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MEASURING LIGHT EMISSIONS FROM LEDS

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Measuring light emission from LEDs

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ABSTRACT

LEDs are used in many applications, and new applications are found every day. To address this market, LEDs often come in vastly different varieties, shapes, sizes, packages and modules. Measurement of these LEDs is required so that they can be compared and selected within a global market. This paper presents the different types of optical quantity that can be measured for these LEDs together with guidelines for measurement. In particular, the protocols for measuring Averaged LED Intensity, Partial LED Flux, luminance and illuminance are presented. Some of these quantities are new, and the reader may be unfamiliar with them. Definitions are provided where appropriate. Many LED measurements have associated standard measurement conditions, which apply to LEDs and not other sources. Other measurements depend critically on setup conditions but lack standardization and hence details of methods used must accompany results. Where standard conditions exist these are detailed and where they do not advice is provided on the best methodologies. Work in establishing standard conditions is on-going, especially in Commission Internationale de l'Éclairage (CIE) technical committees, and information on this work is provided.

Keywords: light, LED, measurement, Averaged LED Intensity, Partial LED Flux, total luminous flux, luminance, illuminance, CIE

Fig. 1. A packaged LED comprises several complex structures in addition to the chip.

1. INTRODUCTION

The production and use of LEDs continues to increase rapidly. They are being used in applications previously occupied by traditional lighting components such as incandescent lamps, as well as indicators, signs, displays and new lighting developments. 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. These measurements must be consistent across the industry to ensure comparisons are valid.

LEDs come in many packages, often with integral lenses, diffusers or phosphors that alter the angular distribution and spectral emission properties (see Fig. 1). A measurement setup that gives accurate results on one LED may be inappropriate for testing a different package type. Devising a single test that applies to all LEDs can be difficult, yet the test equipment must be necessarily kept simple and general for any meaningful comparison to take place. Several test protocols have been established by the Commission Internationale de l'Éclairage (CIE)[1] and Japanese organizations[2] and several more are in the process of preparation.

Traditionally, optical quantities such as luminous intensity, luminous flux, radiant intensity, radiant flux, peak and dominant wavelength, half-band width, chromaticity coordinates, efficacy and efficiency might be used to assess the LED. With LEDs competing in traditional lighting and display applications however, the requirement for other measurements such as illuminance, luminance and color rendering properties increases. Some of these quantities can vary with angle, and goniometric measurements may also be required.

Whether a spectroradiometer, photometer or radiometer is used in measurement, it is the input optic that determines the type of quantity measured. For instance, if a LED is placed in an integrating sphere: a spectroradiometer will measure total spectral flux; a photometer will measure total luminous flux; and a radiometer will measure total radiant flux. Different input optics are required for measurements of total luminous flux, partial luminous flux, luminous intensity, luminance and illuminance. Measurements of the radiometric and spectroradiometric equivalents would generally use the same or similar input optics to those for these photopic quantities. Throughout the following text therefore, reference to photopic quantities implies inclusion of equivalent radiometric and spectroradiometric quantities unless otherwise noted.

Although guidelines for a few measurement types are published, most types do not have the benefit of international guidelines and much work is yet to be done. Discussions in CIE subcommittees on appropriate techniques for LED measurement of partial flux quantities[3], radiance and luminance[4], photo-biological hazards[5], color rendering properties of white LEDs[6], measurement of LED clusters[7], and CIE/ISO standardization of publication 127[8] are all currently underway. These committees are very active in providing future guidance for current and often growing problems experienced by industry.

2. LED OPTICAL PROPERTIES

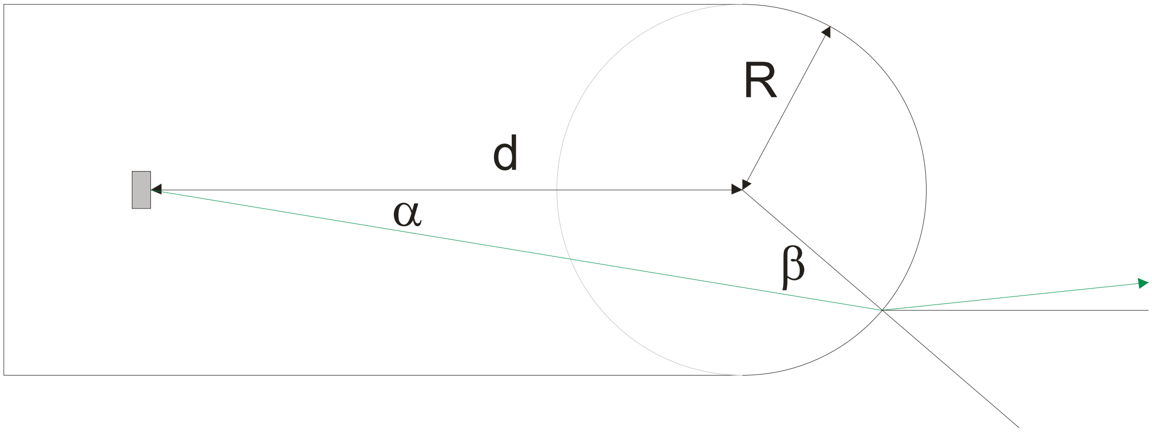

Fig. 2. A simple model lens design consisting of a spherical surface on the end of a cylinder, radius R. The LED chip is located at a variable distance, d, to the center of the spherical surface.

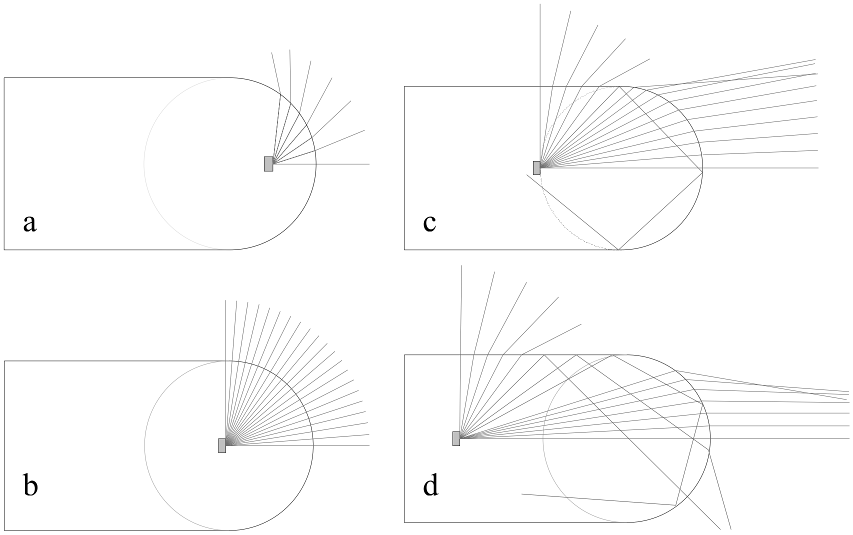

Fig. 3. Ray tracing at (a) d = -0.5R, (b) d = 0, (c) d = R and (d) d = 2R reveal very different exit radiation patterns. All calculations are for a refractive index of 1.5.

Familiarity with how light exits a LED package greatly enhances understanding of how to measure light from LEDs. As can be seen in Fig. 1, a package structure can be quite complex. The metal frame, known as a lead frame, provides structural support, strain relief and electrical connections to the outside. Part of the lead frame is modified to form a cup in which the LED chip sits. The cup provides a base for mounting the chip, electrical contact, thermal dissipation and the sides are angled to redirect any side emission forwards. A thin wire contacts the top of the LED to form the anode connection. All of this is encapsulated in a transparent material specifically shaped to provide the desired beam pattern.

To demonstrate the complexity of

beam patterns possible with even very simple designs, consider the encapsulation to be a spherical surface at the end of a cylindrical rod of radius R as shown in Fig. 2. By varying the distance, d, to the LED chip, ray tracing reveals very different radiation patterns exiting the package. For instance, Fig. 3(b) shows a pattern that is essentially unchanged from the bare chip. Fig. 3(a) has the LED chip closer to the lens surface and directs light away from the normal, providing more light at high angles. Fig. 3(c), where d = R, directs most of the light forward but now light also exits the side (and even the rear via internal reflections). In Fig. 3(d) forward light is even more concentrated and a rough image of the chip would be focused some distance away. Internal reflections become very significant and can exit the package at very high angles.

Although this model is very simple, it demonstrates the components of real LED radiation patterns. Practical versions of all these types are available. You can see these radiation patterns by holding the LED up to a screen or sheet of paper and gain keen insight into the LED design.

A more scientific approach to determining the radiation pattern is to map it with a goniometer. A detector is rotated about the LED and readings are taken at each angle. This method can generate more than just an intensity distribution; it could for instance be used to map correlated color temperature with angle as shown in Fig. 4. This reflects color changes from white (low correlated color temperature) to blue (high correlated color temperature).

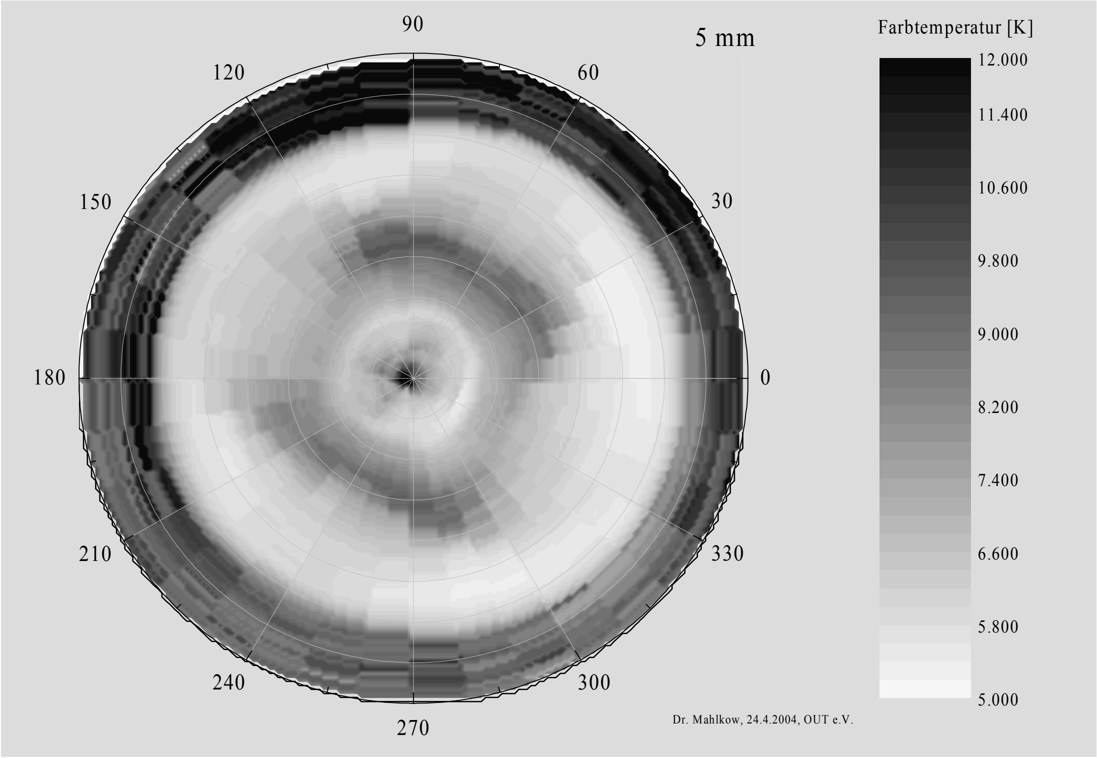

Fig. 4. A 3D polar map of correlated color temperature (Farbtemperatur) of a 5 mm lensed white LED. The center is the LED mechanical axis. Rotation was about the tip of the LED, with the circumference showing rotation about the mechanical axis and diagonals showing rotation normal to the LED axis. Reproduced with permission from Dr. Adrian Mahlkow, Optotransmitter Umweltschutz Technologie (OUT) e.V.

3. MEASUREMENT OF LUMINOUS INTENSITY

3.1 Luminous intensity of point sources

Luminous intensity is the luminous flux per unit solid angle in a given direction from the source. The “unit solid angle” part of the definition imparts an implicit limit to the nature of the source. Like all angles, the apex is a point and hence the definition only really applies to point sources. Practically, this just means that light from the source would obey the inverse-square law. Virtually all sources obey the inverse-square law if you get far enough away; the condition known as “far field”. Here the distances involved are much larger than the source, so it becomes a point source by comparison.

3.2 Luminous intensity of LEDs

Ray tracing, as shown in Fig. 3(a) – (d), gives more than just the radiation pattern. By extending the emergent rays backward, we can identify several “apparent” sources rather than just a single LED chip. In 3(c) the lens bends the rays forward and makes the chip appear further away, although still on axis, as shown in Figure 5(a). The sidewall rays refract light depending on the angle, producing a shifted image that appears below and to the side of the actual chip position, as seen in Fig. 5(b). Rays that are totally internally reflected at first strike can exit the lens at high angle, as illustrated in Fig. 3(d) and shown in Fig. 5(c).

Fig. 5. At least 3 different “apparent” sources can be identified. These correspond to (a) the on-axis lens emission seems to come from an area directly behind the LED package but along the line of the optical axis, (b) emission through side walls seems to come from below and to the side of the chip and (c) an emission from the LED tip at high angles is the result of internal reflections.

LEDs do not behave as point sources and even the positions of the apparent sources may be hard to identify. Moreover, measurements of luminous intensity are often made close to the LED rather than “far field” conditions. It is not surprising therefore that laboratories often disagreed as to the value of luminous intensity of LEDs. The CIE, in an attempt to improve agreement between laboratories, proposed the introduction of a new quantity – Averaged LED Intensity[1]. This quantity uses areas and distances instead of angles, but the unit for Averaged LED Luminous Intensity is lumens/steradian (candelas) just like the classical definition of luminous intensity.

Two conditions for Averaged LED Intensity were set, Condition A and Condition B. Both use the same detector area of 1 cm^2, with Condition A having 316 mm from the tip of the LED to the detector aperture and Condition B having 100 mm. These measurement conditions have been widely adopted throughout industry, resulting in close agreement between laboratories.

Although CIE Publication 127 represented an important milestone in the measurements of LEDs, it is just a recommendation. CIE technical committee TC2-46[8] is engaged in updating it to a CIE/ISO standard.

4. MEASUREMENT OF LUMINOUS FLUX

CIE Publication 127 also addressed the measurement of luminous flux, but left several critical issues unanswered. These have been debated in CIE TC2-45 committee, and the report (Publication 127.2) is currently in the final stages of approval prior to publication. Discussions following are therefore a synopsis of essential features of the last draft.

A new quantity “Partial LED Flux” will be introduced. The term “total luminous flux” will be applied only when the flux in all directions is measured, generally at the center of a sphere. Partial LED Flux is simply the flux contained in a given conical angle, where the angle is defined by strict measurement protocols. All Partial LED Flux measurements are made with a 50 mm diameter circular detector aperture. For any conical angle ***x***, expressed in degrees, the distance ***d*** from the detector aperture to the LED tip is given by:

$$d = \frac{25}{\tan\left(\frac{x}{2}\right)} \quad [mm] \qquad \text{Where } 0° < x \leq 180° \qquad \text{Equation (1)}$$

Any value for the angle can be set using this definition, and the symbol for Partial LED Flux is $\Phi_{LED,x}$. It was established to enable measurements of “useful flux” as opposed to total flux. “Useful flux” is vague and undefined, and will change with application. However, by defining the measurement conditions, certain angles may be established for comparison. It is likely with time that these angles will tend towards a few preferred selections, depending on applications, to minimize the number of required measurements.

These definitions flow logically from the earlier definition of Averaged LED intensity, such that sets of fixed conditions are available to measure any angular component of the LED along the mechanical axis direction. This is shown diagrammatically in Fig. 6. At approximately 2° the Averaged LED Intensity Condition A is the measurement condition of choice, and at about 6.5° Condition B can be used. For larger angles, and other small angles, Partial LED Flux can be used. Note that Partial LED Flux is not defined for angles greater than 180°, so the LED should not be placed inside the sphere (as is commonly practiced with current equipment). The implication of placing it inside the sphere is that total flux is the desired measurement. If the LED is measured at the sphere wall it is the responsibility of the measuring laboratory to establish the measured result represents all the flux and that components are not missed. In other words, the result should agree with correct measurements made at the center of a large sphere.

There are definitions for Partial LED Flux beyond x = 180°, but they are not CIE definitions. Because “General Requirements for Photometric Methods of White LED’s for General Lighting”[2] defines the chip rather than the LED tip as the cone angle apex its Downward Flux, which is a 180° full angle, has part of the LED inside the sphere. Similarly, it defines a “120° Flux” that has a full angle to the chip of 240°. The definition of total flux is the same as CIE’s.

From the LED’s point of view all of these measurements provide a progression of increasing angles. However, from the instrumental requirements several changes must be made. For Averaged LED Intensity a circular detector of 11.3 mm diameter is required, but for Partial LED Flux a 50 mm diameter detector is needed. Also, there is a change in unit between these measurements: Averaged LED Luminous Intensity expresses the flux [lumens] divided by the solid angle [steradians] giving units of lumens/steradian [candelas]; Partial LED Flux expresses the flux [lumens] within the defined cone angle but not divided by the cone angle. The Partial LED Luminous Flux unit is therefore lumens, which is the same as that of total luminous flux. Although they have the same unit it is important that Partial LED Flux is not compared to, or incorrectly mistaken for, total flux. Partial LED Flux has the specified angle as part of its definition and only measurements at the same angle should be compared.

Relatively small angles are used in Averaged LED Intensity, but Partial LED Flux measurements may subtend large angles. As the angle increases, cosine response of the detector becomes critical and hence only instruments of appropriate design should be used. Also, the sphere input port should be a single, thin 50 mm aperture such as shown in Figure 6. In order to assure correct integrating sphere operation and to minimize errors, the sphere should be at least 200 mm diameter and coated with a high reflectance coating.

Beyond angles of 60° direct light from the LED may hit the detector without first hitting the integrating sphere. A small appropriately positioned direct light baffle, as shown in Fig. 6(b), should be part of the design of the measurement instrument. Generally, this baffle is designed to suit all measurements of Partial LED Flux but a different location is required for total flux of center-mounted LEDs, as shown in Fig. 6(d).

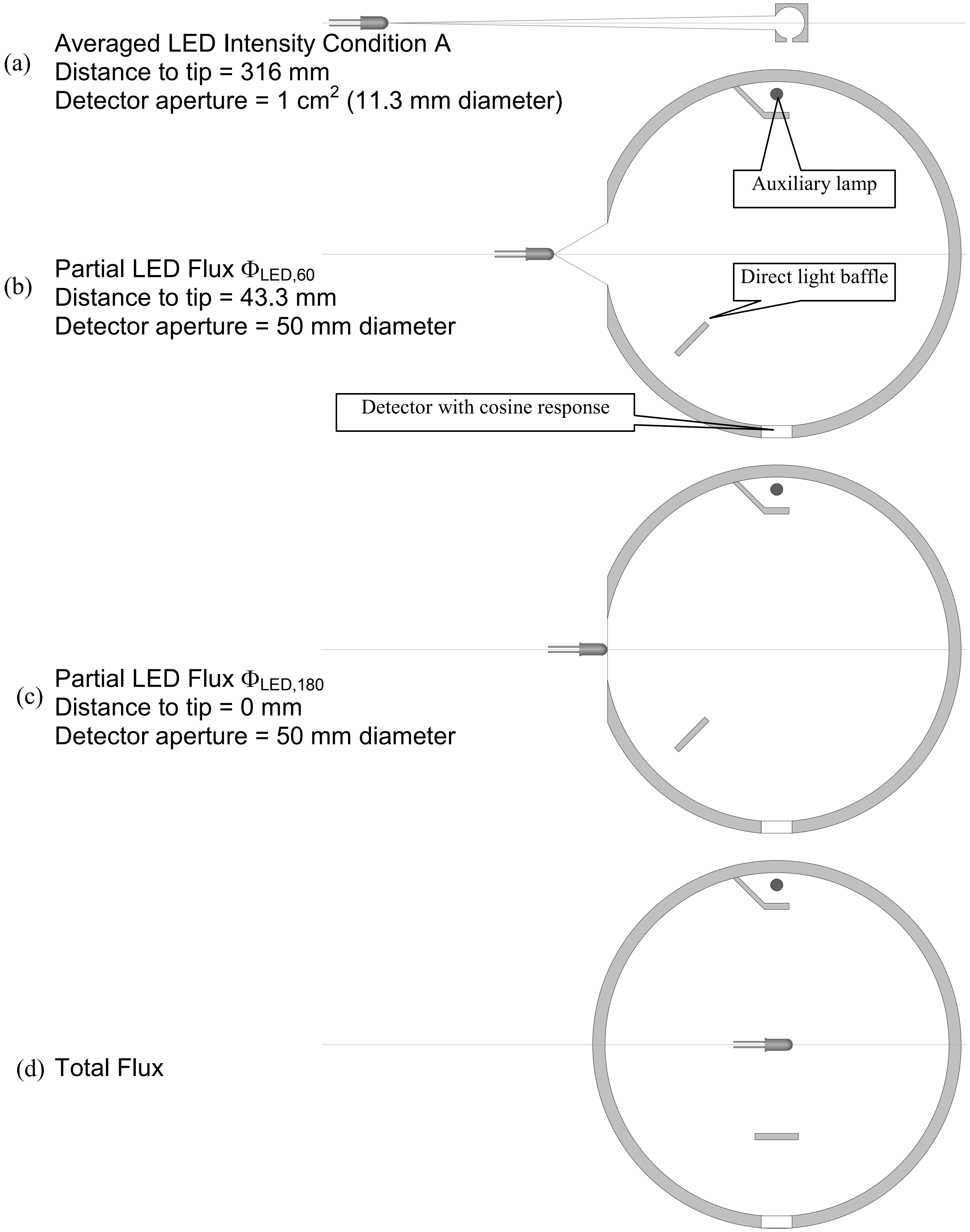

Fig. 6. Definitions of Averaged LED Intensity, Partial LED Flux and total flux form a series of measurements with increasing solid angle.

As the LED gets closer to the sphere input port, light that would escape from the port may be reflected back by the LED or holder. Since this additional light may then go on to be detected it effectively increases the throughput of the sphere and hence the instrument sensitivity relative to when the LED is absent. This interaction of the LED with the measuring instrument can give rise to systematic errors in measurements. These errors can be corrected in one of two ways:

1. Calibrate the system with a LED standard of Partial LED Flux that is identical to the LED being measured. Unfortunately such standards do not exist at this time.
2. Correct the result for the reflection effects using an auxiliary lamp (shown in Fig. 6(b)).

Since the second method is more versatile it is likely to be the method of choice. Following calibration, the calibration source is switched off, the auxiliary lamp is switched on and a measurement taken (S_{cal}). Then the LED under test is placed in the appropriate position and a measurement is taken with the auxiliary lamp on and the LED off (S_{LED}). The ratio of the two auxiliary lamp measurements is the correction that should be applied to the result.

$$\Phi = \Phi' \times \frac{S_{cal}}{S_{LED}}$$ Where Φ' is the measured result and Φ is the corrected result Equation (2)

This same correction technique can be applied to both Partial LED Flux and total flux quantities.

It is important to make the LED holder as black as possible so that reflections from the holder do not contribute to measurements. Also, ambient light needs to be excluded from measurements and any enclosures should be non-reflective for the same reason.

5. MEASUREMENT OF LUMINANCE

5.1 Luminance of single devices

The previous measurements of Averaged LED Intensity and Partial LED Flux involved measuring flux within a given conical angle under defined conditions. The measurements were of the entire LED. When measuring luminance of a single LED device, we must look within the LED structure and isolate the part we want to measure. This requires an imaging optic such as a telescope or microscope.

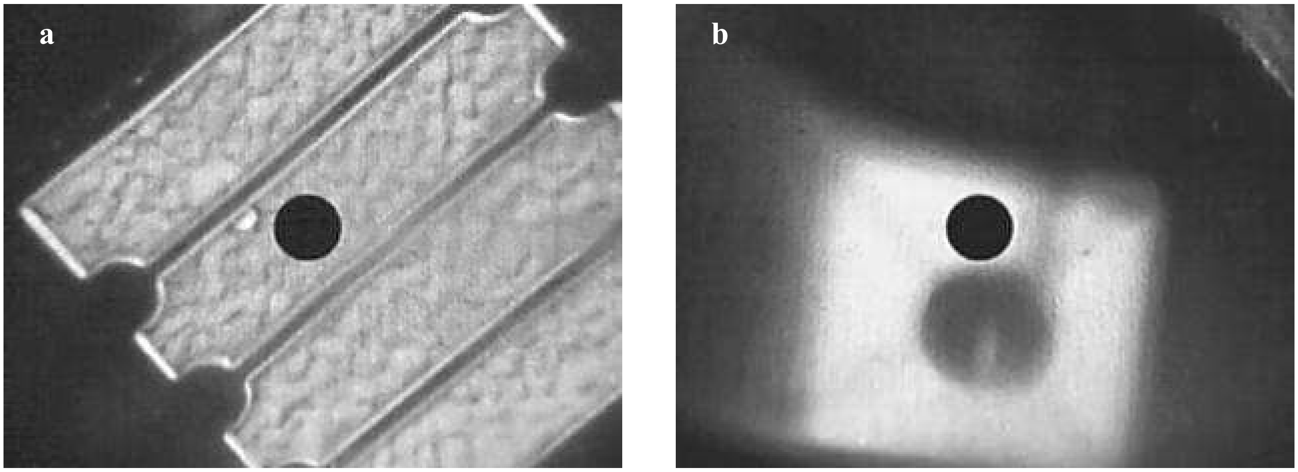

Fig. 7. Images of (a) Luxeon® LED and (b) 5 mm lensed LED. The circular black area in the center is the measurement area.

Figure 7 shows images of some common LED examples. In each case, the area to be isolated and measured is seen as a circular black spot. It is important to select an area of light emission that is clearly bigger than the spot to be measured, the so called “overfill” condition. The Luxeon® Lambertian LED[9] (Fig. 7(a)) shows a clear image of the chip, as would be expected from an LED of the type illustrated in Fig. 3(b). In contrast, the 5 mm lensed LED is similar to the type shown in Fig. 3(c), and is much harder to image clearly.

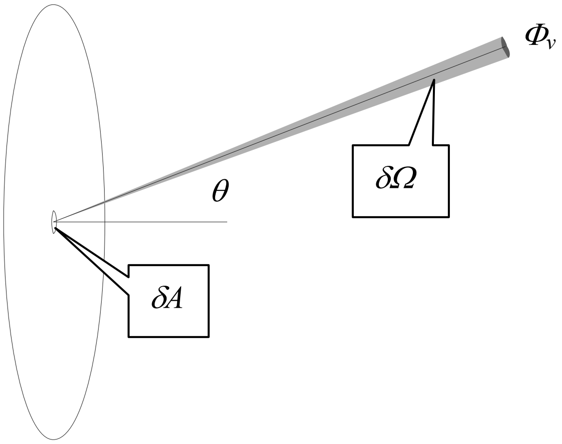

Fig. 8. The parameters defining luminance include the luminous flux Φ_v from an elemental area δA over the elemental cone angle $\delta\Omega$ in a given direction θ.

The formal definition of luminance, L_v, is given by equation 3 where the parameters are defined in Figure 8.

$$L_v = \frac{1}{\cos\theta} \cdot \frac{\delta^2 \Phi_v}{\delta A \, \delta\Omega} \qquad \text{Equation (3)}$$

It is the partial differential of flux with respect to area and solid angle in a given direction, θ. You may have noticed that this equation does not imply anything about the ability or even need for the measurement system to form an image. However, in practical systems the measurement area (A) is finite (figure 7 for example) and the angle of measurement (Ω) is defined by effective lens size of the imaging system. This means that instead of measuring L_v we measure an average luminance $L_v(\theta,\Omega,A)$.

$$L_v(\theta, \Omega, A) = \frac{1}{\cos\theta} \cdot \frac{\Phi_v}{\Omega \cdot A} \qquad \text{Equation (4)}$$

It is expressed as $L_v(\theta,\Omega,A)$ to show that the measured luminance is a function of direction, angle and area. For a perfectly uniform Lambertian emitter the $L_v(\theta,\Omega,A)$ is constant and equal to L_v, but for non-uniform and highly directional sources such as LEDs the exact conditions must be reproduced in order to make two measurements agree.

The sensitivity of luminance values to θ, Ω, and A depends on the rate of change, which is the partial differential portion of Equation 3. If, for example, the Luxeon® LED in Fig. 7(a) were measured we would know from the "Lambertian" description that the rate of change with respect to direction and cone angle is low. Figure 7(a) shows some non-uniformity across the chip so the location and area of measurement may need to be fixed. Generally, this type of LED would be considered to be easy to measure. In contrast, the 5 mm lensed example in Fig. 7(b) is extremely difficult because the luminance varies very rapidly with all parameters. Additionally, there are difficulties in establishing the coordinate system for measuring θ (the chip is encapsulated), and the lens can introduce aberrations and focusing problems.

The radiance of the package should be the same as the radiance of the chip (ignoring absorptions, scattering and reflections), so a lens should not affect the value, only the difficulty in measurement. You will recall that a lensed LED may project a rough image onto a screen. This implies a correlation between location on a chip and direction of the emerging light, and is a natural consequence of small lenses used close to the chip. This co-dependence of location and direction introduces yet another problem in measuring luminance: the "effective" lens stop may not be the size of the telescope lens but may instead be limited by the size of the LED. This means that calibrations are made with one lens stop and measurements with an entirely different one, giving erroneous results. In such cases, small telescope lens stops will give generally higher values than larger lens stops. However, as the lens stop is decreased it may be difficult to align the measurement spot as the co-dependence means progressively smaller areas of the chip are seen in the image.

It is clear that measured values of luminance for LEDs such as that shown in Fig. 7(b) can vary widely. Agreement between measurements for the same LED can only be obtained with rigorous enforcement of procedures and measurement conditions. CIE TC 2-58[4] has been assigned the task of standardizing these procedures and conditions. An alternative approach is to remove the lens and polish the LED flat. Although this is destructive, it simplifies luminance measurements considerably. Another approach is to immerse the LED in index-matching liquid, making the lens effectively disappear. All techniques have their drawbacks as well as advantages.

5.2 Luminance of arrays and clusters

Ultimately, if luminance is an essential property of the LED array to be measured, then it is likely that the array would be used in display applications. These devices would then be typically viewed at large distances so the individual LEDs would not be seen separately. However, prior to assembly the display would consist of individual arrays or clusters and these might require testing.

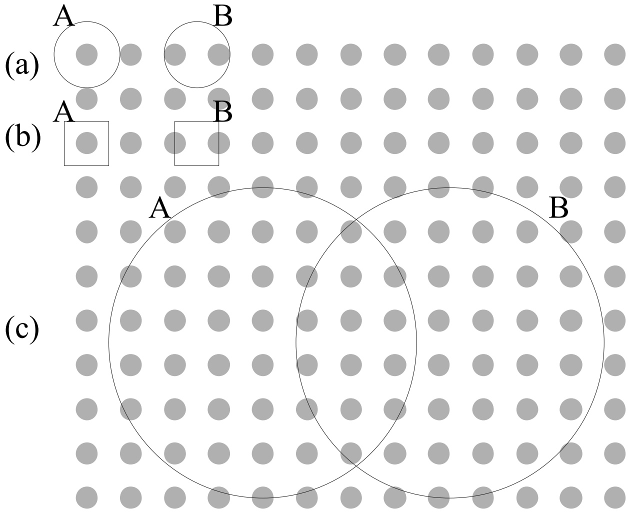

Fig. 9. Illustration of sampling effects when identical measurement aperture pairs, A and B, are at different locations. (a) $L_A \neq L_B$, (b) $L_A = L_B$, (c) $L_A \approx L_B$

Luminance is normally associated with continuous, relatively uniform, areas of emission such as monitors or reflective materials under illumination. In section 5.1 we said it was important to select areas of emission that are larger than the measurement area. This is because the alternative, that the measurement area is larger than the emission area, would measure luminous intensity rather than luminance. That is, the area information has been lost and the entire source is now measured. What if the source consisted of several small discrete emission centers like an array or cluster of LEDs? Is luminance or luminous intensity measured?

Such an array is illustrated in Fig. 9. Technically, this could be considered as simply the extreme example of a non-uniform source. As such, the difficulties should be the same as measuring any non-uniform source: fixing the size and location of the measurement area. In Fig. 9(a) the measurement area is small and the measured value can change dramatically with position. Although measurement areas A and B are identical, B contains two LEDs whereas A contains only one hence the measured luminance $L_A \neq L_B$. One way to get around this problem is to make the measurement area the same shape and size as the repeat unit within the array, as in Fig. 9(b). Here, no matter which location of the area the same number of LEDs is always included ($L_A = L_{B)}$. Using a large measurement area to sample many LEDs at the same time may be more versatile and convenient. If the number of LEDs measured are large, as in the case of Fig. 9(c), then variations in results are small ($L_A \approx L_B$).

In section 5.1, the chip luminance measurements were made using a telescope or microscope. This was because the required measurement areas were very small and the chip was physically inaccessible. With arrays that are inaccessible a telescope is still the best option, but accessible arrays can use a different technique. A black mask of the correct size and shape can be placed onto the array, blocking light from all LEDs outside the desired measurement area. The luminous intensity is then measured at some suitably large (at least ten times the mask diagonal) distance away. Divide the measured luminous intensity by the mask area to give the luminance. This is relatively simple to do and if the mask is some multiple of the array spacing, the result should correlate with the luminance of the assembled display.

Fig. 10. Illuminance may be from multiple sources.

In the UK, the ‘LED Clusters’ Focused Interest Group (FIG) was set up within the National Physical Laboratory’s Optical Radiation Measurement Club to address these problems. Their report, which includes similar recommendations to this paper, will be published soon[10]. CIE Technical Committee 2-50 is also working on appropriate standard conditions and definitions for LED cluster measurement[7].

6. MEASUREMENT OF ILLUMINANCE

In previous sections, measurements of illuminance under set conditions were used to provide values of Averaged LED Luminous Intensity, Partial LED Flux and even luminance (with the mask technique). However, illuminance is a general measurement of flux passing through a unit area of a plane and does not necessarily include set conditions. The general method of measurement is independent of how many sources or their positions. When we say “illuminance of a source” we are implying it is now the only source contributing to the measurement, and that a set of distance and orientation conditions will be part of the "illuminance" definition.

Key elements to accurate measurements of illuminance include the uniformity of detector response over the measurement area and the cosine response[11]. The cosine response is required to correctly measure sources at an angle to the plane normal and for extended sources. As illustrated in Fig. 10, the radiation pattern at the plane may be non-uniform, and if measured with a non-uniform detector the illuminance result may be erroneous.

Even if the detector responds uniformly and with good cosine response, measurements of non-uniform radiation patterns would give different results depending on detector size and location. When comparing illuminance values, it is important to make sure the same conditions of measurement were used.

7. GENERAL CONSIDERATIONS APPLYING TO ALL TYPES OF MEASUREMENT

LEDs are temperature sensitive. The intensity and spectral distribution of emission changes with temperature so fixed temperature conditions must be used or reported with the values. However, the fixed condition is not that of ambient environment, though it contributes, it is the temperature of the LED chip that is important. When electrical power is applied to the LED not all of it is converted to light; some appears as heat. This heat is generated directly in the LED and as the chip gets hotter, the emission decreases. It is extremely important to remove the heat from the LED and since most heat is transferred via electrical or thermal contacts, the position and thermal resistance of any leads or heat sinks attached to the LED are critical in determining the final equilibrium temperature. Under constant current, the temperature of the chip correlates well with the forward voltage drop across the LED. Many standard LEDs use this fact by applying heat in a feed-back loop to achieve a constant forward voltage. If the LED under test is not regulated in this way, forward voltage should be reported along with current and optical measurement results.

Many measurements are made using short pulses of current to the LED in order to minimize the heating effect and maximize the measured intensity. Such non-equilibrium measurements can only be compared if the conditions are identical or if results are "corrected" to equivalent equilibrium conditions using correlation.

All measurement results have an associated uncertainty. Accreditation and conformance requirements make it increasingly important to state these uncertainties along with the measurement result. The subject of uncertainty determination is beyond the scope of this paper, but is detailed elsewhere[12,13].

Traceability is also essential to assessing quality of measurement results. All measurements should be traceable to a National Metrology Institute (NMI). This means that all standards used should be connected via an unbroken chain of traceability, including uncertainty at each stage of transfer, to a standard provided by a NMI (KRISS, NMIJ, NIST etc).

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