Application Note

Ambient Light Sensor Application Guide - OPT3XXX/ OPT4XXX

ABSTRACT

Electronic devices that use light sensors are becoming much more prevalent. Devices ranging from outdoor lighting to display backlighting use light sensors to implement light control based on ambient lighting conditions. The OPT series (OPT3XXX/OPT4XXX) ambient light sensors (ALS) are designed to have a similar spectral response to that of the human eye. This application report describes how to integrate any OPT light sensor into an optical system that best enhances the human experience. This document describes how to calculate the proper sizing of a window, and compensate for the added effects of translucent material.

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1 Introduction

An ALS is a device that outputs a signal proportional to the amount of visible light incident upon the sensor. An issue with an ALS is that users of the end products do not want to see the sensor. This creates many constraints in how the system around the ALS can be designed, including using small windows (to minimize exposure of the sensor) and tinted glass. A key concern regarding the optomechanical system design is ensuring enough light transmission for proper operation. The following sections describe the proper sizing of a window and compensating for the added effects of a glass window.

2 Window Materials

When an ALS is placed behind a glass or plastic window, the type of window material used plays a large role in the end performance of the overall system. The level of overall light transmission (both visible and infrared) and the refractive index of the material are important characteristics. The active sensing area of the OPT series is rectangular, but its size and location vary by device as shown in Table 2-1.

Table 2-1. Sensing Area Dimensions and Location

Package Type	Active Area (mm × mm)	Location of Active Area	Devices
USON	0.39 × 0.49	Offset from geometric center	OPT3001, OPT3001-Q1, OPT3002, OPT3004
USON	0.31 × 0.40	Centered	OPT4001-Q1, OPT4003-Q1
SOT-5X3	0.30 × 0.38	Centered	OPT3004, OPT3005, OPT4001, OPT4048, OPT4060
PicoStar™	0.30 × 0.38	Centered	OPT3006, OPT3007, OPT4001, OPT4001-Q1

For devices where the active sensing area is offset from the geometric center (OPT3001, OPT3001-Q1, OPT3002, and OPT3004), the window aperture must be centered on the sensor's active region rather than the outer package outline. See Figure 2-1 for the exact location of the active sensing area relative to the package outline.

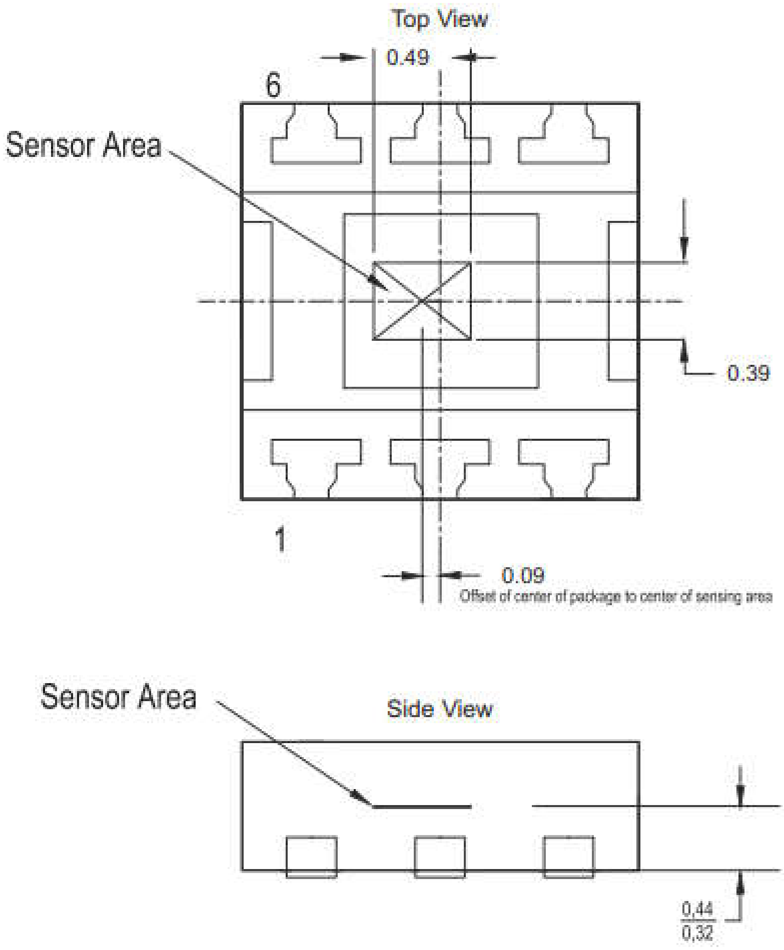


Figure 2-1. OPT3XXX USON Package Sensor Position

For all other devices, the sensing area is centered with respect to the package outline, so no additional centering of the window aperture is required. For complete package dimensions, refer to the device-specific datasheet.

2.1 Attenuation Compensation

In many applications, seeing the ALS is not desired. The use of a dark window prevents the ALS from being seen, but also prevents a portion of the visible light from reaching the sensor, and results in signal attenuation.

2.1.1 Choosing the Dark Window

There are several approaches to selecting and compensating for a dark window.

Choose a window that is dark enough to optimize the balance between the aesthetics of the device and sensor performance.

Note

The aesthetic evaluation is the subjective opinion of the designer; therefore, seeing the window on the physical design is more important than referring to the specifications of the window transmission on paper.

The chosen window must not be darker than absolutely necessary, because a darker window allows less light to illuminate the sensor, and therefore impedes sensor accuracy.

For designs requiring very dark coverglass (Ex. <5% transmission at 550 nm), the choice of sensor becomes an additional design consideration. If the application can accomodate a relatively higher transmission window, an OPT3XXX series device is perfectly acceptable, as the additional light through the window keeps the signal well above the device's noise floor, preserving its specified accuracy. Conversely, when a design demands a darker window, the finer resolution of the OPT4XXX series, which can have a resolution as low as 312.5 µLux, would be the better choice.

In the following application example, the dark window has less than 7% transmission at 550 nm.

Figure 2-2 shows the normalized spectral response of the dark window.

Note

The equipment used to measure the transmission spectrum is not capable of measuring the absolute accuracy (non-normalized) of the dark window sample, but only the relative normalized spectrum. The window is much more transmissive to infrared wavelengths longer than 700 nm, than to visible wavelengths between 400 nm and 650 nm.

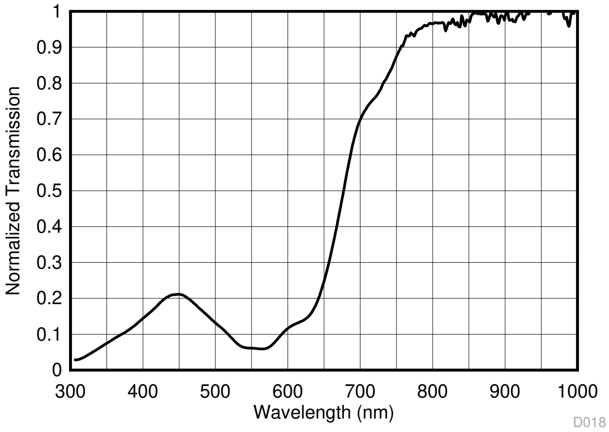


Figure 2-2. Normalized Transmission Spectral Response of the Chosen Dark Window

The imbalance between infrared and visible light decreases the ratio of visible light to infrared light at the sensor. Although it is preferable to have the window decrease this ratio as little as possible (by having a window with a close ratio of visible transmission to infrared transmission), the OPT series ambient light sensors still perform well due to their excellent IR rejection. Figure 2-3 shows the expected output performance for the OPT3001 under a dark window illuminated by fluorescent, halogen, and incandescent sources. As can be seen, the device maintains a high level of accuracy under a dark glass even when illuminated by high IR sources.

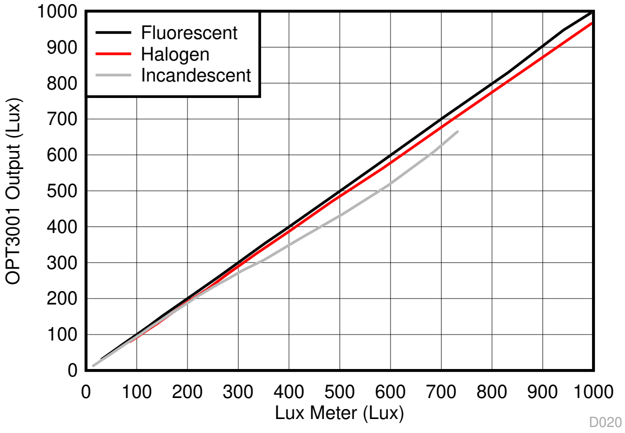


Figure 2-3. Compensated Output of the OPT3001 Under a Dark Window Illuminated by Fluorescent, Halogen, and Incandescent Light Sources

The next step is to measure the attenuation factor of the coverglass. The following sections outline the two methods for calculating this factor.

In the first method, there is no requirement for any additional equipment. This method is referred as the ALS-only based approach.

In the second method, a lux meter and a fluorescent light source are required. The second method is more accurate than the previous method.

2.1.2 ALS-Only Based Approach

1. Place a light source that uniformly illuminates the ALS with no window or glass to attenuate the light transmission.
2. Read the ALS output, and note the result as ALS_{AIR}.
3. Using the same light source on the ALS, place a glass window in front of the sensor and maintain the same sensor position relative to the light source.
4. Read the ALS output, and note the result as ALS_{GLASS}.

Calculate the visible attenuation factor, as shown in Equation 1

$$Visible\ Attentuation\ Factor = ALS_{AIR}/ALS_{GLASS} \tag{1}$$

During normal system operation when the ALS is placed behind the optical window, use this visible attenuation factor to determine the calibrated lux of the scene by using Equation 2

$$Calibrated_{Output} = Measured_{Output} \times Visible\ Attenuation\ Factor \tag{2}$$

2.1.3 Lux-Meter Based Approach

To calculate the compensation factor due to the attenuating effect of the dark window, first measure a fluorescent light source with a lux meter, then measure that same light with the ALS under the dark window. To measure accurately, use a fixture that can accommodate either the lux meter or the design containing the ALS and dark window, with the center of each of the sensing areas being in exactly the same X, Y, Z location; see Figure 2-4 . The Z placement of the design (distance from the light source) is the top of the window, and not the ALS itself.

Figure 2-4. Fixture With One Light Source Accommodating Either a Lux Meter or the Design (Window and ALS) in the Exact Same X,Y,Z Position

The fluorescent light in this location measures 1000 lux with the lux meter, and 73 lux with the ALS under the dark window within the application. Thus, the window has an effective transmission of 7.3% for the fluorescent light. This 7.3% is the weighted average attenuation across the entire spectrum, weighted by the spectral response of the lux meter (or photopic response).

For all subsequent ALS measurements under this dark window, the following formula is applied.

$$Compensated\ Measurement = \frac{Uncompensated\ Measurement}{(7.3\%)} \tag{3}$$

2.2 Refractive Index and Dispersion

One property of the window material that affects the design is the refractive index of the material. This property is the *optical density* of the material. Almost all glass and optical plastics have a refractive index between 1.5 and 2. The index of refraction of the glass is used to determine how much light bends as it travels through the material.

Color dispersion is another property of the window material. This dispersion comes because the refractive index of a material is slightly different for every wavelength. Occasionally, blue and red light may have quite different indices of refraction. In such cases, the optical path length becomes a function of the wavelength of the light, and leads to dispersion. The Abbe number of a material is a measure of how much light is dispersed transmitting through that material. The higher the Abbe number, the lower the amount of dispersion in the material. Although dispersion is undesirable in some complex imaging systems, most ALS systems are only concerned with the total energy of the transmitted light (typically not affected by dispersion).

While this document is intended as a guide for optomechanical designers, understand all materials and their properties thoroughly before using them in any system.

3 Field-of-View and Window Size

The field of view (FOV) of any optical device can be defined as either the half field-of-view (HFOV), where FOV = ±θ, or the full field-of-view (FFOV), where FOV = θ. In this document, the HFOV definition of FOV = ±θ is used. Figure 3-1 shows the relationship between FFOV and HFOV. Figure 3-2 shows a 3D illustration of the sensor on a printed circuit board (PCB) beneath a window.

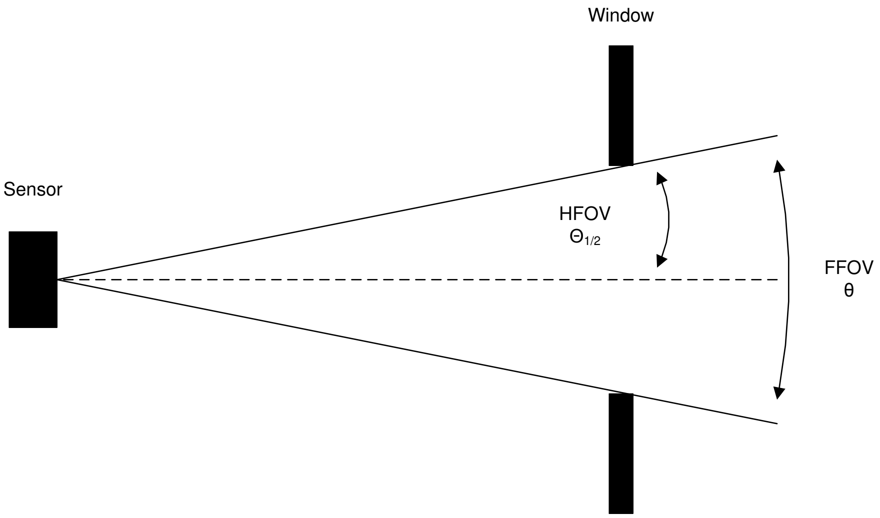


Figure 3-1. Field of View

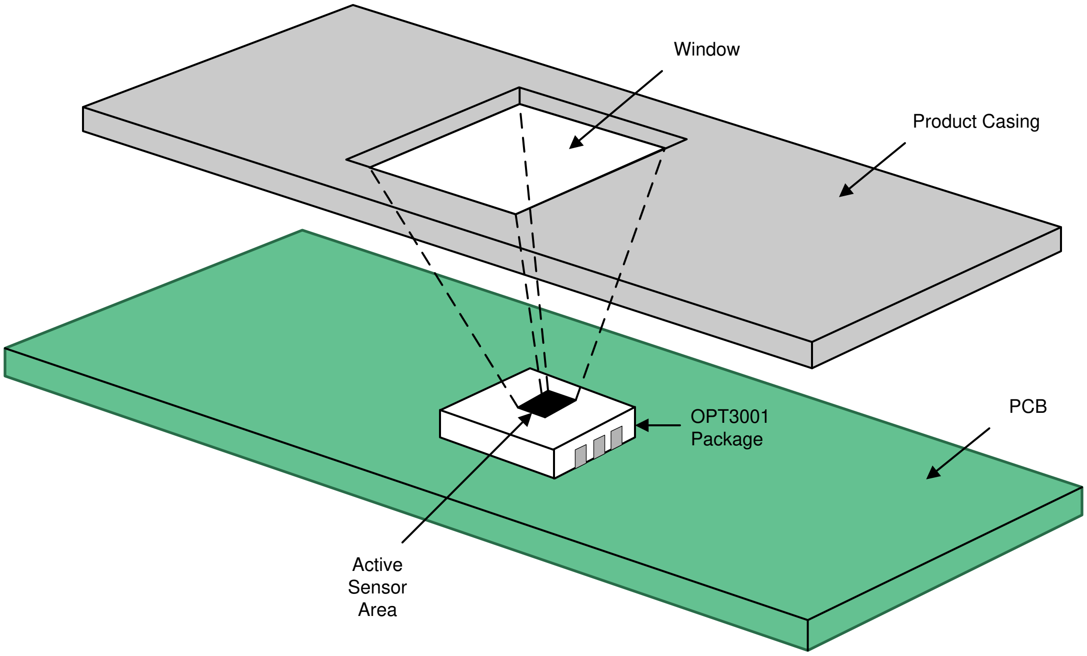


Figure 3-2. 3D Field of View

Defining the FOV of the system is important for many lighting situations. The scene must be properly viewable so that the sensor is able to accurately detect the lighting. The boundary condition for FOV is defined as the viewing angle where 50% or more of the incident light is detected. For example, the OPT3001 has a field-of-view of approximately ±45°, as shown in Figure 3-3.

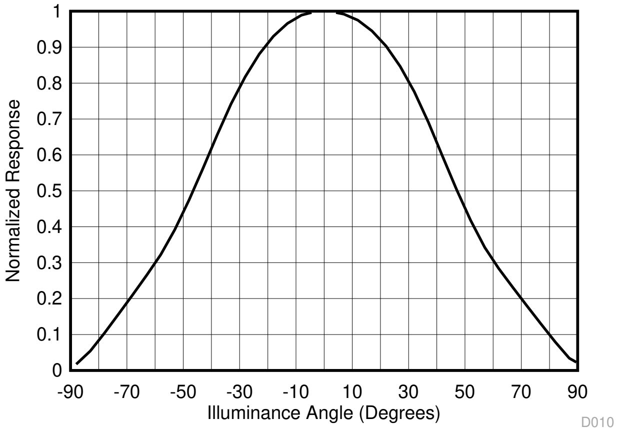


Figure 3-3. OPT3001 Normalized Angular Response

Note the tradeoffs between FOV and performance. A smaller FOV can be used for some targeted applications; however, in most situations, a small FOV cannot survey enough of the scene for an accurate measurement. The angular response curve of an ALS indicates how much signal is expected as a function of the FOV. In most physical designs, a window is placed in front of the sensor, defining the FOV with a strict cutoff. When designing a window opening for the ALS, use the bare sensor's FOV to determine the dimensions of the opening. For example, in the case of the OPT3001, an FOV of ±45° should be used when designing a window. A larger window that increases the FOV past the sensor's effective FOV takes up more space, but only increases the signal slightly. The sensor FOV begins at the edge of the sensor. Consider the total width of the sensor and height above the PCB when calculating FOV and window size. These concepts are illustrated in the following examples.

Note

TI recommends to design for at least a ±35° FOV to ensure optimal performance.

When making calculations for the field of view, consider the refraction (or bending) of light as the light passes through the window. This is described by Snell’s Law, as shown in Equation 4 and Figure 3-4:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{4}$$

where

- n_1 and n_2 are the refractive indices of each material.
- θ_1 and θ_2 are the propagation angles counterclockwise from the surface normal in each material.

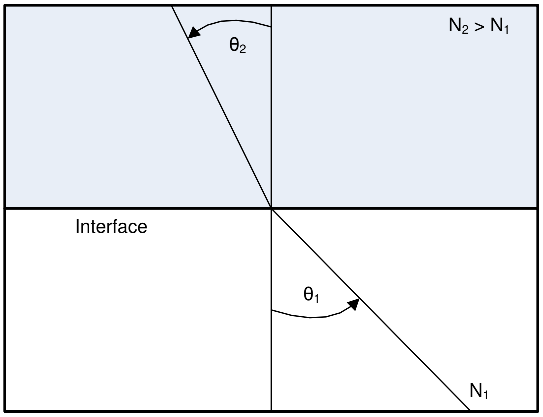


Figure 3-4. Snell's Law

Use the thickness of the window (t) and the angle of incidence (θ_1) to calculate the total width of the window, as shown in Section 3.2.

3.1 Product Casing or Thin Film

There are two commonly-encountered window designs when using an ambient light sensor. A straightforward method implements a window of clear or semitransparent glass or plastic inside the product casing. This method assumes that a glass or plastic window is inserted into an opaque metal or plastic casing that covers the rest of the PCB and circuitry. However, in smartphones and tablets, the entire front surface of the device is typically a single, clear, glass panel with a thin film. This film is printed to the bottom of the glass and completely blocks out anything that must remain unseen. Examples of both types of window designs are described in the following section and are illustrated in Figure 3-5.

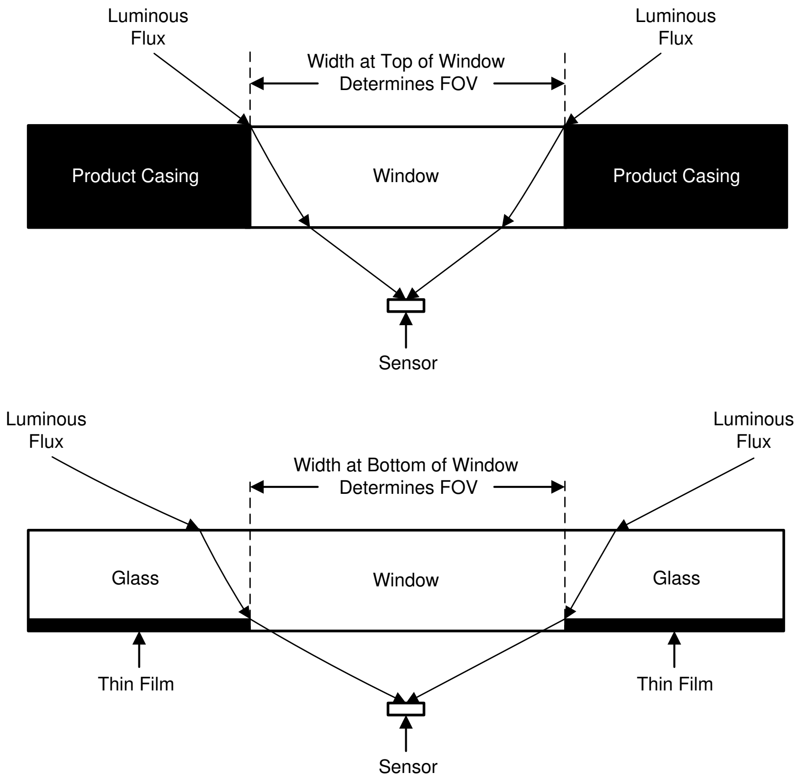


Figure 3-5. Comparison of Window in Product Casing (top) versus Glass Coated with Thin Film (bottom)

3.2 Window Size Calculation Examples

Note

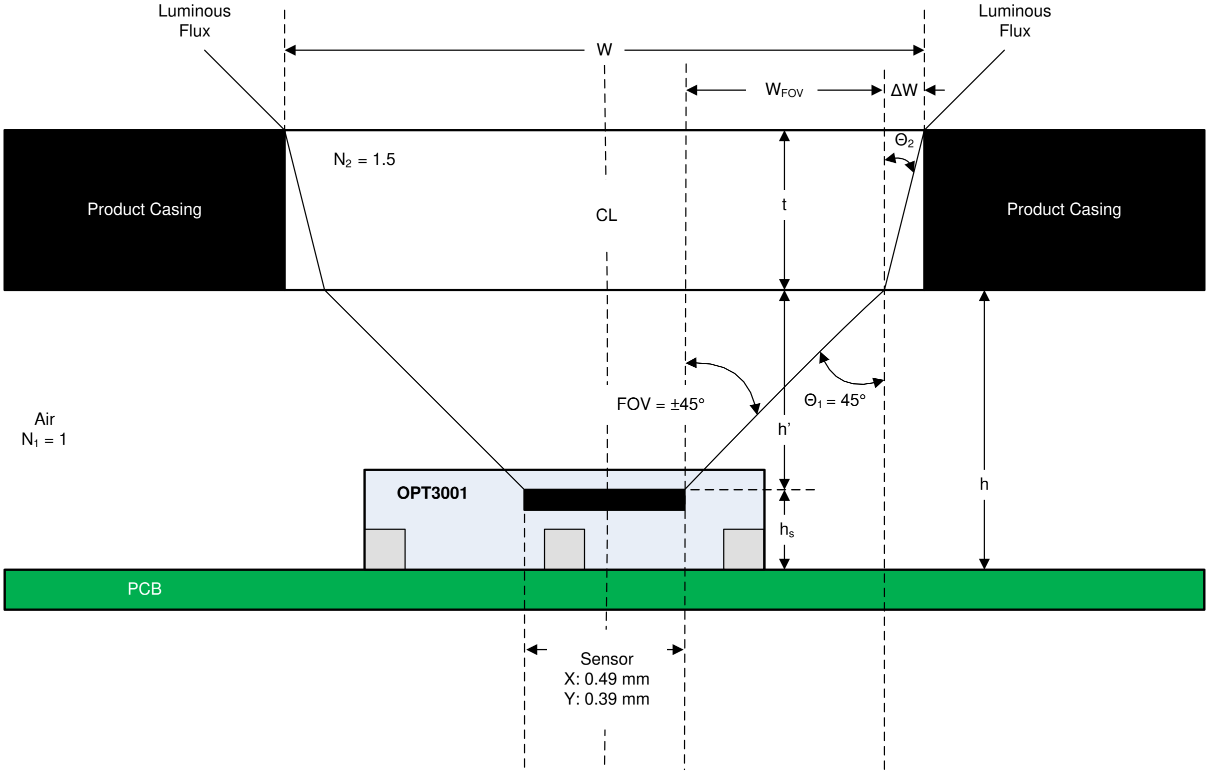
The equations and step-by-step procedures shown in Sections 3.2.1 - 3.2.3 are generic geometric derivations. These calculations can be used for any package type (USON, SOT-5X3, PicoStar™) by accounting for the difference in sensing area size.

3.2.1 Product Casing Window Calculation

This example illustrates a design using a transparent or semitransparent glass or plastic window inserted into a product casing, as shown in Figure 3-6. System-level requirements:

- Desired FOV is ±45°
- Thickness of window (t) is 1 mm
- Height from the PCB to the bottom of the window (h) is 5 mm
- Index of refraction of the window material (N_2) is 1.5

The given values are provided for use in demonstrating the calculations to determine the overall window dimensions. Actual requirements in a real application may differ according to end-product requirements. The width of the OPT3001 sensor area is given as 0.49 mm or 0.39 mm, depending on whether or not the X-dimension or Y-dimension is used. This value is a device parameter and is independent of end-product requirements.



h_s = sensor height above the PCB, typically 0.38 mm (refer to OPT3001 data sheet) h = product casing height above the PCB h' = h – h_s. W = width of window W_{FOV} = window dimension defined by FOV angle and distance from sensor ΔW = window dimension defined by light bending as a function of window refractive index and thickness N_1 = refractive index of material between sensor and bottom of window (presumed to be air) N_2 = refractive index of window material t = glass thickness Sensor X = measurement (in mm) of sensor in the X direction (refer to OPT3001 data sheet) Sensor Y = measurement (in mm) of sensor in the Y direction (refer to OPT3001 data sheet) Θ_1 = angle from surface normal to the incident light ray Θ_2 = angle from surface normal to the incident light ray in material of refractive index N_2 CL = optical centerline passing through the center of the sensor (refer to OPT3001 data sheet for the sensor center to package center offset dimension)

Figure 3-6. Product Casing Design Example with ±45° FOV

This first example determines the total window width (W) based upon the system and device information provided. The OPT3001 has a rectangular active sensor area (0.39 mm × 0.49 mm). Because of this rectangular sensor area, the resulting window shape must also be rectangular to maintain a sensor FOV of ±45° for both X and Y dimensions. Equation 5 describes the relationship between the window width and the system and device requirements and parameters:

$$W = \text{sensorwidth}_{X \text{ or } Y} + 2 \cdot (W_{FOV} + \Delta W) \tag{5}$$

where

- $W_{FOV} = h' \tan(\theta_1)$
- $h' = h - h_S$
- $\theta_1 = \pm FOV°$
- $\Delta W = t \tan(\theta_2)$
- $\theta_2 = \sin^{-1}\left(\frac{N_1 \sin(\theta_1)}{N_2}\right)$

Use the following system-level requirements and OPT3001 device information for the purposes of demonstrating a numerical example:

- $\theta_1 = 45°$
- $h' = 5\text{ mm} - 0.38\text{ mm} = 4.62\text{ mm}$
- $W_{FOV} = 4.62\text{ mm} \cdot \tan(45°) = 4.62\text{ mm}$
- $\theta_2 = \sin^{-1}\left(\frac{1 \cdot \sin(45°)}{1.5}\right) = 28°$
- $\Delta W = 1\text{ mm} \cdot \tan(28°) = 0.532\text{ mm}$

The results are shown in Equation 6 and Equation 7:

$$W_X = 0.49\text{ mm} + 2 \cdot (4.62\text{ mm} + 0.532\text{ mm}) = 10.794\text{ mm} \approx 10.8\text{ mm} \tag{6}$$

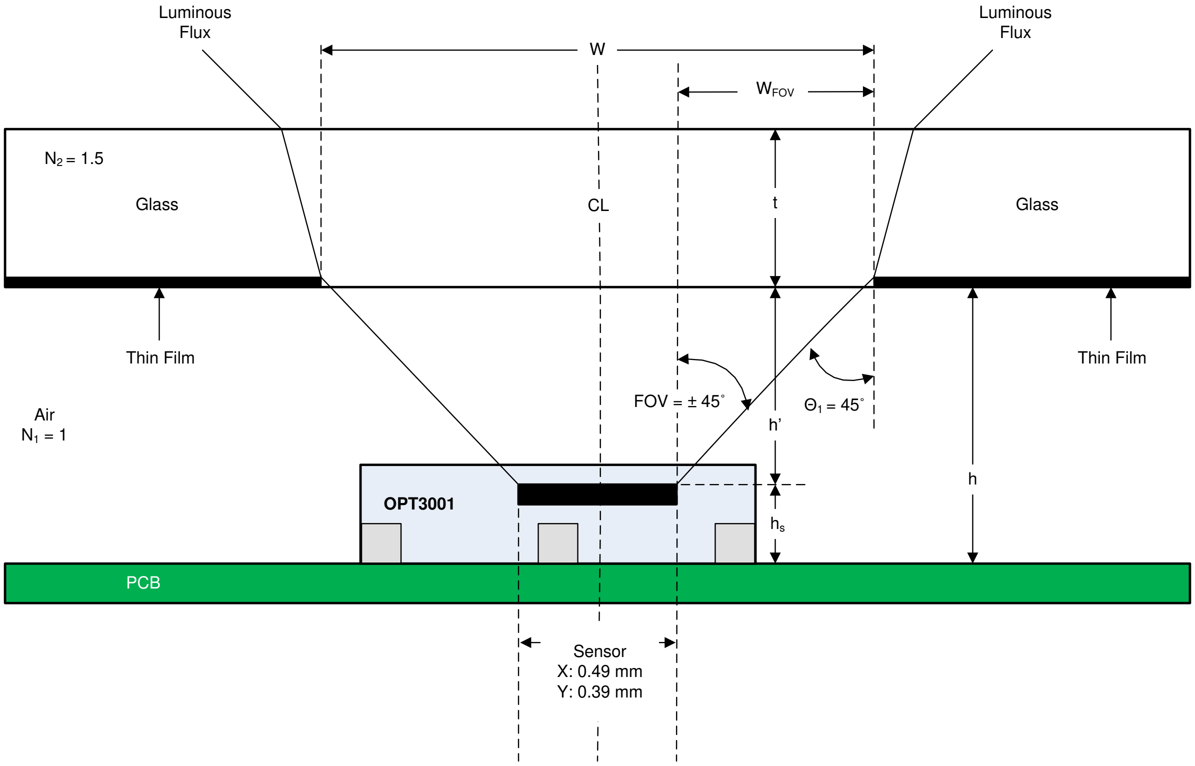
$$W_Y = 0.39\text{ mm} + 2 \cdot (4.62\text{ mm} + 0.532\text{ mm}) = 10.694\text{ mm} \approx 10.7\text{ mm} \tag{7}$$

3.2.2 Thin-Film Window Calculation

In this second example, a design using a transparent sheet of glass to cover the system surface is used, as shown in Figure 3-7. A thin film of ink is applied to the underside of the glass to define the window. System-level requirements for this example:

- Desired FOV is ±45°
- Thickness of window (t) is 1 mm
- Height from the PCB to the bottom of the window (h) is 5 mm
- Index of refraction of the window material (N_2) is 1.5

The given values are provided for use in demonstrating the calculations to determine the overall window dimensions. Actual requirements in a real application may differ according to end-product requirements. The width of the OPT3001 sensor area is given as 0.39 mm or 0.49 mm, depending on whether or not the X-dimension or Y-dimension is used. This value is a device parameter and is independent of end-product requirements.



h_s = sensor height above the PCB, typically 0.38 mm (refer to OPT3001 data sheet) h = thin-film height above the PCB h' = h – h_s W = width of window W_{FOV} = window dimension defined by FOV angle and distance from sensor N_1 = refractive index of material between sensor and bottom of window (presumed to be air) N_2 = refractive index of window material t = glass thickness Sensor X = length of sensor in the X direction (refer to OPT3001 data sheet) Sensor Y = length of sensor in the Y direction (refer to OPT3001 data sheet) Θ_1 = angle from surface normal to the incident light ray CL = optical centerline passing through the center of the sensor (refer to OPT3001 data sheet for the sensor center to package center offset dimension).

Figure 3-7. Thin Film Design Example with ±45° FOV

This second example determines the total window width (W) based upon the system and device information provided. The OPT3001 has a rectangular active sensor area (0.39 mm × 0.49 mm). Because of this rectangular sensor area, the resulting window shape must also be rectangular to maintain a sensor FOV of ±45° for both X and Y dimensions. Equation 8 describes the relationship between the window width and the system and device requirements and parameters:

$$W = \text{sensorwidth}_{X\text{ or }Y} + 2 \bullet W_{FOV} \tag{8}$$

where

- $W_{FOV} = h' \tan(\theta_1)$
- $h' = h - h_S$
- $\theta_1 = \pm FOV°$

Use the following system-level requirements and OPT3001 device information for the purposes of demonstrating a numerical example:

- $\theta_1 = 45°$
- $h' = 5\text{ mm} - 0.38\text{ mm} = 4.62\text{ mm}$
- $W_{FOV} = 4.62\text{ mm} \bullet \tan(45°) = 4.62\text{ mm}$

The results are shown in Equation 9 and Equation 10:

$$W_X = 0.49\text{ mm} + 2 \bullet 4.62\text{ mm} = 9.73\text{ mm} \tag{9}$$

$$W_Y = 0.39\text{ mm} + 2 \bullet 4.62\text{ mm} = 9.63\text{ mm} \tag{10}$$

3.2.3 Circular Window Calculations

The previous subsections described calculations for rectangular windows. However, sometimes for aesthetic or simplistic reasons, a circular window is desired. With a circular window, the radius of the window must be made large enough so that the entire sensor fits inside the circle. When performing this calculation, replace the sensor width (W_X or W_Y) of either 0.39 mm or 0.49 mm with 0.626 mm, the device-related constant value equal to the radius of a circle that encompasses the OPT3001 sensor area, as shown in Figure 3-8. Follow the procedure described in either of the two previous examples, depending upon whether the circular window is defined by a piece of transparent or semi-transparent glass or plastic inserted into an opaque product casing (first example), or if the circular window is defined by a layer of thin film or ink applied to the underside of a sheet of transparent glass (second example).

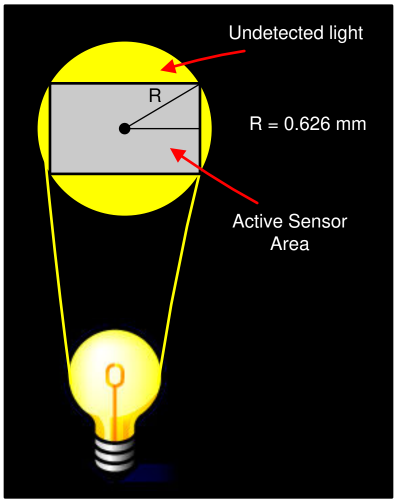


Figure 3-8. Circular Window

3.2.4 FOV Considerations For PicoStar™ Package

In the PicoStar™package, the photosensitive region is located on the bottom side of the die, on the same surface as the solder pads. As a result, light can only reach the sensing area through an opening in the FPCB. The geometry of this cutout - its shape, dimensions, and placement - acts as an additional aperture that limits the sensor's effective FOV. As shown in the figure below, light entering the FPCB opening can be blocked by the edges of the FPCB, causing shadowing and reducing the effective field of view.

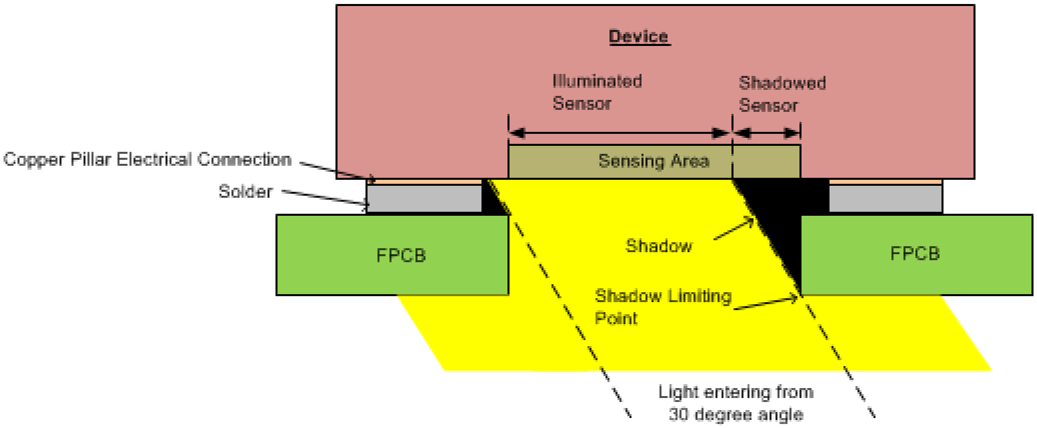


Figure 3-9. Cross-Sectional Diagram of PicoStar™ Device Soldered to an FPCB With a Cutout, Including Light Entering From an Angle

To maximize optical performance, the FPCB cutout size should be made as large as possible within the constraints of the PCB layout. The upper bound on cutout size is typically determined by the manufacturing capabilities of the FPCB fabrication and assembly vendor, as well as the required clearance between the cutout edge and the solder pads. This clearance can be very small, and consultation with the FPCB vendor is recommended to determine the minimum achievable value.

All PicoStar™ devices with the exception of the OPT3006 have a 4-pin design. For these devices, the diagonal distance between the pads is >800µm, which enables a cutout with a very large field of view (>50°) with a simple circular cutout. Using a plus-shaped cutout maximizes the field of view even further in the directions where the pads do not restrict the opening size enabling best optical performance. Example dimensions for both the circular and plus-shaped openings are provided in the figure below.

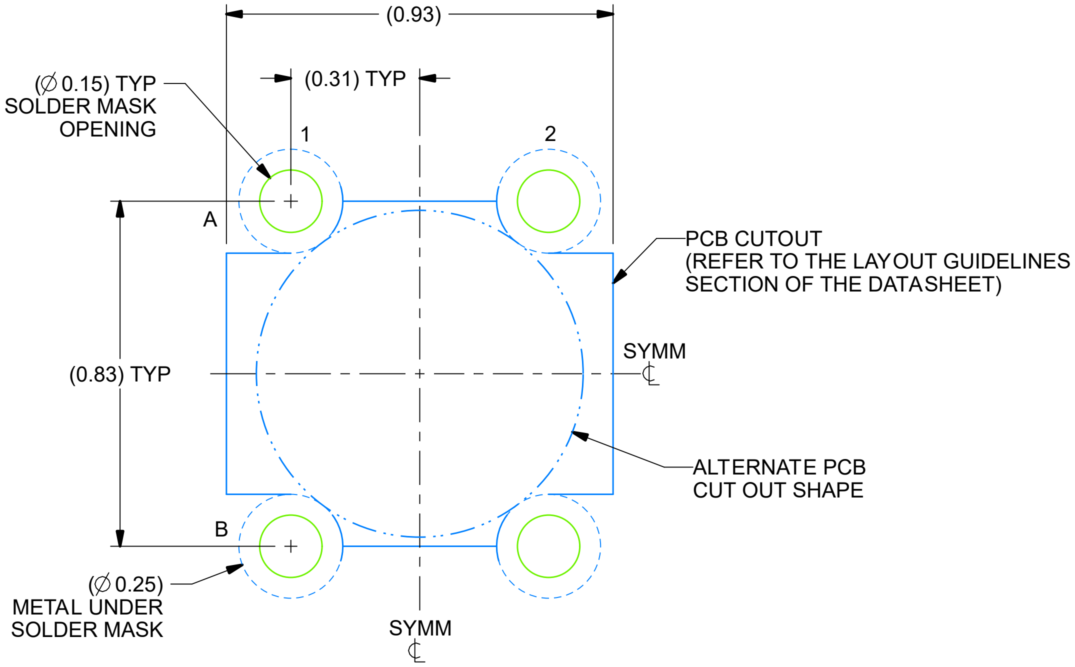


Figure 3-10. Flex PCB Cutout Recommendations

For 6-pin PicoStar™devices like the OPT3006, the cutout options are limited due to the restrictions imposed by the two center pads. In this case, it is recommended to expand the opening on the axis that is not restricted. A rectangular cutout can enable the largest field of view in one direction similar to the plus cutout, but can restrict the field of view in the opposing direction. Examples of FPCB layout and cutout shapes for the plus and rectangular cases are shown in the following figures.

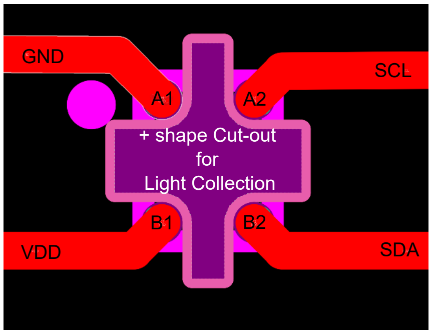


Figure 3-11. Layout Example With a Plus Shaped Cut Out

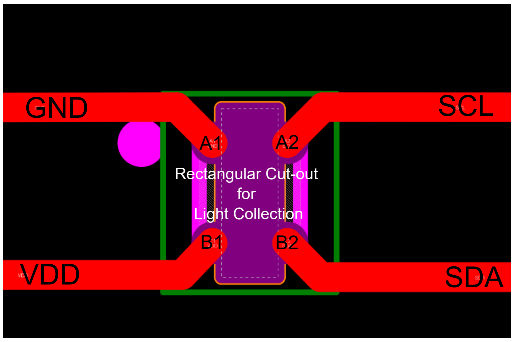


Figure 3-12. Layout Example With a Rectangular Shaped Cut Out

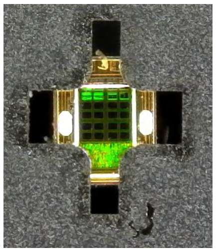


Figure 3-13. Image of FPCB With Device Mounted, Receiving Light Through the Cutout with a Plus Shape

Figure 3-14. Image of FPCB With Device Mounted, Receiving Light Through the Cutout with a Rectangular Shape

Table 3-1 summarizes the recommended FPCB cutout shapes for each PicoStar™ device.

Table 3-1. PicoStar™ FPCB Cutouts

Cutout Shape	Supported Devices	Design Considerations
Circular	OPT4001, OPT4001-Q1, OPT3007	Low complexity and large FOV
Plus-Shaped	OPT4001, OPT4001-Q1, OPT3007	High complexity but maximizes FOV on all axes
Rectangular	OPT3006	Low complexity but can only provide a large FOV on one axis due to center pad restrictions

4 Outdoor Use

The use of ambient light sensors for outdoor purposes is increasing, and exposure to direct sunlight creates a new set of design constraints. This section helps designers using any OPT series sensor solve problems caused by constant exposure to direct sunlight.

4.1 Infrared Compensation

Many ambient light sensors are placed behind a translucent piece of glass so the device cannot be seen without close examination. Translucent glass prevents most of the light from within the visible spectrum from reaching the sensor, but often does very little to prevent infrared (IR) wavelengths from transmitting to the sensor. This placement can create issues with the use of an ALS if the sensor is sensitive to IR wavelengths because they reach the sensor with a disproportionally high energy relative to visible light. With the exceptional IR rejection of the OPT series ambient light sensors, a window that allows IR transmission does not have any adverse effects. Thus, do not add any infrared blocking filters to the window design when using an OPT device.

5 Ultraviolet Compensation

On the other side of the visible spectrum, ultraviolet (UV) wavelengths can be harmful to the device performance in different ways. While most semiconductors are not responsive to UV light, high-energy UV waves can cause damage to the device packaging over time. While this problem is specific for parts that are left outdoors for months or years at a time, small amounts of exposure have negligible effects. Combating this natural degradation of the materials used in the product packaging and die is crucial. One method to mitigate this problem is to place the ALS behind an acrylic window. Standard acrylic polymethylmethacrylate (PMMA) does not transmit any light with a wavelength below 300 nm to 350 nm, a range that is near the natural cutoff for the human eye. Therefore, the presence of PMMA does not prevent visible light from reaching the sensor. When using a acrylic such as PMMA to fix this problem, a question arises about whether or not PMMA suffers from the same degradation as the original package. PMMA is manufactured to prevent degradation from exposure to UV light (for example, becoming yellow or opaque over time), while still absorbing a large percentage of the UV. There are many applications that use PMMA for outdoor uses, and PMMA durability has been proven over time. These aging properties are exclusive to the PMMA variation of acrylic and not to many of the other common variations, such as styrene, PETG (polyethylene terephthalate glycol), or polycarbonate. An example of such a material recommended for use in outdoor applications is ACRYLITE® OP2, a UV filtering acrylic sheet.

A Definitions of Lux and other Radiometric Quantities

In optics, the measurement and manipulation of power transfer is called radiometry. Radiometry is a broad way of measuring power transfer. Radiometry encompasses the entire electromagnetic spectrum and does not account for any realistic limits in measurement. Photometry on the other hand, only indicates the amount of light within the visible spectrum. The units between radiometry and photometry are related. The key difference is that photometric quantities are all scaled according to the photopic curve (as shown in Figure A-1) with a range that closely matches the spectral response of the human eye. Thus, any light with a wavelength outside the visible spectrum has no photometric power, but does have radiometric power.

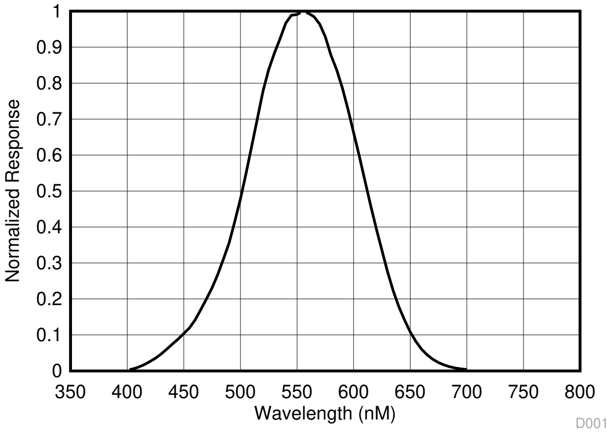


Figure A-1. Photopic Luminous Efficiency

The units associated with standard radiometric and photometric quantities are shown in Table A-1. The similarities can easily be seen, with the watt and the lumen being the base unit of power for each measurement, respectively. While many of these units of measurement look very similar, having the same units in some cases, they each represent a unique aspect of the power of an optical system. A lumen (lm) is the scaled version of a watt with respect to the photopic curve. In photometry, the most commonly-used unit is the lux (1 lx = 1 lm / m^2) because it describes the amount of power per unit area. This value is useful when looking at the total amount of energy in a given system. Radiometric terms are described as *radiant* quantities, whereas the corresponding photometric terms are described as *luminous* quantities.

Table A-1. Radiometric and Photometric Terms

Radiometric Quantity	Symbol	Definition	Unit		Photometric Quantity	Symbol	Definition	Unit
Radiant energy	Q	$\int \Phi \, dt$	J		Luminous energy	Q_v	$\int \Phi_v \, dt$	lm*s
Radiant energy density	U	dQ/dV	J/m^3		Luminous energy density	U_v	$(dQ_v)/dV$	(lm*s)/m^3
Radiant flux	Φ	dQ/dt	W		Luminous flux	Φ_v	$(dQ_v)/dt$	lm
Radiant exitance	M	dΦ/dA	W/m^2		Luminous exitance	M_v	$(d\Phi_v)/dA$	lm/m^2
Irradiance	E	dΦ/dA	W/m^2		Illuminance	E_v	$(d\Phi_v)/dA$	lm/m^2
Radiance	L	$(d^2 \Phi)/dAd\Omega$	W/(m^2 sr)		Luminance	L_v	$(d^2 \Phi_v)/dAd\Omega$	lm/(m^2 sr)
Radiant intensity	I	dΦ/dΩ	W/sr		Luminous intensity	I_v	$(d\Phi_v)/d\Omega$	lm/sr

B Glossary of Terms

n: Refractive Index	The ratio of the speed of light in a vacuum to the speed of light in a material. $n > 1$ for all materials.
θ_1: Incident Ray Angle	The angle at which a light ray first interacts with a surface. It is measured counterclockwise from the surface normal.
θ_2: Refracted Ray Angle	The angle at which a light ray travels after interacting with a surface. This angle is smaller, or closer to the surface normal, than the incident ray angle as long as $n_1 < n_2$. If $n_1 > n_2$, then the refracted ray angle is larger than the incident ray angle.
FOV: Field of View	Defined as either a Half FOV(±θ) or a Full FOV(θ). The outermost point of a scene that can be detected at the output of an optical system.
ω: Solid Angle	The ratio of the subtended area on the surface of a sphere and the square of the radius of that sphere. The area on the surface of the sphere is contained within a defined angular range.
Ω: Projected Solid Angle	The solid angle projected onto the plane of the observer. This is essentially a projection of the area from the surface of a hemisphere on to the base plane of the hemisphere.
V(λ): Photopic Curve	The standard approximation for the spectral response of the human eye.
Q: Radiant Energy	The total amount of energy passing through a system.
Q_v: Luminous Energy	The total amount of energy, derived from the luminous flux, passing through an optical system.
U: Radiant Energy Density	The total amount of energy that is present in an optical system within a defined volume in 3D space.
U_v: Luminous Energy Density	The total amount of energy, derived from the luminous flux, that is present in an optical system within a defined volume in 3D space.
Φ: Radiant Flux	The total amount of power that is present within an optical system.
Φ_v: Luminous Flux	The total amount of power, scaled to the photopic curve, that is present within an optical system.
M: Radiant Exitance	The amount of power per unit area that is leaving a defined surface.
M_v: Luminous Exitance	The amount of power, scaled to the photopic curve, per unit area that is leaving a defined surface.
E: Irradiance	The amount of power per unit area that is incident on a defined surface.
E_v: Illuminance	The amount of power, scaled to the photopic curve, per unit area that is incident on a defined surface.
L: Radiance	The amount of power per unit area and per unit projected solid angle leaving a defined surface. Radiance is conserved along any single ray traveling through an optical system.
L_v: Luminance	The amount of power, scaled to the photopic curve, per unit area and per unit projected solid angle leaving a defined surface. Luminance is conserved along any ray traveling through an optical system.
I: Radiant Intensity	The amount of power per unit solid angle.
I_v: Luminous Intensity	The amount of power, scaled to the photopic curve, per unit solid angle.

8 Revision History

Changes from , to , (from Revision A (September 2017) to Revision B (June 2026)) **Page**

- Updated all references to OPT3001 3
- Added Table 2-1 4
- Updated *Choosing the Dark Window* section 5
- Updated Lux-Meter Based Approach section 6
- Added Section 3.2.4 16

Changes from Revision * (October 2014) to Revision A (September 2017) **Page**

- Updated *Choosing the Dark Window* section 5
- Updated Lux-Meter Based Approach section 6

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