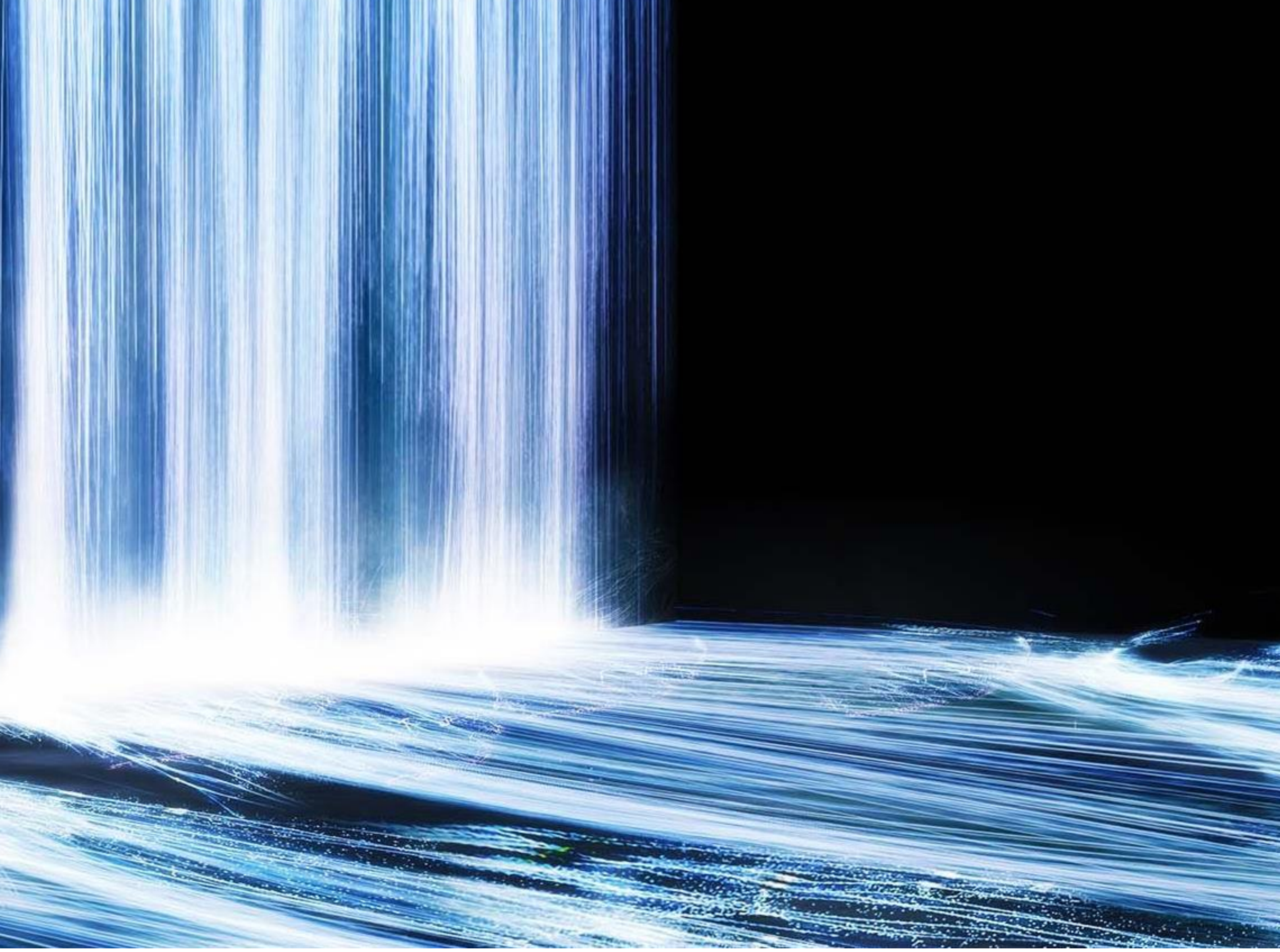


TECHNICAL GUIDE

A general guide to high-efficiency LED exposure systems

This technical guide is intended for those who want to deepen their knowledge on high-efficiency lighting systems without getting lost in the translation of datasheets. It could also appeal to anyone interested in LED-based technologies. The following topics are covered: telecentric lighting, collimation angle, homogenization optics, radiometric units, irradiance measurement.

idonus
creative engineering and manufacturing

Authored by C. YAMAHATA, PhD

Issued in September 2019
by idonus sàrl, Switzerland
www.idonus.com

This technical guide deals with nonimaging optics, the branch of optics which is concerned with the optimal transfer of light radiation from a source to a target. Nonimaging optics finds applications in the fields of (i) illumination and (ii) solar energy concentration. We will focus on the first topic and will emphasize on UV exposure systems for photolithography. The following explanations are limited to the general case of light collection from incoherent light sources, such as LEDs (Light Emitting Diodes), incandescent lamps or sunlight.

1. Telecentric versus non-telecentric illumination

In optics, telecentricity is the property of optical systems in which the rays are highly collimated and parallel to the optical axis. Telecentric illumination is achieved when the light source is placed at the front focal plane of the lens system (see Figure 1). The dimensions of the light source and the focal length of the optics influence ray parallelism.

Due to the parallelism of the chief ray path (*i.e.*, rays emerging from the front focal point come out perpendicular to the back focal plane), the diameter of the lighting system must be at least as large as the exposure area. For example, telecentric UV exposure of a 6-inch wafer (∅150 mm) implies that the front lens be at least of diameter 150 mm. Such exposure can be completed with the idonus *UV-EXP150R* exposure system which provides a circular effective exposure area of ∅150 mm.

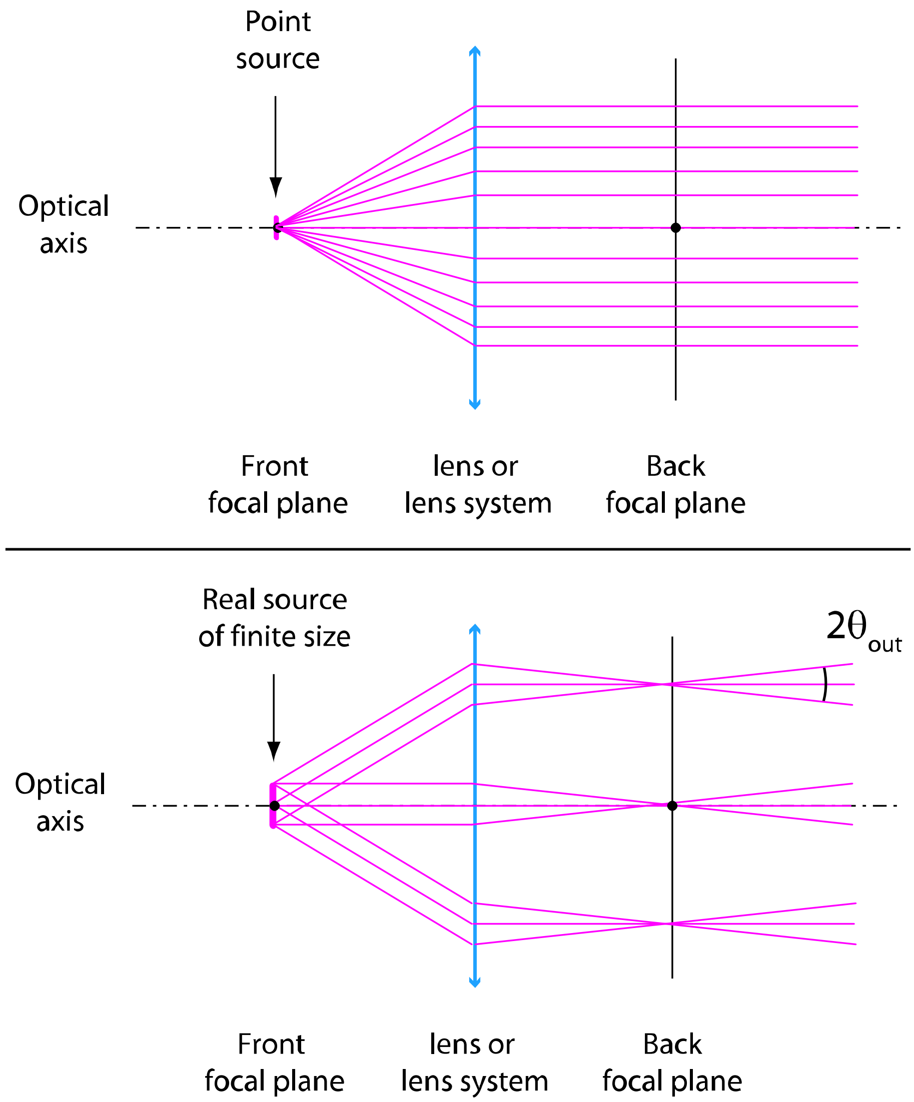


Figure 1: *Telecentric illumination, ideal versus real source. In reality, a light source is not a point source. Therefore, a telecentric system is as in the lower part of this illustration.*

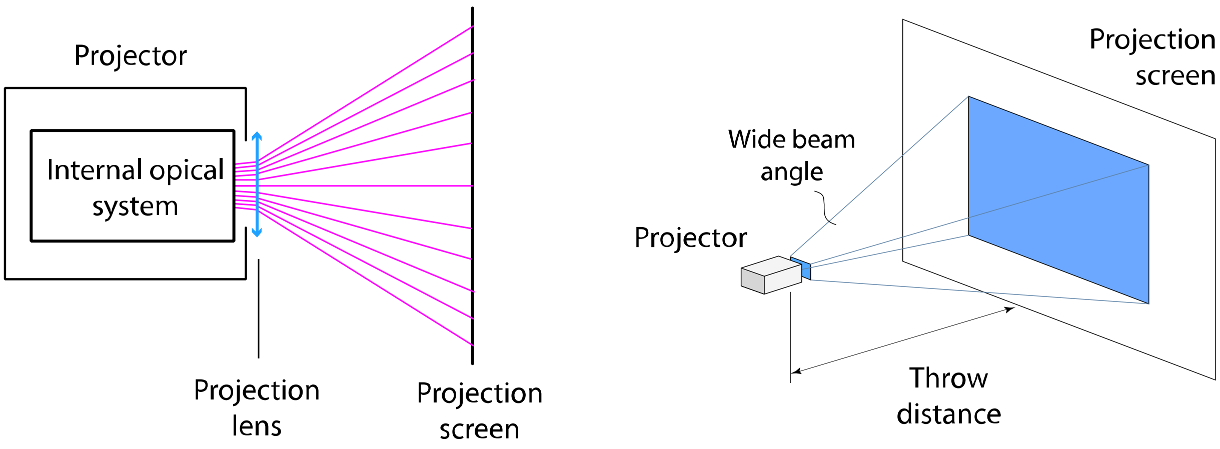


Figure 2: *A typical example of non-telecentric illumination is found in video projectors.*

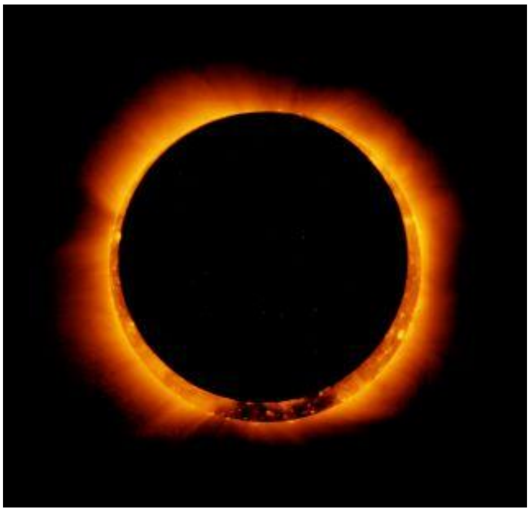
An example of a non-telecentric illumination system can be found in digital projectors (see schematic in Figure 2). The internal architecture may be telecentric but the light beam from the projection lens is necessarily non-telecentric to achieve magnification of the image on a wide screen.

2. Collimation angle

A point source exists only theoretically. Indeed, a source of energy confined to an infinitely small spot would have an infinite energy density. Because of the finite size of light sources, light rays are collimated down to a given angle, as illustrated in Figure 1 (bottom).

2.1. Angular diameter

If you observe the Sun and compare it to the Moon, you will find that they have about the same apparent diameter (see Figure 3). In astronomy, this apparent diameter is known as the angular diameter, that is the angle the object subtends as seen by an observer. In average, the angular diameter of the Sun is given by the angle $2\theta_{Sun} = 0.5°$ (more precisely, 31.5 – 32.5 arcmin). From this observation, it follows that direct rays of light from the Sun arrive at the Earth slightly uncollimated by an angle of $2\theta_{Sun} = 0.5°$. Here, we have intentionally used the half-angle $\theta_{Sun} = 0.25°$ to avoid any confusion.



Annular solar eclipse as seen by the Solar Observing Satellite Hinode on January 4, 2011.

Figure 3: *Annular eclipse of the Sun. An annular eclipse happens when the Moon is slightly further from Earth than on average. Because its apparent diameter is smaller than that of the Sun, it does not block the entire view of the Sun.*

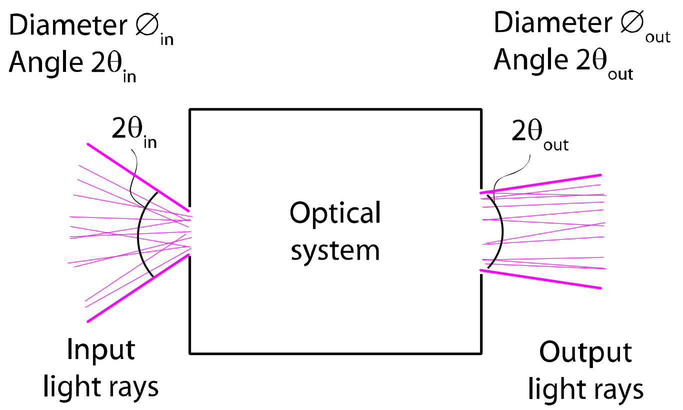


Figure 4: *Illustration of the principle of étendue conservation.*

2.2. Measurement of the collimation angle

To characterize the collimation angle of our exposure systems, we also make use of the angular diameter: we measure the diameter of the light source as seen from the back focal plane. In our datasheets, we make use of the half-angle at full width half maximum (FWHM). Thus, when we specify a collimation angle lower than +/-1°, it means that the beam angle at FWHM is smaller than 2°.

3. Etendue conservation

The collimation angle can be reduced through the use of a diaphragm (or aperture stop) placed in front of the light source. However, this is achieved at the cost of a loss of energy. Another means to reduce the collimation angle without losing energy is to design an optical system that widens the diameter of the ray beam (see Figure 4). The physical law known as étendue[1] conservation proves that the beam angle and the beam diameter are intimately connected: in an energy conserving system, for a given light source, it is not possible to reduce the angle without increasing the beam diameter.

If you now compare Figure 1 (bottom) with Figure 4, you can easily figure out how a lens can collimate light. In the telecentric illumination system of Figure 1 (bottom), the output angle is clearly reduced compared to the input angle, while the output diameter is increased.

4. Homogenization optics

The light source is inhomogeneous. For example, consider the filament in an incandescent light bulb. Without a homogenization optical system, the light would also come out inhomogeneous. In the worst case, the light source would be re-imaged on the target (*e.g.*, filament visible in a resulting microscopy image). This issue is known as "filament image". The use of a diffuser is a simple yet inefficient means to homogenize the light. To address these limitations, August Köhler (1866–1948), who was working for the Carl Zeiss corporation, devised an optimal illumination method for specimen microscopy imaging. Köhler illumination method uses a perfectly defocused image of the light source to illuminate the sample.

Based on Köhler's principle, a means to produce highly uniform illumination is to use a fly's eye homogenizer, also known as Köhler integrator. An example of use of such a device is illustrated in Figure 5. The picture shows the internal architecture of an LED-based digital video projector. Light beams from the RGB colour LEDs are first collimated and combined with a set of lenses and dichroic beamsplitters. Before reaching the micromirrors of the Digital Light Processing system (DLP), the mixed light beam reaches the fly's eye homogenizer. The homogenizer consists of an array of 11 × 9 lenses that act as multiple Köhler illumination sources and produce a highly uniform distribution of the light. In our LED exposure systems, we use that principle and homogenise the light with a matrix of lenses.

---

[1] The term "étendue", comes from the French "étendue géométrique," which literally means "geometrical extent." Etendue conservation is a central concept in optics and the term is widely used in nonimaging optics. Etendue conservation is also known by various names including extent, étendue, acceptance, and Lagrange invariant. For a comprehensive explanation on this principle, the reader is referred to the following reference: Roland Winston, Juan C. Miñano and Pablo Benítez, "*Nonimaging Optics*," Elsevier Academic Press, 2005. DOI: 10.1016/B978-0-12-759751-5.X5000-3.

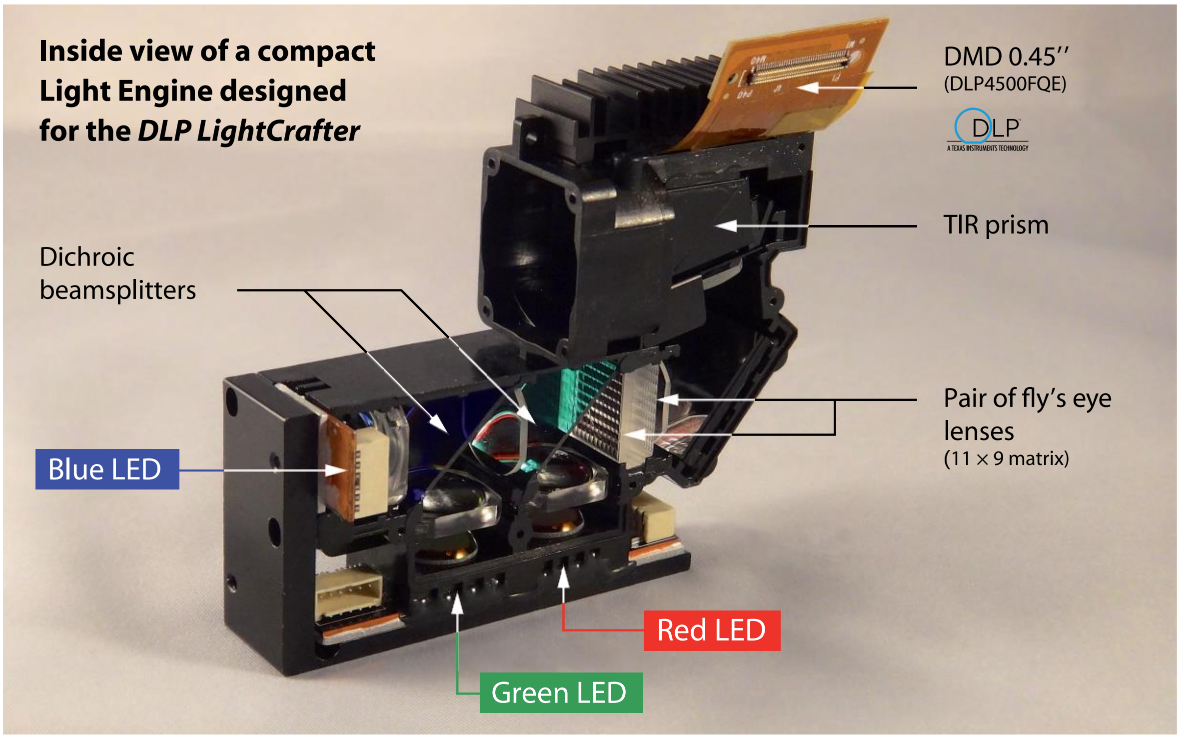
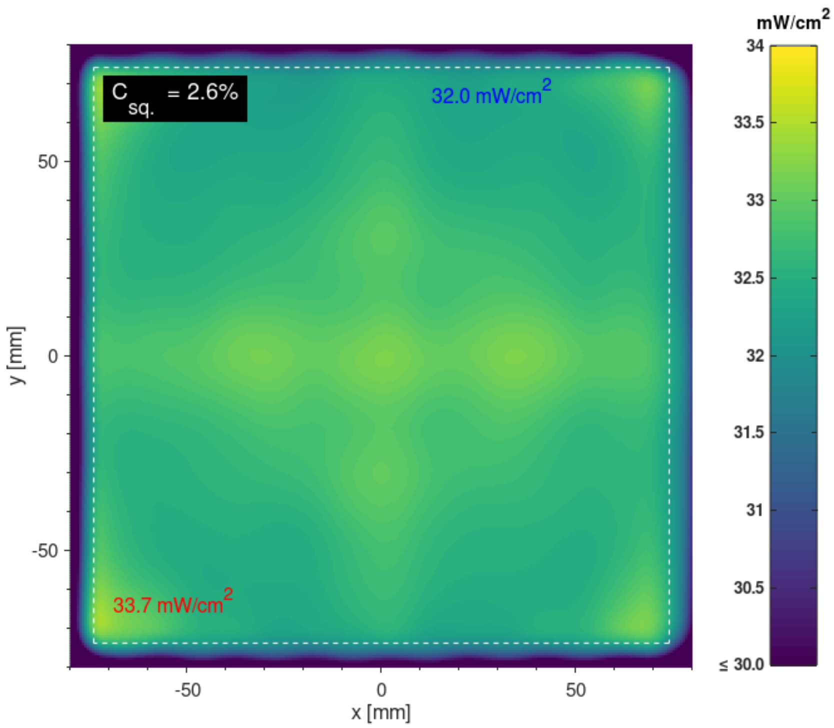


Figure 5: *Typical illumination architecture found in DLP projectors. This disassembled view shows the internal design of a compact light engine developed by iView Ltd for the Texas Instrument DLP LightCrafter 4500.*

5. Characterization of the non-uniformity of an exposure system

Non-uniformity of an exposure system is evaluated from the minimum (Min) and maximum (Max) irradiance values measured at a given time over a specified exposure area. In photolithography, it is the contrast ratio C, or "Michelson contrast", which is used in the specifications. The Michelson contrast is calculated as follows:

$$C = (Max - Min) / (Max + Min)$$



This irradiance map was measured on our UV exposure system model *UV-EXP150S* (150 mm × 150 mm exposure area) configured with a high-power UV-LED emitting at 365 nm peak wavelength.

In our Quality Control procedure, the equipment was set at mid-power. A reference sensor mounted on an automated XY-stage continuously measured the irradiance during the scan. It is noteworthy that this irradiance map was generated from 3000 data points.

Here, the contrast ratio inside the square area (dotted line, 150 mm × 150 mm) is C = (33.7 – 32.0) / (33.7 + 32.0) = 2.6%.

Figure 6: *Typical "irradiance map" recorded during the final control of one of our UV exposure systems.*

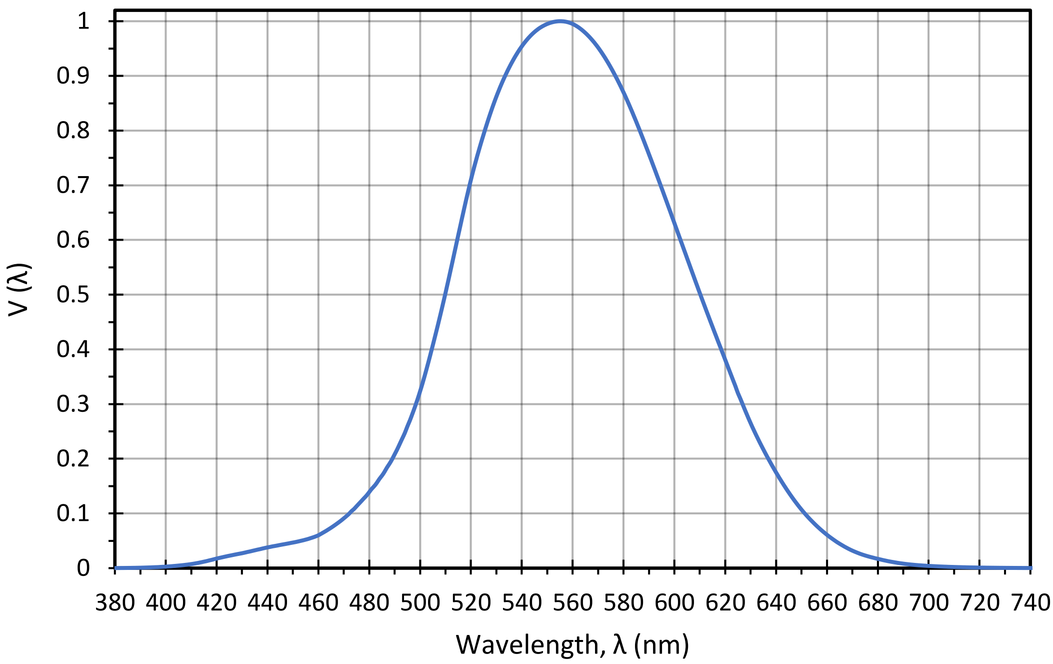


Figure 7: *Photopic luminosity function established by the CIE.*

Our standard products are specified with a non-uniformity lower than +/-3%, or C<3%. Consider for example UV exposure at a mean irradiance of 100 W/m^2 (10 mW/cm^2) and a non-uniformity of +/-3%. Min is -3% lower than the mean irradiance, Max is +3% higher than the mean irradiance. We can verify that C = (103 - 97) / (103 + 97) = 3%. Indicating that the non-uniformity is lower than 3% may be misunderstood by our clients. For this reason, we also indicate that it is equivalent to a non-uniformity of +/-3%. In Figure 6, we show an example of non-uniformity measurement completed on one of our products.

6. Photometry, human perceived light

The visible spectrum is the part of the electromagnetic spectrum which is visible to humans. For a typical human eye, it corresponds to electromagnetic wavelengths in the range of about 380 nm (violet) to 740 nm (red). In day vision, or photopic vision, the peak of sensitivity is found at a wavelength of 555 nm (green). The photopic luminosity function V(λ) describes the average spectral sensitivity of the human eye (see Figure 7).

It is currently the Commission Internationale de l'Éclairage (CIE) that oversees and maintains data evolution for the photopic luminosity function. In the field of metrology, the photopic function V(λ) is used to convert radiant intensity (watt per steradian, W/sr) into luminous intensity (candela, cd).

7. SI base units

Acknowledging the importance of light in daily life, the candela was adopted as a base unit by the Bureau International des Poids et Mesures (BIPM) in 1954. Since then, the candela is defined as the SI unit of luminous intensity in a given direction. It is noticeable that among the seven base units of the International System of Units (SI), the candela is the only unit that is based on a physiological factor. The seven SI base units (second, meter, kilogram, ampere, kelvin, mole, candela) are listed in Table 1.

8. Radiometric units

Radiometric quantities are of prime importance to describe optical radiation and evaluate the performance of optical systems. They are purely physical and are applicable for all optical systems. For some applications, it can nevertheless be more relevant to take into account how the typical human eye records optical radiation. In this case, rather than the absolute physical values from radiometric quantities, this evaluation is described in terms of photometric quantities. All the photometric units are based on the candela which is a physiological derived unit that carries information about human vision. This evaluation is somewhat limited to the small part of the visible spectrum.

Quantity name	Unit name	Unit symbol	Dimension
Time	second	s	**T**
Length	meter	m	**L**
Mass	kilogram	kg	**M**
Electric current	ampere	A	**I**
Thermodynamic temperature	kelvin	K	**Θ**
Amount of substance	mole	mol	**N**
Luminous intensity	candela	cd	**J**

Table 1: *The seven SI base units of measure defined by the International System of Units (SI).*

For non-visible light – *e.g.* ultraviolet (UV) light below 380 nm or infrared (IR) light above 740 nm, the candela and its derived units are definitely unusable because the photopic luminosity function introduced in section 6 gives V(λ) = 0. For example, consider an UV-LED with a peak emission at 365 nm and a spectral bandwidth of Δλ = 20 nm (+/-10 nm around peak wavelength). Whatever the radiant flux (radiant power, W) the LED can provide, if you try to estimate its luminous flux (luminous power, lm = cd.sr), you will always end up with zero lumen (0 lm). For this reason, the emphasis will be made on radiometric quantities. Table 2 shows some of the commonly used radiometric quantities in nonimaging optics.

- The "**radiant exposure**" is often referred to as the dose (or sometimes radiant fluence). This is especially the case in UV photolithography. Also, radiant exposure, or dose, is most often expressed in mJ/cm^2.
- To evaluate LED performance, **radiant flux** is expressed in watts (W) for high-power LEDs or mW for other LEDs. Because the radiant flux is measured in watts, it is often referred to as "radiant power" or "optical power". From our own experience, the term "**optical power**" is well understood by most of our interlocutors. It also clearly emphasizes that the watts are not those measured from the electric power consumption.
- **Irradiance** may also be found as radiant flux density. However, since irradiance is unambiguous, we discourage the use of any other term. Irradiance is often expressed in mW/cm^2. Notice that 1000 W/m^2, which is the order of magnitude of the light received from the Sun, is equivalent to 100 mW/cm^2. It is therefore convenient to use mW/cm^2 for many industrial applications with commensurate dimensions.

The field of solar energy generation is a good example of where irradiance measurement is used extensively. In photovoltaics, the "total solar irradiance" (TSI) received on Earth is used as a reference for the prediction of energy generation from solar power plants. Mean TSI is commonly evaluated from a parameter called "solar constant," which is a measurement of the mean solar irradiance above the atmosphere. It is measured as being 1361 W/m^2 (*i.e.*, 136.1 mW/cm^2). Considering energy absorbed by the atmosphere, night and day conditions and seasons, among others, the mean incoming irradiance that can effectively be collected at the ground level by solar panels is about 20 – 25% of the TSI.

Quantity name	Symbol *	Unit name	Unit symbol	Dimension **
Radiant energy	Q_e	joule	J	**M.L^2.T^{-2}**
Radiant exposure	H_e	joule per square meter	J.m^{-2}	**M.T^{-2}**
Radiant flux	Φ_e	watt	W	**M.L^2.T^{-3}**
Irradiance	E_e	watt per square meter	W.m^{-2}	**M.T^{-3}**
Radiant intensity	I_e	watt per steradian	W.sr^{-1}	**M.L^2.T^{-3}**
Radiance	L_e	watt per steradian per square meter	W.sr^{-1}.m^{-2}	**M.T^{-3}**

* The subscript "e" stands for energetic. The subscript "v" standing for visible is used for the corresponding quantities measured with photometric units.

** See Table 1 for the dimensions and corresponding quantities.

Table 2: *Commonly used SI radiometric quantities.*

9. UV sensor for the measurement of irradiance

9.1. The ideal radiometer

There is no commercially available broadband UV radiometric sensor with uniform and low-uncertainty response. As a result, it is extremely difficult to compare measurements completed with different radiometric sensors. The complexity lies in the fact that the output signal of an irradiance meter is a function of both:

- the spectral irradiance of the (UV) source and
- the responsivity of the sensor.

Reliable irradiance measurements can only be achieved with a UV meter having a "flat" spectral response curve (responsivity vs. wavelength) in the spectral range of the UV source to be measured. We will see in section 9.2 that when it is non-flat, the emission spectrum (relative radiant flux vs. wavelength) of the UV-LED must be considered (*i.e.*, emission spectrum should be considered for the calculations)[2].

9.2. Gallium phosphide technology

The selection of the appropriate UV sensor firstly depends on the spectral emission of the source. For UV-LEDs emitting at wavelengths 365 nm, 385 nm, or 395 nm, photodiodes based on Gallium Phosphide (GaP) technology are highly suitable. The primary information to look after when selecting a sensor is the responsivity ($\Re$) of the photodetector which measures the electrical output per optical input. The units of $\Re$ are amperes per watt (A/W), where the watts come from the radiant flux (optical power). A typical responsivity curve of a GaP photodiode is shown in Figure 8. In Figure 9, we also show a typical spectral emission of an UV-LED with 385 nm peak wavelength.

Under certain conditions that will be discussed hereafter, the output signal V_0 of the sensor can be considered as being proportional to the radiant power Φ_e received by the photodiode times the responsivity $\Re(\lambda_{pk})$ at the peak wavelength of the source:

$$V_0 \propto \Re(\lambda_{pk})\Phi_e \qquad \textit{Equation 1}$$

$$E_e \propto \Phi_e \quad \rightarrow \quad E_e = K_\lambda V_0 \quad \text{with} \quad K_\lambda \propto \frac{1}{\Re(\lambda_{pk})}$$

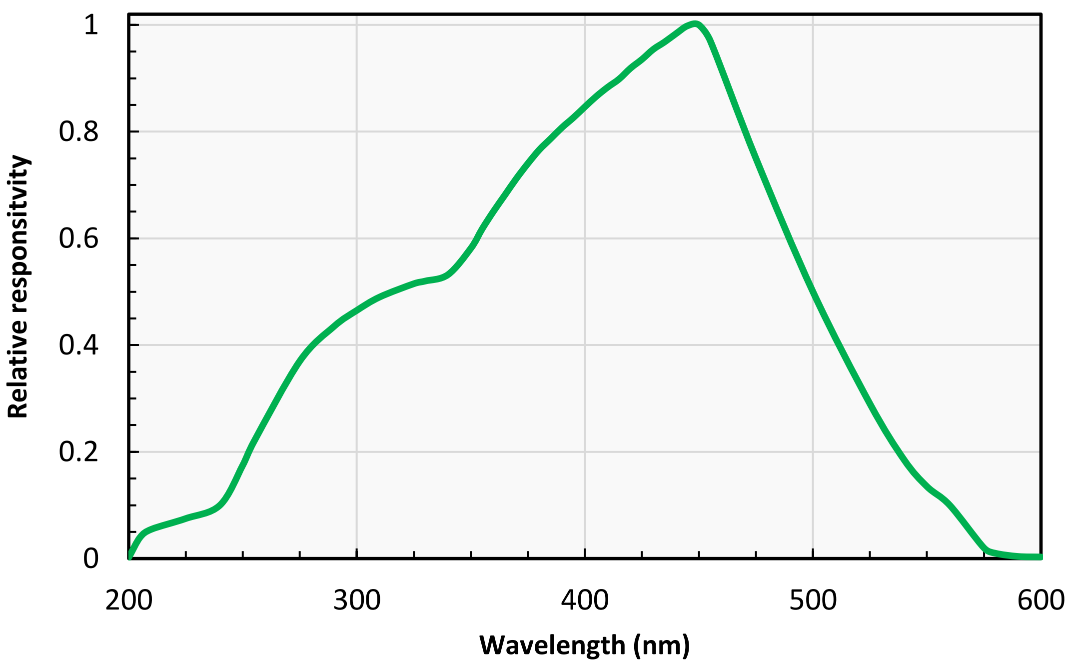


Figure 8: *Typical spectral responsivity of GaP photodiodes.*

[2] You will notice that the weighting by the sensor responsivity is analogous to the way the photopic function is incorporated in photometric calculations.

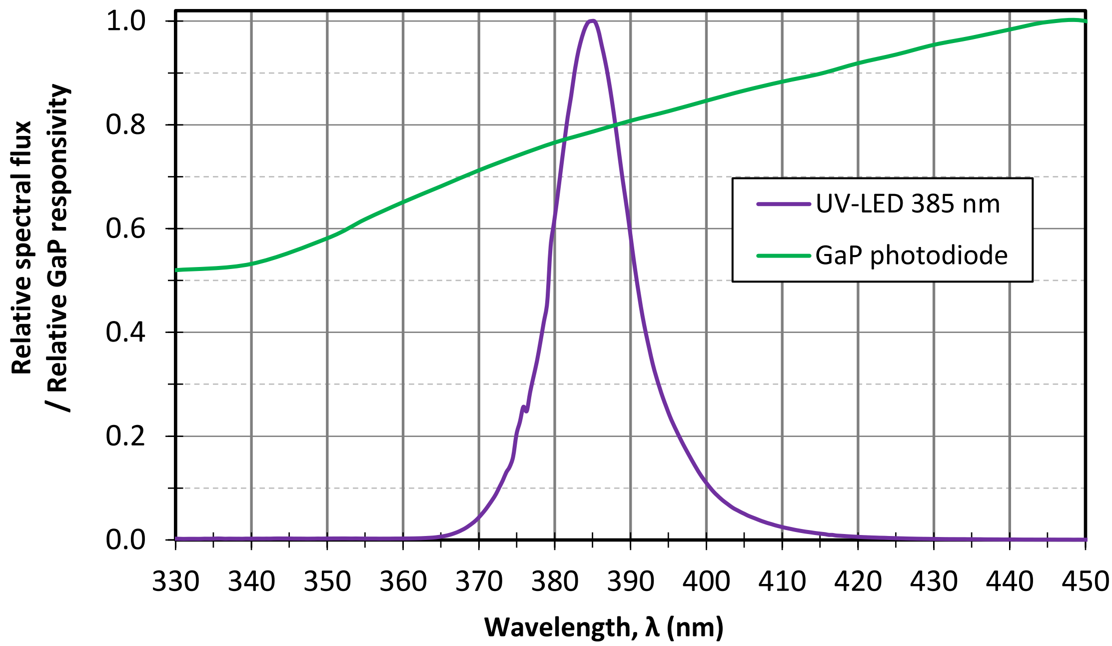


Figure 9: *GaP photodiode responsivity vs. the typical spectral flux of an UV-LED with 385 nm peak wavelength.*

K_λ is a calibration parameter that must be chosen according to the wavelength of the source. Irradiance E_e can then be straightforwardly obtained from the output signal V_O of the sensor or directly displayed on a radiometer.

Although the GaP responsivity curve is non-flat, Equation 1 is applicable if the emitting source has a narrow spectral bandwidth $\Delta\lambda$, *i.e.* if $\Re(\lambda) \approx \Re(\lambda_{pk})$ for all wavelengths within this bandwidth.

Equation 1 is also applicable in the case of the singly peaked spectral distribution shown in Figure 9. The error remains neglectable as long as $\Re(\lambda_{pk})$ is used in the calculation. This is due to the symmetry of the spectral distribution around λ_{pk}, together with the relatively good linearity of $\Re(\lambda)$ around λ_{pk}.

If we look at Figure 9, it seems quite surprising that the GaP photodiode can be used to measure accurately the irradiance of the UV-LED. This statement might question you. We will therefore take a few lines to illustrate it numerically. In Table 3, we have reported a few values of $\Re(\lambda)$ and $E(\lambda)$ extracted from the data shown in Figure 9. $\Re(\lambda)$ is the relative responsivity of the sensor, $E(\lambda)$ is the relative spectral irradiance of the LED. These quantities are dimensionless.

λ	$\Re(\lambda)$		$E(\lambda)$	$\Re(\lambda)\ E(\lambda)$	$(1/\Re_\lambda) \sum \Re(\lambda)\ E(\lambda)$	
	$\Re_\lambda$	*value*			*value*	*error*
365	$\Re_{365}$	0.68	0.07	0.05	1.84	15.6%
375	$\Re_{375}$	0.74	0.23	0.17	1.69	6.2%
385	$\Re_{385}$	0.79	1	0.79	1.58	-0.5%
395	$\Re_{395}$	0.83	0.24	0.20	1.51	-5.3%
405	$\Re_{405}$	0.87	0.05	0.04	1.44	-9.6%
			$\sum E(\lambda)$	$\sum \Re(\lambda)\ E(\lambda)$		
			1.59	1.25		
			$\propto$ *irradiance*	*sensor output*		

Table 3: *Numerical calculations illustrating the influence of the approximation made in Equation 1.*

First, it should be reminded that we are ultimately interested in measuring the irradiance E_e, which is proportional to $\sum E(\lambda)\Delta\lambda$. This can be rewritten as follows: $E_e \propto \sum E(\lambda)$. In our numerical example, the exact value we are looking for is $\sum E(\lambda) = 1.59$. However, this information cannot be obtained directly. Instead, we can measure a signal $V_O = \sum \Re(\lambda)\, E(\lambda)$.

Indeed, from the physics perspective, part of the photon energy received by the photodiode is converted into an electric current and the efficiency of this conversion depends on the wavelength. What the photodiode does can be translated mathematically as follows: $V_O = \sum \Re(\lambda)\, E(\lambda)$. In our numerical application, this leads to an output signal $V_O = 1.25$.

With Equation 1, our statement is that we can assume that $V_O \approx \Re_{385} \sum E(\lambda)$ since the peak wavelength of the LED is 385 nm. The irradiance can be calculated from the formula: $\sum E(\lambda) \approx V_O / \Re_{385}$. At 385 nm wavelength, the relative responsivity of the GaP sensor is $\Re_{385} = 0.79$. Thus, we get the estimate $\sum E(\lambda) \approx 1.58$. This is close to the exact value of $\sum E(\lambda) = 1.59$. Thus, the error is only -0.5% if we use the responsivity at peak wavelength, $\Re_{385}$.

In the last columns of Table 4, we have also reported what would be the error if we mistakenly used another wavelength for the responsivity $\Re_\lambda$. We clearly see that the assumption made in Equation 1 is only valid if we use the sensor responsivity measured for the corresponding peak wavelength of the source.

In other words, the same photodiode can be used to individually characterize UV-LEDs emitting at different wavelengths, but the radiometer must each time be configured with the appropriate setting for the wavelength (calibration parameter K_λ). Finally, you should be aware that at the present time, broadband radiometric LED measurements with flat responsivity and low-uncertainty results are not available. If you want to investigate more on this topic, we invite you to read this paper:

G. P. Eppeldauer *et al.*, "Broadband Radiometric LED Measurements", *Proc. SPIE Int. Soc. Opt. Eng.*, Vol. 9954, 99540J, 2016. DOI: 10.1117/12.2237033

10. Understanding the datasheet of an LED

In this section, we will go through some of the specifications found in an LED datasheet. The example chosen is a warm white LED model LCW G6CP from OSRAM Opto Semiconductors (see Figure 10). Because this model of LED is intended for use in lighting applications, the specifications are provided with photometric quantities. Fortunately, OSRAM's website also provides some valuable information about the corresponding radiometric quantities. We have summarized the data in Table 4 and, for each quantity, we have also introduced symbols that are consistent with the convention used throughout this document.

We can understand from the spectral emission curve shown in Figure 10 that the white colour is produced using a blue LED chip (peak wavelength around 440 nm) combined with a yellow phosphorus material. The phosphorus layer absorbs portion of the blue light and re-emits light at longer wavelengths. Colour temperature of white light LEDs is controlled by the amount of phosphorus material.

10.1. Lambert's cosine law

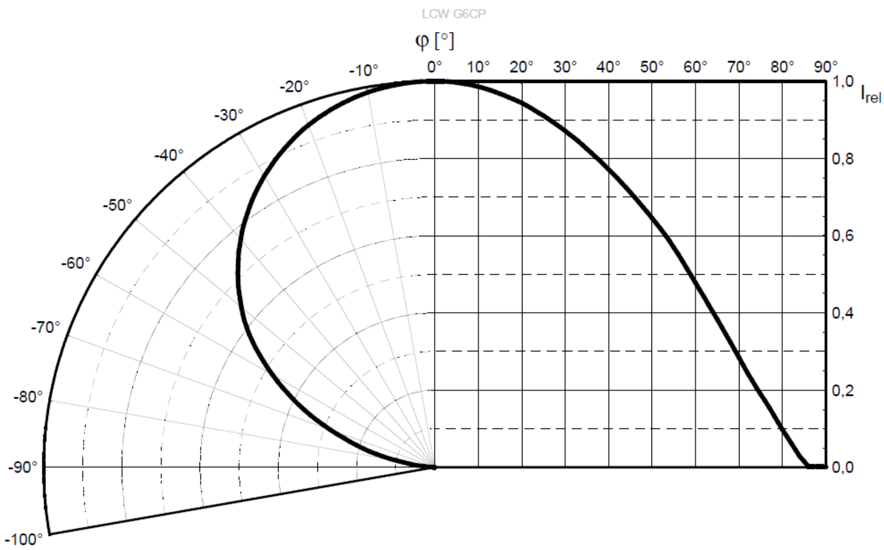
LED sources (without additional optics) can be considered as Lambertian emitters. In optics, Lambert's cosine law says that the radiant intensity, I_e, observed from a Lambertian emitter is directly proportional to the cosine of the angle θ between the direction of the incident light and the surface normal: *[continued on page 12]*

Quantity	Symbol	Value and unit	Dimension
Viewing angle (beam angle at FWHM)	$2\theta_{FWHM}$	120°	**1**
Forward voltage (typ.)	V_F	3.30 V	**$M.L^2.I^{-1}.T^{-3}$**
Forward current (test condition)	I_F	0.140 A	**I**
Electric power consumption	P_{elec}	0.462 W	**$M.L^2.T^{-3}$**
Radiant flux	Φ_e	0.105 W	**$M.L^2.T^{-3}$**
Luminous flux	Φ_v	33.5 lm	**J**
Radiant intensity	$I_{e,max}$	35.3 mW.sr^{-1}	**$M.L^2.T^{-3}$**
Luminous intensity	$I_{v,max}$	11.3 cd	**J**

Table 4: *Some of the specifications of LED model LCW G6CP from OSRAM. For each quantity, we have introduced symbols that are consistent with the convention used in our document.*

Device Name, Product Brand	Color, Wavelength [nm]	Electrical Power	Brightness				∢
			Φ_V	I_V	Φ_E	I_E	
 LCW G6CP Advanced Power TOPLED +D +A	White	0.462 W	33.5 lm	11.3 cd	105 mw	35.3 mW/sr	120°

Radiation Characteristics 5) *page 27*
Abstrahlcharakteristik 5) *Seite 27*
$I_{rel} = f(\phi)$; $T_S = 25$ °C



Relative Spectral Emission - V(λ) = Standard eye response curve 5) *page 27*
Relative spektrale Emission - V(λ) = spektrale Augenempfindlichkeit 5) *Seite 27*
$I_{rel} = f(\lambda)$; $T_S = 25$ °C; $I_F = 140$ mA

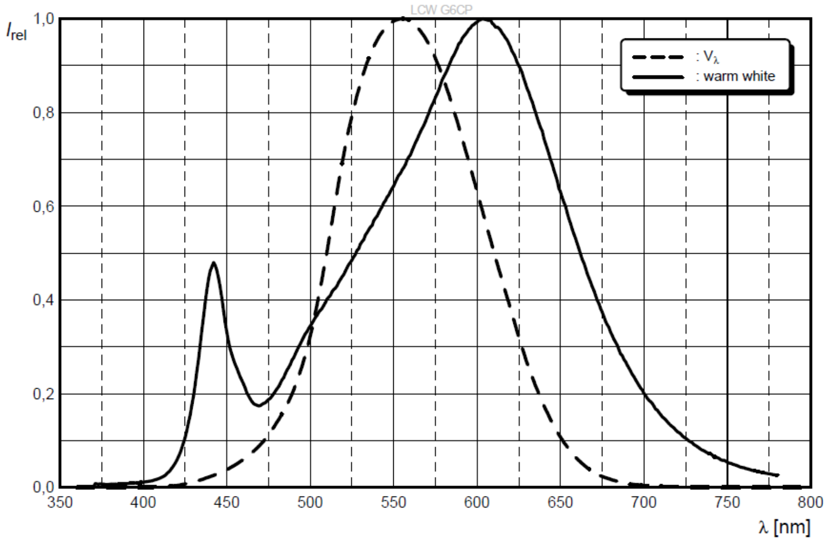


__Figure 10:__ An example of LED specifications found on OSRAM Semiconductor's website. The model shown is a "warm white" LED with reference LCW G6CP. Notice the photopic function V_λ included in the last graph.

$$I_e(\theta) \propto \cos\theta$$

Observing that cos(0°) = 1 and cos(60°) = 0.5, it follows that: the maximum radiant intensity is $I_e(0) = I_0$ and is measured at θ = 0°; above 60°, the radiant intensity is lower than $\frac{I_e(0)}{2}$. In other words, the half-angle at FWHM is θ_{FWHM} = 60°. Thence, the viewing angle is $2\theta_{FWHM}$ = 120°. It can be seen from the datasheet that the relative radiant intensity $I_{e,rel}(\theta)$ closely satisfies the Lambert's cosine law:

$$I_{e,\mathrm{rel}}(\theta) = \frac{I_e(\theta)}{I_0} \approx \cos\theta \quad \text{for} \quad -90° \leq \theta \leq 90°$$

10.2. Electric power and radiant flux

We have explained in section 8 that we like to use the term "optical power" when talking about the radiant flux Φ_e. This makes sense here since we want to compare the electric power consumption to the output radiant flux. Only part of the electric power is converted into optical power; the remaining power is lost as heat. Comparing P_{elec} = 0.462 W with Φ_e = 0.105 W, we get a clear idea of the energy efficiency, η, of the LED: $\eta = \Phi_e / P_{elec}$ = 22.7%.

10.3. Radiant intensity

Radiant intensity and radiant flux are related by the equation:

$$I_e(\theta) = \frac{\partial\Phi_e}{\partial\Omega}$$

Ω is the solid angle (measured in steradian, sr) of a cone with apex angle 2θ:

$$\Omega = 2\pi(1 - \cos\theta)$$

Because the LED closely follows Lambert's cosine law, the relation between the radiant intensity and the radiant flux is simply found as:

$$\Phi_e = \pi I_0$$

This simplified calculation gives I_0 = 33.4 mW/sr. This calculated value is close to the one found in the datasheet ($I_{e,max}$ = 35.3 mW/sr).

10.4. Luminous flux

The spectral emission curve provided in the datasheet includes the photopic luminosity function V(λ) already introduced in section 6. As explained above, this is because photometric quantities are all calculated from the V(λ) function. We will now see how V(λ) is used to convert radiant flux Φ_e into luminous flux Φ_v. Φ_v is calculated using the following equation:

$$\Phi_v = K_{cd} \int_{\lambda} \frac{\partial\Phi_e}{\partial\lambda} V(\lambda) d\lambda = K_{cd} \int_{\lambda=380\,nm}^{\lambda=740\,nm} \Phi_{e,\lambda} V(\lambda) d\lambda$$

$\Phi_{e,\lambda}$ is the spectral flux, or radiant flux per unit wavelength. The spectral flux is commonly measured in W/nm. The integration is only carried out over the wavelengths for which V(λ) $\neq 0$, *i.e.* 380 nm $\leq \lambda \leq$ 740 nm.

The constant K_{cd} is defined in the SI standard as follows:

> *The luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W.*

Note that 540×10^{12} Hz corresponds to the wavelength 555.17 nm (peak of sensitivity of the eye in day vision), as calculated from the speed of light in vacuum, c = 299 792 458 m/s.

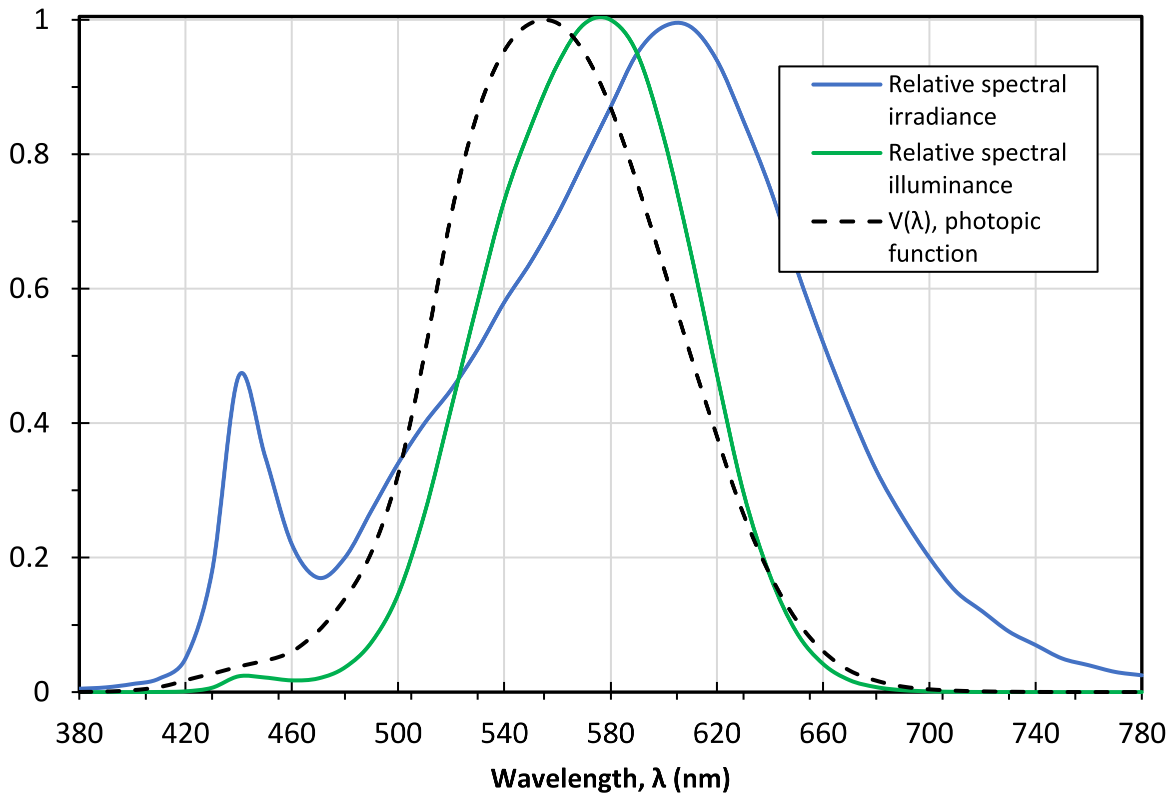


Figure 11: *Relative spectral emission of LED model LCW G6CP (OSRAM), radiometric data and photometric calculation.*

We can complete the integration numerically using the relative spectral irradiance provided in the datasheet. In Figure 11, we have reported the function V(λ), the relative spectral irradiance $E_{e,\lambda}$ and the product V(λ) $E_{e,\lambda}$ (normalized). From these data, using the radiant flux Φ_e = 0.105 W provided in the datasheet, we find a luminous flux Φ_v = 33.48 lm. Our calculated value is very close to the one found in the datasheet (33.5 lm).

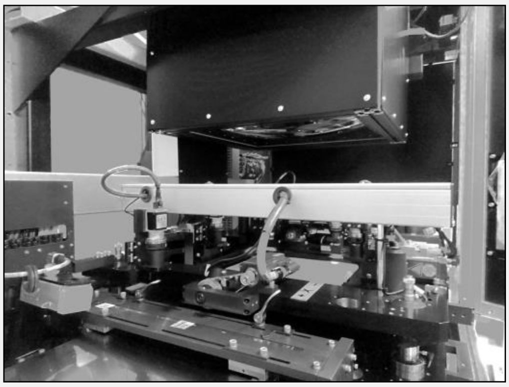
10.5. Luminous intensity

From the reasoning given in section 10.3, we can easily deduce the luminous intensity:

$$I_{v,max} = \frac{\Phi_v}{\pi}$$

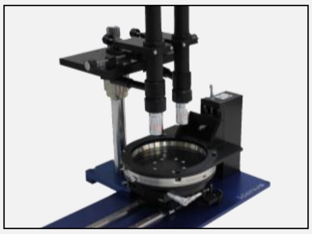
We find $I_{v,max}$ = 10.7 lm/sr. Again, the calculated value is close to that found in the datasheet (11.3 lm/sr). The difference is only -5% and is identical to that calculated for the radiant intensity.

Creative engineering and manufacturing • Our engineering team is accustomed to developing products according to client's needs. In-house machining and assembling facilities shorten the time from concept to finished products.

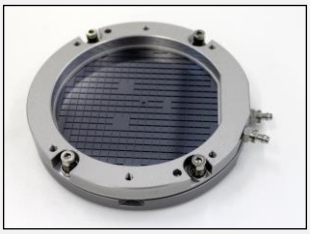


Customized UV-LED exposure system installed on a roll-to-roll machine

Visit our website to have an insight into our other products and activities. Contact us for further technical information and to obtain a quotation.



Double image microscope



A model of wafer chuck

About Idonus

Founded in 2004, Idonus is a Swiss company that develops and manufactures special equipment for the MEMS and watchmaking industries. Our product portfolio includes UV-LED exposure systems for photolithography, IR microscope for wafer inspection, and vapor phase chemical etcher for silicon-based devices. Since 2016, we also provide ion implantation services and machines for the surface treatment of materials.

Contact us for more details:

Christian Spoerl
Managing Director
sales@idonus.com

creative engineering and manufacturing

idonus sàrl
Rouges-Terres 61
2068 Hauterive
Switzerland

T: +41 32 724 44 40
info@idonus.com
www.idonus.com