Measurement, calibration and measurement uncertainty of LEDs

Application Note

Published by ams-OSRAM AG
Tobelbader Strasse 30,
8141 Premstaetten Austria
Phone +43 3136 500-0
ams-osram.com

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Valid for:
all LEDs

Abstract

With the recent rapid growth of the LED market and the development of its applications, LEDs have become more common. They can now be found in many new applications within the lighting community. These new applications have placed increasingly stringent demands on the measurement of LEDs. Hence, accuracy and precision are the keys in the optical measurement of LEDs. The radiometric, photometric and colorimetric quantities of the LEDs are typically derived from the optical measurement.

This application note focuses on the measurement of LEDs and provides a fundamental understanding of optical measurement, calibration and measurement uncertainty.

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1 Optical properties[1]

1.1 Radiometry

Radiometry is the science of the measurement of the energy and the physical properties of the electromagnetic radiation in which the spectrum covers the full range from ultraviolet (UV) to

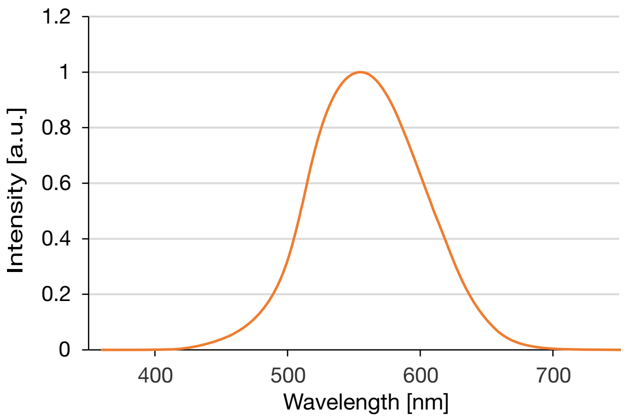
(1)[1] CIE 127:2007, Chapter 2.1.

infrared (IR) light. Radiometry is independent of the sensitivity of the human eye to brightness and color.

1.2 Photometry

Light is the visible part of the electromagnetic radiation spectrum. Photometry involves the physical measurement of visible light energy that characterizes the light's interaction with the human eye. Each radiometric quantity has a corresponding luminous quantity which considers the visual perception of the human eye with the V(λ) curve. The V(λ) curve describes the spectral response function of the human eye in the 380 nm to 780 nm wavelength range (Figure 1).[2]

Figure 1: Human eye response curve or relative spectral luminous efficiency curve V(λ)



1.3 Colorimetry[3]

Colorimetry describes the color perception by the human eye. For the quantitative and qualitative description of color the tristimulus XYZ system was defined and established by the International Commission on Illumination (CIE) in 1931. The tristimulus system is based on the assumption that every other color can be represented by a combination of the primary colors red, green and blue.

To describe the color of a light source by the XYZ system, the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ (see Figure 2) are multiplied with the spectral power distribution of the light source (See Figure 3 for an example of the spectral power distribution of a white LED) and integrated over the wavelength range of the spectral response function of the human eye (380 nm to 780 nm).

(2) [2] DIN 5031-9:1976-05 Photometry.

(3) [3] G. Leschhorn, R. Young, Handbook of LED and SSL Metrology, Chapter 2.3; [4] J. Schanda, Colorimetry, Chapter 1; [5] CIE 15:2004, Colorimetry, Chapter 1; [6] CIE 170:2015, Fundamental Chromaticity Diagram with Physiological Axes, Part 2.

The CIE developed the two-dimensional chromaticity diagram (Figure 2, left) in order to enable a simplified representation of the three dimensional color space. The 1931 CIE diagram and the color matching functions for a 2 degree observer, shown in Figure 2, are widely used in the LED industry.

Figure 2: The CIE 1931 diagram and Color matching functions

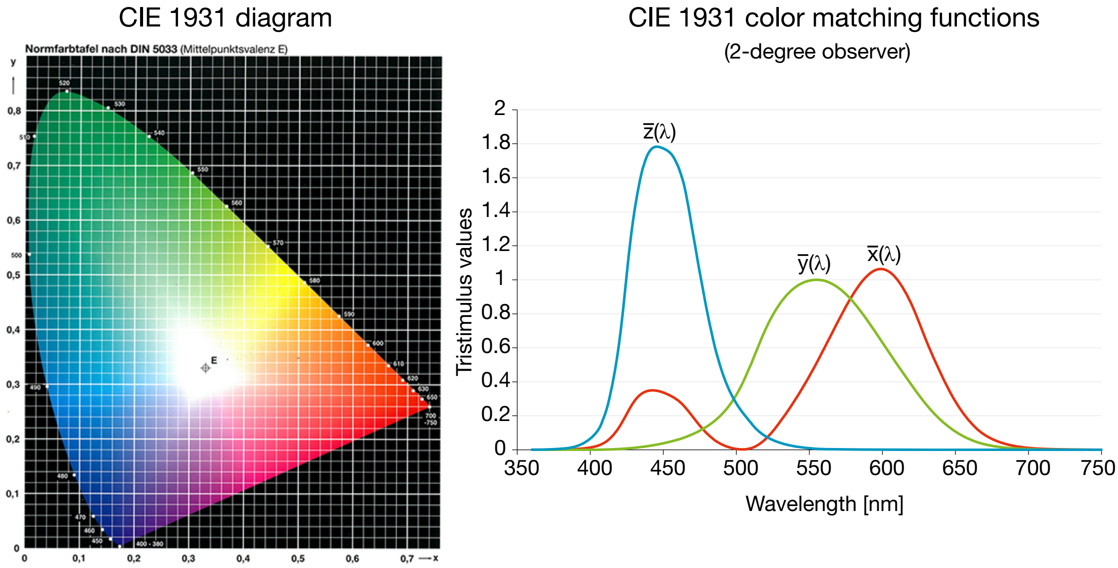
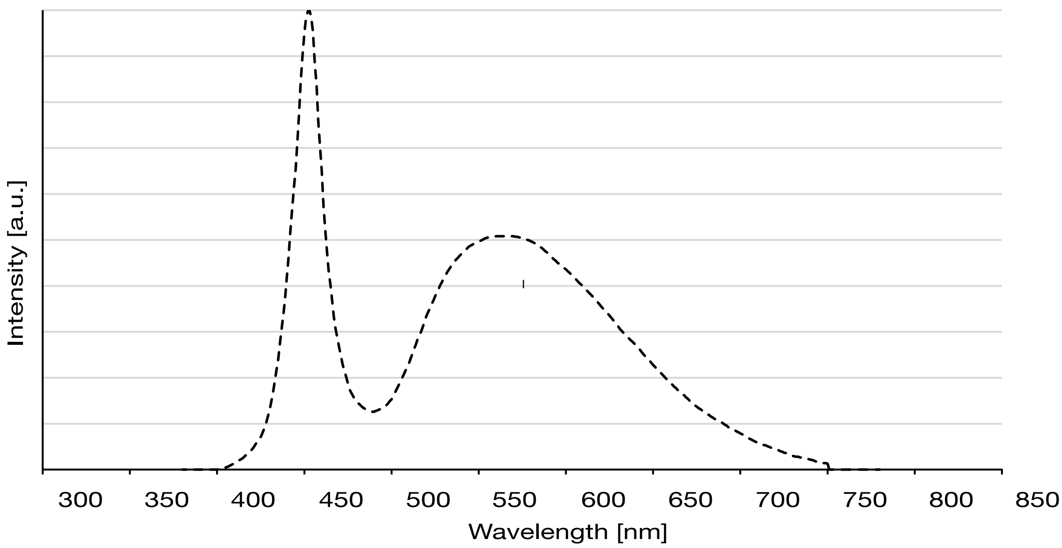


Figure 3: Example of the spectral distribution of a white LED



2 Equipment and quantities

The quantities previously mentioned can be measured by photometer or spectroradiometer. The simplest and quickest way to measure the total luminous flux of an LED is to use an integrating sphere coupled with a photometer or spectroradiometer. Alternatively, a goniophotometer may be used. A spectroradiometer is fast and is broadly used in the LED industry, whereas a goniophotometer is generally more accurate but time-consuming. The spectral power distribution of a light source measured by spectroradiometer is useful for the derivation of other color quantities such as the chromaticity coordinates xy, dominant wavelength, peak wavelength, centroid wavelength, purity, correlated color temperature (CCT) and color rendering index (CRI).

Some brief explanations of relevant colorimetric and photometric quantities for LEDs are listed below.[4] Where applicable, the reference to the official definition in the International Lighting Vocabulary (ILV) from 2011 is given in parenthesis (ILV CIE S 017/E:2011).[5] For more detailed information refer to DIN 5032 and DIN 5033.

- Luminous flux is total emitted optical power weighted by the standardized spectral response function of the human eye $V(\lambda)$. Unit: lm (ILV CIE S 017/E:2011 17-738). For the definition of $V(\lambda)$ refer to ILV CIE S 017/E:2011 17-1222.
- Luminous intensity is the luminous flux emitted per unit solid angle in a given direction. Unit: cd = lm/sr (ILV CIE S 017/E:2011 17-739). For a definition of the solid angle refer to ILV CIE S 017/E:2011 17-1201.
- Chromaticity coordinates xy are determined from the XYZ tristimulus values according to the formulas $x= X/(X+Y+Z)$; $y= Y/(X+Y+Z)$. Unit: 1 (ILV CIE S 017/E:2011 17-144). Additional explanations can be found in CIE 15 “Colorimetry”.
- Dominant wavelength (of a color stimulus): wavelength of the mono-chromatic stimulus which, when additively mixed in suitable proportions with the specified achromatic stimulus, matches the color stimulus considered in the CIE 1931 x, y chromaticity diagram. It can be determined from the chromaticity coordinates by drawing a straight line from the equal energy white point to the sample point and to the boundary of the color diagram. This intersection represents the dominant wavelength. The equal energy white point is $x = 1/3$ and $y = 1/3$. Unit: nm (ILV CIE S 017/E:2011 17-345)
- Peak wavelength refers to the maximum intensity of the spectrum.
- Centroid wavelength is the wavelength that divides the integral of a spectrum into two equal parts.
- Excitation Purity is the ratio of the distance of the straight line from the equal energy white point E to the chromaticity point and the distance from the equal energy white point E to the boundary of the chromaticity chart. (ILV CIE S 017/E:2011 17-408)
- Correlated Color Temperature (CCT) is the color temperature of a black body radiator which is closest to the color coordinates of the light source in the uv color space. (ILV CIE S 017/

(4) [3] G. Leschhorn, R. Young, Handbook of LED and SSL Metrology, Chapter 2.1; [7] Technical Guide: The Radiometry of LEDs, Chapter 3.1.

(5) [8]ILV CIE S 017/E:2011.

E:2011 17-258). For the definition of uv (= u';2 / 3v') color space refer to ILV CIE S 017/ E:2011 17-162.

- Color rendering index (CRI) is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with a reference light source of the matching CCT (ILV CIE S 017/E:2011 17-222). Further and more detailed explanations can be found in CIE 13 "Method of Measuring and Specifying Colour Rendering of Light Sources" as well as in DIN 6169.

3 Calibration procedure[6]

Precise calibration of the optical measuring instrument is highly critical for accurate measurement. It is recommended that the spectroradiometer used to measure the LED quantities is calibrated regularly by an accredited calibration laboratory. The laboratory must have a calibration capability and traceability linked to NMI (National Metrology Institute) for reliable measurements. Ideally, an ISO 17025 accredited laboratory is recommended. Generally it is recommended that the calibration stages mentioned below are carried out by a calibration laboratory.

3.1 Wavelength calibration

Wavelength calibration is carried out to to serialize and assign the CCD sensor or detector to the specific known wavelength of atomic emission lines from mercury argon (HgAr), HeNe, or a fixed frequency laser line sources. This establishes the relationship between the CCD pixels and the specific known wavelength of atomic emission lines. HgAr and HeNe are physical standards and do not require calibration by the NMI, whereas a fixed frequency laser is not considered to be a physical standard and thus requires calibration by the NMI.

3.2 Spectral calibration

Spectral calibration is carried out to determine the relative spectral response of the system over the specified wavelength range. This is basically determined by the sensitivity curves of the detector, the grating and the optical probe used. The relative sensitivity curve of the spectrometer measured and the spectral data of the broadband tungsten halogen lamp (traceable to a National Metrology Institute, NMI) are used to generate the correction function. The lamp current must be stabilized to achieve a constant operating state for a reproducible spectrum.

(6) [1] CIE 127:2007, Measurement of LEDs, 2.2; [7] Technical Guide: The Radiometry of LEDs, Chapter 4.7 — 5.0.

3.3 Absolute calibration

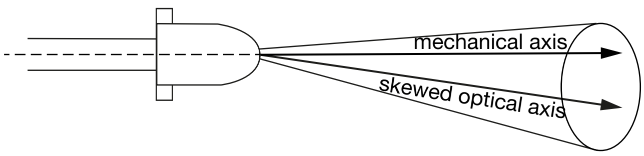
Absolute calibration is carried out by using a reference LED with a traceable reference value of the luminous flux and/or the intensity given by a national metrology institute. Absolute calibration is then used to adjust the absolute sensitivity of the CCD sensor or detector.

4 Measurement setup

4.1 Averaged LED intensity[7]

The directional alignment of an emitted optical radiation must be considered during a measurement, not only in relation to the emitting diode but also to the receiving or measuring detector. For example, the mechanical and optical axes may not be parallel, see Figure 4. This influences the measurement result and the related measurement uncertainty is high.

Figure 4: An example of a skewed radiation of an LED between mechanical axis and optical axis[8]



To minimize such variations in results, ams-OSRAM AG has adopted the CIE 127 recommendation for the measurement of LEDs, i.e. luminous flux and average LED intensity. Figure 5 and Table 1 show the CIE standard conditions for the measurement of the averaged LED luminous intensity.

(7)[2] DIN 5031-9:1976-05 Photometry; [1] CIE 127:2007, Chapter 4.3; [9] CIE 225:2017, Optical Measurement of High-Power LEDs, Chapter 5.

(8) [1] CIE 127:2007, Chapter 2.4.

Figure 5: CIE standard conditions for the measurement of the averaged LED luminous intensity. The tip of the LED acts as a reference point, with a distance of 316 mm (condition A) or 100 mm (condition B) between the LED and the detector[9]

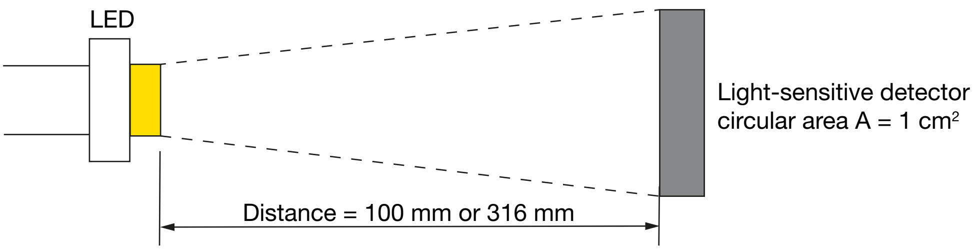


Table 1: CIE standard conditions for the measurement of the averaged LED luminous intensity

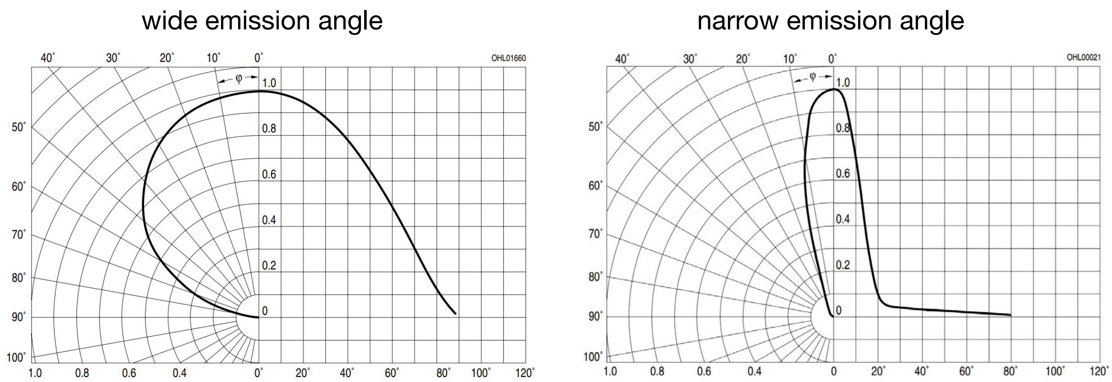
CIE recommendations	Distance between LED tip and detector	Solid angle
Condition A	316 mm	0.001sr
Condition B	100 mm	0.01sr

CIE condition B is the most commonly used geometry used for LEDs with a wide emission angle, whereas condition A is mostly used for LEDs with a narrow emission angle (typically an aperture angle of ± 20°). Under ideal laboratory conditions this procedure is reliable and reproducible.

However, the production measurement of LEDs faces certain difficulties due to inherent positioning tolerances. To overcome these difficulties ams-OSRAM AG introduced the partial flux measurement. For detailed information please refer to the application note "Partial flux — Measurement reliability of lensed LEDs.

Figure 6 shows an example of a wide emission angle radiation pattern with an aperture angle > ± 60° and a narrow emission angle radiation pattern with a an aperture angle < ± 20°.

Figure 6: Emission angle radiation patterns

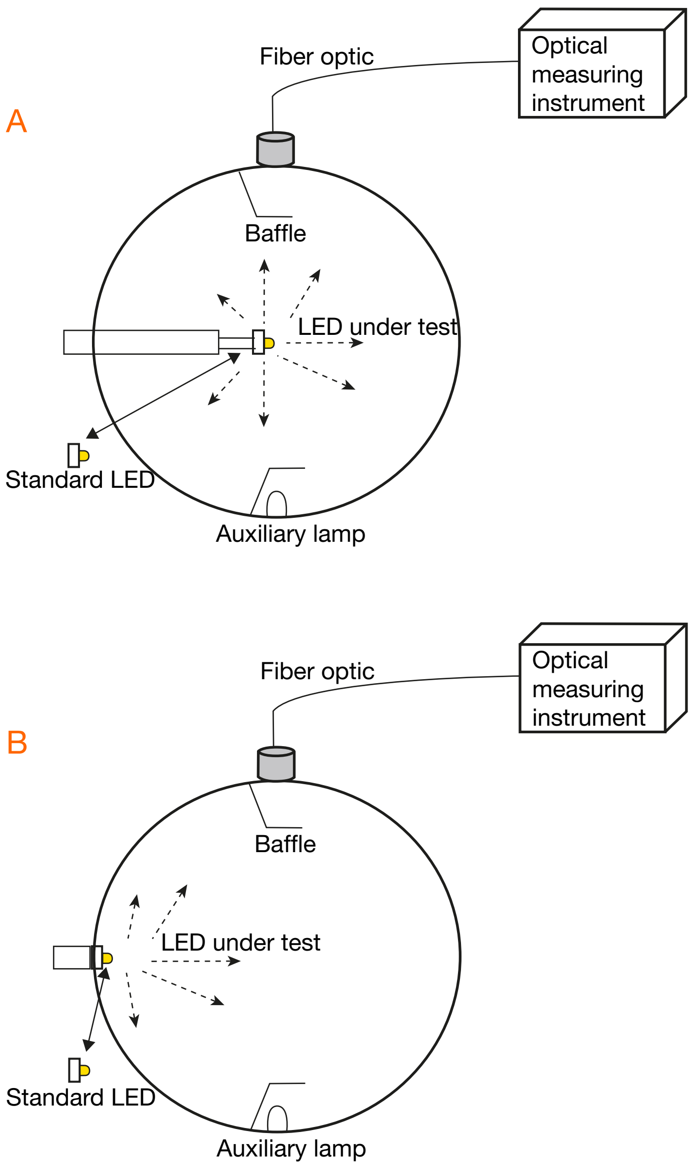


(9) [1] CIE 127:2007, Chapter 4.3.

4.2 Luminous flux[10]

An integrating sphere is used to spatially integrate the light and produce diffuse radiation to average the radiation emitted into the sphere, resulting in equal radiance at any point on the sphere wall. The CIE has recommended different sphere geometries for the total luminous flux measurement of LEDs. Figure 7 illustrates two different sphere geometries. The 4π configuration (geometry A) is recommended for all types of LEDs, whereas the 2π configuration (geometry B) is for LEDs with no backward emission. Geometry B has the advantage that the test LED can be easily mounted on the sphere wall and is therefore the method of choice in typical LED production and laboratory testing.

Figure 7: Sphere geometries for the LED total luminous flux measurement for all types of LEDs (A) and for LEDs with no backward emission (B)[11]



(10) [1] CIE 127:2007, Chapter 6; [2] DIN 5032-9.

For luminous flux measurements within an integrating sphere it is recommended that you apply self-absorption correction factors prior to any optical measurement made by utilizing an auxiliary lamp. In certain cases, the self-absorption can be ignored if the test LEDs and the test fixture are small. Baffles are mandatory to avoid direct illumination from the LEDs under test reaching the detector and causing skewed readings.

4.3 Measurement conditions (general)[12]

LEDs can be measured under constant direct current (DC) operating conditions and in single-pulse operation mode. Under normal operating conditions (between the start-up range and steady-state condition) the optical radiation emitted by the LEDs is strongly correlated to the electrical current supplied.

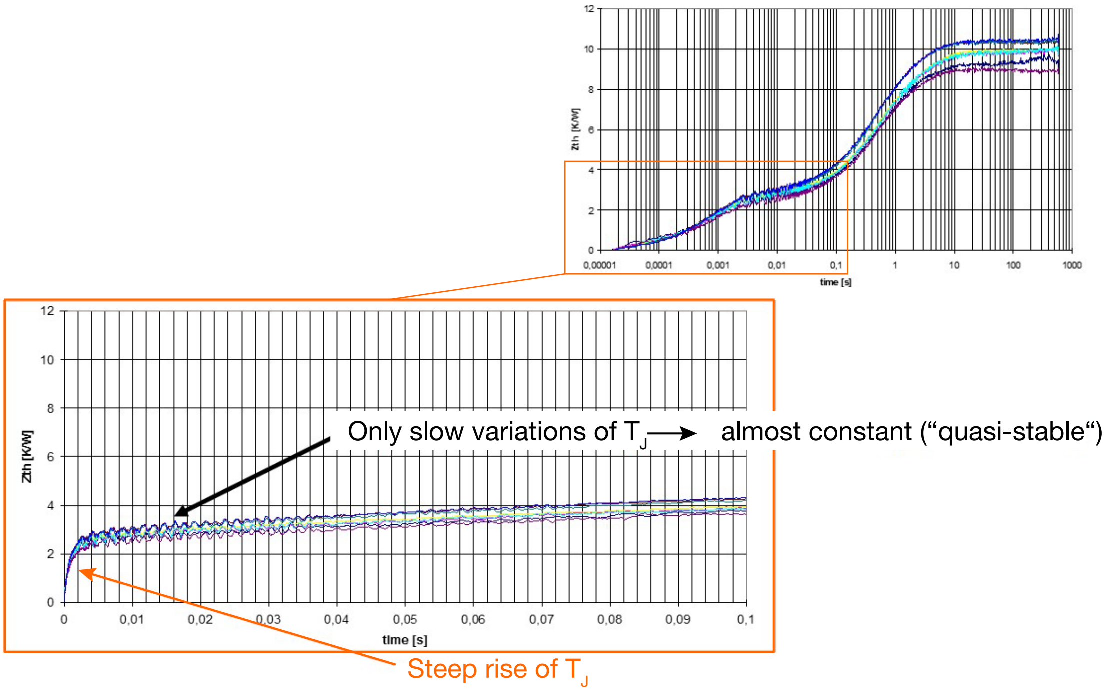
The constant direct current (DC) is used in most LED applications. Thereby the LEDs junction temperature can reach up to the device's maximum specified junction temperature, which can be as high as 175 °C. The light output and the spectral distribution change depending on the temperature of the pn-junction of the LED. LEDs are heating up during operating require a certain stabilization time before they reach the steady state (see Figure 8). High power LEDs require thermal heat management in the LED applications to prevent undesired degradation or device failure. As an effect of the LED behavior, the light output is reduced and the spectral power distribution changes at these higher temperatures. For good measurement results it is necessary to find a time-slot where the LED is not heated up too much and the temperature does not change significantly. Depending on the LED type the measurement setup is selected to reach reproducible and almost stable results.

For the most LEDs this is the case in a range of 25 ms. This shows the detail part of Figure 8, where only slow variations of T_J are pictured.

(11) [1] CIE 127:2007, Chapter 6.2.2.

(12) [9] CIE 225:2017; [10] 226:2017, High-Speed Testing Methods for LEDs; [2] DIN 5032-9; [11] IES LM-85-14, Electrical and Photometric Measurement of High-Power LEDs.

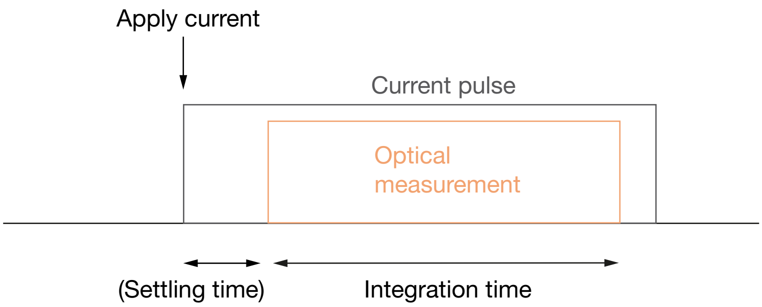
Figure 8: Transient thermal behavior of a typical LED



During production testing it is essential that electrical and optical measurements follow a well-defined sequence in order to ensure reproducible results. The rise of the temperature T_J in relation to time depends on the LED type. Every LED has a drop of luminous flux (Φv) when T_J rises. This leads to different measurement results between a pulse and a DC measuring.

LED manufacturers normally use the pulse operation mode to measure and bin the LEDs. Immediately before the measurement the current pulse is switched on, based on the assumption that the junction temperature is close to the ambient temperature, typically 25 °C. During production, the LEDs under test are pulsed with a constant current equal to that of normal operations but only lasting several or tens of milliseconds. A rectangular current pulse is applied to the LEDs under test and the electrical (voltage) and optical properties (color, luminous flux or intensity) are measured during this pulse. Figure 9 shows an example of a measurement sequence in the single-pulse operation mode. The heating of junction temperature must be taken into consideration because it influences the optical measurement. Hence, for most of our products the measurement time should be shorter than 20 – 30 ms to ensure reproducible results.

Figure 9: Example of a measurement sequence in the single-pulse operation mode



Exceptional cases of this timing are possible, for example for LEDs with a very low heat capacity or LEDs with long optical rise times caused by the phosphor. In the first case we have a significant shorter timing to reduce self-heating effects and in the second case we have after the start of the current biasing a delay time before starting the electro-optical measurements to ensure that the phosphor behaves like the DC case.

In all cases the timing of the measurement is mentioned in each datasheet in the glossary section. Figure 10 shows exemplary the footnote and glossary entry of a datasheet.

Figure 10: Example of the datasheet footnote and glossary for the measurement timing

Ordering Information

Type	Luminous Intensity [1]	Luminous Intensity [1]

Glossary

(1) **Brightness**: Brightness values are measured during a current pulse of typically 25 ms, with an internal reproducibility of ±8 % and an expanded uncertainty of ±11 % (acc. to GUM with a coverage factor of k = 3).

5 Measurement uncertainty[13]

A measurement provides the properties of the measured item, however it can never be absolutely accurate because it is always subject to a certain amount of uncertainty. For every measurement — even if it is performed using the most careful handling procedures, precise and accurate measuring equipment — there is always a margin of doubt.

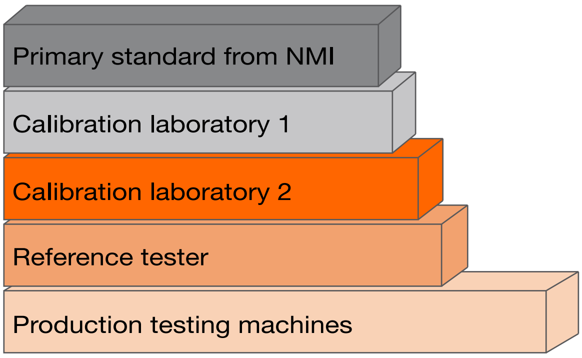
According to the ISO GUM definition[14], the measurement uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values which could reasonably be attributed to the measurand. In other words, it is the doubt that exists about the result of any measurement.

ams-OSRAM AG follows the recommendation of the ISO GUM guide to the expression of uncertainty in measurement to calculate its uncertainty. For the calculation of measurement uncertainty ams-OSRAM AG adds the variances (σ^2) of each subsequent calibration step starting with the variance of the primary standard, schematically shown in Figure 11. The uncertainty factors include NMI, the calibration laboratory, the reference tester and the testing machine. In Figure 11 the length of the beam represents the sum of the variances to this point, e.g. the dark orange beam represents the combined uncertainties of the primary standard for NMI, calibration laboratory 1 and calibration laboratory 2.

(13) [12] JCGM 100:2008, Evaluation of measurement data; [13] CIE 198:2011, Determination of measurement uncertainties in photometry; [14] CIE 198_SP1 Part 1-4., [8] CIE 225:2017, Chapter 10.

(14) [12] JCGM 100:2008, Chapter 2.2.

Figure 11: Pyramid of measurement uncertainties



The “absolute measurement uncertainty” reflects the full traceability of measurements including the primary standard and describes how much a measurement result determined by ams-OSRAM AG may reasonably deviate from the result established by the NMI. The term “internal reproducibility” only covers the measurements inside ams-OSRAM AG and describes, in principle, the consistency of measurements performed by ams-OSRAM AG across different sites and over time.

Both values are connected via the uncertainty of the primary standard established by the NMI (e.g. PTB in Germany):

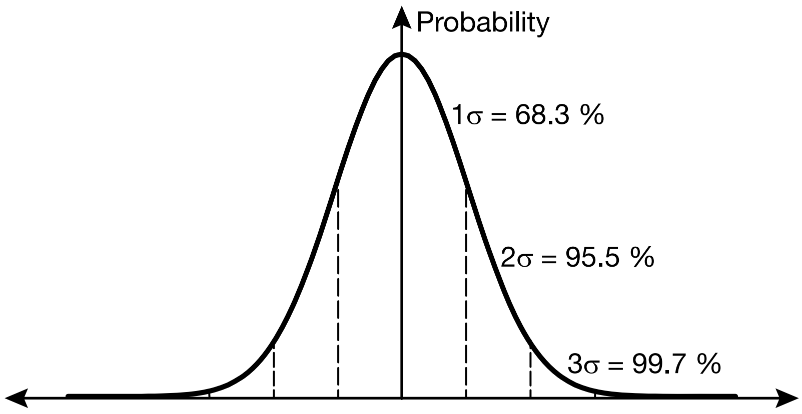
$$\sigma_{absolute} = \sqrt{\sigma^2_{primary} + \sigma^2_{internal\ reproducibility}}$$

Uncertainty (such as absolute measurement uncertainty or internal reproducibility) is reported in the form of the expanded uncertainty U. The expanded uncertainty U is obtained by multiplying the combined standard uncertainty σ by a coverage factor k, where k defines the level of confidence of the measurement.[15] Figure 12 shows the k values for a normal Gaussian distribution.

For example, an expanded measurement uncertainty with a k-factor of k = 2 allows 4.5 % of the measurements to be beyond the specific error limit. In comparison, for a k factor of k = 3 only 0.3 % of the measurements are allowed to be beyond the uncertainty range.

(15) [12] JCGM 100:2008, Chapter 6; [1] CIE 127:2017.

Figure 12: Gaussian distribution curve including k values



In cases where no k-factor is explicitly stated, a k-factor of k = 2 may be assumed, in accordance with international procedure.

Especially for LEDs in automotive applications, ams-OSRAM AG states its reproducibility and the coverage factor in the data sheet. For example, the brightness of LEDs can have an internal reproducibility of ± 8 % and an expanded uncertainty of ± 11 % with a coverage factor of k = 3, according to GUM.

6 Reference standards

Reference standards are usually provided by the respective National Metrology Institutes, NMI globally or ISO 17025 accredited laboratories. The NMIs such as NIST (US), PTB (Germany), NMIJ (Japan), KRISS (South Korea), NIM (China) and others provide reference standard lamps or LEDs including measurement uncertainty for calibration. The calibration reference standard light sources used at ams-OSRAM AG are traceable to the PTB (Physikalisch-Technische Bundesanstalt) – National Metrology Institute of Germany.[16]

7 Potential sources of measurement discrepancy[17]

There are many sources of errors, uncertainties and challenges that influence the measurement accuracy of LEDs, commonly stated as below.

1. LEDs are operated in different operating conditions, i.e. constant direct current (DC) and

(16) [3] G. Leschhorn, R. Young, Handbook of LED and SSL Metrology, Chapter 2.3

(17) [15] Technical Guide: Integrating Sphere Radiometry and Photometry, Chapter 7.5; [10] CIE 226:2017.

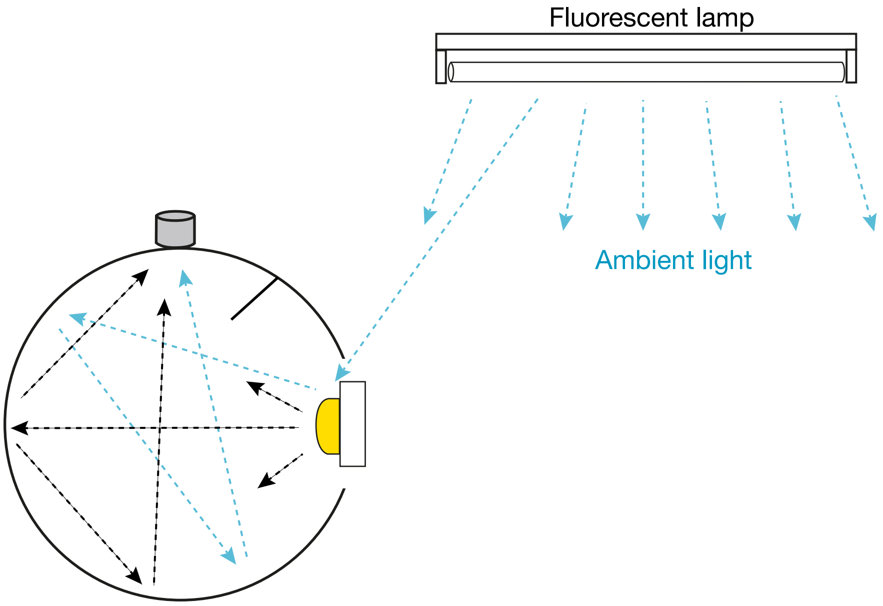
single-pulse operation mode. In single-pulse operation mode the current only flows through the LEDs for a few milliseconds during an optical test. This short period of time is not sufficient to guarantee a steady state. The values measured under these test conditions differ from those obtained under a steady state. As a result of this, different junction temperatures of the LEDs during optical measurement periods between DC and single-pulse operation mode are obtained. LED manufacturers usually provide information on how an LED's photometric values change over temperature for the user. For further information please also refer to chapter "8 Dependencies of ambient temperature and driving current".

2. Precise mechanical setup plays an important role in optical measurement. The LED position and its alignment on the test fixture are particularly important for the averaged LED intensity. Typically, the intensity of an LED follows the inverse square law, i.e. the intensity reduces with the square of increasing distance. Hence, for measurements of LED average intensity condition B, a distance error of only 2 mm results in a measurement error of 4 %.

3. In optical measurement, a stable and accurate current source must be taken into consideration as well. For the electrical contacting of the LED, it is advisable that the LED is operated using a four-wire system in order to ensure reliable V_F measurements for the LED device.

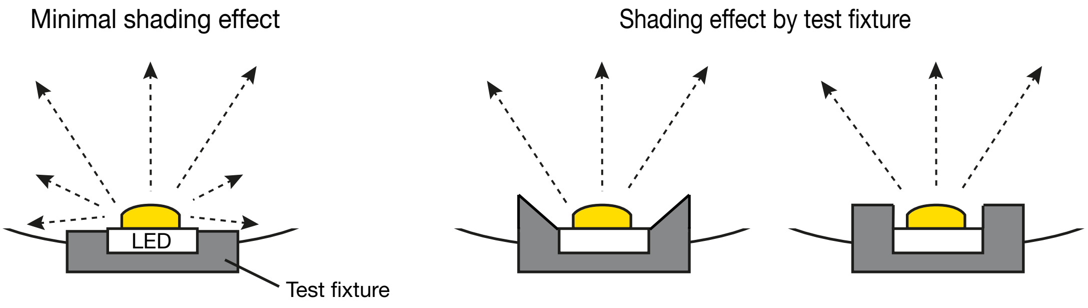
4. External influences such as ambient light must be taken into account as they contribute to the optical measurement error, especially for low biasing current LEDs with low light power. It is advisable to cover and protect the test station to prevent ambient light reaching the LEDs under test or the detector (see Figure 13).

Figure 13: Influence of ambient light contributing to the optical measurement error



5. Another influencing factor and noise to be considered in optical measurements is the undesired reflection or shading effect of the test fixture or the LED itself (Figure 14). The reflections from the test fixture reaching the detector may impact the optical measurement value. The mechanical test fixture shall not obstruct any radiation from the LEDs under test.

Figure 14: Shading effects



6. The measurement geometry setup also plays an important role in optical measurements. CIE 127 measurement of LED recommends a standardized geometry setup for luminous flux and average LED intensity. Using the same geometry setup ensures reproducible and comparable measurement results across different test stations.

7. The measurement gap between different national metrology institutes also contributes to the potential gap between different laboratories, as where it has been linked and referenced to the respective local NMIs. It is impossible that different NMIs can measure the same LEDs and give exactly the same absolute value. There must be certain measurement gaps due to the different setup, conditions, calibration, environment, handling method, equipment used and so forth, whereby these sources of uncertainty can be estimated and computed in accordance with the recommendation of GUM in accordance with the ISO guide to expression of uncertainty in measurement (GUM).

8 Dependencies of ambient temperature and driving current

Measurement differences might also occur from the differences between testing conditions in production and the consumer application conditions.[18] Therefore, examples are given below on how to calculate the junction temperature and the luminous flux from the supplier data.

Typically, higher temperatures reduce the radiation output. The pulse length of the driving current, the ambient temperature and the driving current itself all contribute to the higher temperature. The light output of an LED at a constant current varies as a function of its junction temperature. The steady-state junction temperature can be calculated using the following equation:

$$T_J = T_S + I_F \cdot V_F \cdot R_{thJSelec}$$

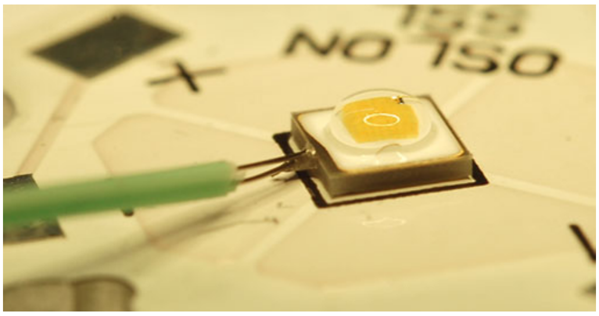
,where T_J is the junction temperature of the LED (°C), T_S is the solder pad temperature on the PCB (°C), I_F is the forward current of the system (A), V_F is the forward voltage of the system (V) and $R_{th\ JSel}$ is the thermal resistance of the LED according to the data sheet (K/W).

(18) [9] CIE 225:2017, [10] CIE 226:2017.

The solder pad temperature can be measured by using thermocouple wire as shown in Figure 15. The closer the thermocouple wire can be positioned to the LED the better.

For further information please also refer to the application notes "Thermal management of light sources based on SMT LEDs" and "Temperature measurement with thermocouples".

Figure 15: Placement of the thermocouple wire on the LED for T_S measurement



Example of the calculation of T_J for the OSLON Square GW CSSRM2.EM:

- Measured T_S = 80 °C
- I_F = 700 mA
- V_F = 2.8 V
- $R_{th\ Jselec}$ = 1.8 K/W

The junction temperature is calculated according to the previous equation:

- T_J = 80 °C + (0.7 x 2.8 x 1.8) °C
- T_J = 80 °C + 3.5 °C
- T_J = 83.5 °C

The expected lumen can be calculated from the T_J values.

Example for the calculation of the luminous flux for the OSLON® Square GW CSSRM2.EM and the OSLON® SSL 80° GR CS8PM1.23:

For example, Figure 16 shows the light output of the OSLON® Square GW CSSRM2.EM (White) and the OSLON® SSL 80° GR CS8PM1.23 (Red) as a function of the respective junction temperature. In general, the temperature dependency is less for InGaN LEDs (e.g. Blue, Green, White) than for InGaAlP LEDs (e.g. Red and Yellow).

1. The typical luminous flux of the OSLON® Square GW CSSRM2.EM at 3000 K CCT, 85 °C is 248 lm. The luminous flux (Lumen) for different junction temperatures can be calculated as

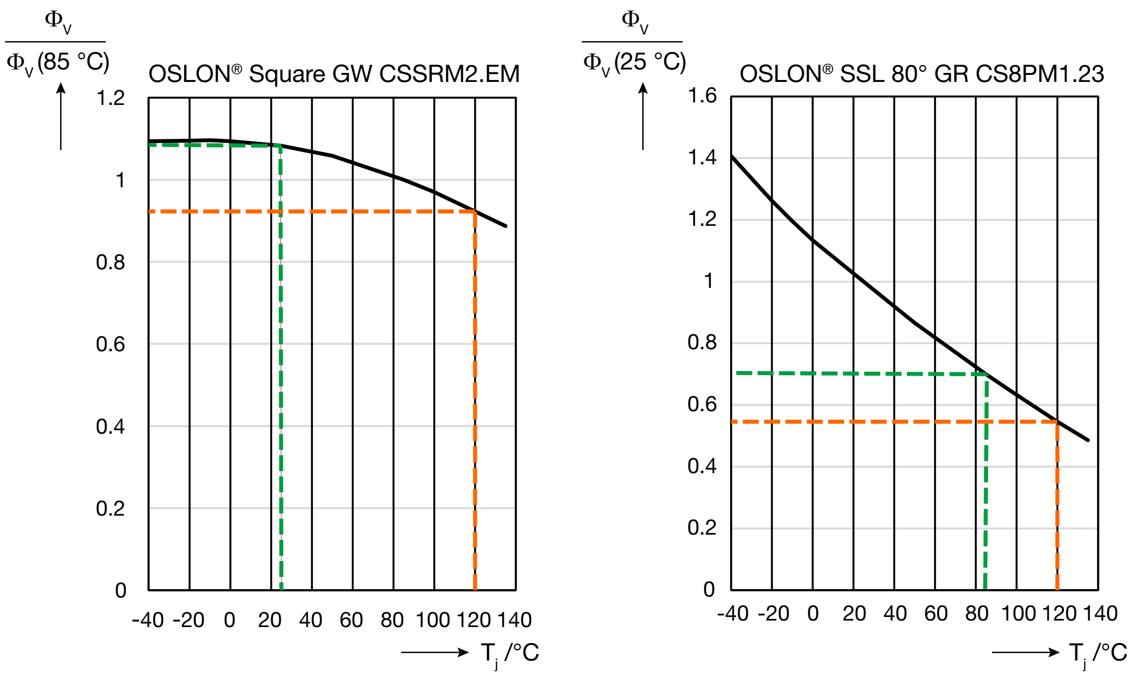
shown below:

- Φ_V (T_J = 85 °C) = 248 lm
- Φ_V (T_J = 25 °C) = 1.083 x 248 lm = 268.6 lm
- Φ_V (T_J = 120 °C) = 0.923 x 248 lm = 228.9 lm

2. The typical luminous flux of OSLON® SSL 80° GR CS8PM1.23 at 25 °C is 68 lm. The luminous flux for different junction temperatures can be calculated as shown below:

- Φ_V (T_J = 25 °C) = 68 lm
- Φ_V (T_J = 85 °C) = 0.700 x 68 lm = 47.6 lm
- Φ_V (T_J = 120 °C) = 0.546 x 68 lm = 37.1 lm

Figure 16: Relative light output as a function of the junction temperature



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[4] János Schanda, Colorimetry: Understanding the CIE System, John Wiley & Sons, Inc., 2007

[5] CIE 15:2004, 3rd edition Colorimetry

[6] CIE 170-2:2015 Fundamental Chromaticity Diagram with Physiological Axes — Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

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8141 Premstaetten Austria
Phone +43 3136 500-0
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