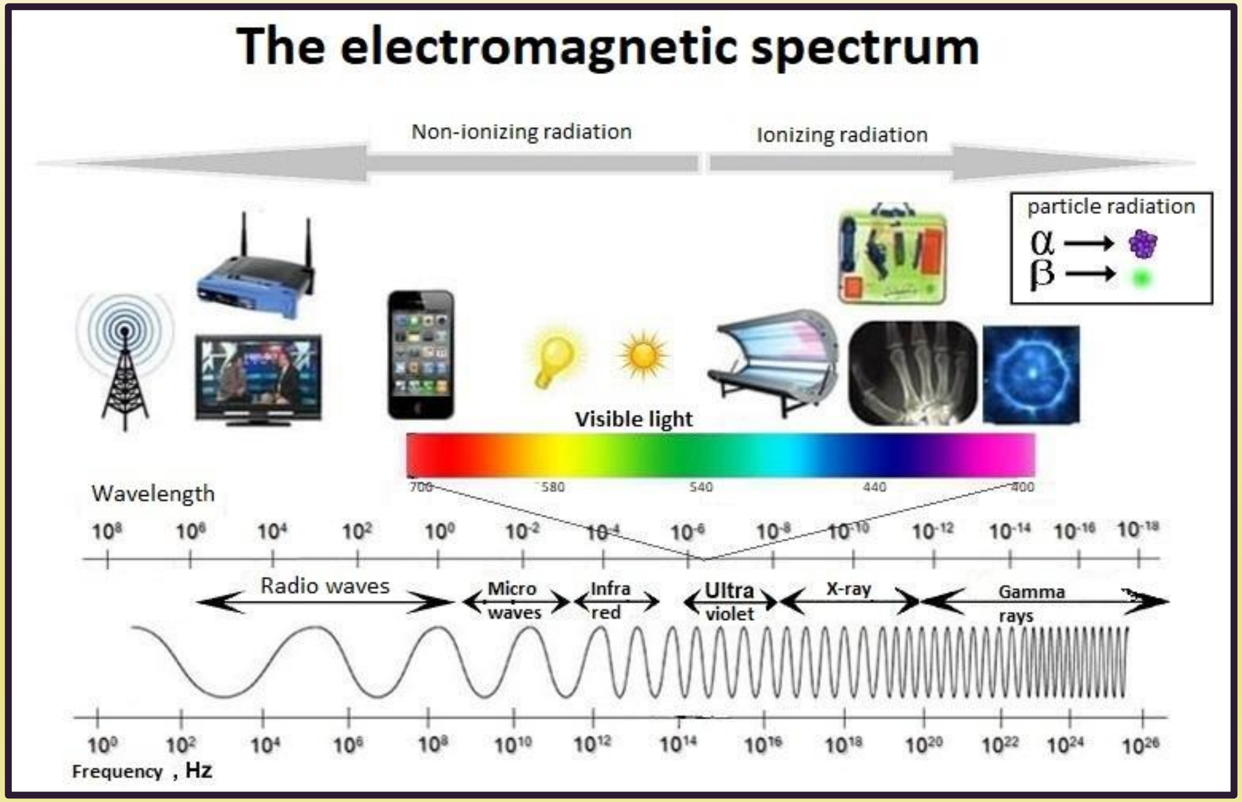
OPTICAL COMPONENTS FOR SENSORS

Energy of QUANTA

Light is a very efficient form of energy for sensing a great variety of stimuli. Among many others, these include distance, motion, temperature, chemical composition, pressure, etc. Light has an electromagnetic nature. It may be considered as propagation of either quanta of energy or electromagnetic waves. This confusing duality nowadays is well explained by quantum electrodynamics and both the quantum and wave properties are used for sensing.

Different portions of the radiation spectrum are studied by separate branches of physics and employed by different branches of engineering. It spreads from X rays (the shortest wavelength is around 1 pm) to radio waves (the longest with the wavelength of hundreds of meters).

Energy of QUANTA



$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = 299792458.7 \pm 1.1\ m/s$$

$$v = \frac{c}{n}$$

$$\nu = \frac{c}{\lambda}$$

$$E = h\nu$$

$\downarrow \lambda \Rightarrow \uparrow T \Rightarrow \uparrow E$ (Wien's law $\lambda_m = \frac{2898}{T}$)

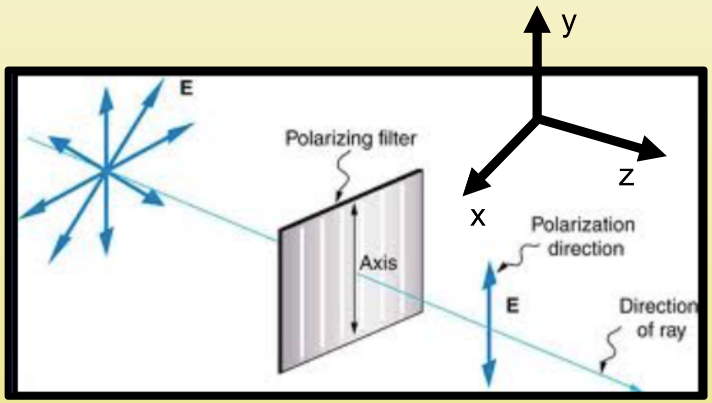
$$h = 6.63 \cdot 10^{-34}\, J \cdot s = 4.13 \cdot 10^{-15}\, eV \cdot s$$

Energy of QUANTA

The UV and visible photons carry relatively large energy and are not difficult to detect by the sensors based on the photo effect. However, when temperature of an object drops and the emanated wavelength increases, moving to the infrared portion of the spectrum, the detection becomes more and more difficult. For example, a near-infrared photon having a wavelength of 1 µm has the energy of 1.24 eV. Hence, an optical quantum detector operating in the range of 1 µm must be capable of responding to that level of energy. If we keep moving even further toward the mid- and far-infrared spectral ranges, we deal with smaller and smaller energies. Human skin (at 34 ºC) radiates the near- and far-infrared photons with energies near 0.13 eV which is an order of magnitude lower than the red light, making them much more difficult to detect:

- low-energy radiation is detected by thermal detectors (less sensitive requiring a lot of photons);
- high energy radiation is detected by the quantum (photon) detectors that respond to individual quanta of light.

Polarization



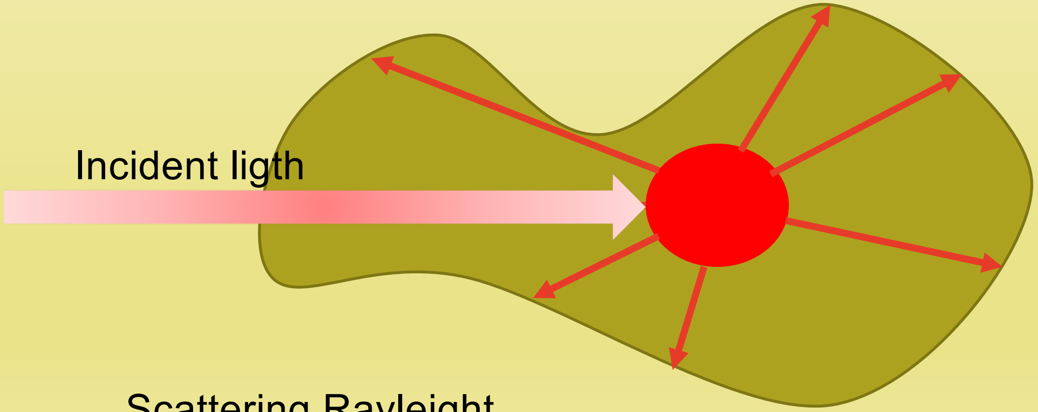
The electromagnetic wave has the additional characteristic that is the plane polarization. This means that the alternating electric field vectors in space are parallel to each other for all points in the wave. The wave in the picture is traveling in the z-direction. It is said the wave to be polarized in the xy-plane because the electric field vectors are all parallel to this plane. The plane defined by the direction of propagation (the z-axis) and the direction of polarization (the y-axis) is called the plane of vibration. In a polarized light, there are no other directions for the field vectors.

A randomly polarized light is the type of light that is produced by the Sun and various incandescent light sources, the emerging beam in most laser configurations is polarized. If unpolarized light passes through a polarization filter (Polaroid), only specific planes can pass through.

Light scattering

In empty space and away from the astronomically massive objects, light travels along straight lines. But if space is not entirely empty, this rule may be broken. Scattering is an electromagnetic phenomenon where light is forced to deviate from a straight path by one or more localized nonuniformities in the medium [2]. Examples of nonuniformities are smoke particles, dust, bacteria, water droplets, and gaseous molecules. When a particle is larger than the wavelength of incident light and happens to be in the light path, it serves as a reflector.

Smaller particles cause a different type of scattering. It is typical for particles that are at least ten times smaller than the wavelength of light. In a simplified way, the scattering mechanism by a small particle can be explained as absorption of the light energy and re-emitting it in all directions

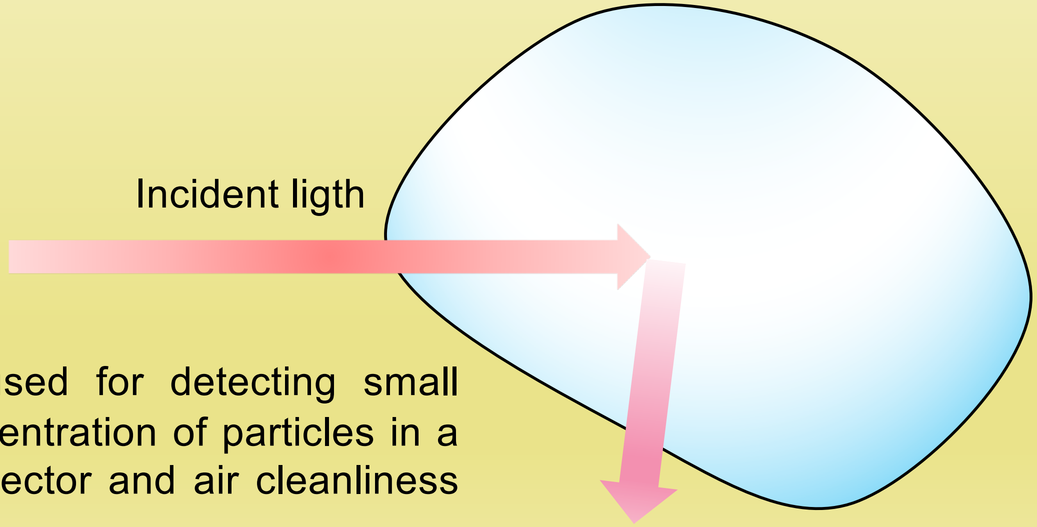


Scattering Rayleight

Light scattering

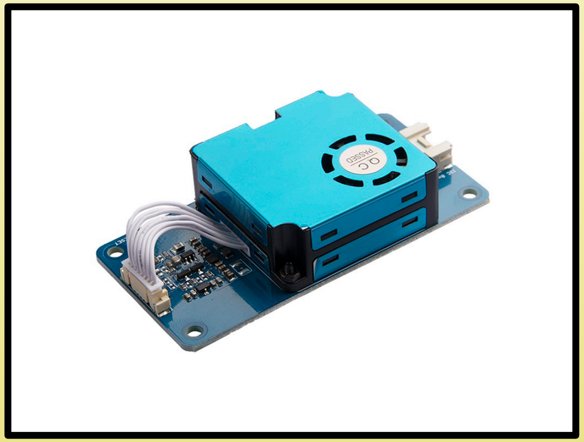
When a particle is larger than the wavelength of incident light and happens to be in the light path, it serves as a reflector. The reflection is governed by general laws of reflection.

Scattering depends on **size of the particle** or **irregularity**, **the wavelength of light**, and **angle between the scattered and incident lights**.



Light scattering is a phenomenon that can be used for detecting small impurities in gases and liquids and for sensing concentration of particles in a fluid. Examples of the applications are a smoke detector and air cleanliness monitor that senses presence and density of dust.

Light scattering



Adafruit: PM2.5 Air Quality Sensor

DFRobot: Turbidity Sensor (Water Suspended Particles)

Geometrical optics

Light modifications, such as reflection, refraction, absorption, interference, polarization, and speed are the powerful utensils in the sensor designer's toolbox. Optical components help to manipulate light in many ways. We will describe light propagation in terms of *rays*. The *ray* in geometrical optics is an abstraction that can be used to approximately model how light will propagate. Light rays are defined to propagate in a rectilinear path as they travel in a homogeneous medium. We consider light as a moving front or a ray which is perpendicular (normal) to that front. In cases of very small objects, the methods of quantum electrodynamics (QED) need to be employed. When using geometrical optics, we omit properties of light that are better described by quantum mechanics and quantum electrodynamics.

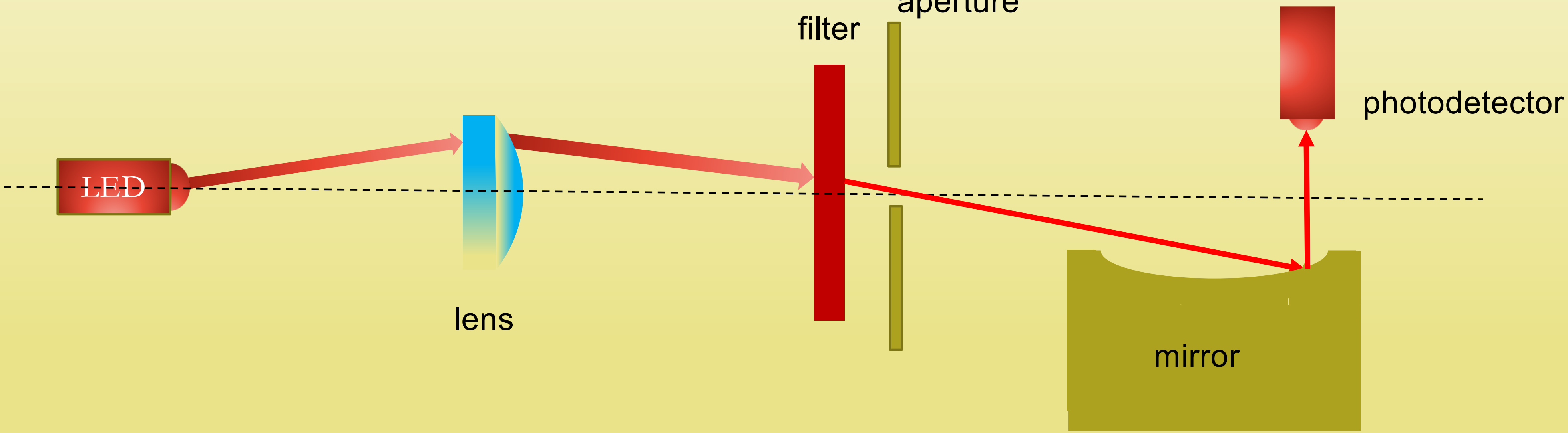
Before light can be manipulated, first we need to have the light generated. There are several ways to produce light. Some sources of light are natural and exist without our will or effort, while some must be incorporated into a measurement device. The natural sources of light include celestial objects, such as sun, moon, stars, fire, etc.

Geometrical optics

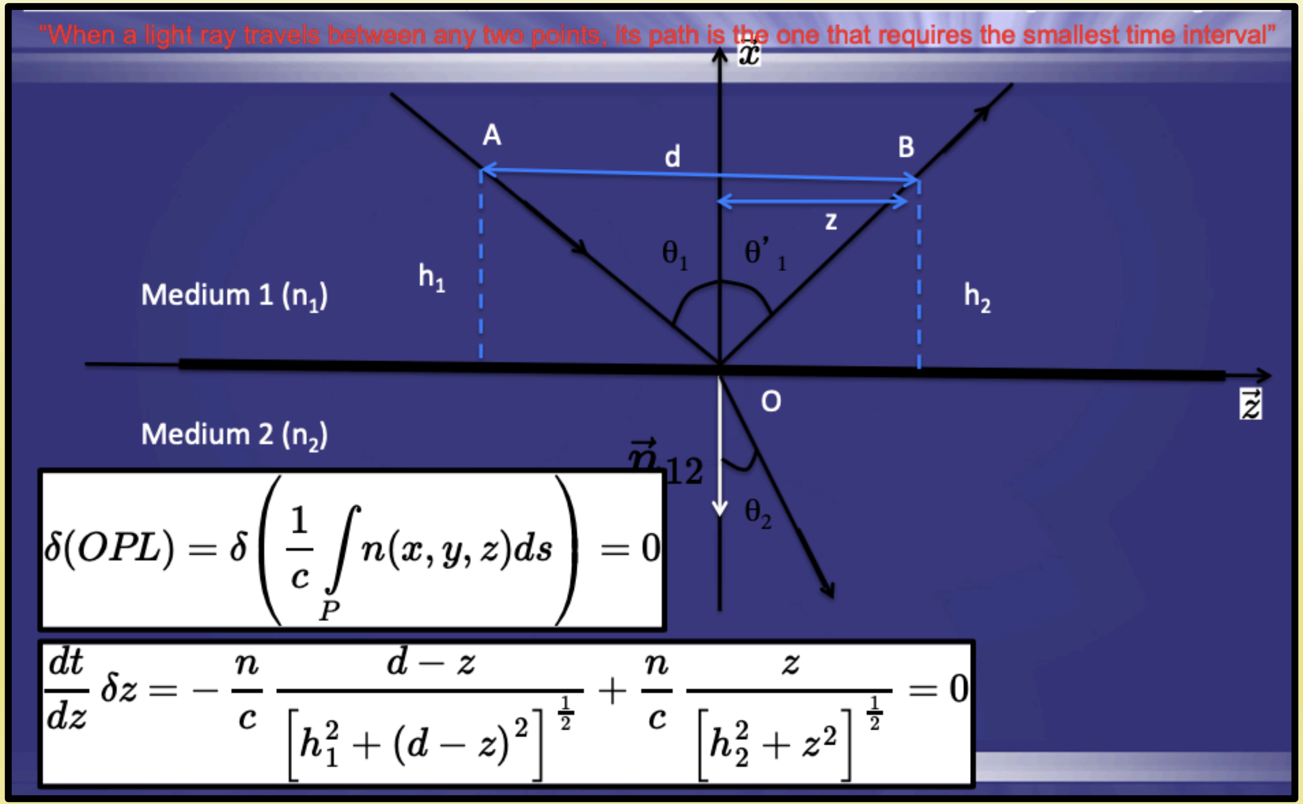
Also, natural sources of light in the mid- and far-infrared spectral ranges include all material objects that radiate electromagnetic waves depending on their temperatures. These include fire, exothermic chemical reactions, living organisms, and other natural sources whose thermal radiation can be selectively detected by the special optical devices. The man-made sources of light include filaments in the electric bulbs, light emitting diodes (LED), gas discharge lamps, lasers, laser diodes, heaters, etc.

After light is generated, it can be manipulated in many ways. Most of these methods involve changing direction of light, while some use a selective blocking of certain wavelengths. The latter is called filtering. *The light direction can be changed by use of reflection with the help of mirrors, prisms, optical waveguides, optical fibers, and many reflective objects*. Also, the light direction can be changed by refraction with the help of lenses, prisms, windows, chemical solutions, crystals, organic materials, and biological objects. While passing through these objects, properties of light may be modified (modulated) by a measured stimulus. **Then, the task of a sensor designer is to arrange a conversion of such a modulation into electrical signals that can be related to the stimulus.**

Geometrical optics



Geometrical optics



"When a light ray travels between any two points, its path is the one that requires the smallest time interval"

$$\delta(OPL) = \delta\left(\frac{1}{c}\int_P n(x,y,z)ds\right) = 0$$

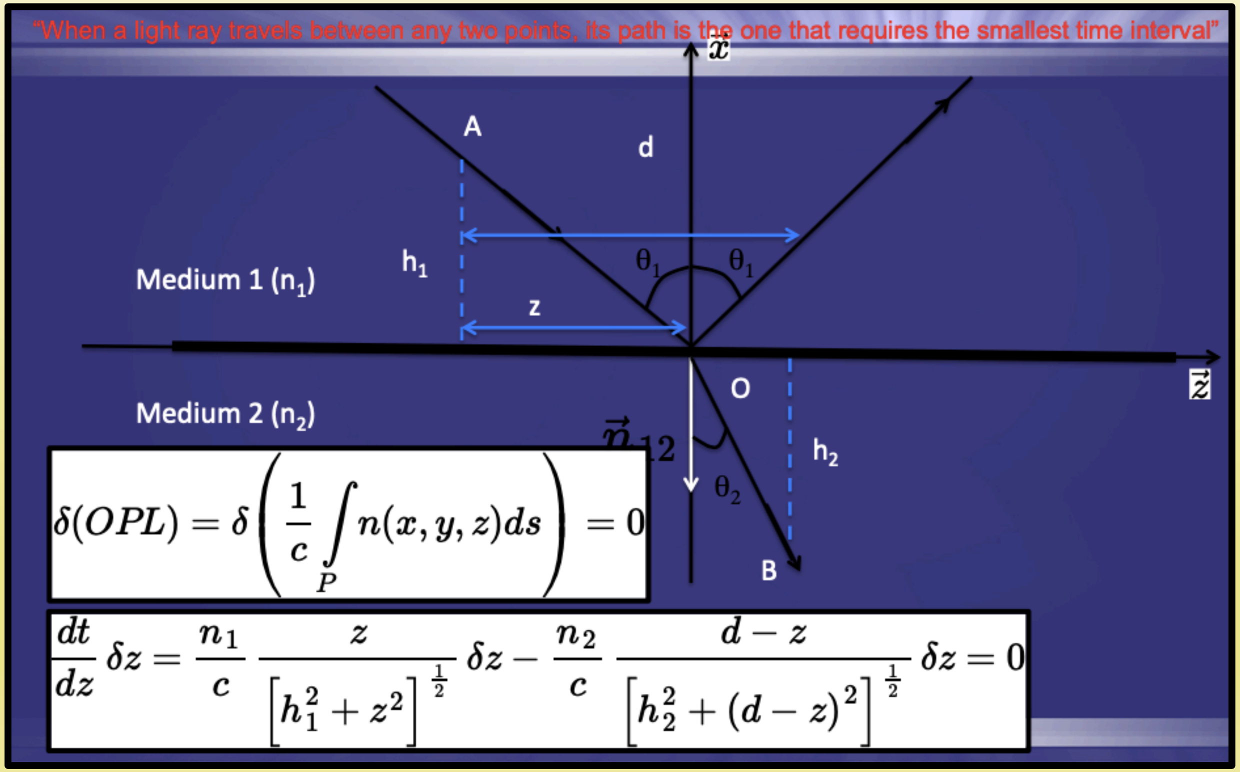
$$\frac{dt}{dz}\delta z = -\frac{n}{c}\frac{d-z}{\left[h_1^2+(d-z)^2\right]^{\frac{1}{2}}} + \frac{n}{c}\frac{z}{\left[h_2^2+z^2\right]^{\frac{1}{2}}} = 0$$

Reflection law

$$\boxed{Sin(\theta_1) = Sin(\theta_1{}')}$$

$$\boxed{\theta_1 = \theta_1{}'}$$

Geometrical optics



"When a light ray travels between any two points, its path is the one that requires the smallest time interval"

$$\delta(OPL) = \delta\left(\frac{1}{c}\int_P n(x,y,z)ds\right) = 0$$

$$\frac{dt}{dz}\delta z = \frac{n_1}{c}\frac{z}{\left[h_1^2 + z^2\right]^{\frac{1}{2}}}\delta z - \frac{n_2}{c}\frac{d-z}{\left[h_2^2 + (d-z)^2\right]^{\frac{1}{2}}}\delta z = 0$$

Refraction law

$$\boxed{n_1 Sin(\theta_1) = n_2 Sin(\theta_2)}$$

$$n = \frac{c}{v}$$

$$n(\lambda, T) = \sqrt{\varepsilon_r}$$

Radiometry and photometry

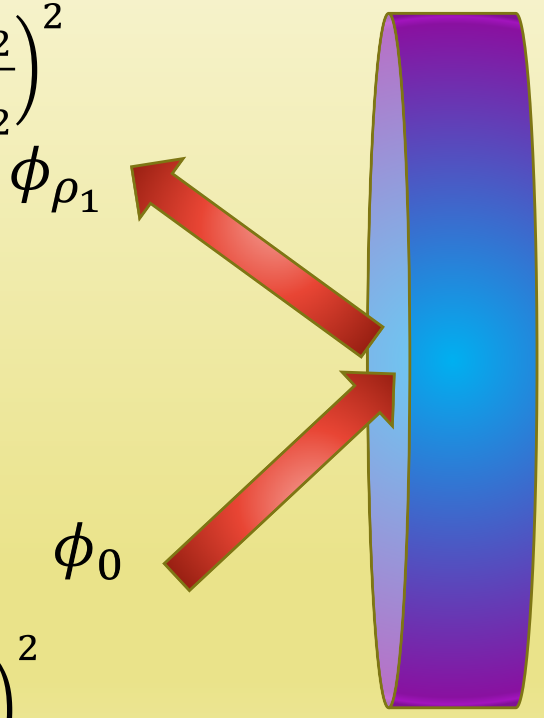
Photometry is a system of language, mathematical formulations, and instrumental methodologies used to describe and measure the propagation of *light* through space and materials. In consequence, the radiation so studied is confined to the visible (VIS) portion of the spectrum. Only light is visible radiation. The human eye responds only to light having wavelengths between about 360 and 800 nm. **Radiometry** deals with electromagnetic at all wavelengths and frequencies, while photometry deals only with visible light, the portion of the electromagnetic stimulating vision in the human eye.

Radiometry and Photometry

Description	Radiometric	Photometric
Total flux	Radiant flux ϕ in watts	Luminous flux ϕ in watts
Emitted flux density at a source surface	Radiance emittance (W) in W/cm^2	Luminous emittance (L) in lumens/cm^2
Source intensity point	Radiant intensity (I_r) in watts/steradian	Luminous intensity (L_r) in (candela)
Source intensity (area source)	Radiance (B_r) in watts/steradian/cm^2	Luminance (B_l) in lumens/steradian/cm^2 (lambert)
Flux density incident on a receiver surface	Irradiance (H) in watts/cm^2	Illuminance (E) in lumens/cm^2 (candle)

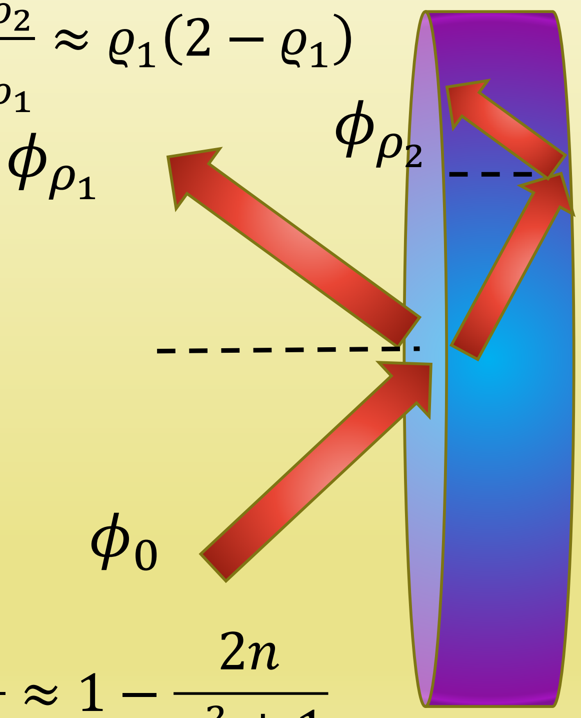
Radiometry

$$\rho_1 = \frac{\phi_{\rho_1}}{\phi_0} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$



$$\rho_1 = \frac{\phi_{\rho_1}}{\phi_0} = \left(\frac{n - 1}{n + 1}\right)^2$$

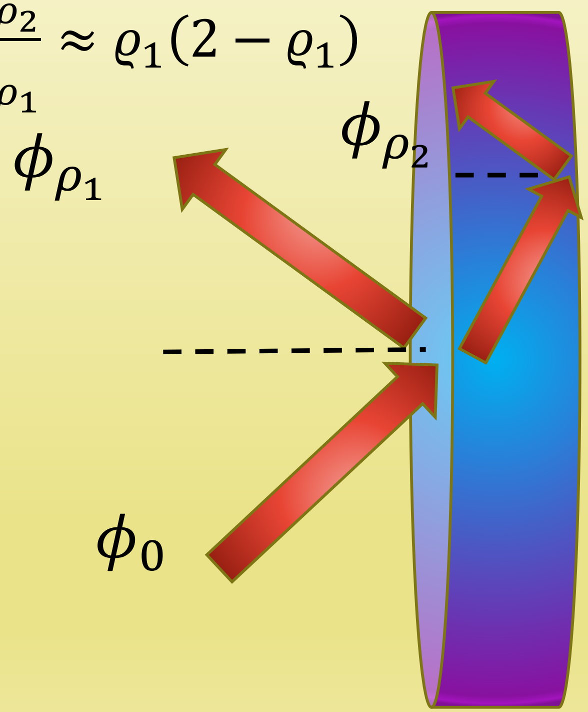
$$\rho_2 = \frac{\phi_{\rho_2}}{\phi_{\rho_1}} \approx \varrho_1(2 - \varrho_1)$$



$$\rho_1 = \frac{\phi_{\rho_1}}{\phi_0} \approx 1 - \frac{2n}{n^2 + 1}$$

Radiometry

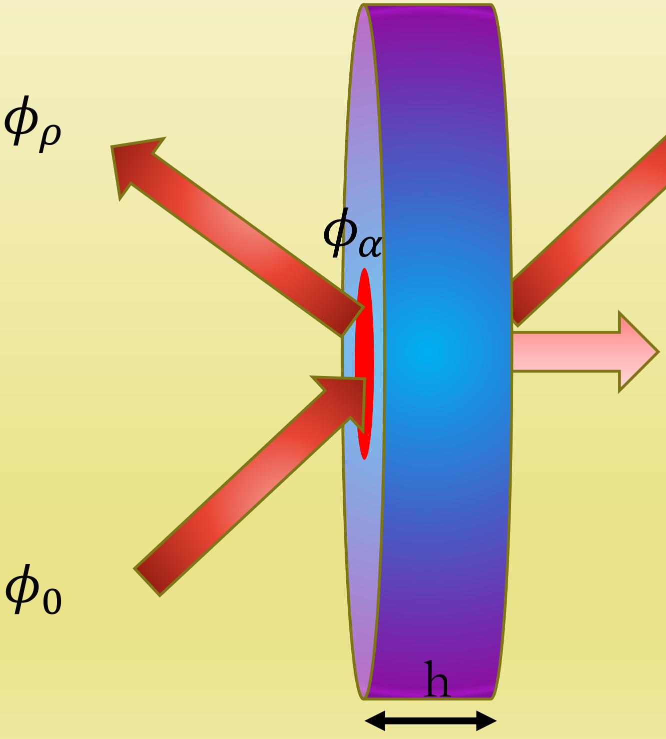
$$\rho_2 = \frac{\phi_{\rho_2}}{\phi_{\rho_1}} \approx \varrho_1(2 - \varrho_1)$$



$$\left.\begin{aligned} &\rho_2 + \alpha + \gamma = 1 \\ &\alpha \approx 0 \\ &\gamma = 1 - \rho_2 \end{aligned}\right\} \quad \gamma = 1 - \rho_2 \approx \frac{2n}{n^2 + 1}$$

Radiometry

The radiated spectrum relates to a temperature of the material, its chemical composition and is situated in the mid- and far-infrared regions of the optical spectrum. The spectral distribution of the secondary radiation corresponds to the absorption distribution of the material.



$$\phi_\varepsilon = \phi_\alpha - \Delta P$$

Secondary radiation

$$\alpha = \frac{mc}{\phi_c}\frac{2n}{n^2+1}\left(\frac{dT_g}{dt} - \frac{dT_l}{dt}\right)T_0$$

$$\gamma \approx (1-\rho_2)e^{-gh}$$

c = specific heat,
T_g = slope of the rising part of the temperature curve of the material,
T_l = slope of the lowering part of the temperature curve of the material,
T_0 test temperature

Photometry

When using the light sensitive devices (photodetectors), it is critical to take into consideration both the sensor and light source. In some applications, light is received from independent sources, while in others the light source is part of the measurements system. In any event, the so-called photometric characteristics of the optical system should be accounted for. Such characteristics include light, emittance, luminance, brightness, etc. o measure radiant intensity and brightness, special units have been devised. **Radiant flux** (energy emitted per unit time) which is situated *in a visible portion of the spectrum* is referred to as **luminous flux**. This distinction is due to the inability of the human eye to respond equally to like power levels of different visible wavelengths. For instance, one red and one blue light of the same intensity will produce very different sensations: the red will be perceived as much brighter.

Comparing lights of different colors, the *watt* becomes a poor measure of brightness and a special unit called a *lumen* was introduced. It is based on a standard radiation source with molten platinum formed in a shape of a blackbody and visible through a specified aperture within a solid angle of one steradian.

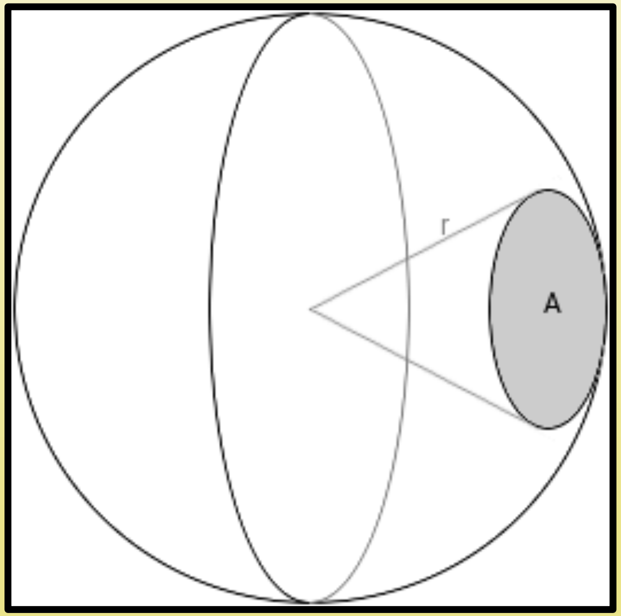
Photometry

$$\omega = \frac{A}{r}$$ Solid angle

$$\omega = \frac{1}{r}$$ Steradian (A=r)

$$E = \frac{d\phi}{dA}$$ Illuminance (lumens/cm^2)

$$I_l = \frac{d\phi}{d\omega}$$ Luminous intensity (lumens/steradian)



Photometry

In selection of electro-optical sensors, the design considerations of light sources are of prime concern. A light source will effectively appear as either **a point source**, or as **an area source**, depending upon the relationship between the size of the source and the distance between the source and the detector. Point sources are *arbitrarily* defined as those whose diameter is less than 10 % of the distance between the source and the detector. While it is usually desirable that a photodetector is aligned such that its surface area is tangent to the sphere with the point source at its center, it is possible that the plane of the detector can be inclined from the tangent plane. Under this condition, the incident flux density (irradiance) is proportional to the cosine of the inclination angle φ:

$$H = \frac{I_r}{cos\varphi}$$

irradiance

$$E = \frac{I_r}{r^2} cos\varphi$$

illuminance

Photometry

The area sources are arbitrarily defined as those whose diameter is greater than 10 % of the separation distance. A special case that deserves some consideration occurs when radius R of the light source is much larger than the distance r to the sensor. Under this condition

$$H = \frac{B_r A_s}{r^2 + R^2} \approx \frac{B_r A_s}{R^2}$$

B_r = radiance

A_s = area light source

If $A_s = \pi R^2$

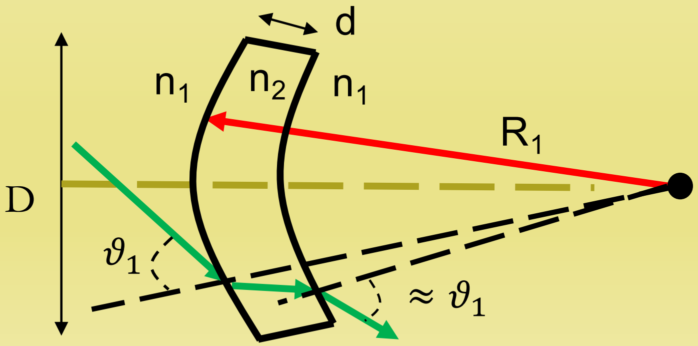
$$H = \frac{B_r A_s}{r^2 + R^2} \approx B_r \pi = \mathrm{W}$$

⬇

emitted and incident flux are equal

Windows

The main purpose of windows is to protect interiors of optical sensors and detectors from environment. A good window should transmit light rays in a specific wavelength range with minimal distortions. Therefore, windows should possess appropriate characteristics adapted for a particular application. For instance, if an optical detector operates under water, perhaps its window should posses the following properties: a mechanical strength to withstand water pressure, a low water absorption, a transmission band corresponding to the wavelength of interest, and an appropriate refractive index preferably should be close to that of water. A useful window shape that can better withstand high pressures is spherical.



To minimize optical distortions, three limitations should be applied to a spherical window: an aperture D (its largest dimension) should be smaller than the window's spherical radius R_1, a thickness d of the window should be uniform, and much smaller than radius R_1. If these conditions are not met, the window becomes a concentric spherical lens.

Windows

A surface reflectivity of a window should be considered for its overall performance. To minimize a reflective loss, windows may be given antireflective coatings (ARC) which are applied on either one or both sides of the window. These are the coatings that give blue and amber appearances to photographic lenses and filters. Due to refraction in the window, a passing ray is shifted by a distance L which for small angles Θ_1 may be found from formula:

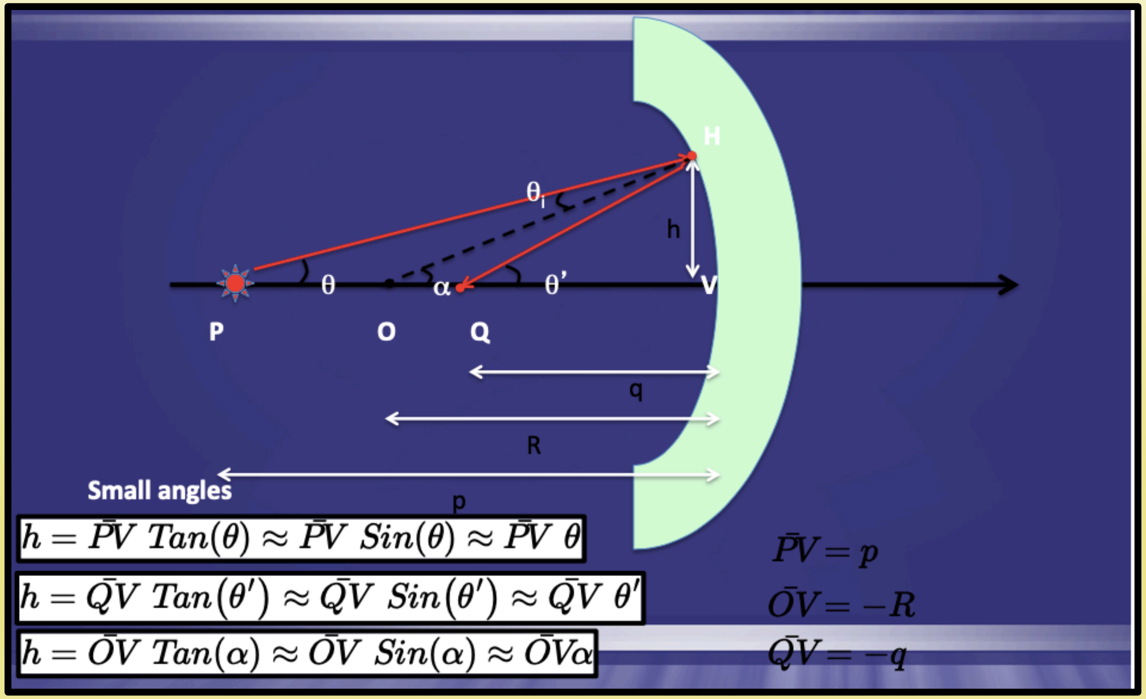
$$L = d\frac{n-1}{n}$$

Sensors operating in the mid- and far-infrared ranges require special windows which are opaque in the visible and ultraviolet (UV) spectral regions and quite transparent in the wavelength of interest. Several materials are available for fabrication of such windows.

When selecting material for a mid- and far-infrared window, the refractive index shall be seriously considered because it determines coefficients of reflectivity, absorptivity, and eventually transmittance.

Mirrors

A mirror is the oldest optical instrument ever used or designed.



Small angles

$h = \bar{PV}\ Tan(\theta) \approx \bar{PV}\ Sin(\theta) \approx \bar{PV}\ \theta$

$h = \bar{QV}\ Tan(\theta') \approx \bar{QV}\ Sin(\theta') \approx \bar{QV}\ \theta'$

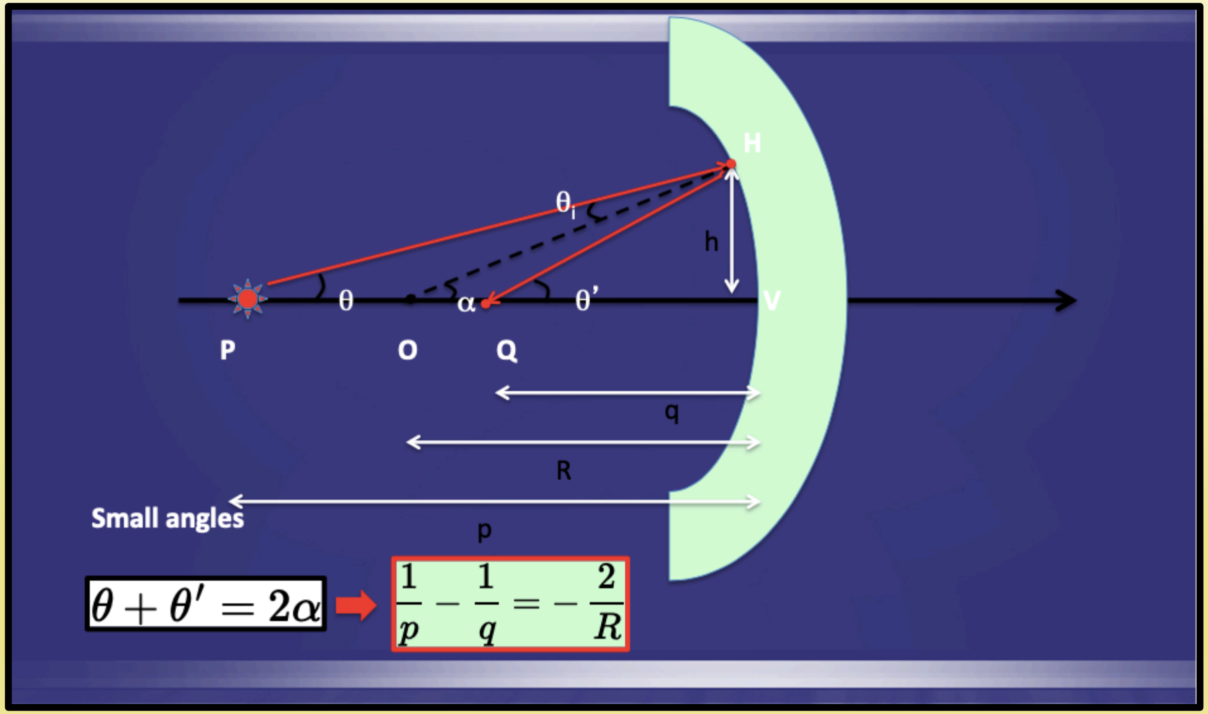
$h = \bar{OV}\ Tan(\alpha) \approx \bar{OV}\ Sin(\alpha) \approx \bar{OV}\alpha$

$\bar{PV} = p$

$\bar{OV} = -R$

$\bar{QV} = -q$

Mirrors

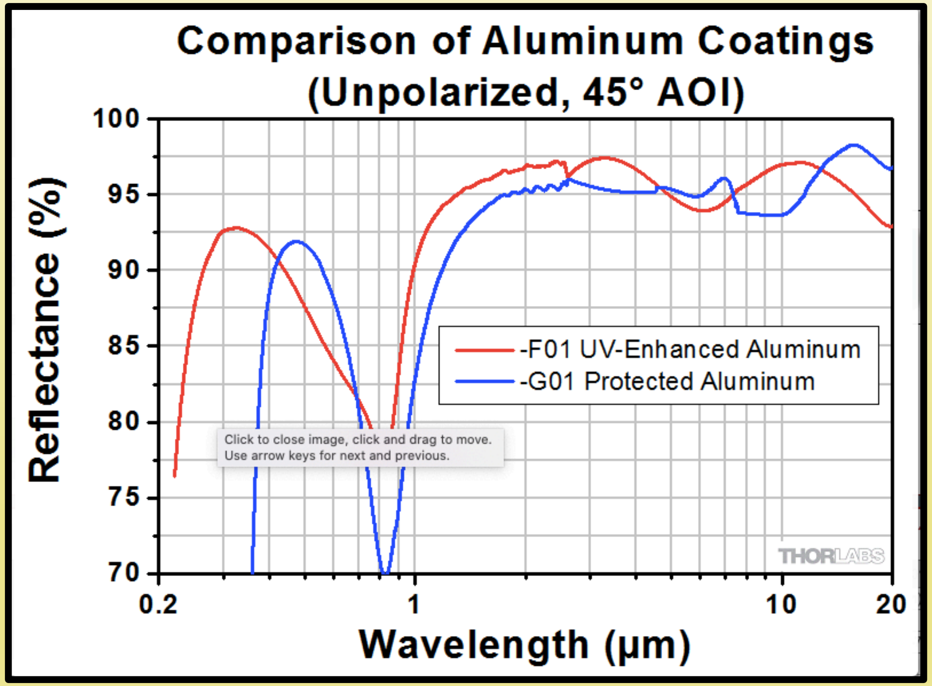


Small angles

$$\boxed{\theta + \theta' = 2\alpha} \Rightarrow \boxed{\frac{1}{p} - \frac{1}{q} = -\frac{2}{R}}$$

Mirrors

Reflecting coatings applied to a surface for operation in the visible and near- infrared range can be silver, aluminum, chromium, and rhodium. Gold is preferable for the mid- and far-infrared spectral range devices. By selecting an appropriate coating, the reflectance may be achieved of any desired value from nearly 0 to almost 1.



https://www.thorlabs.com/

Mirrors

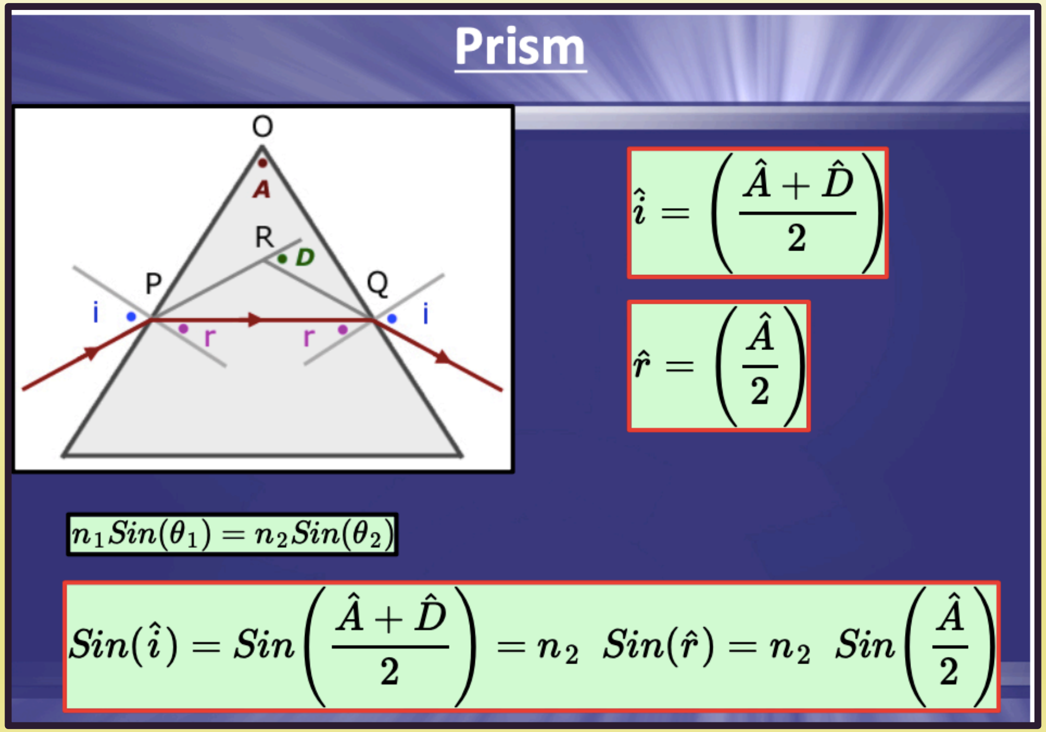
A reflective surface may be sculptured practically in any shape to divert the direction of the light travel. In optical systems, curved mirrors produce effects equivalent to that of lenses. The advantages they offer include:

- **higher transmission**, especially in the longer wavelength spectral range where lenses become less efficient due to higher absorption and reflectance loss,
- **absence of distortions** incurred by refracting surfaces due to dispersion (chromatic aberrations),
- **lower size and weight** as compared with many types of lenses.

Spherical mirrors are used whenever light must be collected and focused.

A spherical mirror is astigmatic, meaning that the off-axis rays are focused away from its focal point.
Nevertheless, such mirrors prove very useful in detectors where no quality imaging is required, for instance in infrared motion detectors.
A parabolic mirror is quite useful for focusing light off-axis. When it is used in this way, there is complete access to the focal region without shadowing.

Prism



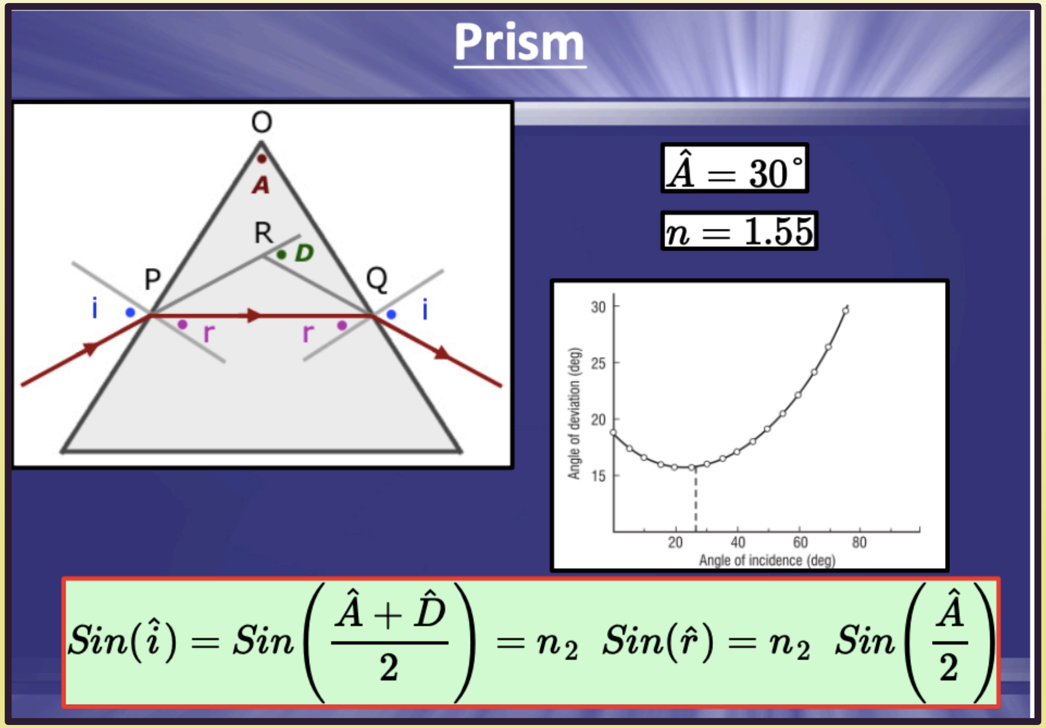
Prism

$$\hat{i} = \left(\frac{\hat{A}+\hat{D}}{2}\right)$$

$$\hat{r} = \left(\frac{\hat{A}}{2}\right)$$

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

$$Sin(\hat{i}) = Sin\left(\frac{\hat{A}+\hat{D}}{2}\right) = n_2 \ \ Sin(\hat{r}) = n_2 \ \ Sin\left(\frac{\hat{A}}{2}\right)$$



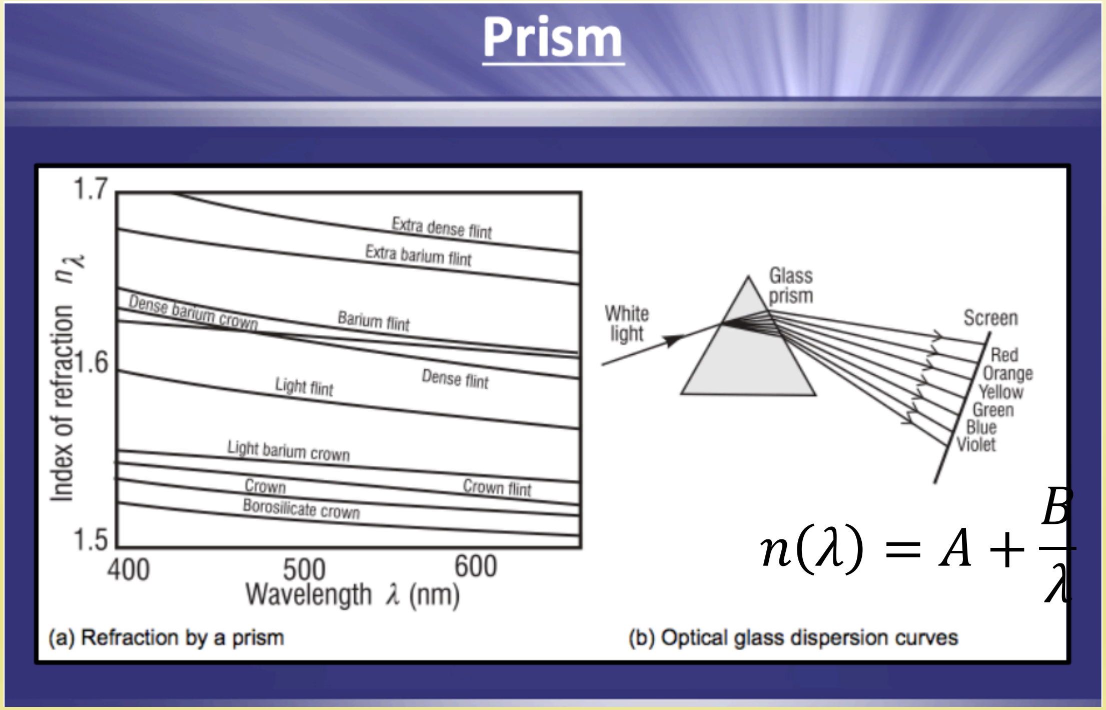
Prism

$$\hat{A} = 30^{\circ}$$

$$n = 1.55$$

$$Sin(\hat{i}) = Sin\left(\frac{\hat{A}+\hat{D}}{2}\right) = n_2 \ \ Sin(\hat{r}) = n_2 \ \ Sin\left(\frac{\hat{A}}{2}\right)$$

Prism

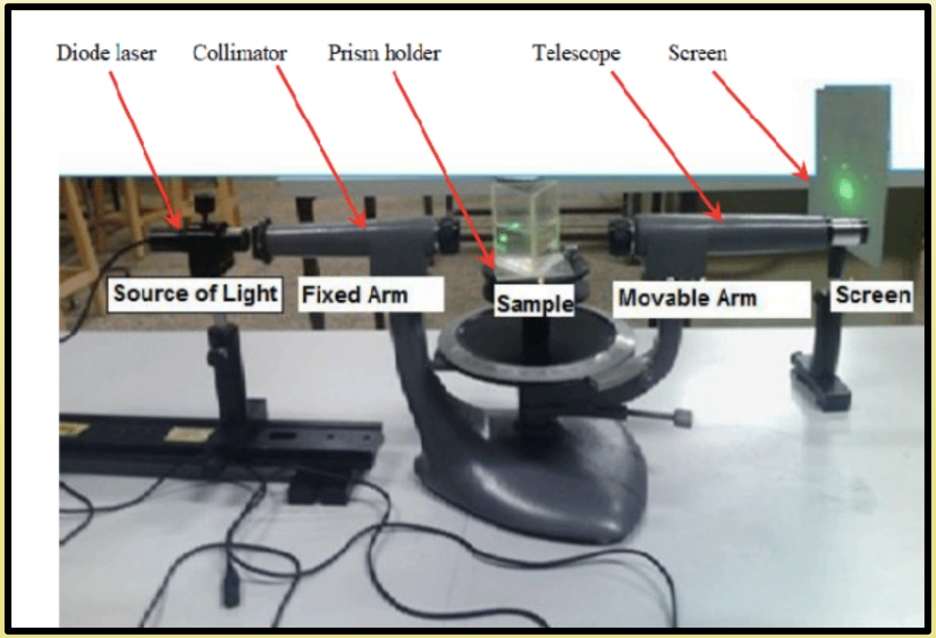


Prism

(a) Refraction by a prism

(b) Optical glass dispersion curves

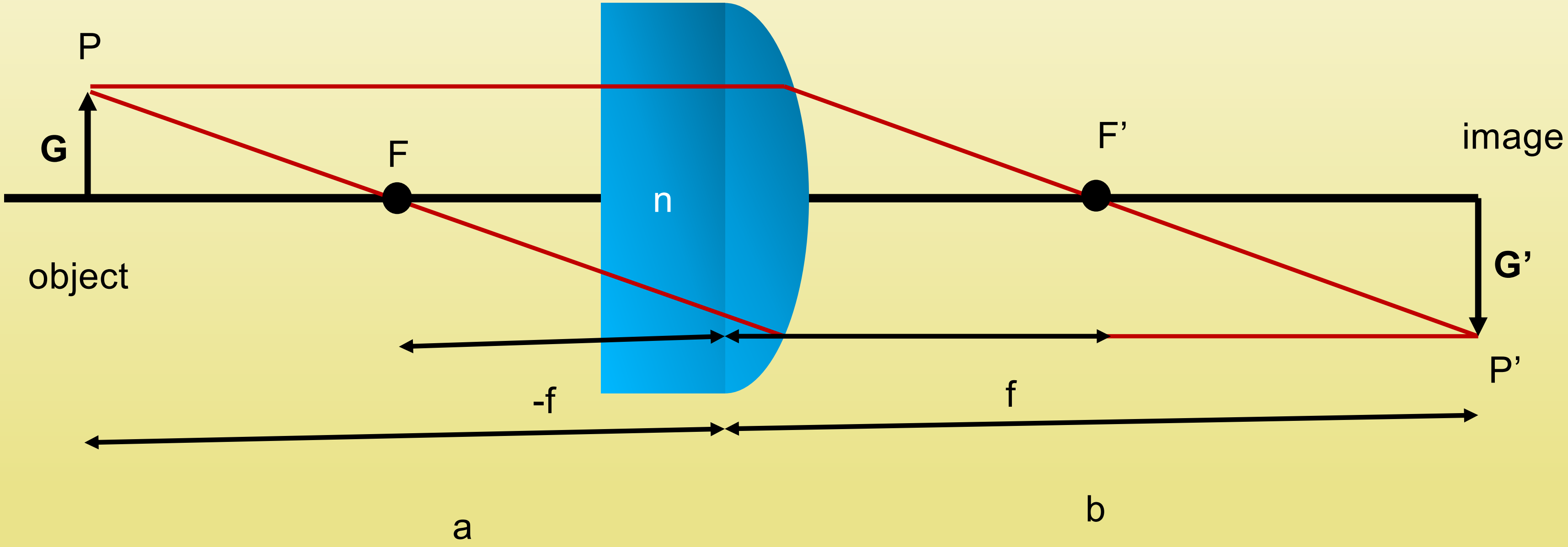
$$n(\lambda) = A + \frac{B}{\lambda}$$



Lenses

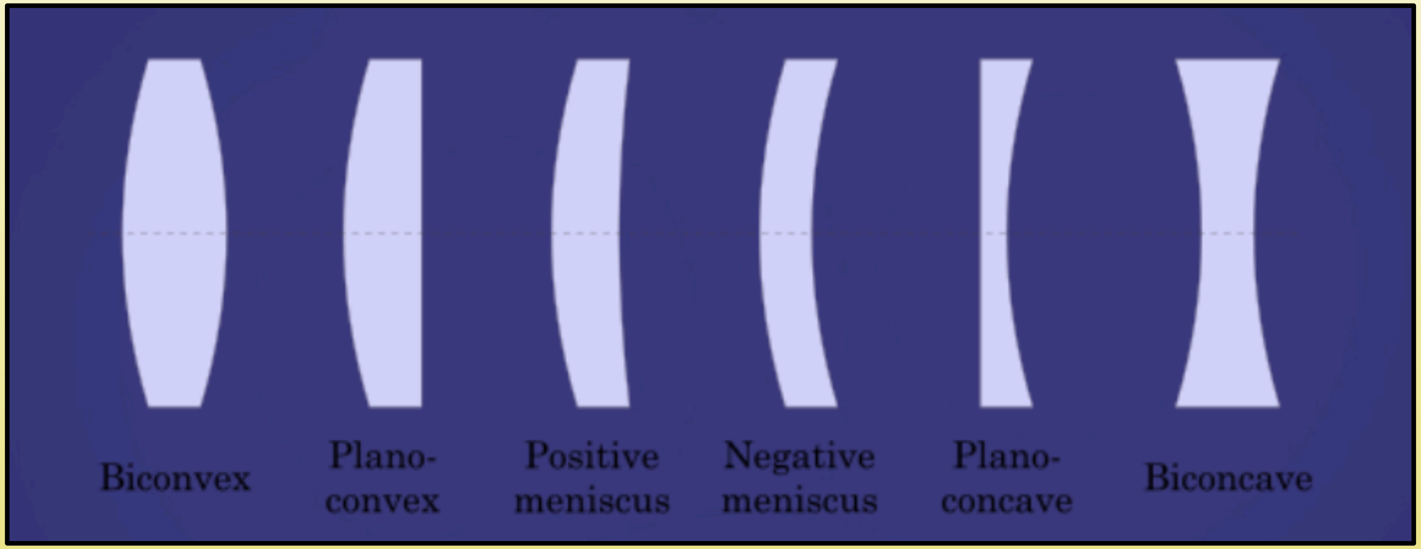
Like the mirrors, lenses are employed in sensors and detectors to divert the direction of light rays and arrange them in a desirable fashion. But unlike the mirrors that use reflection, lenses use refraction, the effect based on Snell Law . The main idea behind the lens is a bending of light ray while crossing the lens surface and entering and exiting to another medium, such as air. By sculpturing the lens surface, rays can be predictably diverted to a desired location, for example, a focal point or focus.

Lenses



$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

Lenses

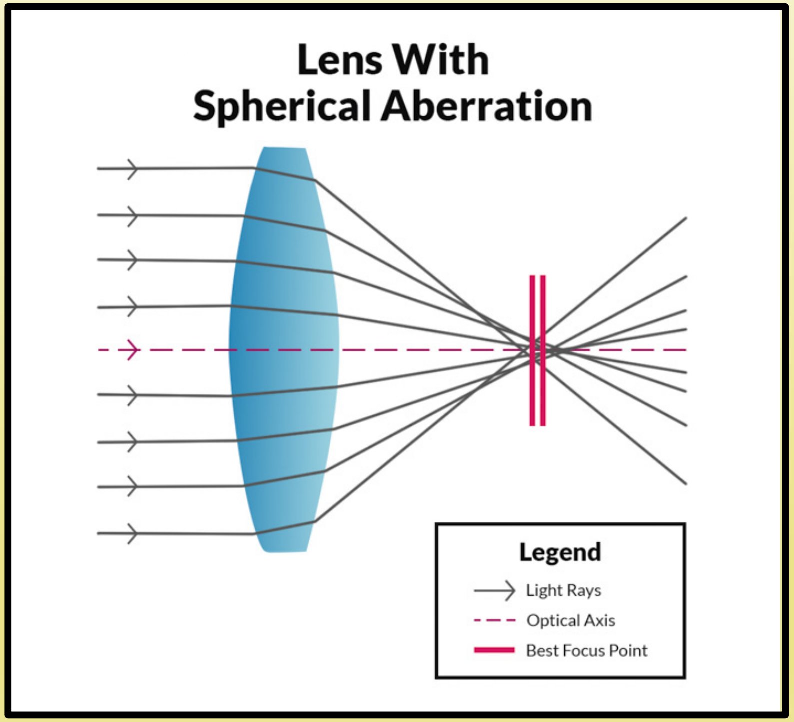


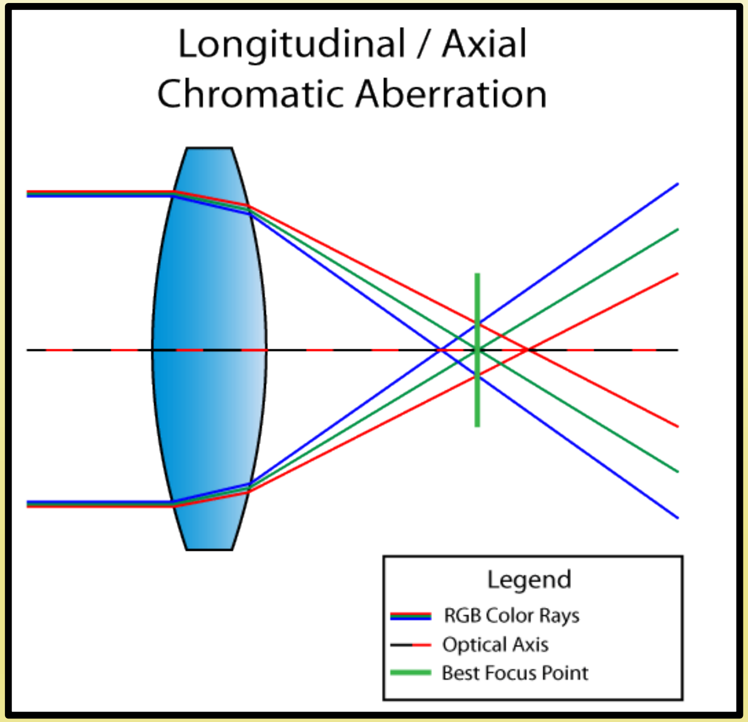
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)t}{nR_1R_2}\right)$$

Lenses

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$





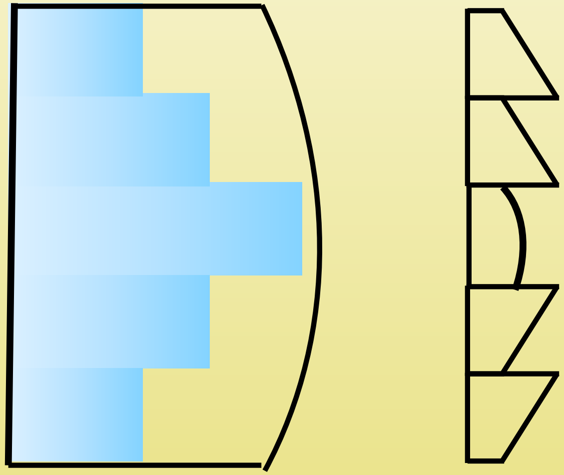
$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

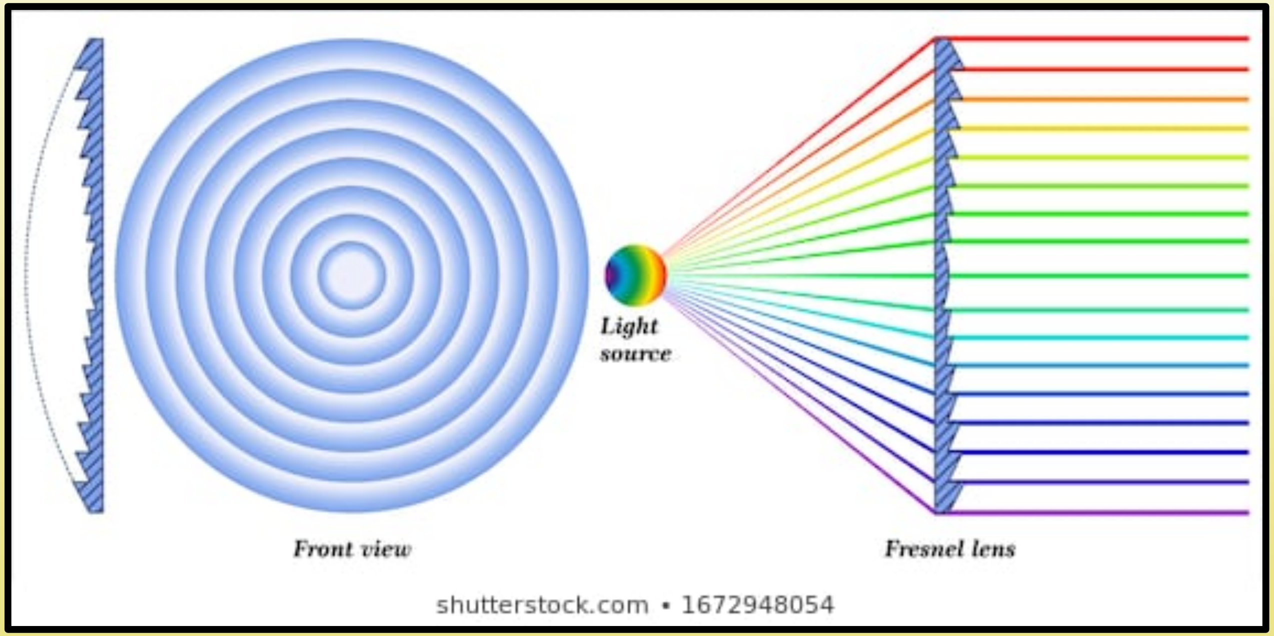
Fresnel lenses

Fresnel lenses are optical elements with the step-profiled surfaces. **They prove to be very useful in sensors and detectors where a high quality of imaging is not required**, **while minimizing the lens weight and cost are the key requirements**. Major applications include light condensers, magnifiers, and focusing element in the infrared thermometers and occupancy detectors. Fresnel lenses may be fabricated of glass, acrylic (visible and near-infrared range), silicon or polyethylene (mid- and far-infrared ranges).

The history of Fresnel lenses began in 1748, when Count Buffon proposed grinding out a solid piece of glass lens in steps of the concentric zones in order to reduce thickness of the lens to a minimum and to lower energy loss. He realized that only the surface of a lens is needed to refract light, because once the light is inside the lens, it travels in a straight line. His idea was modified in 1822 by Augustin Fresnel (1788–1827), who constructed a lens in which the centers of curvature of the different rings receded from the axis according to their distances from the center, so as to practically eliminate spherical aberration.

Fresnel lenses





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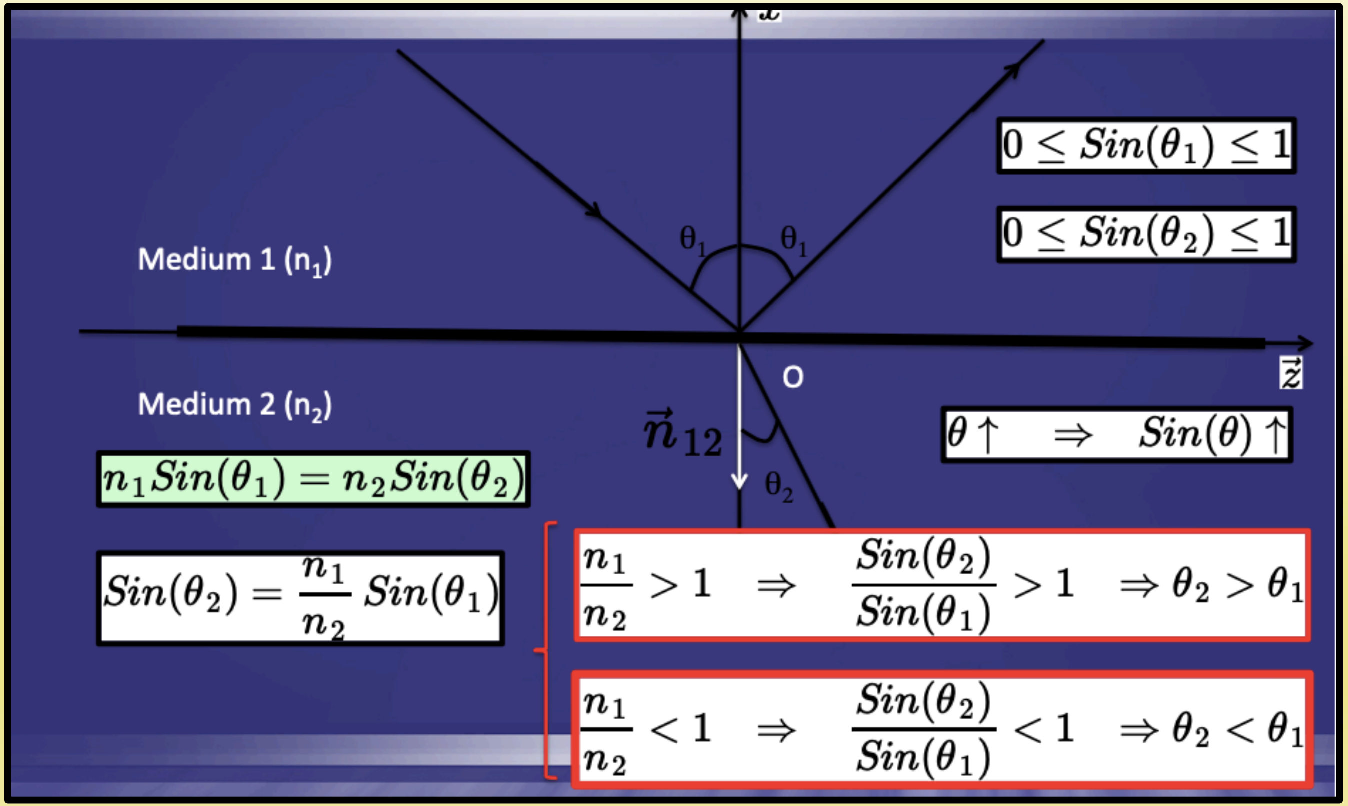
The lens is sliced into several concentric rings. After slicing, all rings still remain lenses that refract parallel incident rays into a common focus. A change in an angle occurs when a ray exits a curved surface, not inside the lens,.

Fiber optics and waveguides



$0 \leq Sin(\theta_1) \leq 1$

$0 \leq Sin(\theta_2) \leq 1$

$\theta \uparrow \quad \Rightarrow \quad Sin(\theta) \uparrow$

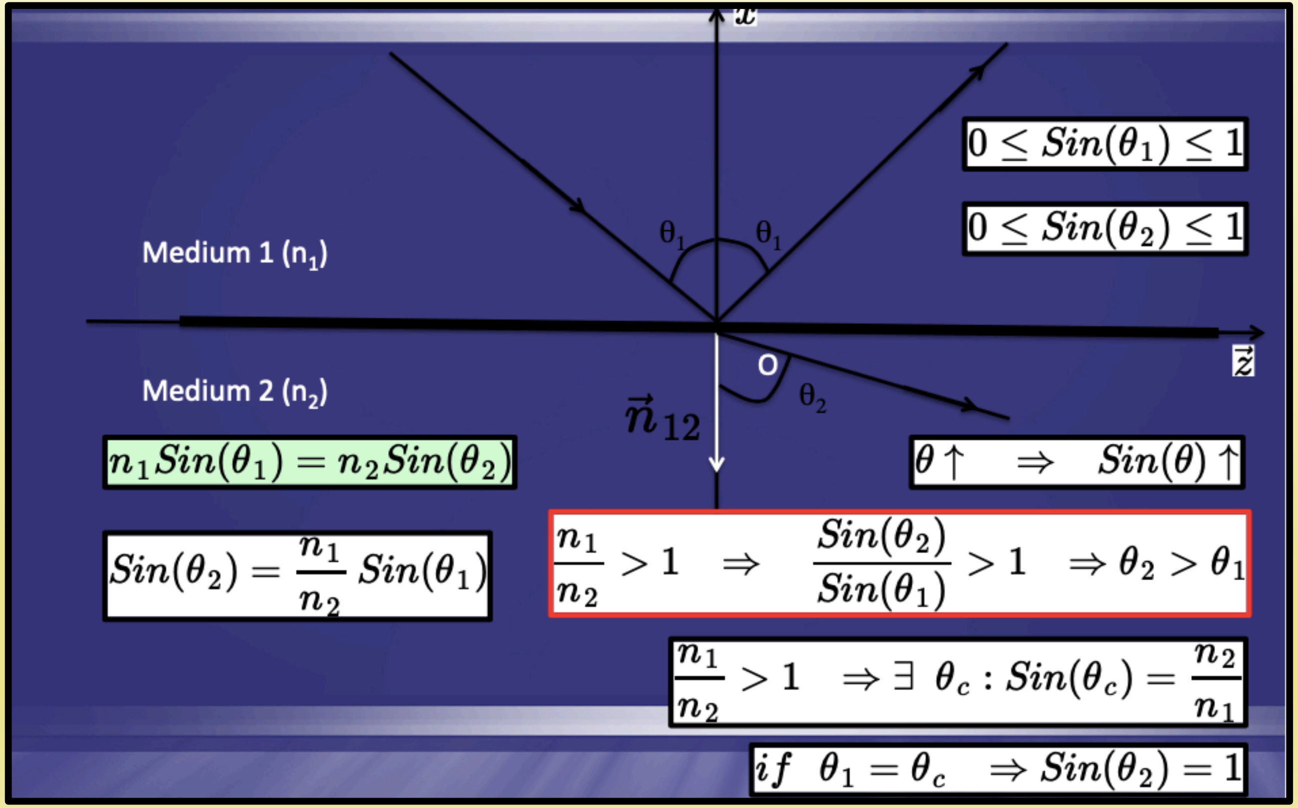
$n_1 Sin(\theta_1) = n_2 Sin(\theta_2)$

$Sin(\theta_2) = \frac{n_1}{n_2} Sin(\theta_1)$

$\frac{n_1}{n_2} > 1 \quad \Rightarrow \quad \frac{Sin(\theta_2)}{Sin(\theta_1)} > 1 \quad \Rightarrow \theta_2 > \theta_1$

$\frac{n_1}{n_2} < 1 \quad \Rightarrow \quad \frac{Sin(\theta_2)}{Sin(\theta_1)} < 1 \quad \Rightarrow \theta_2 < \theta_1$

Fiber optics and waveguides



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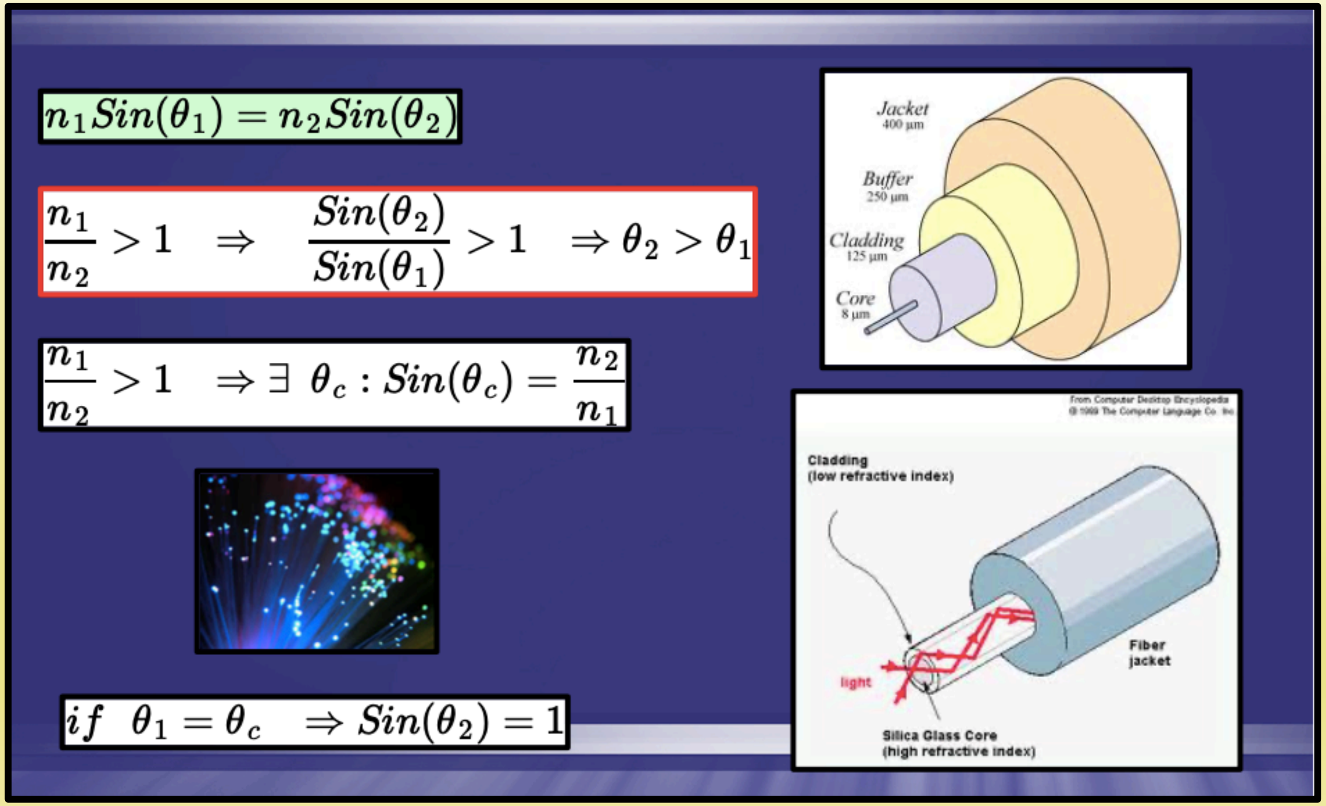
$\frac{n_1}{n_2} > 1 \quad \Rightarrow \exists \ \theta_c : Sin(\theta_c) = \frac{n_2}{n_1}$

$if \ \ \theta_1 = \theta_c \quad \Rightarrow Sin(\theta_2) = 1$

Fiber optics and waveguides



$$\boxed{n_1 Sin(\theta_1) = n_2 Sin(\theta_2)}$$

$$\boxed{\frac{n_1}{n_2} > 1 \quad \Rightarrow \quad \frac{Sin(\theta_2)}{Sin(\theta_1)} > 1 \quad \Rightarrow \theta_2 > \theta_1}$$

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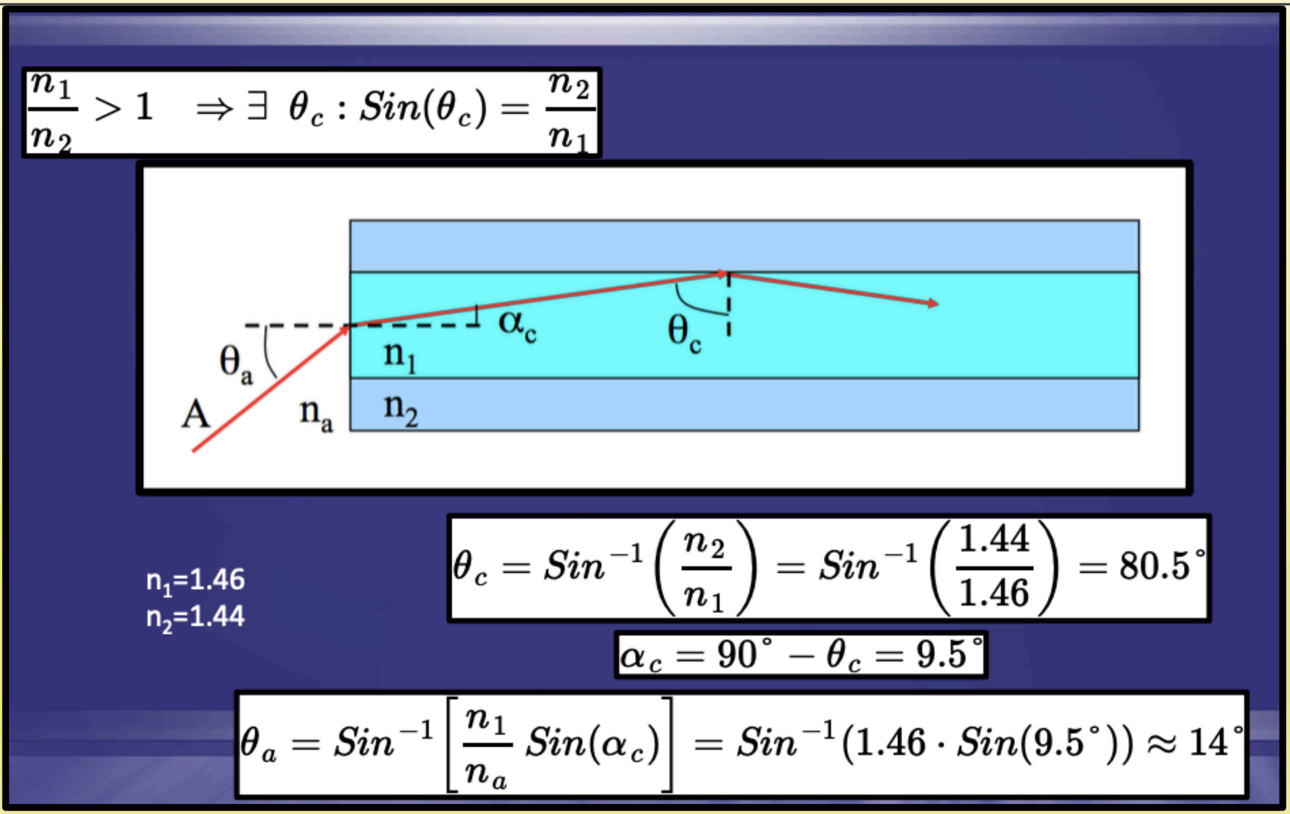
Fiber optics and waveguides



$$\frac{n_1}{n_2} > 1 \quad \Rightarrow \exists \ \theta_c : Sin(\theta_c) = \frac{n_2}{n_1}$$

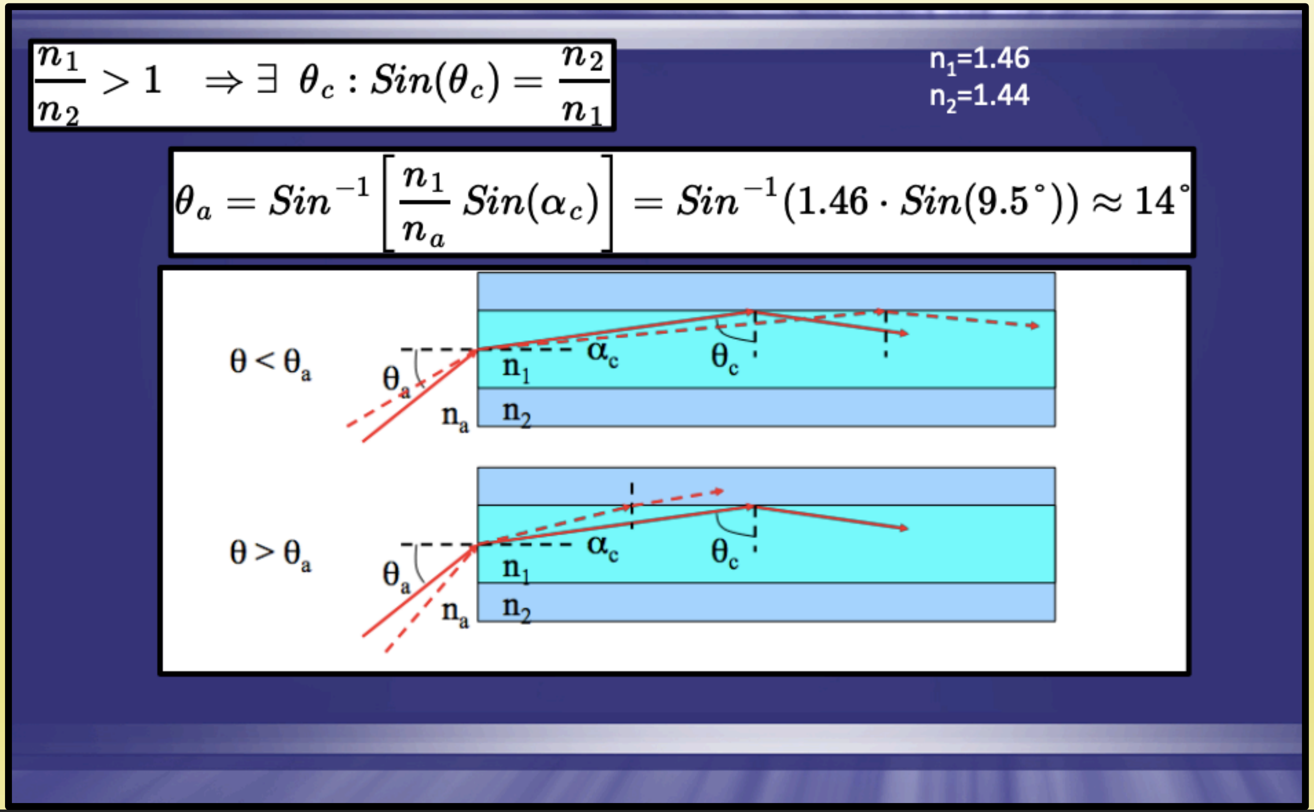
n_1=1.46
n_2=1.44

$$\theta_c = Sin^{-1}\left(\frac{n_2}{n_1}\right) = Sin^{-1}\left(\frac{1.44}{1.46}\right) = 80.5^\circ$$

$$\alpha_c = 90^\circ - \theta_c = 9.5^\circ$$

$$\theta_a = Sin^{-1}\left[\frac{n_1}{n_a} Sin(\alpha_c)\right] = Sin^{-1}(1.46 \cdot Sin(9.5^\circ)) \approx 14^\circ$$

Fiber optics and waveguides



$$\boxed{\frac{n_1}{n_2} > 1 \quad \Rightarrow \exists\ \theta_c : Sin(\theta_c) = \frac{n_2}{n_1}}$$

n_1=1.46
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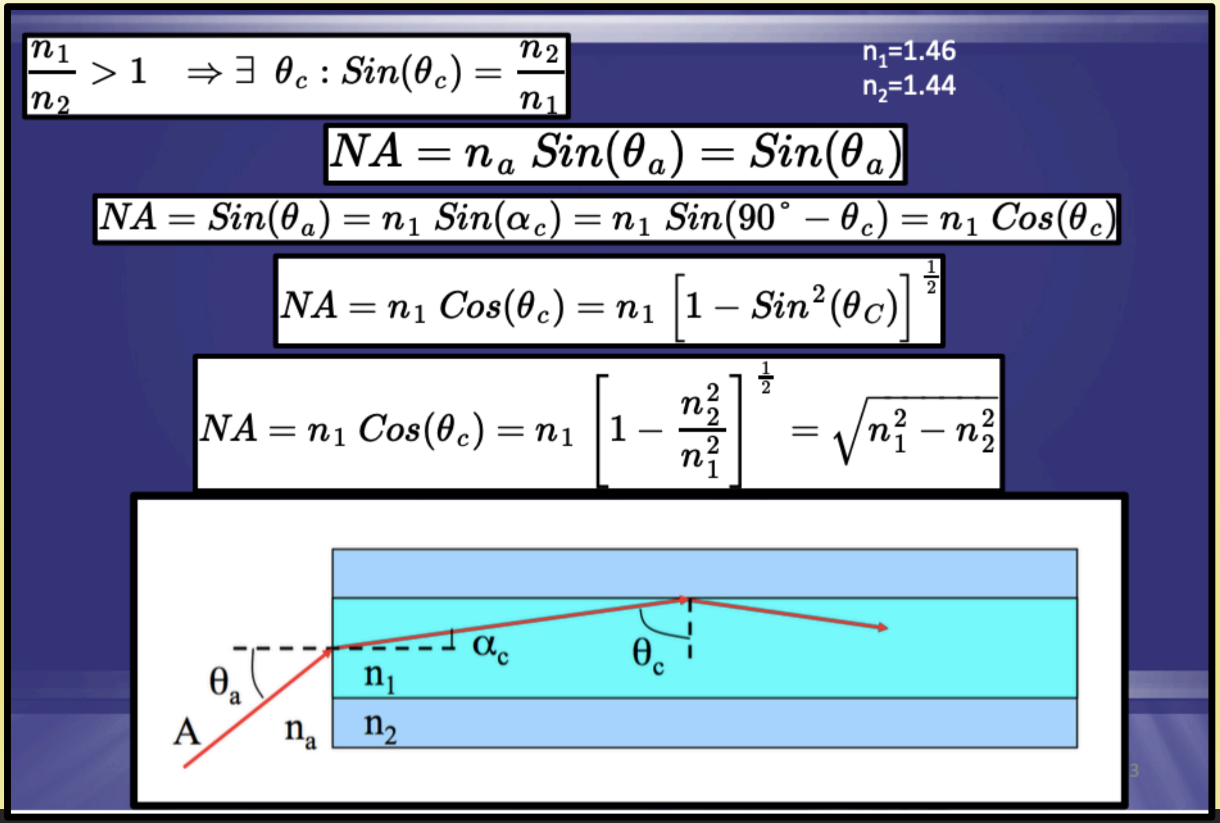
Fiber optics and waveguides



$$\frac{n_1}{n_2} > 1 \quad \Rightarrow \exists\ \theta_c : Sin(\theta_c) = \frac{n_2}{n_1}$$

n_1=1.46
n_2=1.44

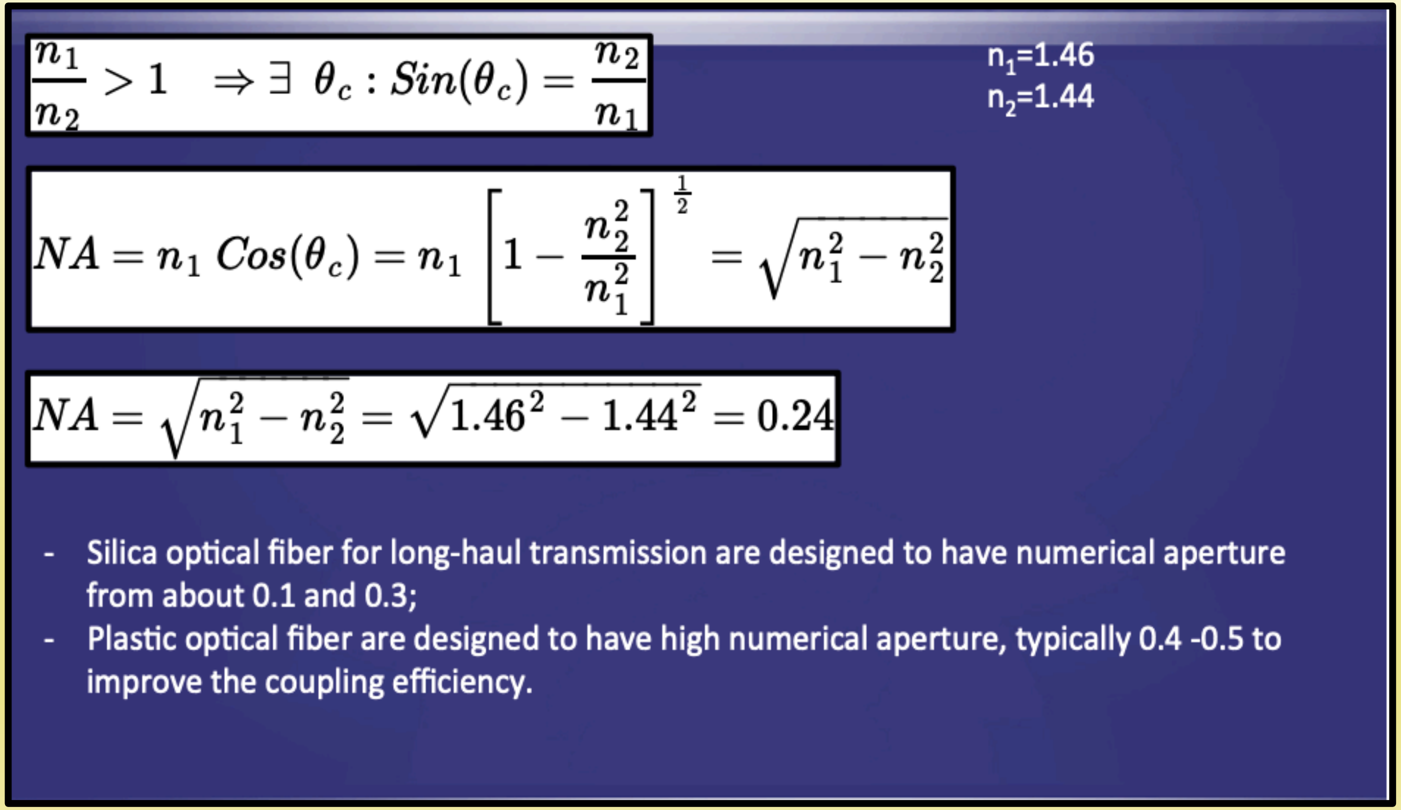
$$NA = n_a\ Sin(\theta_a) = Sin(\theta_a)$$

$$NA = Sin(\theta_a) = n_1\ Sin(\alpha_c) = n_1\ Sin(90^\circ - \theta_c) = n_1\ Cos(\theta_c)$$

$$NA = n_1\ Cos(\theta_c) = n_1\ \left[1 - Sin^2(\theta_C)\right]^{\frac{1}{2}}$$

$$NA = n_1\ Cos(\theta_c) = n_1\ \left[1 - \frac{n_2^2}{n_1^2}\right]^{\frac{1}{2}} = \sqrt{n_1^2 - n_2^2}$$

Fiber optics and waveguides



$$\frac{n_1}{n_2} > 1 \quad \Rightarrow \exists\ \theta_c : Sin(\theta_c) = \frac{n_2}{n_1}$$

$n_1=1.46$
$n_2=1.44$

$$NA = n_1\, Cos(\theta_c) = n_1 \left[1 - \frac{n_2^2}{n_1^2}\right]^{\frac{1}{2}} = \sqrt{n_1^2 - n_2^2}$$

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{1.46^2 - 1.44^2} = 0.24$$

- Silica optical fiber for long-haul transmission are designed to have numerical aperture from about 0.1 and 0.3;
- Plastic optical fiber are designed to have high numerical aperture, typically 0.4 -0.5 to improve the coupling efficiency.

Concentrators

There is an important issue of increasing density of the photon flux impinging on the sensor's surface. In many cases, when only the energy factors are of importance, while focusing or imaging is not required, special optical devices can be used quite effectively. These are the so-called non-imaging collectors, or concentrators. They have some properties of the waveguides and some properties of the imaging optics (like lenses and curved mirrors). The most important characteristic of a concentrator is a ratio of the input aperture area and area of the output aperture. The ratio is called the concentration ratio C. Its value is always more than unity. That is, the concentrator collects light from a larger area and directs it to a smaller area where the sensing element is positioned. A theoretical maximum for C is:

$$C_{max} = \frac{1}{(\sin \vartheta_i)^2}$$

ϑ_i Is the maxim input semi-angle

Concentrators

Under these conditions, the light rays emerge at all angles up to π/2 from the normal to the exit face. This means that the exit aperture diameter is smaller by $\sin\vartheta_i$ times the input aperture. This gives an advantage in the sensor design as its linear dimensions can be reduced by that number while maintaining a near equal efficiency. The input rays entering at angle ϑ_i will emerge within the output cone with the angles dependent of point of entry. The concentrators can be fabricated with reflective surfaces (mirrors) or refractive bodies (Fresnel lenses, e.g.), or as combinations of both.

Coating for thermal absorption

All thermal radiation sensors rely on absorption or emission of electromagnetic waves in the mid- and far-infrared spectral ranges. According to Kirchhoff’s discovery, absorptivity α and emissivity ε is the same thing. Their value for the efficient sensor’s operation must be maximized, i.e., it should be made as close to unity as possible. This can be achieved by either a special surface processing of a sensing element to make it highly emissive, or by covering it with a coating having high emissivity. Any such coating should have a good thermal conductivity and a very small thermal capacity, which means it shall be thin, but not too thin, a preferred thickness is at least 1 maximum wavelength it should absorb.

Several methods are known to give a surface the emissive (absorptive) properties. Among them a deposition of thin metal films (like Nichrome) having reasonably good emissivity, a galvanic deposition of porous platinum black, and evaporation of metal in atmosphere of low-pressure nitrogen. The most effective way to create a highly absorptive (emissive) material is to form it with a porous surface. Particles with sizes much smaller than the wavelength generally absorb and diffract light. High emissivity of a porous surface covers a broad spectral range, however, it decreases with the increased wavelength. A film of goldblack with a thickness corresponding to 500 $\mu g/cm^2$ has an emissivity over 0.99 in the near-, mid-, and far-infrared spectral ranges.

Antiriflective coating (ARC)

Windows and lenses for use in the mid- and far-infrared spectral ranges are fabricated of materials having high refractive indices that cause a strong reflection at the boundary with air. For example, a Ge plate, in the wavelength from 4 to 16 μm due to a reflective loss, has transmission of only about 40 %. To reduce reflective loss, both sides of the window or lens may be coated (vacuum evaporation) with the **antireflective coating** (ARC) to form a gradual transition from air to the lens (window) refractive index. For example, an ARC layer having thickness of a quarter wavelength (λ/4) of YbFe3 (Ytterbium Fluoride) is applied on the front and back surface of a lens. YbFe3 has a relatively low-refractive index (1.52), yet is transparent in a broad wavelength range from UV to over 12 μm. Thus, its thin layer serves as a buffer, reducing reflection and passing more light through the window boundary.

For even a further improvement in transmission, a multilayer ARC may be applied. As a result, the transmission of light, especially in the mid- and far-infrared ranges, is substantially increased.