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CIE

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

TECHNICAL REPORT

MEASUREMENT of LEDs

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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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LA COMMISSION INTERNATIONALE DE L'ÉCLAIRAGE

La Commission Internationale de l'Éclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant 40 pays plus un territoire géographique, et de 12 membres individuels.

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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.

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Die Ziele der CIE sind :

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 Ländern zu sein.
2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, 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 Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 2-34 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.

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Contents:

Summary

Measurement of LEDs

There are significant differences between LEDs and other light sources which made it necessary for the CIE to introduce a new quantity for their characterization with precisely defined measurement conditions. The new quantity has been given the name "Averaged LED Intensity". It can be used to provide meaningful and reproducible data for many of the different types of LEDs now on the market.

The evaluation of the luminous flux must be carried out with caution, utilizing specially constructed integrating spheres. Best results will be obtained if luminous intensity and luminous flux are measured using a comparison method and every laboratory should have available a standard, temperature controlled and calibrated LED with the same spectral and spatial power distribution as the test LEDs to allow measurements to be made on this basis.

Spectroradiometric measurements can be performed using the same technique as for other light sources with careful alignment along the optical axis.

Résumé

Mesure des diodes électroluminescentes (DEL)

Les différences significatives existant entre les diodes électroluminescentes et les autres sources de rayonnement rendent nécessaire la définition d'une nouvelle grandeur pour les caractériser : "l'intensité moyenne de la diode électroluminescente" mesurée dans des conditions parfaitement définies. Cette grandeur permet d'obtenir des valeurs numériques reproductibles et significatives pour la plupart des diodes électroluminescentes disponibles sur le marché.

La détermination du flux lumineux demande une attention particulière et nécessite l'utilisation d'une sphère d'intégration réalisée spécialement pour ces composants. La mesure de l'intensité lumineuse et du flux lumineux par méthode de comparaison permet d'obtenir les meilleurs résultats; dans chaque laboratoire, une diode électroluminescente étalon, stabilisée en température et étalonnée, ayant les mêmes distributions spectrale et spatiale que les diodes électroluminescentes à mesurer devrait être disponible pour les mesures par comparaison.

Les mesures spectro-radiométriques peuvent être effectuées selon les mêmes techniques que celles utilisées pour les sources classiques mais en prenant soin d'aligner correctement la diode électroluminescente selon l'axe optique du système de mesure.

Zusammenfassung

LED Messungen

Wesentliche Unterschiede in den Abstrahleigenschaften von LEDs zu anderen Lichtquellen haben die Einführung einer neuen Einheit für deren Charakterisierung erforderlich gemacht: Der "LED-Intensitätsmittelwert" (engl.: Averaged LED Intensity) mit genau festgelegten Meßbedingungen. Diese Größe kann bei einer großen Vielzahl von am Markt befindlichen LEDs angewendet werden um aussagefähige und reproduzierbare Meßwerte zu erhalten.

Die Bestimmung des Lichtstromes muß sehr sorgfältig durchgeführt werden, wobei hierfür speziell für LEDs konstruierte Ulbricht-Kugeln verwendet werden sollen.

Für die Messung der Lichtstärke und des Lichtstromes können die besten Ergebnisse nach der Vergleichsmethode erzielt werden. Deshalb sollte in jedem Meßlabor eine kalibrierte und temperaturstabilisierte Standard-LED verfügbar sein. Diese sollte ferner eine gleiche Verteilung der spektralen und räumlichen Leistung wie die Test-LEDs aufweisen, um so Vergleichsmessungen zu erlauben.

Spektralradiometrische Messungen können nach den gleichen Methoden wie für andere Lichtquellen erfolgen. Hierbei ist eine sorgfältige Ausrichtung der optischen Achse wichtig.

Measurement of LEDs

1. Introduction

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, conventional LEDs.

Laser diodes, like other types of lasers, emit radiation in a coherent, spatially narrow beam with quasi-monochromatic spectral characteristics. They require a completely different measurement technique to ordinary LEDs and are not dealt with in this report.

1.2 Terminology

Strictly speaking, the term LED should only be applied to those diodes which 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 are widely referred to as LEDs and, since most of the measurement techniques and characterizations are identical for the two groups, the term LED is used throughout this report to cover both types. The sections relating to photometric and colorimetric quantities clearly apply only to those devices emitting visible light, but if there is any uncertainty this will be made clear at the appropriate point.

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 the wide range of different types of LEDs is combined with the multi-dimensional properties of the emitted optical radiation which 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 with which the spectral and spatial distributions can be measured and, in order to increase the signal at the detector, it has become common practice to measure an averaged value of a spatial quantity such as directional intensity. Until the publication of the present report, however, no agreed procedure had been put forward to standardize the conditions for this averaging process.

Definitions of the various radiometric, photometric and colorimetric quantities used to characterize 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 which can be used to specify the properties of LEDs.

Although they are frequently used in combination with physical detectors, LEDs that emit visible light are also widely used in applications where information has to be conveyed to the human eye. This report, therefore, deals with the characterization 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 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 apparent 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, 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 emitting radiation at shorter wavelengths, and that by this means the document will be kept relevant and up to date.

1.4 Categories of LED measurement

LED measurements can be divided into two categories:

A. *Laboratory measurements*

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

B. *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.

Where routine measurements of LEDs are carried out outside a specialist laboratory, it is of primary importance to obtain stabilized, 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 comparison between similar kinds of device.

In these recommendations we consider primarily case A. It is the responsibility of the manufacturers and users to ensure that, after obtaining a well characterized working standard from their laboratory, the test set-up used for routine production checks will measure quantities properly, but, here again, the theoretical considerations and possible sources of error have to be carefully examined before the test equipment is installed.

2. Properties of LEDs

2.1 Optical properties of LEDs

The radiation from an LED can be characterized 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 characterize the optical radiation emitted by an LED.

Note that for every radiometric quantity there is a photometric analogue. The only difference is that, for the radiometric quantity, the radiation is evaluated in energy units while for photometric quantities the radiation is weighted by a spectral luminous efficiency function, generally $V(\lambda)$ and expressed in the appropriate photometric units (see [1]) 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 easily be substituted by the radiometric equivalent.

Characterization 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 will be found in Publication CIE 17.4, The International Lighting Vocabulary [2]. The basic concepts of photometry and colorimetry are described in Publication CIE 18.2, The Basis of Physical Photometry [1] and Publication CIE 15.2, Colorimetry [3], respectively. A fuller and more general treatment of the measurement of optical radiation and colour can be found in references [4] and [5].

There are some hundred 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 quite logical to apply some of the quantities normally used to describe the radiation from luminaires to characterize the radiation from LEDs.

2.1.1 Spatial distribution

The optical radiation produced by an 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 or coloured filters. A selection of some of the different spatial distributions of luminous intensity found in LEDs is presented in figure 2.1, showing the considerable variety that can be found and the associated difficulties of defining a uniform method of measurement and characterization.

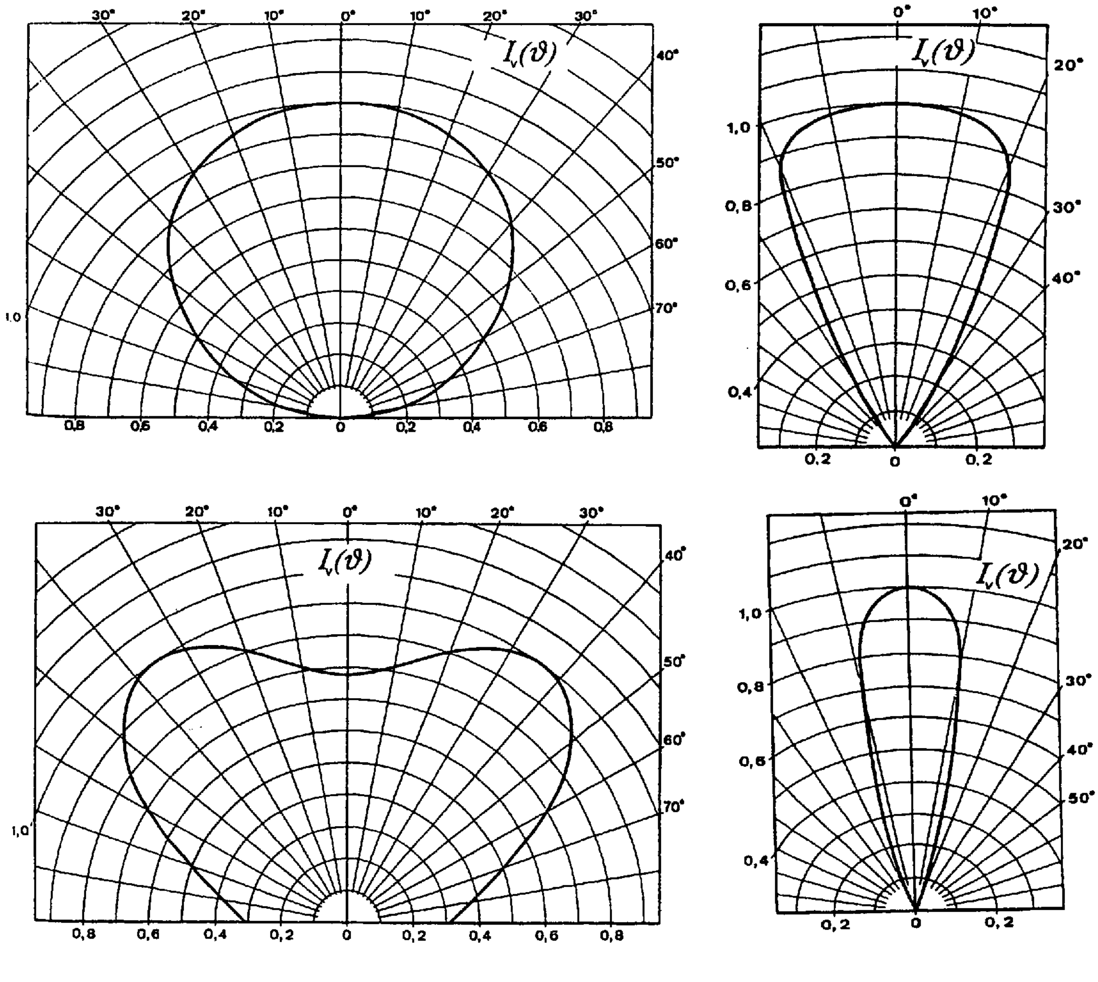

***Fig. 2.1.** Spatial distributions of the luminous intensity emitted by a selection of different LEDs. The distributions have been plotted with the maximum values normalized to unity.*

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. Compared to these, the radiant power is neither monochromatic (as emitted by lasers) nor broad-band (as found with incandescent lamps), but something between the two, with a spectral bandwidth of some tens of nanometres and a peak wavelength somewhere in the visible or near infrared region of the spectrum. Typical relative spectral distributions are shown in figure 2.2.

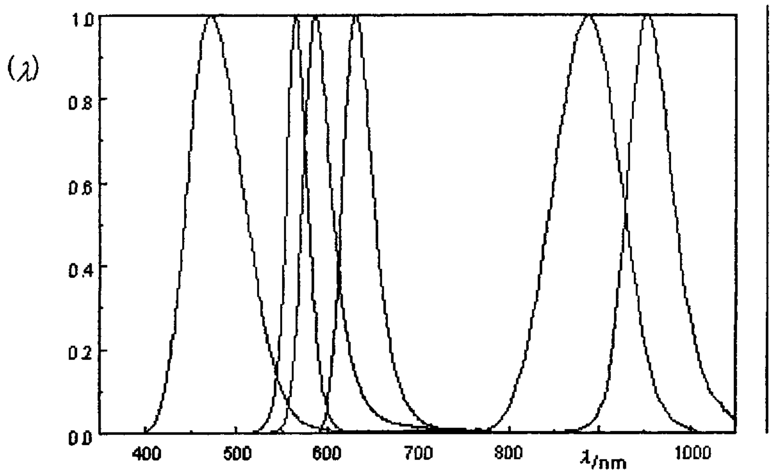

Fig. 2. 2. *Relative spectral distributions of the radiation emitted by a series of typical LEDs and IREDs. Values have been normalized to unity at the peak wavelength.*

2.1.3 Area of emittance

The small packages used for LEDs offer a variety of sizes and shapes for the window emitting the optical radiation. In figure 2.3, a few typical packages are shown together with the related sizes of the areas of emittance.

The area of emittance is characterized by its shape, size and the pattern of the luminance across it. The luminance of the whole exit window is an averaged value of the luminance distribution over the emitting area. Typically, the luminance is a maximum in the centre of the exit window with significantly lower values at the edges.

In some applications, LEDs are used under conditions where the distance between the exit window of the package and the detector is relatively short and the window large enough, by comparison, to act as an extended area so that the radiation can no longer be treated as if it was emitted by 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 [6].

In contrast, the situation where the size of the emitting area is small enough, compared to the measurement distance, for the inverse square law to be valid and when the radiation pattern is already independent of the distance from the emitter, is referred to as the "far-field" condition. The present report is mainly concerned with measurements made under the "far-field condition". The concepts of the "near-field" and "far-field" conditions are discussed in chapter 5.

2.2 Electrical characteristics

2.2.1 Electrical operating conditions

2.2.1.1 Operation at constant current

LEDs are usually operated in a forward bias direction from a DC power supply and at a constant current I_F associated with a certain voltage U_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 Φ_{el} consumed by the LED is calculated from

$$\Phi_{el} = U_F \cdot I_F \qquad \ldots 1$$

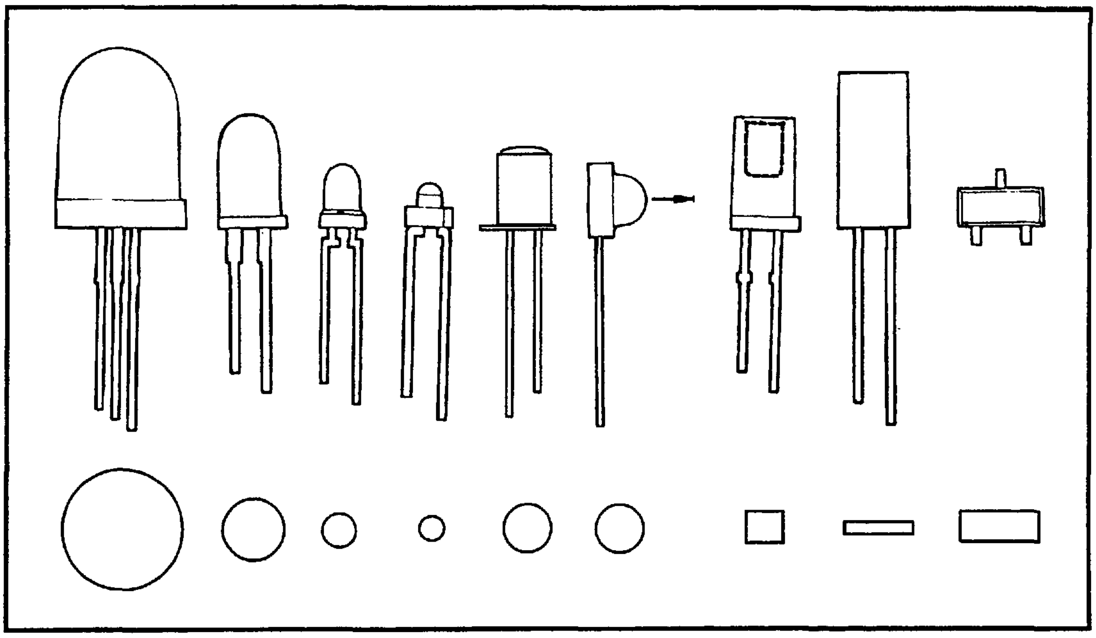

Fig. 2.3. Examples of typical LED packages with the related sizes of the areas of emittance.

At low currents, the radiant power (luminous flux) rises faster than 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 strongly correlated to the electrical current. Thus operation at constant current is recommended for measurements intended to characterize the properties of LEDs.

2.2.1.2 Operation at constant electrical power

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 an LED is reduced at higher ambient temperatures. Adjusting the electrical operating conditions to stabilize the power consumed by an LED will change the chip temperature, thus affecting the voltage drop across the LED. For this reason, stabilization of the electrical power is not recommended as a means for improving the stability of the radiant output of an LED.

2.2.1.3 Operation at constant optical output

In the case of an LED intended for use as a reference standard for comparison measurements it is common practice to build an optical feedback system via a so-called "monitor channel" to maintain a stable optical output from the source. Because the spectral distribution of the emitted radiation depends on the current, stabilization of this type has to be done using detectors with a relative spectral responsivity matched to the optical quantity of interest, (i.e. a spectrally flat response for radiometric quantities, a $V(\lambda)$ corrected detector for photometric quantities and for certain colorimetric quantities two detectors, corrected perhaps to monitor a red/green ratio* . With such systems, it is important to be quite sure that the monitor detectors remain stable.

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* Traditional red, yellow or green LEDs are highly saturated sources, i.e. their chromaticity lies near to the green - red part of the spectrum locus. Thus the dominant wavelength can be precisely determined by measuring a red/green ratio. This technique cannot be applied with blue LEDs. The concept of dominant wavelength is explained in 7.3.

2.2.1.4 Reference standards

The apparatus used to measure LED characteristics should be calibrated with LED reference standards which have been specially selected and prepared. They should be operated at a constant current with the temperature of the chip artificially maintained at a level higher than that produced directly by the power consumed at the ambient temperature of 25 °C. If a supplementary heating system is used to control the temperature of the chip, the LED can be stabilized using the temperature dependent forward voltage as an indicator to be maintained at a specified value.

The specially manufactured LEDs used as reference standards have a separate resistor or transistor mounted inside the package of the LED to optimise the thermal contact between heater and chip[12, 13]. Figure 2.4 shows such a reference standard with its current supply. This operating procedure is strongly recommended for all reference standards.

The calibration of reference standards should ideally be performed by a National Standards Laboratory or by a laboratory traceable to a National Standards Laboratory. A precise description of the measurement technique and a statement of errors should be given with each calibrated standard LED. The National Laboratory to which the calibration is traceable should also be identified.

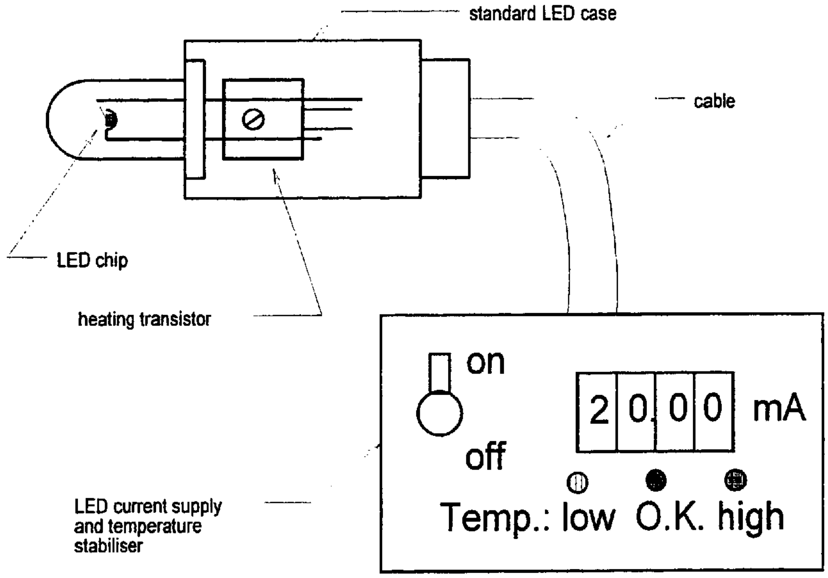


Fig. 2.4. *Schematic diagram of a temperature stabilized standard LED and power supply.*

2.2.2 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 when reporting data characterizing the properties of LEDs to identify the mode of operation corresponding to the values reported.

2.2.2.1 Modulated current

Increasing the current increases 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 η_e, which is the ratio of the radiant power Φ_e to the electrical input power Φ_{el}, is a function of the current, even if the LED is operating well within the normal working region between start-up and saturation levels.

2.2.2.2 Single-shot operation

During production control, the measurements made to characterize the properties of each LED are often carried out as single-shot operations within some ten milliseconds and at current levels approximating to those typically used under steady state conditions. For most LEDs the heat capacity of the chip and package is too large for the temperature of the chip to reach the value of steady state operation, which modifies the values obtained for the LED characteristics. Fortunately, these values are nearly always strongly correlated to the values for steady state operation, so that the true characteristics can be calculated from those measured once the correlation for the particular type of LED has been determined by a few supplementary measurements.

2.2.2.3 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 restricts itself 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 photodetector and the photocurrent measuring device average the light linearly.

2.2.3 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 U_F of an individual LED also depends on the current I_F and on the temperature T_C of the semiconductor chip.

$$U_F = U_F(T_C, I_F) \qquad \text{...2}$$

The total derivative $\mathrm{d}U_F$ separates the two influences.

$$\mathrm{d}U_F = \frac{\partial U_F}{\partial I_F} \cdot \mathrm{d}I_F + \frac{\partial U_F}{\partial T_C} \cdot \mathrm{d}T_C \qquad \text{... 3}$$

2.2.3.1 Forward voltage dependence on current

Under stabilized temperature conditions, the relationship between the forward voltage of an 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

$$\frac{\partial U_F}{\partial I_F} \approx 10\ V/A \qquad \text{...4.a}$$

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

$$R_{F0} = \Delta U_{F0} / \Delta I_{F0} \qquad \text{... 4.b}$$

then the voltage/current characteristics can be approximated by

$$U_F(I_F) = R_{F0} \cdot I_{F0} \log\left(b \frac{I_F}{I_{F0}} - 1\right) \qquad \text{... 5.a}$$

where

$$b = \exp\left(\frac{U_{F0}}{R_{F0} \cdot I_{F0}}\right) \qquad \text{... 5.b}$$

In figure 2.5, the relationship between the forward voltage of an LED and the current is shown at a single working point, corresponding to U_{FO} = 2 V and I_{FO} 20 mA, for four different values of the differential resistance R_{FO}.

2.2.3.2 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

$$\frac{\partial U_F}{\partial T_C} \approx -1{,}5 \; .... \; -2{,}5 \; {}^{mV}\!/_{K} \qquad \text{...6}$$

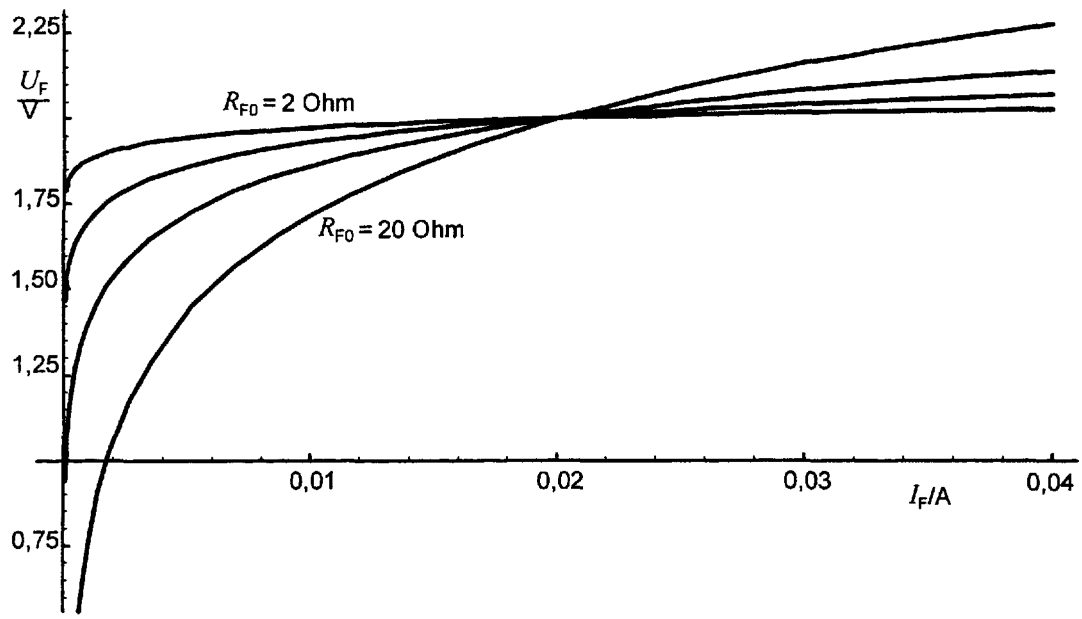


Fig.2.5. *Relationship between forward voltage and current for a typical LED at a working point corresponding to U_{FO} = 2 V and I_{FO} = 0,02 A shown for values of R_{FO} equal to 2 Ω, 5 Ω, 10 Ω and 20 Ω.*

2.2.4 Ambient temperature

Unless otherwise specified, an ambient temperature of T_{amb} = 25 °C is assumed for LED characterization. Because of the power consumed in the LED chip, the chip temperature T_C rises after the power has been turned on and stabilizes later at a value $T_C > T_{amb}$. The rate of the temperature change depends on the level of the power input and the heat capacity of the LED package. After thermal equilibrium has been reached, the value of T_C is governed by the heat transfer to the surroundings, which takes place mainly 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 2.2.2 above.

2.3 Influence of temperature on the radiation

2.3.1 Shift of peak wavelength with temperature

Constant current and a temperature stabilized voltage will result in constant consumption of electrical power by the LED. It should be noted, however, that stabilizing 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 distribution will shift significantly in the direction of longer wavelengths (for blue LEDs the shift is in most cases toward shorter wavelengths). For a typical LED, this shift is about

$$\frac{\partial \lambda_p}{\partial T_C} \approx 0{,}1 \ldots 0{,}3 \ \mathrm{nm/K} \qquad \ldots 7$$

2.3.2 Effects of temperature on efficiency and efficacy

As long as the power consumed remains constant, small temperature changes have very little effect on the radiant flux emitted by an LED. That means that there is little change in the radiant efficiency. 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 $V(\lambda)$ function. The luminous efficacy of a coloured LED with a peak wavelength on the slopes of the $V(\lambda)$ 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, be changed by relatively small temperature changes.

Since the spectral distribution of an LED depends on both the power consumed and the temperature of the chip, stabilization of current and temperature offers the best way of controlling the operating conditions and maintaining a constant spectral distribution.

3. Production tolerances

Some of the most important quantities used to characterize the optical radiation from LEDs are related to a specific direction. It is, therefore, important to align the LEDs precisely for these measurements. Unfortunately, the two axes of rotational symmetry, one of the package and the other of the spatial distribution of the emitted radiation, seldom have the same direction, and 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.

Figure 3.1 shows an LED for which the geometric axis of the case 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.

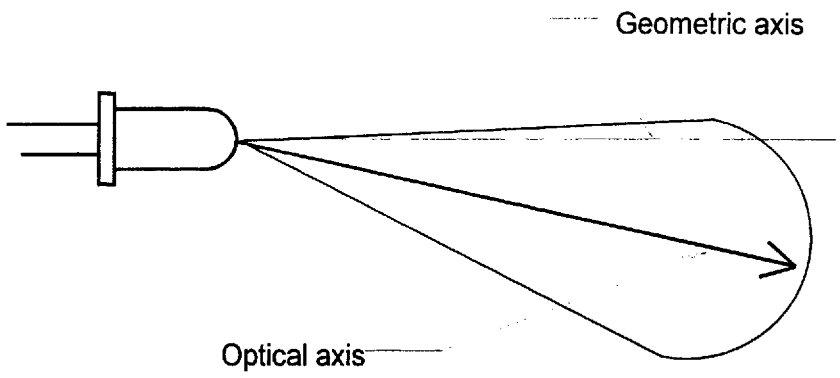


Fig. 3.1. An LED where the geometric and optical axes are aligned in different directions.

4. Properties of the detector

Measurements of optical radiation are generally carried out using photodetectors, usually silicon photodiodes. These are manufactured with a flat entrance aperture which is often covered by a thin layer of quartz or glass. They are sensitive in the near ultraviolet, visible and near infrared regions of the spectrum, about the same range as that covered by the radiation emitted by the different types of LEDs. The responsivity of silicon detectors is a maximum at about 900 nm, decreasing on either side of the maximum to zero at the limits of this spectral range.

The responsivity across the entrance aperture of the detector should be uniform, to ensure that all the radiation reaching the detector is measured with the same weight. In addition, the responsivity should be independent of the angle of incidence over the range of angles at which the radiation is incident on the detector.

The detector should have an aperture located directly in front of the photocell and any filters required to correct the spectral responsivity. For this type of measurement, cosine corrected detectors are not recommended.

4.1 Spectral responsivity of the detector

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

$$s(\lambda) = s_0 \, . \, s_r(\lambda) \qquad \ldots 8$$

For recommendations on the procedure for determining the spectral responsivity of optical radiation detectors see reference [7].

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

$$i = X_0 \, s_0 \int s_r(\lambda) \, S(\lambda) \, d\lambda \qquad \ldots 9$$

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

---

* In the subsequent equations wavelength integrals are written as indefinite integrals for the sake of simplicity; they should read always as $\int_{0\,\text{nm}}^{\infty\,\text{nm}} X(\lambda)\, d\lambda$.

measured (see 7.1.2.).

For photometric measurements the relative spectral responsivity of the detector should be corrected to approximate as closely as possible to $V(\lambda)$, the CIE spectral luminous efficiency function for a photopic observer [8]. Commercially available photometers are usually classified according to their f_1' number and a photometer used to measure LEDs should have an f_1' value < 1,5%, where

$$f_1' = \int \left| s_r^*(\lambda) - s_T(\lambda) \right| d\lambda / \int s_T(\lambda)\, d\lambda \qquad ...10$$

The values of the relative spectral responsivity of the detector $s_r^*(\lambda)$ in equation 10 have been normalized using the equation

$$s_r^*(\lambda) = s_r(\lambda) \,.\, \int S(\lambda)_A\, s_T(\lambda)\, d\lambda / \int S(\lambda)_A\, s_r(\lambda)\, d\lambda \qquad ...11$$

where $s_T(\lambda)$ is the target spectral responsivity corresponding to the ideal detector, which in the photometric case is $V(\lambda)$. $S(\lambda)_A$ is the relative spectral distribution of Standard Illuminant A, which is included to take account of the fact that, when photometers are given an absolute calibration, they are customarily calibrated using a tungsten filament lamp set to the colour temperature of CIE Standard Illuminant A.

Radiometric measurements should be made with a non-selective detector. That is to say, a detector for which the output current is directly proportional to the radiant power over the entire spectral range for which measurements are required. This type of detector is sometimes described as having a "flat" response.

The detector used to measure the radiant output of LEDs could also be characterized by an f_1' value which could again be calculated from equations 10 and 11, but, since the ideal detector for use in radiometric measurements should be totally non-selective, the appropriate $s_T(\lambda)$ function for this application will have a constant value equal to unity. There is, at present, no definitive guidance as to how the calculation of such an f_1' value should be performed. Future Division 2 publications will hopefully address this question.

4.2 LED measurements with a detector using the comparison method

By far the best measurement technique for measuring the characteristics of an LED is to compare the test LED to a reference standard LED. This requires a reference standard LED that has been calibrated for whatever quantity is to be measured on the test LEDs. The reference standard LED should be mounted in a specially designed package and should be an LED typical of the kind to be tested that has been pre-selected and "aged" (i.e. burnt-in), for a minimum of 500 hours. 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 level above room temperature and provide a constant current setting, usually 20 mA, to ensure a constant optical output (see 2.2.1 above).

Measurements can then be performed by comparing the two photocurrent readings obtained from the detector for the standard and the test LEDs. The positions of the two LEDs must be the same in order to guarantee the same distance between LED and detector and the same orientation of the LEDs relative to a given reference axis.

$$i_1 = X_{(1)0}\, s_0 \int s_r(\lambda)\, S_{(1)}(\lambda)\, d\lambda \qquad ...\ 12$$

and

$$i_2 = X_{(2)0}\, s_0 \int s_r(\lambda)\, S_{(2)}(\lambda)\, d\lambda \qquad ...13$$

Here subscripts (1) and (2) refer to the standard and the test LEDs respectively. If the relative spectral distribution is the same for standard and test LEDs, then equations 12 and 13 reduce to a simple ratio.

$$X_{(2)0} = X_{(1)0} \,.\, i_2 / i_1 \qquad ...\ 14$$

Unfortunately, in practice, small deviations usually occur because the test and standard LEDs have slightly different relative spatial and spectral distributions. It is difficult to apply any correction for variations in spatial distribution and these can cause serious errors.

The effect of variations in the spectral power distribution, on the other hand can be fairly easily corrected, so long as the relative spectral responsivity of the detector $s_r(\lambda)$, and the relative spectral distributions of the standard and test LEDs $S_{(1)}(\lambda)$ and $S_{(2)}(\lambda)$ are all known. In the case of a photometric measurement, the spectral correction factor (*SCF*) can be calculated from the equation

$$SCF = \frac{\int S_2(\lambda)V(\lambda)\mathrm{d}\lambda}{\int S_1(\lambda)V(\lambda)\mathrm{d}\lambda} \times \frac{\int S_1(\lambda)s_r(\lambda)\mathrm{d}\lambda}{\int S_2(\lambda)s_r(\lambda)\mathrm{d}\lambda} \qquad \text{...15}$$

Combining equations 14 and 15,

$$X_{(2)_0} = X_{(1)0} \times \left({}^{i_2}\!/_{i_1} \right) \times SCF$$

$$= X_{(1)0} \times \left({}^{i_2}\!/_{i_1} \right) \times \frac{\int S_2(\lambda)V(\lambda)\mathrm{d}\lambda}{\int S_1(\lambda)V(\lambda)\mathrm{d}\lambda} \times \frac{\int S_1(\lambda)s_r(\lambda)\mathrm{d}\lambda}{\int S_2(\lambda)s_r(\lambda)\mathrm{d}\lambda} \qquad \text{...16}$$

For radiometric measurements, a non-selective detector is required, but, if the detector employed deviates from the ideal "flat" response, a similar spectral correction factor can be determined using equation 15 or 16 modified by substituting the value of unity for $V(\lambda)$.

5. Quantities defining spatial relations

5.1 Normalization factor and relative spatial distribution

In general, the luminous intensity $I(\theta,\phi)$ 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 $\mathrm{d}\Omega$ and this requires a detector where the diameter of the input aperture is small compared to the distance from the source. If the absolute value of the intensity $I(\theta,\phi)$ is measured in a specified reference direction corresponding to $\theta = \theta_0$ and $\phi = \phi_0$ and denoted by $I_{00} = I(\theta,\phi)$, then this can be used as a normalizing factor and a relative spatial distribution $G(\theta,\phi)$ defined. The spatial intensity distribution $I(\theta,\phi)$ can be expressed as

$$I(\theta,\phi) = I_{00} \cdot G(\theta,\phi) \qquad \text{...17}$$

which can be rewritten as

$$G(\theta,\phi) = I(\theta,\phi) \,/\, I_{00} \qquad \text{...18}$$

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

The simplest form of the function $G(\theta,\phi)$ is

$$G(\theta) = G \qquad \text{...19}$$

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, which has a luminance independent of the direction of view. With θ measured as the angle between the direction considered and the perpendicular to the surface, the spatial distribution for all values of ϕ is given by

$$G(\theta) = G_0 \, |\cos\theta| \qquad ...20$$

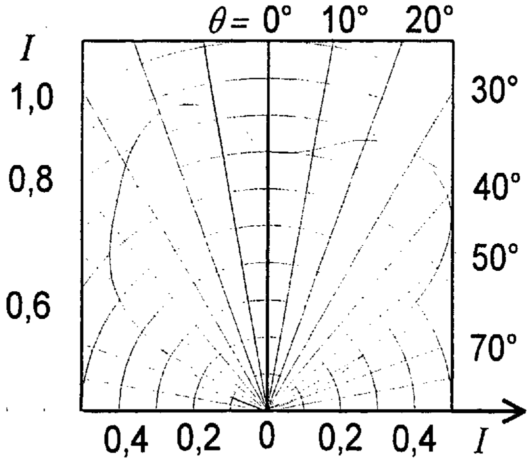
where the range of angles is limited to a hemisphere with $0 \le \theta \le \pi / 2$. This spatial distribution is normally used as a reference.

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 [9].

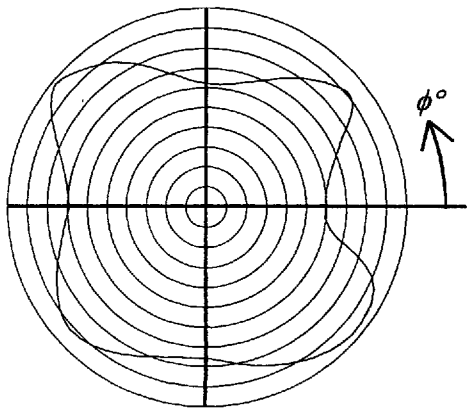
The majority of LEDs are designed to provide a distribution with the maximum intensity in the direction $\theta = 0°$, but this is not always the case and for some LEDs the construction of the device gives a significantly lower value in the direction of the optical axis than for some off-axis angles. One of the examples in figure 2.1 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 figure 3.1). 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 which shows perfect axial symmetry. Figure 5.1 shows two common forms of asymmetric spatial distribution which are sometimes found in LEDs and can lead to alignment problems. The spatial distribution of the LED depicted in figure 5.1.a shows a small minimum in the direction of the package axis ($\theta = 0°$), and a maximum in an off-axis direction. Figure 5.1.b shows $I(\phi)$ plotted at constant θ for an LED in which the non-circular shape of the intensity distribution indicates the departure from rotational symmetry.



5.1.a.



5.1.b.

Fig. 5.1. *Two common asymmetric power distributions. In 5.1.a the optical axis is at an angle to the geometric axis. In 5.1.b the spatial power distribution lacks rotational symmetry.*

5.2 Measurement of directional quantities

5.2.1 Luminous intensity

Luminous intensity is defined as the quotient of the flux $d\Phi$ leaving the source and propagated in the element of solid angle $d\Omega$ containing the given direction, by the element of solid angle.

$$I = d\Phi / d\Omega \qquad ...21$$

Although this may appear, at first sight, to be simply a question of making a measurement of the luminous flux per unit 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 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.

5.2.2 Illuminance

The illuminance $E(\theta,\phi)$, produced at a distance d from a source in a direction (θ,ϕ) on an element of surface normal to that direction, is related to the luminous intensity $I(\theta,\phi)$ in that direction by the equation

$$E(\theta,\phi) = I(\theta,\phi) / d^2 \qquad \text{...22}$$

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.

Equation 22 is known as the "inverse square law", but it can be rewritten as

$$I(\theta,\phi) = E(\theta,\phi) \cdot d^2 \qquad \text{...23}$$

This is the basis of all practical measurements of luminous intensity. The quantity actually measured is the illuminance at the surface of a detector and the intensity is then calculated on the basis of equation 23 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 detector. Since the actual location of the effective light centre of an LED can be difficult to determine, distances are often measured from an arbitrary location on the LED package.

5.2.3 Location of the effective emitting surface

If the measurement distance is large enough, the exact position of the light centre shouldn't matter very much, but, because of the large variety of different types of LED available, no general rule can be laid down to determine the minimum safe distance for accurate measurement (see[10]). This is the reason that CIE recommends the use of the concept of averaged LED intensity, see Section 5.3.

5.2.4 "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 detector 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 at the surface of the detector will be given by $E = I / d^2$ (equation 22), where I is the luminous intensity of the source 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.

5.3 Averaged LED intensity

In manufacturers literature, one of the parameters most commonly quoted as a measure of the directional output of an 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 5.2.1.

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 often have to be made at relatively short distances, typical of the distances at which the LEDs are likely to be used in practice, 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", in which measurements made at different distances do not obey the inverse square law. 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 intensity; averaged that is for the various individual elements which 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**.

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

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 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 detector.

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

$$I_{\mathrm{LED}} = E \,.\, d^2 \qquad \text{...24}$$

where E is the average illuminance in lm m^{-2} 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 plane angles are approximately 2° for Condition A and 6,5° for Condition B.

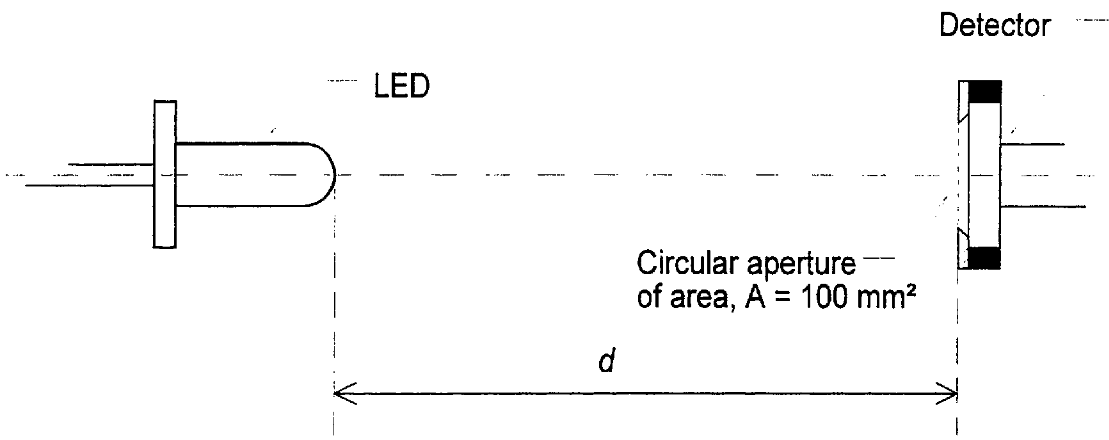


***Fig. 5.2.** Schematic diagram of CIE Standard Conditions for the measurement of Averaged LED Intensity. Distance d = 0,316 m for Condition A, d = 0,100 m for Condition B.*

5.4 Measurement of spatial and directional properties

It is desirable that 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. A measurement to check this should be carried out as a first step in selecting a suitable standard. If the laboratory is equipped with a goniophotometer, it should be used to perform a direct measurement of the spatial distribution of intensity. If the exact location of the emitting surface is unknown, 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 simplified test will help to identify LEDs with similar spatial power distributions for use as working standards. First, a measurement should be made of the illuminance at a point a fixed distance along the reference axis of each of the LEDs to be compared, measuring the distance from the front tip of each LED. Secondly, the luminous flux should be measured using an integrating sphere. If the ratio of the two measured values is the same, or very close, then the LEDs have similar spatial power distributions. If the difference in the ratios is larger then 3%, then the LEDs are too dissimilar to be used as working standards.

6. Measurement of total luminous flux

6.1 Goniophotometer method

If it is possible to use a goniophotometer, the total luminous flux can be determined independently of the source related co-ordinate system. Imagine that the source is totally surrounded by an imaginary sphere and the rotating detector of the goniophotometer scans over the surface of that sphere. The surface is irradiated by the source inside the sphere. The partial fluxes $\mathrm{d}\Phi$ incident on each element $\mathrm{d}A$ of the surface (related to the direction θ, ϕ) represent an illuminance

$$E(\theta,\phi) = \frac{\mathrm{d}\Phi}{\mathrm{d}A} \qquad ...25$$

which can be weighted and integrated to give the value of the total flux Φ,

$$\Phi = \int_{(A)} E \,\mathrm{d}A \qquad ...26$$

6.2 Integrating sphere method

Another and simpler way to measure the total luminous flux from an LED is to use a well constructed integrating sphere [10] to compare it to a standard LED with similar spatial and spectral power distributions. If no perfectly matched standard is available, a correction for small colour differences can be calculated as shown in section 4.2. Corrections for spatial power differences are much harder to quantify and need to be assessed for each different type of sphere.

Since the integrating spheres used in many laboratories for LED testing are no more than 10 cm in diameter, an auxiliary LED of the same type should be inserted into the sphere to enable a correction to be applied for the self-absorption of the test LED. Spheres with two entrance ports and a third port as exit port for the detector have been used successfully. Figure 6.1 illustrates the geometry of three integrating spheres. The simple arrangement shown in figure 6.1.a is not suitable for spheres less than 30 cm in diameter. Figures 6.1.b and 6.1.c show possible positions for baffles and the auxiliary LED used to correct for the self-absorption of the test LED in spheres 10 cm in diameter. The most reliable comparison measurements of total flux were obtained with sphere 6.1.c when small sphere size was important and there were some differences between the spatial distributions of the standard and test LEDs [10]. If a larger sphere with a high reflectance coating can be used, then the size of the central baffle can be considerably reduced to give a closer approximation to ideal conditions. In this case, a simple comparison measurement with well selected standards should result in flux measurements with a precision of better than ± 5%.

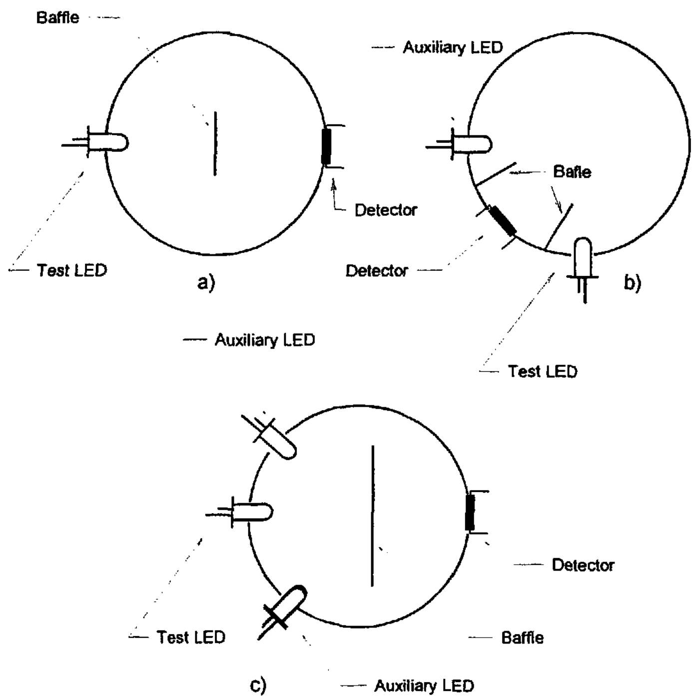


Fig. 6.1. *Three integrating sphere arrangements used to measure the luminous flux from LEDs.*

7. Quantities related to spectral distribution

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 λ and is given by

$$X_\lambda(\lambda) = \mathrm{d}X_e(\lambda) / \mathrm{d}\lambda \qquad ...27$$

$X_\lambda(\lambda)$ is also known as the spectral distribution of that quantity. This function is a wavelength dependent function. The dimensions of the spectroradiometric unit are those of the radiometric unit divided by the unit of length, the metre. For example, the dimensions of the unit of radiant intensity I_e are W sr^{-1} and the dimensions of the unit of spectral radiant intensity $I_{e\lambda}(\lambda)$ (often written simply as $I(\lambda)$) are W sr^{-1} m^{-1}, usually reported as mW sr^{-1} nm^{-1} or µW 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 characterize the spectral distribution of LEDs.

7.1.2 Normalization factor and relative spectral distribution

LEDs emit optical radiation over a limited wavelength range given by $\lambda_1 \le \lambda \le \lambda_2$. It is often helpful to normalize the spectral distribution function and divide it into two parts, an absolute normalization factor X_{e0} taken at wavelength $\lambda = \lambda_0$ with the unit of the spectral concentration

$$X_{e0} = X_\lambda(\lambda = \lambda_0) \qquad \text{...28}$$

and a relative function $S_X(\lambda)$

$$S_X(\lambda) = \frac{X_\lambda(\lambda)}{X_{e0}} \qquad \text{...29}$$

called relative spectral distribution, which comes with a dimension of unity, but is still associated with the geometric measurement conditions as defined for the original quantity. From equation 29, the (absolute) spectral distribution can be written as

$$X_\lambda(\lambda) = X_{e0} \cdot S_X(\lambda) \qquad \text{...30}$$

7.2 Characteristic wavelengths and spectral bandwidth

Figure 7.1 illustrates the locations of the characteristic wavelengths described in the following sections. Although the actual curve shown represents a blue LED, the shape is typical of that of all LEDs, with zero values outside the wavelength range $\lambda_1 \le \lambda \le \lambda_2$ and one significant maximum in between. Figure 2.2 shows typical spectral distributions for a representative selection of the various LEDs and IREDs currently available commercially.

7.2.1 Peak wavelength

The wavelength at the maximum of the spectral distribution is known as the peak wavelength λ_p. The (absolute) spectral distribution is usually normalized 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 level

The spectral bandwidth at half intensity level $\Delta\lambda_{0,5}$ is calculated from the two wavelengths $\lambda'_{0,5}$ and $\lambda''_{0,5}$ on either side of λ_p, where the intensity has fallen to 50 % of the peak value:

$$\Delta\lambda_{0,5} = \lambda''_{0,5} - \lambda'_{0,5} \qquad \text{...31}$$

Note: In some applications the $\Delta\lambda_{0,1}$ value is also used (see Fig. 7.1). This is the bandwidth between the two wavelength where the intensity has fallen to one tenth of the maximum.

7.2.3 Centre wavelength of half intensity bandwidth

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

$$\lambda_{0,5m} = \left(\lambda'_{0,5} + \lambda''_{0,5}\right)/2 \qquad \text{...32}$$

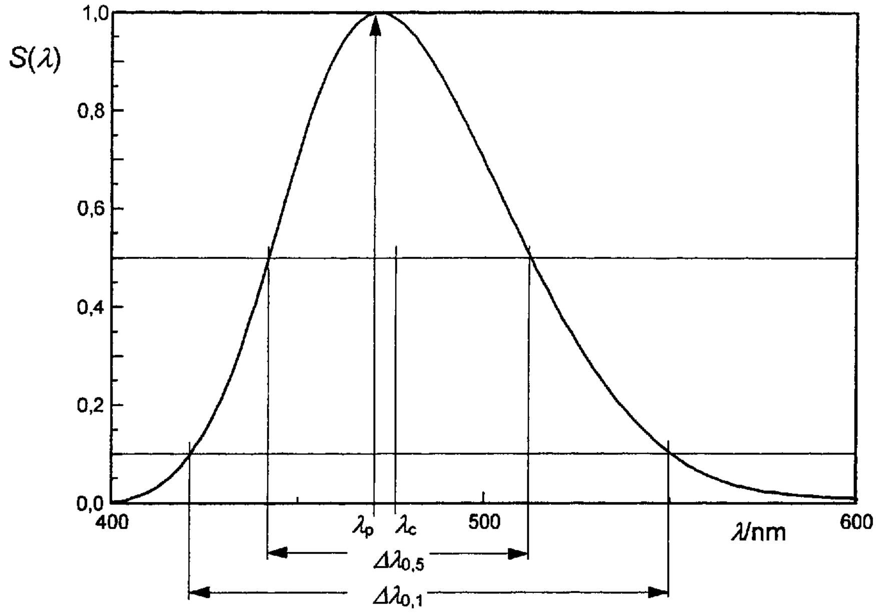


Fig. 7.1. Typical relative spectral distribution of an LED showing the location of the characteristic wavelengths and wavelength intervals.

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

$$\lambda_c = \int_{\lambda_1}^{\lambda_2} \lambda \cdot S_X(\lambda) \mathrm{d}\lambda \Bigg/ \int_{\lambda_1}^{\lambda_2} S_X(\lambda) \mathrm{d}\lambda \qquad \text{...33}$$

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 an LED may be specified in terms of its chromaticity co-ordinates and these are best obtained by calculation from the spectral power distribution.

Two alternative quantities also sometimes used to characterize the colour of LEDs are dominant wavelength and purity. 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. Figure 7.2 illustrates the concepts of dominant wavelength and excitation purity. For further information on colorimetric concepts and calculations, see reference [3].

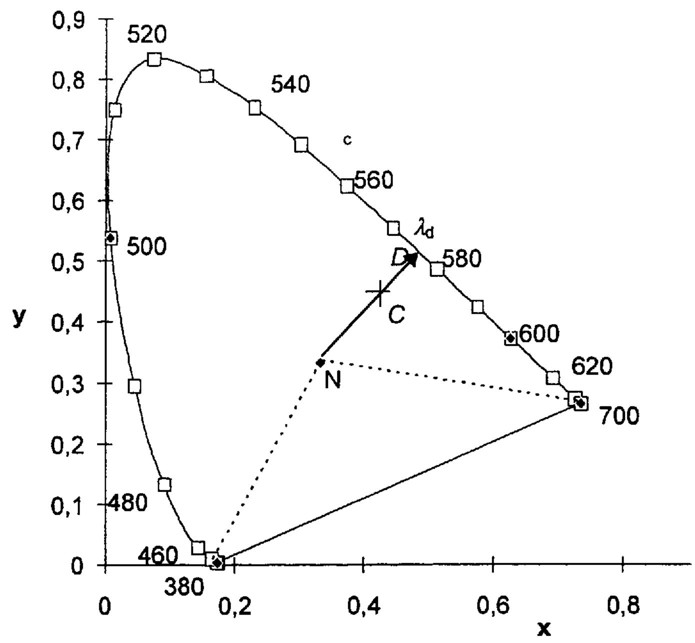


Fig. 7.2. CIE 1931 chromaticity diagram showing distances and intersections for dominant wavelength and excitation purity calculations.

7.3.1 Dominant Wavelength

The dominant wavelength λ_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 characterizing LEDs, the reference achromatic stimulus should be an equal 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 co-ordinates x_E = 0,3333, y_E = 0,3333.

7.3.2 Purity

For characterizing LED purity 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 or 1964 standard colorimetric system, 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:

$$p_e = \frac{y - y_n}{y_d - y_n} \quad \text{or} \quad p_e = \frac{x - x_n}{x_d - x_n} \qquad ...34$$

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 reference stimulus.

7.4 Measurement of the spectral distribution

A measurement of spectral power distribution generally consists of a comparison between two sources, a reference standard of known spectral power distribution and a test source. When this is done, it is essential to ensure that the optical path through the monochromator is exactly the same for both sources. Thus care must be taken that the reference source used to calibrate the instrument is of exactly the same size and occupies exactly the same position as the LED [11]. If the spectral power distribution related to the total flux is required, the measurement should be carried out by placing the LED inside an integrating sphere. With some types of LED it has been observed that the spectral power distribution is not the same in every direction. To characterize such LEDs completely, it may be necessary to measure the spectral power at different angles.

The wavelength resolution of the spectroradiometer used to measure the spectral power distribution of an LED should be better than 1 nm to enable it to follow the steep slopes of the spectral distribution near the half intensity levels. The uncertainty of the wavelength scale should be less than 0,5 nm if the characteristic wavelengths are to be specified with the necessary accuracy. The sensitivity of the spectroradiometer should be high enough to measure all parts of the distribution with a resolution better than 1 % of the level at the peak wavelength. After compensation, any zero error in the output signal of the spectrometer should be less than ± 0,1 % of the level at the peak wavelength. For further guidance on spectroradiometric measurement procedures and possible sources of error see reference [11].

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