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Approved Method: Electrical and Photometric Measurements of High-Power LEDs

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INTRODUCTION

This document is a guide developed for the measurement of high-power light emitting diodes (LEDs), normally in a form of LED packages, used for lighting products. High-power LEDs are those that require a heat sink for their normal operation. The light output of an LED depends strongly on its thermal conditions, in particular, the junction temperatures T_j. Junction temperature, however, is difficult to measure. Various different methods have been used to operate LEDs for photometric measurements and the results could not be compared. This document provides uniform test methods for operation of high-power LEDs and test methods for photometric and colorimetric measurement of high-power LEDs.

The photometric measurement of high-power LEDs has been difficult because they are highly sensitive to thermal operating conditions, and there has been a lack of common methods that can be used by both LED manufactures and users to acquire reproducible results. LED manufacturers normally use pulse operation, whereby, LEDs are measured with no heat sink and with the underlying assumption that the junction temperature under these conditions is equal to the room temperature, typically 25°C. Therefore, published LED specifications are normally at junction temperature of 25°C. High-power LEDs in actual lighting products, however, are operating in DC and at much higher temperatures (typically junction temperature is 60°C to over 100°C), where their photometric and colorimetric values tend to deviate significantly from the room temperature condition. To assist users, LED manufacturers make efforts to provide thermal characteristics data for higher operating temperatures; however, because LEDs are usually binned by LED manufacturers for their optical and electrical characteristics at T_j equal to 25°C, manufacturer data for higher operating temperatures is of limited use. There have been no standard methods for measuring high-power LEDs at high temperatures. This document provides reproducible measurement methods of LEDs at a given junction temperature in pulse or DC mode and provides the grounds for specification of LEDs at high temperature conditions.

Lighting product manufacturers often need to know the performance of LEDs operating in full rated DC current at a thermal equilibrium at much higher temperatures than 25°C. To set or measure thermal conditions of the LED, "case temperature", "pin temperature", "board temperature", "solder-point temperature", or "heat sink temperature" are commonly used depending on the type of LED. While these methods are useful to reproduce the same condition for the particular LED, the results using these different methods cannot be compared with each other and cannot be reconciled into a universal standard method. Due to the optical characteristics of LEDs and their dependence on junction temperature, the only way to obtain reproducible results universally for all types of LEDs is by setting them to a specified junction temperature. The test method described in this document is to set the LED under test to a pre-determined junction temperature, for measurement at either pulse mode or DC mode operation. Such a method can establish equivalence of results between the pulse mode tests (normally performed by LED manufacturers) and the DC mode tests (often preferred by users of LEDs).

The photometric and radiometric information typically required for high-power LEDs for lighting products is total luminous flux (lumens), total radiant flux (watts), total photon flux (mol/s), and luminous efficacy (lm/W). The colorimetric information includes chromaticity coordinates (for all LEDs); correlated color temperature (CCT), Duv, and color rendering index (CRI) for white LEDs; dominant wavelength, centroid wavelength, and peak wavelengths (for colored LEDs). For the purpose of this document, the determination of these values are referred to as optical measurements.

The electrical characteristics typically required for high-power LEDs for lighting products are, input DC current, forward voltage, and input power. For the purpose of this document, the determination of these values are referred to as electrical measurements.

For special purposes, it may be useful to determine the characteristics of LEDs when they are operated at conditions other than the nominal conditions described in this approved method. When measurements are conducted at conditions other than the nominal conditions, the results are valid only for the particular conditions under which they were obtained; these conditions shall be stated in the test report.

1.0 SCOPE

This document describes the procedures to be followed and precautions to be observed in performing accurate measurements of total luminous flux, total radiant flux (optical power), total photon flux, electrical power, luminous efficacy, color quantities, and wavelength characteristics of high-power light emitting diodes (LEDs) including white LEDs as well as single color LEDs. This document covers LED packages (defined in ANSI/IES RP-16-10) including those with multiple chips and remote-phosphor LED packages. This document covers measurement under pulse operation as well as steady DC operation of LEDs, and in all cases, the thermal condition of LEDs refers to their junction temperature. The approved methods apply to laboratory measurements.

This document does not cover LED arrays or modules, nor LED lighting products; it does not cover AC driven LEDs, and does not apply to measurements in LED manufacturer's production control nor relative measurements of LED thermal characteristics.

2.0 NORMATIVE REFERENCES

2.1 ANSI/IES RP-16-10, *Nomenclature and Definitions for Illuminating Engineering.*

2.2 CIE S017/E:2011 ILV, *International Lighting Vocabulary.*

2.3 ISO 23539:2005(E)/CIE S 010/E 2004, *Photometry - The CIE System of Physical Photometry.*

2.4 ISO 11664-1:2007(E)/CIE S 014-1/E 2007, *Colorimetry – Part 1: CIE Standard Colorimetric Observers*

3.0 DEFINITIONS

3.1 Device Under Test (DUT)

High-power LED package under test.

3.2 Duv

The closest distance from the chromaticity coordinate of the light source to the Planckian locus on the CIE (u', 2/3 v') coordinates with "+" sign for above and "-" sign for below the Planckian locus.

3.3 Goniophotometer

Photometer for measuring the directional light distribution characteristics of sources, luminaires, media or surfaces. In this document, "goniophotometer" includes gonio-colorimeter and gonio-spectroradiometer.

3.4 Gonio-Colorimeter

Goniophotometer equipped with a tristimulus colorimeter head as the detector.

3.5 Gonio-Spectroradiometer

Goniophotometer equipped with a spectroradiometer as the detector.

3.6 Heat Sink

A device attached to an LED assembly (package, array or module) to dissipate heat.

3.7 High-Power LED

LED package that requires a heat sink or other means of thermal management for its normal operation.

3.8 National Metrology Institute (NMI)

A national laboratory that maintains the SI units for the country and authorized to disseminate calibration standards for measurements.

3.9 Photometer Head

A unit containing a detector, a $V(\lambda)$-correction filter, and any additional components (aperture, diffuser, amplifier, etc.) within the unit.

3.10 Remote Phosphor LED Package

An LED package containing a phosphor that is spatially separated from the pump or source radiation element, but contained within the LED package.

3.11 Settling Time

Time needed for a signal to reach a stable level after a fast transition.

3.12 Sphere-Photometer

Integrating sphere equipped with a photometer head as the detector.

3.13 Sphere-Spectroradiometer

Integrating sphere equipped with a spectroradiometer as the detector.

Note: This type of instrument measures total spectral radiant flux (unit: W/nm), from which total luminous flux, total radiant flux, and color quantities are obtained.

3.14 Temperature-Controlled Platform (TCP)

A device that incorporates a cooling and/or heating component(s) to maintain its temperature at a set value. TCP is used to control temperature of a high-power LED mounted on it for testing purposes. A thermoelectric cooler/heater is often used for a TCP. TCP is often also called temperature-controlled heat sink though it may provide heat to a DUT.

3.15 Thermal Chamber

A chamber used to maintain a local ambient temperature.

4.0 PREPARATION FOR MEASUREMENTS

4.1 Seasoning

Seasoning is not required for the methods described in this document.

4.2 Operating Orientation

The light emission process of an LED is not affected by orientation. The effect of thermal convection due to different operating position of the LED, if any, is considered negligible with the methods described in this document when the DUT's junction temperature is kept constant.

4.3 Thermal Conditions

4.3.1 Junction Temperature Photometric values and electrical characteristics of the DUT vary with the junction temperature, T_j. The junction temperature of the DUT can be set by the methods provided in **Sections 5** and **6**. Reports of photometric values of the DUT shall always include the junction temperature used in the measurement. T_j at 25°C is the nominal condition; however, elevated junction temperatures, e.g., 50°C to 100°C, may also be used to represent the temperature of the DUT operating in real applications.

4.3.2 Temperature Control of the DUT Using the ambient temperature to control the temperature of the DUT:

For operation in one of the pulse modes, the junction temperature of a DUT is set by the ambient air temperature. This method is suitable for the nominal condition (T_j at 25°C). This method is not preferred for elevated temperature conditions, as a thermal chamber will be required, which may make the total luminous flux measurement difficult.

Using a TCP to control the temperatue of the DUT:

This method is always used for the DUT operating in the DC mode and may also be used for the DUT operating in pulse modes. The temperature of the DUT is set by a TCP on which the DUT is mounted. This method is preferred for elevated temperatures when one of the pulse modes is used.

4.3.3 Ambient Temperature Ambient temperature, T_a is critical if it is used to set the junction temperature in pulse-mode measurement; conversely, if the junction temperature is controlled by a TCP, the effect of ambient temperature on the DUT's photometric output is insignificant, unless remote phosphor type LEDs, which are more sensitive, are used.

Generally, the ambient temperature is measured at a point not more than 0.5 m from the DUT and at the same height as the DUT. The temperature sensor should also be shielded from the direct radiation from the DUT.

5.0 METHODS OF MEASUREMENT UNDER PULSE-MODE OPERATION OF DUT

This section describes two methods for pulse-mode operation; single pulse mode and continuous pulse mode. Either method can be used.

5.1 General

In the pulse-mode methods, the DUT is operated using current pulses with the pulse widths sufficiently short enough that the increase in junction temperature is considered to be negligible; therefore, the junction temperature is assumed to be equal to the ambient air temperature. In many cases; however, the difference between ambient and junction temperature is not negligible, and corrections need to be applied. This method requires a pulse current source and optical measurement instruments that have capabilities to measure pulsed radiation from the DUT for photometric and colorimetric quantities.

5.2 Single Pulse Mode

In this operation mode, a single current pulse (normally the rated current) in a shape of rectangular form is applied to the DUT, and optical measurement is made quickly during the duration of the pulse. In this operation mode, the junction temperature of the DUT is assumed to be approximately the same as the ambient temperature if the pulse is short enough. Optical measurement of the DUT emission needs to be made within the duration of the pulse; therefore, the pulse width must be determined by the minimum integration time of the photometric or spectroradiometric instrument used. Typical minimum measurement time required by a fast array-spectroradiometer is several milliseconds, and it can be much longer depending on the instrument. **Figure 1** shows an example of the current pulse applied and timing of optical measurement in this method.

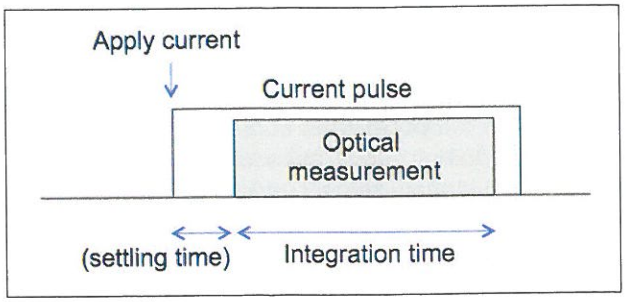

Figure 1. An example of measurement sequence in the single pulse mode

The junction temperature of the DUT may increase significantly during such duration of current pulse. The increase of junction temperature and the resulting decrease of the measured light output of the DUT should be evaluated, and the errors should be corrected if they exceed acceptable measurement uncertainties. The uncertainty of the measured photometric or colorimetric quantities, with respect to the value T_j at 25°C (or other set temperature), with or without correction, should be evaluated.

5.2.1 Ambient Temperature Condition The ambient temperature is critical if the junction temperature is set using the ambient temperature. In this case, the ambient temperature shall be within ±2 °C from the specified junction temperature for measurement (e.g., 55 °C), and it shall be measured and reported. If the ambient temperature is not in the specified range, corrections shall be made from the temperature dependence of the DUT characteristics so that results show the values at the required ambient temperature condition. In this case, the measured ambient temperature and the correction factor shall be reported.

The ambient temperature of the DUT shall be measured at the same height of the DUT and at a distance less than 0.5 m from the DUT. If the ambient air temperature is measured for sphere measurement, an alternative ambient temperature measurement can be made for the air temperature inside the sphere.

If a temperature-controlled platform is used to set the junction temperature, the ambient temperature is, therefore, not critical and the room temperature can be used. In this case, the ambient air temperature during the optical measurement of the DUT shall be measured and reported. For the DUTs of remote phosphor LEDs; however, the ambient temperature condition, ±2 °C from the specified junction temperature, shall be met.

5.2.2 Optical and Electrical Measurement Procedures The following measurement steps shall be taken:

Step 1: Temperature stabilization

Stabilize the temperature of the DUT to the desired junction temperature.

When using ambient temperature control: For the nominal temperature condition or elevated temperature condition using a thermal chamber, set the ambient temperature or thermal chamber air temperature to desired DUT's junction temperature. The DUT shall be turned off, and is thermally stabilized for a minimum of 30 minutes if the temperature of the DUT is not monitored. If the temperature of the DUT at its thermal contact point (pin, case, board) is monitored, it is considered stabilized if the monitored temperature remains within ±2°C from the specified junction temperature.

When using a TCP: Mount the DUT on the TCP, set the TCP temperature to the specified junction temperature, and wait until the TCP temperature reaches and stabilizes to the set temperature. The TCP temperature is considered stabilized if it remains within ±2°C from the specified junction temperature for at least 1 minute.

Step 2: Applying the current to the DUT

Turn the power on for the DUT and wait for the settling time as recommended by the DUT manufacturer for the type of DUT. If no recommendation is available, 5 milliseconds (ms) shall be used.

Step 3: Optical measurement

Complete the optical and electrical measurement within the time duration (quasi-stable time) recommended by the DUT manufacturer. If no recommendation is available, the time duration shall be less than or equal to 20 ms. It should be ensured that trigger timing for measurement is correct (see **Annex C**) and that measurement integration is done within the current pulse.

Step 4: Correction of result.

If necessary, corrections should be made for the effect of the estimated junction temperature rise, or add to measurement uncertainty budget.

5.2.3 Estimation of Uncertainty and Correction due to Junction Temperature Error The uncertainty of measurement related to the junction temperature rise should be estimated. An example of an analysis using a thermal model of the DUT is given in **Section B1** of **Annex B**. From the estimated rise of junction temperature, and the sensitivity coefficient of luminous flux or color quantities to junction temperature of the DUT, the error due to rise of junction temperature is estimated. Corrections should be applied if the estimated error exceeds the acceptable uncertainty of measurement. If the correction is applied, the correction method and correction factor shall be reported; residual uncertainty will still be present after the application of the correction factor. If correction is not made, the estimated error is considered to be a component of uncertainty.

5.3 Continuous Pulse Mode

In this operation mode, continuous current pulses (normally the rated current) with a very small duty cycle, e.g., 1%, at a certain frequency are applied to the DUT, and optical measurement is made for the time-averaged signal, similar to steady DC light measurement. With this method, the duty cycle must be small enough so that optical measurement errors due to the increase of junction temperature are within acceptable measurement uncertainty; if they are not, corrections shall be made. A duty cycle of 1% or less is recommended. **Figure 2** shows an example of current pulses applied and sequence of measurement in this method. D_w is the width of each current pulse and D_e is the period of repetition of pulse, so the duty cycle is given by D_w/D_e.

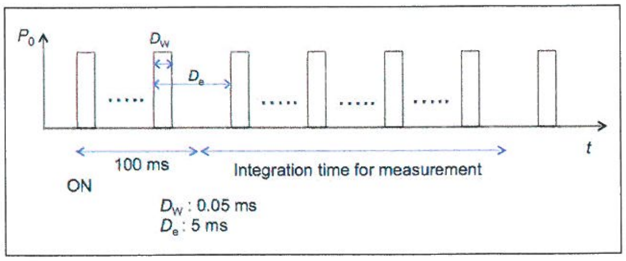

Figure 2. An example of measurement sequence in the continuous pulse mode.

In this method, because the duty cycle of the pulse is very low, the detector signals of instrument have very high peaks compared to the reading of the instrument. Special care should be taken so that photometric or spectroradiometric instruments are not saturated with the high peak emission of the pulsed DUT (**Section C2** of **Annex C**).

If the instrument is calibrated with steady DC light, the measured photometric output of the DUT, in principle, is divided by the duty cycle of the current waveform, to obtain the final value; thus, calibration of the duty cycle is critical, especially when the current pulse waveform is very short and not perfectly rectangular.

5.3.1 Ambient Temperature Condition The same requirements as **Section 5.2.1** apply for the continuous pulse mode.

5.3.2 Optical and Electrical Measurement Procedures The following procedures shall be taken.

Step 1: Temperature stabilization

Stabilize the temperature of the LED to the desired junction temperature.

When using the ambient temperature control: For the nominal temperature condition or elevated temperature condition using a thermal chamber, set the ambient temperature or thermal chamber air temperature to desired junction temperature, then the DUT shall be turned off and is thermally stabilized for a minimum of 30 minutes if the temperature of the DUT is not monitored. If the temperature of the DUT at its thermal contact point (pin, case, board) is monitored, it is considered stabilized if the monitored temperature remains within ±2°C from the specified junction temperature.

When using a TCP: Mount the DUT on the TCP, set the TCP temperature to the specified junction temperature and wait until the TCP temperature reaches and stabilizes to the set temperature. The TCP temperature is considered stabilized if it remains within ±2°C from the specified junction temperature for at least 1 minute.

Step 2: Applying the continuous pulse current

Wait for a specified settling time as recommended by the manufacturer for the type of the DUT. If no recommendation is available, 100 ms shall be used.

Step 3: Optical and electrical measurements.

Perform all measurements for a specified duration of integration time or read time-averaged signal in steady condition.

The integration time shall be exactly an integer multiple of the period of the pulses to avoid errors due to the timing of integration. (The DUT pulse and start of integration need not be synchronized.)

Step 4: Divide the measured photometric or radiometric values by the duty cycle of the current waveform.

Step 5: Apply corrections as necessary for the estimated rise of junction temperature, or add to the measurement uncertainty budget.

5.3.3 Estimation of Uncertainty and Correction due to Junction Temperature Error The uncertainty of measurement related to the rise of junction temperature should be estimated. An example of an analysis using a thermal model of the DUT for continuous pulse mode is given in **Section B2** of **Annex B**. Corrections should be applied if the estimated error exceeds the acceptable uncertainty of measurement. If the correction is applied, the correction method and correction factor shall be reported.

6.0 METHOD OF MEASUREMENT UNDER DC-MODE OPERATION OF DUT

6.1 General

The DC-mode method may be suitable for users of the DUTs who prefer to use photometric and colorimetric instruments designed for steady DC input. In this method, pulse measurements are required only for electrical quantities (current and voltage) to set the operating conditions of the DUT, and optical measurements can be performed for steady DC operation. This method requires a TCP, a pulse current power supply, and a fast volt meter to measure the forward voltage. Further information on this method is available in **Reference 1.**

6.2 Ambient Temperature Condition

In this method, since the junction temperature is controlled to constant, the ambient temperature is not critical and is typically the room temperature. Ambient temperature shall be measured and reported. Remote phosphor LED packages are not covered by this method.

6.3 Measurement Procedures

The following procedure shall be followed to set the junction temperature of the DUT.

Step 1: Mounting DUT

Mount a DUT on a TCP by using a MCPCB or any similar mounting technique.

Step 2: Setting temperature of TCP

Set the temperature of the TCP to the desired junction temperature , which shall be stabilized to within 0.5°C from the specified junction temperature. The DUT shall not be turned on and it shall wait for at least 1 min so the junction temperature of the DUT is stabilized to the temperature of TCP.

Step 3: Applying current to the DUT

Apply the rated DC current as a step pulse or a short pulse to the DUT and measure its instantaneous forward voltage, $V_F(0)$, immediately after the forward voltage is electrically stabilized (**Figure 3-a**); or, alternatively, apply multiple short pulses of the rated current to measure the $V_F(0)$ repeatedly for higher accuracy (**Figure 3-b**). For highest accuracy, the $V_F(0)$ is determined by fitting and extrapolating the $V_F(t)$ heating curve to t at 0 second (**Figure 3-c**).

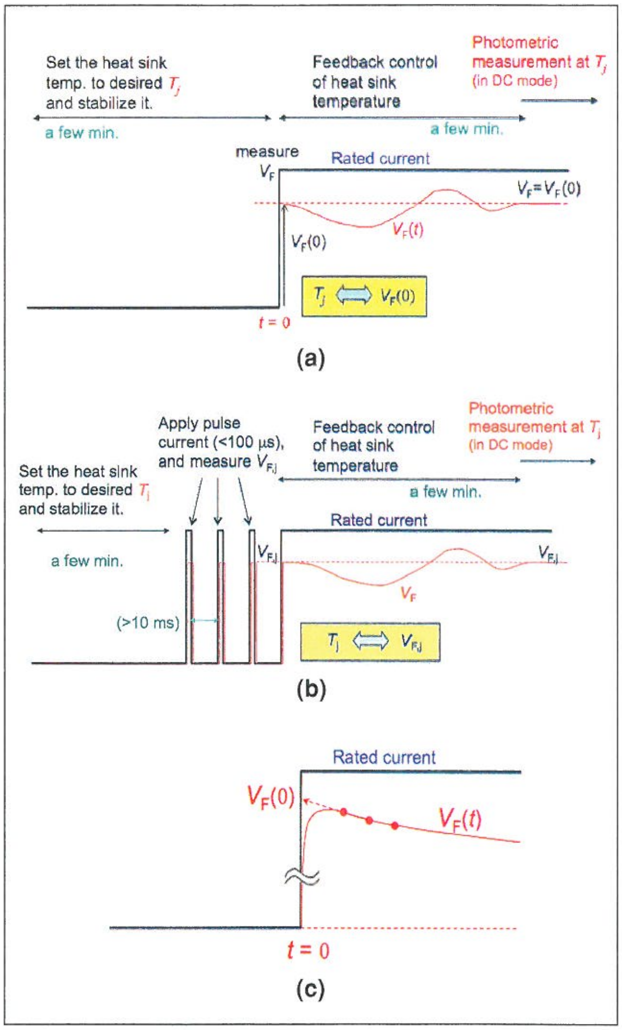

Figure 3. Illustration of the procedures to set an LED at a given junction

Step 4: Adjusting temperature of the TCP

While the DUT is kept operating on the specified DC current and heating up, adjust (lower) the temperature of the TCP, so that the measured V_F is equal to $V_F(0)$ and; thus, maintaining the same junction temperature when the DUT reaches the thermal equilibrium. This can be achieved by a feedback control. When V_F has stabilized to $V_F(0)$, the DUT is set to the specified junction temperature.

Step 5: Optical and electrical measurements.

Measure any optical (radiometric, photometric, and colorimetric) quantities of the DUT under the DC condition. The results obtained are values at specified junction temperature.

The timing in Step 3 should be determined depending on the type of the DUT. As an example for the DUT at 350 mA, the forward voltage stabilizes typically within 10 μs, and the V_F may be measured within 100 μs.

7.0 OPTICAL MEASUREMENT AND EQUIPMENT

The methods described here are applicable to both the pulse-mode method and DC-mode method. If the pulse-mode method is used, the photometer or the spectroradiometer shall have capability to measure optical pulses (**Annex C** for guidance).

One or more of the following instruments are used for the measurement of photometric, colorimetric and radiometric quantities.

a) Sphere-spectroradiometer (for total luminous flux, total radiant flux, photon flux, and color quantities);

b) Sphere-photometer (for total luminous flux);

c) Gonio-spectroradiometer (for luminous intensity distribution, total luminous flux, total radiant flux, color quantities, chromaticity spatial uniformity);

d) Goniophotometer (for luminous intensity distribution, total luminous flux);

e) Gonio-colorimeter (for luminous intensity distribution, total luminous flux, chromaticity spatial uniformity).

Note: See **Annex D** for guidance on selection of instruments.

7.1 Total Luminous Flux

Total luminous flux of the DUT shall be measured using a sphere-spectroradiometer, a sphere-photometer, or a goniophotometer satisfying the following requirements:

7.1.1 Sphere-Spectroradiometer A sphere-spectroradiometer shall be equipped with an auxiliary lamp. Self-absorption measurements shall be carried out and a correction made for each product under test, unless the correction factors are found negligible for the type of products to be tested.

The sphere-spectroradiometer should have appropriate geometries with a detector port, a light source under test, and an auxiliary lamp. Baffles shall be used between them to shield light.

Note: Common integrating sphere geometries for the DUT measurements are shown in **Annex E**.

The sphere-spectroradiometer shall cover the wavelength range of at least 380 nm to 780 nm for luminous flux and color measurement, and the bandwidth (full width half maximum) and scanning interval shall be no greater than 5 nm.

The spectroradiometer's input optics at the detector port of the integrating sphere (normally equipped with a diffuser) or the photometer head of the sphere-photometer shall have approximate cosine correction, with the f_2 value[6] of 15 % or less.

If the single pulse mode is used, a sphere-spectroradiometer or a sphere photometer shall have fast enough response for integration of such short pulses and shall have capability of measurement synchronized with the DUT current pulse. (**Annex C**)

A sphere-spectroradiometer shall be calibrated with a total spectral radiant flux standard traceable to an NMI. The standards shall be calibrated in appropriate geometries (2π or 4π) depending on the geometry of the sphere system used (**Annex E**).

Note 1: If total spectral radiant flux standard lamps are not available from the local NMI, the standard may be derived by the user from spectral irradiance standard lamp(s) and total luminous flux standard lamp(s); both shall be traceable to an NMI. In this case, the derivation methods and related data (e.g., angular uniformity of spectrum or correlated color temperature of the standard lamp) shall be reported.

Note 2: If total spectral radiant flux standard lamps suitable for the small integrating sphere used for the DUT measurement are not available from the local NMI, a method may be taken where the relative total spectral radiance flux is calibrated with radiation introduced into the sphere from an external spectral irradiance standard lamp and the total luminous flux scale can be calibrated against a luminous flux standard source (LED) traceable to an NMI. See **Annex E Figure E2** for such an example.

7.1.2 Sphere-Photometer A sphere-photometer shall have the total relative spectral responsivity (sphere plus photometer head) that meet the f1' value of 3% or less.

When single color DUTs are measured, spectral mismatch correction (see **Reference 7** and **Reference 8**) shall be applied to all measurement results, unless the DUT is compared with the same type of standard LEDs with the same peak wavelength within ±5 nm as that of the DUT.

The photometer head of the sphere-photometer shall have approximate cosine correction, with the f2 value of 15% or less.

A sphere-photometer shall be equipped with an auxiliary lamp. Self-absorption measurements shall be carried out and corrections made for each product under test, unless the correction factors are found negligible for the type of products to be tested.

A sphere-photometer shall be calibrated with total luminous flux standard lamps or LEDs traceable to an NMI. The standards shall be calibrated in appropriate geometries (2π or 4π) depending on the geometry of the sphere system used (**Annex E**)

Note 1: For white LEDs, spectral mismatch correction is not required but is recommended.

Note 2: If f_1' of the total sphere system is not available from the manufacturer, guidance on how to measure the relative spectral responsivity of a sphere-photometer system is available in **Section 6.3.2** of **Reference 7**.

Note 3: Guidance on how to measure f_1' and how to apply spectral mismatch correction is available in **Section 9.2.6** of **Reference 8**.

Note 4: Further guidance on construction and use of a sphere-spectroradiometer and a sphere-photometer for measurement of LED packages is available in **Annex E to K**.

7.1.3 Goniophotometer with a Photometer Head The photometer head shall have an f_1' value of 3% or less.

When single color DUTs are measured using a goniophotometer with a photometer head, spectral mismatch correction (see **Reference 7** and **Reference 8**) shall be applied to all measurement results, unless the same type of LEDs with the same peak wavelength within ±5 nm as the standard LED traceable to an NMI are measured.

Note 1: For white LEDs, spectral mismatch correction for a photometer head (ff_1' < 3%) is not required but it is recommended.

Note 2: Guidance for spectral mismatch correction is available in **Reference 7** and **Reference 8**.

The goniophotometer (except gonio-spectroradiometers) used for total luminous flux measurement shall be calibrated with a luminous intensity standard or illuminance standard traceable to an NMI, and measured total luminous flux value (lm) shall be verified by measuring total luminous flux of reference LEDs traceable to an NMI. Alternately, the goniophotometer may be calibrated against a total luminous flux standard lamp or LEDs traceable to an NMI.

Goniophotometers shall have an angular scan range covering the entire solid angle to which the DUT emits light.

The scanning interval for goniometric measurements depends on the smoothness and beam angle of the DUT. For total flux measurements, the interval required is very dependent on the erratic change of the luminous intensity distribution of the DUT measured.

For DUTs having near-Lambertian distribution, the minimum required half-plane interval is 22.5° and the angle interval within the vertical plane is 5°. DUTs that have rapidly changing luminous intensity distributions may require smaller intervals.

The range of the angular scan of a goniophotometer must cover the entire solid angle to which the DUT emits light. Note that some DUTs have emission over solid angles larger than 2π.

Note 3: Care should be taken to minimize stray light errors.

The goniophotometers should be installed in a dark enclosure with low reflectance wall surfaces so the errors due to reflections and stray light from surrounding surfaces are minimized.

The photometer head or the input of the spectroradiometer should be equipped with a hood or aperture screens so that it receives light only from the angle range in which the DUT is contained.

7.1.4 Gonio-Spectroradiometer Gonio-spectroradiometers shall be calibrated for spectral irradiance (unit: W sr^{-1} m^{-2} nm^{-1}) or spectral radiant intensity (unit: W sr^{-1} nm^{-1}) traceable to an NMI.

The spectroradiometer used in the gonio-spectroradiometer shall cover the wavelength range of at least 380 nm to 780 nm for photometric quantities, color measurement, and the bandwidth (full width half maximum) and scanning interval to be no greater than 5 nm.

The same requirement for scanning intervals described in Section 7.1.3 apply.

Note: Note 3 in Section 7.1.3 applies.

7.2 Luminous Efficacy

The electrical input power *P* (watt) of the LED under test shall be measured according to **Section 5** or **Section 6**. The luminous flux Φ_v (lumen) shall be measured according to **Section 7.1**.

The luminous efficacy (lm/W) of the DUT, η_v, is given by:

$$\eta_v = \frac{\Phi_v}{P} \tag{1}$$

Note: luminous efficacy described above is *luminous efficacy of a source* as defined in normative **Reference 2**. It should not be confused with *luminous efficacy of radiation* (symbol: *K*), which is the ratio of luminous flux (lumen) to radiant flux (watt) of the source.

Luminous efficacy (lm/W) may not be very useful for single color LEDs. Radiant efficiency (or external quantum efficiency) is often more useful for single color LEDs. The radiant efficiency of an LED, η , is given as the quotient of measured total radiant flux (optical power) Φ_e [W] and the measured electrical input power *P* [W] of the LED under test as:

$$\eta = \frac{\Phi_e}{P} \times 100\,[\%] \tag{2}$$

7.3 Total Radiant Flux

7.3.1 Using Sphere-Spectroradiometer or Gonio-Spectroradiometer Total radiant flux (unit: W) of the DUT may be measured using a sphere-spectroradiometer described in **Section 7.1.1** or a gonio-spectroradiometer, which shall meet the requirements in **Section 7.1.4**. Total radiant flux Φ_e is obtained from total spectral radiant flux Φ_e (λ) as:

$$\Phi_e = \int_\lambda \Phi_\lambda(\lambda)\,\mathrm{d}\lambda \tag{3}$$

7.3.2 Conversion Method For visible LEDs, if the total spectral radiant flux is not available, and if the relative spectral distribution of the LED *S*(λ) can be accurately measured, total radiant flux Φ_e [W] of an LED can be converted from the total luminous flux Φ_v [lm] by:

$$\Phi_e = \Phi_V \cdot \frac{\int_\lambda S(\lambda)\;\mathrm{d}\lambda}{K_m \int_\lambda S(\lambda)\,V(\lambda)\;\mathrm{d}\lambda} \quad (K_m = 683\ \mathrm{lm/W}) \tag{4}$$

7.4 Total Photon Flux

The total photon flux in the unit of mol s^{-1} is given by:

$$\Phi_p = \int_\lambda \frac{\lambda}{Nhc} \cdot \Phi_\lambda(\lambda)\mathrm{d}\lambda \tag{5}$$

where $\Phi_\lambda(\lambda)$ is the total spectral radiant flux, *N* is the Avogadro's number, *h* is Planck's constant, and *c* is the speed of light in a vacuum.

7.5 Luminous Intensity Distribution

Luminous intensity distribution of the DUT shall be measured with a goniophotometer or gonio-spectroradiometer described in **Section 7.1.3** or **Section 7.1.4**.

Luminous intensity distributions are measured as one of:

a) CIE Averaged LED Intensity A (at 31.6 cm distance, see **Reference 9**);

b) CIE Averaged LED Intensity B (at 10 cm distance, see **Reference 9**);

c) luminous intensity (at far field distance).

For luminous intensity a sufficient photometric distance should be used considering the effect of the lens in front of the chip, – generally, longer than 0.5 m is appropriate for DUTs that do not have a narrow beam angle.

7.6 Color Quantities

Color quantities to be measured for the DUTs include chromaticity coordinates (*x*, *y*) and/or (*u*', *v*') for all LEDs, and correlated color temperature (CCT), Duv, and general Color Rendering Index (CRI R_a) for white LEDs. The special CRI (R_i) is optional, but to be reported if required by the customer or regulations. Color quantities are calculated from the measured relative spectral power distribution of the DUT according to the definitions given in **Reference 10** for chromaticity coordinates and CCT,

Reference 3 for Duv, and **Reference 11** for CRI. Further characteristics used for single-color DUTs are described in **Section 7.7**.

The color quantities of DUTs shall be measured as spatially averaged values, with their value at each point weighted by the intensity and the solid angle, over the angular range where light is emitted from the DUT. Such spatially averaged color quantities are measured in the following instruments.

7.6.1 Sphere-Spectroradiometer A sphere-spectroradiometer automatically measures the spatially averaged spectral power distribution, from which spatially averaged color quantities can be calculated. The sphere-spectroradiometer to be used shall meet the requirements in **Section 7.1.1**.

7.6.2 Gonio-Spectroradiometer or Gonio-Colorimeter Spatially averaged color quantities can also be measured with a gonio-spectroradiometer or a gonio-colorimeter. In this case, the angular scan shall be made for at least two vertical planes at 90° apart (ϕ angle), and at 10° increments for vertical angle scan (θ angle) in each vertical plane. For DUTs with a narrow beam distribution, the θ angle increments shall be 1/10 or less of the beam angle (diameter of the angular cone emitting more than 1/2 of the peak intensity) but no larger than 10°. The color quantities and (relative) luminous intensity at each goniometer angle, which are used for the calculation of spatially averaged color quantities, shall be recorded over the angle range where the luminous intensity is more than 10% of the peak intensity.

The color quantity values are weighted by the solid angle (represented by the θ angle) and the luminous intensity of the point. An example of such calculation is available in **Section 12.2** of **Reference 8**.

If a gonio-colorimeter is used, the chromaticity at one of the angular points shall be measured with a spectroradiometer to calibrate the colorimeter head, and all measured results by the colorimeter shall be corrected based on the spectroradiometer reading.

Note: If necessary, chromaticity spatial uniformity can be measured using a gonio-spectroradiometer or a gonio-colorimeter. See **Section 12.5** of **Reference 8** for further guidance.

7.7 Wavelength Characteristics

The following quantities related to color or spectral distribution are used for single-color DUTs. Measurement results of one or more of these quantities should be reported per request.

7.7.1 Dominant Wavelength The dominant wavelength λ_d of a color stimulus is defined as:

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

Note: For characterizing DUTs, the reference achromatic stimulus should be an equi-energy spectrum, a stimulus whose spectral concentration of power as a function of wavelength is constant (sometimes known as illuminant E) and which has the chromaticity coordinates xE = 0,3333, yE = 0,3333.

7.7.2 Centroid Wavelength The centroid wavelength λ_c of a spectral distribution, which is calculated as the "center of gravity wavelength" according to the equation

$$\lambda_c = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot S_x(\lambda)\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} S_x(\lambda)\mathrm{d}\lambda} \qquad (6)$$

Note 1: Centroid wavelength is commonly used for single color LEDs, not for white LEDs.

Note 2: The centroid wavelength of typical LEDs may be strongly affected by the diminishing tails of the curve, where measurement uncertainty is increased due to the influence of stray radiation, noise effects, or amplifier offsets.

7.7.3 Peak Wavelength Peak wavelength λ_p is the wavelength at the maximum of the spectral distribution.

7.8 Uncertainties

If statement of uncertainty is required, follow the recommendations given in the **References 4** and **5**. For all photometric measurements, use expanded uncertainty with a confidence interval of 95%; thus, in most cases, using the coverage factor k=2.

To verify the measurement uncertainty, the measurement results of some DUTs can be compared with measurements traceable to an NMI.

8.0 ELECTRICAL MEASUREMENT AND EQUIPMENT

8.1 Pulse Current Source and Pulse Current/ Voltage Meter

In all the methods described in **Section 5** and **Section 6**, a pulse current source and a pulse current/voltage meter are required. Commercial instruments, called Source Measure Units (SMUs), can measure the peak current and voltage automatically synchronized with the current pulse; these instruments are suitable for this purpose.

8.2 Uncertainties

The uncertainty of the steady DC current and forward voltage measurements shall be less than 0.1%. The uncertainty of the pulse current/voltage meters, or SMUs, varies depending on the pulse width, and in any case, shall be less than 1%.

Note: Uncertainty here refers to relative expanded uncertainty with a 95% confidence interval, normally with a coverage factor k=2, as prescribed by standards. If the manufacturer's specification does not specify uncertainty as described here, then the manufacturers should be contacted for proper conversion.

9.0 TEST REPORT

The report shall list all pertinent data concerning conditions of testing. The report shall also list type of equipment, the DUT, and reference standards used. Typical items reported are:

a) Date of measurement and testing agency.

b) Manufacturer's name and designation of the DUT.

c) Measured quantities: total luminous flux, luminous efficacy, total radiant flux, radiant efficiency, chromaticity, etc.

d) Rated electrical values: electrical input power and forward current, nominal CCT (for white LED).

e) Method of measurement: single pulse, continuous pulse, DC mode, pulse width (for pulse modes), and duty cycle (for continuous pulse mode).

f) Junction temperature of the DUT and ambient temperature.

g) Instrument used: sphere-spectroradiometer, sphere-photometer, 2π or 4π geometry, goniophotometer.

h) Designation and type of reference standard used: wattage, 2π or 4π total spectral radiant flux standard lamp or standard LEDs, CCT for white LED standard or peak wavelength for single color LED standard.

i) Correction factors applied (e.g, self-absorption, spectral mismatch, etc.).

j) Optical measurement conditions (diameter of the sphere, radius of goniophotometer).

k) Measurement results: input current, forward voltage, power, total luminous flux, and/or total radiant flux.

l) Color quantities: chromaticity coordinates, CCT, Duv, CRI as applicable for white DUTs, , dominant wavelength, peak wavelength, or centroid wavelength, as applicable for colored LEDs.

m) Spectral power distribution (if applicable).

n) Bandwidth of spectroradiometer, if spectral distribution and/or color quantities are reported.

o) Other equipment used.

p) Statement of uncertainties (if required).

q) Deviation from standard operating procedures, if any

Table 1. Example table for measurement results for e) to l) and p)

Measurement Quantities	Result	Expanded Uncertainty (k=2) (if required)
Method of measurement	Single pulse mode	-
Pulse condition	Pulse width 20 ms	
Junction temperature	55° C	-
Photometric method	Sphere spectroradiometer (2π)	-
Reference standard	75W total spectral radiant flux standard lamp	-
Correction factors	Self-absorption	-
Photometric condition	0.5 m sphere	-
Input current	350.0 mA	0.5%
Forward voltage	4.083 V	0.5%
Electrical power	1.429 W	0.7%
Total luminous flux	67.0 lm	4.2%
Luminous efficacy	46.9 lm/W	4.3%
Total radiant flux	0.2127 W	4.2%
Radiant efficiency	14.9%	4.3%
Chromaticity coordinate u'	0.2407	0.0014
Chromaticity coordinate v'	0.5040	0.0027
Correlated color temperature	3421K	60 K
Duv	-0.0066	0.0014
CRI Ra	79.3	1.1

REFERENCES

1. Zong, Y. and Ohno, Y., 2008, *New Practical Method for Measurement of High-Power LEDs*, Proceedings, CIE Expert Symposium 2008, July 2008, Turin, Italy, CIE x033:2008, 1002-106 (2008).
2. ANSI-NEMA-ANSLG C78.377-2011 *Specifications for the Chromaticity of Solid State Lighting Products*, 2008.
3. ANSI/NCSL Z540-2-1997, U.S. *Guide to the Expression of Uncertainty in Measurement*, 1997.
4. ISO/IEC Guide 98-3:2008. *Uncertainty of measurement — Part 3:Guide to the expression of uncertainty in measurement* (GUM:1995).
5. IES LM-78-07, *Approved Method for Total Luminous Flux Measurement of Lamps Using an Integrating Sphere Photometer*, 2007.
6. IES LM-79-08, *Approved Method: Electrical and Photometric Measurements of Solid State Lighting Products*, 2008.
7. CIE 127: 2007 *Measurement of LED*, 2nd edition.
8. CIE 15:2004, *Colorimetry*, 3rd edition.
9. CIE 13.3-1995, *Method of Measuring and Specifying Colour Rendering of Light Sources*, 1995.

ANNEX A PULSE-MODE AND DC-MODE METHODS FOR LED OPERATION

This document describes pulse-mode methods for LED operation (**Section 5**) and DC-mode method for LED operation (**Section 6**) for measurement of LEDs at a specified junction temperature. The pulse-mode methods are normally used by LED manufacturers for measurement without using a temperature-controlled platform (at T_j=25°C) for fast measurement in-production process. The pulse-mode methods require fast optical measurements (in the order of tens of milliseconds) and it is generally more difficult to achieve low uncertainties (see **Annex B**). Optical measurement instruments designed for optical pulse measurement are required.

The DC-mode method, on the other hand, allows for optical measurements of LEDs in steady DC operation with no requirement of speed; therefore, allows using common photometric and colorimetric instruments used in the lighting industry, such as integrating sphere photometers and goniophotometers used for measurement of traditional lamps. Theoretically, the DC-mode method can set the junction temperature of a test LED at higher accuracy than the pulse mode operation. The uncertainty of the set T_j with this method is considered to be within ±1° C if correct procedures are taken, and the uncertainty in optical measurement due to error in T_j is considered practically negligible. Since optical measurement can be made in steady DC mode, optical measurements tend to be in lower uncertainty than in pulse mode.

ANNEX B ESTIMATION OF T_j RISE AND CORRECTION

B1 Analysis example for single pulse mode

A detailed thermal model of the LED and mount, if available, may be used to calculate the transient thermal characteristics of LEDs being tested using pulsed waveforms. These models represent the LED thermal path as a ladder network composed of thermal resistances and capacitances. Each resistor/capacitor pair defines a thermal time constant in the overall thermal response. Usually these time constants correspond to physical structures in the LED thermal path. Using this network and standard circuit analysis techniques, the LED junction temperature vs. time may be calculated for any arbitrary signal, such as the one-shot excitation signal.(See **References B1** and **B2**) A further reference on measurement of thermal resistance is available. (See **Reference B3**)

An example of analysis on a 3 W white LED with 50 ms pulse width is shown in **Figure B1**. In this example, the junction temperature rises by 16°C at 20 ms and 19°C at 50 ms pulse width. If optical measurements are made for such a pulse duration (e.g., from 5 ms to 25 ms), the measurement results, e.g., luminous flux and chromaticity, should be corrected for the average rise of junction temperature (approx. 15°C in the example above) during the optical measurement, based on the temperature dependence of photometric and colorimetric quantities (separately determined). If the estimated error is not significant and not corrected, it may be included in the uncertainty budget. The temperature dependence of luminous flux varies significantly with different products and typically from 0.1%/°C to 0.5%/°C.

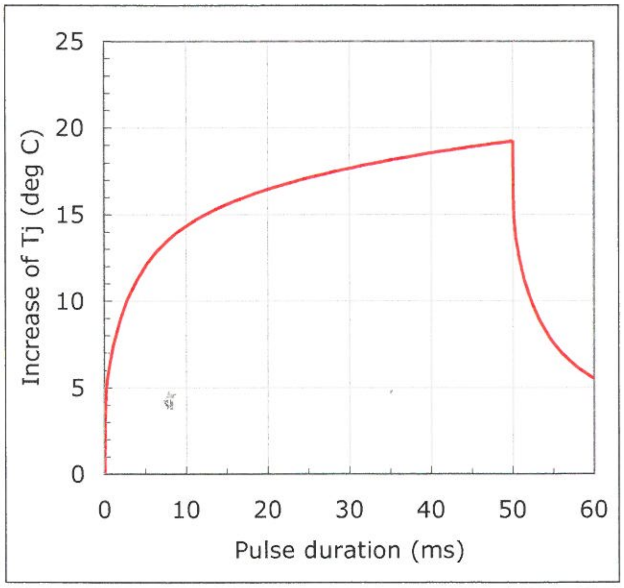

Figure B1. Example of pulse duration versus junction temperature rise.

B2 Analysis example for continuous pulse mode

The temperature of LEDs increases slightly even though the duty cycle is very small. In the case of such continuous pulse operation, the increase of the junction temperature ΔT, immediately before the fall of the pulse, can be calculated by the following equation:

$$\Delta T = \left\{ \frac{t}{T} \cdot R_{\mathrm{TH}} + \left(1 - \frac{t}{T}\right) \cdot r(t+T) + r(t) - r(T) \right\} \cdot P, \quad \text{(B1)}$$

where t is the pulse width, T is the period of the pulse, R_{th} is the thermal resistance of the LED (to the ambient temperature), $r(t)$ is the transient thermal resistance, and P is the electrical power of the LED. An example of $r(t)$ is shown in **Figure B2**.

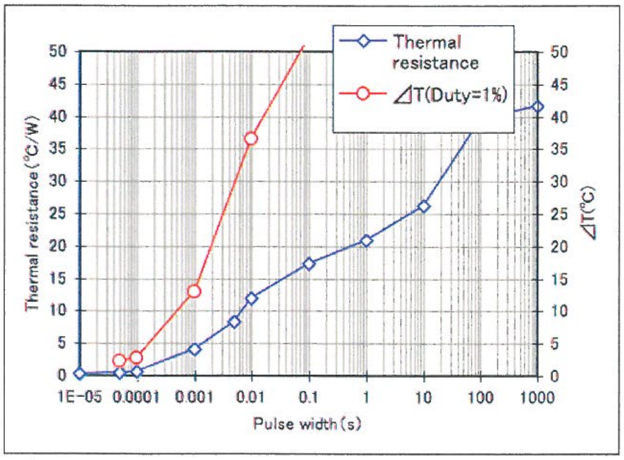

Figure B2. The transient thermal resistance of a typical high power LED

For example, for a 3W LED, with pulse width 0.05 ms and the period 5 ms (200 Hz with duty cycle 1/100), and using the $r(t)$ data in **Figure 2**, the increase of junction temperature will be ΔT ≈ 2.3°C. The error in measured photometric and colorimetric values can be estimated from this ΔT value and the data of temperature dependence of photometric quantities; thereby, allowing corrections to be made, or the uncertainty contribution to be calculated.

REFERENCES FOR ANNEX B

1. V.Székely, Tran Van Bien: "Fine structure of heat flow path in semiconductor devices: a measurement and identification method", Solid-State El, V.31, No.9, pp.1363-1368 (1988).

2. M. Rencz, A. Poppe, E. Kollár, S. Ress, and V. Székely "Increasing the Accuracy of Structure Function Based Thermal Material Parameter measurements", IEEE Transactions On Components And Packaging Technologies, Vol. 28, No. 1, March 2005.

3. JESD51-51, *Implementation of the Electrical Test Method for the Measurement of Real Thermal Resistance and Impedance of Light-Emitting Diodes with Exposed Cooling*, April 2012.

ANNEX C CAUTION FOR OPTICAL MEASUREMENT INSTRUMENTS FOR PULSE-MODE METHODS

C1 Single Pulse Mode

The optical measurement instruments must have a capability to measure optical pulse of short duration (e.g., 20 ms) synchronized with the current pulse. Junction temperature of an LED rises rapidly at the very beginning when the LED is powered on; thus, synchronization between the LED power supply and the spectroradiometer is critical. To ensure accurate synchronization, the hardware trigger mode (not software trigger) should be used. For example, "OUTPUT DONE" signal of the LED power supply is connected to the "TRIGGER" input of the spectroradiometer. Note that the software trigger mode is also available with software provided for power supplies and spectroradiometers; however, a software trigger mode is normally too slow, in some cases, it triggers a spectroradiometer to start measurement at 100 ms after the LED is turned on. Furthermore, timing of a software trigger is not reliable because it depends on the computer hardware, the operating system, and the number of programs running at the same time.

C2 Continuous Pulse Mode

The photometric or spectroradiometric instruments should have a capability to measure pulsed optical radiation accurately. It should be ensured that the detector and measurement circuit do not saturate with the very high peak detector output signal compared to the time averaged reading. If the duty cycle is 1%, the peak detector current is 100 times higher than the time-averaged reading of the pulse. Normal auto-ranging illuminance meters may not work properly for such pulsed light.

If a photometer head using a silicon photodiode is used, typical silicon photodiodes have linear response up to ~100 μA of photocurrent transient output; therefore, the time-averaged reading of the pulse current should be 1 μA or less at duty cycle 1% to ensure the detector does not saturate. This can be checked by testing the linearity of the photometer head. The linearity of the photocurrent amplifier can be tested with a signal generator creating, e.g., 1 μA steady DC current and rectangular current pulses with exactly 1% duty cycle with 100 μA peak current. The time-averaged reading of both signals should be the same if the amplifier works properly.

If an array spectroradiometer is used, its linearity should be tested for measuring such continuous pulses.

ANNEX D INTEGRATING SPHERE AND GONIOPHOTOMETER

Integrating sphere systems and/or goniophotometers are used for photometric, radiometric, and colorimetric measurements. There are two types of integrating sphere systems, one employing a photometer head (sphere-photometer), and another employing a spectroradiometer (sphere-spectroradiometer). Sphere-spectroradiometers are most commonly used for measurement of high-power LEDs. Sphere-spectroradiometers can measure total luminous flux, total radiant flux, photon flux, and luminous efficacy, as well as color quantities. Array spectroradiometers are commonly used. Sphere-spectroradiometers have an advantage in that, theoretically, they do not suffer from spectral mismatch errors; thus, making them suitable for measurement of single-color LEDs as well as white LEDs.

A sphere-photometer is a traditional type of instrument, using a photometer head as the detector for an integrating sphere. This type of instrument is acceptable but less preferred for measurement of LEDs. The spectral mismatch error can be significant for LEDs, especially for single-color LEDs. Spectral mismatch correction is recommended, and is required for measurement of all single-color LEDs. A sphere-photometer does not have the capability to measure color quantities.

Goniophotometers are used when angular intensity distribution is needed. For relative angular intensity distribution measurement, a goniophotometer with a photometer head is sufficient (even for single color LEDs). Goniophotometers can also be used to measure total luminous flux if they are calibrated for absolute scale and stray light is carefully controlled; however, the measurement suffers from spectral mismatch errors, and the measurement is time-consuming compared to integrating spheres. For both angular intensity distribution and color quantities, a gonio-spectroradiometer (goniophotometer equipped with a spectroradiometer) or a gonio-colorimeter (goniophotometer equipped with a tristimulus colorimeter) is available. Such an instrument can also measure the angular color uniformity of a light source. Note that spectral mismatch errors (from tristimulus colorimeter heads) are inevitable with a gonio-colorimeter, whereas a gonio-spectroradiometer does not suffer from spectral mismatch errors. For absolute chromaticity measurement with a gonio-colorimeter, its tristimulus head should be calibrated against a spectroradiometer using the DUT itself, or the same model of light source as the DUT.

General recommendations on photometric and colorimetric measurement of LEDs is also available in **Reference D1**; however, the operating condition or LED in this reference (only ambient temperature is specified) is not applicable to high-power LEDs. General recommendations for the use of integrating sphere photometers for luminous flux measurement are available in **Reference D2** and **Reference D3**. General guidance on use of spectroradiometers is given in **Reference D4**.

REFERENCES FOR ANNEX D

1. CIE 127: 2007 *Measurement of LED*, 2nd ed.
2. IES LM-78-07, *Approved Method for Total Luminous Flux Measurement of Lamps Using an Integrating Sphere Photometer*, 2006.
3. CIE 64:1989 *Measurement of Luminous Flux*, 1989.
4. IESNA LM-58-94, *Guide to Spectroradiometric Measurements*, 1994.

ANNEX E INTEGRATING SPHERE GEOMETRIES AND CALIBRATION METHODS

Integrating spheres used for LED measurements normally employ either 2π geometry, where the LED under test is mounted at the opening on the sphere wall, or 4π geometry, where the LED under test is mounted in the center of the sphere. Other geometries, including integrating hemispheres, are also used.

In any of the sphere geometries described above, the detector port (photometer head or spectroradiometer) must be shielded from the direct illumination from the LED under test. This is achieved by placing a baffle between the detector and the LED. An auxiliary lamp is installed to measure self-absorption, and it has a shield so that its direct light does not hit the detector or the LED under test.

Figure E1 shows common integrating sphere geometries for a sphere-spectroradiometer system. The 2π geometry (a) is suitable for a relatively small integrating sphere, or when the temperature-controlled platform is relatively large. The 2π geometry has an advantage over the 4π geometry, in that the temperature-controlled platform of an LED under test can be outside of the sphere so it does not affect self-absorption. (Relatively smaller spheres can be used compared to 4π geometry. If self-absorption is too large, it cannot be fully corrected by auxiliary lamp measurement.) In 2π geometry, it is also easy to mount the LEDs from outside the sphere without opening the sphere. This geometry requires a hemispherical (2π) standard lamp to calibrate the system.

The 4π geometry (b) is suitable for a large sphere, or when the temperature-controlled platform is relatively small. This system is calibrated either with an omnidirectional 4π standard lamp or a 2π standard lamp. High-power LEDs normally only have forward emission (2π), and; thus, either geometry may be used. In case a test LED has any backward emission (larger than 2π), the 4π geometry should be used.

A typical configuration of an integrating hemisphere is shown in **Figure E2**. This system has similar advantages as the 2π sphere geometry, in that it is easy to mount the LED and that the temperature-controlled platform of the LED is outside the hemisphere and does not affect self-absorption. Compared to the 2π integrating sphere, the integrating hemisphere has an advantage, in that the temperature-controlled platform does not affect self-absorption of the sphere as well as convenience in mounting LEDs. The flat cross-section

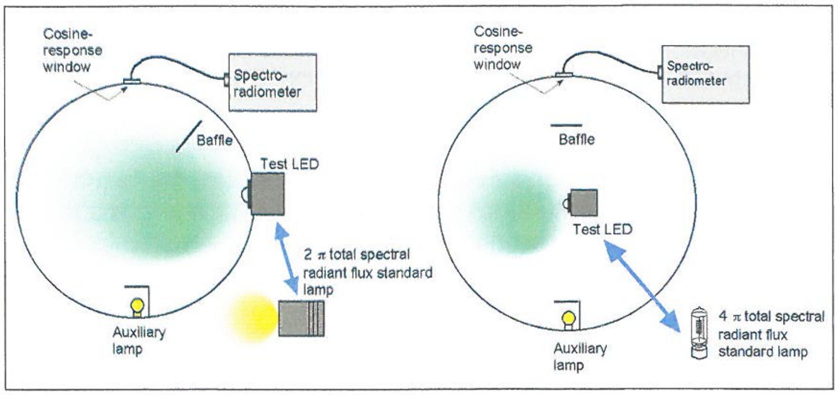

Figure E1 Common integrating sphere geometries for total luminous flux measurement using a sphere-spectroradiometer.

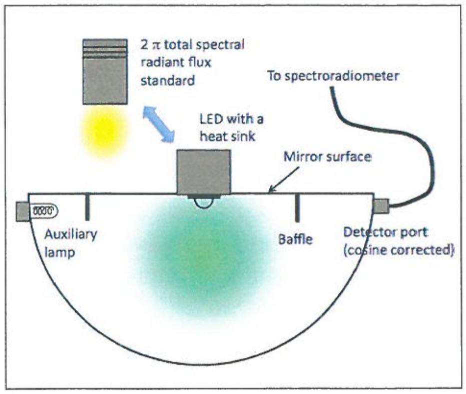

Figure E2 Typical configuration of an integrating hemisphere.

surface of the sphere must be a high-reflectance specular reflector. In principle, this system is suitable for measuring 2π sources (e.g., high power LEDs) and should be calibrated with a 2π standard lamp. It is not recommended to calibrate the system against a 4π standard lamp and measure 2π sources or vice versa.

Other sphere geometries are possible, e.g., the detector port and test LED in 2π geometry can be placed closer than the example shown in **Figure E1** (a). The auxiliary lamp and test LED can be placed closer as well; however, the detector port should not be placed on the other side of the sphere from the LED under test (in this case the baffle is in the direction of main beam from the LED, causing serious spatial nonuniformity of sphere responsivity).

The spectral radiant flux standard lamps should have sufficient spectral power throughout the visible region in order to calibrate the spectroradiometer with sufficient signal levels in its entire spectral range. Tungsten quartz halogen lamps (3100 to 3200 K) are commonly used as such standard lamps. The 2π standard can be a reflector-type quartz halogen lamp or some broadband white LED, and should have angular intensity distribution similar to those of the LEDs under test. Note that the light output of any incandescent standard lamp changes with the burning position. Standard lamps should be operated only in the specified burning position in which the lamp is calibrated.

The orientation of the whole sphere in **Figure E1** or **Figure E2** can be in any direction since the LED light output is not sensitive to its operating position, as its junction temperature is kept constant in this method. In other words, the figure can be taken as side-view or top-view; however, note that incandescent standard lamps are sensitive to operating position and they should be calibrated in the operating position to be used.

When a 4π geometry is used, the LED should not be mounted facing the bottom of the sphere because the bottom often has seams and tends to be contaminated; therefore, the error tends to be larger if the sphere is calibrated with an omnidirectional standard lamp.

In the 4π geometry, the size of the temperature-controlled platform, relative to the size of the sphere, should not be too large in order to avoid large errors in self-absorption correction. As a guideline, the total surface area of the LED temperature-controlled platform should be less than 2% of the total area of the sphere wall. This corresponds to, for example, a 5 cm x 5 cm x 5 cm temperature-controlled platform in a 50 cm sphere.

In the 2π geometry, the LED should be mounted flush with the sphere wall but slightly inside the sphere to ensure all emitted light from the LED (including sideway emission) can be collected by the sphere. The LED should never be recessed from the inner surface of the sphere.

In some cases appropriate total spectral radiant flux standard lamps of a desired power level or size may not be available. When the 2π geometry is used, an alternate calibration method is available. **Figure E3** illustrates such a method. This calibration method uses a spectral irradiance standard lamp (e.g., 1000 W FEL lamp) as an external source, but only the relative spectral distribution should be used to calibrate the system. The absolute scale of the spectroradiometer system should be given from calibrated total luminous/radiant flux standard lamps or LEDs traceable to an NMI. Deriving absolute flux scale from the spectral irradiance lamp is difficult and not recommended. When this method is used, the solid angle subtended by the spectral irradiance standard lamp and the opening of the sphere should not be larger than 0.03 sr. This corresponds to, for example, a 5 cm diameter opening at 25 cm distance from the lamp. Also, to avoid large absorption, the diameter of the sphere opening should not be larger than 1/4 of the diameter of the sphere.

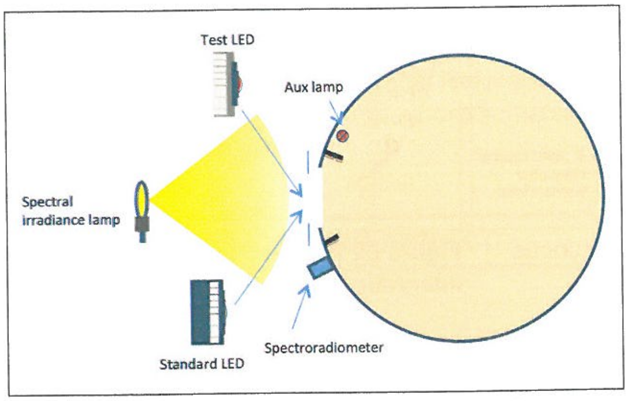

Figure E3. An alternate calibration method for a sphere-spectroradiometer system in 2π geometry.

ANNEX F GENERAL DESIGN OF INTEGRATING SPHERES

The size of the integrating sphere should be large enough to ensure that the measurement errors due to effects of baffle and self-absorption by the test LED are not significant. For measurement of high-power LEDs, the sphere size of 20 cm or larger is recommended. Spheres of 20 cm to 50 cm diameter are commonly used for LED measurement. The larger the sphere, the less errors exist for spatial nonuniformity (due to relatively smaller size of the baffle) and the less sensitivity to self-absorption; however, the signal is also less. As the power level of LEDs becomes higher, a larger sphere will be more appropriate. If the LED has enough light output, much larger integrating spheres, e.g., 1 m or 2 m diameter (typically used for measurement of traditional lamps) may also be used for measurement of high power LEDs.

The size of the baffle in **Figure E1**, and **Figure E2** should be as small as possible to shield the detector port from direct illumination from the largest size of the test LED to be measured or the standard lamp. In the 4π geometry, the baffle should be normally located at 1/3 to 1/2 of the radius of the sphere from the detector port.

An interior coating reflectance of 90% to 98% is generally recommended for the sphere wall, depending on the sphere size and usage of the sphere. Higher reflectance is advantageous for higher signal obtained (particularly for spectroradiometer), and for smaller errors associated with spatial nonuniformity of sphere response (intensity distribution variations of the LEDs measured). With higher reflectance; however, the higher sensitivity of sphere response to contamination of the sphere; thus, the sphere is less stable for long periods of time. Lower reflectance may be preferred where the sphere is heavily used and is not frequently calibrated as in the production environment.

The ambient temperature is not sensitive to the LED junction temperature if it is kept constant, and can be monitored outside the sphere. If ambient temperature is used as the junction temperature in one of the pulse-mode methods, the air temperature inside the sphere should be monitored. In this case, the temperature probe should be shielded from the direct emission from the test LED.

ANNEX G SELF-ABSORPTION CORRECTION

Self-absorption is an effect, in which the responsivity of the sphere system changes due to absorption of light by the light source itself in the sphere. Errors can occur if the size and shape of the test light source is different from those of the standard light source. The self-absorption correction is critical as the physical size and shape of the LEDs under test are very different from the standard lamp.

The self-absorption is measured using an auxiliary lamp installed in the integrating sphere. The auxiliary lamp for a sphere-spectroradiometer must emit broadband radiation over the entire spectral range where measurement has to be made. Normally, a quartz halogen lamp is used for this purpose. The auxiliary lamp should have a baffle so that its direct light does not hit any parts of the test LED or the detector port. Self-absorption is measured with the auxiliary lamp on, and the standard lamp or a test LED is mounted in the sphere but not turned on.

The self-absorption is wavelength dependent because the spectral reflectance of the sphere coating is not spectrally flat. The self-absorption factor is given by:

$$\alpha(\lambda) = \frac{y_{\mathrm{aux,TEST}}(\lambda)}{y_{\mathrm{aux,REF}}(\lambda)} \qquad \text{(G1)}$$

where $y_{\mathrm{aux,TEST}}(\lambda)$ and $y_{\mathrm{aux,REF}}(\lambda)$ are the spectroradiometer readings for the auxiliary lamp when the LED under test or the reference total spectral radiant flux standard, respectively, is mounted in or on the sphere (4π or 2π geometry). In this case, the LED and the reference standard are not operated. Only the auxiliary lamp is operated.

ANNEX H CALIBRATION OF SPHERE-SPECTRORADIOMETER

A sphere spectroradiometer must be calibrated against a reference standard of total spectral radiant flux. Since the integrating sphere is included in this calibration, the spectral throughput of the sphere need not be known. The total spectral radiant flux of an LED under test $\Phi_{\mathrm{TEST}}(\lambda)$ is obtained by comparison to that of a reference standard $\Phi_{\mathrm{REF}}(\lambda)$:

$$\Phi_{\mathrm{TEST}}(\lambda) = \Phi_{\mathrm{REF}}(\lambda) \cdot \frac{y_{\mathrm{TEST}}(\lambda)}{y_{\mathrm{REF}}(\lambda)} \cdot \frac{1}{\alpha(\lambda)} \qquad \text{(H1)}$$

where $y_{\mathrm{TEST}}(\lambda)$ and $y_{\mathrm{REF}}(\lambda)$ are the spectroradiometer readings for the LED under test and for the reference standard, respectively, and $\alpha(\lambda)$ is the self-absorption factor (see **Annex G**).

From the measured total spectral radiant flux $\Phi_{\mathrm{TEST}}(\lambda)$ [W/nm], the total luminous flux Φ_{TEST} [lm] is obtained by:

$$\Phi_{\mathrm{TEST}} = K_{\mathrm{m}} \int_{\lambda} \Phi_{\mathrm{TEST}}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda$$
$$(K_{\mathrm{m}} = 683\ \mathrm{lm/W}) \qquad \text{(H2)}$$

The total radiant flux (or optical power) $\Phi_{\mathrm{e,TEST}}$ [W] is obtained by:

$$\Phi_{\mathrm{e,TEST}} = \int_{\lambda} \Phi_{\mathrm{TEST}}(\lambda)\, \mathrm{d}\lambda \qquad \text{(H3)}$$

ANNEX I. USE OF SPECTRORADIOMETER

If one of the pulse modes (**Section 5**) is used, the spectroradiometer must be an array type and have the capability for pulse measurement. In single pulse mode (**Section 5.2**), the sampling must be synchronized with the pulse. When the DC-mode method (**Section 6**) is used, either mechanical scanning type or array type spectroradiometers may be used. The array spectroradiometer has the advantage of shorter measurement time. The spectroradiometer should have a minimum spectral range from 380 nm to 780 nm while the defined visible spectral region is 360 nm to 830nm[9].

The cosine response of the detector for an integrating sphere is very important. The input optics of the spectroradiometer (normally carried by a fiber bundle) should have an approximate cosine response. Typically a flat diffuser mounted flush to the sphere coating surface, is used. The directional response index f_2 (**Reference I1**) is required to be less than 15%. It should be noted that an optical fiber input (with no additional optics), often provided with array spectrometers, has a narrow acceptance angle and should not be used without additional optics for cosine correction.

Spectroradiometers measure photometric quantities without spectral mismatch errors theoretically; however, there remain many other sources of error associated with imperfection of the spectroradiometer. Major sources of error include wavelength accuracy, bandwidth, scanning interval, spectral stray light, detector nonlinearity, and input geometry.

It should be noted that, when an array spectroradiometer is used, errors due to spectral stray light tend to be large when deep blue LEDs (e.g. 400 nm to 450 nm peak wavelength) are measured. Due to the very low spectral power of an incandescent lamp in the deep blue region, significant stray light errors in the array spectroradiometer occur when it is calibrated against an incandescent lamp. It is recommended that the accuracy of the sphere-spectroradiometer system for blue LEDs be checked by measuring standard LEDs calibrated and traceable to the standards from an NMI.

The spectrometer stray light will be much more serious for UV LEDs. Array spectrometers calibrated with a tungsten halogen lamp are not recommended for measurement of UV LEDs unless special correction techniques are used. Array spectrometers, if calibrated with a UV standard source, may be acceptable for measurement of UV LEDs.

The bandwidth and scanning interval are critical for accuracy of color measurement of LEDs, and are required to be 5 nm or smaller. General guidance on the use of spectroradiometers are found in **Reference I2**.

REFERENCES FOR ANNEX I

1. CIE S 023/E:2013, *Characterization of the Performance of Illuminance Meters and Luminance Meters*, 2013

2. IESNA LM-58-1994, *Guide to Spectroradiometric Measurements*, 1994.

ANNEX J OTHER SOURCES OF ERROR

Errors can also occur when measuring the total luminous flux (lm) of blue LEDs due to fluorescence of integrating spheres. The coating materials themselves generally do not fluoresce, but contamination due to dust particles etc., causes fluorescence and is more problematic with older integrating spheres. This is normally not a problem for measuring white light sources; however, the error can be large for blue LEDs because the fluorescence will appear at the longer wavelength region where the value of V(λ) is much higher and the fluorescence error is magnified. To check such fluorescence of the sphere, the spectrum of a blue LED measured by a sphere-spectroradiometer can be compared with that measured by the directional measurement of the LED spectrum measured outside the sphere (in this case, relative spectral irradiance is measured). It is preferable to use the same spectroradiometer for this comparison (the spectroradiometer is calibrated in each geometry). The difference in the spectral distribution curves at the wing of the LED spectra in the green region would show the fluorescence, assuming that the blue LED's spectrum is constant over different angles. Correction can be made by analyzing such data, if necessary.

Wavelength scale accuracy and bandwidth of the spectroradiometer also affect the accuracy of measurement, especially for total luminous flux for single color LEDs, where the peak wavelengths are at the steep part of the V(λ) function.

ANNEX K SPHERE-PHOTOMETER SYSTEM

This method is a traditional approach of integrating sphere photometry, using a photometer head as the detector for an integrating sphere. This method is less preferable but acceptable for measurement of white LEDs, and generally not recommended for single color LEDs due to the potential for very large spectral mismatch errors. This method may be used for single color LEDs only if strict substitution (calibration against standard LEDs of the same color) is followed or spectral mismatch errors are corrected.

The recommended integrating sphere geometries for this method are similar to those in **Figure E1**, with the spectroradiometer replaced by a photometer head. All the descriptions in **Annex E** apply for this method except that the reference standard lamp is the total luminous flux standard.

The reference standard should be a white LED if white LEDs are measured, and a single color LED if single color LEDs are measured. Traditional incandescent luminous flux standard lamps may be used only if the spectral mismatch correction is applied. The standard white LED should have similar correlated color temperature as that of the test LEDs. Unless spectral mismatch corrections are applied, single color LEDs should be calibrated against a standard LED having the same color with the peak wavelength within ±5 nm. If many different colors of LEDs are measured, standard LEDs of many different colors are required. It is further desirable that the standard LEDs also have similar angular intensity distributions as the test LEDs.

The auxiliary lamp does not have to be an incandescent lamp. It is advantageous to use a stable LED that has a spectral distribution similar to those of the LEDs measured, so self-absorption is measured more accurately. The auxiliary lamp should be stable throughout the self-absorption measurement of all LEDs under test.

Measurement principles: The total luminous flux of the test device is obtained by comparison to that of a reference standard:

$$\Phi_{\mathrm{TEST}} = \Phi_{\mathrm{REF}} \cdot \frac{y_{\mathrm{TEST}}}{y_{\mathrm{REF}}} \cdot \frac{F}{\alpha} \qquad \text{(K1)}$$

where Φ_{REF} is the total luminous flux (lumen) of the reference standard, y_{TEST} and y_{REF} are the photometer signals for LED under test and for reference standard, respectively. F is the spectral mismatch correction factor (**Reference K1** and **Reference K2**), and α is the self-absorption factor (see **Annex G**).

If strict substitution is followed, F=1 should be used, but note some errors will still be present due to the spectral mismatch of the photometer to V(λ) and the difference in spectral distribution between the test LED and standard LED. To reduce measurement uncertainties, it is possible to correct such errors. See **Reference K1** and **K2** for the details of such spectral mismatch correction.

The self-absorption factor α can be measured by:

$$\alpha = \frac{y_{\mathrm{aux,TEST}}}{y_{\mathrm{aux,REF}}} \qquad \text{(K2)}$$

where $y_{\mathrm{aux,TEST}}$ and $y_{\mathrm{aux,REF}}$ are the photometer signals for the auxiliary lamp when the LED under test or the total luminous flux reference standard, respectively, is mounted in or on the sphere (2π or 4π geometry). They are not operated; only the auxiliary lamp is operated. The auxiliary lamp can be an incandescent lamp or a white LED.

The photometer head should have relative spectral responsivity well matched to the V(λ) function. The spectral throughput of the sphere also affects the total spectral responsivity. The f'_1 value of the total sphere system (photometer head plus integrating sphere) should be less than 3%. See **Reference K3** for the details of f'_1 value.

The photometer head should have an approximate cosine response with the f_2 value (directional response index) (**Reference K3**) of less than 15%, and the diffuser surface should be mounted flush to the sphere coating surface. If a satellite sphere is used for cosine response, its opening should not be recessed; the opening edges of the satellite sphere should be flush to the integrating sphere coating surface.

If one of the pulse modes (**Section 5**) is used, the photometer head should have the capability for pulse measurement (e.g., equipped with a photocurrent integrator). In single pulse mode (**Section 5.2**), the photometer head should have very fast response and the sampling should be synchronized with the pulse. In the continuous pulse mode (**Section 5.3**), it should be ensured that the photodiode response and amplifier outputs are not saturated with the high peak of optical pulses and the detector has linear response.

The major source of error in this method is probably the spectral mismatch errors. Even if the substitution method is followed, there are some differences in spectra between the standard LED and test LED, and some errors occur due to the imperfect match of the system responsivity to V(λ). **Reference K1** and **K2** if this error needs to be corrected.

If strict substitution with standard LEDs of the same color is performed, the errors due to sphere fluorescence for blue LEDs tend to be cancelled out; however, if the sphere is calibrated with an incandescent standard lamp, the errors due to sphere fluorescence will not be cancelled and can be very large for blue LEDs.

The sphere-photometer system should be calibrated against total luminous flux standards and/or total radiant flux standards traceable to an NMI.

If the sphere-photometer system is calibrated with an incandescent standard lamp (applying spectral mismatch correction), the system should be tested initially and periodically by measuring LEDs calibrated and traceable to an NMI; the results in total luminous flux or total radiant flux should be compared. The test should use calibrated LEDs of different colors if LEDs of various colors are measured. If the discrepancy is larger than the expected uncertainty, correction factors for each type (color) of LED should be introduced.

REFERENCES FOR ANNEX K

1. IES LM-78-07, *Approved Method for Total Luminous Flux Measurement of Lamps Using an Integrating Sphere Photometer*, 2006.
2. IES LM-79-08, *Approved Method: Electrical and Photometric Measurements of Solid State Lighting Products*, 2008.
3. CIE S 023/E:2013, *Characterization of the Performance of Illuminance Meters and Luminance Meters.*

ANNEX L GONIOPHOTOMETRIC METHOD FOR TOTAL LUMINOUS FLUX

Goniophotometers are used for measurement of luminous intensity distribution, from which total luminous flux can also be obtained. Total luminous flux or total radiant flux can be measured with a goniophotometer or a gonio-spectroradiometer without the problems specific to integrating spheres (fluorescence for blue LEDs, spatial nonuniformity, etc). Any type of goniophotometer can be used, as the operating position of LEDs normally does not affect measurement results.

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

$$\Phi = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I(\theta,\phi)\sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi \qquad \text{(L1)}$$

or if the photometer head is calibrated for measuring illuminance $E(\theta,\phi)$,

$$\Phi = r^2 \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} E(\theta,\phi)\sin\theta \, \mathrm{d}\theta \, \mathrm{d}\phi \qquad \text{(L2)}$$

where r is the rotation radius of the reference plane of the photometer head. A sufficiently long photometric distance, *r*, is required for measurement of luminous intensity distribution.

The distance requirement is not critical if only total luminous flux is to be measured. As indicated by **Equation (L2)**, as long as the illuminance is measured accurately, the total luminous flux can be measured accurately even with a relatively short photometric distance (radius *r*); thus, less space for the goniophotometer is required for a given size of light source to be measured. In this case, the detector must have cosine corrected angular responsivity within its field of view for the test LED package measured. By definition given in **Equation (L2)**, the location of the light source relative to the rotation center is theoretically not relevant and; therefore, the alignment of light source is not critical for measurement of total luminous flux.

The goniophotometer should be calibrated as the absolute photometry method, which measures the light output of the light source directly with reference to a calibrated standard. This type of measurement requires careful evaluation of the responsivity of the goniophotometer's photodetector/amplifier system. With this method, it is necessary to obtain an absolute factor (k) for the photometer using a luminous intensity (candela) standard lamp traceable to an NMI, a total luminous flux (lumen) standard lamp traceable to an NMI, or by directly comparing the goniophotometer's detector system to a detector calibrated for illuminance responsivity traceable to an NMI. It is suggested, but not required, that the absolute factor be established using one of the traceable calibration standard pathways, and then validated within the goniophotometer's uncertainty budget with one of the other traceable pathways.

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