

TECHNICAL GUIDE

RELATIVE EYE RESPONSE

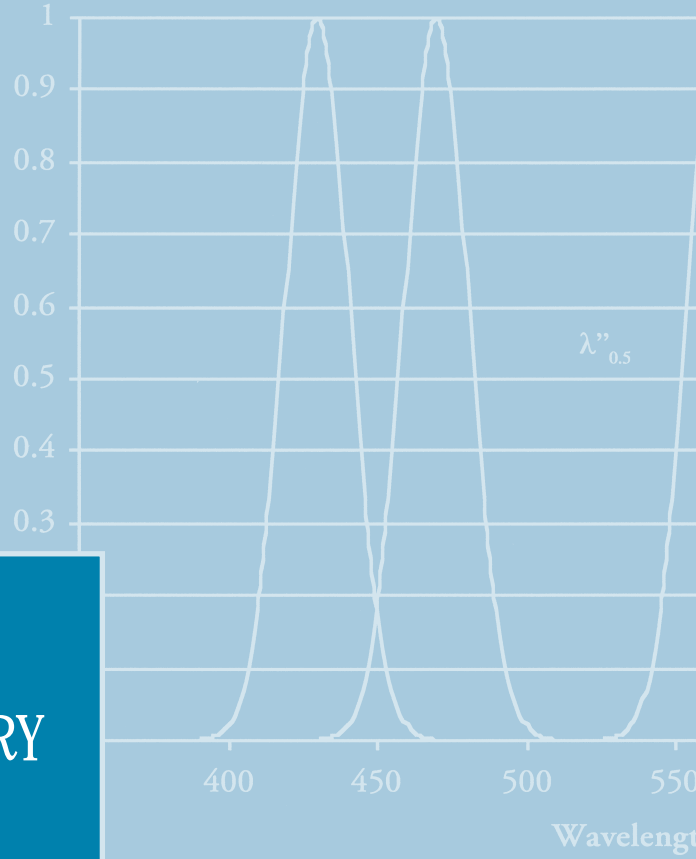
$\lambda_m = 0.555 \mu\text{m}$

RARED RED ORANGE YELLOW GREEN BLUE VIOLET

GaAs CdSe GaP CdS
 $\text{GaAs}_{1-y}\text{Py}$

$\lambda (\mu\text{m})$
0.9 0.8 0.7 0.6 0.5

Relative Spectral Distribution



THE RADIOMETRY OF LIGHT EMITTING DIODES

55 μm

GREEN VIOLET ULTRA
ANGE YELLOW BLUE

GaP CdS SiC Ga

i-yPy

labsphere®
ISO 9001 REGISTERED

$\lambda (\mu\text{m})$

0.8 0.5 0.45 0.4

Sample 2 - - - Sample 3 — Sample 4

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1.0 INTRODUCTION

Almost everyone is familiar with light-emitting diodes (LEDs) from their use as indicator lights and numeric displays on consumer electronic devices. The low output and lack of color options of LEDs limited the technology to these uses for some time. New LED materials and improved production processes have produced bright LEDs in colors throughout the visible spectrum, including white light. With efficacies greater than incandescent (and approaching that of fluorescent lamps) along with their durability, small size, and light weight, LEDs are finding their way into many new applications within the lighting community. These new applications have placed increasingly stringent demands on the optical characterization of LEDs, which serves as the fundamental baseline for product quality and product design.

Characteristics of LEDs, including physical size, flux levels, spectrum and spatial distribution, separate them from typical element sources, which are generally employed and measured for photometric and radiometric quantities. With an LED, it is often difficult to achieve a high level of photometric or radiometric measurement accuracy due to uncertainties within the measurement equipment and improper test setup. In addition, traditional photometers, because of their inability to simulate the response of the human eye at the ends of the visible spectrum generate significantly flawed data when testing red, blue, and some styles of white LEDs.

Specific expertise in LED metrology is needed in order to obtain accurate and reproducible results. This technical guide discusses the special optical characteristics of LEDs and provides recommendations for obtaining accurate measurement results. Our goal is to share our 20+ years of optical radiation measurement expertise and provide not only an introduction to LED metrology for individuals new to this subject area, but also a useful reference for individuals experienced in this area.

2.0 WHAT IS AN LED?

LEDs are solid-state (p-n junction semiconductor) devices that convert electrical energy directly into light (electroluminescence). LED "cold" generation of light leads to high efficiency because most of the energy radiates in the visible spectrum. In comparison, incandescent bulbs convert about 5 percent of their power into visible light, while LEDs approach 15 to 20 percent. Incandescent lamps radiate much of their energy in the non-visible spectrum, generating heat as well as light. For example, the package of an LED may be 10° to 25° C hotter than ambient, but under the same conditions, the envelope of an incandescent bulb can be several hundred degrees C hotter.

2.1 Device Physics and Package Design

An LED in its simplest form is a semiconductor p-n junction device (chip) that, when forward biased, emits photons (light) as the electrons and holes recombine near the junction. The energy of the photons is determined primarily by the energy bandgap of the semiconductor where the recombination occurs. Since the eye is only sensitive to light with photon energy from 3.1 eV to 1.6 eV (0.40 to 0.78 μm), compound semiconductor materials composed of column III and V elements are the materials of choice for LEDs because they have the direct bandgap properties and energies necessary for efficiently producing visible photons. To convert the wavelength (λ) in microns to photon energy, the relationship $\lambda = 1.24 / \text{eV}$ can be used. Figure 2.0 shows the semiconductors of interest with their corresponding photon energies, wavelengths, and the relative response of the human eye.

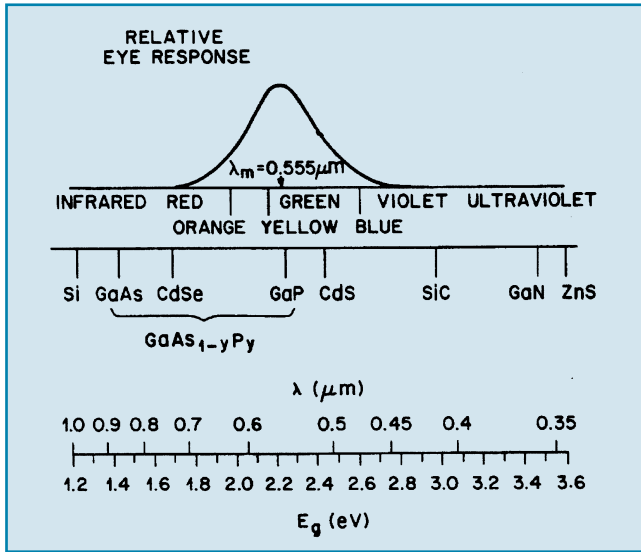


Fig. 2.0. Semiconductors of interest as visible LEDs. Figure includes relative response of human eye

The energy gap of a semiconductor is the minimum energy separating the valence band and the conduction band. Each band contains the possible combinations of energy and momentum for one type of carrier — the valence band for the carriers of positive charge (holes) and the conduction band for negative charge carriers (electrons). An LED's internal quantum efficiency is the number of photons generated divided by the number of minority carriers (electrons) injected into the p-doped region. When an injected electron combines with a hole through radiative recombination, a photon is produced. There are other kinds of transitions that compete with radiative recombination, but these transitions fail to produce photons. These transitions occur at crystal imperfections of various sorts and dissipate their energy into the crystal lattice as heat. For those photons that are generated, there can still be loss through absorption within the LED material, reflection loss when light passes from a semiconductor to air due to differences in refractive index and total internal reflection of light at angles greater than the critical angle defined by Snell's law, lowering the overall quantum efficiency of the LED.

Figure 2.1 represents a basic LED chip structure with an opaque or a transparent substrate. The light-generating LED chip is quite small, typically 0.25 millimeters square. Figure 2.2 depicts a diagram of a typical LED lamp. An LED lamp contains an LED chip and an epoxy molded lens encapsulate. The lens is used to change the direction and control the distribution of light rays (spatial distribution pattern) or colored to serve as an optical filter to enhance contrast. The epoxy encapsulant and lead frame occupy most of the volume. Presently the most common LED is the 5mm LED package (or T 1-3/4).

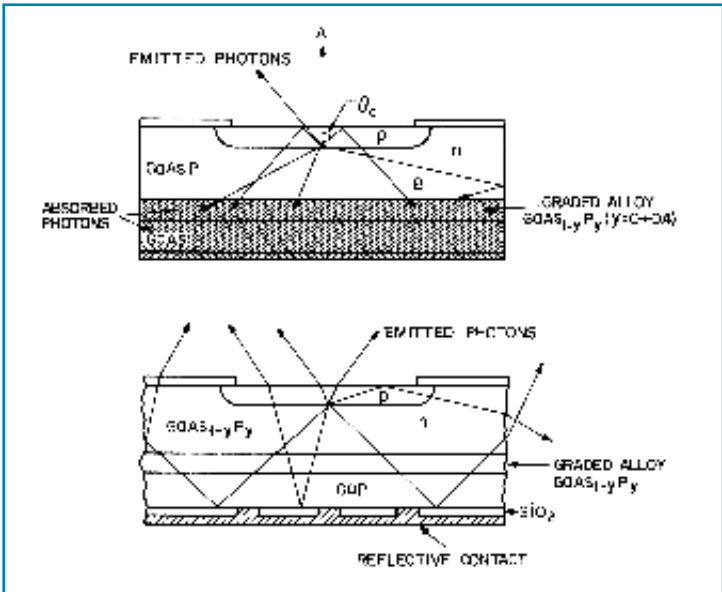


Fig 2.1. Basic LED Chip Structure

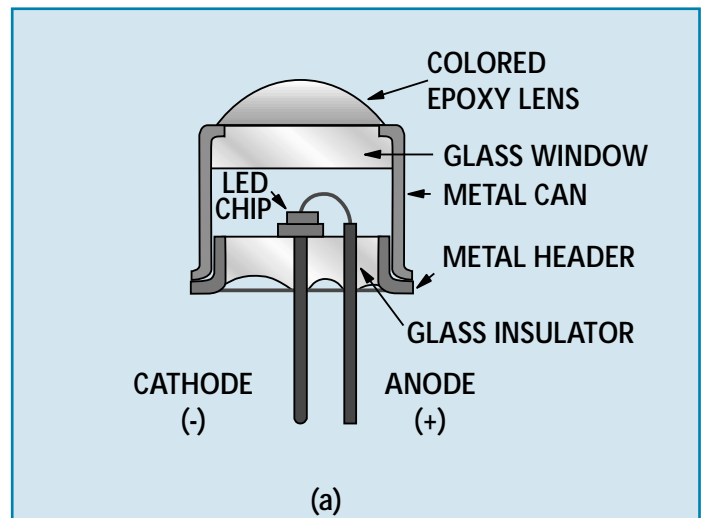


Fig 2.2. LED Lamp Construction

2.2 Electrical Properties

2.2.1 Operation at Constant Current

The drive current through an LED must be controlled. High current densities within the junction of the chip cause partial overheating which damages the crystalline structure of the LED die. At these areas are so called darkline defects, where light ceases to be generated. This should not be confused with the maximum junction temperature of the LED, which is related to the higher temperature at which the optical grade epoxy starts to expand rapidly and increases the risk of catastrophic failures, such as broken wires or lifted LED dies.

To produce light, an LED must be operated in the forward-bias regime. The emitted light is a function of the forward voltage V_f and the forward current I_f . In the lab, LEDs are usually operated in a forward bias direction from a constant current DC power supply. At low currents, the slope of the radiant power (luminous flux) versus time rises faster than the slope of the electrical power (start-up range) versus time. At high currents, the slope becomes flatter (saturation area), which is mainly caused by heating of the LED chip. Under normal operating conditions (between the start-up range and saturation area), the optical radiation emitted by LEDs is strongly correlated to the electrical current, which is why constant current is recommended for measurements intended to characterize the optical properties of an LED.

2.2.2 Modulated or Multiplexed Operation

One efficient method of driving LED devices is to pulse them (usually 100Hz to 1000Hz) with a high peak current for short durations on a low duty factor. This technique is frequently used to multiplex a number of individual LED lamps. The advantage is high light output at low time average power consumption. LED operation under these non-steady-state conditions can create temperature fluctuations at the junction and forward voltage instability, which modifies the characteristic values obtained for the LED under test. Fortunately, these values are strongly correlated to the values for steady-state operations, so that the true characteristics of the LED under test can be calculated once the correlation is derived.

2.2.3 Single-Shot Operation

During production, the measurements commonly made to characterize an LED are often carried out under single-shot operations where the LED under test is pulsed with a DC current equaling that of normal operations but only lasting tens of milliseconds. Similar to modulated operations, the LED fails to reach steady-state conditions, but the correlation between single-shot and steady-state conditions can be established by a few supplementary measurements.

3.0 OPTICAL CHARACTERISTICS OF LEDs

The radiation from an LED can be characterized by radiometric and spectroradiometric quantities. If the LED emits visible radiation, then photometric and colorimetric quantities are also required to quantify its effect on the human eye. Note that for every radiometric quantity there is a photometric analog. The only difference is that, for radiometric quantities the radiation is evaluated in energy units, while for photometric quantities the radiation is weighted against the photopic response of the human eye.

3.1 Spectral Properties of Light Emitting Diodes

The spectral distribution of the optical radiation emitted by LEDs distinguish them from typical element sources. The radiant power is neither monochromatic (as emitted by lasers), nor broadband (as found with incandescent lamps), but rather something between the two. The light output of a typical LED has a narrowband spectral bandwidth between 20nm and 50nm and a peak wavelength somewhere in the near UV, the visible, or near infrared regions of the spectrum.

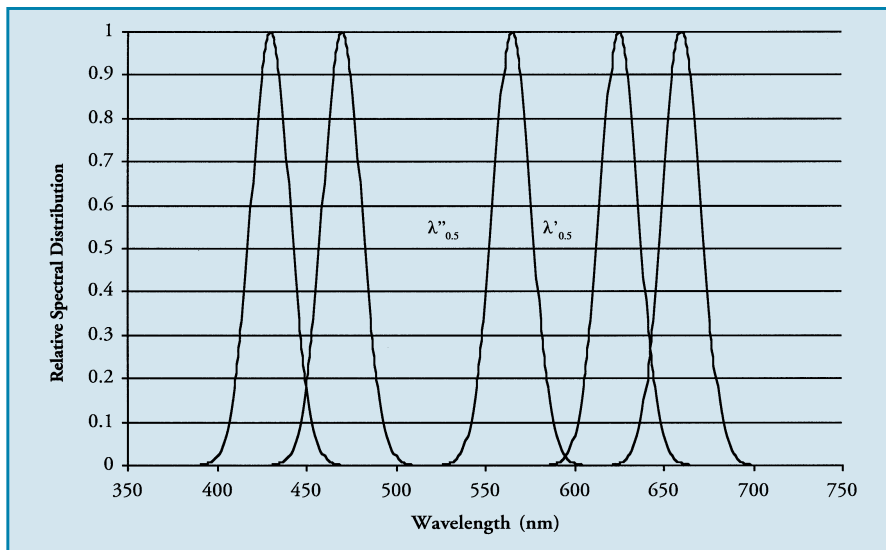


Fig. 3.0.
Sample LED Spectral Distributions

Typical relative spectral distributions are shown in Figure 3.0. The spectral properties of an LED are important to aid manufacturers in their design efforts and process control. End-users use these values in determining the correct LED for their application. An overview of the spectral parameters of an LED is listed below:

Peak Wavelength λ_p :

Wavelength at the maximum spectral power (Reference Figure 3.0). The peak wavelength has little significance for practical purposes since two LEDs may have the same peak wavelength but different color perception.

Full Width Half Max (FWHM):

The spectral bandwidth at half peak $\lambda_{0.5}$ is calculated from the two wavelengths $\lambda'_{0.5}$ and $\lambda''_{0.5}$ on either side of λ_p . $\lambda_{0.5} = \lambda'_{0.5} - \lambda''_{0.5}$ (Reference Figure 3.0).

Center Wavelength λ_m :

The center wavelength is the wavelength halfway between the half-wavelengths $\lambda'_{0.5}$ - $\lambda''_{0.5}$.

Centroid Wavelength λ_c :

The centroid wavelength is the center of moment or the mean of the spectral power distribution.

Dominant Wavelength:

The dominant wavelength is determined from drawing a straight line through the color coordinates of the reference illuminant (usually arbitrarily chosen as illuminant E) and the measured chromaticity coordinates of the LED in the International Commission on Illumination (CIE) 1931 chromaticity diagram. The intersection of this straight line on the boundary of the chromaticity diagram gives the dominant wavelength. It is a measure of the hue sensation produced in the human eye by the LED.

Purity:

Purity is defined as the ratio of the distance from reference illuminant (usually arbitrarily chosen as Illuminant E) to the measured chromaticity coordinates and the distance from reference illuminant to the intersection with the boundary of the chromaticity diagram. Most LEDs are narrow band radiators, with a purity of nearly 100%, i.e. the color cannot be distinguished from a monochromatic beam. Polychromatic sources have low purity approaching zero.

Full Width Half Max Angle _____, Viewing Angle or Beam Angle:

The total cone apex angle in degrees encompassing the central, high luminous intensity portion of a directional beam (200) from the on-axis peak out to the off-axis angles in both directions at which the source's relative intensity is 1/2.

Half-Angle:

The included angle in degrees between the peak and the point on one side of the beam axis at which the luminous intensity is 50% of maximum or half of the beam angle.

Note: Peak Wavelength, Full Width Half Max, Center Wavelength, and Centroid Wavelength are all plotted on a scale of (power / λ) vs. (λ).

3.2 Comparison of Photometers and Spectroradiometers

Photometers use a broadband detector in conjunction with an optical filter in an effort to simulate the spectral luminous efficiency curve of the human eye, $V(\lambda)$, which is referenced using CIE 15.2 Colorimetry, Table 2.1. The detection process involves a change in the characteristics of the detector caused by the absorption of visible photons. The electrical signal generated by the detector is a response to the visible radiation incident on the detector active area. For example, a photometer designed to measure illuminance may be calibrated in photocurrent per lux.

Spectroradiometers can be calibrated to measure the radiant energy or radiant flux from an LED as a function of wavelength. These instruments separate or disperse polychromatic light into its constituent monochromatic components usually by means of prisms or gratings. The photometric value may then be computed (usually by software) from this measured spectrum. This basic difference between spectroradiometers and photometers is extremely important in LED metrology.

A disadvantage of a photometer is the difficulty in designing a filter that, when combined with a detector, fits the spectral luminous efficiency curve of the eye exactly. Because of available filter materials, a mismatch is particularly prevalent in the blue portion of the spectrum. Though corrections can be applied, these corrections require knowledge of the LED spectral distribution and are usually approximations. Figure 3.1 shows the theoretical $V(\lambda)$ function, the relative spectral flux output of a blue LED, the relative spectral distribution of a typical tungsten incandescent lamp, and the typical response of a photopic detector. A typical photopic detector with an $f1'$ response of 4% can have a spectral mismatch as great as a factor of 2 at 470nm between the $V(\lambda)$ function and the response of a photopic detector. If an incandescent source or a source similar in spectral content is measured, the correction for the slopes of the photopic detector to the $V(\lambda)$ curve is minimal since the light is

continuous and there is relatively little light in the blue portion of the spectrum in relation to the higher wavelengths. A mismatch in the response curves results in only a slight error of the measured photometric value.

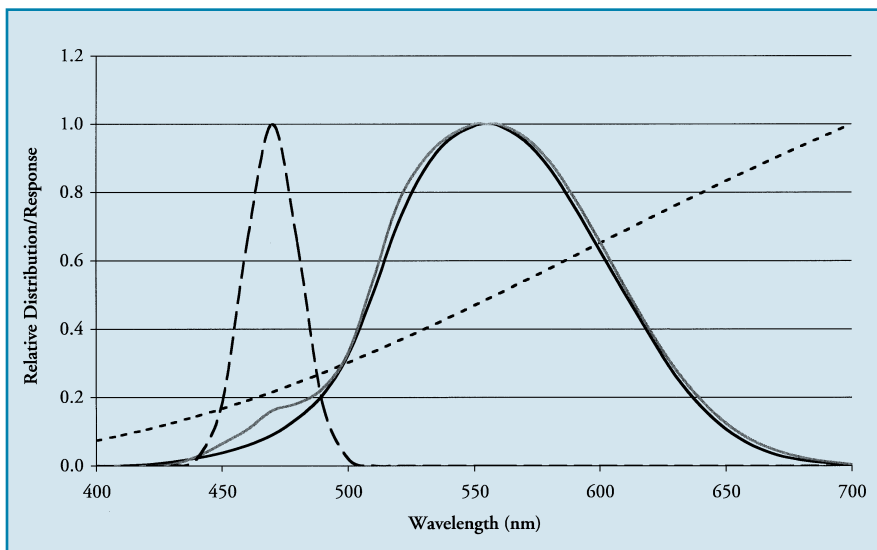


Fig. 3.1. Theoretical $V(\lambda)$ function, relative spectral flux output of a blue LED, relative spectral distribution of a typical tungsten incandescent lamp, typical response of photopic detector with $f1'$ response of 4%.

continuous and there is relatively little light in the blue portion of the spectrum in relation to the higher wavelengths. A mismatch in the response curves results in only a slight error of the measured photometric value.

LEDs, however, have a completely different spectral power distribution, which tends to be narrowband Gaussian with a specific peak and a FWHM of a couple of tens of nanometers. The relatively poor match of the photopic detector to the $V(\lambda)$ function, can result in large deviations in the measured photometric quantities. This is particularly true for blue and red LEDs. Errors exceeding a hundred percent are not unusual for blue LEDs. Spectroradiometers avoid these errors because the photometric quantities are calculated from the spectral data and defined CIE functions. It should be noted that photometers can be used to compare sources having identical spectral distribution, or to measure illumination of the same spectral distribution as that of the source with which it was calibrated. LEDs can have so much variation from one to another, spectroradiometers or photometers fabricated with specially designed filtering should be used for LED metrology.

3.3 Color and Dominant Wavelength

Often used for determining the color of an LED, dominant wavelength is actually a measure of the hue sensation produced in the human eye. Hue designates the basic color being referenced; such as, red, yellow or blue-green. The hue refers to the color impression that a sample makes. Two LEDs can have the same hue, but it is possible for one to appear washed out. For example, one can look red and one can look pink.

In order to guarantee a match in color from one LED to another both dominant wavelength and purity should be referenced. Purity is a characteristic of chroma (also referred to as saturation), which is the degree of color saturation, or the amount of pure color added to obtain the sample. The purer colors of a particular hue sample are placed nearer to the boundary of the chromaticity diagram.

In order to calculate the color properties of an LED, the spectral properties of the LED must be known. Therefore, a photometer cannot be used. In choosing a spectroradiometer with which to calculate these values, it should be noted that the optical bandwidth of a spectroradiometer artificially broadens the spectral shape of any source. For LEDs, this can introduce errors, especially in the calculated chromaticity coordinates and dominant wavelength. A 10nm bandwidth spectroradiometer, measuring 20nm full width half max LEDs, can cause errors as high as:

0.005 in x
0.007 in y
2nm in λ_d

On the other hand, error contributions on color for spectroradiometers with bandwidths of 5nm have been documented to be less than about 0.002 in x,y (0.001 in u',v') and 0.2nm in dominant wavelength. Bandwidths of 1nm or less have no appreciable error contribution. In choosing a spectroradiometer one should be aware of these errors. Spectroradiometers with bandwidths of 5nm or less are accepted for most practical measurements of LEDs of all colors.

3.4 Influence of Temperature on Radiation

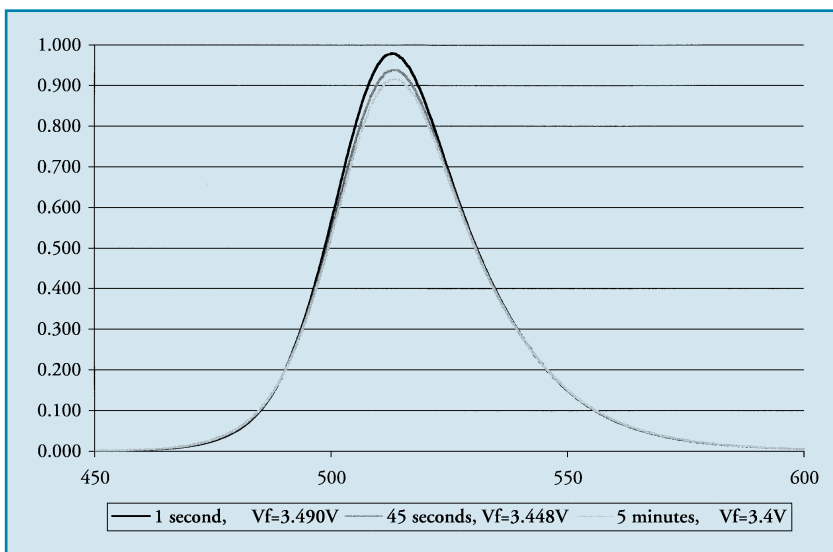


Fig. 3.2.
Example of LED
Stabilization Over Time

Initial Light-up:

The light output of an LED is a function of V_f and I_f , where the LED junction temperature under constant current operation heavily influences V_f . At constant current, the forward voltage of an LED stabilizes as the junction temperature (T_j) stabilizes. The junction temperature of the LED is determined by $T_j = T_a + P_d * R_{th}(j-a)$. Where T_a is ambient temperature, P_d is power dissipation ($V_f * I_f$) and $R_{th}(j-a)$ is the thermal resistance (junction to ambient temperature). During initial light-up, the temperature of the junction increases due to electrical power consumed by the LED chip and then stabilizes at a temperature value $> T_a$. Because of this effect, the emitted light is not stabilized until thermal equilibrium has been reached. After thermal equilibrium, the junction value is governed by the heat transfer to the surroundings, which takes place through the leads of the LED. As a consequence, the thermal properties of the electrical contacts used to

supply the LED, the length of the wires between the chip, and when used the heat sink can significantly affect the output. Figure 3.2 shows the stabilization over time of a green LED. The relative spectral flux and the forward voltage is measured every 5 seconds with a constant current of 20ma flowing through the LED, until a near constant forward voltage is achieved. As depicted by Figure 3.2, the stabilization procedure can take several minutes and will be influenced by the properties of the specific LED measured. Depending on the LED type, spectral distribution effects from junction temperature, as presented in the graph, can create shifts in dominant wavelength

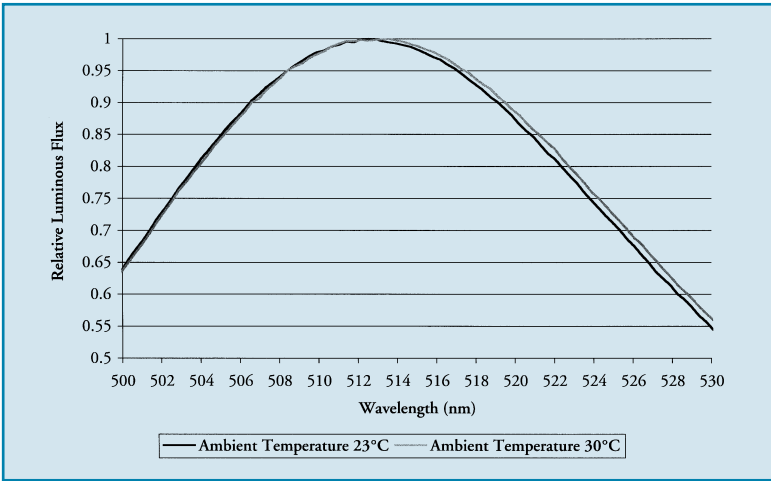


Fig. 3.3.
Spectral radiant flux output of a "green" LED operated in 23°C ambient and 30°C ambient temperatures

as great as 0.7nm and decreases in luminous flux as great as 3.5%. Since the dominant wavelength is dependent upon the intersection on the spectrum locus of the 1931 CIE chromaticity diagram, small spectral distribution changes in "red" and "blue" LEDs can create relatively large changes in dominant wavelength.

Thermal Equilibrium:

Once thermal equilibrium has been reached, the spectral distribution of an LED is dependent upon the ambient temperature surrounding the chip. For a typical LED as the power is stabilized and the ambient temperature rises, there will be a slight change in the shape of the spectrum, and the peak wavelength will shift about 0.1 to 0.3nm/K. For blue LEDs, the shift in most cases is towards shorter wavelengths.

For other LEDs, the whole distribution will shift in the direction of longer wavelengths. The luminous efficacy and color of LEDs can be changed by relatively small ambient temperature changes, making it difficult to achieve constant photometric or radiometric measurement results. Figure 3.3 depicts the spectral radiant flux output of a "green" LED run at 23°C and 30°C. For this example, a 1.1nm shift in peak wavelength resulted in a 0.2nm change in dominant wavelength. As previously described, shifts in the spectra of red and blue LEDs, because of their location on the color curve, will create greater changes in dominant wavelength. Since the spectral distribution of an LED depends on both the junction temperature of the chip and stabilization of current, temperature offers the best way of controlling the operating conditions and maintaining a constant spectral distribution.

4.1 Luminous and Radiant Intensity

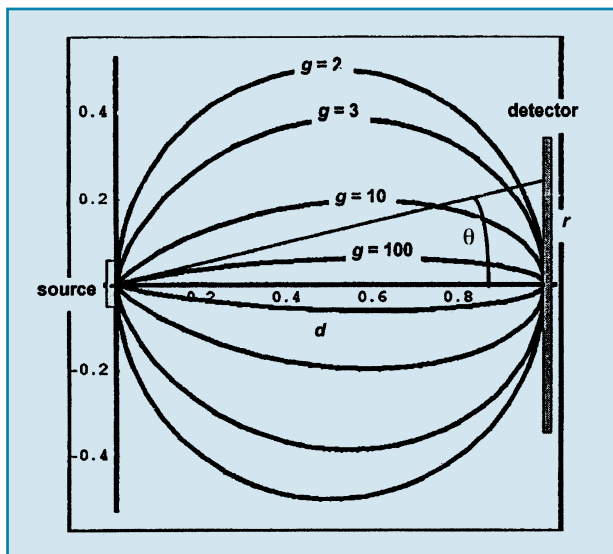


Fig. 4.0.
Angular distribution patterns of radiators with rotational symmetry

Luminous intensity, typically presented in millicandela, is the most measured LED optical parameter. It is also the most misunderstood LED parameter. Luminous intensity is defined as the visible flux per unit solid angle in a given direction from a source. Luminous intensity measurements frequently involve a point source, the inverse square law and the assumption of constant illuminance across the detector. A point source need not be small. For example, a star, which is not small, when seen from a far distance (as from the earth), can be treated as a point source. The angular distribution of various point sources with rotational symmetry can be approximated (Fig. 4.0) by:

$$I = I_0 \cos^{g-1} \theta$$

Where I_0 is the intensity normal to the source itself and $g \geq 1$. For example:

- $g = 1$ for an isotropic point source
- $g = 2$ for a Lambertian point source
- $g > 30$ for an LED point source (LED lamp)

The inverse-square law (which is strictly applicable only for all point sources) states that the illuminance E at a point on a surface (a calibrated detector) varies directly with the intensity I of the source (as defined above for various types of sources), and inversely as the square of the distance d between the source and the point (detector).

$$E = I / d^2$$

If the surface of the detector is not perpendicular to the direction of the incident light, the Cosine law comes into effect and the angle of incidence θ must be considered. The equation may be expressed as follows:

$$E(\theta) = (I(\theta) / d^2) * \cos \theta$$

A useful extension of the Cosine law is the cosine-cubed law. The Cosine-cubed law comes into effect when the surface at the point (detector) is moved up and down in a vertical plane perpendicular to the source. The cosine-cubed law can be expressed as:

$$E(\theta) = (I(\theta) / d^2) * \cos^3 \theta$$

Where "d" is the distance between the source and the detector at θ equal to 0° . For standard lamps, the angular distribution is wide enough that uniform illuminance across the detector is not an issue and these equations hold true within one-half percent when the source as viewed from the detector is in the far-field. For a typical light bulb or luminaire, the far-field distance "d" is defined to be at least ten times the maximum dimension of the source. For an LED, according to industry experts, no such rule-of-thumb exists and, the far-field distance "d" can only be determined by finding the $1/r^2$ irradiance fall off region through measurement.

Once the far-field region is determined, measurement errors can still occur if the illuminance detector in use is "too big" in a relative sense, where the illuminance across the face is not constant. The inverse-square law references E at a point on the surface of a detector. Simply restated, the intensity of the source can only be calculated as the area of the detector goes to zero. For LED lamps, the relative size of the detector in the calculated far-field can be too great, making the angle subtended by the detector at the source a non-point. In such a situation, the illuminance on the detector would not be constant and the detector would be performing an average intensity measurement. In order to minimize or calculate the averaging effect, an equation for the irradiance over the surface area of the detector can be written and solved for, as the solid angle subtended by the detector is taken to go to zero. (Fig. 4.0.):

$$E(\theta) = d\phi / dA = \int I(\theta) dw / \pi r^2$$

Assuming the intensity pattern of an LED can be approximated by $I = I_0 \cos^{g-1} \theta$, $E(\theta)$ can be approximated as:

$$E(\theta) = (I_0 / d^2) * [1 - (((g + 2) / 4) * (r / d)^2)]$$

In this equation the $((g + 2) / 4) * (r / d)^2$ portion of the equation accounts for the averaging effect uncertainty with respect to the true intensity value. By setting this portion of the equation equal to an acceptable chosen uncertainty, one can derive the required relationship between the radius of the detector and the "far-field" measurement distance:

$$d \geq r \cdot \sqrt{[(g+2)/(4\zeta)]}$$

where ζ is the uncertainty in question. For example: if the LED to be measured has a half angle of 15° (30° viewing angle), g can be solved by substituting the half angle of the LED for θ and realizing that $I(\theta) / I_0$ at the half angle is 0.5 by definition, then:

$$\cos^{(g-1)} \theta = 0.5 \text{ where } \theta = \text{half angle}$$

solving for g yields:

$$g = 1 + \text{Ln}(.5) / \text{Ln}(\cos(\text{half angle}))$$

For an LED with a half angle of 15°, $g = 21$. If “ g ” = 21 and ζ is chosen to be 1% then the radius of the detector must be = $d/24$. If “ d ” is chosen to be 100mm (reasonable for most LEDs), the radius of the detector must be equal to or less than 4.2mm in order to maintain the chosen 1% uncertainty. For such a geometrical setup, the plane angle formed by the measurement setup would be 2.4° ($\tan^{-1}(4.2 / 100)$) and the solid angle subtended would be 0.005sr ((area of detector/100²)).

Having discussed the far-field and equating a proper detector size within a chosen uncertainty, the only issue left in calculating intensity is determining the actual location of the effective light center of the LED. Within an LED, the light is produced in the LED chip. A portion of this light goes directly from the chip and is refracted by the epoxy dome. The remainder of the light is reflected by the reflector cup and then refracted by the epoxy dome. The light, which is directly refracted, appears to come from a certain location within the LED, while the light, which is reflected and refracted, appears to come from a different location. In addition, because the LED chip itself has a physical size and is not a point source, the refracted light does not appear to come from a single location, but a range of locations or a focal smear (virtual image). To create the best approximation using a point source model, the center point of the focal smear should be chosen as the location of the point source. Manufacturers often provide the optical position of the point source. If this point is not provided, one can be calculated by taking two different illuminance measurements, E_1 and E_2 in the far-field on the same axis, at distances d and $d+x$ apart. Since the intensity is the same at any point within the same solid-angle within the far-field, then:

$$E_1 \cdot d^2 = E_2 (d+x)^2$$

Since E_1 and E_2 are known measured values d can be solved for:

$$d = (x(E_2 + \sqrt{E_1 E_2})) / (E_1 - E_2)$$

and the intensity can then be calculated.

4.2 CIE 127

As discussed in the previous section, it is very difficult to measure the "true" intensity of an LED and in the real world it has become common practice to measure an "average" directional intensity. In attempt to offer an agreed upon procedure for measuring "average" intensity within the industry, CIE Committee TC 2-34 has published CIE 127, which develops the concept of averaged LED intensity. This concept no longer corresponds to the physically precise definition of luminous intensity, but relates more to the measurement of flux for a fixed geometry.

CIE 127 recommends two measurement geometries, CIE Standard Condition A and B for measuring "average intensity" under such "near-field" conditions. For averaged LED intensities determined under these conditions the symbol $I_{LED A}$ and $I_{LED B}$ are recommended.

Both conditions involve the use of a detector with a circular entrance aperture having an area of 100mm² (corresponding to a diameter of 11.3mm). The LED should be positioned facing the detector and aligned so that the mechanical axis of the LED passes through the center of the detector aperture. It is the distance between the front tip of the LED and detector that constitutes the difference between conditions A and B. The distances, solid angle subtended, and plane angles are shown in Table 4.0.

CIE Recommendations	Distance between LED tip and detector	Solid Angle	Plane Angle (Full Angle)
Condition A	316 mm	0.001 sr	2°
Condition B	100 mm	0.01 sr	6.5°

Table 4.0.

CIE recommendations for the concept of Average Intensity. The area of the detector is always 100mm²

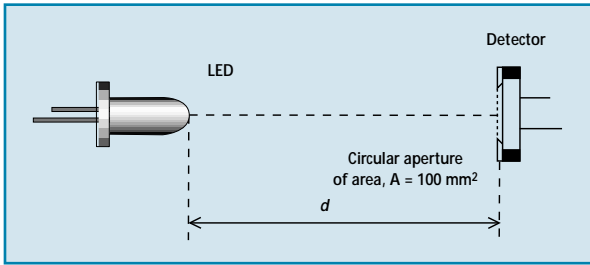


Fig. 4.1.
Schematic Diagram of
CIE Standard Conditions
for the Measurement
of Average LED Intensity

In practice Condition B is the most commonly used geometry since it is most suitable for low brightness LED light sources. Condition A should be used with bright LEDs with very narrow emission angles.

By applying the concepts discussed in section 4.1 of this technical guide, one can calculate the uncertainty between true intensity and the average intensity recommended by CIE 127. Figure 4.1 shows a schematic of the CIE Average LED Intensity measurement setup.

4.3 Spatial Distribution Characteristics

With the use of silver conductive epoxy, the back of the chip (substrate) is connected to the cathode lead of the leadframe. At the location where the die sits, the cathode lead is formed to a little reflector cup to capture the light, which emits from the sides of the LED die. The top of the die is metallized and connected to the anode lead of the leadframe. The leadframe is then dipped into a mold cup filled with optical grade epoxy. The shape of the mold, the insertion depth of the leadframe and the reflector cup surrounding the die determines the radiation pattern of the LED. Typical examples of LED packages are presented in Figure 4.2.

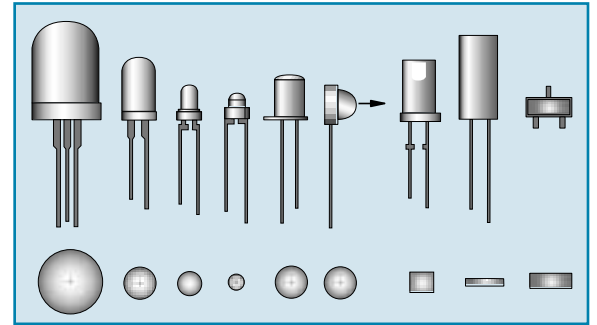


Fig. 4.2.
Examples of LED packages

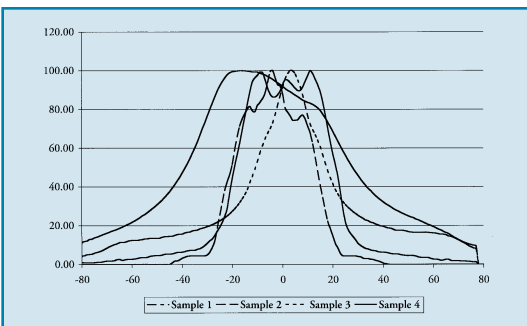


Fig. 4.3.
Examples of LED Spatial Distributions

The many different packages and types of LEDs generate different spatial distribution patterns. Spatial distributions of the luminous intensity emitted by a selection of different LEDs are depicted in Figure 4.3. Precise knowledge of the angle-dependent distribution of radiation is necessary for some applications. For example, in an automotive telltale backlighting design, it is important for a designer to have an understanding of the intensity profile of the LED around which he is designing around. Typically, with an LED backlit telltale, the legend is brightest in the center and lowest in the outer corners. For most applications a telltale, whose luminance profile varies by more than 50% at any two points, will appear non-uniform to a viewer.

The Goniometer

For applications where the angular dependent distribution of radiation is important, a goniometer or goniospectroradiometer can be used. One advantage of a goniospectroradiometer is that all relevant information such as the off axis photometric integral, color coordinates, dominant wavelength, color temperature, etc. can be recorded simultaneously with each measurement.

A goniometer is a device that allows one to change the relative angle (ϕ , θ) at which a detector, (spectrometer or photometer) views the source. This can be accomplished by either moving the detector around a stationary source or by tipping and tilting the source while the detector remains in a fixed position. The angle ϕ is adjusted by rotating the LED about its mechanical axis and the angle θ by pivoting the LED about its tip or about an axis perpendicular to the mechanical axis. The detector is used to determine illuminance E and intensity I (by applying the inverse square law) arising as a result of the flux incident on the detector as a function of the rotation angles. Several measurements are taken for each angle ϕ as ϕ is rotated between 0° and 180° with angle θ varying from 0° to 360° . It has been shown by the Physikalisch-Technische Bundesanstalt (PTB-Germany) that it is irrelevant whether the detector or the LED moves. Since moving the spectroradiometer requires considerable mechanical effort and cost, rotating the LED about its tip is recommended.

The radiation pattern of most LEDs is rotationally symmetric about the optical axis, it is common practice to pivot the LED about its tip and measure the intensity, about the angle θ . This provides a profile of the radiated beam in one plane. If secondary optic elements such as reflector cavities and pillow lenses are being designed, modeling errors from the one-dimensional model may be unacceptable and it may become necessary to record the two-dimensional radiation pattern.

A goniometer also offers another method for determining luminous flux and radiant flux. Total radiant flux is calculated by applying the inverse square law to each calculated value and summing all the values together. For flux in a given beam angle, the same process applies with the values of ϕ , θ adjusted to incorporate only the desired beam angle.

4.4 Luminous Flux and Radiant Flux

There are two principal methods for measuring total luminous flux or radiant flux. One incorporates an integrating sphere and the other, as discussed in Section 4.3, utilizes a goniometer.

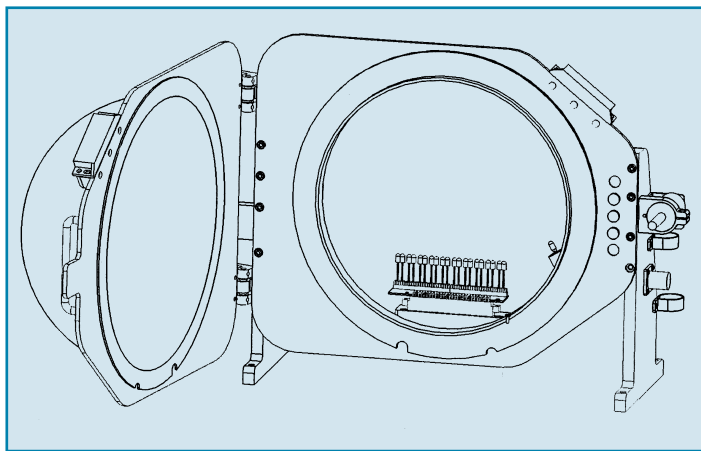


Fig. 4.4.
An integrating sphere designed to measure multiple, individual LEDs for both optical and electrical properties

The Integrating Sphere

The simplest and quickest way to measure the total luminous flux from an LED is to use an integrating sphere coupled with a photometer or spectroradiometer. The integrating sphere is a simple, yet often misunderstood device for measuring optical radiation. The function of an integrating sphere is to spatially integrate light. The theory of the integrating sphere assumes the interior surface is perfectly diffusing and has spatially uniform reflectance. The radiant exchange from diffuse surface to diffuse surface integrates the light, resulting in equal radiance at any point on the sphere wall. Theoretically, light received on any area of the sphere wall surface is directly proportional to light introduced to the sphere. Further discussion on this subject is presented in reference number 8.

The presence of a finite source, its supports, electrical connections, the necessary shield, and the apertures or windows, are all obvious departures from the basic assumption of the integrating sphere. As with any measurement there are potential errors associated in the measurement equipment and application. With an integrating sphere, corrections may be required for self-absorption, and spatial non-uniformity. Whether a photometer or a spectroradiometer is used to detect the indirect illuminance of the source, the user must consider the possible errors that may contribute to the measurement results, including, but not limited to non-linearity, directional and positional effects, detector instability, reference and sample instability, and noise. In order to keep measurement errors to a minimum when measuring LEDs individually, in an array or as a single LED, the use of larger spheres and some method, such as an auxiliary lamp, may be necessary to reduce substitution effects. Increasing the ratio of the sphere area to the size of the ports and the LED is more favorable. Figure 4.4 shows a cross section of an integrating sphere designed to house multiple single LEDs in an array format for high volume luminous flux and color measurements.

Presently there are discussions within industry and CIE regarding proper LED placement within an integrating sphere for flux measurements. For certain applications, it is only useful to measure the flux from a source as it is emitted in a given beam. Recommendations for reflector type incandescent lamp measurement are covered in reference guides such as in publication LM-20-1994, Illuminating Engineering Society of North America (IESNA) Approved Method for Photometric Testing of Reflector-Type Lamps. LM-20-1994 suggests masking the reflector portion of the lamp, which prohibits unwanted light from escaping. Because of their size, LEDs are very difficult to mask and standards are not currently available defining how such measurements should be performed. Careful consideration in the design and use of LED test and measurement equipment is essential to achieve valid measurement results that fit the application.

5.0 TERMINOLOGY

5.1 Radiometric Quantities

Radiant Flux: (Radiant Power)

Radiant flux ϕ also referred to as the power P, is the rate $d\theta/dt$ at which the radiation field transfers radiant energy from one region to another. Where θ is defined as the radiant energy. The unit of radiant power is the watt [W].

Solid Angle:

The solid angle Ω , in units of steradians [sr] subtended by a cone, is given by the expression A/r^2 where A is the area intercepted by the cone on the surface of a sphere of radius r centered on the cone vertex.

Radiant Intensity:

The radiant intensity I is the flux per unit solid angle emitted by an entire source in a given direction. It is expressed as $I = d\phi/d\Omega$ in units of watts per steradian [W/sr]. A detector with an active area A positioned at a distance r from a light source measures radiant power. This configuration assumes a point source, therefore the inverse square law holds true. Distance r and the detector area dA define the solid angle $d\Omega$.

Irradiance:

Irradiance E is the flux per unit area received by a real or imaginary surface element and is expressed as $d\phi/dA$. The unit of irradiance is [W/m²].

Radiance:

Radiance L is the flux per unit-projected area per unit solid angle leaving a source or any other surface. If $d^2\phi$ is the flux emitted into a solid angle $d\Omega$ by a source element of projected area dA, the radiance is defined as $d^2\phi/dA d\Omega$. The unit of radiance is [W/(sr•m²)].

5.2 Photometric Quantities

Photometry differs from radiometry, in that photometry is concerned only with that part of the radiation field which can induce a visual response that can be produced by the radiation. The spectrum of radiant energy waves that we call light is narrow, ranging from approximately 360nm to 830nm. Wavelengths shorter or longer than these do not stimulate the human visual response in the eye. The $V(\lambda)$ curve describes the spectral luminous efficiency for the photopic response of the human eye. It is used to evaluate the corresponding quantity that is a function of wavelength λ . The symbols for photometric quantities are analogous to the radiometric counterpart except followed by a subscript v.

The definition of the photometric unit is:

$$\phi_v = K_m \int V(\lambda) \phi_\lambda(\lambda) d\lambda$$

ϕ_λ is the spectral radiant flux of a signal and K_m is equal to 683 lm/W, which establishes the relationship between the (physical) radiometric unit, watt, and the (psychophysical) photometric unit, lumen.

All other photometric quantities are also obtained from the integral of their corresponding radiometric quantities weighted with the $V(\lambda)$ curve.

Table 5.0.

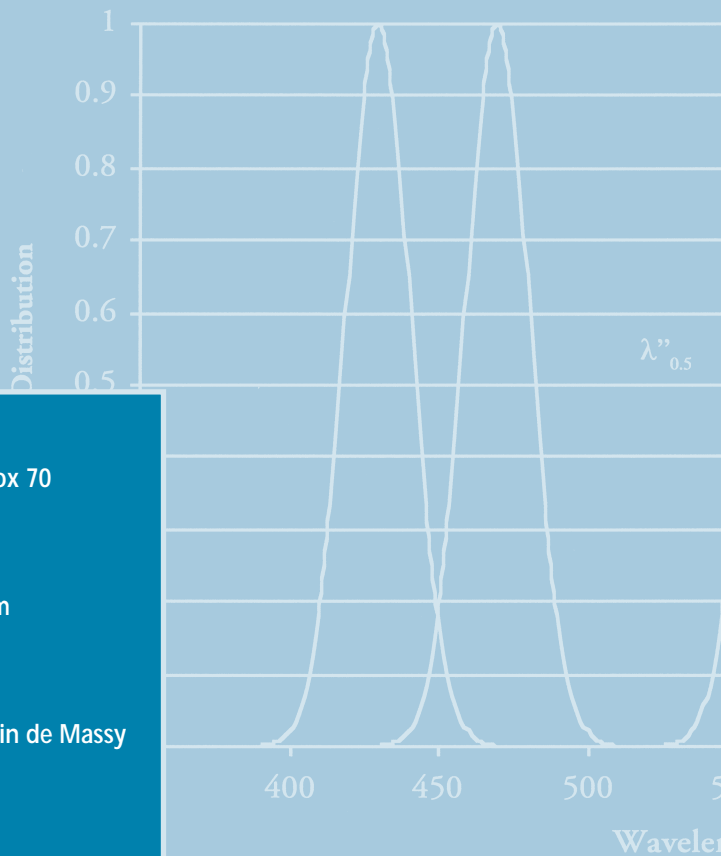
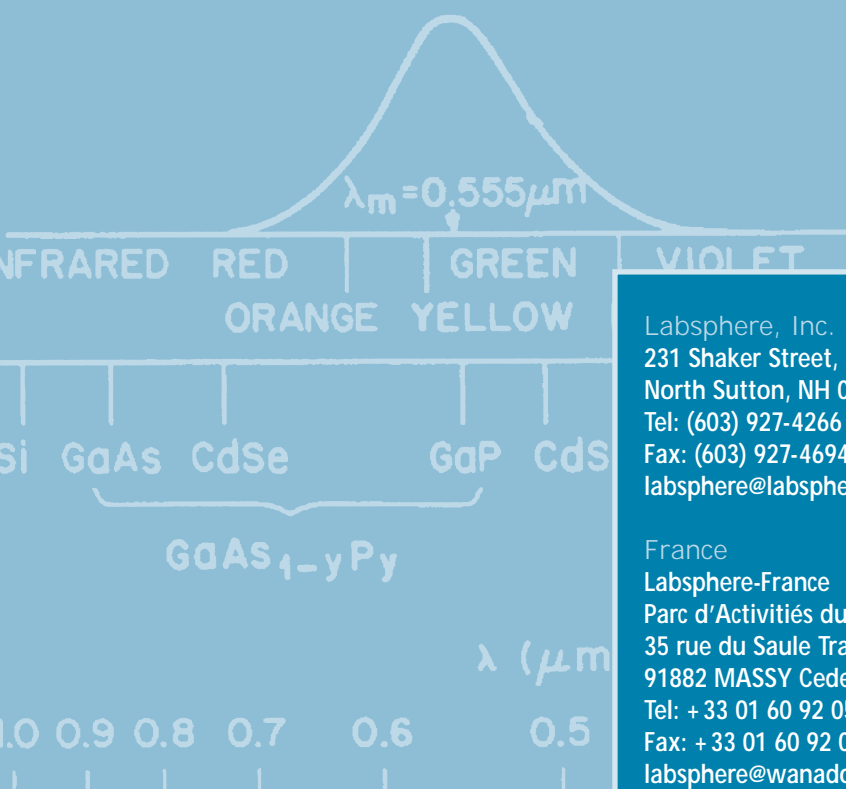
The table shows important photometric quantities along with their radiometric counterparts.

PHOTOMETRY	UNIT	SYMBOL	RADIOMETRY	UNIT	SYMBOL
Luminous Flux	lm	ϕ_v	Radiant Flux	W	ϕ
Luminous Intensity	lm/sr = cd	I_v	Radiant Intensity	W/sr	I
Illuminance	lm/m ² = lx	E_v	Irradiance	W/m ²	E
Luminance	cd/ m ² = nit	L_v	Radiance	W/sr•m ²	L

6.0 REFERENCES

1. SZE, S.M., Semiconductor Devices Physics and Technology, Bell Telephone Laboratories, Inc. 1985, pp. 258-263.
2. Ng, Kwok K., Complete Guide to Semiconductor Devices, McGraw-Hill, Inc. 1995, pp. 372-381.
3. International Commission on Illumination, Measurement of LEDs, Publication CIE 127-1997.
4. Decker, D, and U. Thomas, Progress and Perspectives of LED-Technology for Automotive Signal Lighting, SAE Technical Paper, Series #970651, 1997.
5. IES Lighting Handbook Third Edition, Illuminating Engineering Society, New York, 1962, pp.4:1-4:43.
6. Boyd, R, Radiometry and the Detection of Optical Radiation, John Wiley & Sons, Inc. 1983, pp. 14-25, 95-103.
7. Jones, C.F., and Y. Ohno, Proc. CIE Symposium '99, Budapest, 1999.
8. Labsphere Technical Guide, "A Guide To Integrating Sphere Theory and Applications", Labsphere, Inc., 1998.
9. Hentschel, Christian, Fiber Optics Handbook, 2nd Edition, Hewlett Packard, January 1988.
10. Lumiled, Application Note 1149-5 "Secondary Optics Design Considerations for Super Flux LEDs", 2000.
11. DeCusatis, Casimer, Handbook of Applied Photometry, American Institute of Physics, 1997, USA.
12. Sauter, George, Basic Concepts in Photometry, 2000 NIST Photometry Short Course, USA.

RELATIVE EYE RESPONSE



Labsphere, Inc.
 231 Shaker Street, P.O. Box 70
 North Sutton, NH 03260
 Tel: (603) 927-4266
 Fax: (603) 927-4694
labsphere@labsphere.com

France
 Labsphere-France
 Parc d'Activitiés du Moulin de Massy
 35 rue du Saule Trapu
 91882 MASSY Cedex
 Tel: +33 01 60 92 05 04
 Fax: +33 01 60 92 04 95
labsphere@wanadoo.fr

Germany
 Labsphere-Germany
 Weiherstraße 12
 D-88690 Uhldingen 3
 Tel: +49 7556 50107
 Fax: +49 7556 50108
labsphere@t-online.de

United Kingdom
 Labsphere Ltd.
 The Acumen Centre - First Avenue
 Poynton, Cheshire SK12 1FJ
 Tel: +44 (0) 1625-871188
 Fax: +44 (0) 1625-871778
labsphereltd@cs.com

