Lecture 15

LED MEASUREMENT ISSUES*

A.A. Gaertner
Institute for National Measurement Standards
National Research Council of Canada, Ottawa, Canada

15.1 INTRODUCTION

The development, production and application of Light Emitting Diodes (LEDs) have increased tremendously in the last ten years. From their humble beginnings as panel indicator lights, they are now available in many shapes, sizes, light output levels and colours (Figure 15.1), making them suitable candidates for use in traffic signalling systems, automobile lights and in general lighting applications. The development of the new high power LEDs with a significant increase in efficiency over the earlier versions has resulted in an advantage of close to an order of magnitude of the LED over colour filtered incandescent lamps. Phosphor-converted LEDs (pcLEDs, Figure 15.2), which emit white light by the conversion of the blue light of the LED by the embedded phosphor(s), are now available for general lighting conditions which require good colour rendering. OLEDs (Organic Light Emitting Diodes) are being considered for light sources in sheet form, resulting in the possibility of curtains of light.

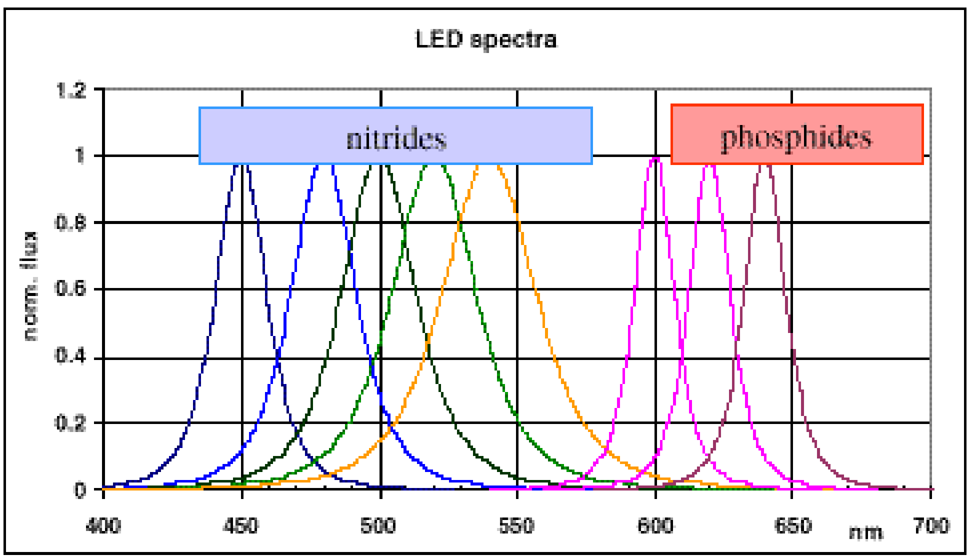

Figure 15.1 Typical LED spectra (from G.O. Mueller [5]).

Strictly speaking, the term LED should only be applied to those diodes which emit visible light, and the term Infrared Emitting Diode (IRED) applied to those devices which emit in the infrared portion of the spectrum.

All these special and useful properties of the LED are accompanied by their commensurate problems in measuring the light output of these devices. Accurately defined and executed mea-

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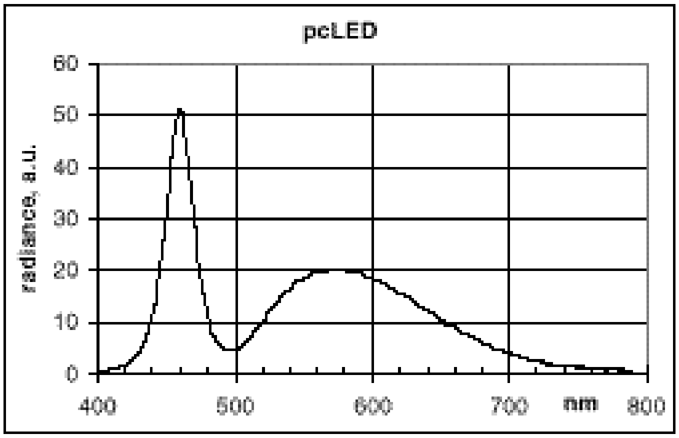

Figure 15.2 Spectrum of a phosphor-converted LED (pcLED) (from G.O. Mueller [5]).

surements of the light output of LEDs must be made to allow both comparison of devices between manufacturers and their application to specific lighting requirements. In this lecture we will examine some of the challenging problems which have arisen, and some of the solutions which the international community is suggesting in their attempts to bring order to this field. More detailed and extensive information may be found in the references listed in the Bibliography. We will consider three main characteristics: geometrical properties, spectral properties, and operating conditions.

15.2 GEOMETRICAL PROPERTIES

We will limit our discussions to the specification and measurement of the geometrical quantities of Intensity and total Flux for LEDs.

15.2.1 Intensity

The quantity intensity is one of the most commonly used characteristics used to indicate the light output of LEDs. However, the construction and packaging of an LED create special difficulties in specifying and measuring a meaningful value for intensity. We need to take closer look at what intensity is and what we can actually measure for an LED.

Recall the definition of the quantity intensity from Lecture 2, and shown in Figure 15.3. The flux Φ is meant to be that flux leaving the source in a particular direction and propagating in the element of solid angle Ω containing the given direction.

This basic diagram using a point source is useful to show the meaning of intensity. However, point sources have several inherent implicit properties which can mislead us when we apply our ideas of intensity to other sources such as LEDs which do not possess these properties. These are related to:

i. the angular distribution of the output flux (at a specific distance from the source), and
ii. the spatial variation of the output flux as a function of distance from the source.

15.2.1.1 angular distribution

The intensity of a point source is the same in all directions. This also has two ramifications:

1. the intensity is the same for all directions with respect to the source, and
2. the intensity is the same for all measurements performed using any solid angle Ω.

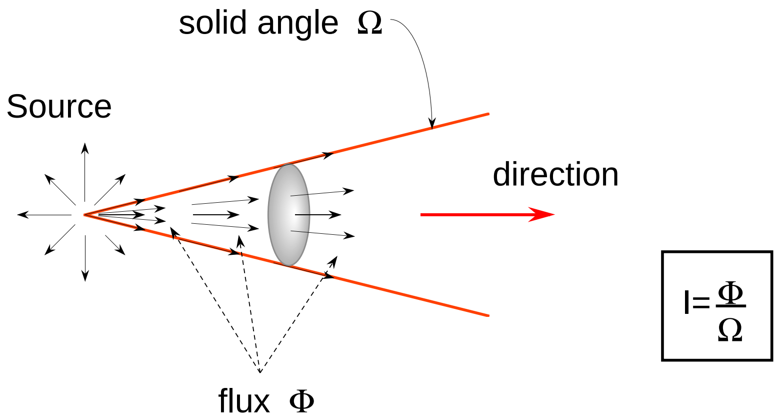

Figure 15.3 Defining geometry for the quantity Intensity (I).

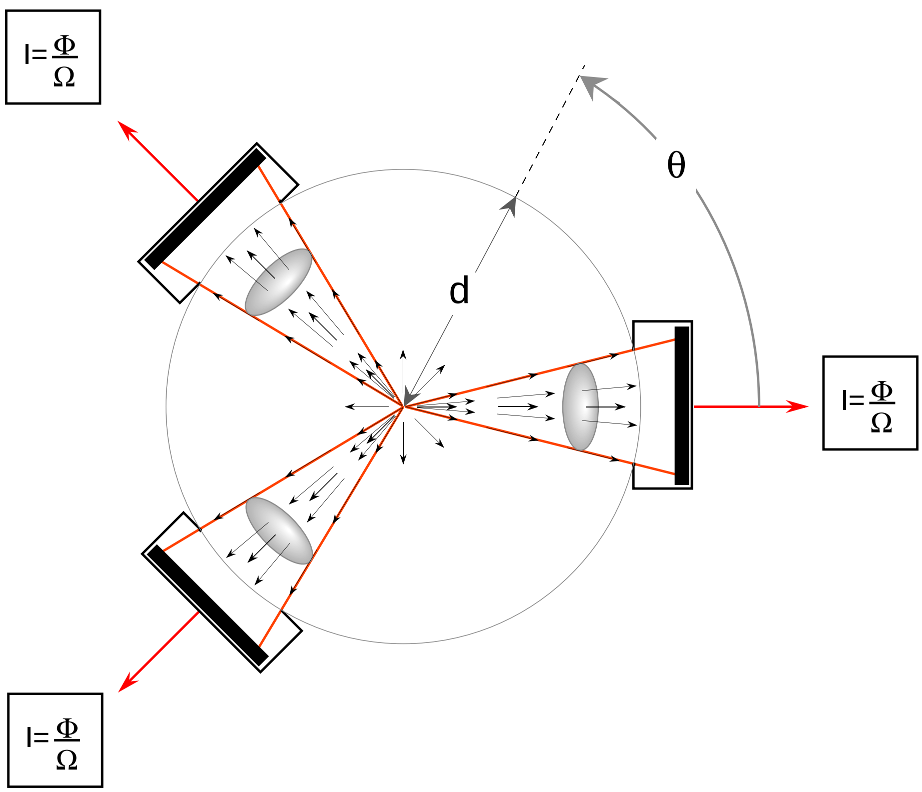

Figure 15.4 **Point Source:** The intensity is the same in all directions.

Consider first the directional aspect, as indicated in Figure 15.4.

The input aperture (of area A) to the detector, together with the distance d of the aperture from the source, defines a solid angle ($\Omega = A/d^2$) for the measurement. If we use this detector, and measure the flux (Φ) at any angle (θ), keeping the distance d constant, we will obtain the same detector measurement value at all angles. Since d and Ω remain constant for all these measurements, the intensity $I = \Phi/\Omega$ is the same at all angles. This is useful, since it does mean that we do not require a critical alignment of our measurement system with respect to the angle θ.

Now consider the effect of using two detectors with different input aperture sizes, as shown in Figure 15.5. The difference in aperture size for the two detectors means that they will be measuring different amounts of flux and sampling different geometric regions of the output of the light source. Since the distance d is the same for both detectors, the increase in aperture area between detector 1 and detector 2 causes a commensurate increase in the solid angle. Since the intensity of the source is constant with angle, the increase in the flux measured by detector 2 is is exactly equal to the increase in the solid angle subtended by detector 2. This is a very useful property of the point source, since it means that the intensity measurements we make do not depend on the particular size (or shape) of the input aperture of our detector.

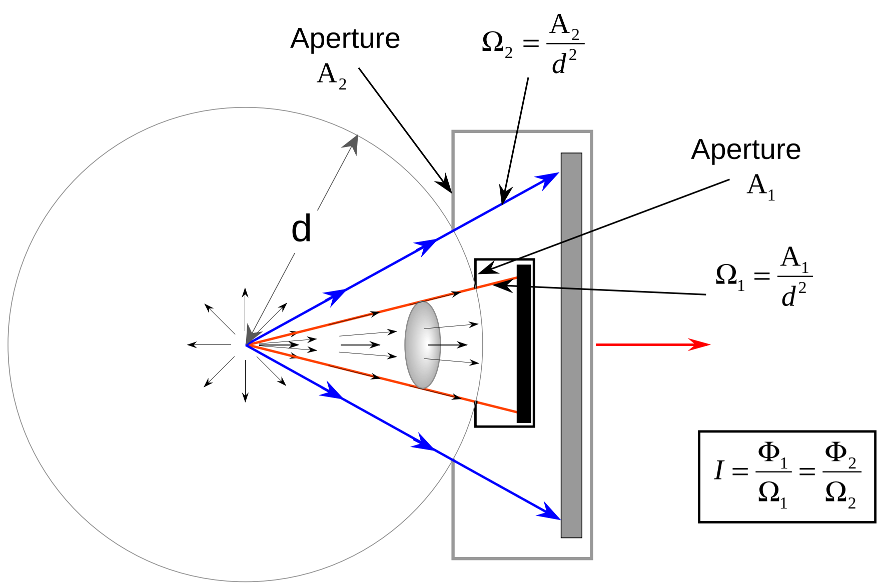

Figure 15.5 **Point Source:** The intensities measured by detectors with different input aperture sizes (A_1 and A_2) are the same.

The intensity of most other sources will depend upon the direction of the output with respect to some defining feature of the source. This information is usually presented on a polar plot where the length of the radius is the value of the intensity I of the source measured from some defined center of, or point on, the source. The intensity is usually normalised to some value I_0 such as the maximum value, or the value in some direction of interest. The intensity is plotted as a function of angle (θ) about the source measured from some defined direction ($\theta = 0$) with respect to some characteristic feature of the source. An example is the plot for a point source shown in Figure 15.6. Since a point source looks the same in all directions, there is no defining feature from which to measure θ, so the $\theta = 0$ direction is arbitrary. The curve of $I(\theta)$ for the point source is rather simple—it is a circle of constant intensity (radius) at all angles θ, centered on the source. The equation for the intensity distribution of a point source is simply $I(\theta) = I_0$, where I_0 is the constant intensity in all directions.

Note that this polar plot is a curve in only one plane of a three-dimensional 'object'. For a full picture of the intensity output of the source we would need to present slices in other 2-D planes of space, or use some of the modern software which can give 3-D impressions on 2-D paper.

As another example, consider the Lambertian source we introduced in Lecture 2. This is a

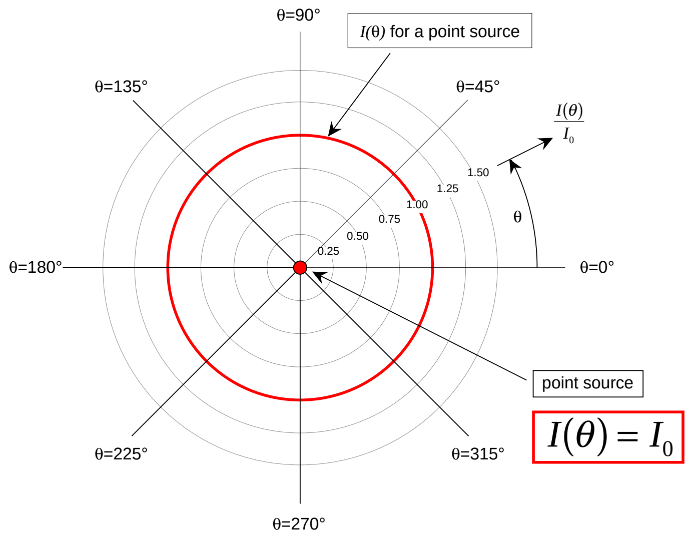

Figure 15.6 **Point Source:** Polar plot showing the Intensity $I(\theta)$ of a point source as a function of angle θ around the point source.

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source which only radiates into one-half of the full 3-D space, and whose intensity (per unit area of source) varies as the cosine of the angle from maximum output (which is perpendicular to the surface). A polar plot of the intensity of this source is given in Figure 15.7. The equation for the intensity distribution of a Lambertian source is $I(\theta) = I_0 cos(\theta)$, where I_0 is the maximum value of the intensity, in the direction normal to the surface.

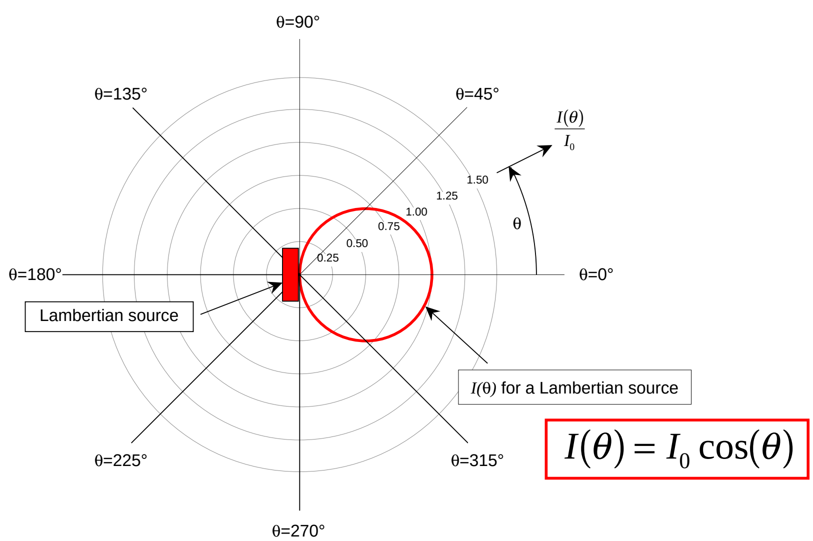


Figure 15.7 **Lambertian Source:** Polar plot showing the Intensity $I(\theta)$ of a Lambertian source as a function of angle θ from the normal to the source surface.

Many LEDs have intensity distributions similar to one of those shown in Figure 15.8. It is readily apparent that the intensity is quite nonuniform in the angular variation, and is often not even symmetric with respect to any angle in this planar view. These types of distributions lead us to two problems:

i. determination of a reference direction for the measurements, and
ii. determination of the solid angle to be used for the measurements.

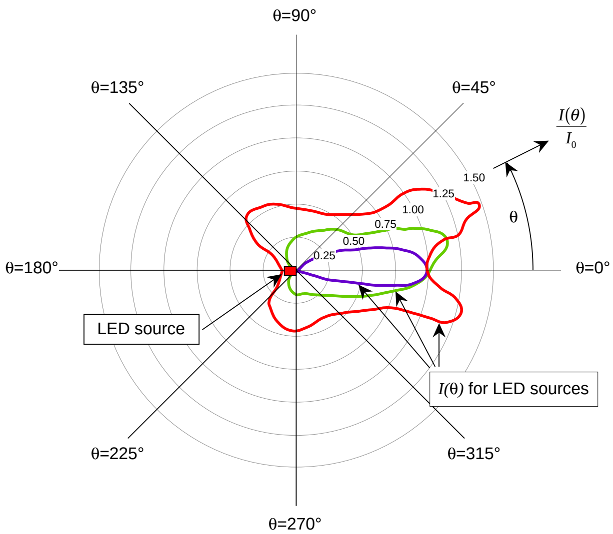


Figure 15.8 **LED Sources:** Polar plot showing the Intensity $I(\theta)$ of sample LED sources as a function of angle θ from the mechanical axis of the LED, and normalised to the value I_0 at $\theta = 0$.

The issues related to determination of the reference direction from which the intensity distribution, or even just a single characteristic intensity value, of the LED should be measured are shown in more detail in Figure 15.9. Definitions of each of the three axis shown have been proposed by CIE TC 2-46 [6ii, Draft 4 May 2001]:

LED front tip: *The LED front tip is center point of the LED light emitting surface on the outer surface of the emitter.*

Optical axis: *This is the axis through the LED emitter front tip in the direction of the centroid of the optical radiation pattern.*

Peak intensity axis: *This is the axis through the LED emitter front tip in the direction of the maximum intensity.*

Mechanical axis: *This is the axis through the LED emitter front tip in the direction of the axis of symmetry of the emitter body or perpendicular to the top surface of the body of the emitter.*

Any of the three different axis shown could be chosen as the reference axis for intensity measurements. The optical axis and the peak intensity axis will require that the output intensity distribution be measured for the LED before these axes can be determined.

The issues related to a determination of the correct solid angle to be used for the measurement of the intensity of an LED are illustrated in Figure 15.10.

Since the intensity varies with angle, we can see that the intensity measured by the two different detectors will be different. Each detector will measure the total flux which enters its input aperture, which will then be divided by the solid angle to determine the intensity. This ‘average’ intensity will be different for the two detectors since the flux output of the LED does not change uniformly

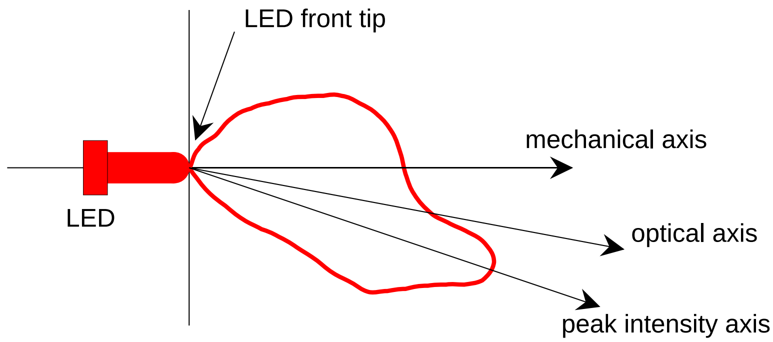


Figure 15.9 Geometric terms for LED intensity measurements.

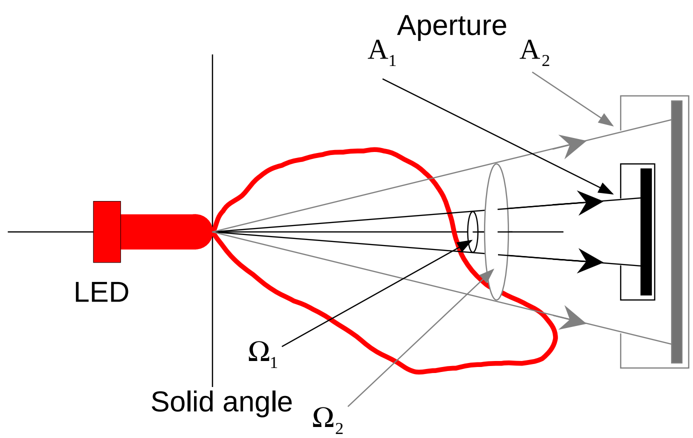


Figure 15.10 Solid angle issues for LED intensity measurements.

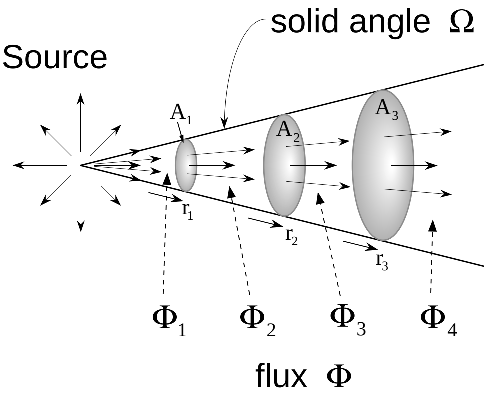
with the (solid) angle. Therefore, the intensity of an LED which we measure will depend on our particular detector aperture size and shape, even when we measure the LED along the same reference axis and at the same distance from the LED!

At this point in our discussion, we note that to obtain intensity distributions, such as indicated in Figure 15.8, the measurements will need to be made with detectors whose apertures are small enough to enable the desired detail in the angular information to be obtained. It should also be pointed out that the spatial responsivity of the detector surface must be better than any uncertainty we wish to have in our final results for the determination of the intensity. (Any non-uniformity will cause an erroneous ‘weighting’ of the flux measured at the different parts of the detector.)

15.2.1.2 spatial (distance from the source) distribution

The intensity of a point source is the same at all distances from the point source. Recall our discussion of the inverse-square-law in Lecture 2. As we can see from Figure 15.11, the total flux propagating within the constant solid angle Ω remains constant at all distances from the source. This is because all light rays from the source are propagating directly out from the same point, and their vector direction is such that none of them leave the solid angle, nor are there any other light rays which enter this solid angle from another direction.

If the source is extended we have a quite different situation, as illustrated in Figure 15.12. This



$$\Omega = \frac{A_1}{r_1^2} = \frac{A_2}{r_2^2} = \frac{A_3}{r_3^2}$$

$$\Phi = \Phi_1 = \Phi_2 = \Phi_3 = \Phi_4$$

$$I = \frac{\Phi}{\Omega}$$

Figure 15.11 Point Source: The intensity is the same at all distances from the source.

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shows a second source which emits a beam of light which intersects our original beam at an angle. It is evident that any measurement of the flux Φ in the constant solid angle Ω within the distances from r_1 to r_2 will be different than that constant value measured for $r \leq r_1$ and $r \geq r_2$.

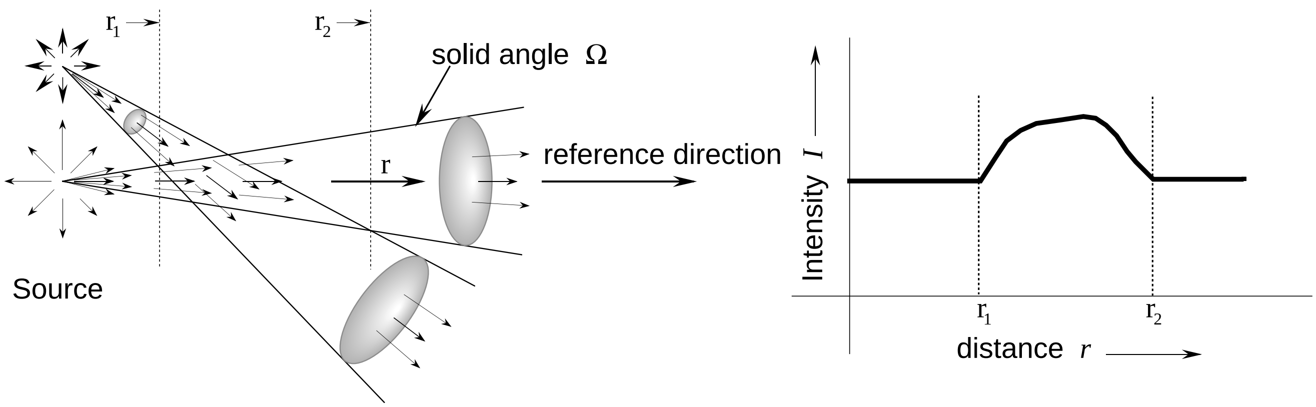

Figure 15.12 Extended Source: The intensity varies with distance from the source.

These considerations show that even at constant solid angle Ω the intensity output of extended sources will change with distance from the source. This behaviour is typical for most sources, since all sources are larger than a point source. The problem can be worse for LEDs since the packaging introduces many components which act as reflectors and concentrators of the light which is emitted from the small source itself.

15.2.1.3 compromise solution

The small size and low output of typical LEDs demands that we place our detectors at small distances from the LED. This will aggravate most of the problems indicated above. Given these problems, is there any solution?

The basic definition of intensity must still remain valid. In the case of LEDs, its value evidently changes with many variables: the distance from the LED, the angle with respect to the LED at which the measurement is made, and the size of the solid angle used. If all these conditions can be specified exactly, it is possible to present an accurate representation of the intensity (distribution) of the LED. However, this is too demanding of experimental accuracy, and too much of a burden for efficient comparison of LEDs during the manufacturing process, or comparison of LEDs between manufacturers, or selection of LEDs for any specific purpose.

In order to provide some assistance and guidance to the international community, the CIE (Commission Internationale de l'Eclairage), through its technical committee structure with members from all interested and knowledgeable parties around the world, is working on a standard which proposes (it is not yet accepted) two defined geometrical configurations for measuring the luminous intensity of LEDs. The reference axis, the solid angle, and the distance from the LED are all defined. The two configurations, called *CIE Standard Conditions A and B*, are summarised in Figure 15.13.

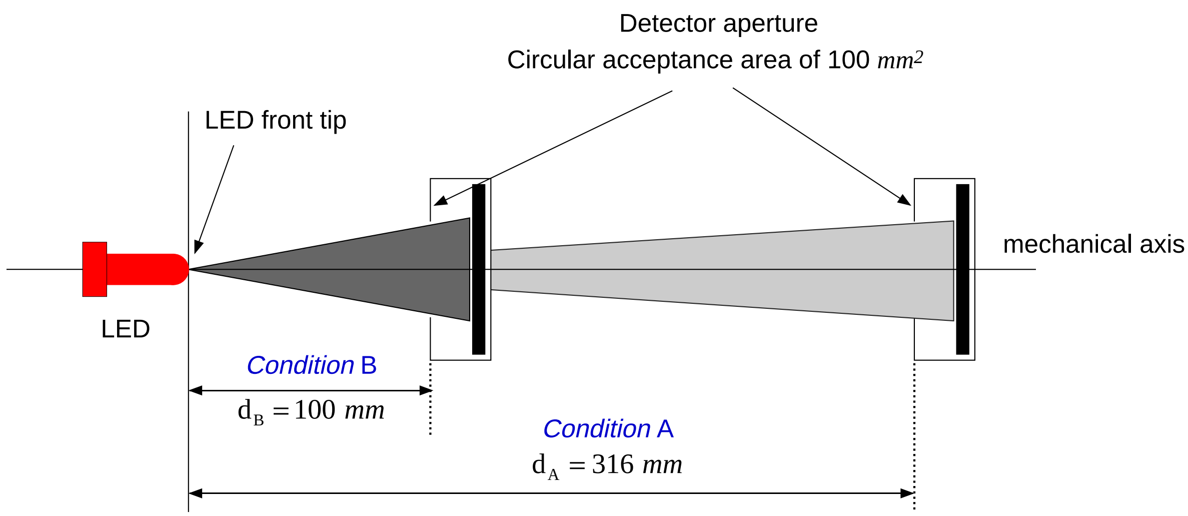

Figure 15.13 (proposed) CIE defined standard conditions (A and B) for the measurement of the *Average LED Intensity* I_{LED}.

For both configurations, the reference point on the LED is defined to be the *LED front tip*, and the reference axis is chosen to be the *mechanical axis*, as defined earlier in connection with Figure 15.9. Also in both configurations, the input aperture size of the detector used is defined as a circular acceptance area of 100 mm^2. The only difference between the two conditions is the distance between the LED front tip and the detector input aperture: Condition A defines $d_A = 316\ mm$, and Condition B defines $d_B = 100\ mm$. With the defined detector aperture and these distances the solid angles for the measurements are $\Omega_A = 0.001\ sr$ and $\Omega_B = 0.01\ sr$.

As we discussed above, any intensity measurement of a source with such intensity variations with angle and distance is an average which is dependant on the measurement configuration used. Therefore, the intensity measurements made under the two defined CIE conditions are to be called *Averaged LED Intensity* I_{LED}, with a further subscript A or B to specify which of the two Conditions is meant. A further subscript e or v is added to indicate whether we have quoted a radiometric or a photometric intensity value, as we discussed in Lecture 2. The symbols for the two quantities then become:

$I_{LED-A,v}$, $I_{LED-B,v}$ for averaged LED luminous intensity (unit: cd),
$I_{LED-A,e}$, $I_{LED-B,e}$ for averaged LED radiant intensity (unit: $W \cdot sr^{-1}$).

15.2.1.4 detector/measurement system considerations

We have already mentioned above the requirement for good spatial uniformity of the detector responsivity across the sensitive area of the detector.

The short distances indicated in the CIE Conditions A, and particularly B, will require considerable care in setting up the measurement equipment for these measurements. Several methods for the calibration of the measurement system are under consideration by CIE TC 2-46:

i. direct substitution method,
ii. detector-based illuminance (irradiance) method, with spectral mismatch correction,
iii. detector-based flux method, with spectral mismatch correction.

Each of these methods may be used, each with their own advantages and disadvantages. Since detailed discussion of each of these methods is beyond the scope of this lecture, I refer you to [5] and the ongoing work of the various CIE Technical Committees [6].

15.2.2 Flux

The 'total' flux output of a light source is required for many applications. As discussed in Lecture 4, the total output flux of a light source may be measured using an integrating sphere or a goniophotometer. While a goniophotometer may be more accurate in its measurement, it is a very specialised piece of equipment, and the many measurements required to obtain the flux of just one LED is considerably more time-consuming than the few measurements required when using an integrating sphere. As a result, most measurements are performed with integrating spheres.

The geometrical properties of LEDs, which have been discussed above in the context of intensity measurements, also create considerable problems in the measurement of the total output flux of the LED. While many of the issues are not yet resolved—CIE TC 2-45 [6i] is working on them—many of the problems are known: LED mounting geometry, treatment of backward emission, and appropriate integrating sphere design such as position of baffles, auxilliary LEDs, detector and LED placement, sphere wall reflectivity, and sphere size.

The basic operation of an integrating sphere for flux measurements was presented in Lecture 4. For an ideal sphere containing an ideal point source emitting total flux Φ, the illuminance E at any point on the interior surface of the sphere is given by

$$E = \Phi \cdot \frac{\rho}{1-\rho} \cdot \frac{1}{4\pi R^2} \tag{1}$$

where R is the inner radius of the sphere and ρ is the reflectivity of the inner surface of the sphere. The term $\rho/(1-\rho)$ is caused by the multiple relections of the flux within the sphere

$$\Phi \cdot (\rho + \rho^2 + \rho^3 + \ldots) = \Phi \cdot \frac{\rho}{1-\rho} \tag{2}$$

and the term $4\pi R^2$ is the surface area of the interior of the sphere.

The ideal sphere calculations assume

1. the sphere wall reflectivity ρ is uniform over the complete inner sphere wall
2. the sphere wall reflectance is Lambertian
3. there are no objects in the sphere.

However, when we use a sphere, we need to put things into it, which will change its behaviour and cause errors in our measurements. We will need:

1. To make any measurements we will need to add a detector.
2. The source will need to be placed into the sphere.
3. A mount for the source will have to be placed into the sphere.

4. Some baffling will need to be added.

We will consider each of these items.

Detector: The purpose of the integrating sphere is to provide us with an unweighted average of the total flux placed into the sphere, or emitted by our source in the configuration we desire. This is provided by the illuminance on any point on the sphere wall as indicated in Equation (1) above. Therefore our detector should be placed at the sphere wall, and measure illuminance. In this configuration it must be well cosine-corrected, as discussed in Lecture 4. It should be noted that detectors which are set back from the sphere wall, or measure the radiance at the back of a baffle placed inside the sphere, are not measuring the illuminance at the sphere wall, and are much more sensitive to any imperfections in the sphere. Since the detector is itself an intrusion into the sphere and will change the characteristics of the sphere, it is evident that it should be as small as possible. The larger the sphere, the less of a restriction this is on the actual size of the detector.

Light Source: The flux we wish to measure will have to be inserted into the sphere somehow. Usually this will mean that the source will have to be placed inside the sphere. The source itself is not a pure source of light. It is an object which will reflect and absorb some of the light in the sphere. This will cause a disturbance in the light distribution within the sphere, and the absorption will cause a reduction in the total flux in the sphere, and an error in our measurement. A correction can be made for this *self-absorption* effect, and is standard practice, even for incandescent lamps[7]. The basic procedure (illustrated in Figure 15.14) is to place flux from another light source (called an auxilliary lamp) into the sphere, and measure the illuminance on the sphere wall from this auxilliary source both with and without the original flux lamp in the sphere. The flux lamp is not turned on for these measurements. The ratio of the measurement of the signal due to the light from the auxilliary lamp without the flux lamp in the sphere, to that with the flux lamp in the sphere, provides a correction factor which can be used for correcting the measurement of the flux from the original flux lamp due to the self-absorption of that flux lamp.

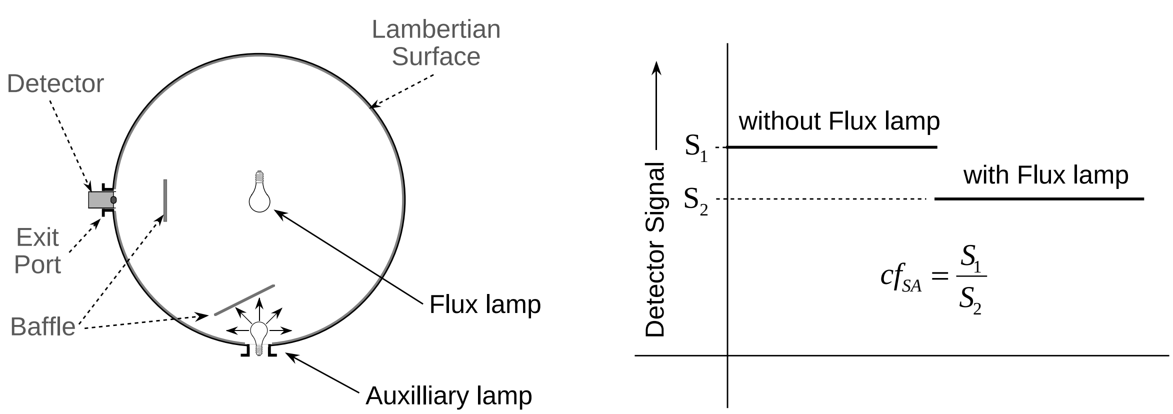

Figure 15.14 **Self-Absorption:** determination of a flux correction factor cf_{SA} due to the self-absorption of the flux lamp.

The self-absorption of the flux lamp will probably vary with wavelength, and the detector used is probably a broadband detector, such as a photometer. In this case, in order that this single correction factor cf_{SA} be applicable to that fraction of its own light which the flux lamp absorbs, the relative spectral output of the auxilliary lamp must be the same as that of the flux lamp. This implies that if you are measuring an LED by comparison with an incandescent Luminous Flux Standard, different auxilliary lamps should be used for determining the correction factor cf_{SA} for each of the two quite different light sources.

Light Source Mounts: The flux source needs to be mounted in the sphere somehow. The fixture and socket used will also absorb some of the light in the sphere, predominantly some of the direct light from the source, since they will be in close proximity to the source. In addition, some of the light reflected from the source mount directly back to the light source will be absorbed by the light source. These *near-field absorption* effects cannot be corrected by using the self-absorption technique described above. Since it is nearly impossible to correct for this type of light absorption, the best solution is to reduce the effect as much as possible by careful construction and positioning of the lamp holder:

1. position the lamp socket as far away from the remainder of the sphere as possible,
2. keep the lamp socket as small as possible,
3. avoid the formation of any cavities which will trap light,
4. coat the socket and any leads with a high-reflectance diffuse coating,
5. position the lamp as far from the socket as possible. With LEDs we can use long wire leads. However, we must be careful to maintain proper thermal sinking of the LED, which is usually done through the leads to the LED.
6. the influence of this near-field absorption can also be reduced by using a strict substitution method for the comparison of lamps—remember the like-with-like comments in our discussion of the spectral correction factor for a photometer in Lecture 4.

Baffles: The illuminance we measure at the sphere wall should be an average value caused by the flux in the sphere, and not contain any light due to any peculiar directional output of the source. The first means of preventing these directional effects is to block any light from passing directly between the source and the detector. This will require inserting at least one baffle into the sphere—between the flux light source and the detector, as shown in Figure 15.14. When we use an auxilliary lamp we must add a second baffle to prevent any light from the auxilliary lamp falling directly on either the detector or the flux lamp. The presence of these baffles will cause a modification to the light distribution in the sphere from that of the ideal sphere.

Having put all these things into our sphere, together with additional problems in the spatial uniformity of our sphere coating ρ, we can see that the illuminance we measure at the sphere wall with our detector will not be solely a measure of the flux output of the light source. However, it is possible to perform a series of measurements to determine the spatial nonuniformity of our particular integrating sphere configuration, and to determine the effect this could have upon our final flux measurements. This method has been extensively researched and developed by Y. Ohno of NIST (National Institute of Standards and Technology) in the USA, and for greater detail and application I refer you to the presentation by Miller and Ohno in Reference [5] and the references in their paper. The procedure is summarised in Figure 15.15.

The basic procedure is to use a narrow beam light source to map out a Spatial Response Distribution Function (SRDF) by scanning all points on the interior surface of the sphere. By combining this information with the spatial output of the flux lamp to be measured, a correction factor to the flux measurement may be determined. This correction factor will be specific to the sphere and its configuration, the spatial output of the particular lamp, and the direction of the lamp output in the sphere. For lamps like LEDs with a beam-like spatial distribution of light output, it has been determined that the best direction to point this beam is into the area of the sphere with least spatial non-uniformity. This should avoid the predominant shadow regions shown in Figure 15.15. It has also been found that these non-uniformity effects may be minimized by using as large a sphere as possible and using a reflectivity ρ as high (close to 1) as possible.

15.3 SPECTRAL PROPERTIES

LEDs are available in a wide variety of peak wavelengths and bandwidths covering the visible and adjacent wavelength ranges. As indicated in Figure 15.1 and Figure 15.2, their output spectrum is quite different from the conventional incandescent sources which are usually used to calibrate and characterize most photometric and radiometric instruments. The narrow bandwidths, typically 20 nm to 40 nm, demand detectors, particularly photometers, which are accurate in their spectral

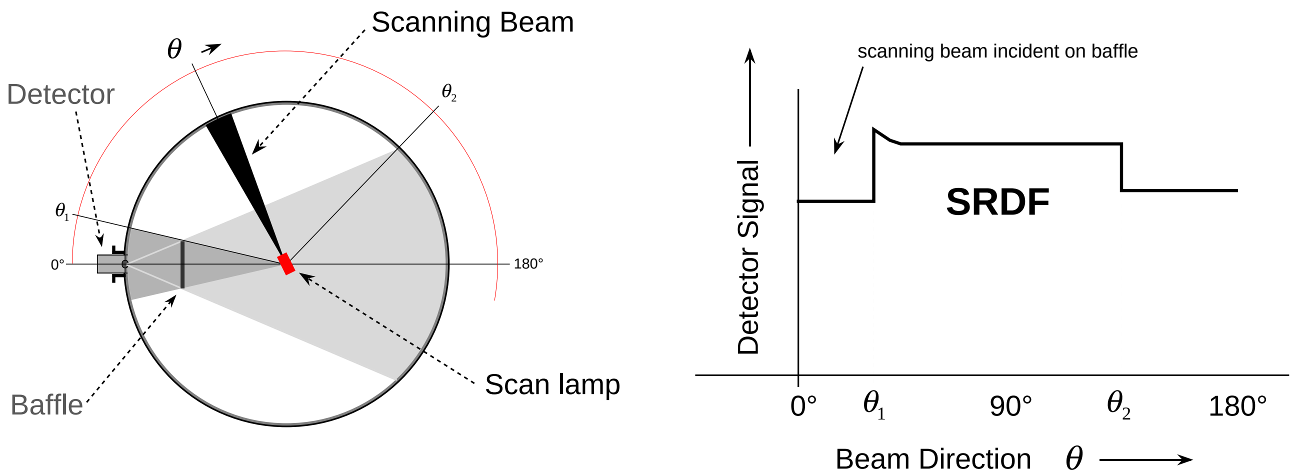

Figure 15.15 Spatial Response Distribution Function(SRDF): measurement of the spatial non-uniformity of the response of an integrating sphere.

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response at all wavelengths, rather than accurate only as an average over a broad wavelength range. The typical calibration and quotation of photometer specifications (usually using CIE Source A) for the measurement of incandescent sources will result in large errors when using a photometer for the measurement of LEDs, even when the photometer is quite accurate for the measurement of broadband sources. Photometric errors of 20%, when measuring red or blue LEDs, are not uncommon for good photometers.

The basic resolution to the problem will be to determine a *spectral mismatch correction factor (SCF)* as was discussed in Lecture 4. This factor was determined to be:

$$SCF = \frac{\int_{360nm}^{830nm} P_e^T(\lambda) \cdot V(\lambda) \cdot d\lambda}{\int_{all\ wavelengths} P_e^T(\lambda) \cdot R(\lambda) \cdot d\lambda} \cdot \frac{\int_{all\ wavelengths} P_e^S(\lambda) \cdot R(\lambda) \cdot d\lambda}{\int_{360nm}^{830nm} P_e^S(\lambda) \cdot V(\lambda) \cdot d\lambda} \tag{3}$$

where:

$P_e^T(\lambda)$ is the relative spectral output of the test source, an LED in our case,
$P_e^S(\lambda)$ is the relative spectral output of the standard source, usually incandescent,
$R(\lambda)$ is the relative spectral responsivity of the photometer, and
$V(\lambda)$ is the spectral luminous efficiency function, which defines a photometric measurement.

The narrow spectral range of $P_e^T(\lambda)$ causes a 'sampling' of the photometer responsivity $R(\lambda)$ only over the narrow range of wavelengths within which $P_e^T(\lambda)$ has an output. Many of the LEDs which we need to measure have peak wavelengths in the red or blue which are in the 'tails' of $R(\lambda)$ where the fit to $V(\lambda)$ is not very good. In addition, in the usual case where the photometer has been calibrated using an incandescent lamp, $P_e^S(\lambda)$ and $P_e^T(\lambda)$ are quite different. As a result, this SCF is significantly different from 1 and will need to be calculated in all cases when measuring LEDs.

This can be quite a time-consuming procedure if we will be measuring a large number of LEDs. The problem can be reduced, but not eliminated, if we can assume that our LEDs will all be similar in spectral output to some particular LED. There are two possibilities:

1. **An assumed typical value $P_e^{T-typical}(\lambda)$:** In this case we can calculate the SCF for this assumed typical LED and correct our photometer readings using this SCF. We will need to determine the spectral distributions required to calculate the SCF: $P_e^{T-typical}(\lambda)$ is assumed, $V(\lambda)$ is a

known and tabulated function [8,9], $R(\lambda)$ will need to be measured, and the $P_e^S(\lambda)$ of the standard source used to calibrate the photometer will need to be obtained. If $P_e^S(\lambda)$ is not easily obtained from the Calibration Laboratory which calibrated the photometer, but it is known that an incandescent similar to CIE Source A was used, we can use the tabulated values for CIE Source A [10], which are close to those of a Planckian black-body operating at temperature 2856 K. We may then calculate, using our assumed $P_e^{T-typical}(\lambda)$ for $P_e^T(\lambda)$ in the formula in Equation (3), a correction factor SCF which may be used to correct our measured photometer values. These corrected values will then be valid for measurements made on any LEDs with relative spectral output equal to $P_e^{T-typical}(\lambda)$.

2. **A Calibration Standard LED:** It may be possible to obtain from a Calibration Laboratory a calibration standard LED which is very similar in spectral output to the LEDs which you are measuring. You may then use this standard LED to calibrate your photometer. (If you are really lucky, maybe the Calibration Laboratory can even calibrate your photometer for you, using this standard LED.) The photometer will now give accurate measurements for any LEDs which have the same relative spectral output as the Calibration Standard LED.

The reason the problem cannot be eliminated is the requirement that the LEDs we are actually measuring be exactly equal in relative output spectrum to the particular value we used for the determination of the SCF we used to correct the photometer readings (item 1 above), or to the Standard Calibration LED used for the calibration of the photometer (item 2 above). Our experience when using incandescent lamps has led us to expect that small changes in the spectrum of the light source we are measuring will not significantly affect the accuracy of our photometer readings, as we saw in Lecture 4. However, this is not true for LEDs. The basic cause of our LED measurement problem is the significant difference between $R(\lambda)$ and $V(\lambda)$ for the LED measurements. The narrow bandwidths of the LED output means that only a narrow region of the photometer responsivity $R(\lambda)$ will be important in the measurement. Many LEDs we need to measure have peak wavelengths in those wavelength regions where the difference between $R(\lambda)$ and $V(\lambda)$ changes rapidly. As a result, a correction or a calibration made for an LED at one wavelength and bandwidth may not be very good for another LED which varies even only a small amount in its peak wavelength or bandwidth from the calibration LED.

This variation of actual LED spectra from a calibration LED spectrum may be taken into account if we are willing to add a further uncertainty to our measurements. Basically, we will correct our photometer readings using one of the above procedures, and then calculate a second SCF (call it scf_i to distinguish it from the original SCF) which would be used to correct our measurement of this actual LED (number i) when measured using the photometer which has been only corrected to the original calibration LED spectrum. If we use a reasonably large set (i) of estimated different possible LED spectra, which should include any LED which we expect to be measuring, we will determine a reasonably large related set of possible scf_i which should therefore include any correction we would have to make to our measured photometric values. Since at any one time we do not know the actual spectrum of the LED we are measuring, our set of scf_i can provide an estimated uncertainty in our measurement due to the effect of the spectral difference between our actual LED and the calibration LED.

Note that I am making the distinction between an error and an uncertainty at this point. An error is something which we can correct in our measurements, as we do when we determine the SCF and correct our measurements. As such, the error itself is not an uncertainty, although the uncertainty in the values we use to calculate the SCF do cause an uncertainty in our value for the SCF, and therefore will cause an uncertainty in our final corrected photometric measurement.

We are assuming that the bulk of the actual spectral correction factor is taken account of by using our SCF correction factor, and that the uncertainty determined from the scf_i will take care of the remainder, which we expect to be significantly smaller than the original SCF. If we require greater accuracy than the uncertainty determined by this method, we will need to determine the SCF for all our measurements, and be certain that the values we use for calculating the SCF will be accurate enough that the uncertainty in our calculated SCF is smaller than the final uncertainty requirements we require.

Several additional notes:

1. If we are using an integrating sphere for our measurements, the photometer is the unit which consists of the detector and the integrating sphere with all its additional components which we described above. The responsivity of this complete unit is what must be used for the factor $R(\lambda)$ in Equation (3) above. A major component in the difference between the detector and the complete unit will be the spectral effect of the multiple reflections inside the sphere as indicated in Equations (1) and (2). This usually has its greatest effect in the blue wavelength region.
2. The sensitivity of photometers to wavelength changes when measuring LEDs in the blue or red should be considered in the situations where we use a calibration standard LED to calibrate our photometer. The operating conditions should be controlled carefully since the wavelength peak and bandwidths can change with operating current and temperature as indicated in the following section.
3. It has been observed that the relative spectral output of LEDs, particularly white LEDs, changes with the direction of the output from the LED.

15.4 OPERATING CONDITIONS

One of the primary requirements for a measurement of the light output of a source is to be able to operate the source under electrical and thermal conditions such that its light output is both stable and reproducible. This will depend on both the inherent means (physical principles) of production of the light and on the method of containing the medium which produces the light. LEDs are a so-called ‘cold’ light—they do not require any heating of the medium to produce the light (but that does not mean that the light output is not affected by the temperature of the medium). Basically, the LED is a solid state device, across which we place an electric voltage which causes electron and holes to flow in opposite directions through the material. When these electrons and holes combine they form an excited state which radiates light. The spectrum of the light emitted is characteristic of the material used and is relatively narrow in bandwidth compared to more common light sources such as incandescent lamps. Typical bandwidths are 20 nm to 40 nm.

To produce light, LEDs are operated with a forward bias. In this condition, the current through the device must be limited externally and LEDs are usually operated at a constant current from a DC power supply. The typical operating current has been approximately 10 mA to 20 mA, but the new high power LEDS use drive currents of 200 mA to 300 mA. It should be noted that the LED light output should be stabilised by stabilising the current through the device, rather than regulating the power applied to the LED.

The general equation for the relation between the current, voltage, and temperature for a diode is given by:

$$i = i_0 \left[exp\left(\frac{eV}{\beta kT}\right) - 1 \right] \tag{4}$$

where i is the current through the diode, i_0 is the reverse saturation current, e is the charge of the electron, V is the voltage across the diode, k is the Boltzmann constant, T is the temperature of the diode, and β is an *ideality factor* which varies between 1 and 2, depending on the semiconductor and the temperature.

This equation may be used to monitor the temperature stability of the LED. At the constant operating current maintained externally, any change in temperature of the LED will be accompanied by a corresponding change in the voltage measured across the LED. For accurate measurements, a four-terminal socket should be used which provides two terminals to supply current to the LED and a separate two terminals to measure the voltage across the diode.

LEDs are usually encased and packaged in a material which is a very poor thermal conductor. As a result, the only means of thermally anchoring the device is through the copper electrical leads. As a result, considerable care must be given to the sockets and lead-in wires used to operate the LED. This becomes very important for the modern high power devices. A current of several hundred milliamperes through a very small device with no proper cooling can quickly and easily cause large temperature changes!

In contrast to incandescent sources, the light output of an LED is lower at higher temperatures. In addition to a change in the magnitude of the light output with temperature, the relative spectral output of an LED is dependent on the temperature of the LED, even if the current through the LED is held constant. A typical example is shown in Figure 15.16. These shifts will cause significant changes in the colorimetric properties of LEDs.

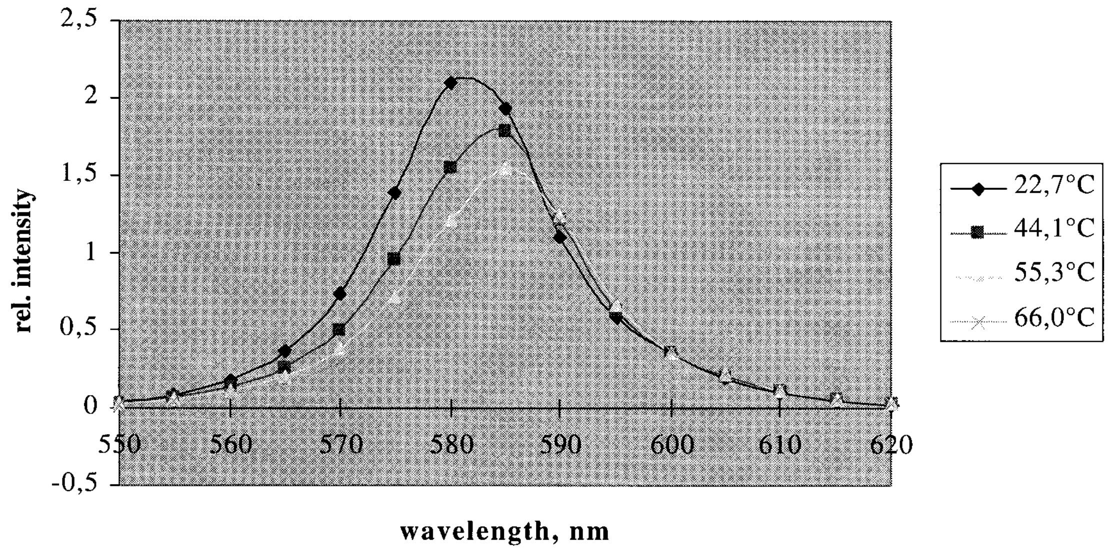

Figure 15.16 Temperature dependance of the spectrum of a traditional green LED (from Schanda *et al* [5]).

15.5 BIBLIOGRAPHY

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* CIE publications are available from the Canadian National Committee of CIE, Dr. K. Frank Lin, General Manager, Lighting Sciences Canada Ltd., 440 Philip Street, Unit 19, Waterloo, Ontario N2L 5R9.

[5] CIE Publication No. x022, *Proceedings of the* 2^{ND} *CIE Expert Symposium on LED Measurement: Standard methods for specifying and measuring LED and LED cluster characteristics*, Central Bureau of the CIE, Vienna, Austria, 2001.

[6] CIE Technical Committees. There are several CIE TCs working on various aspects of LED measurements:

i. TC 2-45 *Measurement of LEDs - Revision of CIE 127.* To revise Publication CIE 127-1997 to include improved definitions of quantities and methods of measurement for total flux and partial flux of LEDs and to re-evaluate other parts including spectral and colour measurements of LEDs. Chair: Kathleen Muray (USA).

ii. TC 2-46 *CIE/ISO Standards on LED Measurements.* To prepare a CIE/ISO Standard on the measurement of LED intensity measurements based on CIE Publication No. 127. Chair: John Scarangello (USA).

iii. TC 2-50 *Measurement of the Optical Properties of LED Clusters and Arrays.* To produce a technical report for measurement of the optical properties of visible LED clusters and arrays, to derive optical quantities for large area arrays and give recommendations for measurement methods and conditions. Chair: Georg Sauter (Germany).

For further information:

a) visit the CIE website at www.cie.co.at/cie

b) the Canadian Member for CIE Division 2 is Dr. Joanne Zwinkels, Institute for National Measurement Standards, National Research Council of Canada, Ottawa, Ontario K1A 0R6.

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[8] CIE, Publication No. 15.2, *Colorimetry, 2nd ed.*, Central Bureau of the CIE, Vienna, Austria, 1986. A disk version of some of the tabulated data is also available.

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