Dipartimento INFOCOM
Università degli Studi di
Roma “La Sapienza”

Departamento de Señales y
comunicaciones
ULPGC

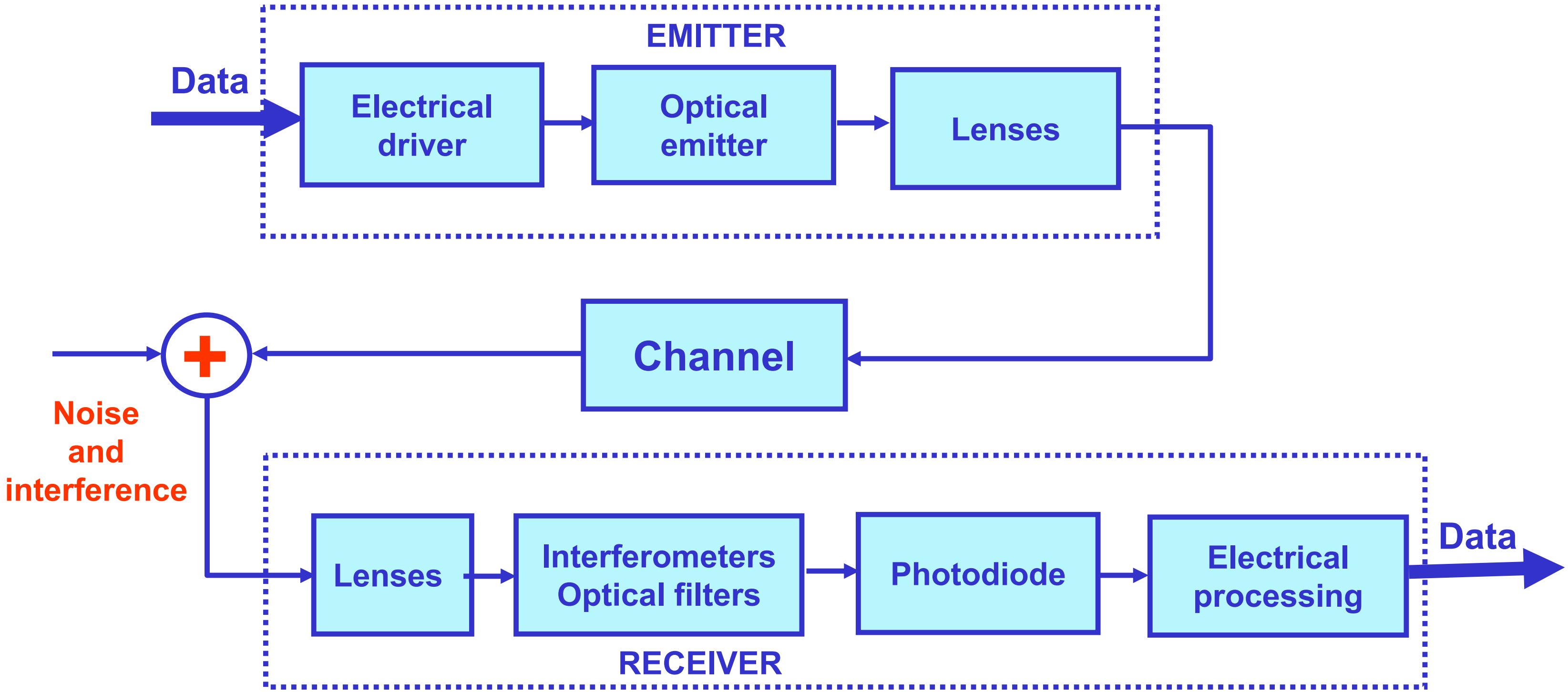
Optical Communications

Telecommunication Engineering
School of Engineering
University of Rome La Sapienza
Rome, Italy
2005-2006

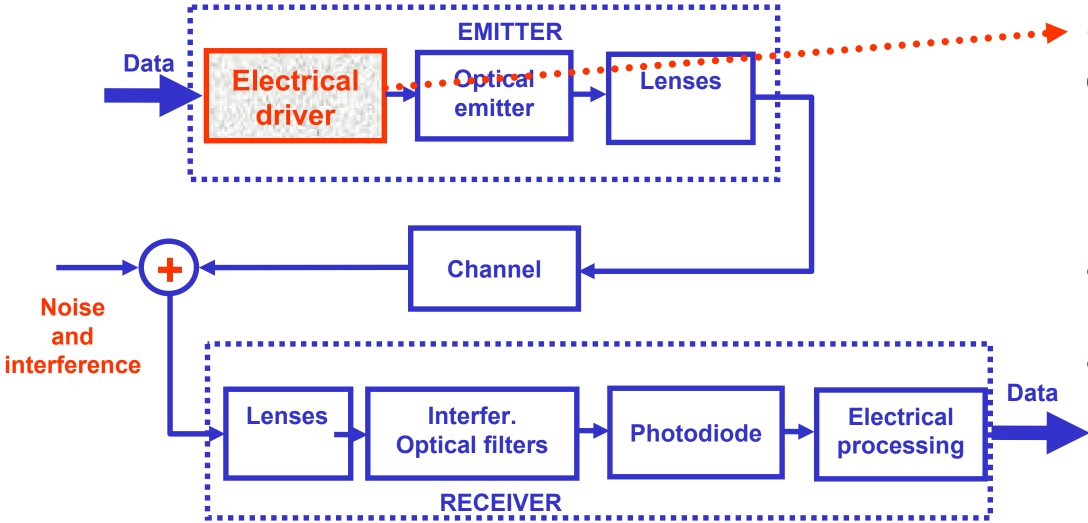
Lecture #2, May 2 2006

The Optical Communication System

BLOCK DIAGRAM OF AN OPTICAL COMMUNICATION SYSTEM (OCS)



OCS: the electrical driver



Generates current for the optical emitter and adapts the input signal

It also may contain thermal adjustment circuits in order to keep the emitted optical power as constant as possible

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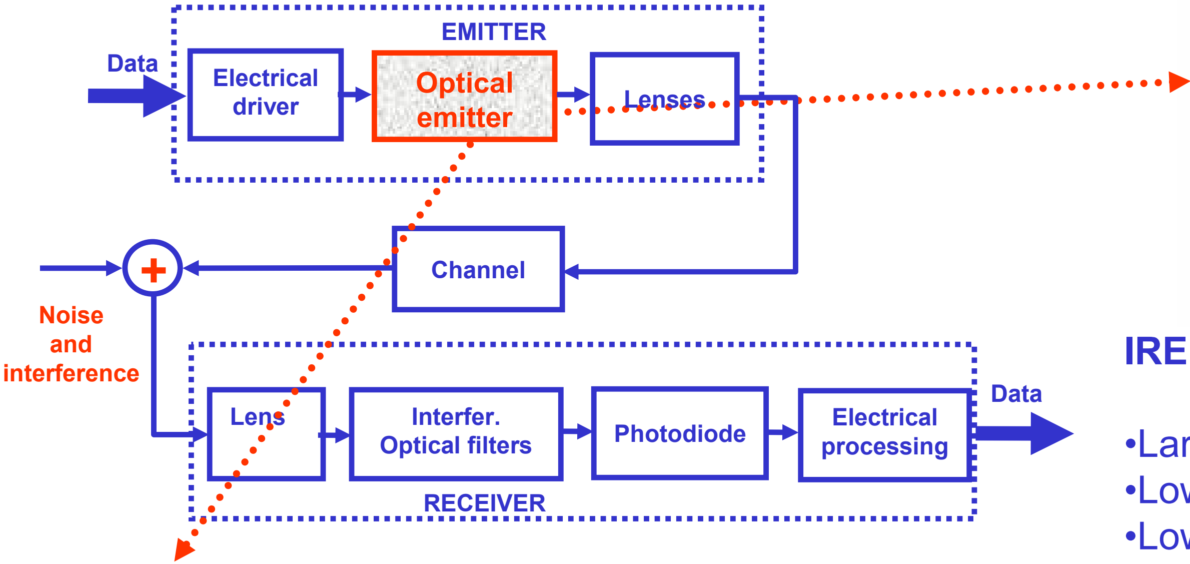
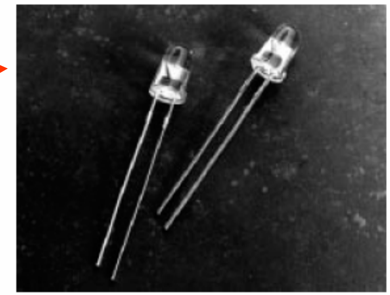
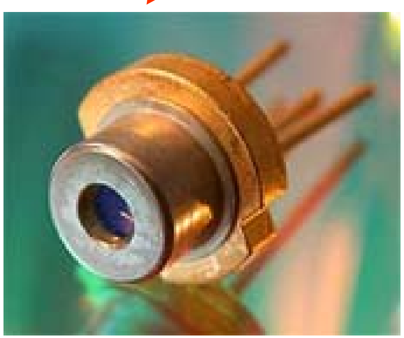
OCS: the optical emitter





IRED (InfraRed Emitting Diode)

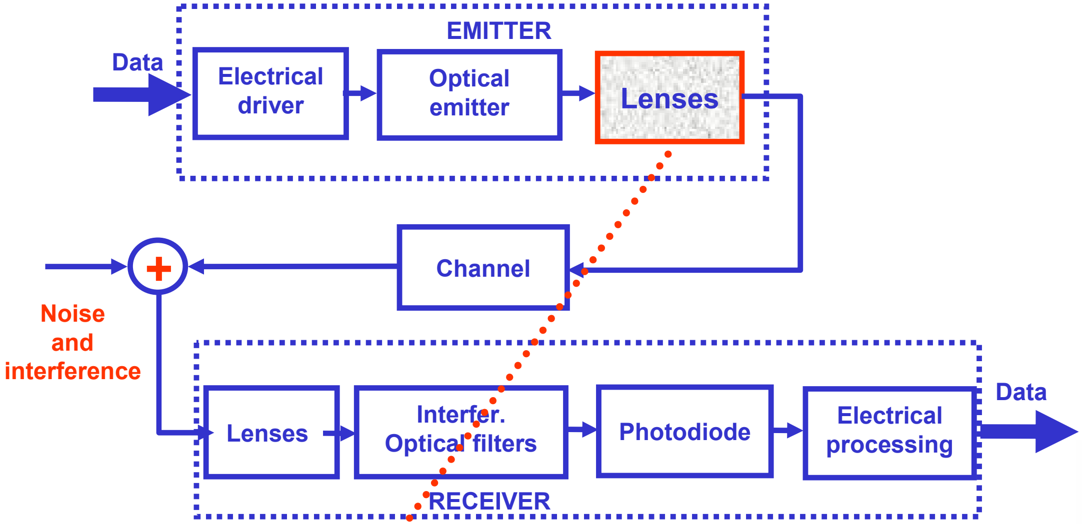
- Large spectral bandwidth
- Low-power
- Low transmission bandwidth

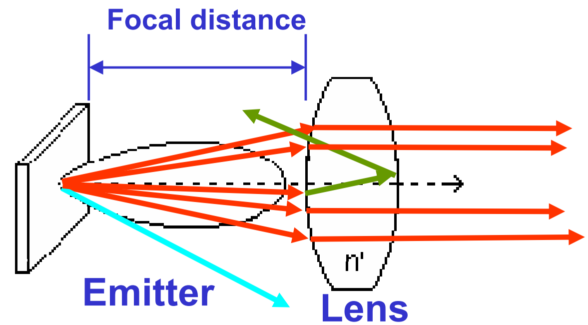


Laser diodes:

- Spectral, spatial and time coherency
- Very large available transmission bandwidth

OCS: lenses

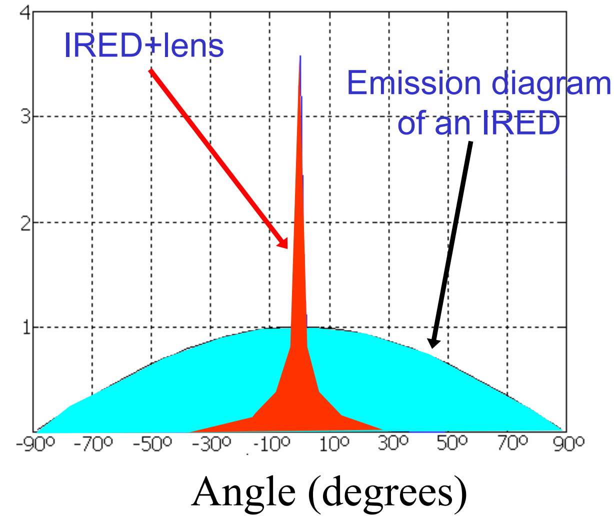




Lenses are used to focus the emitted beam on a reduced area.

There are three sources of losses:

- If the emitter is not at the focal distance some rays are not concentrated and may be go lost
- Due to imperfections in the lens, some rays may eventually be deviated and sent backwards
- All rays are in any case attenuated depending on the material of the lens (plastic, glass…)



OCS: lenses

Lenses are used to change the direction of rays of light. The effect of a lens on light is embodied in the **Snell’s law of refraction**. This law states that, in passing from a rarer medium (low refraction index) into a denser one (high refraction index), light is refracted towards a direction that is closer to the normal of the plane separating the two media. In passing from a denser to a rarer medium, light is refracted away from the normal. The degree of bending or refracting is in accordance with the equation:

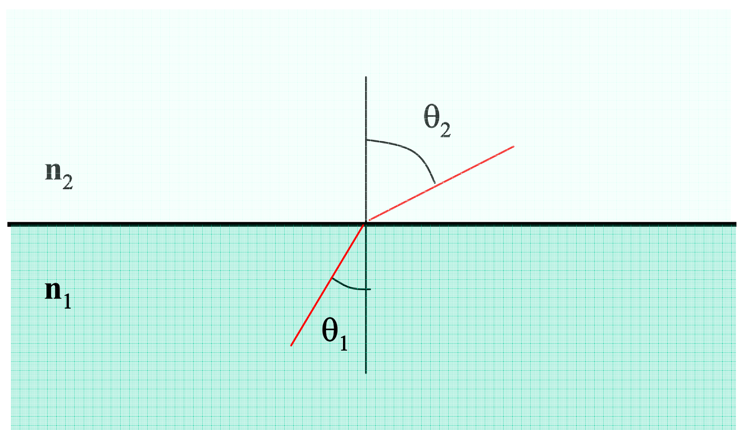
Angle of incidence

Angle of refraction

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

Refraction index of the two media

$n_1 > n_2$



OCS: lenses

The critical angle

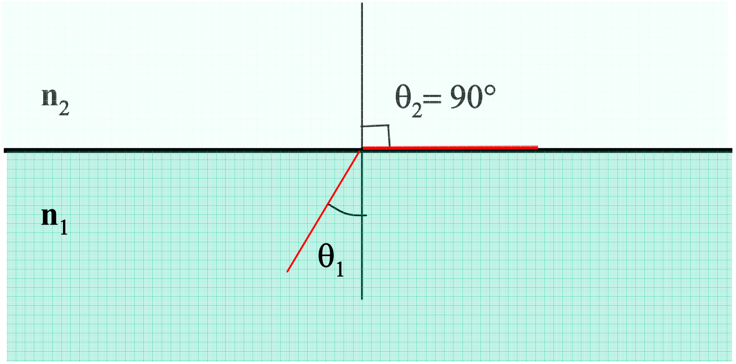
Consider the case θ_2 = 90º. θ_1 is then called the critical angle θ_c. For all angles $\theta_1 > \theta_c$, total internal reflection occurs.

Therefore,

$$\theta_c = \arcsin(n_2/n_1)$$

NOTE that for total reflection to occur n_2/n_1 must be <1, and therefore $n_1 > n_2$

$n_1 > n_2$

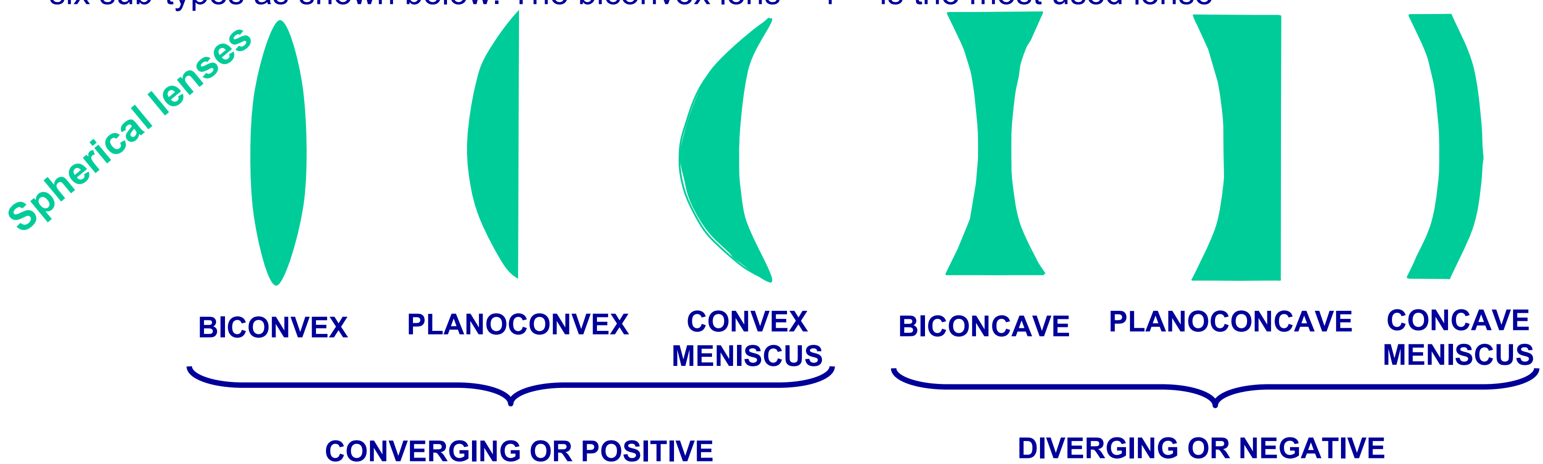


OCS: lenses classification

Converging lenses are known as “positive,” “plus,” or “convex” lenses. They are thicker in the middle than at edges. They cause both parallel rays of light and converging rays of light on the opposite side of the lens.

Diverging lenses are known as “negative,” “minus,” or “concave” lenses. They are thinner in the middle than at the edges. They cause parallel rays of light to diverge or spread in opposite directions on the other side of the lens. If rays initially are diverging towards such a lens, they will diverge even more strongly after passing through the lens.

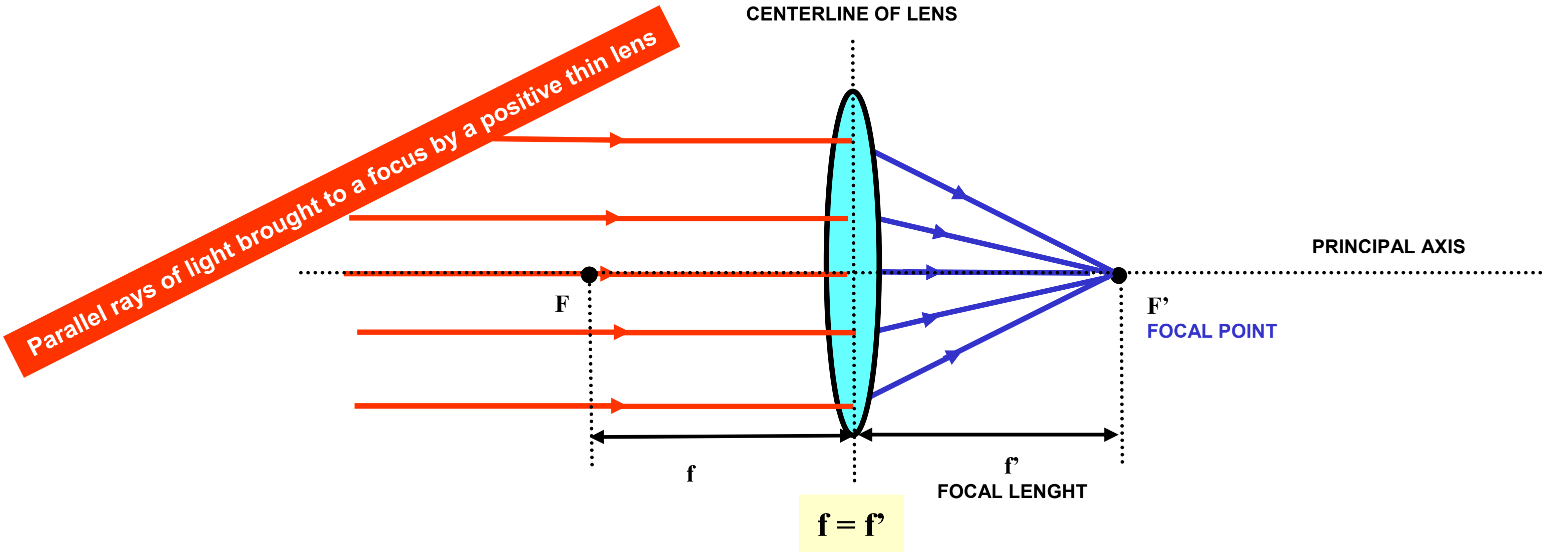
Further subdivisions of these two basic types can be made according to the **curvature** of the lens surface and to the material of the lenses.
Spherical lenses are lenses with surfaces that are spherical in shape. Spherical lenses can be classified into six sub-types as shown below. The biconvex lens—"i"—is the most used lense



OCS: lenses and focal distance

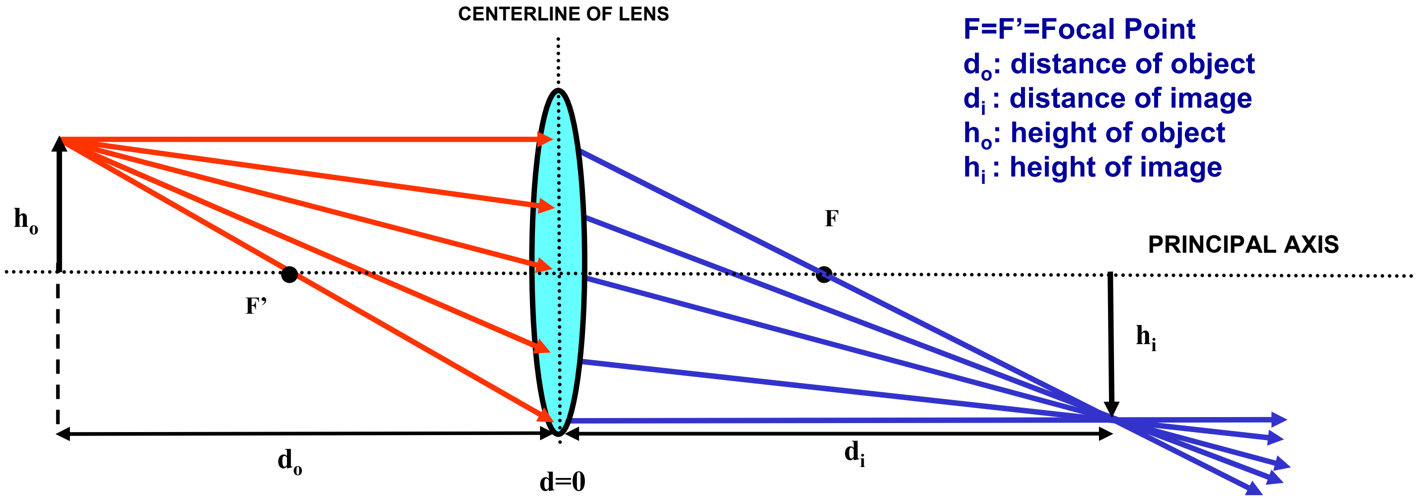
The focal point F' of a positive lens is that point where parallel rays of light that are incident on the lens from left to right converge. The focal point F on the left side of the positive lens is that point to which parallel rays, incident on the lens from right-to-left, would converge.

The **focal length** of a "thin lens" is the distance at which the focal point is with respect to a vertical centerline of the lens.



The same concept is true for diverging lenses but the focal distance of a diverging lens is negative

OCS: lenses and focal distance



The relationship between distances and focal lenght follows the "thin lens equation".
(*remember that the focal distance of a diverging lens is negative*)

$$1/f = 1/d_o + 1/d_i$$

The linear magnification (m) is the ratio of the image size to the object size $|m| = h_i / h_o$

If the image and object are in the same medium then m is simply the image distance divided by the object distance, in negative.

$$m = - (d_i / d_o)$$

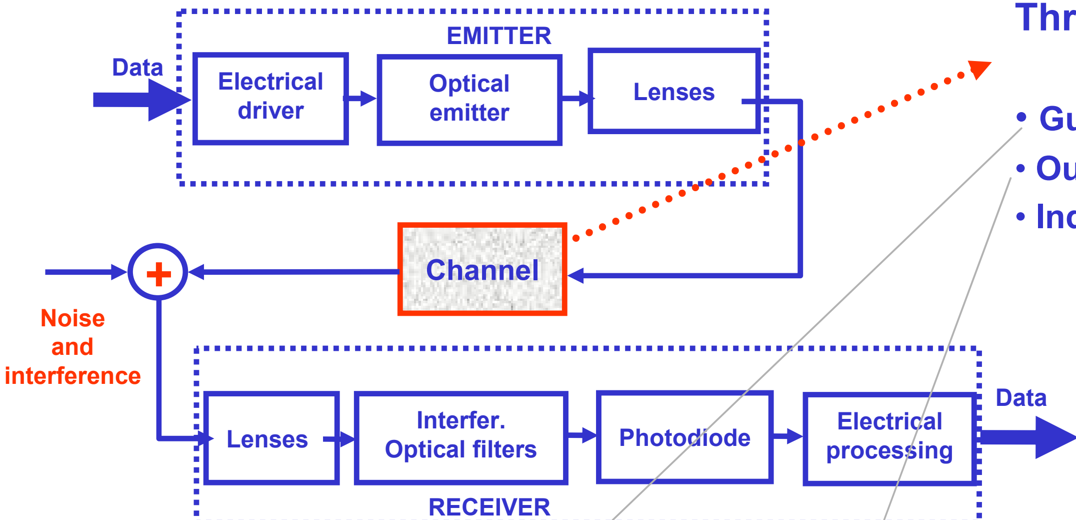
POWER OF LENSES

The **power** of a lens is the reciprocal of its focal length in meters. It measures the ability of the lens to converge or diverge light rays (e.g. the higher the positive power, the more converging the lens)

The unit of power is the "**diopter**" (usually indicated as D). One diopter is the power of a lens with a focal length of one meter. Therefore, a converging lens with a focal length of 20 cm (0.2 m) has a power of 1/0.2 m = 5 D.

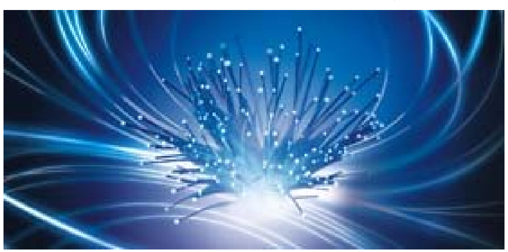
Note that a lens that causes light to converge has a positive power, and a lens that causes light to diverge has a negative power. For example, a diverging lens with a focal length of –25 cm has a power of 1/–0.25 = –4 D.

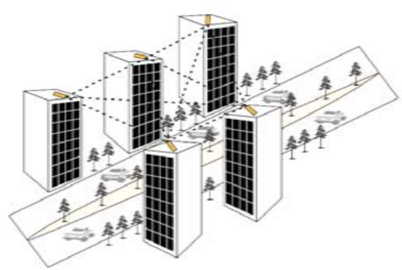
OCS: the channel

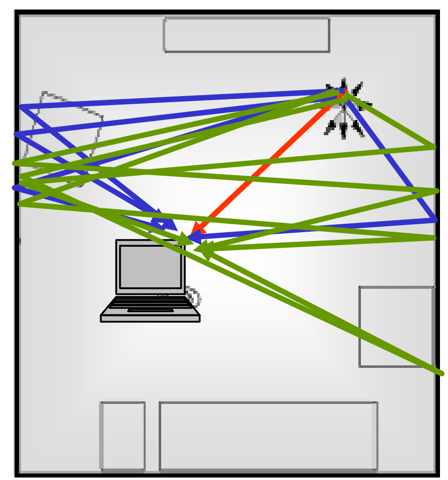


Three different scenarios:

- Guided systems
- Outdoor systems (Line Of Sight-LOS)
- Indoor systems (Diffuse)

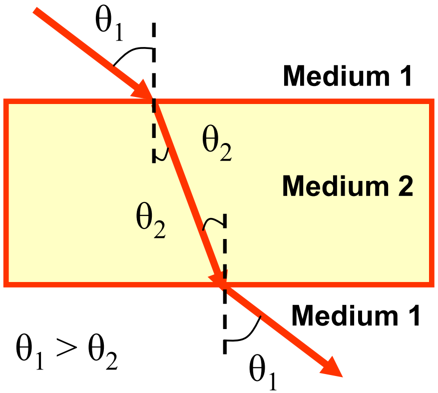






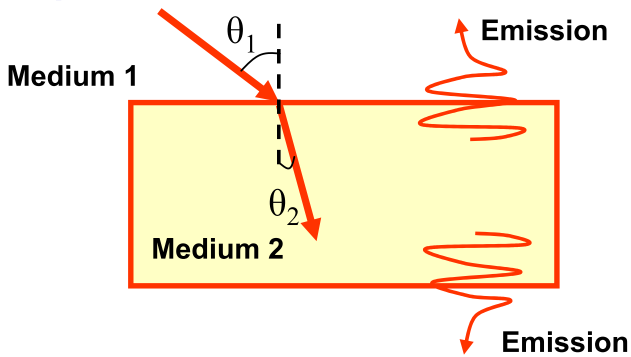
OCS: the channel –transmittance and absorptance

Transmission



Transmittance (τ) - The ratio of the transmitted radiant energy to the total radiant energy incident on a given body.
A fraction (up to 100%) of the radiation may penetrate into specific media such as water, and if the material is transparent and thin in one dimension, it passes through, with some attenuation.

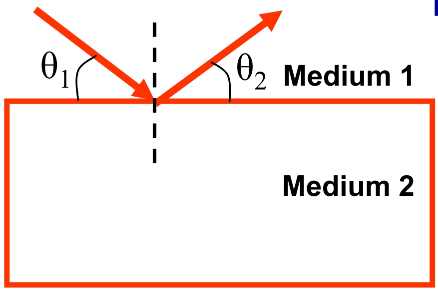
Absorption



Absorptance (α) or absorption factor - The ratio of the radiant energy absorbed by a body to the total energy falling on it.

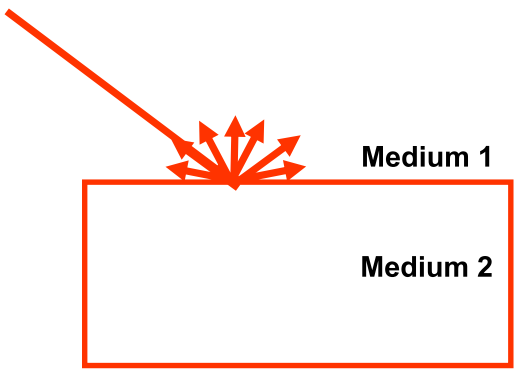
Some radiation is absorbed through electron or molecular reactions and heats the medium, while a portion of this energy is re-emitted, usually at longer wavelengths (smaller energy).

REFLECTION AND SCATTERING



Reflection $\theta_1 = \theta_2$

Reflectance (ρ) - The ratio of the reflected or scattered radiant energy to the total radiant energy incident on a given body.

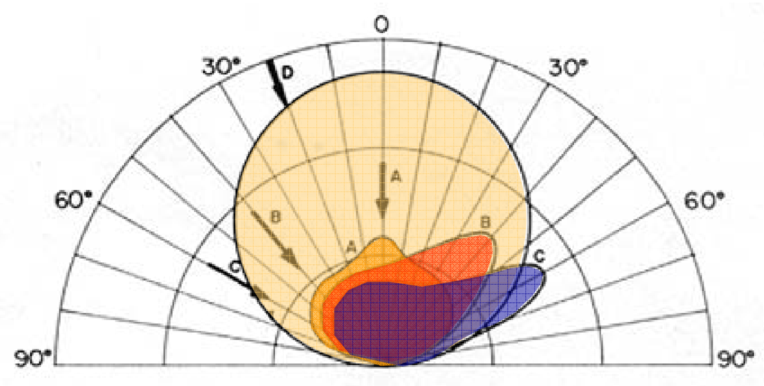


Scattering

REFLECTION AND SCATTERING

There are two general types of reflecting surfaces that interact with electromagnetic radiation: specular (smooth) and diffuse (rough). Radiation impinging on a diffuse surface tends to be reflected in many directions (scattered).

The Rayleigh criterion is used to determine surface roughness with respect to radiation:



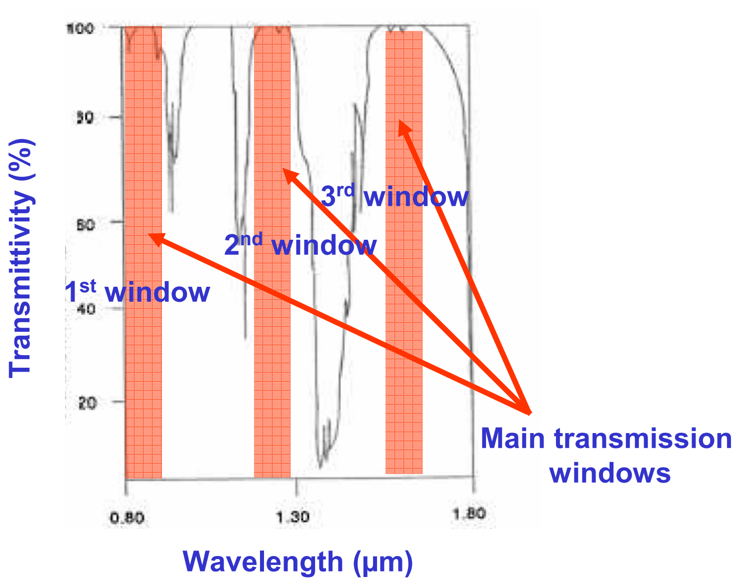
Smooth if: $h < \lambda/8 \cdot \cos\theta$

h is the surface irregularity height (measured in Angstroms, 1°A = 10^{-10} m)
λ is the wavelength (also in Angstroms)
θ is the angle of incidence measured from the normal to the surface.

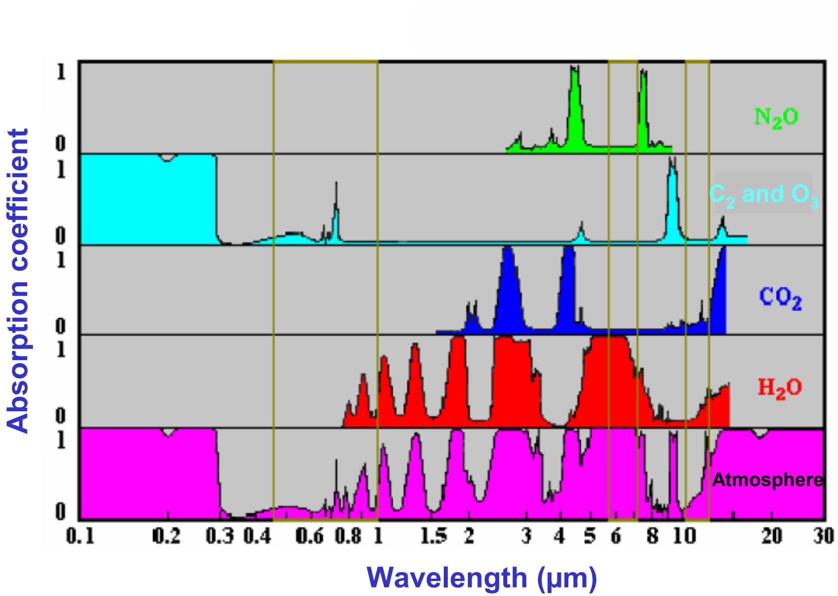
If <, the surface is smooth; if > the surface is rough and acts as a diffuse reflector.

ATMOSPHERICAL ABSORPTION & TRANSMISSION WINDOWS

Main transmission windows are between 0.72 and 1.5 μm. The absorption due to the combination of H_2O and CO_2 prevails between 0.7-2.0 μm.

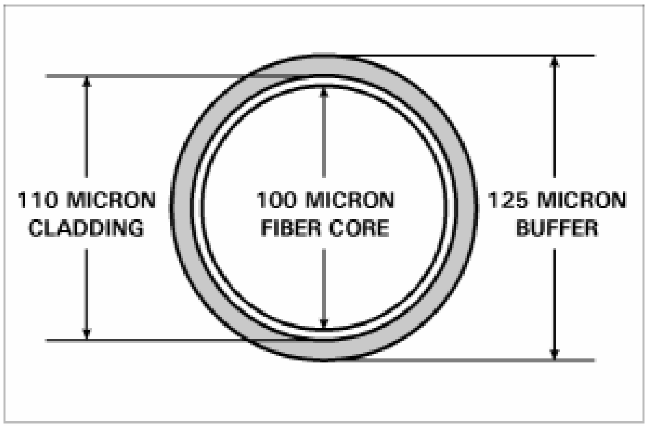


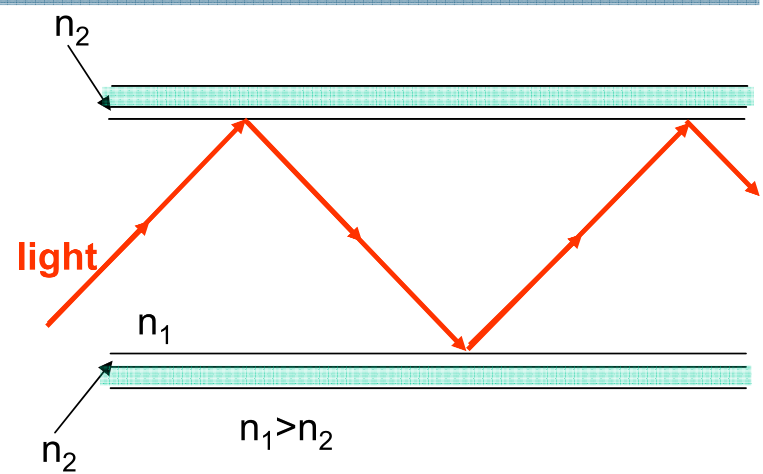
Transmission in the air at sea level, for 1 km distance



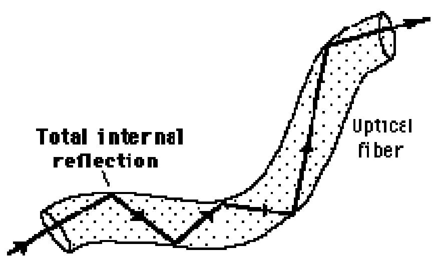
Absorption for different atmospherical components

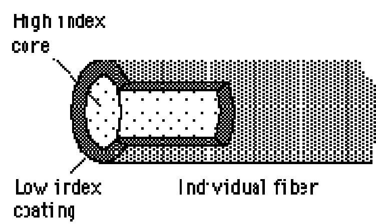
TRANSMISSION OVER OPTICAL FIBER





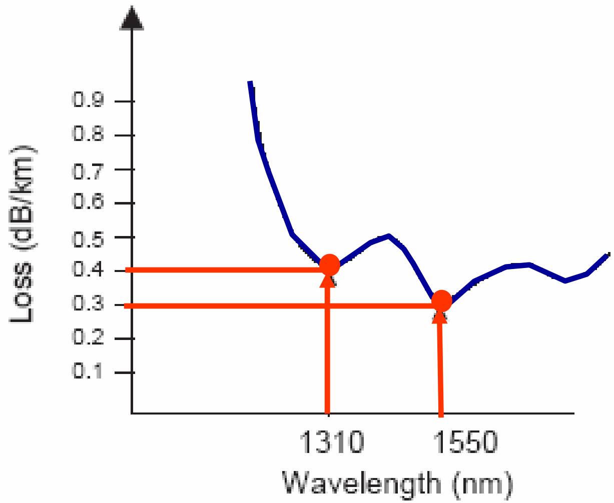
Basic Principle: light is transmitted over an optical fiber by multiple reflections within a long "cylindrical mirror". The mirrored surface occurs at the core/cladding interface. By sending on/off bursts of light within the optical fiber, information can be guided along different paths.





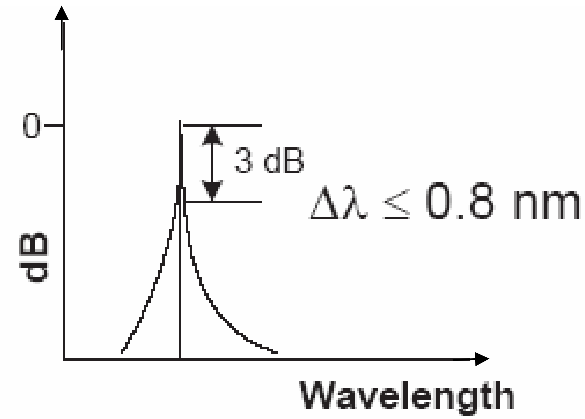
FIBER PARAMETERS

Wavelength: The wavelength of the optical signal determines the cable loss window within which the system operates.



Cables Losses at Various Wavelengths

Linewidth: is a measure of laser spectral purity, and determines the jitter penalty (how much jitter gets added to the signal). At 1310 nm the jitter penalty is approximately 2.5psec/km every nm of deviation from 1310 nm. At 1550 nm the jitter penalty is approximately 17psec/km every nm of deviation.



Example of the spectrum of a Laser

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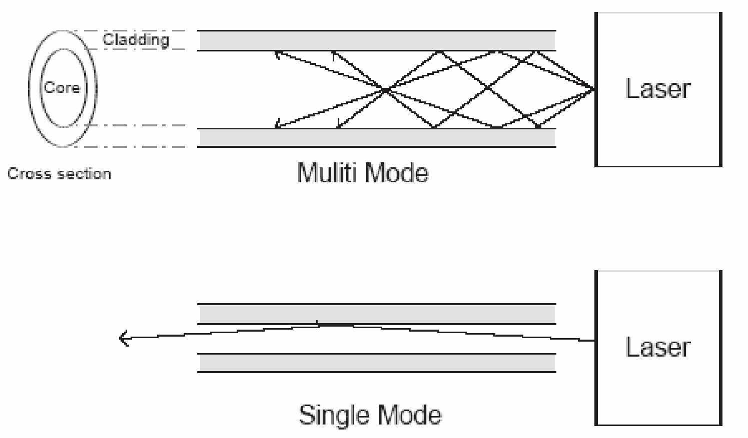
FIBER CLASSIFICATION

Single Mode and Multi Mode fibers:

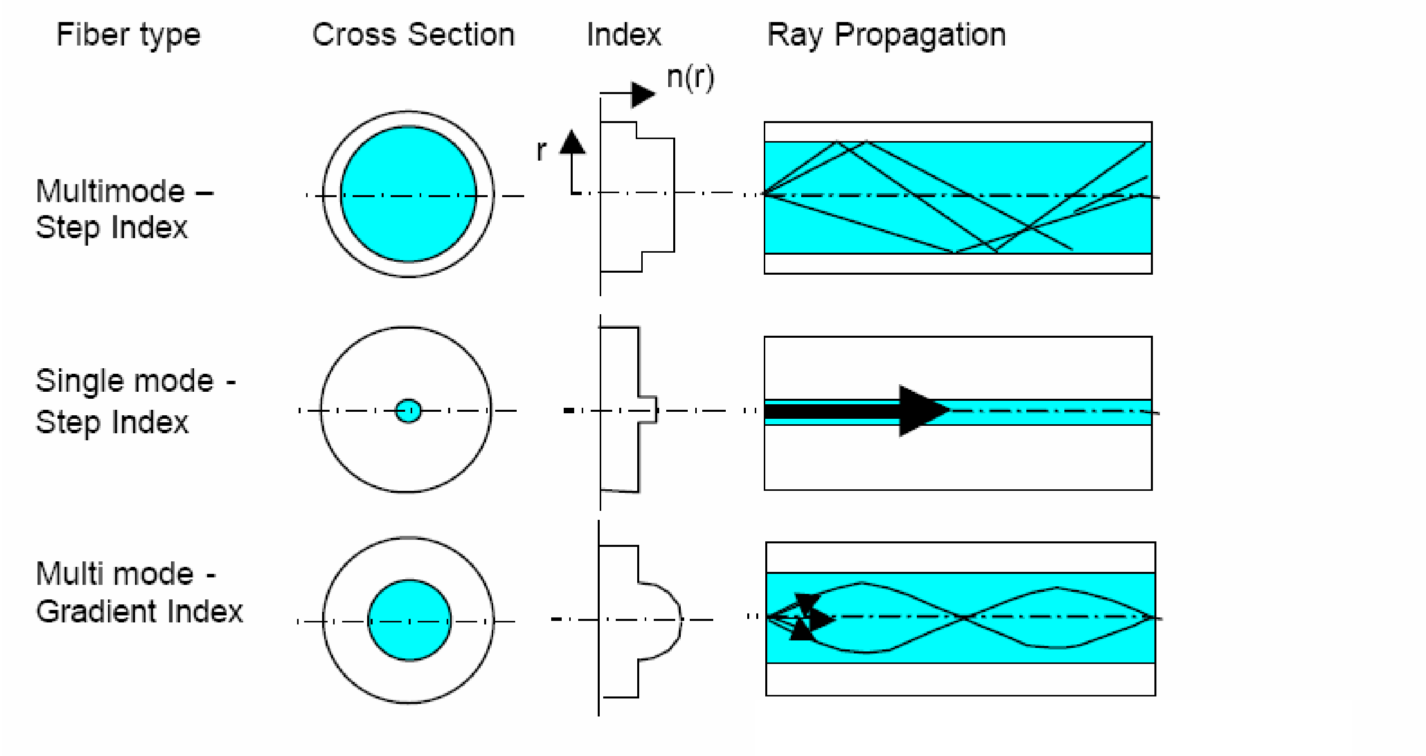
Fibers may be single-mode or multi-mode. Multi-mode fibers have larger core diameters (50μm or 62.5μm) than single-mode fibers (9μm core diameter).

In a multi-mode fiber light is reflected at different angles as it propagates down the transmission path, causing dispersion called modal dispersion.

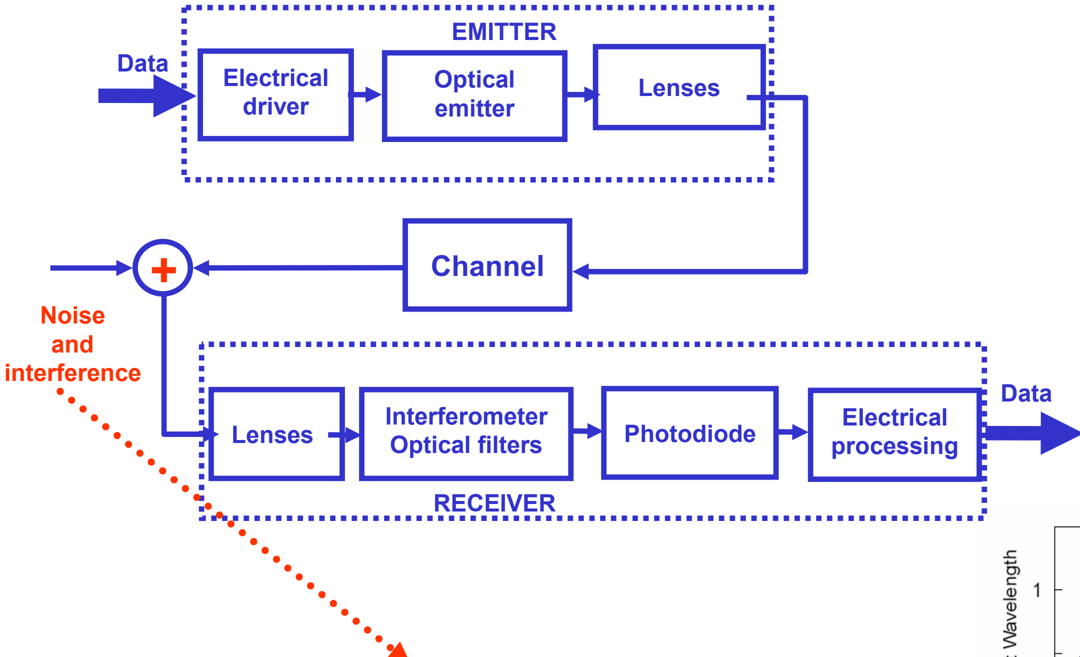
Single-mode fibers are thinner, confine the optical signal to a straighter path with fewer reflections, significantly reducing dispersion. Larger distances can therefore be covered.



FIBER TYPES

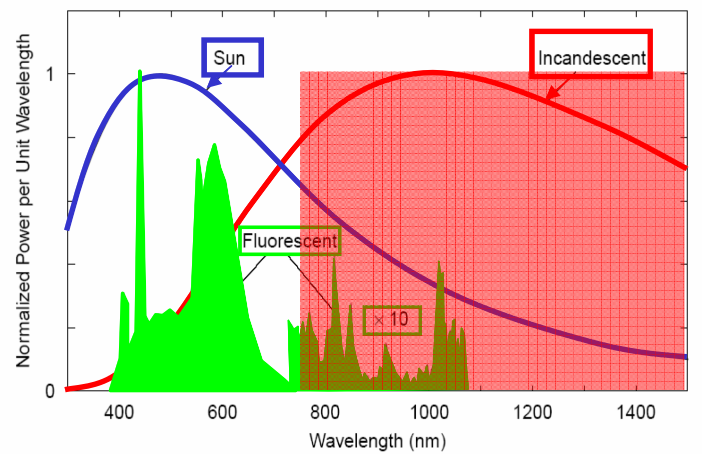

Fiber type
Cross Section
Index
Ray Propagation
n(r)
r
Multimode –
Step Index
Single mode -
Step Index
Multi mode -
Gradient Index

OCS: noise and interference

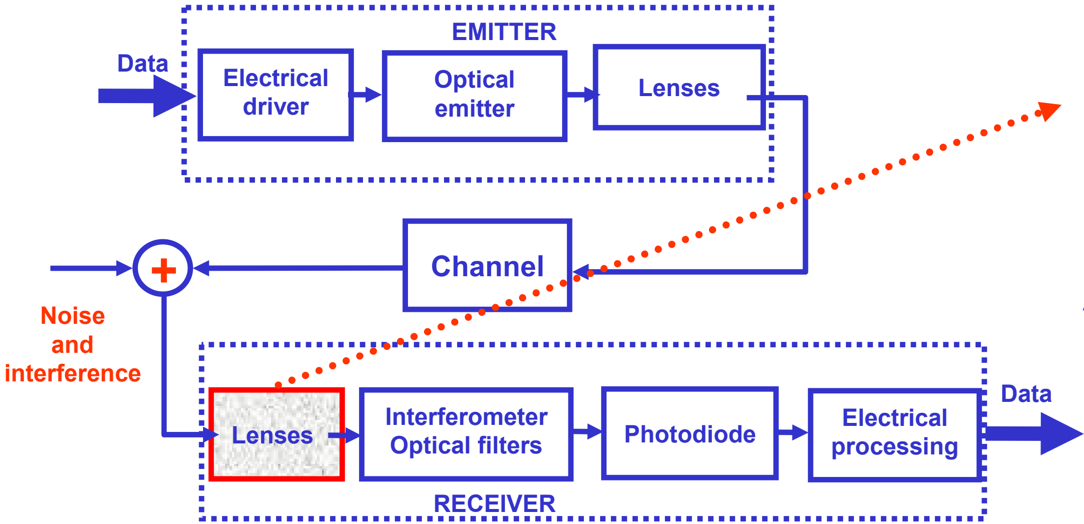


Main noise sources are light (from natural and artificial illumination) and thermal noise

Infrared communications noise spectra

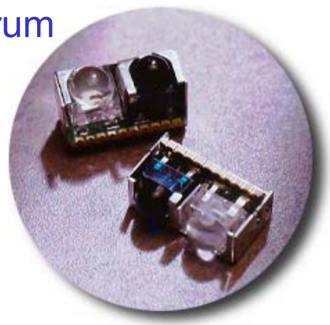


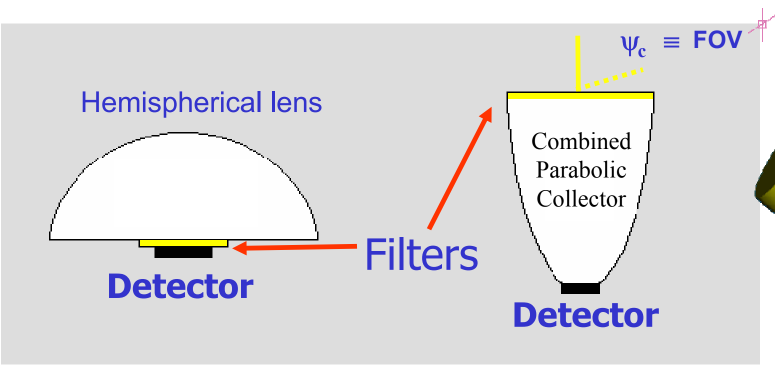
OCS: lenses at the receiver

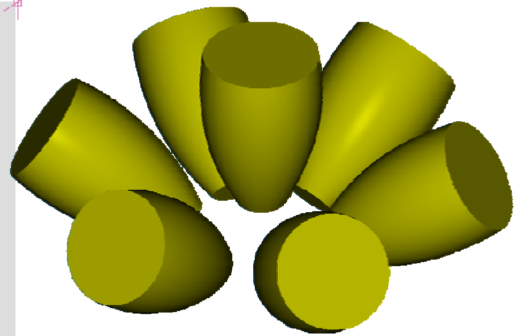


Increased Field-of-view (FOV) implies more received optical power but also more multipath dispersion due to different delays inside the lens itself

A tinted lens may act as a filter for avoiding sun light in the visible part of the spectrum

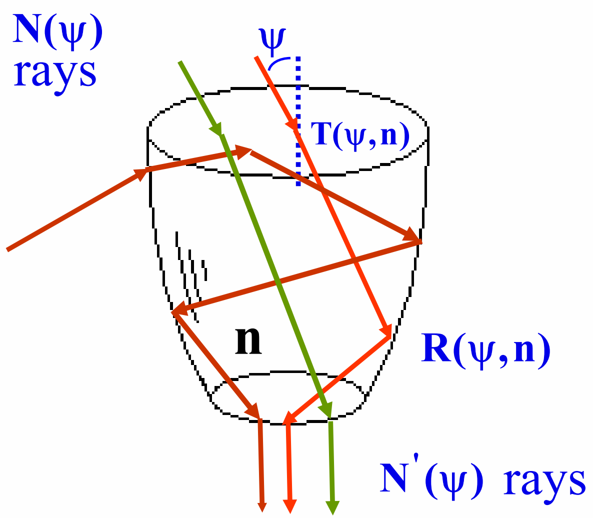






One can also combine several lenses to further increase FOV (spatial diversity)

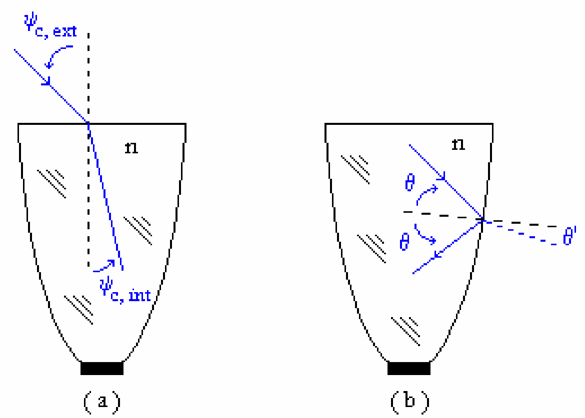
COMBINED PARABOLIC COLLECTOR (CPC)



n is the refraction index

CPCs are a special class of concentrators, originally developed for solar energy applications.

They are characterized by a large FOV, that implies high optical efficiency but also severe multipath effects (especially in indoor diffuse systems) and variable propagation delays inside the lens.



- Step (a) the ray is conveyed in the lens
- Step (b) the ray is totally reflected

OPTICAL EFFICIENCY OF A CONCENTRATOR

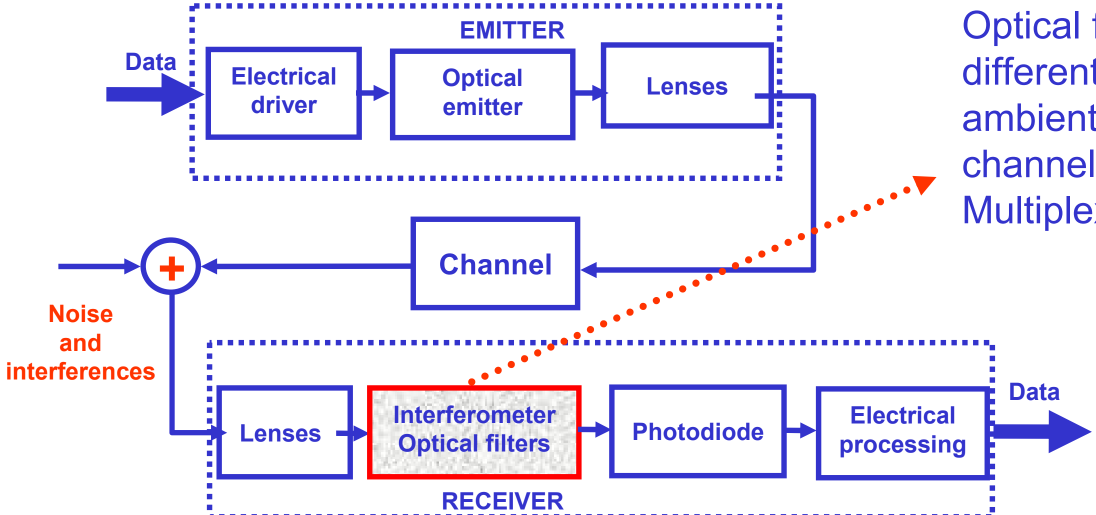
The optical efficiency $\eta(\psi)$, for a given incidence angle ψ, is the part of the total incident power $P_S(\psi)$ that arises at the lens output $P_T(\psi)$. $\eta(\psi)$ depends on the in-lens reflection losses and non-linear effects.

$$\eta(\psi) = \frac{P_S(\psi)}{P_T(\psi)}$$

All concentrators produce an increment of the received optical power that can be seen as a gain proportional to the ratio between the lens area and the "active area" at the receiver.

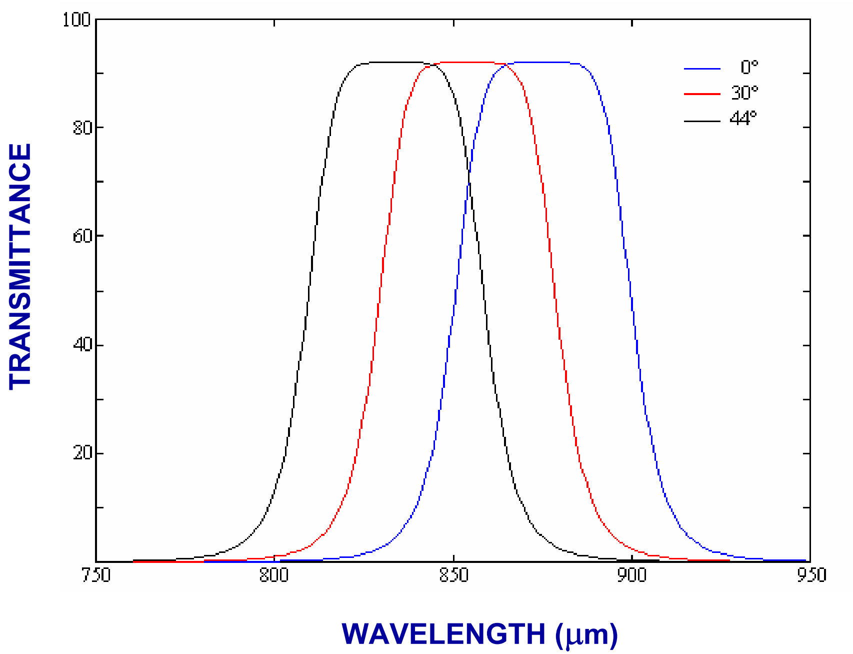
$$G = \frac{A_{lens}}{A_{receiver}}$$

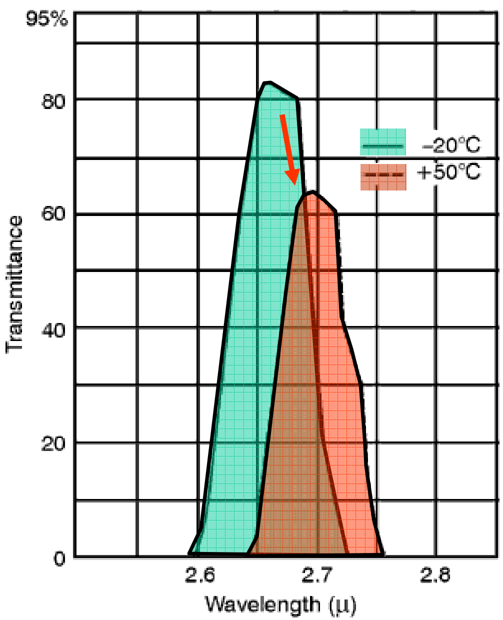
OCS: optical filters



Optical filters can be used to isolate different wavelengths in order to reduce ambient noise or to isolate different channels (Wavelength Division Multiplexing)

OCS: wavelength filters

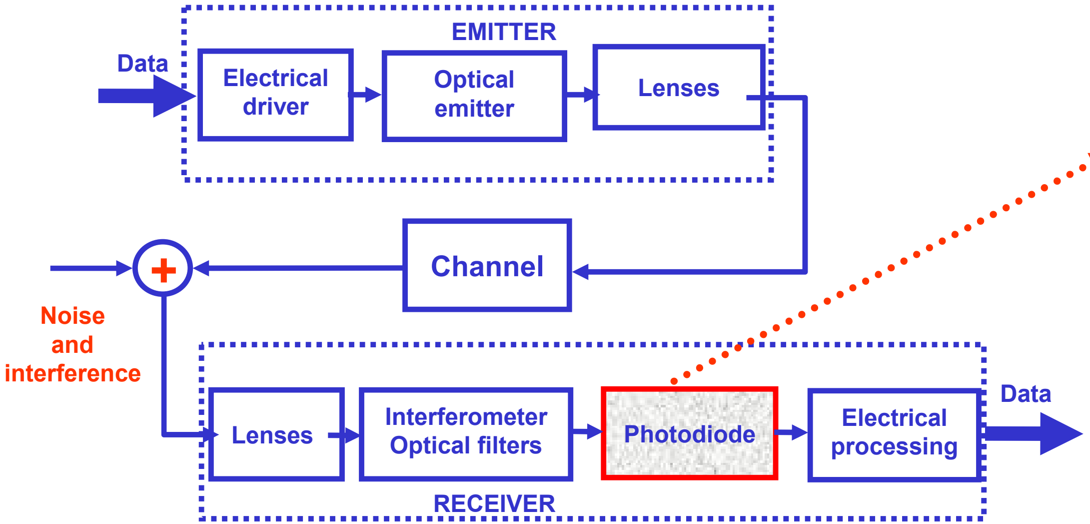




In a wavelength filter, transmittance is limited to a range of values (in the same way as in a bandpass electrical filter)

Distortion of transmittance curve due to temperature rise

OCS: the photodiode

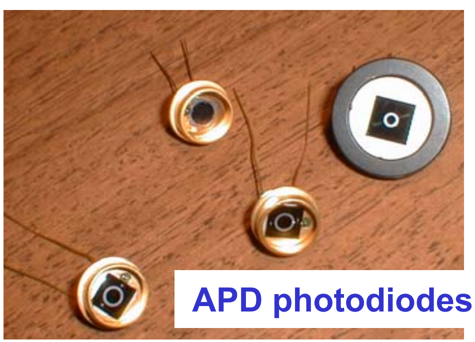


Inverse biased diode, usually based on Si, GaAs o InGaAs, sensible to infrared radiation, that produces an electrical current proportional to the input optical signal.

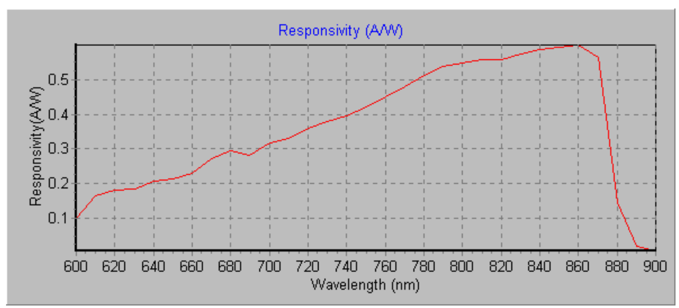
The larger the active area, the more the received optical power

Two different families:

PIN photodiodes and APD photodiodes



APD photodiodes

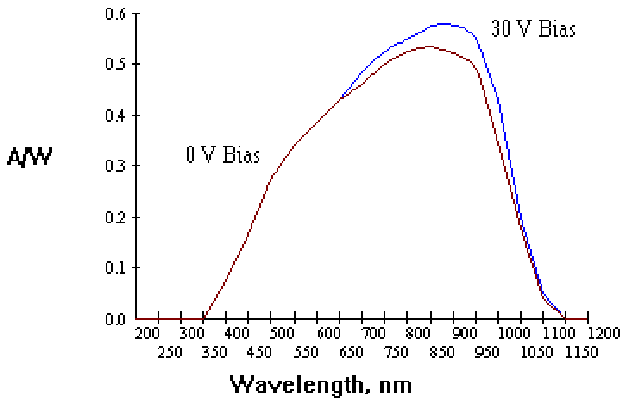


PIN photodiode

OCS: the photodiode responsivity and quantum efficiency

Photodiode Responsivity:

The measure of responsivity ρ is the ratio between the output photodiode current in Ampères and the radiant power (in watts) incident on the photodiode. It is expressed in A/W.
The photodiode responsivity depends on quantum efficiency as defined below.



A typical responsivity curve as a function of wavelength

Quantum efficiency:

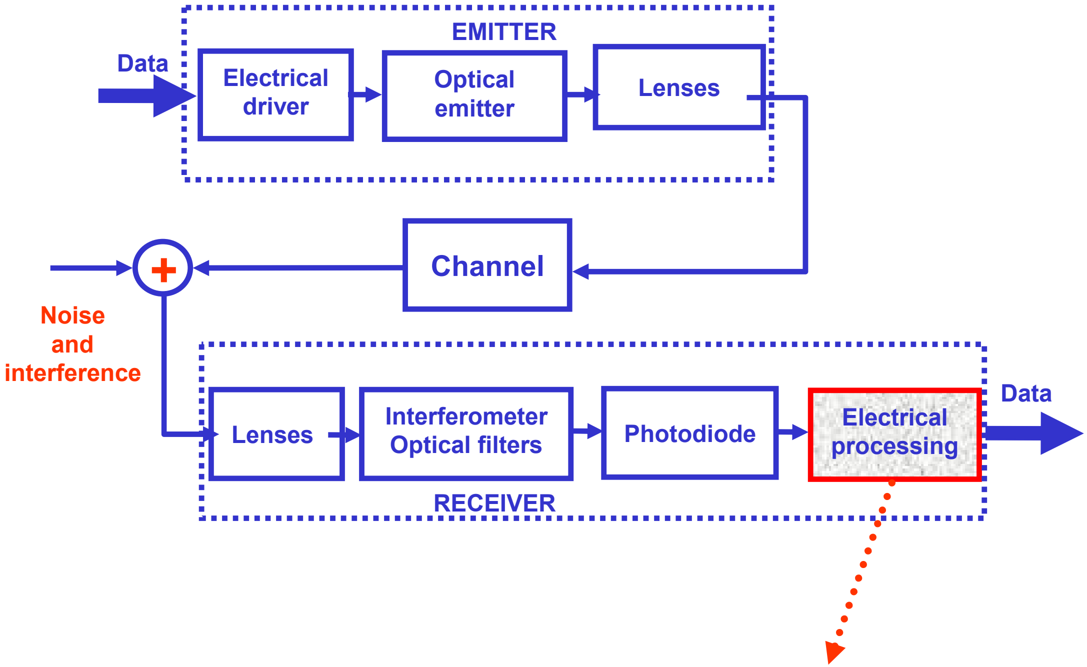
Quantum efficiency η is a factor expressing the photodiode capability to convert optical energy into electrical energy.

Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching η=0.8

$$\rho = \eta \frac{q}{hf}$$

where q is the elementary charge= $1.6 \cdot 10^{-19}$ Coulombs (A·sec)

OCS: electrical processing



Electrical filtering and detection of the transmitted signal. The output is given to a circuitry that is similar to the one used in RF systems

FURTHER READING

A comprehensive tutorial on optical communications and in particular on laser-based communications can be found at the following address:

http://repairfaq.ece.drexel.edu/sam/CORD/leot/