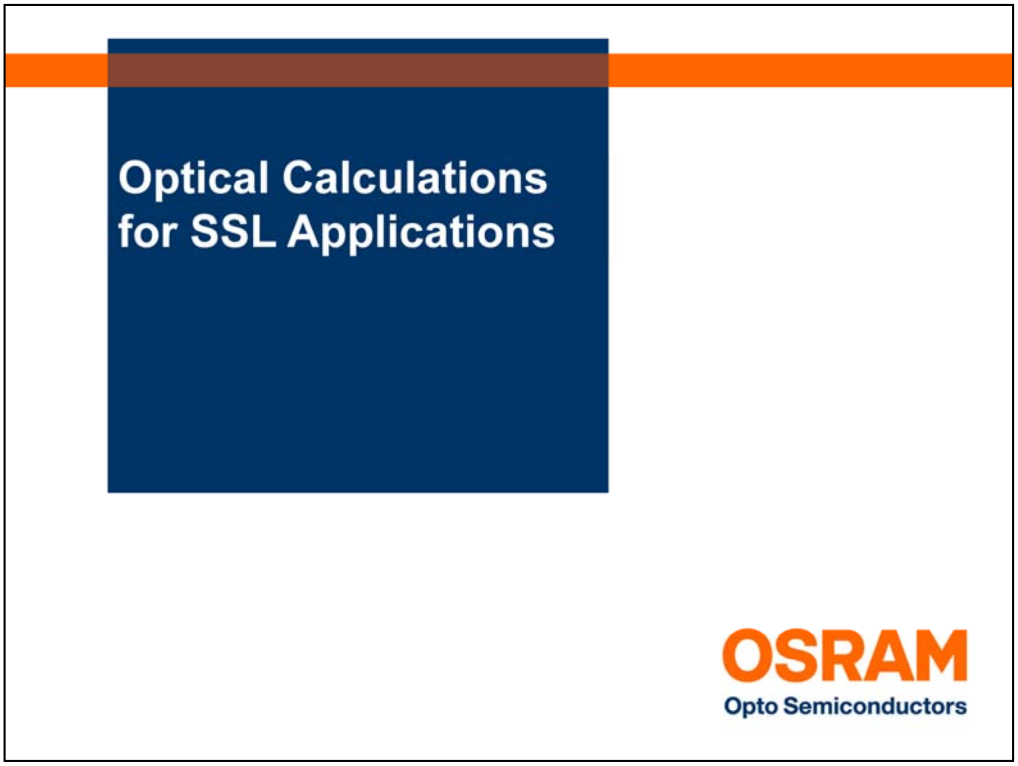
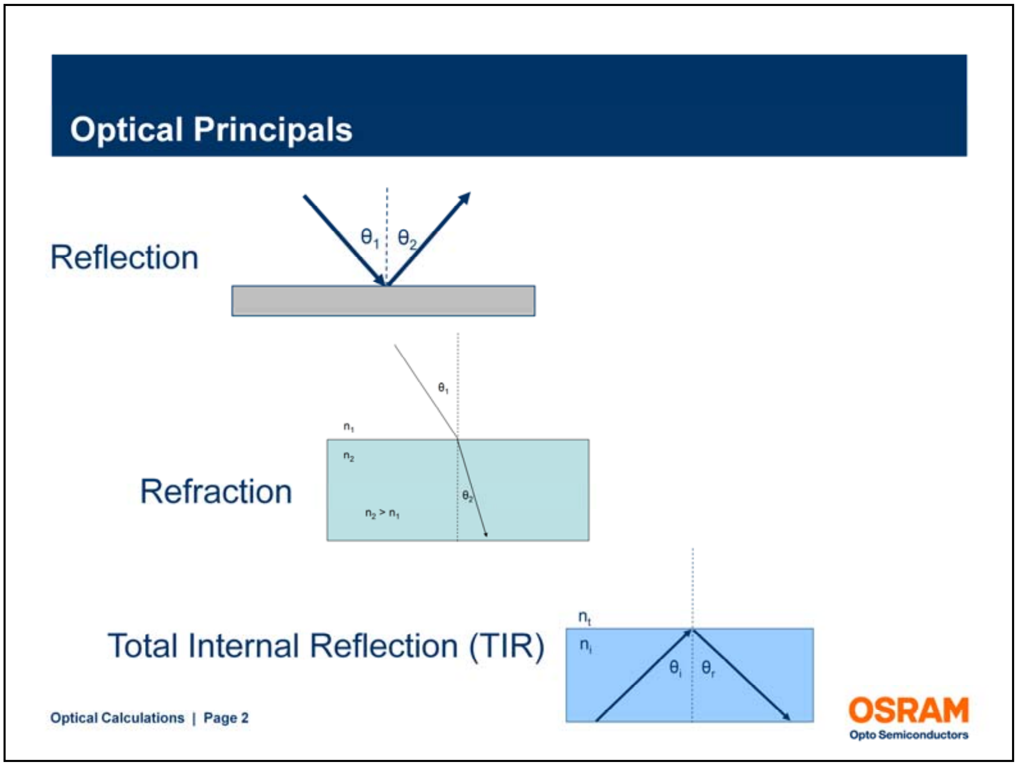
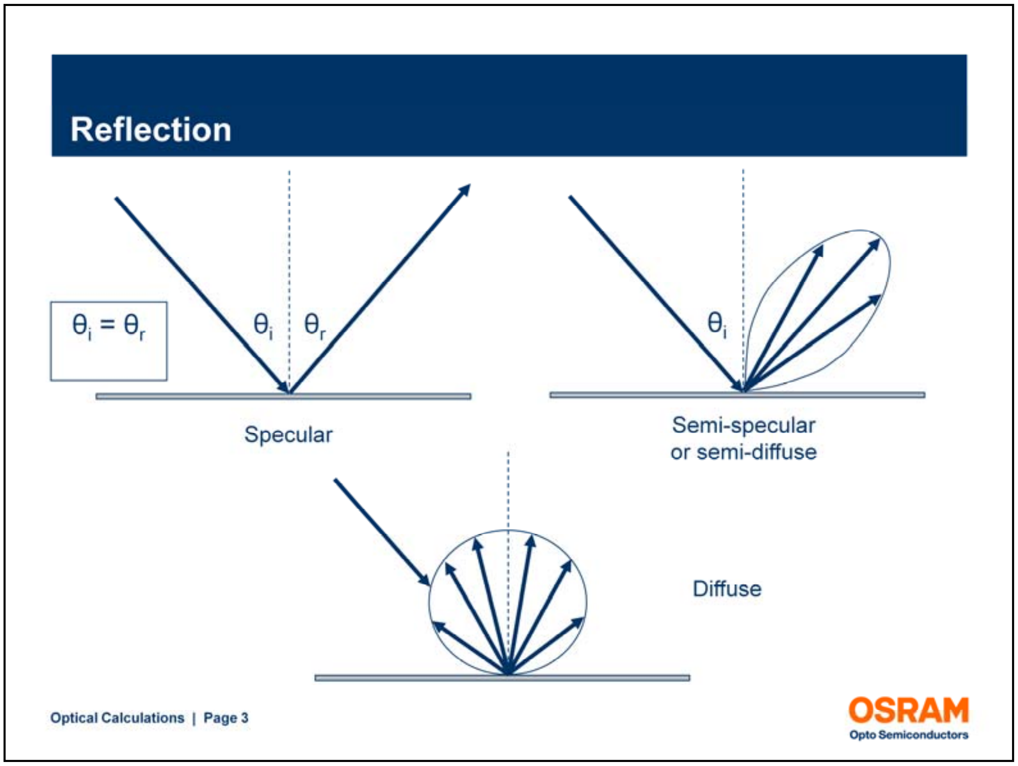


Welcome to this presentation on Optical Calculations for SSL Applications by OSRAM Opto Semiconductors.

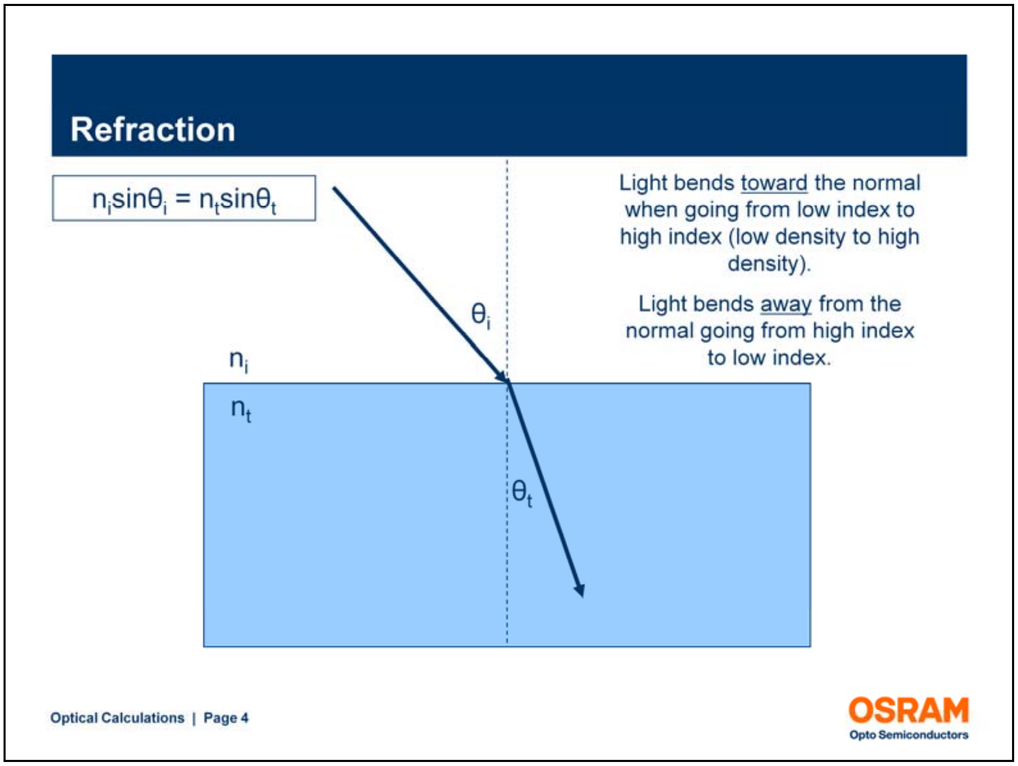


A basic understanding of the underlying optical principals is important. The important principals for solid state lighting applications are reflection, refraction, and total internal reflection. These are the basis for all the calculations that follow.

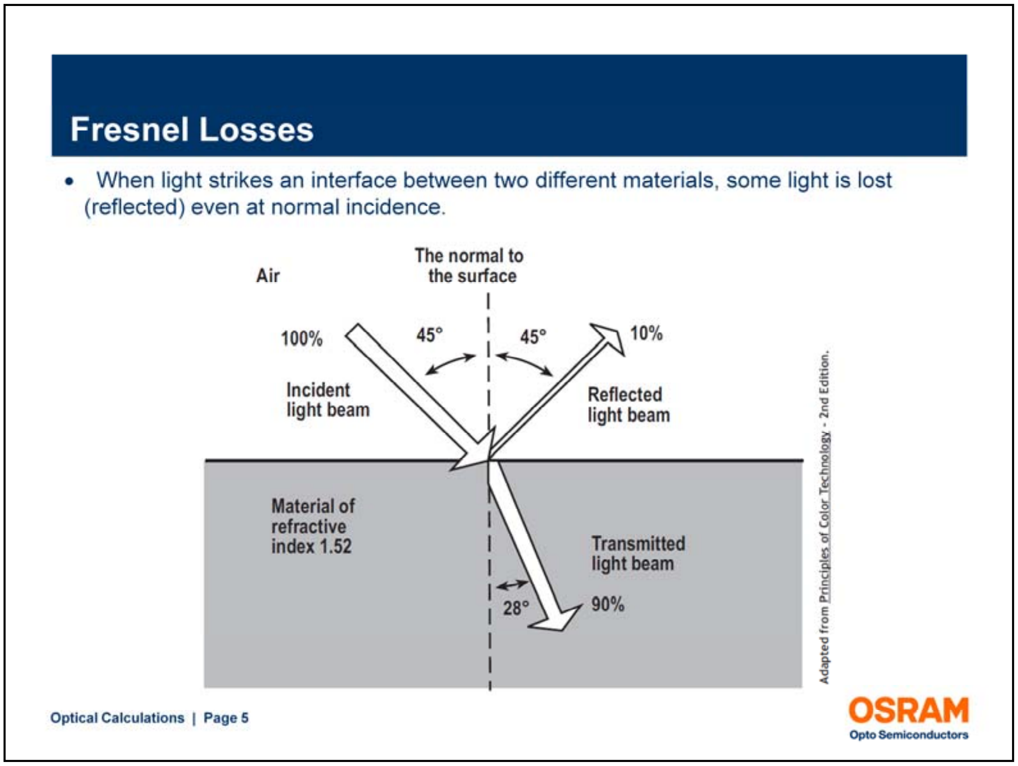


Consider a light ray striking a mirrored surface. The angle of the light ray with respect to the surface normal is theta I and is called the “angle of incidence”. The Law of Reflection states that the angle of incidence is equal to the angle of reflection. This also the definition of a “specular” reflection. For a surface with some roughness, some of the light will reflect in the specular direction and some will be reflected in other directions. This can be called “semi-specular” or “semi-diffuse” reflection. A “diffuse” reflection sends light in all directions.

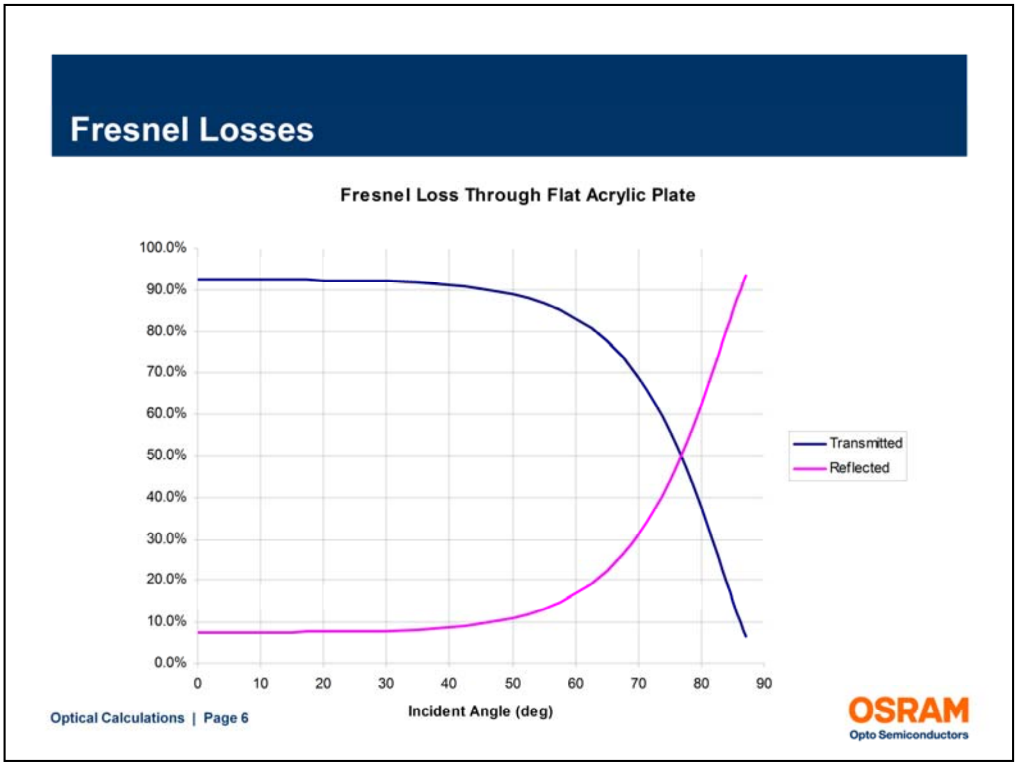
It should be noted that transmission works in a similar fashion.



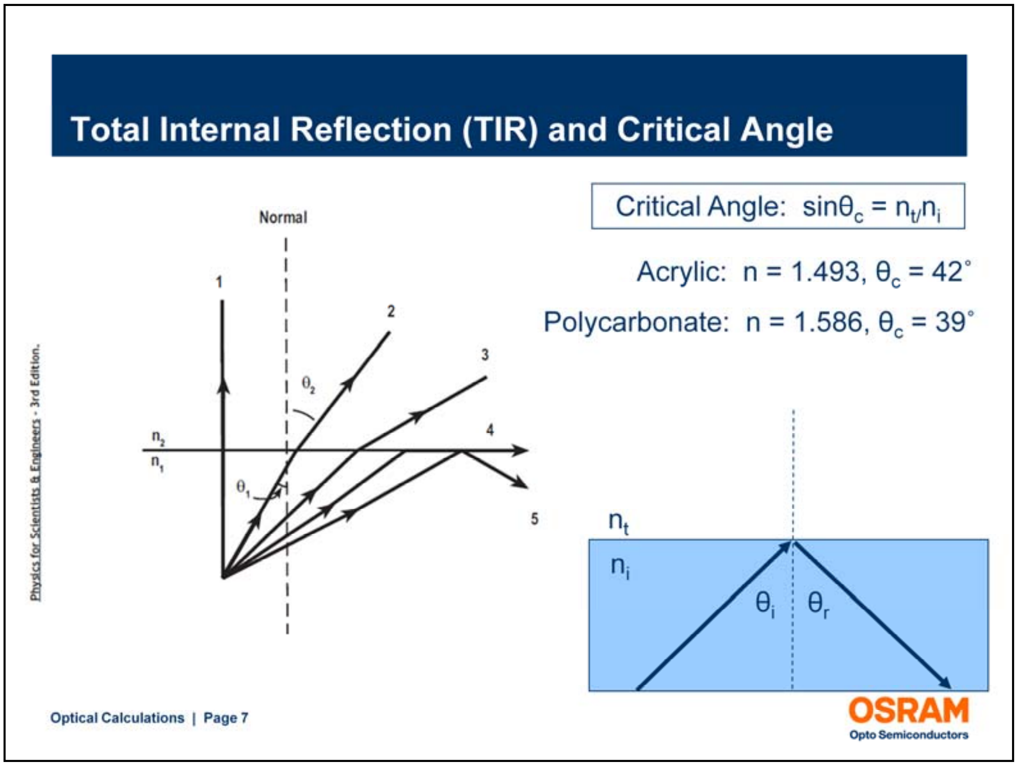
Refraction takes place when light passes from one media or material to another, for example, from air to plastic. Light bends towards or away from the surface normal depending on the indicies of refraction of the materials and the angle of incidence. The equation which describes the relationship between the angle of incidence and the angle of transmission is known as "Snell's Law". In general, light bends toward the normal when going from a low index to high index, such as air to plastic. Light bends away from the normal when going from high to low index, for example plastic to air.



An important consideration when light strikes an interface between different materials is Fresnel loss. When light is going from air to plastic or vice-versa, for example, part of the light is transmitted and part is reflected, even at normal incidence. The percentages of transmitted and reflected light depend primarily upon the angle of incidence and index of refraction. The polarization state can also be important, but for general lighting an average polarization is assumed when making calculations.



Here is a graph showing the percentages of transmitted and reflected light through an acrylic sheet surrounded by air. As you can see, significant transmission losses occur at angles of 60 degrees and beyond. Fresnel losses can significantly impact optical system efficiency if not considered.



A special case of refraction is called total internal reflection, or TIR. This occurs when light is traveling from a high index material to a low index material. Referring to the figure on the left, as the angle of incidence increases from 1 to 2 to 3, the angle of transmission also increases. When the angle of incidence reaches the so-called "critical angle", illustrated by ray 4, the light remains confined in the high index material. Beyond this angle, light reflects off the high index-low index boundary according to the Law of Reflection.

Converting to Photometric Units

- Power (Watts) is converted to luminous flux (lumens) via the relation:

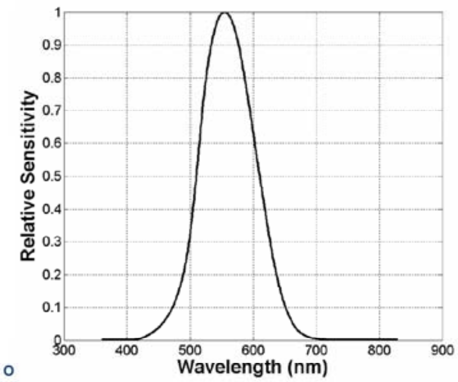
$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

Φ_v = flux (lumens)

P_e = Power

V = photopic response function of the human eye

K = constant (683 lm/W for photopic)



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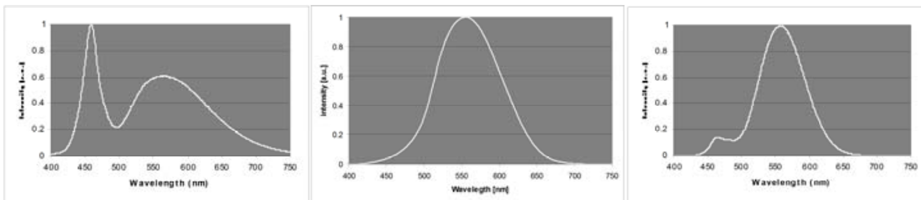
Radiometric power is converted to luminous flux via the integral equation. V-lambda is the spectral response of the human eye in daylight, otherwise known as the photopic curve. The unit of luminous flux is the lumen.

Convert Radiometric to Photometric

$P_e(\lambda)$ $V(\lambda)$ → $P_v(\lambda)$



$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

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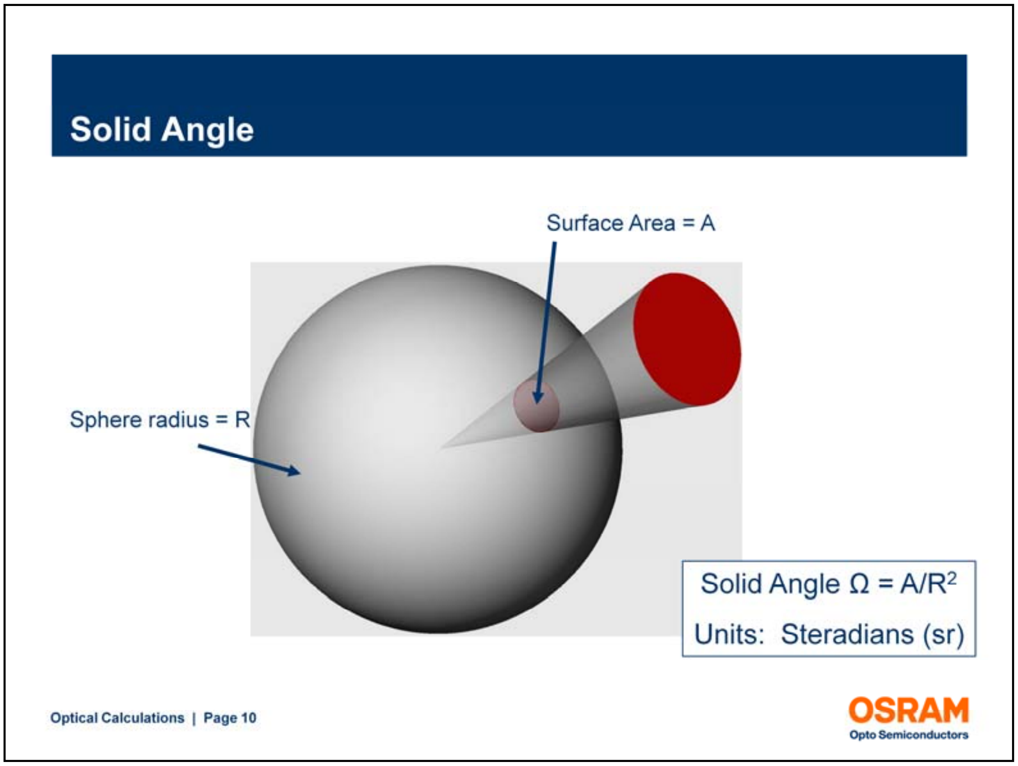
This slide shows graphically the radiometric spectral power distribution multiplied by the photopic curve V-lambda P sub e. By taking the area under the resulting P sub v curve and multiplying by the constant K, the luminous flux in lumens is calculated.

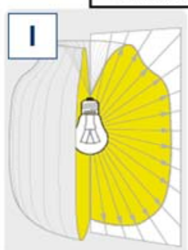


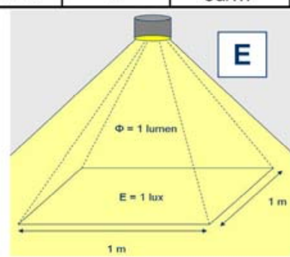
Solid angle is the 3 dimensional analog of an ordinary angle. In the figure, the edge of a circular disk is projected to the center of a sphere. The projection intersects the sphere and forms a surface area A. Solid angle is the area A on the surface of a sphere of radius R divided by the radius squared. The units of solid angle are steradians. Note that it is a dimensionless quantity.

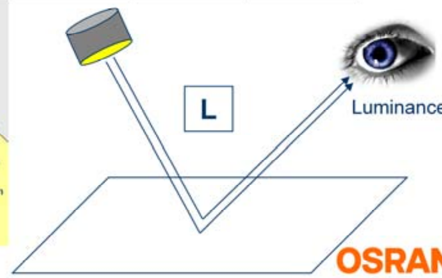
Solid angle is defined as the area A on a sphere of radius R subtended by a portion of the surface whose area is equal to the square of the sphere's radius.

Photometric Units and Symbols

Photometric Units					
Quantity	**Symbol**	**Metric Units**	**Name**	**English Units**	**Name**
Luminous Flux	Φ	lumens (lm)	lumens		
Luminous Intensity	I	lm/sr	candela (cd) or candlepower		
Illuminance	E	lm/m^2	lux (lx)	lm/ft^2	Ft-candle
Luminance	L	cd/m^2	nits	$cd/\pi*ft^2$	Ft-Lambert







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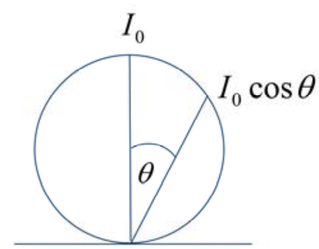
The most common photometric quantities are shown in the table. We have already discussed luminous flux. Luminous intensity, or just Intensity, is “light in a direction.” The units of intensity are lumens per solid angle, or steradians. Note that intensity does not depend on measurement distance. The next quantity, Illuminance, is “light falling on a surface,” with units of lumens per area. Finally, Luminance is “light from a surface in a direction.” The units are lumens per area per solid angle; it is the perceived brightness.

Lambertian Source

- Brightness (luminance) is independent of angle
- Intensity falls off as cosθ
- Many LEDs are very nearly Lambertian sources

$$L(\theta) = L(0)$$

$$I(\theta) = I_0 \cos\theta$$



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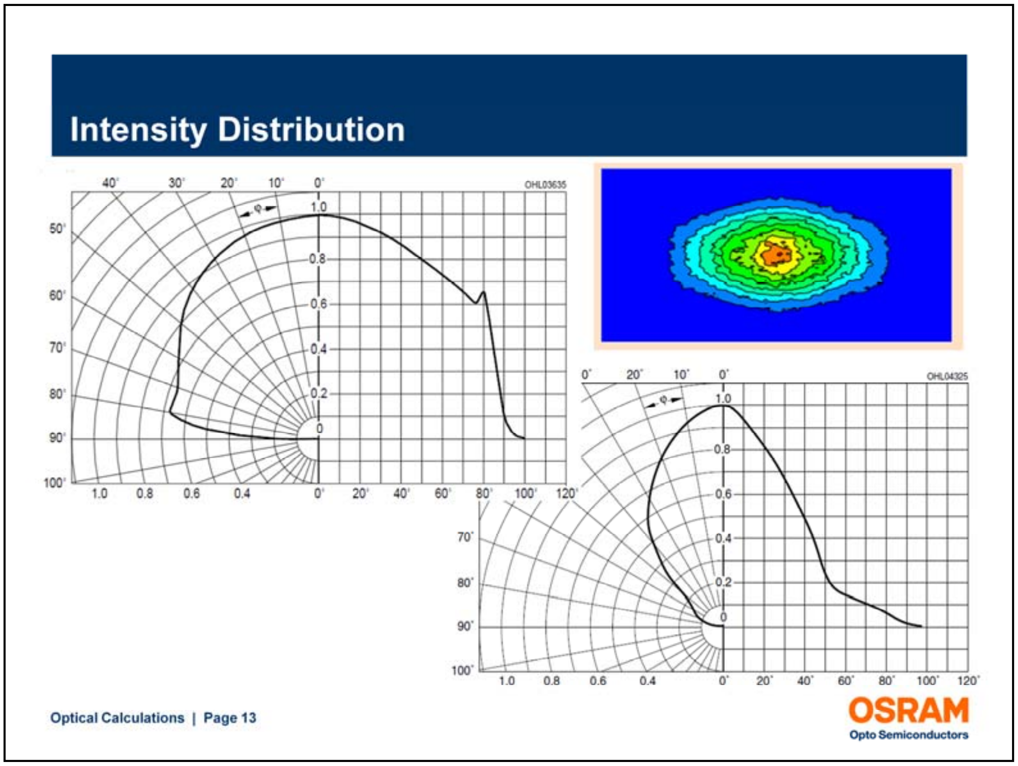
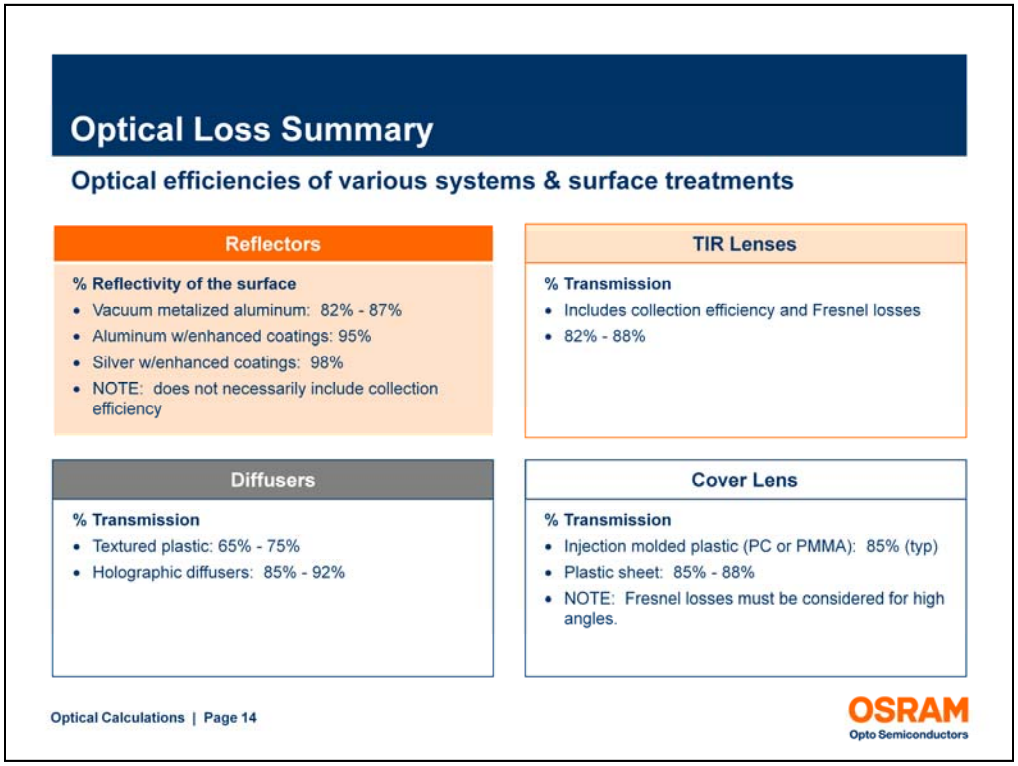
A Lambertian source is defined as one in which the brightness (or luminance) is independent of angle – in other words, the off-axis luminance is the same as on-axis. Such a source has an intensity vs. angle profile that falls off as the cosine of the angle. Historically, many LED sources have had nearly Lambertian beam distributions, simplifiying certain calculations.



For SSL applications, OSRAM Opto Semiconductors has developed several LEDs with non-Lambertian distributions. These distributions have been designed to suit specific applications.



In order to calculate the lumens required for an application (and hence, the number of LEDs), optical loss factors must be included. This table shows some rule-of-thumb efficiencies for various optical elements.

(Refl)

To compute a loss factor for a reflector, remember that the reflectivity only affects light which actually strikes the reflector.

(TIR)

The transmission for TIR lenses includes collection efficiency and Fresnel losses. A value of 85% is a good first estimate.

(Cover)

Standard refractive lenses and lens covers have similar transmission values. Remember to consider additional Fresnel losses for high angle light.

(Diffusers)

Finally, some applications add a diffuser to increase the uniformity of the lit appearance or the beam pattern. Transmission can vary greatly depending upon the optical method used.

Application Case Study: Streetlight LED Retrofit

- Use LED + optic on angled boards to create beam pattern
- Only use one optic type for simplicity & cost
- Lower drive current to meet power consumption, thermal, and lifetime goals (even though light output is reduced)
- Consider these optical losses:
  - Stock optic
  - Cover lens (globe)
  - Light blocked by pole
- Total LED count is 66.

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Now we are ready to look at a case study. This particular project involved retrofitting an existing streetlight with LEDs. There were a number of project goals which helped define the number of LEDs and the optical system. The main optical losses were due to the optics, the cover lens, and light blocked by mechanical structures. In this case, we wanted to estimate the number of lumens out of the luminaire.

These pictures show how the LEDs and optics were configured inside the fixture. Off-the-shelf optics were used over each LED, and the optical efficiency was reported by the vendor. Losses for blocked light due to the cap and the pole were estimated to be 10%. One important non-optical loss factor for any LED application is thermal loss. As the LED heats up, its light output drops. The thermal loss depends on the LED junction temperature. *which in turn depends on the ambient temperature*

Lumen Calculations

Datasheet Lumens:	112
Optic loss factor:	0.85
Outer lens loss factor:	0.85
Blocked light loss factor:	0.9
# LEDs:	66
Thermal loss factor:	0.9
Total Beam Lumens:	4311

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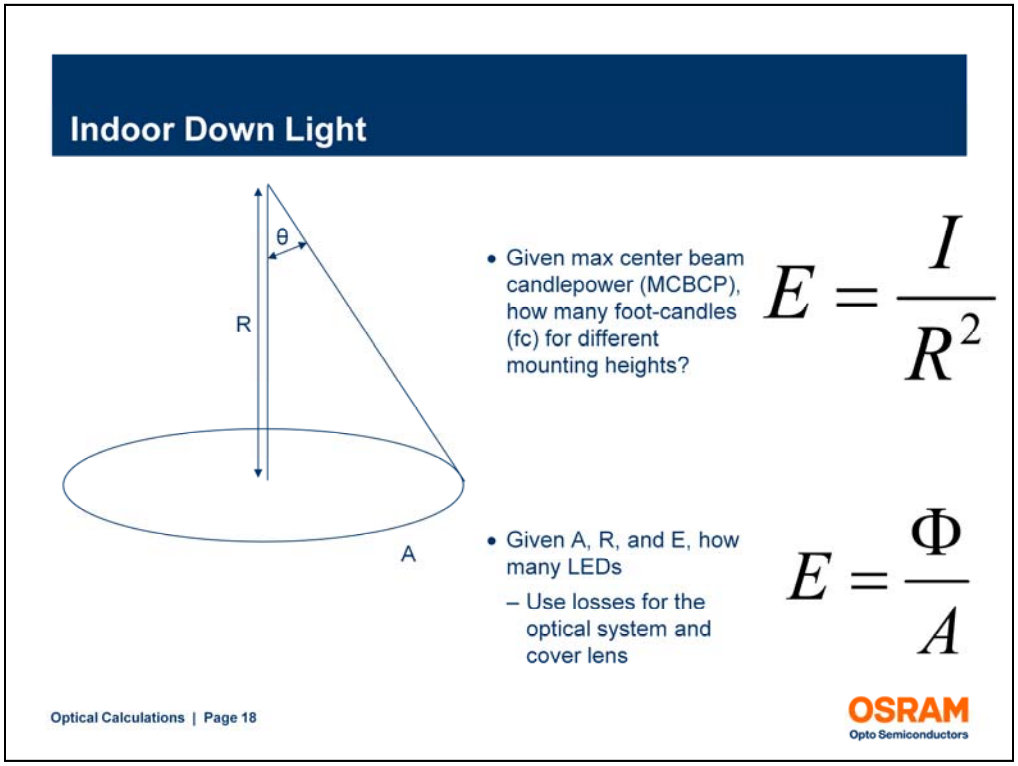
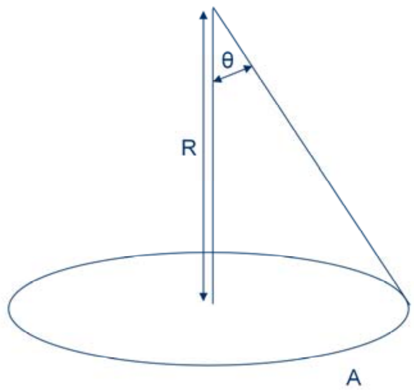
We start with the lumens specified on the datasheet for a single LED, in this case 112, and then multiply that number by the loss factors and number of LEDs for a total of about 4300. The prototype luminaire measured 4400 lumens, so our back-of-the-envelope calculations were very close.



For our second case study, we consider an LED downlight. Suppose we are given a maximum center beam candlepower value. What is the illuminance, in foot-candles, at different mounting heights? To solve this, we use the inverse square law, which states that the illuminance is equal to intensity divided by the square of the distance.

Indoor Down Light

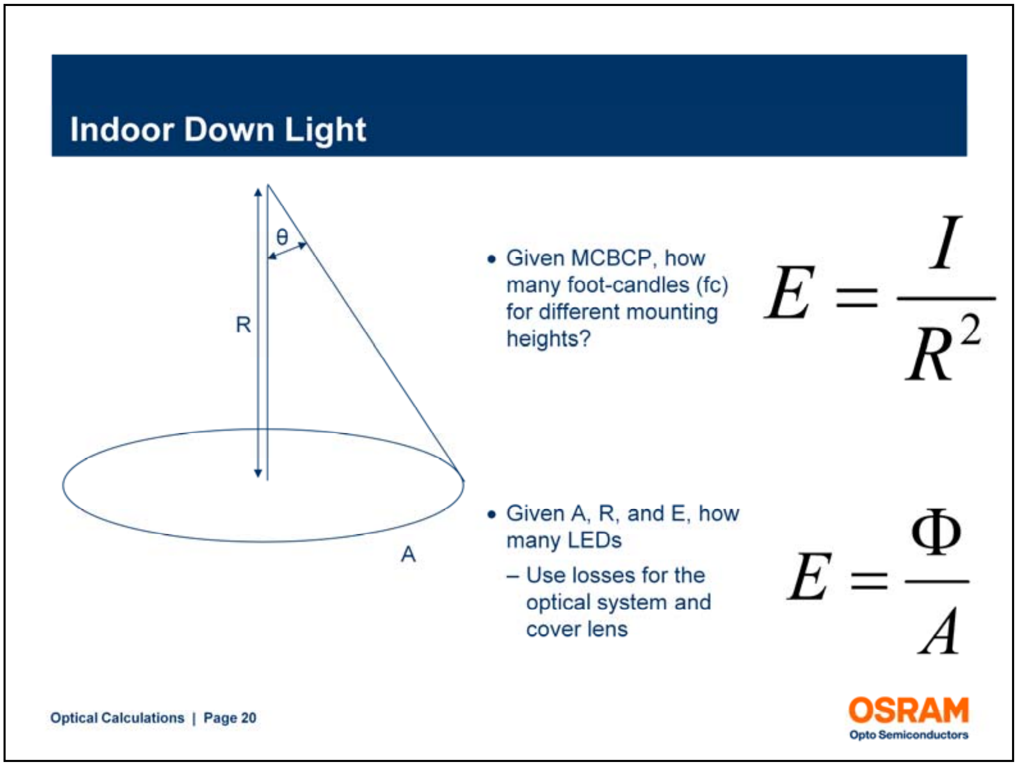


- Given MCBCP, how many foot-candles (fc) for different mounting heights?

$$E = \frac{I}{R^2}$$

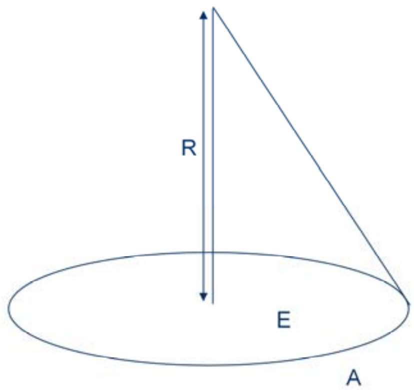
Mounting Height *R* (ft)	Max Illuminance *E* (fc)
8	15.63
10	10.00
12	6.94

Using a center beam candlepower of 1000 cd, the table shows illuminance for different mounting heights. Note that these illuminance values are at the center of the beam.



Let's look at another calculation. Suppose you want to calculate the number of LEDs required in a downlight given certain illuminance and beam pattern targets, as well as the mounting height. Assume the system will use secondary optics and a cover lens. How do you make the calculation?

Indoor Down Light



$$E = \frac{\Phi}{A}$$

Mounting height *R* (m)	2.50
Area *A* (m^2)	3.37
Average illuminance *E* (lx)	150
Req'd Lumens Φ in Area *A*	**505**
Optic Loss	0.85
Cover Lens Loss	0.85
Thermal Loss	0.80
Req'd Source Lumens	**743**
Min. LED Lumens (KR bin)	82
# LEDs	**9.1**

The governing equation is shown here, where E is the average illuminance over the area A, and phi is lumens. Given a desired beam angle and mounting height, an estimate of average illuminance can be derived. In the table, a value of 505 lumens has been calculated to meet the illuminance target. Optical losses are assumed for the secondary optics and the cover lens, and a thermal loss is also assigned. Applying these losses yields the required source lumens of 743. By dividing this number by the LED lumens, the number of LEDs is calculated.

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