**SIEMENS**

# LEDs and Photometry
# Appnote 1

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The observed spectrum of electromagnetic radiations, extends from a few Hz to beyond $10^{24}$ Hz, covering some 80 octaves. The narrow channel from 430 THz to 750 THz would be entirely negligible, except that more information is communicated to human beings in this channel than from the rest of the spectrum. This radiation has a wavelength ranging from 400 nm to 700 nm and is detectable by the sensory mechanisms of the human eye. Radiation observable by the human eye is commonly called light.

Measurements of the physical properties of light and light sources can be described in the same terms as any other form of electromagnetic energy. Such measurements are commonly called radiometric measurements.

Measurements of the psychophysical attributes of the electromagnetic radiation we call light are in units, other than radiometric units. Those attributes which relate to the luminosity (sometimes called visibility) of light and light sources are called photometric quantities. The measurement of these aspects is the subject of *photometry*.

Electronics engineers who are starting to apply light emitting diodes and other optoelectronic devices to perform useful tasks will find the subject of photometry to be a confused mass of strange units, confusing names for photometric quantities, and general disagreement about the important requirements are for his/her application.

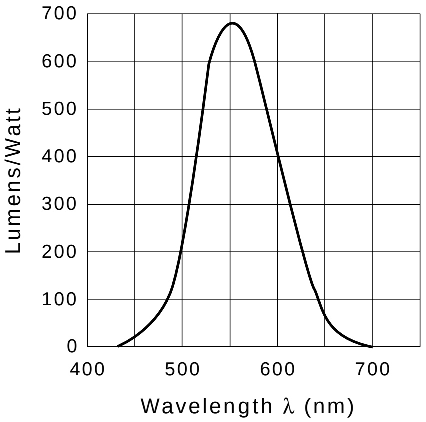
The photometric quantities are related to the corresponding radiometric quantities by the C.I.E. Standard Luminosity Function (Figure 1) or colloquially, the standard eyeball. We can think of the luminosity function as the transfer function of a filter which approximates the behavior of the average human eye under good lighting conditions.

**Figure 1. Relationship between radiometric units and photometric units**

The eye responds to the rate at which radiant energy falls on the retina, i.e., on the radiant flux density expressed as Watts/$m^2$. The corresponding photometric quantity is Lumens/$m^2$. Therefore the standard luminosity function is a plot of Lumens/Watt as a function of wavelength.

The function has a maximum value of 680 Lumens/Watt at 555 nm and the half power points occur at 510 nm and 610 nm (Figure 2).

**Figure 2. CIE standard photopic luminosity function**

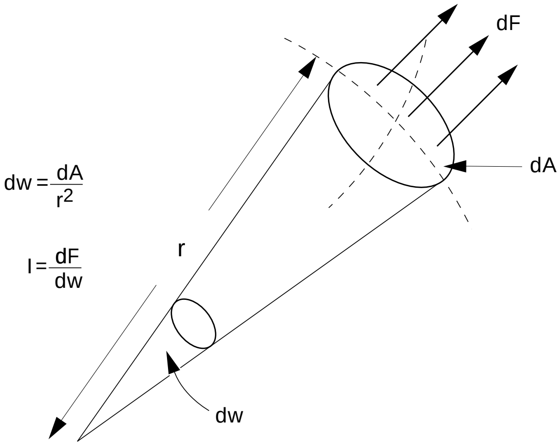


The lumen is the unit of luminous flux and corresponds to the watt as the unit of radiant flux.

Thus the total luminous flux emitted by a light source in all directions is measured in lumens, and can be traced back to the power consumed by the source to obtain an efficiency number.

Since it is generally not practical to collect all the flux from a light source and direct it in some desired direction, it is desirable to know how the flux is distributed spatially about the source. If we treat the source as a point (far field measurement), we can divide the space around the source into elements of solid angle ($d\omega$), and inquire as to the luminous flux (dF) contained in each element of solid angle ($df/d\omega$). The resulting quantity is Lumens/Steradian and is called *luminous intensity* (I), Figure 3. The unit of luminous intensity is called the *candela*, sometimes loosely called the candle, or candle power.

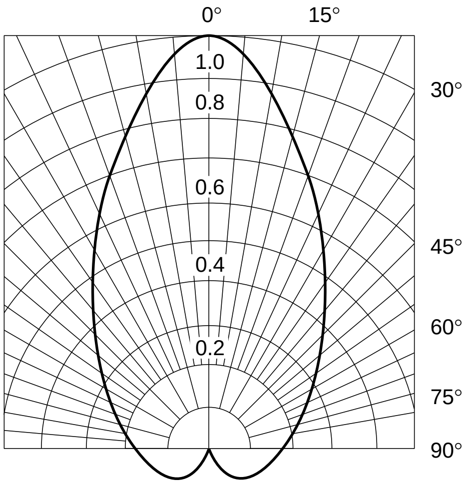
**Figure 3. Solid angles and luminous intensity**



Since the space surrounding a point contains 4 π steradians, it is apparent that an isotropic radiator of one candela intensity emits a total luminous flux of 4 π Lumens.

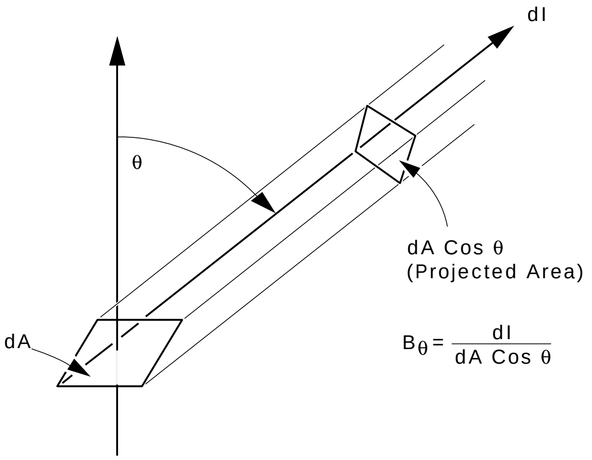
No real light source is isotropic, so it is quite common to show a plot of luminous intensity versus angle off the axis (Figure 4). If the source has no axis of symmetry, a more complex diagram is required.

**Figure 4. Spatial distribution pattern**



For an extended radiating surface, (such as an LED chip), each element of area contributes to the luminous intensity of the source in any given direction. The luminous intensity contribution in the given direction divided by the projected area of the surface element in that direction is called the *luminance* (B) of the source (in that direction), Figure 5. The quantity is sometimes called photometric brightness, or simply brightness. Using the term brightness on its own should be discouraged as brightness involves various subjective properties such as texture, color, sparkle, apparent size, etc., that have psychological implications.

**Figure 5. Definition of luminance**



The fundamental quantitative standard of the photometric system of units is the standard of luminance.

The luminance of a black body radiator at the temperature of freezing platinum (2043.8°K) is 60 candela per square centimeter. A blackbody radiator is a perfect absorber of all electromagnetic energy incident on it. In thermal equilibrium at a given temperature, it emits radiation, spectrally distributed according to Planck's Formula.

$$W\lambda = \frac{C_1 \lambda^{-5}}{exp\left(\frac{C_2}{\lambda}\right) - 1}$$

The units of luminance in present use are an engineering nightmare.

1 candela/cm$^2$ is called a *Stilb*
1/π candela/cm$^2$ is called a *Lambert*
1 candela/m$^2$ is called a *Nit*
1/π candela/m$^2$ is called an *Apostilb*
1/π candela/ft$^2$ is called a *foot-Lambert*

The foot Lambert is the most commonly used unit in the U.S.

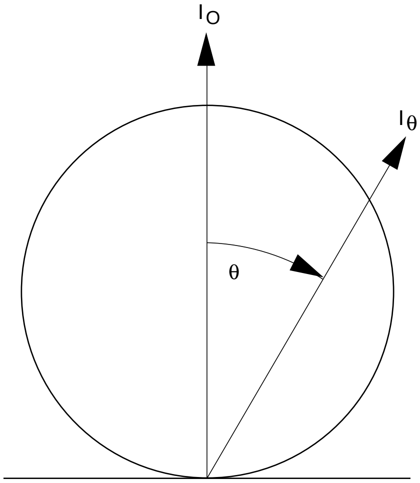
Of particular interest is a source whose angular distribution pattern is a circle (Figure 6). For such a source we have I θ= $I_o$ Cos θ, the luminance of such a source in a given direction q, is then given by:

$$B\theta = \frac{dI\theta}{dA\cos\theta} = \frac{dI_o Cos\theta}{dACos\theta} = \frac{dI_o}{dA}$$

The luminance is seen to be the same in all directions. Such a source is called a *lambertian source*. It can be shown that a perfectly diffusing surface behaves in this fashion. The formula governing a diffusing surface Iθ = $I_O$ Cos θ is called Lambert's Cosine Law.

It can be shown that a flat LED chip is a very good approximation to a Lambertiian Source.

**Figure 6. Lambertian radiation pattern**



If we now take a surface element (dA) and determine the intensity contribution in each direction we can determine the total flux (dF) emitted by the surface element. The resultant ratio (dF⁄dA) Lumens/m$^2$ is called the *luminous emittance* (L). For a flat surface we may calculate L from:

$$L = 2\pi \int_0^{\frac{\pi}{2}} B_{(\theta)} Sin\, \theta Cos\, \theta d\theta$$

The corresponding radiant emittance in watts/m$^2$ is of considerable interest for GaAs infrared LEDs where total output power is an important parameter.

The total luminous flux emitted by a light source can then be calculated from $F_{total} = \int LdA$.

These photometric quantities are sufficient to describe the properties of light sources such as light emitting diodes.

When light falls on a receiving surface, it is either partially reflected in the case of a purely passive surface, or partly converted into some other form of energy by what we may describe as an active surface (such as a phototransistor or photomultiplier cathode). In either case we are interested in how much flux falls on each element of the surface; Lumens/m$^2$ in the case of a passive surface which we wish to illuminate, or the eye; and Watts/m$^2$ in the case of other active surfaces. The quantity Lumens/m$^2$ in this case is called the *illuminance* sometimes loosely referred to as the illumination. The unit of illuminance is the *lux* also referred to as the metercandle. Another commonly used unit of illuminance, in the U.S. is the *foot candle*, equal to one lumen per square foot. One lumen per square cm is called a *phot*.

Many of these photometric quantities and units are in common use in the field of illumination engineering. While English units are the most common in the U.S., a mixed system of units is involved in common usage.

## Application to Light Emitting Diodes

The above description of photometric quantities should indicate that there are many ways in which the photometric properties of LEDs can be stated. There is no general agreement among LED makers and users as to the best way to specify LED performance leading to much confusion and misunderstanding.

Many factors must be taken into account when evaluating LED specifications for a particular application, and electronic engineers will need to develop a knowledge of these factors to use LEDs effectively in new designs.

Presently available light emitting diodes are made from III-V, II-VI, and IV semiconductors, with Gallium Arsenide Phosphide and Gallium Phosphide being the major materials. Gallium Aluminum Arsenide is also used but is less common. Gallium Arsenide is commonly included in this group, but GaAs emits only infrared radiation around 900 nm which is not visible to the eye and can't properly be called light. All specifications of non-visible emitters must be in radiametric units.

GaP emits green light between 520 and 570 nm peaking at 550 nm, very close to the peak eye sensitivity. It also can emit red light between 630 and 790 nm peaking at 690 nm.

$GaAs_{(1-x)}\ P_X$ emits light over a broad range from green to infrared depending on the percentage of phosphorus in the material (x). For x in the 0.4 region, red light between 640 and 700 nm peaking at 660 nm is obtained. For x=0.5, amber light peaking around 610 nm is obtained.

$Ga_{(1-x)}\ Al_XAS$ as presently available emits red light between 650 and 700 nm peaking at 670 nm and also emits into the infrared range.

The efficiency of these materials is very dependent on the emitted wavelength, with drastic fall off in efficiency as the wavelength gets shorter. Fortunately the standard eyeball filter favors the shorter wavelength (down to 555 nm) and gives some measure of compensation. Some typical efficiencies reported by device makers, and the resulting overall luminous efficiency (Lumens/electrical watt) are as follows:

GaP.red .72% at 20 Lum/Watt=14 Lum/Watt overall

$GaAs_6P_4$ red .3% at 50 Lum/Watt=.15 Lum/Watt overall

GaAlAs red 1.5% at 40 Lum/Watt=.024 Lum/Watt overall

GaP green .006% at 675 Lum/Watt=.04 Lum/Watt overall

$GaAs_5P_5$ amber .0044% at 340 Lum/Watt=.015 Lum/Watt overall

For simple status indicator applications, front panel lamps and similar applications, several factors must be considered:

1. Color—LED lamps and displays are available in a variety of standardized colors of emitted light: red, high efficiency red, soft orange, yellow, green and blue—although not every component is available in every color.

2. Apparent source size—Various combinations of chip size and optical systems are available so that apparent source sizes from about 5 mils to about 300 mils diameter are available as standard products. Other things being equal, a larger source size is more visible.

3. Angular distribution. GaAsP diode chips are nearly Lambertian, but GaP are nearly isotropic. With suitable optical design, the angular distribution pattern can be changed from very broad to quite narrow. By placing the chip at the focus of the lens system a narrow high intensity beam is obtained. The off axis visibility is drastically reduced. By using diffusing lens materials, a large area source with good off axis visibility is obtained but the luminance is reduced.

4. Luminous intensity. This will govern the visibility under optimum background contrast conditions, when viewed at normal distances. 1 millicandela is typical for red lamps of either GaAsP or GaP at normal operating conditions.

5. Luminance. When it is not possible to provide a dark contrasting background, or when the source is viewed at very close distances, the luminance becomes important. Values from 100 ft-L to 5000 ft-L are typical.

These factors are all related to the design of the device and the user should understand the trade offs. High luminance values in excess of 10,000 ft-L are easily obtained by running very high current densities in the LED chip but can lead to shortened life if carried too far.

For a given drive current the luminous intensity of two different chips will be similar, while the luminance will be inversely proportional to the active area of the chip.

If the designer can use filter screens or circularly polarizing filters in front of the light source, excellent protection from background illumination can be obtained. In this case a diffusive lens giving a large apparent source with lower luminance, is more visible than a high luminance point source.

When a LED is used with an optical system to activate a remote sensor such as a cadmium sulphide or cadmium selenide cell (red light), or a GaAs IR emitter is used with a silicon photo detector, the performance requirements are somewhat different. It can be shown that for a given optical arrangement the irradiance of the detector determines the detected signal and this is proportional to the radiance of the source, which is comparable to the luminance (brightness) of the source. The intensity of the source will not be a factor unless the detector active area is larger than the incident beam.

When average power consumption must be minimized but good visibility is required, or detection at a considerable distance is required, pulsed operation can be used. With GaAs and GaAsP emitters using low duty cycle short pulses, very high peak intensity levels can be reached permitting communication over considerable distances. This technique is not useful with GaP diodes since they do not exhibit a linear relationship between optical output and instantaneous forward current, becoming saturated at moderate current levels. GaPalso has a 50% higher rate of fall off in light output with temperature increase, than GaAsP which further inhibits high power applications.

Using LEDs to give a “heads up” projected display, such as for an automobile speedometer readout, or aircraft cockpit application places severe requirements on the display luminance. For easy visibility, the projected image must be sufficiently contrasted with the ambient illumination. This requires very high luminance values for the LEDs together with the use of photochromic windshields and probably polarizing screens.

The foregoing is a necessarily simplified description of a very complex subject. For more information read the standard textbook literature on these subjects.

References:
R. Kingslake, *Applied Optics & Optical Engineering Committee on Colorimetry of the O.S.A., The Science of Color.*
Warren J. Smith, *Modern Optical Engineering*