduce a beam of light from a reference tungsten lamp. Measure the spectral distribution of the lamp with a spectroradiometer (irradiance mode) in the direction of the entrance opening. Then, measure the spectral distribution at the detector port of the integrating sphere using the same spectroradiometer. The spectroradiometer must have good cosine-correction. The ratio of the measured spectral distribution at the sphere detector port to the data measured directly of the lamp will give the relative spectral throughput of the sphere.

Note that this method is susceptible to errors if the sphere coating is inhomogeneous and/or has fluorescence. The tungsten lamp to be used in this measurement should be small enough relative to the size of the sphere (e.g., a miniature tungsten halogen lamp may be appropriate for a 20 cm sphere).

It is possible to determine the sphere throughput $T_{\mathrm{rel}}(O)$ via calculation also:

$$T_{\mathrm{rel}}(O) \quad k \; \frac{U(O)}{1 \quad U(O)} \qquad (33)$$

where $U(O)$ is the spectral reflectance of the sphere coating, and k is a normalizing constant. Note that the coating ages and its surface is being contaminated as the sphere is used. Thus, the results calculated from data of a coating sample may not be accurate for actual integrating spheres. The $U(O)$ must be measured in hemispherical illumination geometry. In addition, due to the denominator, 1- $U(O)$, measurement errors in $U(O)$ tend to be magnified.

6.2.3.3 Use of a spectroradiometer

A spectroradiometer may be used as the detector for the integrating sphere, and the total luminous flux can be measured without spectral mismatch correction if the spectroradiometer is configured to measure total spectral radiant flux of LEDs. (See Section 7.4.2.1.)

7. S ECTRAL MEASUREMENT

7.1 The concept of spectral distribution

7.1.1 Spectral concentration

For any given radiometric quantity X_e, the spectral concentration of that quantity is the differential of the quantity with respect to wavelength O and is given by

$$X_O(O) \quad \frac{d X_e(O)}{d O} \qquad (34)$$

$X_O(O)$ is also known as the spectral distribution of that quantity. This function is a wavelength dependent function. The unit of the spectroradiometric quantity is that of the radiometric quantity divided by the unit of length, the metre. For example, the dimension of the unit of radiant intensity I_e is W · sr^{-1} and the dimension of the unit of spectral radiant intensity $I_{el}(O)$ (often written simply as I_O are W · sr^{-1} m^{-1}, usually reported as mW · sr^{-1} nm^{-1} or PW · sr^{-1} nm^{-1}, to provide a more convenient range of numbers for the values reported.

Note: Spectral concentration can also be expressed as a function of frequency or wave number, but the wavelength function is the one normally chosen to characterise the spectral distribution of LEDs. The shape of the spectral distribution will change slightly depending on the bandwidth of the spectroradiometer used. The bandwidth in full width at half maximum (FWHM) used at the measurement and any correction applied for zero-bandwidth should be reported when spectral distribution data are presented. The bandwidth should not be larger than 5 nm.

7.1.2 Normalisation factor and relative spectral distribution

LEDs emit optical radiation over a limited wavelength range given by O_1 d O d O_2. It is often helpful to normalise the spectral distribution function and divide it into two parts, an absolute normalisation factor X_{e0} taken at wavelength $O = O_0$ with the unit of the spectral concentration

$$X_{e0} \quad X_O(O \quad O_0) \quad (35)$$

and a relative function $S_X(O)$

$$S_x(O) \quad \frac{X_O(O)}{X_{e0}} \quad (36)$$

called relative spectral distribution, which comes with a unit of unity, but is still associated with the geometric measurement conditions as defined for the original quantity. From Eq. 36, the (absolute) spectral distribution can be written as

$$X_O(O) \quad X_{e0} \quad S_x(O) \quad (37)$$

7.2 Quantities related to spectral distribution

Fig. 11 illustrates the locations of the characteristic wavelengths described in the following subsections. The shape is typical of that of all LEDs, with zero values outside the wavelength range O_1 d O d O_2 and one significant maximum in between. Fig 2 shows typical spectral distributions for a representative selection of the various LEDs currently available commercially.

7.2.1 Peak wavelength

The wavelength at the maximum of the spectral distribution is known as the peak wavelength O_p The (absolute) spectral distribution is usually normalised at this wavelength rather than at an arbitrary wavelength, to give a relative spectral distribution with a maximum value of unity.

7.2.2 Spectral bandwidth at half intensity levels

The spectral bandwidth at half intensity level $' O_{0,5}$ is calculated from the two wavelengths $O_{0,5}$ and $O'_{0,5}$ on either side of O_p, where peak intensity drops to 50 %:

$$' O_{0,5} = O'_{0,5} - O_{0,5} \quad (38)$$

Note: In some applications also the $' O_{0,1}$ value is used (see Fig. 11), the bandwidth between those two wavelengths where the intensity drops to one tenth of the maximum.

7.2.3 Centre wavelength of half intensity bandwidth

The wavelength mid-way between the two limiting wavelengths $O_{0,5}$ and $O'_{0,5}$ of the spectral bandwidth at the 50 % level is specified as $O_{0,5\,m}$. It is calculated from

$$\lambda_{0,5m} \quad \frac{1}{2} \quad \lambda'_{0,5} \quad \lambda''_{0,5} \qquad (39)$$

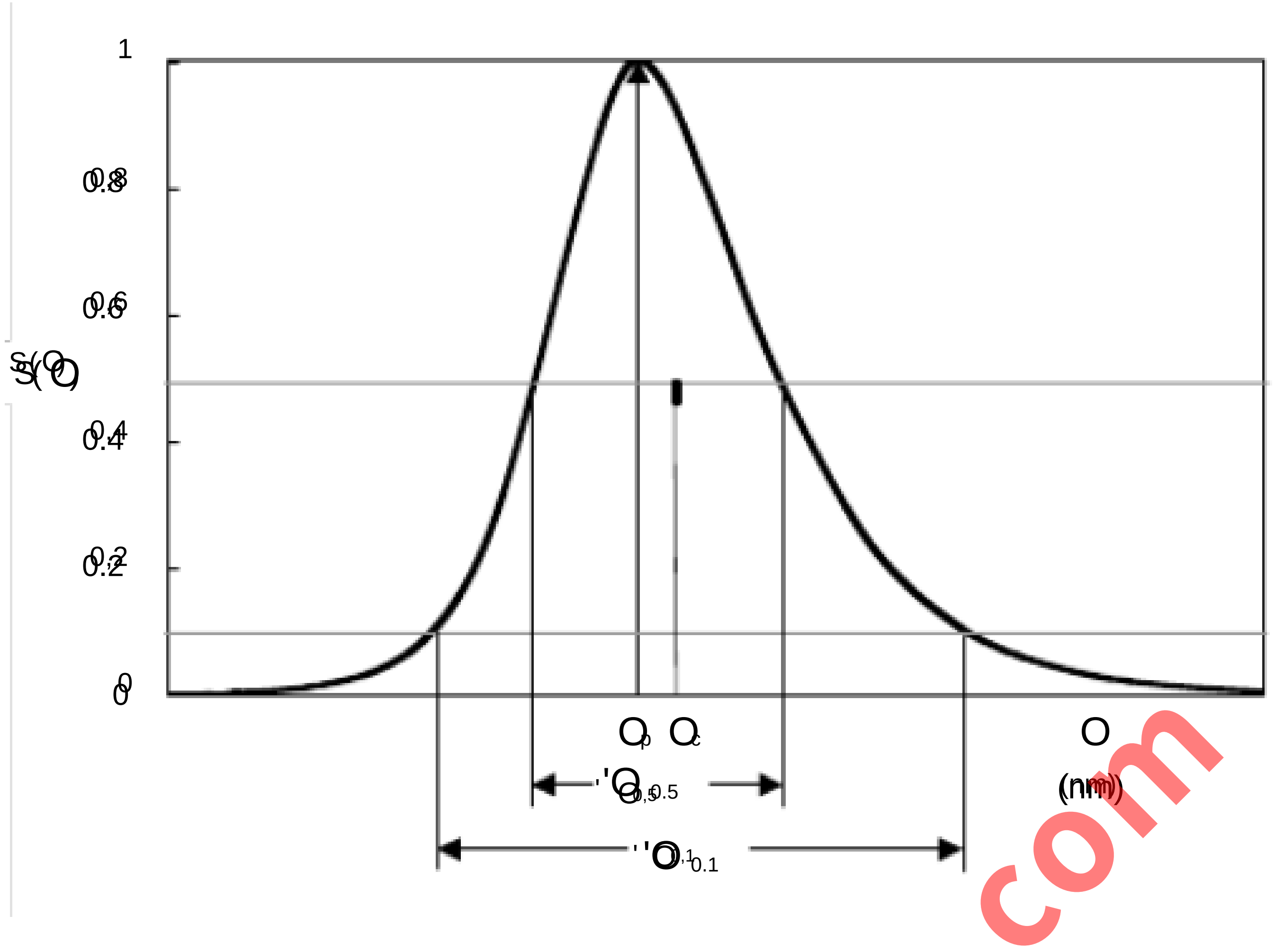


Fig. 11. Typical relative spectral distribution of a LED showing the location of the characteristic wavelengths and wavelength intervals.

7.2.4 Centroid wavelength

The centroid wavelength λ_c of the spectral distribution, which is calculated as the "centre of gravity wavelength" according to the equation

$$\lambda_c \quad \int_{\lambda_1}^{\lambda_2} \lambda \, S_X(\lambda)\, d\lambda \Big/ \int_{\lambda_1}^{\lambda_2} S_X(\lambda)\, d\lambda \qquad (40)$$

It should be noted that unlike the other characterizing wavelengths defined here, the centroid wavelength, when calculated for the types of spectral distribution typical of many LEDs, may be strongly affected by the very small values of the relative spectral distribution at the diminishing tails of the curve, where measurement uncertainty is increased due to the influence of stray radiation, noise effects or amplifier offsets.

7.3 Colorimetric quantities determined from the spectral distribution

The colour of the light emitted by a LED may be specified in terms of its chromaticity coordinates and these are best obtained by calculation from the spectral power distribution. Two alternative quantities also sometimes used to characterize the colour of single-colour LEDs are dominant wavelength and purity, they can not be used for white LEDs. They can be used to provide a quantitative measure of the hue and saturation of the colour and can be calculated from the chromaticity co-ordinates as explained below. Fig. 12 illustrates the concepts of dominant wavelength and excitation purity. For further information on colorimetric concepts and calculations, see reference (CIE, 2004). White LEDs are characterized by their correlated colour temperature.

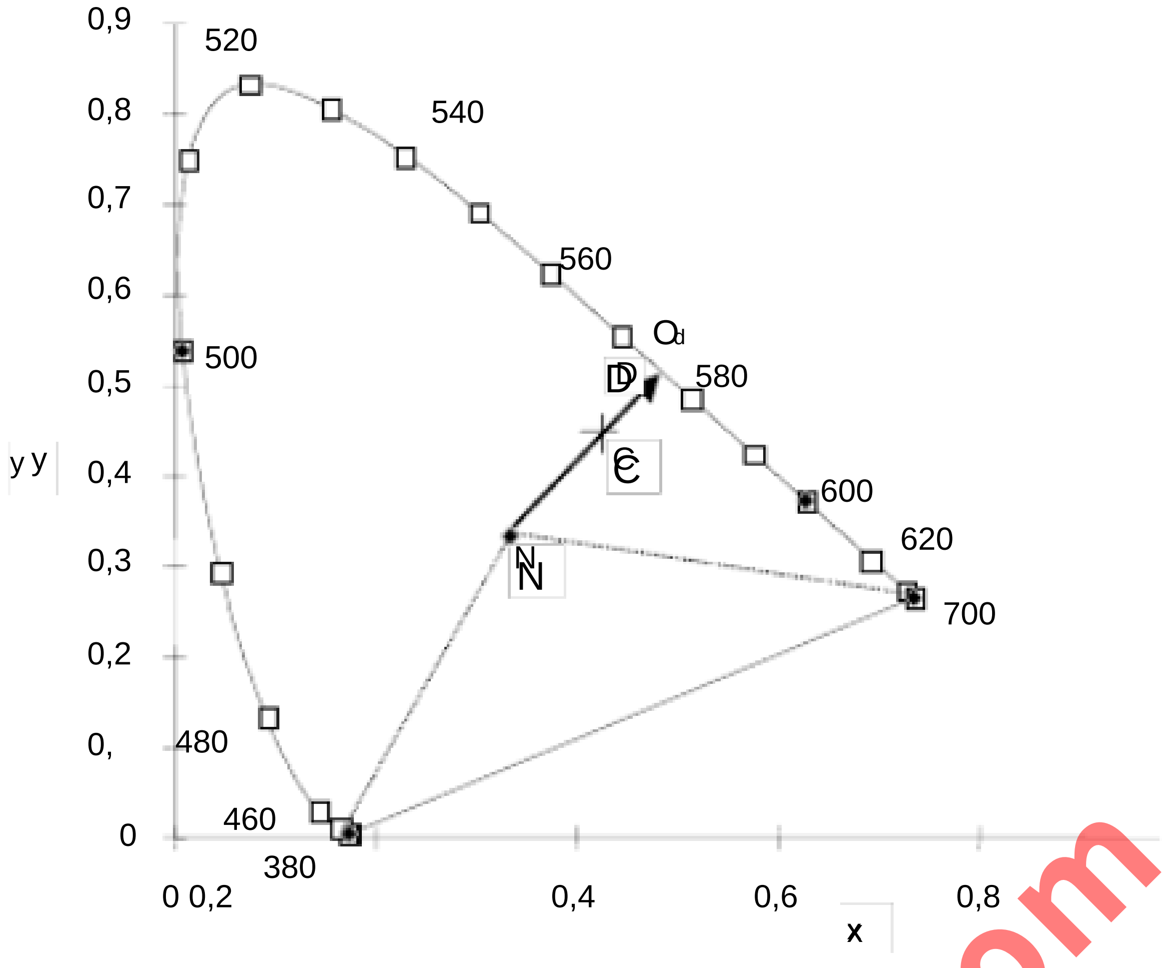


Fig. 12. CIE 1931 chromaticity diagram showing distances and intersections for dominant wavelength and excitation purity calculations.

7.3.1 Dominant wavelength

The dominant wavelength Q_d of a colour stimulus is defined as follows:

Wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the specified achromatic stimulus, matches the colour stimulus considered.

For characterising LEDs, the reference achromatic stimulus should be an equi-energy spectrum, a stimulus whose spectral concentration of power as a function of wavelength is constant (sometimes known as illuminant E) and which has the chromaticity coordinates $x_E = 0{,}3333$, $y_E = 0{,}3333$.

7.3.2 Purity

For characterising purity of LED emission, the term excitation purity p_e is used. This is defined as follows:

quantity defined by the ratio NC/ND of two collinear distances on the chromaticity diagram of the CIE 1931 standard colorimetric system (the 1964 diagram gives slightly different values for lower saturation), the first distance being that between the point C representing the colour stimulus considered and the point N representing the specified achromatic stimulus; the second distance is that between the point N and the point D on the spectrum locus at the dominant wavelength of the colour stimulus considered

The definition leads to the following expressions:

$$p_e = \frac{y - y_n}{y_d - y_n} \quad \text{or} \quad p_e = \frac{x - x_n}{x_d - x_n} \qquad (41)$$

where (x, y), (x_n, y_n), (x_d, y_d) are the x, y chromaticity co-ordinates of the points C, N, and D, respectively.

Note: The value of excitation purity is unity if the chromaticity under test is located on the spectrum locus. The value is zero if the chromaticity under test has the same chromaticity co-ordinates as the specified achromatic stimulus.

7.4 Spectral measurement of LEDs

For general guidance on spectral measurement of light sources, refer to CIE 63 (CIE, 1984b). This section describes requirements of spectroradiometers specifically for LEDs. The spectral distribution and colour of LEDs can be measured with a spectroradiometer in four different modes: 1) irradiance mode, 2) total flux mode, 3) partial flux mode and 4) radiance mode. In irradiance mode, the spectral distribution and colour of a test LED are measured in one direction, whereas, in total flux mode, they are measured as an average for all directions. The partial flux mode is in between. The radiance mode measures the spectral radiance of the LED surface, using an imaging optic with the photometer. The irradiance mode can be used for most typical single-colour LEDs, which have spatially uniform distribution of colour. White LEDs tend to have non-uniform spatial distribution of colour, in which case the total flux mode or partial flux mode is recommended to measure the average colour.

7.4.1 Irradiance mode

The radiation from a test LED propagating in one direction within a given small solid angle is measured. Fig. 13 shows some examples of the input geometry for the irradiance mode arrangement. The spectro-radiometer is calibrated with a spectral irradiance standard lamp (normally, a quartz-halogen tungsten lamp). It is important that the radiation from the standard lamp and test LED is introduced to the spectroradiometer (entrance slit or fiber input) exactly in the same spatial and angular distribution, and with the same polarization condition. (Note that tungsten lamps are slightly polarized.) To achieve this, a small integrating sphere (e.g., 50 mm diameter) or a diffuser is normally needed for the input optics. Such input optics should provide spatially and angularly uniform illumination for the dispersive element, independent of the source size and its intensity distribution. Therefore, the LED and standard lamp can be different in size, and can be placed at different positions for similar signal level.

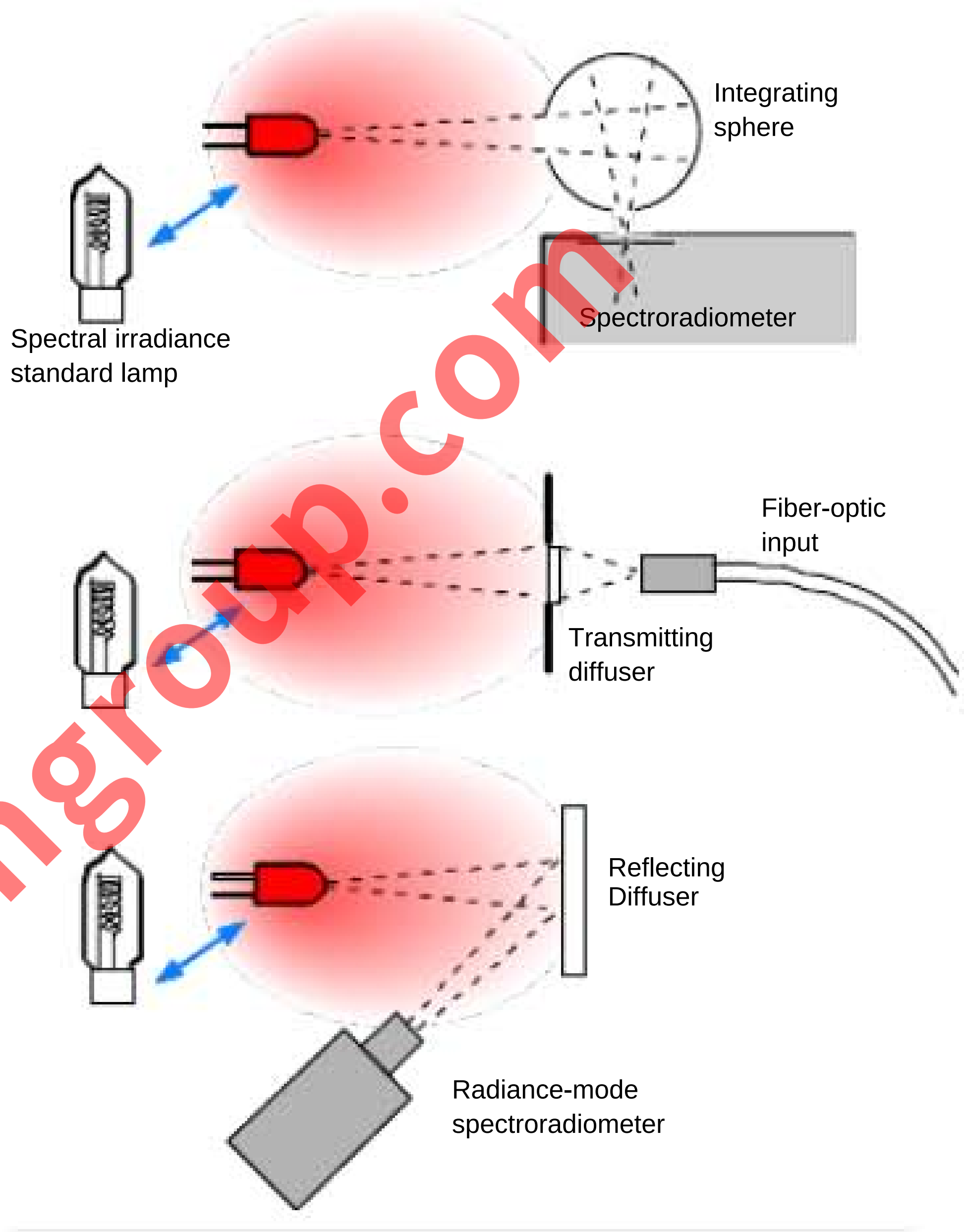


Fig. 13 . Examples of input geometry for irradiance mode spectroradiometer.

Among the examples given in Fig. 13, the use of integrating sphere (not limited to the geometry shown in the figure) is most recommended for any spectroradiometer, though the sensitivity is the lowest. Reflecting diffusers may be used when higher sensitivity is required. When using a diffuser (especially when combined with fiber optics), caution should be paid to the spatial nonuniformity of irradiance responsivity over the diffuser surface. It may not be suitable for Averaged LED Intensity measurement if the spatial uniformity of responsivity is poor (see Section 3.2). A diffuser exhibiting poor spatial uniformity would work only if it is illuminated uniformly by the source being measured. Use of a fiber-optic input without diffuser should be avoided even for simple colour measurement, since the measurement would be sensitive to incident angle, and thus, the size of the source. For colour measurement of typical LEDs, the collection angle should be chosen to be 10 ° (+/- 5 °) or less. If enough signal is obtained, use of CIE Condition B or CIE Condition A geometry (see Section 4.3 Averaged LED Intensity) is recommended. For Averaged LED Intensity measurement, the size of the aperture should be chosen to satisfy the CIE Condition A or CIE Condition B geometry.

7.4.1.1 Measurement of Averaged LED Intensity

If the spectroradiometer with the irradiance mode input optics is arranged in CIE-B or CIE-A geometry, and is calibrated for absolute spectral irradiance, a test LED can be measured for absolute spectral irradiance $E(\lambda)$ [Wm^{-2} nm^{-1}]. From this and the distance d [m] of the LED position (100 mm or 316 mm), the Averaged LED Intensity I_{LED} can be obtained by

$$I_{LED} = d^2 K_m \int E(\lambda) V(\lambda)\, d\lambda; \quad (K_m = 683\ \text{lm/W}) \qquad (42)$$

When this method is adopted, the results should be checked by measuring standard LEDs of different colours. If the agreement is within the stated uncertainty of measurement, the results are valid with no correction. Disagreement by more than combined uncertainties at coverage factor $k = 2$ may indicate incomplete uncertainty budgets and should be investigated (ISO, 1993). If desired, the spectral calibration can be taken as only relative, and the absolute scale should be given from the standard LEDs.

7.4.2 Total flux mode

The (spatially) averaged spectral distribution of the test LED is measured. This mode is commonly used to measure the spectral distribution and colour of discharge lamps for general illumination, since they tend to have spatially non uniform distribution of colour. This mode, if calibrated in absolute units, will measure total spectral radiant flux (unit: W/nm) of the source. An example of the total flux mode geometry is shown in Fig. 14. The sphere is the same geometry as one for total luminous flux given in Fig. 9(a) with its photometer replaced by a spectroradiometer. The standard LED and auxiliary LED are also replaced by a standard lamp and auxiliary lamp. The spectral flux is spatially integrated over the entire solid angle (4π sr). Such a system (spectroradiometer + sphere) is calibrated with a total spectral radiant flux standard lamp (normally, a tungsten lamp).

The self-absorption will be a function of wavelength, so, even if the measurement is for relative spectral distribution, a self-absorption correction should be applied.

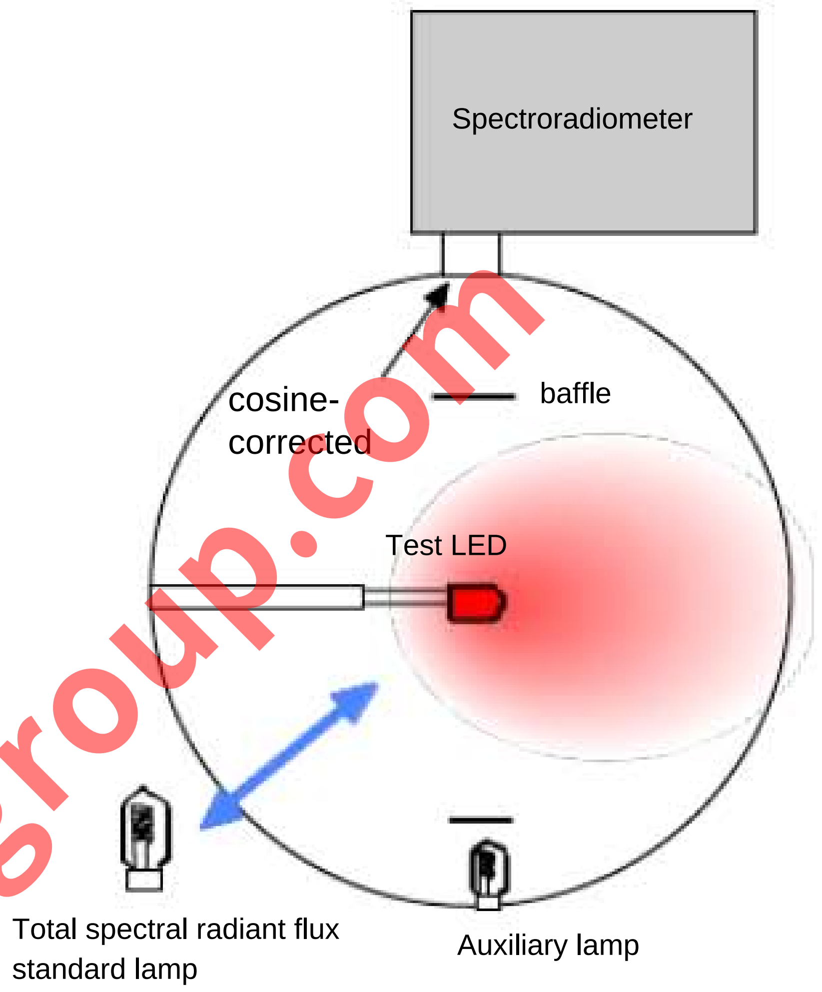


Fig. 14. An example of the geometry for total flux mode spectroradiometer.

7.4.2.1 Measurement of total luminous flux

If the spectroradiometer in total flux mode is calibrated for absolute total spectral radiant flux, a test LED can be measured for absolute total spectral radiant flux $\Phi(\lambda)$ [W/nm]. From this, the total luminous flux Φ_v [lm] can be obtained by

$$\Phi_v = K_m \int \Phi(\lambda) V(\lambda)\, d\lambda \quad (K_m = 683\ \text{lm/W}) \qquad (43)$$

For such absolute measurement, the self-absorption correction (spectrally) is critical, since the size and shape of the standard lamp is very different from LEDs.

When this method is adopted, the results should be verified by measuring standard LEDs of different colours. If the agreement is within the stated uncertainty of measurement, the results are valid with no correction. Disagreement by more than combined uncertainties at $k = 2$ may indicate incomplete uncertainty budgets and should be investigated. If desired, the spectral calibration can be taken as only relative, and the absolute scale can be given from the standard LEDs. In general, the calibration path that leads to lowest measurement uncertainties should be adopted as the primary calibration procedure.

7.4.3 Partial flux mode

A spectroradiometer can be used also for partial flux mode. Fig. 15 shows an example of such geometry. This is the same sphere geometry as the one for Partial LED Flux (Fig. 10), with the photometer head replaced by the spectroradiometer, and the auxiliary LED replaced by the auxiliary lamp. The same recommendations on the construction of the sphere given in Section 6.2.2.2 apply, except that the requirement for the aperture is not critical if only relative spectral distribution is measured with this arrangement.

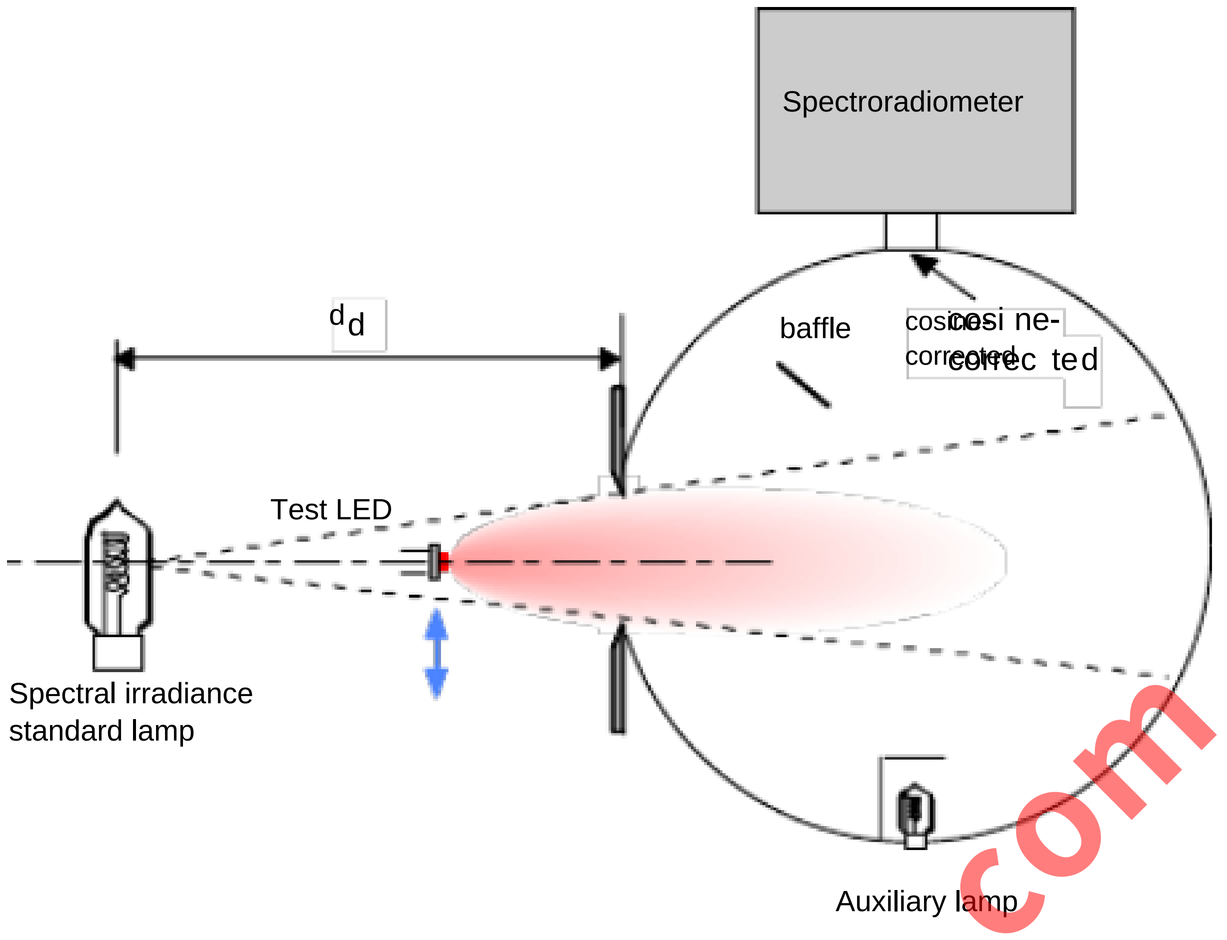


Fig. 15. An example of the geometry for partial flux mode spectroradiometer.

The integrating sphere system with the spectroradiometer can be calibrated with a spectral irradiance standard lamp. The standard lamp is placed outside the sphere at the distance d from the aperture, at the same distance where the spectral irradiance is calibrated. (For example, a 1000 W FEL type lamp is normally calibrated at 50 cm to 70 cm distance.)

If the area of the aperture A [m^2] is known, the spectral radiant flux $\Phi_{\mathrm{ext}}(\lambda)$ [W/nm] introduced into the sphere is calculated from the spectral irradiance $E(\lambda)$ [Wm^{-2}nm^{-1}] by

$$\Phi_{\mathrm{ext}}(\lambda) = k_a \cdot A \cdot E(\lambda) \quad (44)$$

where k_a is the correction factor for average irradiance over the sphere opening with respect to the small area over which the irradiance from the lamp is calibrated. Spectral irradiance standard lamps are normally calibrated for much smaller collection angle (so, much smaller area). k_a can be obtained by spatially mapping the irradiance distribution of the lamp over the area corresponding to the sphere opening. For only relative spectral measurement (e.g., only for colour), k_a and A can be practically ignored.

7.4.3.1 Measurement of Partial LED Flux

If the spectroradiometer in partial flux mode is calibrated against the absolute spectral radiant flux $\Phi_{\mathrm{ext}}(\lambda)$, a test LED can be measured for partial spectral radiant flux $\Phi_{\mathrm{e,\,LED,\,x}}(\lambda)$ [W/nm], from which Partial LED Flux $\Phi_{\mathrm{LED,\,x}}$ [lm] is obtained by

$$\Phi_{\mathrm{LED,\,x}} = K_m \int \Phi_{\mathrm{e,LED.x}}(\lambda) V(\lambda)\, d\lambda; \quad (K_m = 683 \text{ lm/W}) \qquad (45)$$

If the test LED has a mount which is not neglectable and/or placed closer to the opening, the self-absorption measurement using an auxiliary lamp should be performed and a correction applied. In some cases self-absorption can be ignored if the test LED and mount is small and placed far from the opening. When this method is adopted, the results should be verified by measuring standard LEDs of different colours. If the agreement is within the stated uncertainty of measurement, the results are valid with no correction. Disagreement by more than combined uncertainties at $k = 2$ may indicate incomplete uncertainty budgets and should be investigated. If desired, the spectral calibration can be taken as only relative, and the absolute scale can be given from the standard LEDs. In general, the calibration path that leads to lowest measurement uncertainties should be adopted as the primary calibration procedure.

7.4.4 Consideration for bandwidth and scanning interval

When a spectral measurement is made, errors will occur due to the bandwidth of the spectroradiometer as well as the scanning interval (CIE, 1984b). These errors are more prominent with LEDs, which have narrow-band emissions. The bandwidth of a spectroradiometer has an effect of broadening the measured spectra, which will result in errors in colour quantities obtained. For example, a 10 nm bandwidth (FWHM, triangular shape) would cause an error of ~0,003 in $u'v'$ chromaticity for a red and blue LED, and ~0,002 for green LED. Such errors due to the bandwidth of a spectrometer are proportional to the square of the increase of bandwidth. With a 5 nm bandwidth, the errors in $u'v'$ chromaticity will be less than 0,001 for LEDs of any colour. For practical LED measurements, a bandwidth of 5 nm or less is acceptable and recommended. Bandwidths of larger than 5 nm are generally not recommended for LED measurements, but might be used with appropriate bandpass correction (see Section 7.4.4.1).

The scanning interval also causes errors though much smaller than the errors due to bandpass. For example, the error due to a 10 nm data interval (with 0 nm bandwidth) for typical LEDs are less than 0,0005 in $u'v'$. The errors for a 5 nm data interval are negligible (<0,00001 in u',v'). Though it is a common practice to match the bandwidth and scanning interval for colorimetry of discharge lamps, the mismatch hardly affects the errors in chromaticity of LEDs. Rather, smaller bandpass is important for a given scanning interval. The scanning interval, however, is important to obtain such quantities as peak wavelength and spectral width (spectral shape) of LEDs. If only chromaticity is to be measured, a scanning interval of 5 nm or less is well acceptable. For measuring peak wavelength and spectral width, an interval of 2,5 nm or less is recommended. Over-sampling (e.g., 2,5 nm interval for 5 nm bandwidth) is advantageous for colour measurement, since, for a given bandwidth, it will reduce colorimetric errors due to random noise as well as due to sampling errors

While the bandwidth and scanning interval are fixed and not changeable in many commercial instruments (e.g., diode-array type), these parameters are selectable in most mechanical-scanning type instruments. Smaller bandpass is desirable for less errors but the signal will be less. Smaller interval is desirable but measurement takes more time, so these parameters are set depending on the intensity of LEDs and the uncertainty required.

7.4.4.1 Bandpass correction

For highest accuracy applications, or if the bandwidth is more than 5 nm (but no more than 10 nm), it is recommended that a bandpass correction be applied. The Stearns and Stearns method (S-S method) (Stearns and Stearns, 1988) is very simple to apply, and very effective. To apply the S-S method, it is required that the bandpass must be a triangular function, and the bandwidth $\Delta\lambda_{0,5}$ and scanning interval $\Delta\lambda_{step}$ must be matched ($\Delta\lambda_{0,5} = n \Delta\lambda_{step}$; n: integer). For example, for 5 nm bandwidth and 5 nm scanning interval, the corrected spectral value S_i' is recalculated from the original values at neighbouring 5 points by

$$S_i' = (S_{i-2} - 12 S_{i-1} + 120 S_i - 12 S_{i+1} + S_{i+2}) / 98 \qquad (46)$$

where the values of S_{i-2}, S_{i-1}, S_i, S_{i+1} and S_{i+2} correspond to, for example, the values at 440 nm, 445 nm, 450 nm, 455 nm, and 460 nm. The bandpass errors will be mostly removed if the bandpass requirements are physically satisfied accurately. If the bandwidth is 5 nm and the scanning interval is 2,5 nm, the original values of every other 5 points around the wavelength are used for the calculation.

Note: In real spectroradiometers, their bandwidth is not perfectly triangular shape and not perfectly constant over the visible region. Therefore, the results of correction will not be as perfect as predicted by simulation. Some residual errors should be taken into account even after the correction. Improved methods that can apply to non-triangular bandpass and do not require that bandwidth and scanning interval to be matched, have also become available (Ohno, to be published; Gardner, to be published).

7.4.5 Other uncertainty components

Other than bandwidth and scanning interval effects, there are many other uncertainty components in spectral measurements of light sources, such as wavelength error, noise, stray light, fluorescence, linearity of detector, uncertainty in spectral standards, etc. Noise (dynamic range) and stray light are particularly critical for LED measurements because typical LEDs have emission only in a part of the visible region. If stray light signal falls on the region where the LED has no emission, the effect in colour will be large. Some commercial instruments do not allow negative values, of spectral distribution (due to noise) which is not acceptable for LED colour measurement. In the region where a LED has no emission, if negative noise is all truncated to zero, the remaining positive noise would result in similar effects to stray light and can cause significant error in chromaticity. In the case of UV-LEDs, the measurement uncertainty due to fluorescence is becoming more significant.

Uncertainties in spectral values or in wavelength uncertainties will propagate into the uncertainties in colour quantities (such as chromaticity coordinates, correlated colour temperature, dominant wavelength) by statistical methods (ISO, 1993). Practical methods to calculate colour uncertainties of light sources (including LEDs) from the uncertainty of spectral values or uncertainty in wavelength are available (Ohno, 2001; Gardner, 2000).

Other details of uncertainties in spectral measurements are common with measurement of general light sources, and are beyond the scope of this report. These are covered in Ref. (CIE, 1984b).

8. REFERENCES

CIE, 1983. CIE 18.2-1983. *The Basis of Physical Photometry*, 1983.

CIE, 1984a. CIE 64-1984. *Determination of the Spectral Responsivity of Optical Radiation Detectors*, 1984.

CIE, 1984b. CIE 63-1984. *The Spectroradiometric Measurement of Light Sources*, 1984.

CIE, 1987a. CIE 17.4-1987. *International Lighting Vocabulary*, 1987.

CIE, 1987b. CIE 69-1987. *Methods of Characterising Illuminance Meters and Luminance Meters*, 1987.

CIE, 1987c. CIE 70-1987. *The Measurement of Absolute Luminous Intensity Distributions*, 1987.

CIE, 1989. CIE 84-1989. *Measurement of Luminous Flux*, 1989.

CIE, 2004. CIE 15:2004. *Colorimetry*, 2004.

CIE, to be published a. *Photometry Using V(O)-corrected Detectors as Reference and Transfer Standards*. A report from TC 2-37. To be published.

CIE, to be published b. *Determination of Measurement Uncertainties in Photometry*. A report from TC 2-43. To be published.

CSUTI, P., KRANICZ, B., and SCHANDA, J., to be published. Description of a partial f_1' error index recommended for LED photometry. To be published in: *Svetoteckhnika/Light & Engineering*.

GARDNER, J.L., 2000. Uncertainty estimation in colour measurement. *Color Res. & Appl.*, **25**, 349-355, 2000.

GARDNER, J.L., to be published. Bandwidth Correction for LED Chromaticity. *Color Res. & Appl.*, to be published.

GOURE, J.P. and MASSOT, J.N., 1982. Commentaires sur la détermination de la loi de luminance L(P,q) d'une source semi-conductrice en champ proche. *Optical and Quantum Electronics*, **14**, 5, 1982.

GRUM, F. and BARTELSON, C.J., 1980. *Optical radiation measurements, Vol. 2, Color Measurements*. Academic Press, New York, 1980.

ISO, 1993. *Guide to the Expression of Uncertainty in Measurement*, 1993.

OHNO, Y., 2001. A Numerical Method for Color Uncertainty. In *Proc. CIE Expert Symposium 2001 on Uncertainty Evaluation*, CIE x020-2001, 8-11, 2001.

OHNO, Y., to be published. A Flexible Bandpass Correction Method for Spectrometers. In *Proc., AIC ’05*, Granada, Spain, 9-13 May, 2005, to be published.

STEARNS, E.I., and STEARNS, R.E., 1988. An Example of a Method for Correcting Radiance Data for Bandpass Error. *Color Res. & Appl*. 13, 257-259, 1988.

WYSZECKI, G. and STILES, W.S., 1982. *Color Science, 2nd ed.* John Wiley & Sons, New York, 1982.