Application Report

SBEA002A–October 2014–Revised September 2017

OPT3001: Ambient Light Sensor Application Guide

ABSTRACT

Electronic devices that use light sensors are becoming much more prevalent. Devices ranging from outdoor lighting to display backlighting use a light sensor to alter lighting conditions, or lighting control based on the ambient lighting of the scene. The OPT3001 is an ambient light sensor (ALS) that is designed to have a similar spectral response to that of the human eye. This application report describes how to integrate the OPT3001 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

If the OPT3001 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. It is also important that the OPT3001 active sensor area is rectangular in shape (0.39 mm × 0.49 mm) and is offset in one direction. When placing the OPT3001 behind an optical window, the active sensor area, and not the entire package, is centered with respect to the window (or opening). See OPT3001 data sheet for complete mechanical dimensions.

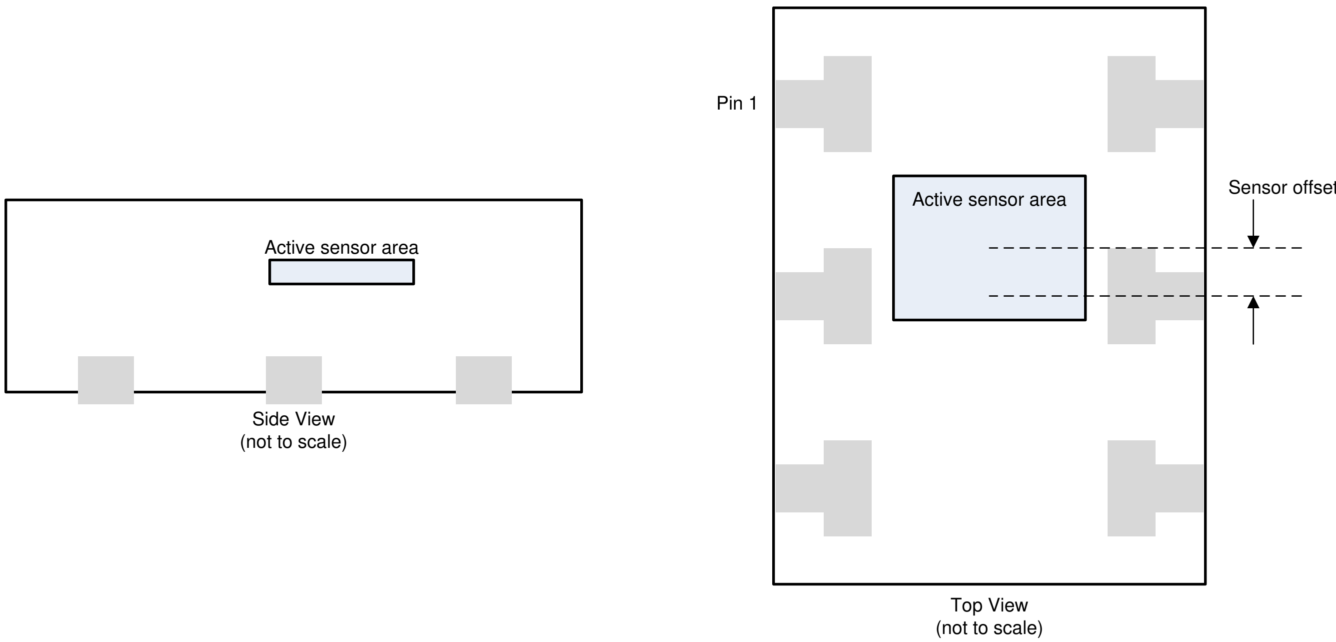


Figure 1. OPT3001 Sensor Position

2.1 Attenuation Compensation

In many applications, seeing the ALS is not optimal. 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.

The window chosen for this application example is dark, and has less than 7% transmission at 550 nm.

Figure 2 shows the normalized response of the spectrum.

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.

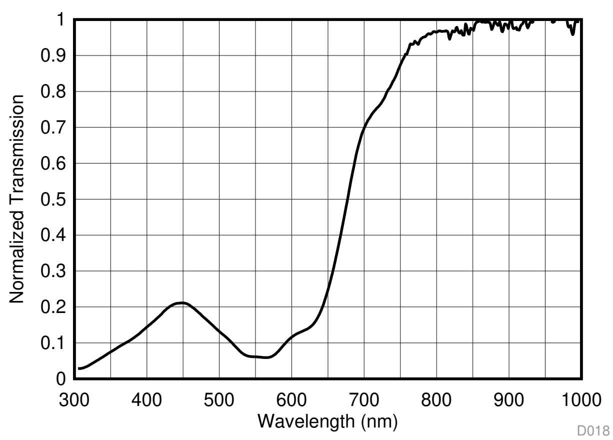


Figure 2. Normalized Transmission Spectral Response of the Chosen Dark Window

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 OPT3001 still performs well, see Figure 3 for the output performance.

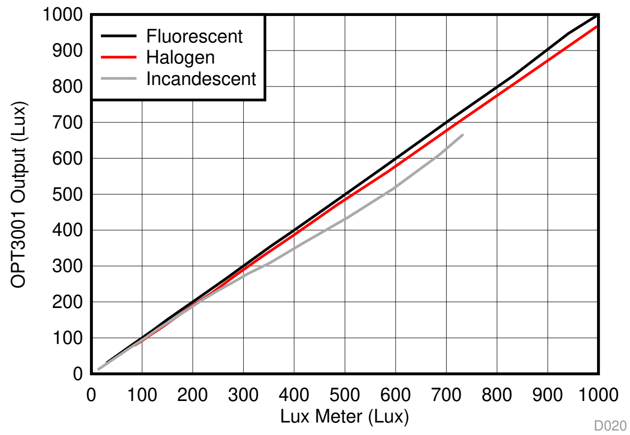


Figure 3. Compensated Output of the OPT3001 Under a Dark Window Illuminated by Fluorescent, Halogen, and Incandescent Light Sources

The next step is to measure this attenuation factor. There are several methods to find this attenuation factor. The following sections outline two of them.

In the first method, there is no requirement for any additional equipment. This method is referred as the OPT3001-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 OPT3001-Only Based Approach

1. Place a light source that uniformly illuminates the OPT3001 with no window or glass to attenuate the light transmission.
2. Read the OPT3001 output, and note the result as $OPT3001_{AIR}$.
3. Using the same light source on the OPT3001, place a glass window in front of the sensor and maintain the same sensor position relative to the light source.
4. Read the OPT3001 output, and note the result as $OPT3001_{GLASS}$.
5. Calculate the visible attenuation factor, as shown in Equation 1:

$$\text{Visible Attenuation Factor} = \frac{OPT3001_{AIR}}{OPT3001_{GLASS}} \quad (1)$$

During normal system operation when the OPT3001 is placed behind the optical window, use this visible attenuation factor to determine the calibrated lux of the scene by using Equation 2:

$$\text{Calibrated}_{\text{Output}} = \text{Measured}_{\text{Output}} \bullet \text{Visible Attenuation Factor} \quad (2)$$

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 OPT3001 under the dark window. To measure accurately, use a fixture that can accommodate either the lux meter or the design containing the OPT3001 and dark window, with the center of each of the sensing areas being in exactly the same X, Y, Z location; see Figure 4. The Z placement of the design (distance from the light source) is the top of the window, and not the OPT3001 itself.

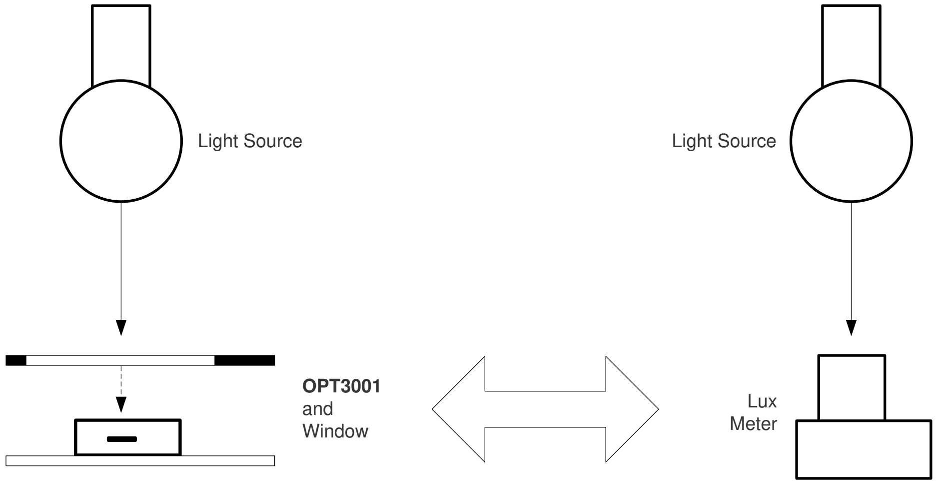


Figure 4. Fixture With One Light Source Accommodating Either a Lux Meter or the Design (Window and OPT3001) in the Exact Same X,Y,Z Position

The fluorescent light in this location measures 1000 lux with the lux meter, and 73 lux with the OPT3001 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 OPT3001 measurements under this dark window, the following formula is applied.

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

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 = $\pm\theta$, or the full field-of-view (FFOV), where FOV = θ. In this document, the HFOV definition of FOV = $\pm\theta$ is used. Figure 5 shows the relationship between FFOV and HFOV. Figure 6 shows a 3D illustration of the sensor on a printed circuit board (PCB) beneath a window.

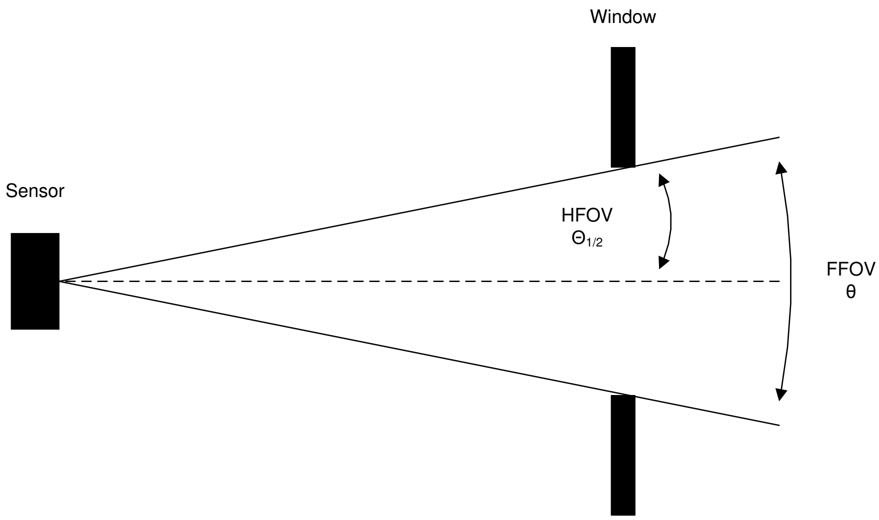


Figure 5. Field of View

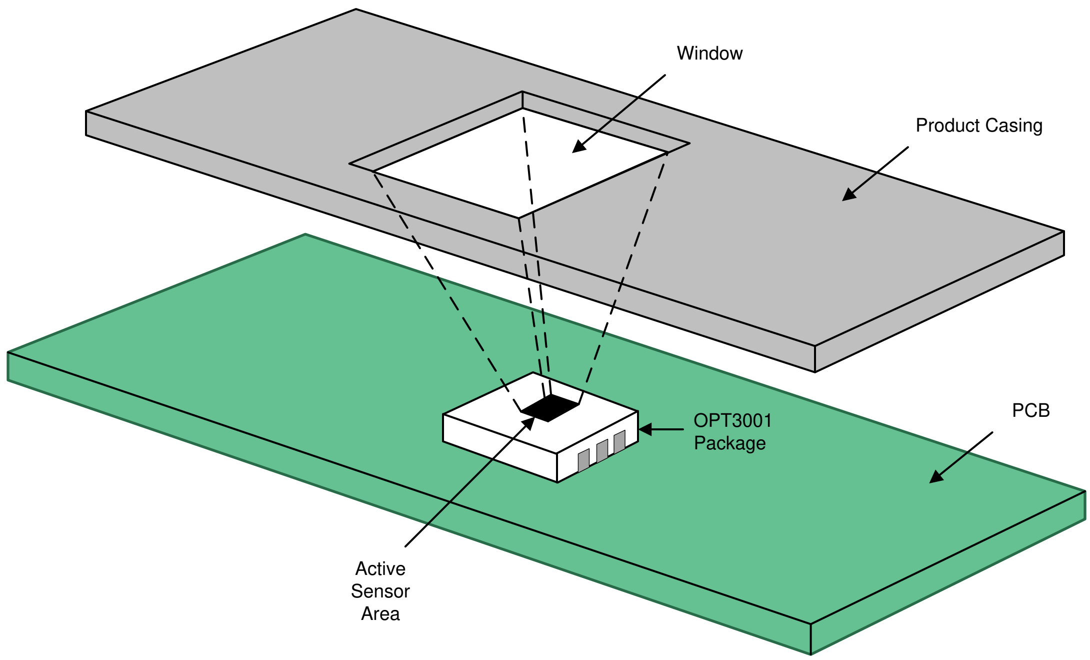


Figure 6. 3D Field of View

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. The OPT3001 has a field-of-view of approximately ±45°, as shown in Figure 7.

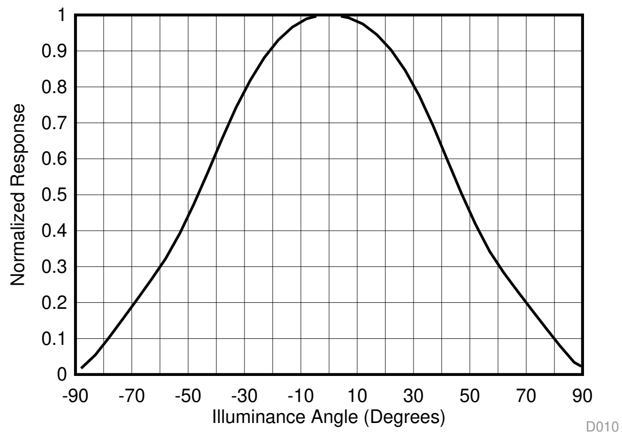


Figure 7. OPT3001 Normalized Angular Response

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 the OPT3001 indicates how much signal is expected as a function of the FOV. In most physical designs, a window is placed in front of the OPT3001, defining the FOV with a strict cutoff. Use an FOV of ±45° when designing a window. A larger window that increases the FOV past ±45° 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.

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 8:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

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. (4)

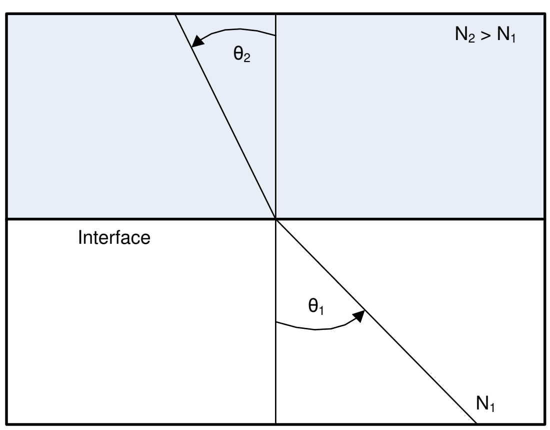


Figure 8. Snell's Law

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 9.

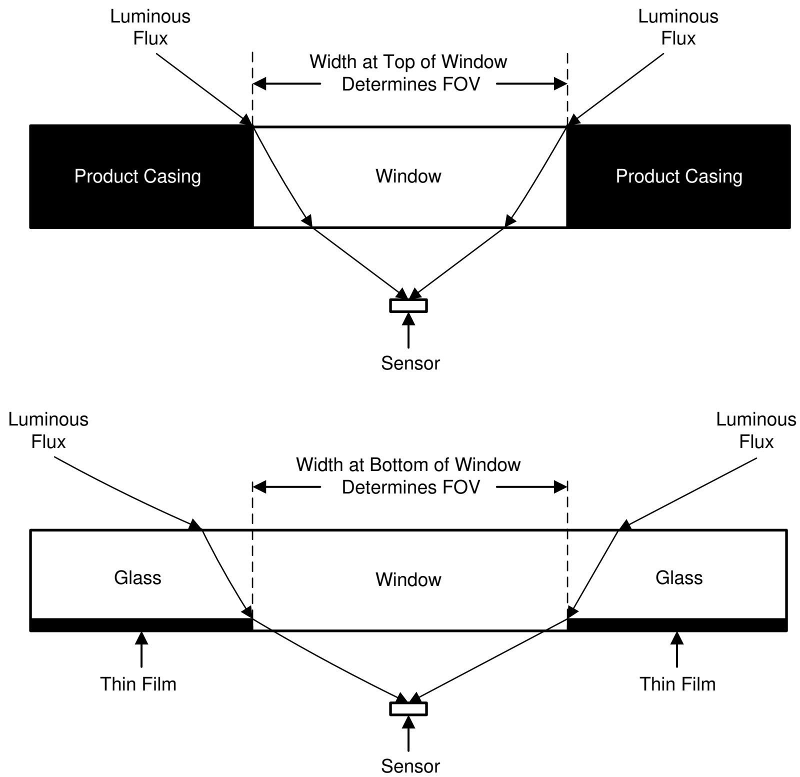


Figure 9. Comparison of Window in Product Casing (top) versus Glass Coated with Thin Film (bottom)

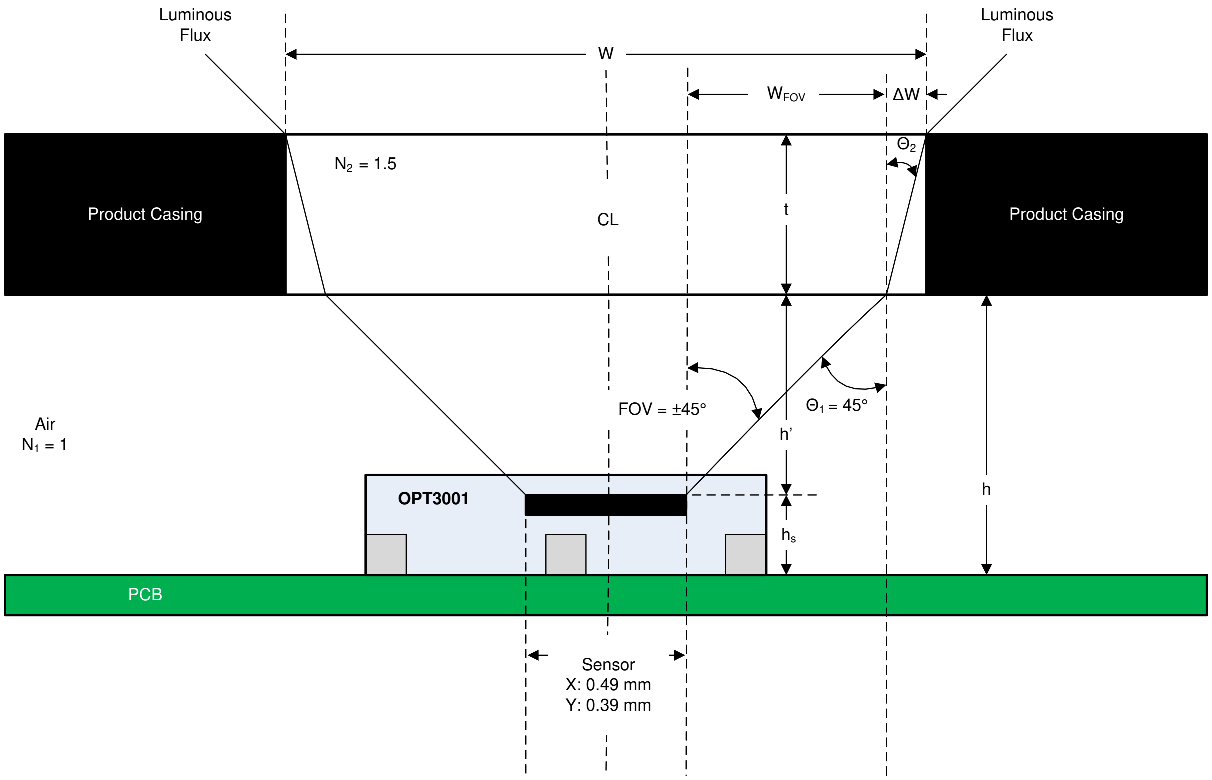
3.2 Window Size Calculation Examples

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 10. 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.



NOTE: 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 10. Product Casing Design Example with ±45º 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:

$$W = \text{sensorwidth}_{X\text{ or }Y} + 2 \bullet \left(W_{FOV} + \Delta W\right)$$

where

- $W_{FOV} = h' \tan\left(\theta_1\right)$
- $h' = h - h_S$
- $\theta_1 = \pm FOV°$
- $\Delta W = t \tan\left(\theta_2\right)$
- $\theta_2 = \sin^{-1}\left(\dfrac{N_1 \sin\left(\theta_1\right)}{N_2}\right)$ (5)

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

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

The results are shown in Equation 6 and Equation 7:

$$W_X = 0.49\text{ mm} + 2 \bullet \left(4.62\text{ mm} + 0.532\text{ mm}\right) = 10.794\text{ mm} \approx 10.8\text{ mm} \quad (6)$$

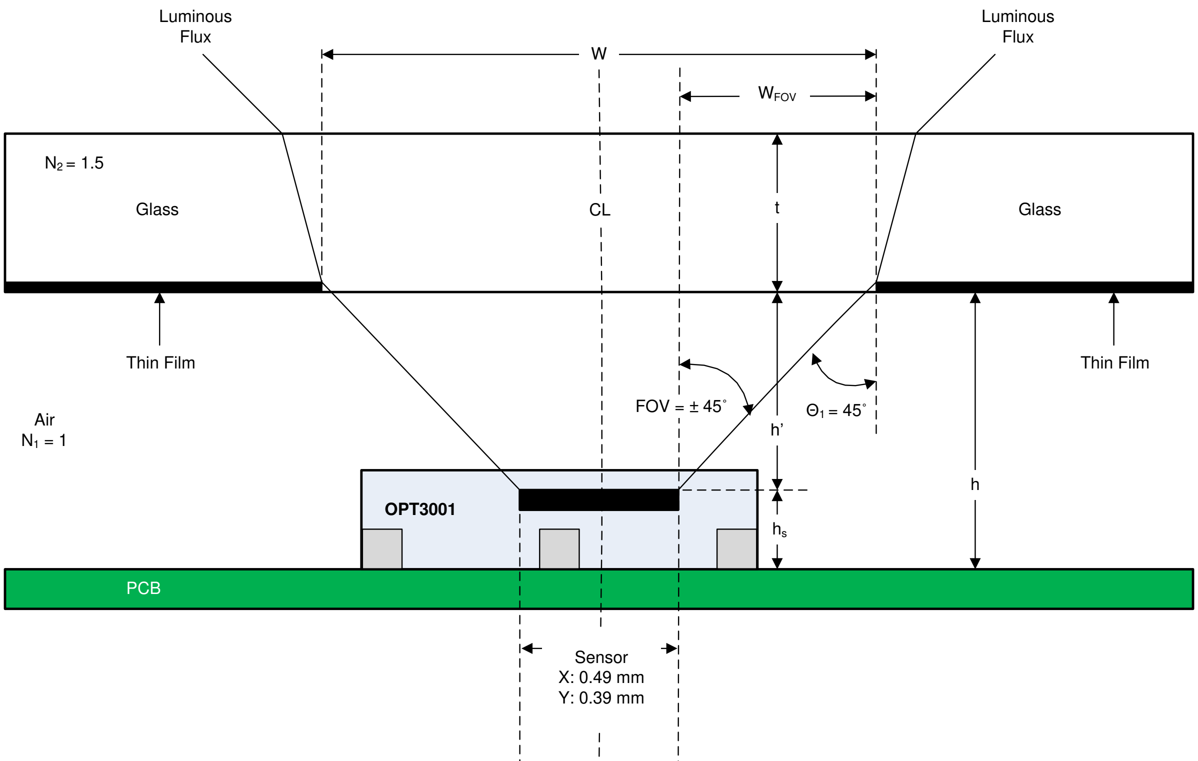
$$W_Y = 0.39\text{ mm} + 2 \bullet \left(4.62\text{ mm} + 0.532\text{ mm}\right) = 10.694\text{ mm} \approx 10.7\text{ mm} \quad (7)$$

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 11. 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.



NOTE: 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 11. Thin Film Design Example with ±45º 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:

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

where

- $W_{FOV} = h' \tan(\theta_1)$
- $h' = h - h_S$
- $\theta_1 = \pm FOV°$ (8)

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:

$$W_X = 0.49\text{ mm} + 2 \bullet 4.62\text{ mm} = 9.73\text{ mm} \quad (9)$$

$$W_Y = 0.39\text{ mm} + 2 \bullet 4.62\text{ mm} = 9.63\text{ mm} \quad (10)$$

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 12. 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).

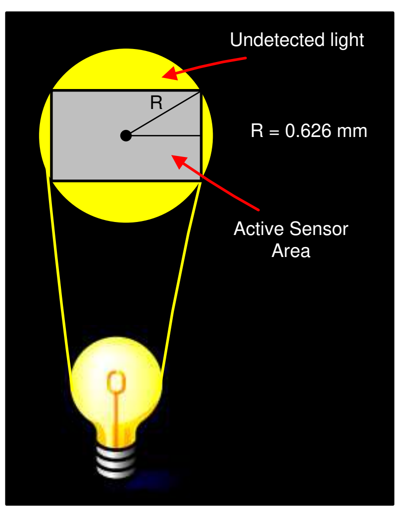


Figure 12. Circular Window

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 the OPT3001 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 OPT3001, 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 the OPT3001.

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 OPT3001 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.

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 13) 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.

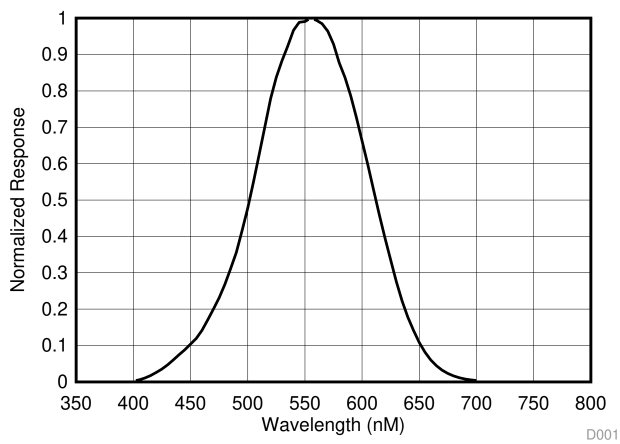


Figure 13. Photopic Luminous Efficiency

The units associated with standard radiometric and photometric quantities are shown in Table 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 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	$d\Phi/dA$	W/m^2		Luminous exitance	M_v	$(d\Phi_v)/dA$	lm/m^2
Irradiance	E	$d\Phi/dA$	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	$(d^2\ \Phi_v)/dAd\Omega$	$lm/(m^2\ sr)$

Table 1. Radiometric and Photometric Terms (continued)

Radiometric Quantity	Symbol	Definition	Unit		Photometric Quantity	Symbol	Definition	Unit
Radiant intensity	I	$d\Phi/d\Omega$	W/sr		Luminous intensity	I_v	$(d\Phi_v)/d\Omega$	lm/sr

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($\pm\theta$) 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.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (October 2014) to A Revision	Page
• Updated Choosing the Dark Window section.	4
• Updated Lux-Meter Based Approach section.	5