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LED MEASUREMENT INSTRUMENTATION

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ABSTRACT

The production and use of LEDs is increasingly rapid. They are being used in applications previously occupied by traditional lighting components such as incandescent lamps, as well as providing indicators, signs and displays. Proper measurements of LED devices are required so that performance can be assessed, both in relation to other LED devices and as replacements for existing applications.

Traditionally, optical quantities such as luminous intensity, luminous flux, radiant intensity, radiant flux, peak and dominant wavelength, kurtosis, chromaticity coordinates, efficacy and efficiency might be used to asses the LED. With LEDs competing in traditional lighting and display applications, however, the requirement for other measurements, such as illuminance and luminance, increases.

Whether a spectroradiometer, photometer, or radiometer is used in measurement, it is the input optic that determines the **type** of measurement. For instance, if an LED is placed in an integrating sphere a spectroradiometer will measure total spectral flux; a photometer will measure total luminance flux; and a radiometer will measure total radiant flux. Different input optics are required for measurements of total luminous flux, "2π luminous flux," luminous intensity, luminance, and illuminance. Measurements of the radiometric and spectroradiometric equivalents will generally use the same or similar input optics to those for these luminous quantities.

Details of the input optic design for total luminous flux, "2π luminous flux," luminous intensity, luminance, and illuminance will be given, including:

1. What is to be measured? Definitions and geometries.
2. Do LEDs fit those geometries? Some practical definitions and discussions.
3. Sources of error.

Keywords: LED, measurement, instrument, photopic, radiometric, spectroradiometric, flux, intensity, luminance, illuminance, radiance, irradiance, goniometric, ray tracing, errors, uncertainties

1. INTRODUCTION

LEDs require many types of optical measurement, but these can be broadly categorized according to the quantity measured. The type of instrument selected depends on these categories:

- Photopic quantities
  - *A photometer or spectroradiometer is used*
- Radiometric quantities
  - *A radiometer or spectroradiometer is used*
- Wavelength and chromatic quantities
  - *A spectroradiometer is used*

If we are measuring radiometric intensity, a radiometer or spectroradiometer is used, but we also need to identify the instrument necessary to give the "intensity" part of the measurement. This is determined by the input collection optics. In fact, regardless of the type of quantity, the measurement type is determined by the input collection optics so the same optics would be used for:

- *Luminous, radiometric, and spectroradiometric intensity*
- *Luminance, radiance, and spectral radiance*
- *Luminous, radiometric, and spectroradiometric flux*
- *Illuminance, irradiance, and spectral irradiance*

1.1 Luminous, radiometric and spectroradiometric intensity

A baffle tube is used to define the solid measurement angle, though a telescope can be used in some circumstances.

- ***Basic Units:***
  - Luminous intensity
    - ⇨ *Candela [cd = lm sr^{-1}]*
  - Radiometric intensity
    - ⇨ *W sr^{-1}*
  - Spectroradiometric intensity
    - ⇨ *W sr^{-1} nm^{-1}*

1.2 Luminance, radiance and spectral radiance

A telescope is used to define the area and solid angle of measurement, though a baffle tube can be used in some circumstances.

- ***Basic Units:***
  - Luminance
    - ⇨ *cd m^{-2}*
  - Radiance
    - ⇨ *W sr^{-1} m^{-2}*
  - Spectral Radiance
    - ⇨ *W sr^{-1} m^{-2} nm^{-1}*

1.3 Luminous, radiometric and spectroradiometric flux

An integrating sphere is used to measure total flux (LED at the center of the sphere) and forward (2π) flux (LED at the sphere wall). Goniometers can also be used and will often give more accurate results than spheres but take longer to make measurements.

- ***Basic Units:***
  - Luminous flux
    - ⇨ *lm*
  - Radiometric flux
    - ⇨ *W*
  - Spectroradiometric flux
    - ⇨ *W nm^{-1}*

1.4 Illuminance, irradiance and spectral irradiance

A cosine collector, either diffuser or integrating sphere, is used.

- **Basic Units:**
  - Illuminance
    - ⇨ *Lux [lux = lm m^{-2}]*
  - Irradiance
    - ⇨ *W m^{-2}*
  - Spectral Irradiance
    - ⇨ *W m^{-2} nm^{-1}*

In the following sections, references to photopic quantities imply the analogous radiometric and spectroradiometric quantities unless otherwise specified.

2. Measurement of Luminous Intensity

Consider a point source of light that emits in all directions equally. We can measure the luminous intensity [lm sr^{-1}] by measuring the flux [lm] in any given solid angle $d\Omega$ [sr]. Now consider a point source that emits different amount of light in each direction. The luminous intensity depends on which direction is measured but is constant with distance from the source for any given $d\Omega$. Early metrologists used this "directional point source" model to describe LEDs and established the normal practice of measuring 2° and 6.5° angles, corresponding approximately to 0.001 and 0.01 sr. Inconsistencies between laboratories, each with different setups to achieve the desired 2° and 6.5° angles, lead to disagreements in values. Clearly, measurement protocols required revising.

If the source were directional and not a point source, then values of luminous intensity would vary with direction, solid angle and distance from the source. In other words, defining just a solid angle is not enough. Metrologists realized this model to define "luminous intensity" is better for LEDs. They applied fixed measurement conditions (CIE Publication 127[1]) as shown in Figure 1:

- **Condition A.**
  - *This corresponds to 0.001 sr solid angle using the tip of the LED as the point of origin. A 1 cm^2 circular detection area is placed at 31.6 cm distance.*
- **Condition B.**
  - *This corresponds to 0.01 sr solid angle using the tip of the LED as the point of origin. A 1 cm^2 circular detection area is placed at 10.0 cm distance.*

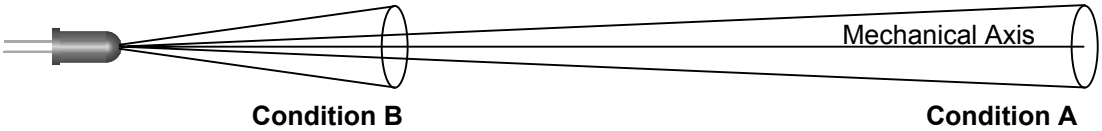

Figure 1. Measurement conditions for averaged luminous intensity as described in CIE Publication 127.

The definition of luminous intensity assumes a point source, and is not a valid term for this measurement. Instead, the term "averaged luminous intensity" should be used as described in CIE Publication 127.

Most laboratories now measure averaged luminous intensity and obtain good agreement. However, luminous intensity is just one type of measurement required, and setup conditions may need to be defined to obtain agreement for other LED properties. It helps to understand the optical properties of LEDs in defining these conditions.

3. LED Optical Properties

LEDs are not just chips. They are housed in a complex structure to maximize effective intensity. The sides of the LED package are generally tapered to facilitate removal from the mold. A cup structure is added to reflect light forward from the sides of the die. LEDs come in many packages, from single chip to sophisticated multi-directional aspheric lens designs. They may include lenses, colored materials, diffusers and phosphors, all of which can alter the spatial and spectral distribution relative to the basic chip. Packages may include dies of different size, different types and different locations. Packages and die locations may have different mechanical tolerances.

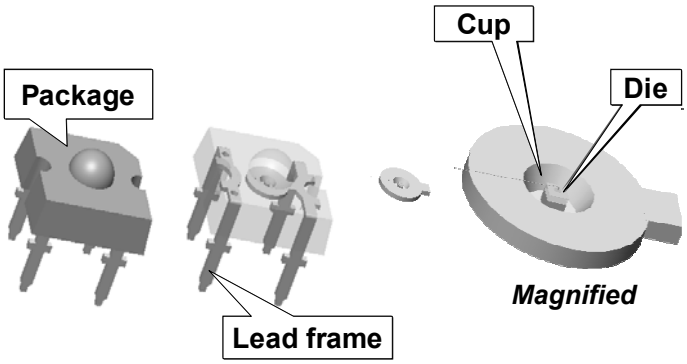

Figure 2. The basic structure of a LED package

It would be impossible to discuss all measurements for all package types in such a short article as this; hence we will concentrate on the T1-¾ package to illustrate the basic principles. If we calculate how the rays from the die exit the package, as in Figure 3, we can see that it involves many components.

We can see from Figure 3 that light falling onto a screen confirms the ray traces. As the body of the LED is made longer, as in a T1-¾ package, the angles encompassed by the "focused" light become narrower; but internal reflections, high-angle light via the lens and sidewall emissions increase.

The structure inherent in the light falling on the screen, and hence a detector, makes measurements critically dependent on the distance, measurement aperture and location of the detector relative to the light pattern. Since these may vary, even within LEDs of the same type, strict adherence to measurement protocols is required to ensure agreement between laboratories.

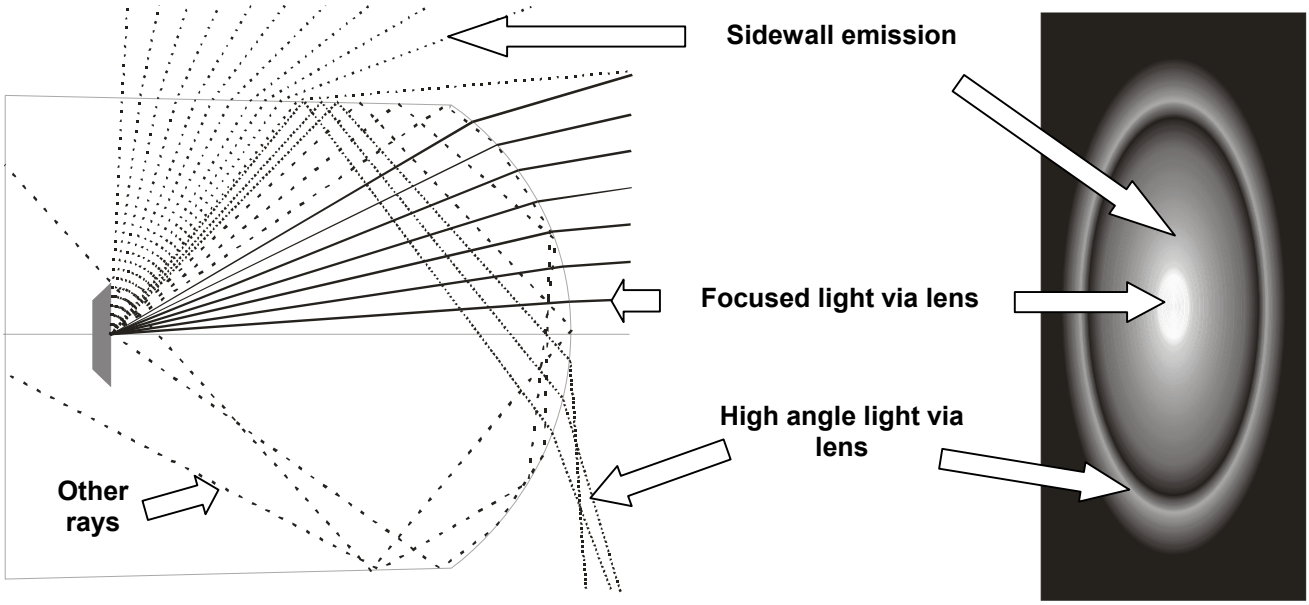

Figure 3. Left: ray tracing how light exits the package. Right: a typical image of the light falling onto a screen (the aspect ratio is altered for clarity).

4. Goniometric Measurements

If we make luminous intensity measurements over a range of angles, θ and φ, this is called goniometry. Figure 4 shows the geometry involved in the measurement. A point source is assumed, both in the definition of $d\Omega$ for luminous intensity and as the center of rotation in defining θ and φ. We already know that LEDs do not behave as point sources for luminous intensity measurements and might expect such knowledge to translate into protocols for goniometry. However, there are no set protocols, and goniometric measurements are often done at different laboratories with very diverse rotational radii and detector apertures.

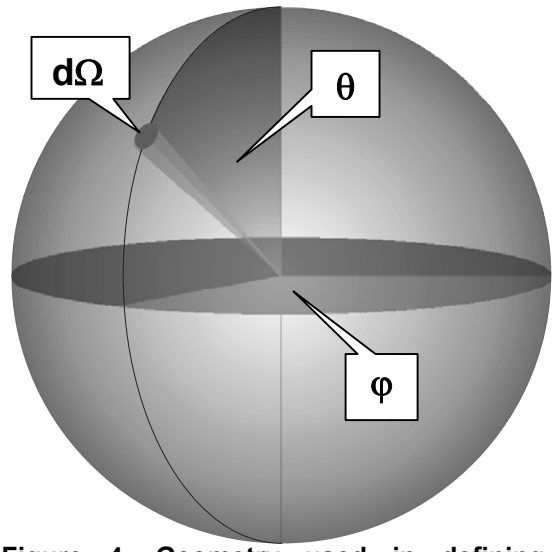

Figure 4. Geometry used in defining goniometric measurements.

If we examine the LED ray trace of Figure 3, we can see another problem in doing goniometric measurements of LEDs. By extending the rays backwards until they meet, we can determine the "apparent" centers of emission for the LED. Figure 5 shows that at least three such centers can be identified, each at a distinctly different location and not necessarily within the physical limits of the LED. Therefore, we cannot choose a center about which to rotate without having other apparent centers rotating off axis. This leads to the angle, θ or φ, that is set not representing the effective angle of emission.

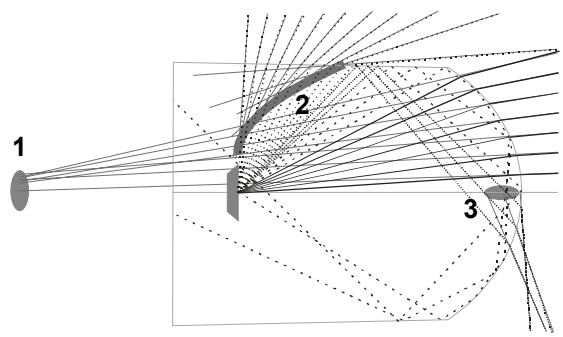

Figure 5. Back-tracing the rays of Figure 3 shows at least three areas of apparent emission.

We can represent the different locations and angular emission properties of the LED diagrammatically to illustrate this effect, as shown in Figure 6. If rotation is about the tip of the LED, then only region 3 is close to the rotation center. There will be significant differences between θ_{set} and $\theta_{effective}$ for regions 1 and 2 therefore. To keep these differences below 1 degree for most common LEDs, the radius of measurement should be greater than 300 mm. Many laboratories use radii much less than this and hence should expect significant errors. It is worth noting that if the protocol for measurement were fixed with a 316mm radius and a circular 1 cm^2 detector, it would provide data in accordance with Condition A Averaged LED intensity. This is simply an observation rather than a current recommendation of the CIE.

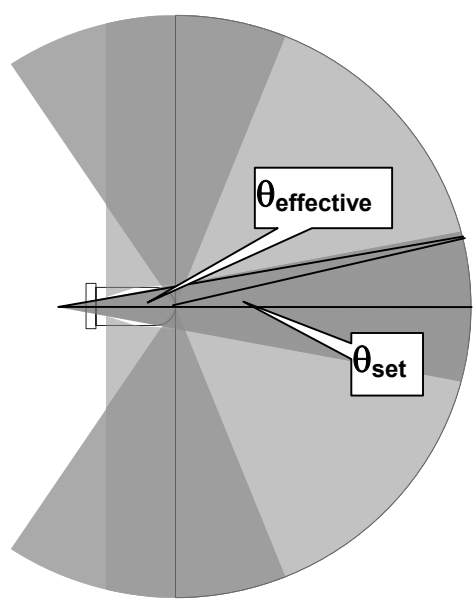

Figure 6. Apparent emissions from a LED, showing the goniometric set and effective angles are different.

5. Measurement of Luminance

Measurement of luminance involves isolating a specific area on the LED emitting-surface and telescope or microscope is normally used. The telescope or microscope forms an image, and an aperture is placed at this image plane to isolate the part to be measured. The telescope lens defines the measurement angle, $d\Omega$, and the aperture defines the area and position of measurement. Several designs of telescope or microscope can be used, but it is recommended that misalignments between viewing the image and positioning the aperture be kept as small as possible.

When calibrating, a sphere source or other uniform diffuse source is used. With this source, and indeed most "normal" sources, the angular and spatial characteristics are not linked. It is possible to change the size of the image aperture without affecting the collection angle, $d\Omega$. However, the lens on the T1-¾ package introduces a co-dependence of angular and spatial parameters for LEDs. Consider a point on the chip surface. If we envisage that light from this point travels via the lens and exits as a near-parallel beam, then the width of the beam is close to the diameter of the T1-¾ package. No matter the size of the telescope lens, once it is larger than this beam diameter it will not collect any more light from that point on the LED chip. This means the lens of the telescope no longer defines $d\Omega$ and measurements of luminance can vary widely depending on the details of the telescope or microscope design.

The interaction of spatial and angular characteristics presents another problem. Suppose we reduced the telescope lens diameter until it matched the LED diameter. By restricting the "angle," a corresponding restriction in the spatial dimensions of the image occurs. This means that not enough of the image is seen to effectively show the area or position of the measurement aperture.

Determining the luminance of a T1-¾ packaged and other lensed LEDs is probably the most difficult type of measurement to make accurately. In order to do it in any practical sense, a reasonably large lens is required, and this leads to a lower value of luminance being measured. The best one can say is that the "true" value is greater than or equal to the measured value. To establish a protocol ensuring all laboratories measure the same luminance value would involve defining the telescope or microscope design very rigidly. This approach is similar to that previously adopted by CIE for luminous intensity.

For non-lensed or diffused type packages, measurement of luminance is straightforward and can be achieved easily.

Some of the dependence of results on telescope lens size still applies to lensed LEDs when they are included in LED arrays, but there is no longer a requirement to image the LED chip. Instead, the array is imaged and entire LEDs form points within the image. The LEDs in the array are separated from one another, and any measured luminance is an average of bright (LED) areas and dark (separations) areas. The easiest way to measure the luminance of an array is with an image aperture that includes a large number of individual LEDs. In this way, the fraction of light and dark areas within the aperture is close to the actual ratio. Care should be exercised when using apertures that include just a few LEDs to ensure that the ratio of light and dark areas is correct. Working with these small apertures can also lead to variations in results due to sampling errors, where different locations on the image give different contributions of light and dark areas. Small apertures should be avoided unless absolutely necessary.

6. Measurement of Total Luminous Flux

Section 4 described goniometric measurements of luminous intensity. If the results at all possible angles are integrated, then the result is the total number of lumens emitted from the LED regardless of direction. This quantity is known as luminous flux, but is also commonly referred to as total luminous flux.

It takes time to measure the luminous intensity at all possible angles, so an integrating sphere is generally used to measure total luminous flux. For this measurement, the LED is placed at the center of the sphere and the photopic detector is placed at the wall of the sphere.

A typical total flux sphere arrangement is shown in Figure 7. A section of the sphere has been "removed" so you can see what is inside.

The LED is placed in the center of the sphere and the detector is on the surface. Between the two, there is a baffle to prevent direct light from the lamp hitting the detector. The sphere and baffle are both coated with a highly reflective material.

It would appear that light from the lamp should hit the sphere wall unobstructed in every direction, with the exception of the area behind the small baffle. However, the baffle not only affects light from the lamp hitting the sphere but also the way the detector "sees" the sphere walls. Figure 8 illustrates the shadow areas created by the baffle. In these shadow areas, the light from the lamp hitting the sphere for the first time (aptly named the "first strike") is not fully measured. The light must be reflected to another part of the sphere before the detector can see it. Since the sphere coating does not reflect 100% of the light, these areas represent a lower response than other parts of the sphere.

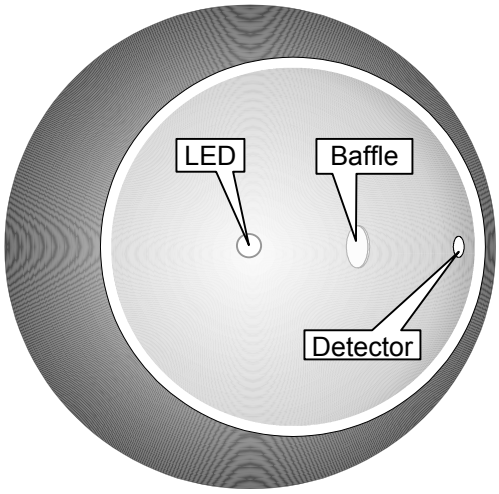

Figure 7. A typical sphere design for total luminous flux measurement.

A perfect response would see light from the LED equally, regardless of direction. Since the baffle is necessary and the baffle creates a non-ideal response, a perfect sphere for total flux measurements exists only in theory. Practical spheres can come very close however, and how close depends on attention to small design details.

Sphere response is best graphed as a radar plot, as in Figure 9. The relative response is plotted as a distance from the center vs. angle. Ideally, this would be a 3D plot. You can imagine rotating the shape around the horizontal axis, out of the plane of the paper, to visualize what it would look like in three dimensions.

The plot in Figure 9 is for a sphere coated with a 95% reflective material. The effect of the shadow areas, causing a decrease in responsivity, can be clearly seen to the right and left of the plots. The angular extent of the effect decreases with increased sphere diameter, so a 2m sphere is much better than a 0.5 m sphere. The change in responsivity in the shadowed regions is only slightly affected by sphere size and is due primarily to the coating reflectivity. Spheres with coatings of 98% or more reflectivity are commonly used, giving a much more ideal response than that shown. Other spheres have a reflectivity of about 80%, but this results in large geometric errors that make measurements of directional sources, such as LEDs, more difficult.

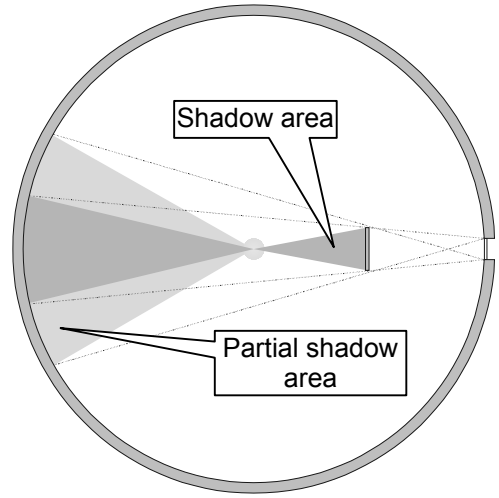

Figure 8. Ray tracing shows the shadow and partial shadow areas of a sphere.

Close inspection of the radar plot also shows a slightly higher than ideal response to the right of the plot, just outside the limits of the baffle. This is due to sphere reflections hitting the baffle on the detector side, increasing the signal at the detector. This increase will occur in all spheres but is very dependent on baffle design and can be much worse in some commercial spheres than others.

The sphere responses detailed in the previous sections assume that the detector obeys the cosine law (explained in Section 7). This is essential for the detector to "see" the sphere correctly. If the detector does not obey the cosine law, some angles will contribute more and others less than they should, making it unsuitable for total flux measurements.

Light emission from LEDs is often highly directional. For best results, they should be oriented so that their strongest emission is directed at the areas of uniform response rather than the shadow areas. Since the extent of the shadow areas decreases with increasing sphere size, and decreases with decreasing baffle size, it makes sense to choose a sphere that is as large as possible with baffles as small as possible. This is even more important when the sphere coating has low reflectivity.

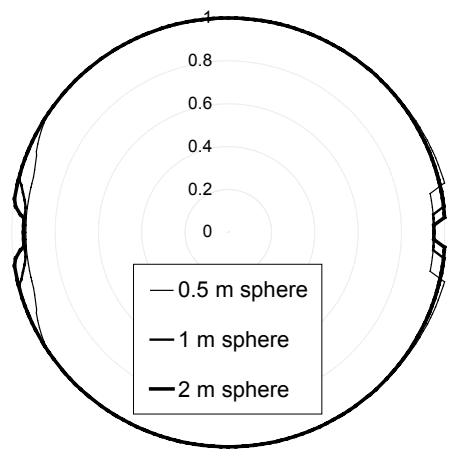

Figure 9. Sphere response radar plot for 0.5, 1 and 2 m spheres with 95% reflectivity.

If something that absorbs light is placed in the sphere, it will decrease the average number of reflections in the sphere. This is equivalent to decreasing the coating reflectivity and has a dramatic effect on the efficiency of the sphere. Unfortunately, this includes LEDs, holders, sockets, cables, etc. With high reflectivity spheres, significant changes in throughput are seen with objects that are only one ten-millionth of the sphere volume. It is unlikely that the standard lamp used in calibration and the LED to be measured will be identical. They will consequently have different effects on the throughput of the sphere. To measure a LED correctly, we have to measure the change in throughput between the standard lamp and LED, as well as the sources themselves.

An auxiliary lamp, permanently housed in the sphere, is used to measure the changes in throughput as standard lamps, LEDs, holders, sockets and cables are changed. The auxiliary lamp is normally located

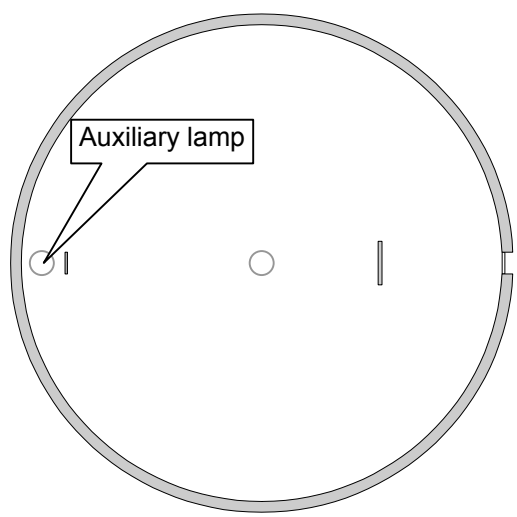

Figure 10. The auxiliary lamp measures changes in sphere throughput.

on the opposite side of the sphere to the detector, in the shadow area, to reduce its impact on sphere response, as shown in Figure 10.

The auxiliary lamp is powered up with the standard lamp in the center of the sphere (but not switched on), and readings are taken from the detector. It is then powered up again with the LED in the center of the sphere (but not switched on), and detector readings taken. The ratio of the readings is the change in throughput due to the differences between the lamps. This procedure is normally part of the calibration and does not slow down measurements.

If a photometer or radiometer is used as the detector, most accurate results will be obtained if the standard and auxiliary lamps are LEDs of the same spectral distribution as the LED being measured. For spectroradiometers, it is essential that good calibrations are achieved over the entire spectral region, including the "tails" of the LED spectral distribution, so white light sources are much better. Calibrated LEDs make excellent verification artifacts for spectroradiometer systems however.

If all laboratories measured LED total luminous intensity using a sphere as described above, there would be reasonable agreement. However, many laboratories place the LED in a port on the sidewall of the sphere. This does not measure all flux so the term 2π (or forward looking) flux is often used. Unfortunately, this method often leads to disagreements between laboratories because:

- There is no standard location of the LED with respect to the port.
  - *How much of the LED is within the sphere determines how much of the LED flux is measured. Different laboratories use different locations.*
- Holding the LED by its sidewalls can restrict the emission.
  - *Section 3 showed that some LED emission is internally reflected from or transmitted through the sidewalls. Any contact with the sidewalls above the plane of the chip can prevent internal reflection and absorb this light.*
- Interactions with the sidewall next to the LED can lead to large errors.
  - *To prevent these errors, large spheres with large port opening should be used but many laboratories use small spheres with small port openings.*
- Auxiliary lamps are sometimes not used.
  - *Many laboratories use spheres that have no auxiliary lamp capability. Couple this with a small sphere size and huge errors can result.*
- LED holders may vary in reflectance
  - *Backward-looking light from the LED that hits the holder may be reflected into the sphere and be measured as part of the forward-looking flux.*

Since the measurement of forward-looking luminous flux is so fraught with inconsistencies and lack of standardization, the question might be asked "why is it so common?" Some of the answer lies in convenience: it is quicker and easier to place an LED into a hole and make a measurement than to open a sphere, place the LED inside and close the sphere before making the measurement. Another reason is size: spheres designed to be opened, have the lamps at the center, and fitted with auxiliary lamps tend to be large. The industry has shown a preference for small spheres that unfortunately compromises accuracy.

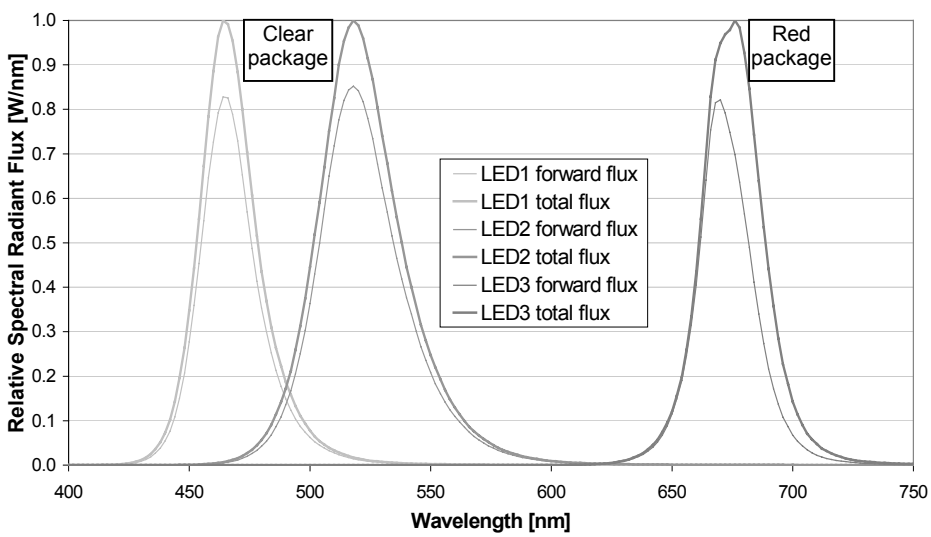

Figure 11. Total and forward-looking spectral flux measurements for three common LEDs.

Another unfortunate tendency within the industry is to equate total luminous flux with forward-looking luminous flux (and sometimes mislabel the latter as the former). They are not the same quantity, value, or even spectral distribution in some cases. Figure 11 shows some common LEDs, in terms of total spectral flux measured with a 0.5m sphere, and forward-looking spectral flux measured with a typical setup on a 15cm sphere.

7. Measurement of Illuminance

Illuminance is the photopic flux falling onto a surface. The light may come from any direction and from multiple sources. The total light falling onto the surface, regardless of the direction it comes from, must be measured.

As illustrated in Figure 12, the apparent area of any surface varies with the cosine of the angle. This is called the

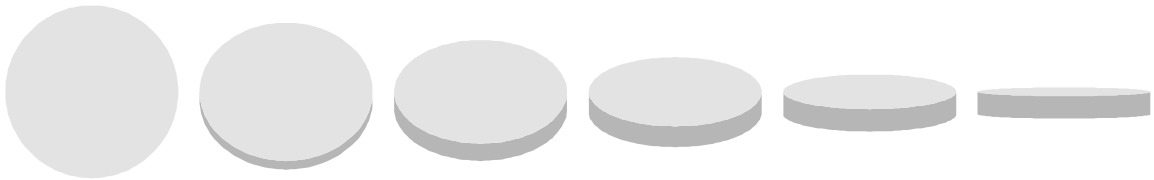

Figure 12. The apparent area of a surface varies with the cosine of the angle to it. This is known as the cosine law.

cosine law. A measurement device that obeys the cosine law is called a cosine collector. Good cosine response of the instrument is essential when measuring the illuminance of almost any source.

We saw from Figure 3 that the light falling onto a surface from a single LED is non-uniform. This means that measured values of illuminance will vary depending on the size, location and distance of the cosine collector.

It should be noted however that illuminance is technically not a property of a LED. It is a property of the illumination conditions at the time of measurement regardless of the position, orientation, or number of sources providing that illumination. It is included in this paper for completeness and because LED lighting components are currently under development.

8. Discussions

The preceding sections describe the instruments and techniques for measuring various parameters of LEDs. In particular, reasons for discrepancies between measurements and laboratories were given in the hope that better understanding would lead to more consistent results.

We have seen that LEDs present unique measurement problems. These problems fall into three main categories:

1. Definitions
   - *Many parameters assume point sources in their definitions. Most packaged LEDs do not behave as point sources, leading to variations in "interpretation" of the definition as applied to LEDs.*
2. Sensitivity
   - *Simplified, the uncertainty of a measurement associated with a particular variable is the uncertainty in that variable multiplied by the sensitivity of the result to that variable. For instance, this means that measurements of the intensity of a source in a particular direction have a greater inherent variation if the source is highly directional.*
3. Control
   - *There are two non-optical variables associated with ensuring the LED maintains the same optical output: thermal and electrical conditions. The preceding discussion assumes these are held constant but in reality they may vary, e.g. by attaching electrical connections at different points on the lead frame. Any variations in output will lead to changes in results, regardless of how well or badly they are being measured. Without adequate control of thermal (lead or chip temperature) and electrical conditions, improvements in optical measurement techniques may be wasted.*

The sensitivity of measurements to the LED characteristics and control of the LED are the prime reasons for variation of results within the same laboratory measuring the same parameters on the same LED. When comparing two laboratories, differences in the interpretation of definitions and control methods increase these variations. To some extent, replacing luminous intensity with measurements of averaged LED luminous intensity, where the exact conditions of measurement have been defined, has alleviated some of these problems. However, the measurement problems associated with LEDs are not limited to luminous intensity, and unacceptable variations in results for other parameters continue. Standardization of conditions for all types of measurement is required to improve agreement of results.

9. Acknowledgements

Thanks to Dave Jenkins, Andrew Riser and William Cassarly of Optical Research Associates for their ray-tracing drawings of LEDs.

10.REFERENCES

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[1] Commission Internationale de l'Éclairage: Measurement of LEDs, CIE **127**-1997.