Light Emitting Diode

Luminous Flux Measurement

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1. Overview

LEDs are used in various applications such as luminaries. In order to meet the performance such as brightness, color, etc. desired for the chosen application, suitable product design and evaluation should be selected. Measurement plays an important role in evaluating product performance. Measurement is fundamental to manufacturing activities because quantitative evaluation can be achieved only by quantifying the product performance through measurement. However, the actual values obtained from measurement vary depending on various factors such as measurement methods, equipment, and environments. In order to perform a highly accurate measurement, it is necessary to fully understand the measurement concept together with the characteristics of LEDs.
This application note explains luminous flux measurement that is generally used to evaluate LEDs, the precautions, and the traceability system.

2. Luminous Flux Measurement

Luminous flux measurement is generally performed by using either an integrating sphere or a directivity measurement system. Both of these instruments have their pros and cons as shown in Table 1. Considering these pros and cons, customers should select the appropriate measurement instrument depending on the type of light source and the characteristics of light that need to be measured. Sections 3 and 4 explain the considerations when selecting the instrument used for luminous flux measurement.

Table 1. Pros and Cons of the Measurement Instruments

	Integrating Sphere	Directivity Measurement System
Pros	- Short measurement time - Dark room and a complicated instrument are not required	- Able to measure directivity characteristics - Able to measure large-sized light sources
Cons	- Size of the light source that can be measured is limited - Measurement errors due to self-absorption of the light source	- Requires a long measurement time - Requires a dark room and a complicated instrument

3. Integrating Sphere Measurement

3.1. Integrating Sphere

An integrating sphere, as its name implies, is an optical measurement instrument with a spherical shape. The inside surface is covered with a highly reflective coating and the light incident on the inner surface is evenly distributed to the surface by multiple scattering and reflections. By measuring the illuminance of the light evenly distributed to the inner surface, the total luminous flux is obtained without being affected by the directivity characteristics of the light source (see Figure 1.).
As listed in Table 1, integrating sphere measurement has advantages such as the measurement time is short, a dark room or a complicated instrument is not required. Due to these advantages, an integrating sphere is the most widely used instrument for luminous flux measurement. However, since the measurable size of the light source is limited by the diameter of the integrating sphere, it is suitable for measuring relatively small light sources. The typical characteristics (luminous flux, chromaticity,

color rendering, etc.) detailed in the specifications for Nichia's LEDs are obtained by using an integrating sphere[1].

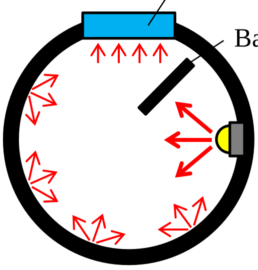


Figure 1. Image of an Integrating Sphere

3.2. Precautions for Luminous Flux Measurement

Figure 2 shows an example of a configuration of an integrating sphere measurement system. The luminous flux of a device under test (DUT) can be obtained by measuring the light that is sufficiently diffused and uniformly scattered inside the integrating sphere with a spectroscope or illuminometer and then comparing it with the measured value of a standard light source that has a known reference value. In an integrating sphere, the direct illumination from the DUT that can cause measurement errors is shielded from the detector with a baffle. There are various other factors that contribute to measurement errors and uncertainties.
This section explains five main factors leading to measurement errors during an integrating sphere measurement: 1. integrating sphere measurement configurations, 2. sizes of integrating spheres, 3. self-absorption of the light source, 4. types of standard light sources, and 5. LED temperature characteristics.

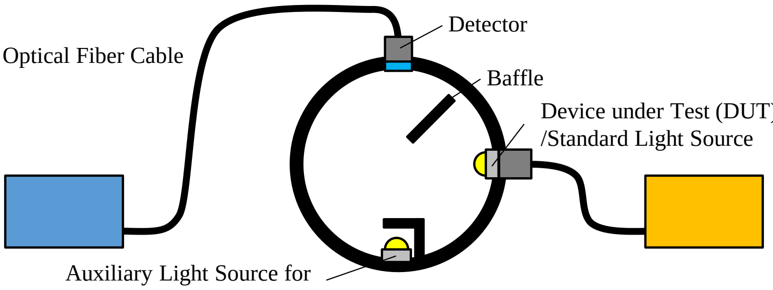


Figure 2. A Configuration of an Integrating Sphere Measurement System

3.2.1. Integrating Sphere Measurement Configurations

There are two common sphere measurement geometries: 2π and 4π configurations. A 2π configuration is used for 2π-space (180-degree field) measurement to evaluate a forward emitting light source. On the other hand, a 4π configuration is used for 4π-space (360-degree field) measurement to evaluate an omnidirectional light source. Since the 2π configuration does not need to measure a backward emitting light, the diameter of the integrating sphere can be reduced. However, the measurable sizes

[1] Instead of using an integrating sphere, other measurement instruments that are correlated with Nichia's internal standard light source may be used in Nichia's sorting process for mass-produced LEDs.

and types of light sources that can be used for this configuration are limited; thus, it is necessary to select an integrating sphere that is suitable for the directivity.

Figure 3 shows examples of the different integrating sphere measurement configurations. For typical surface mount LEDs that emit light only in the forward direction, the measurement can be performed under the 2π configuration (see Figure 3-a). In the case of conventional luminaires such as incandescent light bulbs, fluorescent lamps, and discrete LEDs/LED luminaries with a wide directivity, since these luminaires emit light not only in the forward direction but also in the backward direction, the measurement under 4π configurations (see Figure 3-b and 3-c) must be performed.

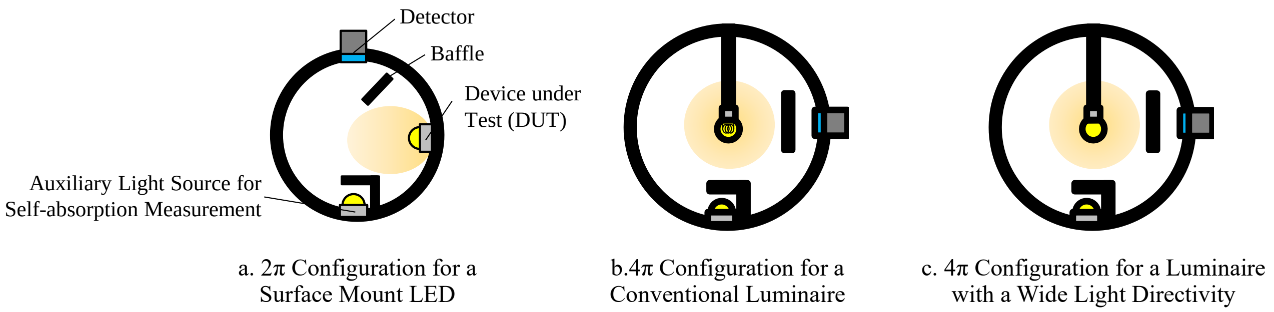


Figure 3. Images of Integrating Sphere Measurement Configurations

3.2.2. Size of Integrating Sphere

Customers are required to select an integrating sphere that is suitable for the size of the light source that needs to be measured. When measuring an LED that is only a few millimeters in size, customers should use an integrating sphere with a diameter of several centimeters to several tens of centimeters. When measuring a large-sized luminaire or a straight tube fluorescent lamp of one meter or longer, customers should use an integrating sphere with a diameter of two to three meters.

If a light source is too large for the size of the integrating sphere, the number of reflections on the inner surface may be reduced and the uniformity (measurement accuracy) of the illuminance on the inner surface may decrease. In addition to this, when the amount of the light absorbed by the surface of the light source increases, the measurement accuracy will further decrease (see Section 3.2.3. self-absorption of a light source). Therefore, IESNA LM79 recommends that the total surface area of a light source should be less than 2% of the total surface area of the integrating sphere under the 4π configuration. Also, it recommends that the length of a long and narrow light source should be less than 2/3 of the diameter of the integrating sphere under the 4π configuration.

Moreover, when the power consumption of a light source is large, the effects of heat generation should be considered. IESNA LM79 recommends that customers should use an integrating sphere with a diameter of 2m or greater when measuring a light source whose power consumption is 500W.

3.2.3. Self-absorption of a Light Source

When measuring a light source, customers should consider the decrease in the luminous flux due to the light absorption (self-absorption) on the emitting surface of the light source and the surface of the housing. If the surface area of the light source is large and/or its housing has colors that absorb more light such as black, the decrease in the luminous flux will become large. To minimize the effects of the self-absorption, it is necessary to apply a self-absorption correction.

Self-absorption correction factors are obtained from Equation 1 by using an auxiliary light source for self-absorption measurement that is positioned separately from the light source (see Figure 2.). The decrease in the luminous flux due to self-absorption can be corrected by multiplying the measured value of the light source with the self-absorption correction factor.

Equation 1: $$\alpha = \frac{i_{s,1} / i_{s,0}}{i_{t,1} / i_{t,0}}$$

where:

α = Self-absorption correction factor

$i_{s,0}$ = The output of the detector when the auxiliary light source for self-absorption measurement, whose relative spectral distribution is the same as the standard light source, is lit without having the standard light source in the integrating sphere.

$i_{s,1}$ = The output of the detector when the auxiliary light source for self-absorption measurement, whose relative spectral distribution is the same as the standard light source, is lit when the standard light source is in the integrating sphere.

$i_{t,0}$ = The output of the detector when the auxiliary light source for self-absorption measurement, whose relative spectral distribution is the same as the device under test (DUT), is lit without having the DUT in the integrating sphere.

$i_{t,1}$ = The output of the detector when the auxiliary light source for self-absorption measurement, whose relative spectral distribution is the same as the device under test (DUT), is lit when the DUT is in the integrating sphere

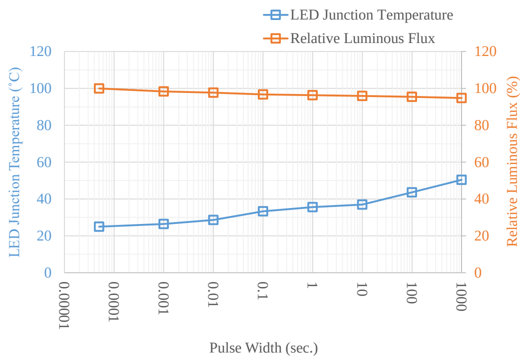
3.2.4. Types of Standard Light Sources

In order to perform a comparative measurement with a standard light source that has a known reference value, which is obtained with a standard measurement instrument, customers should select a standard light source that has similar characteristics to those of the DUT and ensure that the standard light source is placed in the same position as that of the DUT within an integrating sphere so that their illumination directions are the same. If the placement location/direction is different between the standard light source and the DUT, and/or their directivity characteristics and the spectral distribution characteristics is significantly different between them, the measurement errors tend to become large.

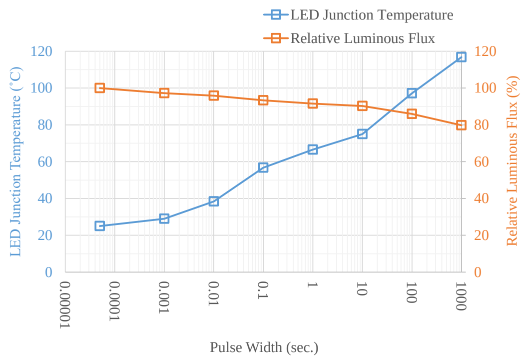
3.2.5. LED Temperature Characteristics

LEDs generate heat while they are emitting light. When the LED junction temperature rises due to this heat, the optical characteristics change due to the temperature characteristics. However, since the LED junction temperature can also change depending on external factors such as the PCB on which the LED is mounted, the measurement environments, etc., the increase in the LED junction temperature should be minimized to obtain the original performance of the discrete LED.
In order to minimize the increase in the LED junction temperature, it is effective to shorten the illumination time during the measurement. Figure 4 shows the relationships between the LED junction temperature/luminous flux and the illumination time (pulse width). These graphs indicate that the shorter the illumination time of the measurement is, the smaller the increase in the LED junction

temperature and the decrease in the luminous flux become. However, it should be noted that even for a very short illumination time of 1msec, a slight decrease in the luminous flux occurs. When operating an LED under a high current, the amount of heat generated from the LED is larger than that under a low current even though the illumination time is the same, causing the LED junction temperature to become high.



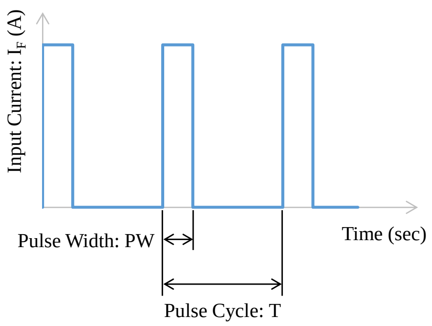
a. LED Operation under a Low Current



b. LED Operation under a High Current

Figure 4. Relationships between the Junction Temperature/Luminous Flux of NCSW170F LEDs and the LED Illumination Time (Pulse Widths) at T_A = 25˚C

Nichia performs the measurement under the pulse current operation shown in Figure 5 in order to minimize the increase in the LED junction temperature[2]. The pulse width is 0.05msec, which is very short, and the duty ratio is 1%. Under this operation, the increase in the LED junction temperature is extremely small.



Item	Symbol /Formula	Value
Pulse Width	PW	0.05 msec
Pulse Cycle	T	5 msec
Duty Ratio	D=PW/T	1%

Figure 5. Nichia's Measurement Condition

When customers need to perform a measurement that takes into consideration the increase in the LED junction temperature, the measurement should be done by using the dedicated power source that is incorporated in the luminaire instead of by using a power source for pulse current measurement. Before performing this measurement, the luminaire should be operated under the conditions /environments in which the luminaire is actually used (e.g. configuration of the luminaire, installation direction) for a certain period of time so that the LED junction temperature and the light output become stable. After confirming those stabilities, the measurement can be performed.

[2] The pulse width, the pulse cycle, and the duty ratio specified in Nichia's specifications vary depending on the LED type.

4. Directivity Measurement

4.1. Directivity Measurement Equipment

Directivity measurement equipment is used to measure the light intensity emitted from the light source in a particular direction by rotating either its detector or the light source (DUT). The main purpose is to measure directivity characteristics; however, directivity measurement equipment can also measure the total luminous flux by measuring the luminous intensity in each particular direction and summing them up.
Unlike integrating sphere measurements, there are neither measurement errors due to self-absorption of the light source (DUT) nor effects of heat from the light source on the directivity measurement equipment. Due to these advantages, directivity measurement equipment is suitable for measuring of large-sized and high-power luminaries.
However, measuring with directivity measurement equipment requires a long measurement time and appropriate measurement environments such as a dark room. For this reason, when only luminous flux needs to be measured, measuring with an integrating sphere is more common since it can be done in a shorter measurement time.

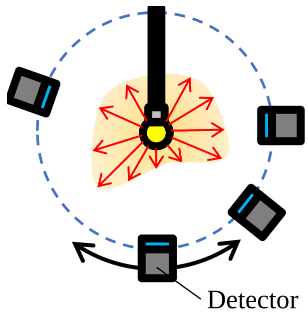


Figure 6. Image of Directivity Measurement Equipment

4.2. Directivity Characteristics

There are two directivity characteristics: far-field and near-field characteristics. Since the measurement methods and the properties of the resulting data of these two are different are different, customers should select either a far-field characteristic measurement or a near-field characteristic measurement depending on the type of light source or its intended purpose.

4.2.1. Far-field Characteristics

Far-field characteristics are the directivity characteristics when the light source is viewed from a distance. Far-field characteristics are obtained with a measurement distance that is far enough to simulate the light source as a point light source. The far-field characteristics are used for various light sources such as small light sources, which are discrete LEDs, luminaries, and automobile headlight modules. Generally, directivity characteristics indicate far-field characteristics. The directivity characteristics detailed in Nichia's specifications show the far-field characteristics (see Figure 7).

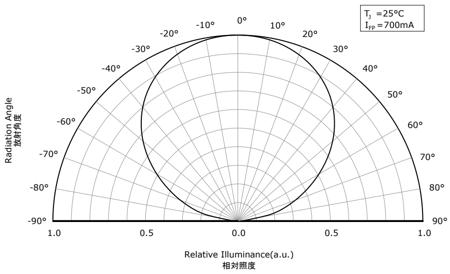


Figure 7. An Example of LED Directivity Characteristics

4.2.2. Near-field Characteristics

When measuring near-field characteristics, the light source is regarded as an area light source that has a size and shape. The luminance distribution within the light emitting area is captured with an image sensor by changing the direction of the light source. This measurement shows which part of the light source each light ray is emitted from and its angular direction; thus, near-field characteristics are mainly measured to create ray data for optical design simulations of light emitting devices such as LEDs (see Figure 8). Nichia offers ray data for various optical simulation software. Customers can contact a local Nichia sales representative for details, including available data formats.

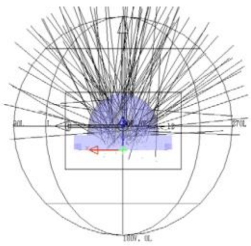


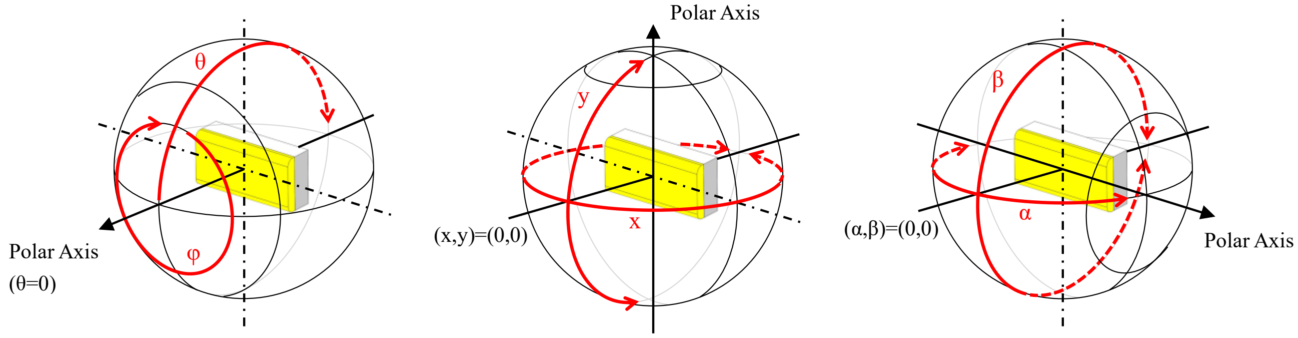
Figure 8. An Example of Ray Data Emitted by an LED

4.3. Coordinate Systems for Directivity Measurements

Figure 9 shows the coordinate systems used in directivity measurements. These three types of the coordinate systems are mainly selected depending on the type of light source that needs to be measured and its intended purpose. However, in some measurement instruments, there are limitations on the available coordinate systems; thus, customers should select a directivity measurement instrument with this taken into consideration (see Section 4.4. Types and Features of Directivity Measurement Instruments).

In the θφ coordinate system shown in Fig. 9-a, the direction perpendicular to the emitting surface of the light source is the polar axis (i.e. rotation axis), the tilt angle with respect to the polar axis is expressed as θ and the rotation angle around the polar axis is expressed as φ. The θφ coordinate system corresponds to the C-plane system detailed in CIE 121 and is commonly used in directivity measurements. The θφ coordinate system is available in many directivity measurement instruments.

The other two coordinate systems are the xy coordinate system and the αβ coordinate system whose polar axis is horizontal to the emitting surface of the light source. The xy coordinate system and αβ coordinate system correspond to the A-plane and B-plane detailed in CIE 121, respectively.



a. θφ Coordinate System b. xy Coordinate System c. αβ Coordinate System

Figure 9. Coordinate Systems for Directivity Measurements

4.4. Types and Features of Directivity Measurement Instruments

A directivity measurement instrument consists of a detector such as an illuminometer or spectrometer and a goniometer that rotates the light source or the detector. Directivity measurement instruments are classified into various types depending on the structure and the rotation method of the goniometer. The typical types of directivity measurement instruments are shown in Figure 10: rotating light source, rotating detector, and mirror. The features of these three instruments are described in the following sections.

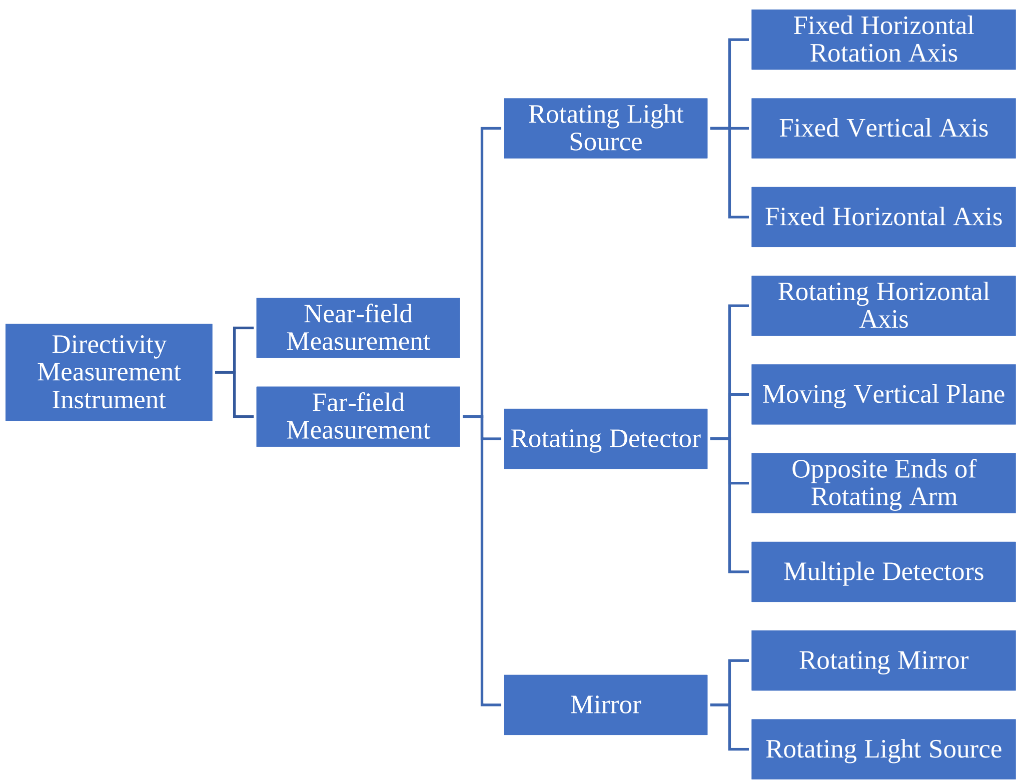
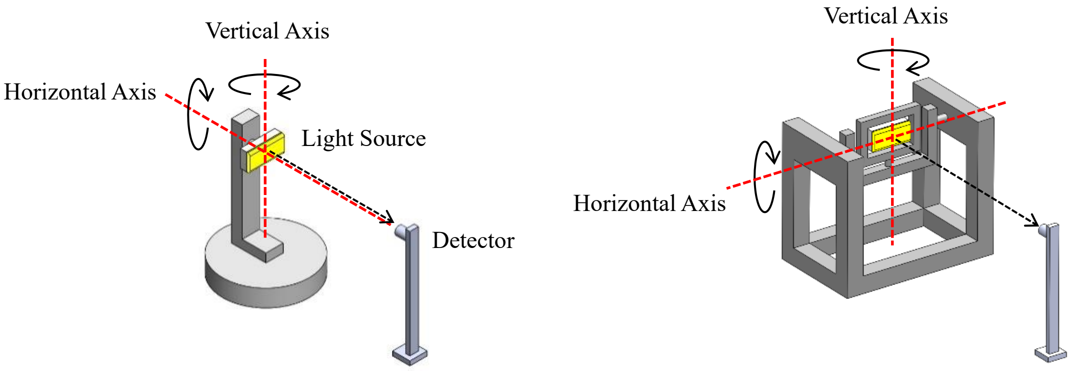


Figure 10. Typical Types of Directivity Measurement Instruments (Goniometers)

4.4.1. Rotating Light Source

In a measurement with a rotating light source, the detector is fixed and only the light source is rotated to measure the directivity characteristics. Depending on the rotation direction of the light source, this is classified into three types: fixed horizontal rotation axis, fixed vertical axis, and fixed horizontal axis. In the measurement with the fixed horizontal rotation axis shown in Figure 11-a, the light source is positioned on the same horizontal rotation axis as the detector, then the light source rotates on the vertical and horizontal rotation axes; this corresponds to the θφ coordinate system. In the measurement with the fixed vertical axis shown in Figure 11-b, the light source is positioned on the vertical axis and it rotates horizontally and vertically; this corresponds to the xy coordinate system and the αβ coordinate system. In a measurement with a fixed horizontal axis, the light source is positioned on the horizontal axis; this corresponds to the xy coordinate system and the αβ coordinate system.

Although the structure of the rotating light source is simple, a large and heavy goniometer stage is required to reduce vibration from the rotation of the light source. Since the direction of the light source changes significantly during the measurement, the output of the light source is susceptible to the effects of gravity; thus, where necessary a correction should be applied to the output obtained at the measurement angle considering the difference from the output obtained at the angle in which the light source is actually placed.

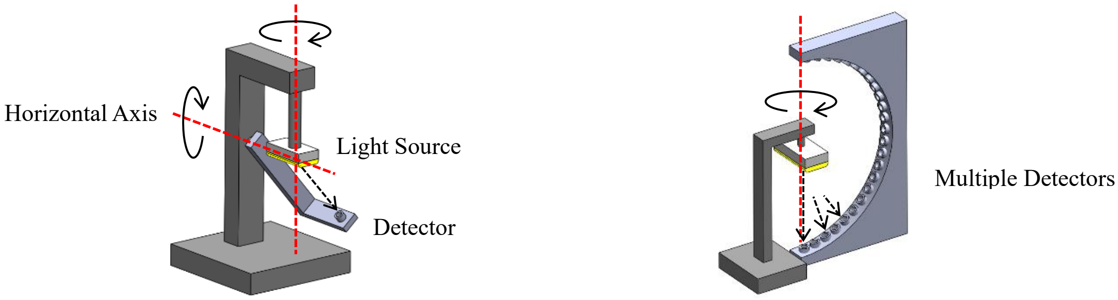


a. Fixed Horizontal Rotation Axis b. Fixed Vertical Axis

Figure 11. Example Configurations for Rotating Light Sources

4.4.2. Rotating Detector

In a measurement with a rotating detector, the light source rotates and the detector revolves around the light source to measure the directivity characteristics. Depending on the revolution direction of the detector, this is classified into four types: rotating horizontal axis, moving vertical plane, opposite ends of rotating arm, and multiple detectors. As examples, in the measurement with the rotating horizontal axis shown in Figure 12-a, the detector revolves around the horizontal axis and the light source rotates around the vertical axis. In the measurement with the multiple detectors shown in Figure 12-b, the revolution of the detector is not required since multiple detectors are placed on the orbit around which the light source rotates, reducing the measurement time. Since the distance between the light source and the detector is short due to this configuration, this measurement is limited to small-sized light sources; however, the compact measurement system integrated with a detector is easy to install.



a. Rotating Horizontal Axis b. Multiple Detectors

Figure 12. Example Configurations for Rotating Detectors

4.4.3. Mirror

In a measurement with a mirror, the light reflected by the mirror is measured. Depending on whether either the mirror or the light source revolves, this is classified into two types: rotating mirror and rotating light source (the mirror is fixed). In both of the types, since the optical distance is increased by the mirror reflection, the actual distance between the light source and the detector can be shortened. As an example, in the measurement with the rotating mirror shown in Figure 13, the light source rotates around the vertical axis and the mirror revolves around the light source. In this measurement, the direct light incident on the detector can cause measurement errors; thus, a light shield should be placed to block the direct light.
Since a large mirror is used in the measurement, the maintenance is complicated and dust and dirt on the mirror may lead to measurement errors. In addition, due to the polarization effects induced by the mirror, using this type of the measurement may not be possible depending on the type of light source.

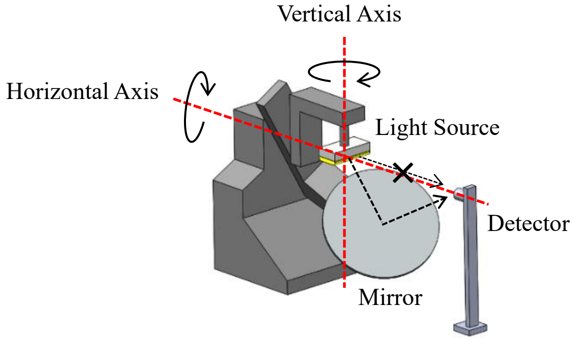


Figure 13. Example Configuration for Mirror

4.5. Precautions for Directivity Measurement

Figure 14 shows an example configuration of a directivity measurement system. A spectroscope or illuminometer connected to the detector measures only light that travels straight from the center of the light source. By rotating and revolving the light source and/or detector with a goniometer, the light emitted from the light source in a particular direction is measured. However, since it is necessary to do a large number of measurements by changing the measurement angle, the measurement is time-consuming.

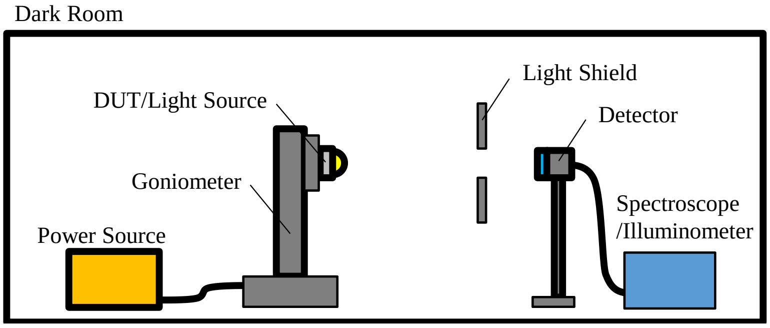


Figure 14. Example Configuration for Light Distribution Measurement System

This section explains the possible factors that can cause measurement errors in the directivity measurements: 1. measurement angle, 2. measurement distance, 3. types of standard light sources, and 4. LED temperature characteristics.

4.5.1. Measurement Angle

If the number of the measurements by changing the measurement angle is insufficient, accurate directivity characteristics and luminous flux cannot be obtained. By narrowing the measurement angle and increasing the number of measurements, the measurement accuracy can be improved; however, when the number of the measurements is doubled, the measurement time is also doubled. Therefore, it is not efficient to increase the number of the measurements without careful consideration. To conduct an efficient measurement, it is necessary to optimize the measurement angle (e.g. widening the measurement angle in the illuminated area with a small change in brightness) depending on the directivity of the luminaire that needs to be measured.

4.5.2. Measurement Distance

When performing a far-field measurement, a sufficient measurement distance should be maintained between the light source and the detector. When a far-field measurement is performed considering the luminaire as a point light source, a distance that is at least five times longer than the longitudinal length of the light emitting surface of the luminaire is required.

4.5.3. Types of Standard Light Sources

In a similar manner to an integrating sphere measurement, in order to perform a comparative measurement with a standard light source that has a known reference value, which is obtained with a standard measurement instrument, customers should select a light source that has similar characteristics to those of the DUT (see Section 3.2.4. Types of Standard Light Sources).

4.5.4. LED Temperature Characteristics

In a similar manner to an integrating sphere measurement, customers should consider LED temperature characteristics (see Section 3.2.5. LED Temperature Characteristics). It is necessary to operate an LED under a pulse operation that is less susceptible to heat or to thermally saturate an LED sufficiently so that the brightness does not change during the measurement. In addition, since it takes

some time to measure directivity characteristics, the temperature of the dark room should be controlled to maintain a constant temperature to avoid temperature changes due to time elapsed.
When a measurement with a rotating light source (see Section 4.4.1. Rotating Light Source) is performed while the light source is saturated, the light source is rotated at different angles during the measurement; this may cause the original heat dissipation performance to not be achieved. In this case, it is necessary to apply a correction against the measured values using the difference between the brightness obtained at the original illuminating direction of the light source and the brightness obtained at the measurement angle.

5. Traceability

5.1. Traceability and Uncertainty

Calibration of measurement instruments is essential for accurate measurements. Measurement instruments are calibrated using a standard measurement instrument and this standard measurement instrument is calibrated by a higher-level standard instrument that has been calibrated to achieve further accuracy. Through this hierarchical calibration system, the measurement instrument is eventually traceable to a national standard instrument (or an international standard instrument). This chain system of calibrations is referred to as traceability.
Traceability is defined by JIS Z 8103 as a “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty”. Therefore, the established calibration of traceability must meet the conditions such as “clarification of uncertainty at each calibration hierarchy”, “unbroken traceability chain to a national measurement standard”, and “documentation of calibration procedures and results”.
Uncertainty is also defined by JIS Z 8103 as a “parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand” and is an indicator of how far a measured value obtained from a measurement is from the true value (dispersion). The possible factors that can cause uncertainty during luminous flux measurement include individual differences between measurement instruments, measurement noises, and measurement environments (temperature and humidity).

5.2. Nichia’s Traceability System

Figure 15 illustrates Nichia’s traceability system. Uncertainties contained in the characteristics of the LEDs that are shipped from Nichia as finished products includes all uncertainties existing in the hierarchical calibration from a national standard instrument to Nichia’s sorting machines used in mass production[3]. Note that this uncertainty represents the correlation to a national standard instrument and does not represent the difference between the characteristics of the LEDs and the measurement values obtained by other measurement organizations that are outside of Nichia’s traceability system.

[3] The tolerances listed in Nichia’s specifications have been determined based on the uncertainties within Nichia’s traceability system.

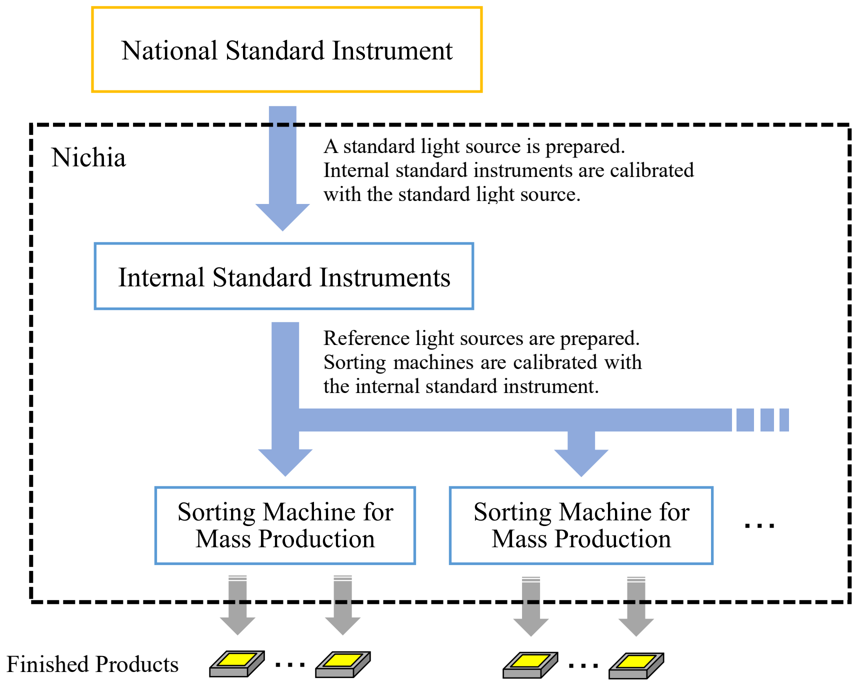


Figure 15. Nichia's Traceability System

6. Summary

In this application note, Nichia provided luminous flux measurement methods by using integrating spheres and directivity measurement instruments. Since both types of measurement instruments have their pros and cons, customers should select the appropriate measurement instrument depending on the characteristics of the light source that need to be measured and the purpose of measurement.
This application note also explained that there are various factors that contribute to measurement errors. Nichia recommends establishing appropriate measurement environments and procedures to minimize measurement errors and designing the chosen application with sufficient margins for the intended performance.

References:

- IESNA LM79 IESNA Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products
- CIE 121 The Photometry and Goniophotometry of Luminaires
- JIS C 8105-5 Luminaires -- Part 5:Gonio-photometric methods
- JIS C 8152 Photometry of white light emitting diode for general lighting
- JIS Z 8103 Glossary of Terms Used in Measurement

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