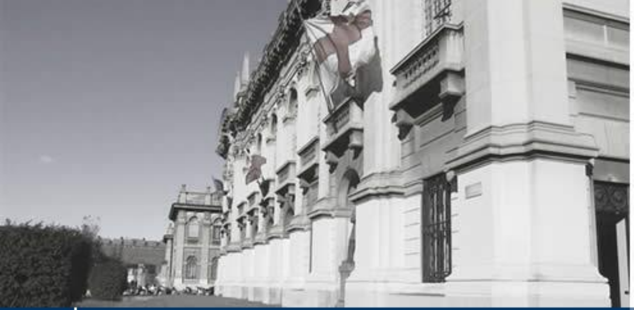
DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA



POLITECNICO DI MILANO

Lecture 11
LEDs and optical fibers

Optoelectronic systems

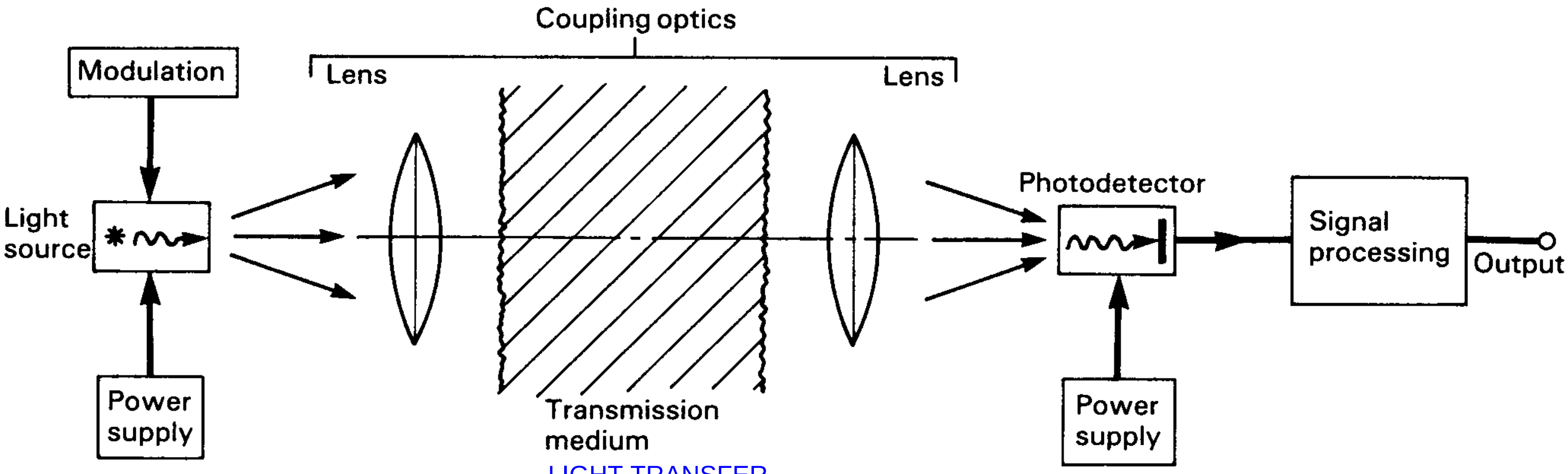


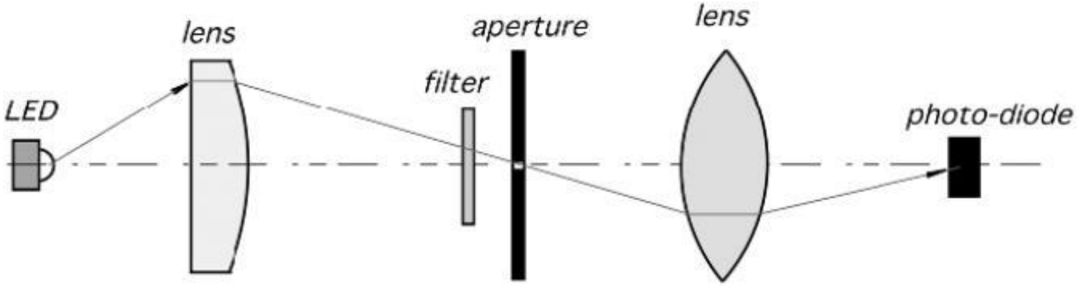
Fig. 1.1 Elements of a typical optoelectronic system.

Light source	Light transfer	Sensor
• LED • Laser • Incandescent lamps • Fluorescent lamps The light is also filtered	• Direct nothing in between the S/S • Indirect, through lenses and mirrors • Indirect, through light guides / optical fibers	• Photodiode • Photomultiplier • Photographic film • CCD and diode arrays basically array of sensors

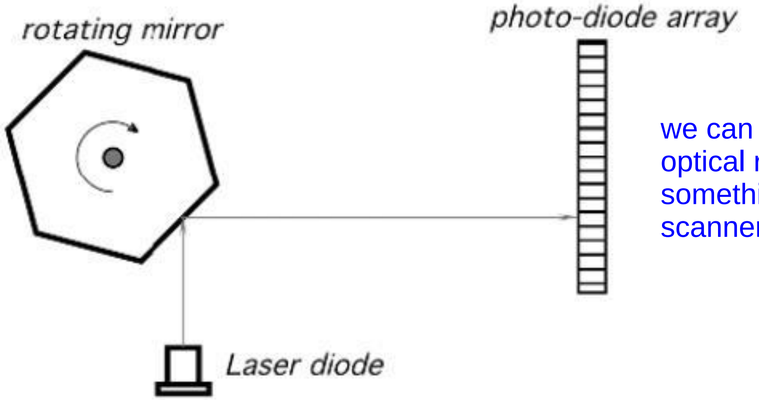
Optical fiber: generally speaking: like a cable in which light is passing through, and it's transferd from one point to another without losing power. (Basically a light conductor). Light guide is not always an optical fiber but that's the idea.

Examples of optical systems that use refraction (A) and reflection (B,C)

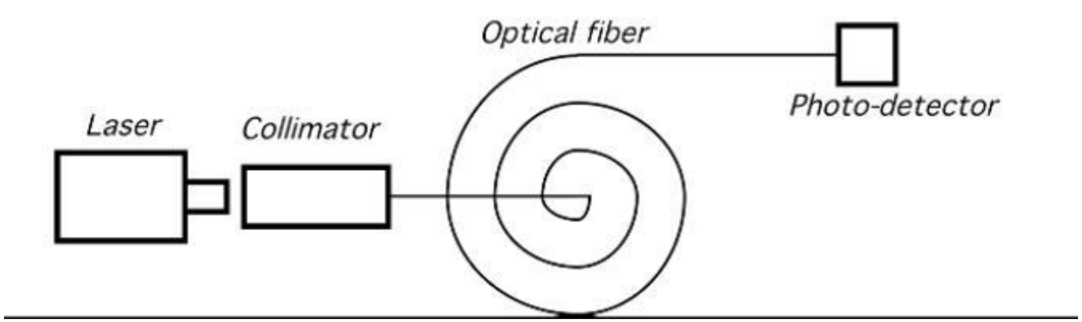
We have different ways of deflecting the light



ofc whenever it passes through something the light loses some power! (it's absorbed) plus some it's also reflected, and we may or may not want that! (meaning that we could want only refraction and not reflession



we can have like a "scanning", continuosly repeaing the optical reading from 1 to N element. Like there could be something to measure in front of the array. It could be a scanner of biological things



Index of refraction (or refractive index) n of an optical or dielectric medium = Ratio between the speed of light in vacuum (*c*) and the speed of light in the substance (v):

each material has its own n

$$n = c/v$$

The refractive index of electromagnetic radiation equals:

$$n = \sqrt{\varepsilon_r \cdot \mu_r}$$

where ε_r is the material's relative permittivity, and μ_r is its relative permeability. For most naturally occurring materials, μ_r is very close to 1 at optical frequencies therefore n is approximately

$$n = \sqrt{\varepsilon_r}$$ permittivity

The refractive index depends on the considered wavelength λ. For example, in glass n decreases with increasing λ.

In a semiconductor material, the refractive index typically decreases with increasing energetic gap Eg.

Empirical and semi-empirical relationships exist between n and Eg, e.g.:

$$n^2 = 1 + \left(\frac{A}{E_g + B} \right)^2$$

where A $\approx$ 13.6 eV and B $\approx$ 3.4 eV

TABLE 4.1 Approximate Indices of Refraction of Various Substances*

Air	1.000 29
Ice	1.31
Water	1.333
Ethyl alcohol (C_2H_5OH)	1.36
Fused quartz (SiO_2)	1.4584
Carbon tetrachloride (CCl_4)	1.46
Turpentine	1.472
Benzene (C_6H_6)	1.501
Plexiglass	1.51
Crown glass	1.52
Sodium chloride (NaCl)	1.544
Light flint glass	1.58
Polystyrene	1.59
Carbon disulfide (CS_2)	1.628
Dense flint glass	1.66
Lanthanum flint glass	1.80
Zircon ($ZrO_2 \cdot SiO_2$)	1.923
Fabulite ($SrTiO_3$)	2.409
Diamond (C)	2.417
Rutile (TiO_2)	2.907
Gallium phosphide	3.50

*Values vary with physical conditions—purity, pressure, etc. These correspond to a wavelength of 589 nm

Snell's law

When light moves from one medium to another, it changes direction, i.e. it is refracted. If it goes from a medium with refractive index n_1 to one with refractive index n_2, with an incidence angle to the surface normal of θ_1, the refraction angle θ_2 can be calculated from Snell's law:
($n_1 > n_2$)

Oi = O1
Ot= O2

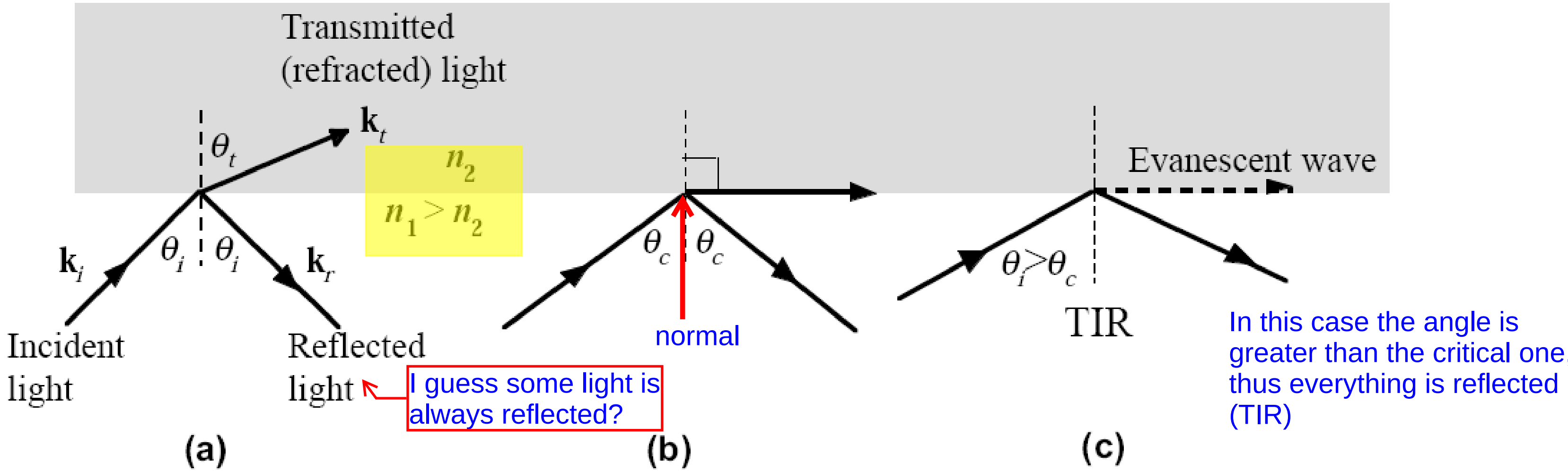
$$\mathbf{n_1 \sin\vartheta_i = n_2 \sin \vartheta_t}$$

The incidence angle is called "critical angle" (θ_c), when θ_t = 90°, i.e. the refracted light runs parallel to the surface.

For incident angles > θ_c, the light is reflected totally in the first medium

Ofc Oc can be calculated imposing the Ot = 90

Snell's law, critical angle, total internal reflection



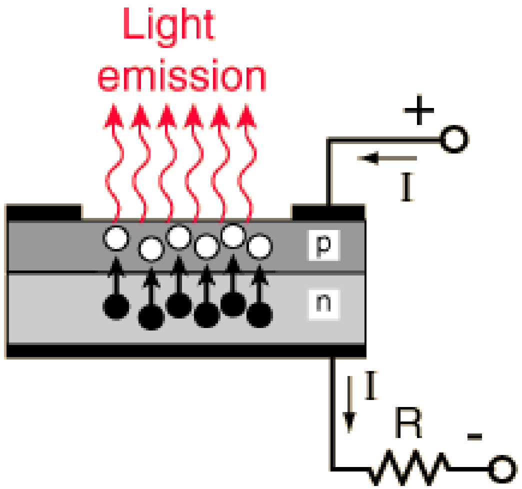
Light wave travelling in a more dense medium strikes a less dense medium. Depending on the incidence angle with respect to θ_c, which is determined by the ratio of the refractive indices, the wave may be transmitted (refracted) or reflected. (a) $\theta_i < \theta_c$ (b) $\theta_i = \theta_c$ (c) $\theta_i > \theta_c$ and total internal reflection (TIR).

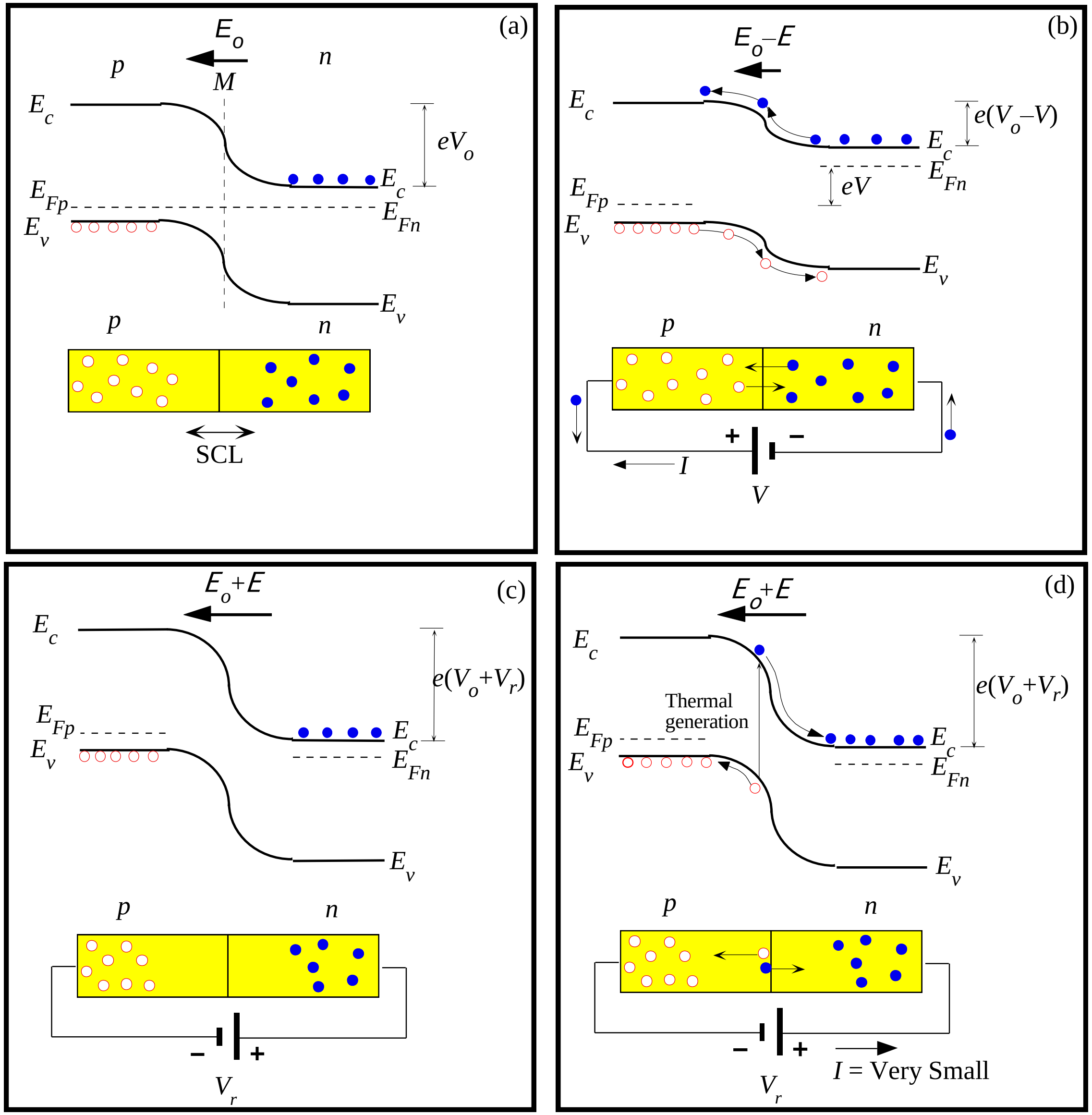
$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Light Emitting Diodes, LEDs

Light Emitting Diodes (LED) are semiconductor light sources constituted by p-n junctions made by materials like Gallium arsenide (GaAs), Gallium arsenide phosphide (GaAsP), Gallium phosphide (GaP), designed to emit visible or infrared light.

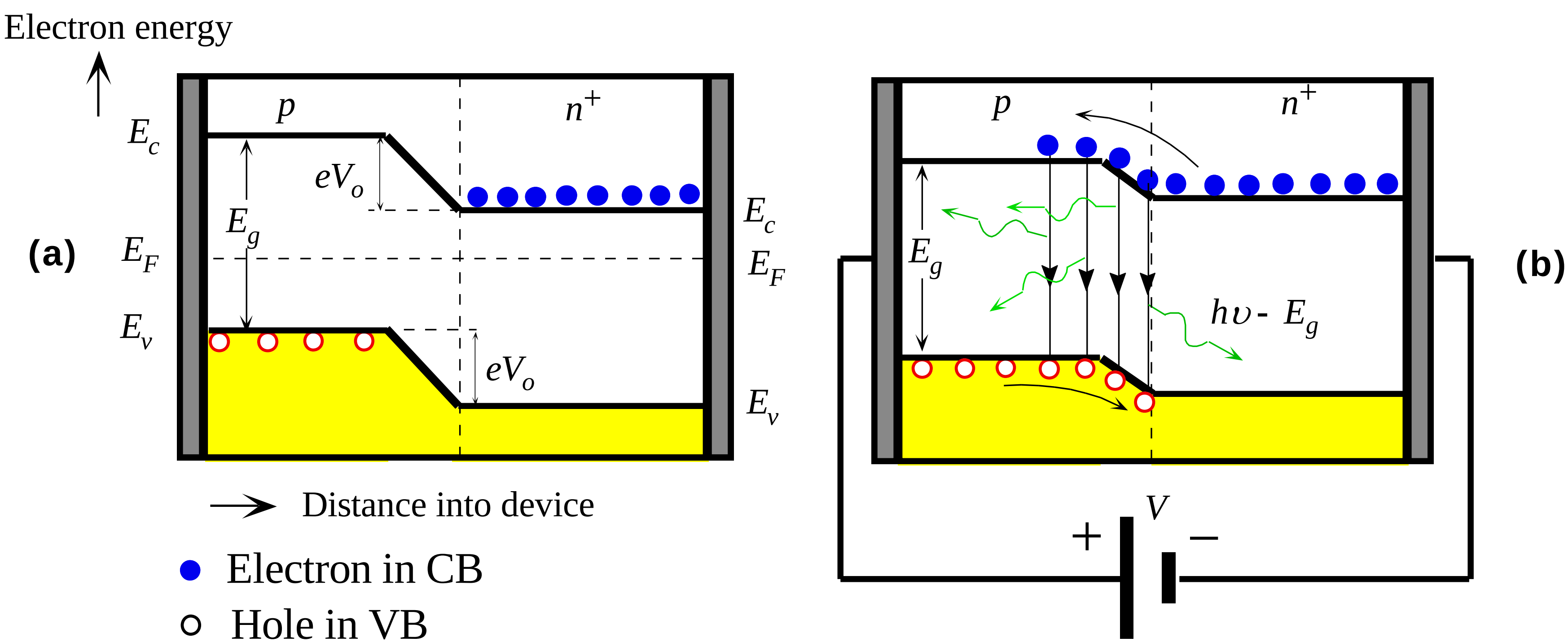




Energy band diagrams for a *pn* junction under (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.

In a LED, the p-n junction works in forward bias: when electrons cross the junction from n- to p-region (and holes from p- to n- region) the electron-hole pair recombination process produces photons in the visible or infrared light spectrum.

The engery of a wave is given by Eg= h*v. So the energy changes and thus the frequency of the wave too (According to the material).

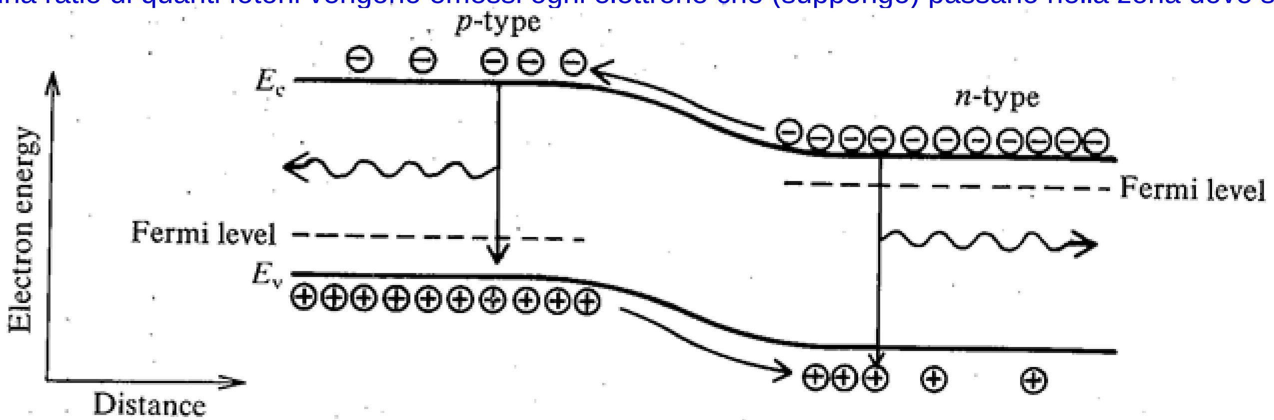


(a) The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.

In other terms, in condition of forward bias, the majority charge carriers cross the barrier potential and enter the other side, where they are minority charge carriers. In this way they make the concentration of minority carriers greater than normal (*injection of minority charge carriers*). The excess of minority carriers determines the recombination with the majority carriers and the photon emission.

In reality, this phenomenon depends on the quantic efficiency, defined as the ratio between photons' emission and electrons' injection.

tipo una ratio di quanti fotoni vengono emessi ogni elettrone che (suppongo) passano nella zona dove sono minority



Planck's relation

$$E_g = E_c - E_v = h\nu = hc / \lambda_g$$

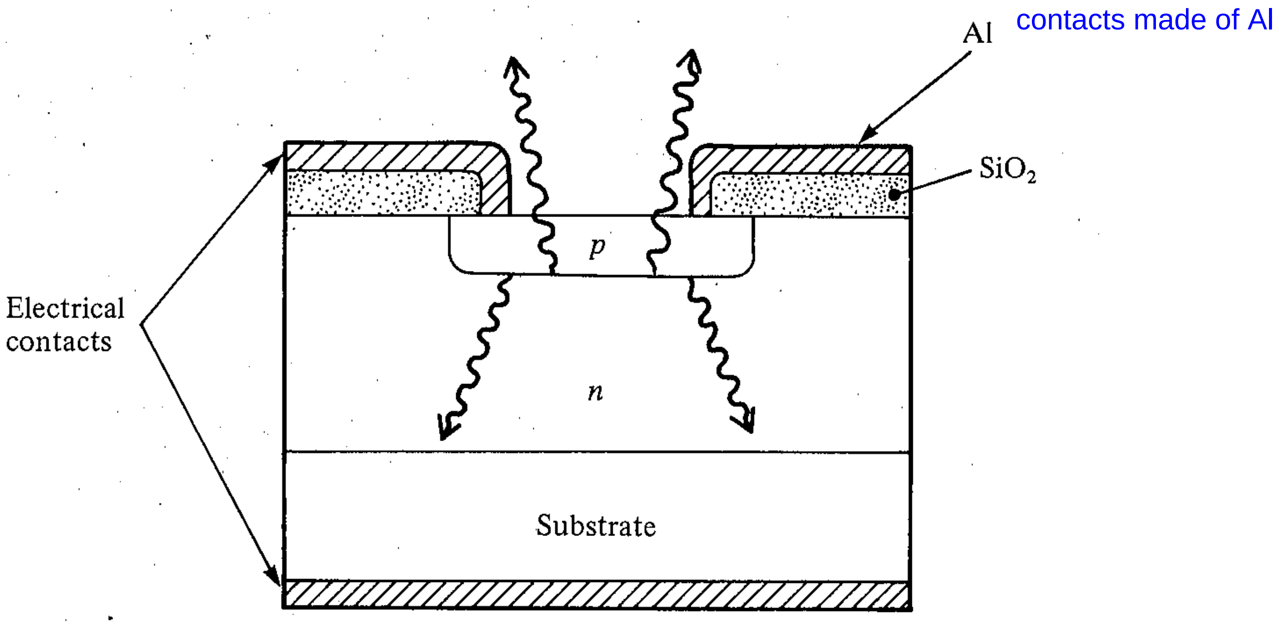
$$\lambda_g = hc / E_g$$

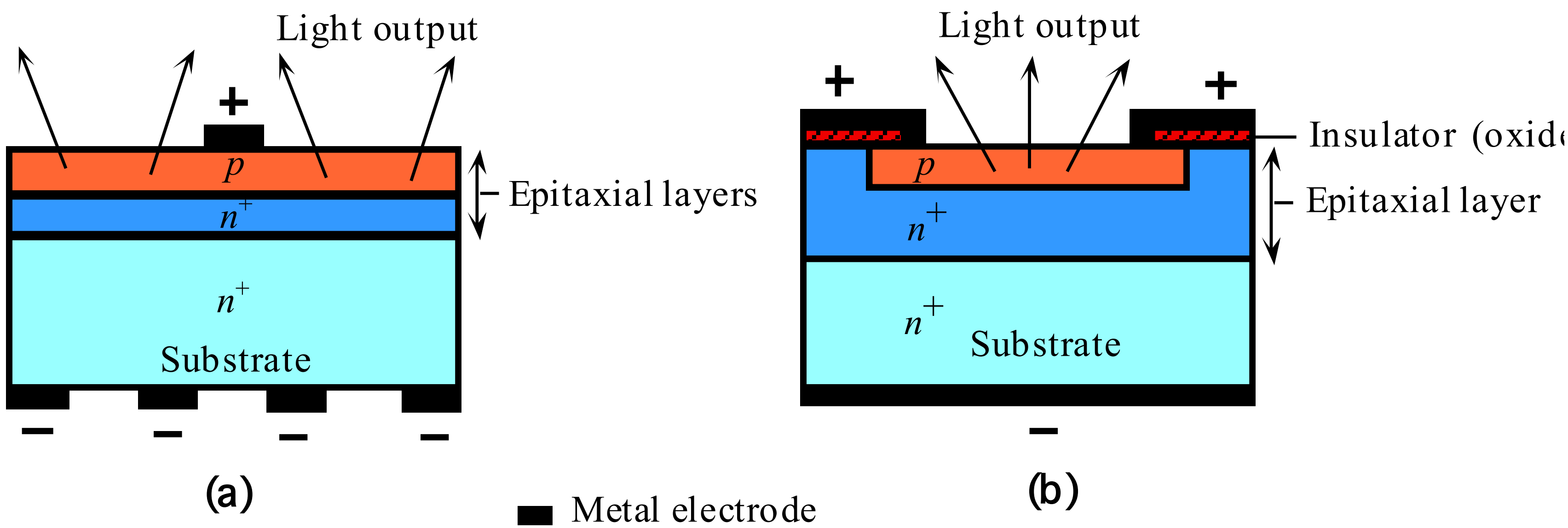
$$\lambda_g\,(nm) = 1240 / E_g(eV)$$

	$E_g\,(eV)$	$\lambda_g\,(nm)$
Si	1.12	1106
Ge	0.67	1850
SiC	3.00	413
GaP	2.26	549
GaAs	1.443	860

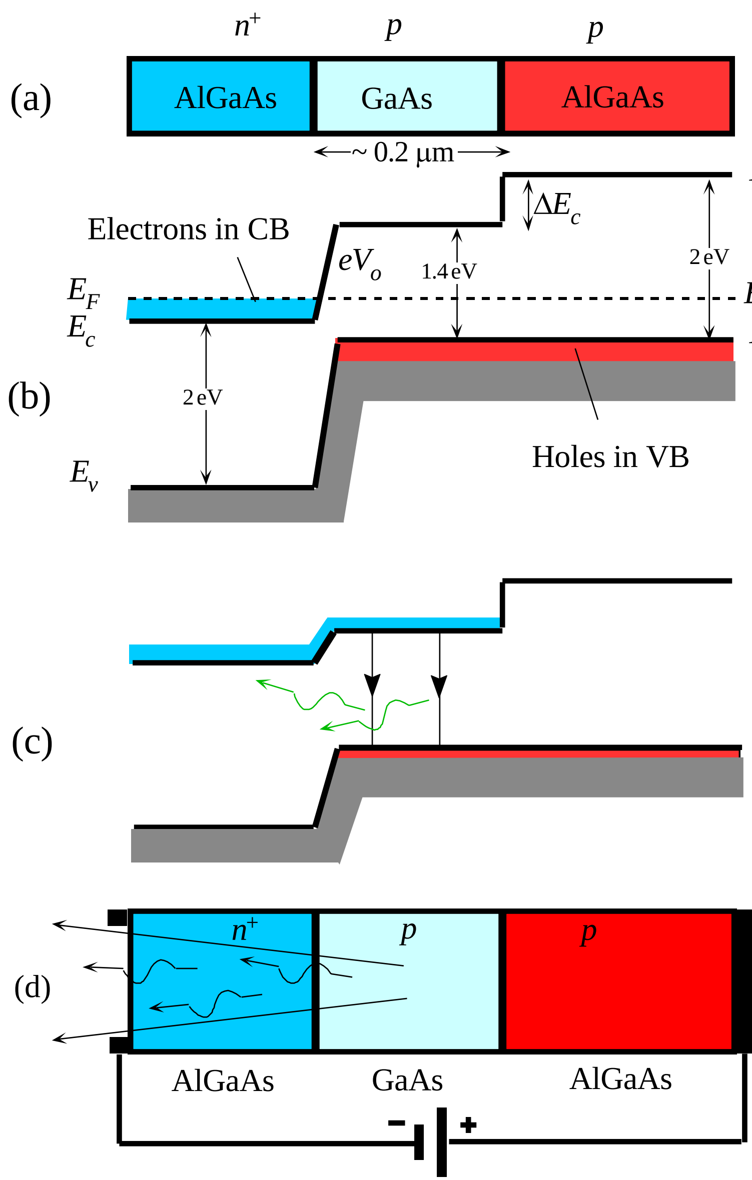
LED - structure

One possibility to make a LED is to create p- and n- layers on a substrate.
In this way, radiations will be emitted in all directions.





A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epitaxially on an n^+ substrate. (b) First n^+ is epitaxially grown and then p region is formed by dopant diffusion into the epitaxial layer.



(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs)

(b) A simplified energy band diagram with exaggerated features. E_F must be uniform.

(c) Forward biased simplified energy band diagram.

(d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

Combining different layers we can obtain different heterostructures

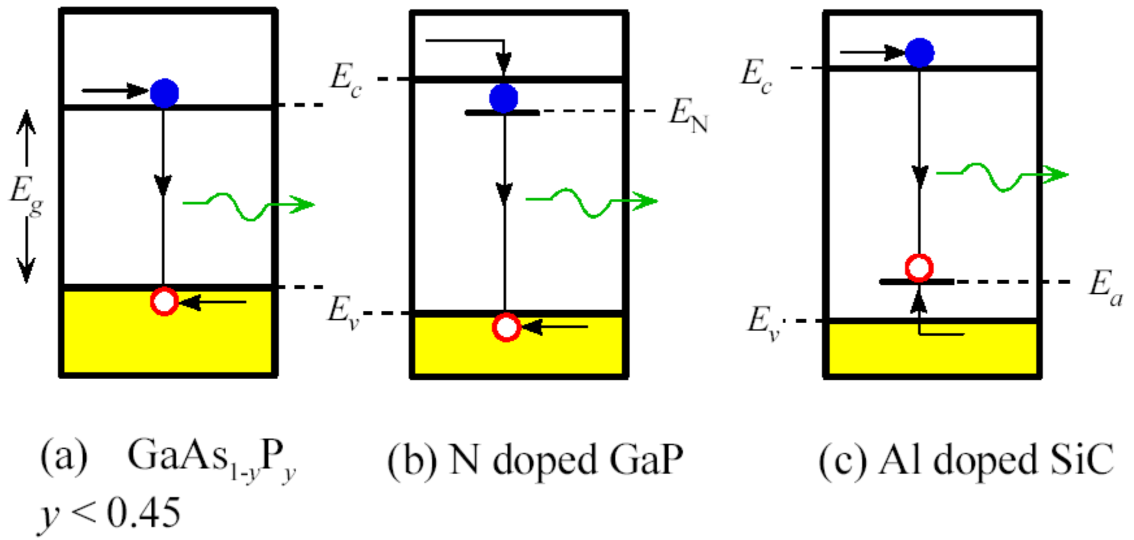
LED - materials

(veloce)

-GaAs and AlAs to form $Al_xGa_{1-x}As$ (ternary alloys) (x=fraction)

-GaAs and InP to form $Ga_xIn_{1-x}As_yP_{1-y}$ (quaternary alloys)

-…

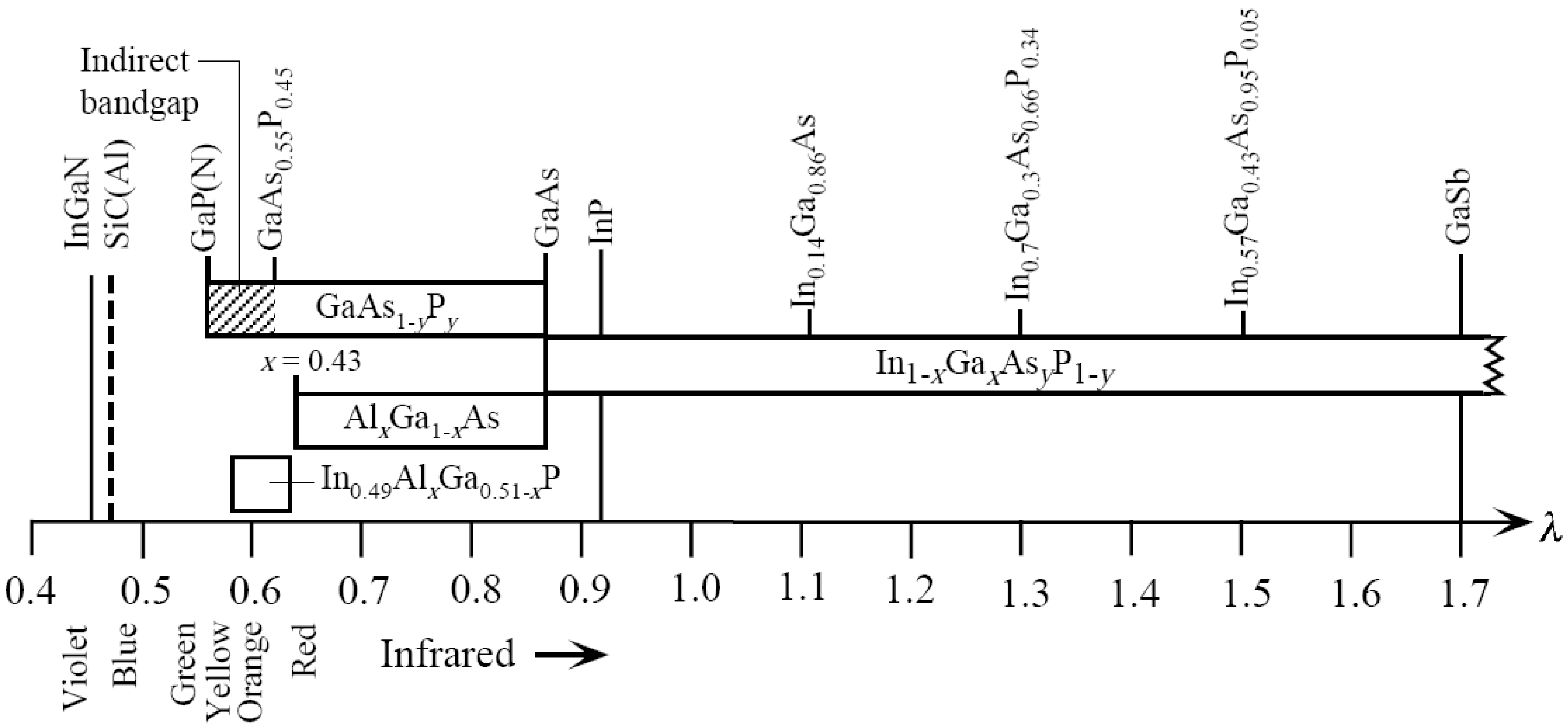


(a) Photon emission in a direct bandgap semiconductor. (b). GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at E_N. Direct recombination between a trapped electron at E_N and a hole emits a photon. (c) In Al doped SiC, EHP recombination is through an acceptor level like E_a.

LED - materials

(veloce)

we have covered many different colours with different materials

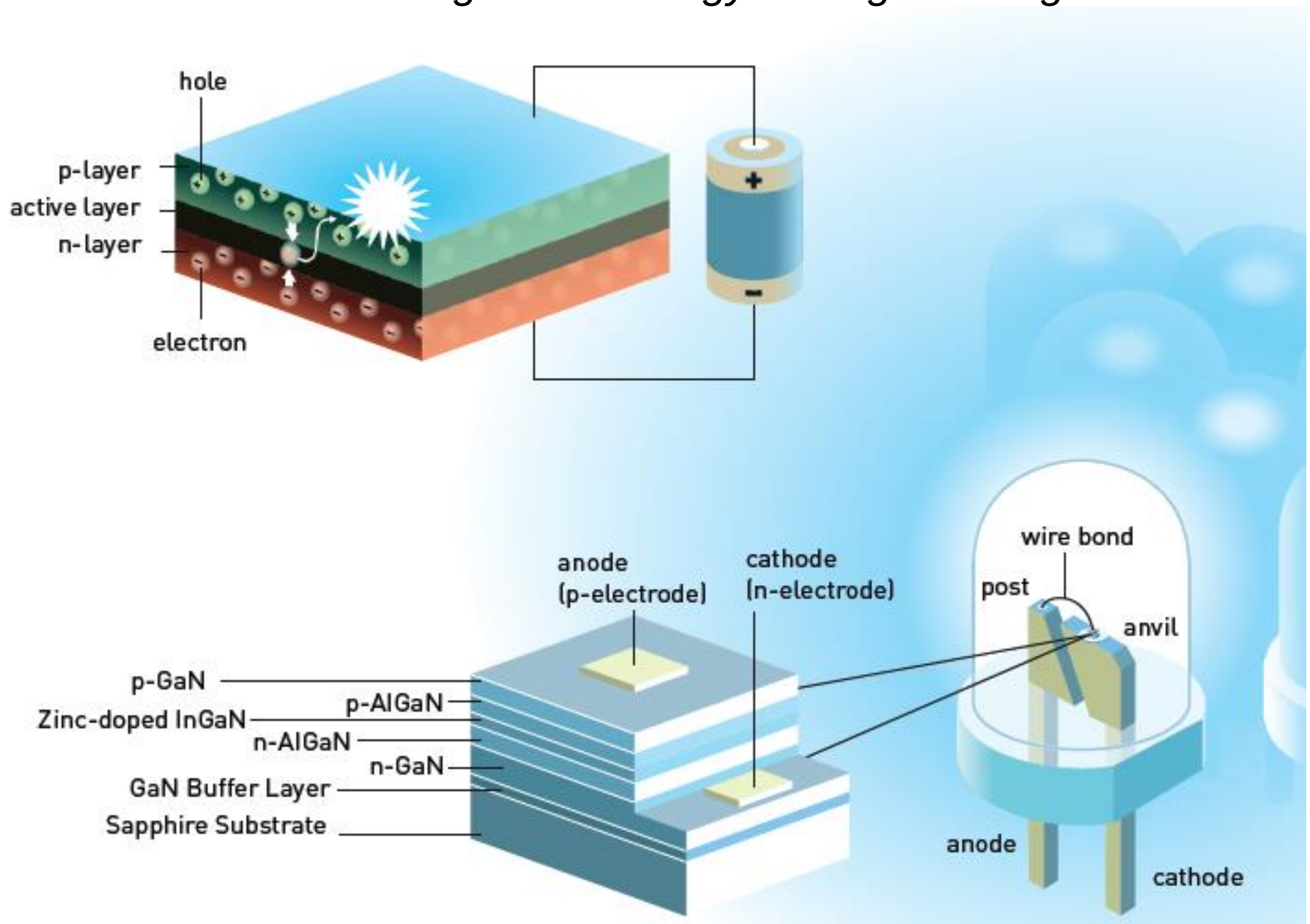


Nobel prize in Physics 2014

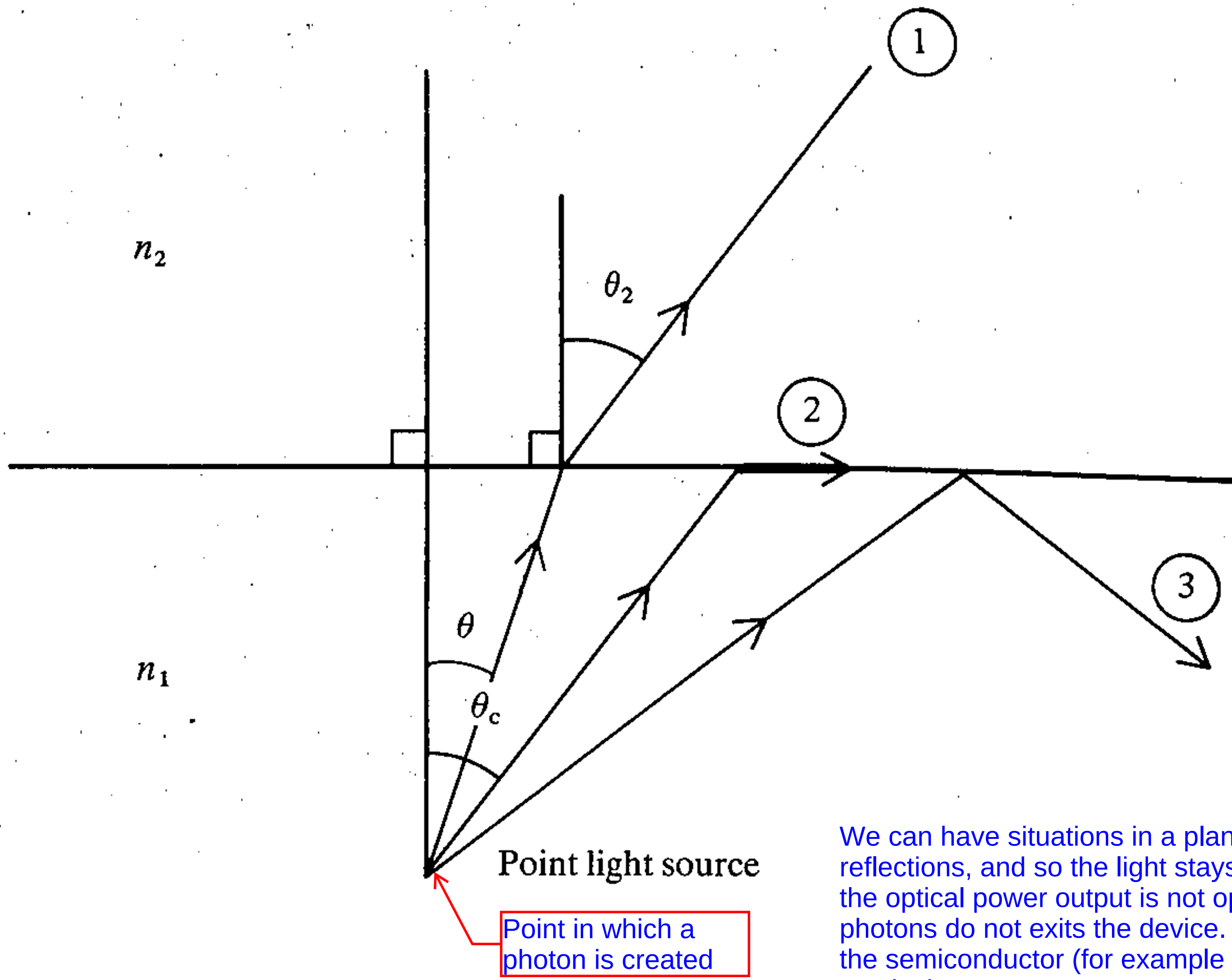
The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*.

This is an heterostructure able to reproduce blue light.

It's very efficient, meaning very good energy saving

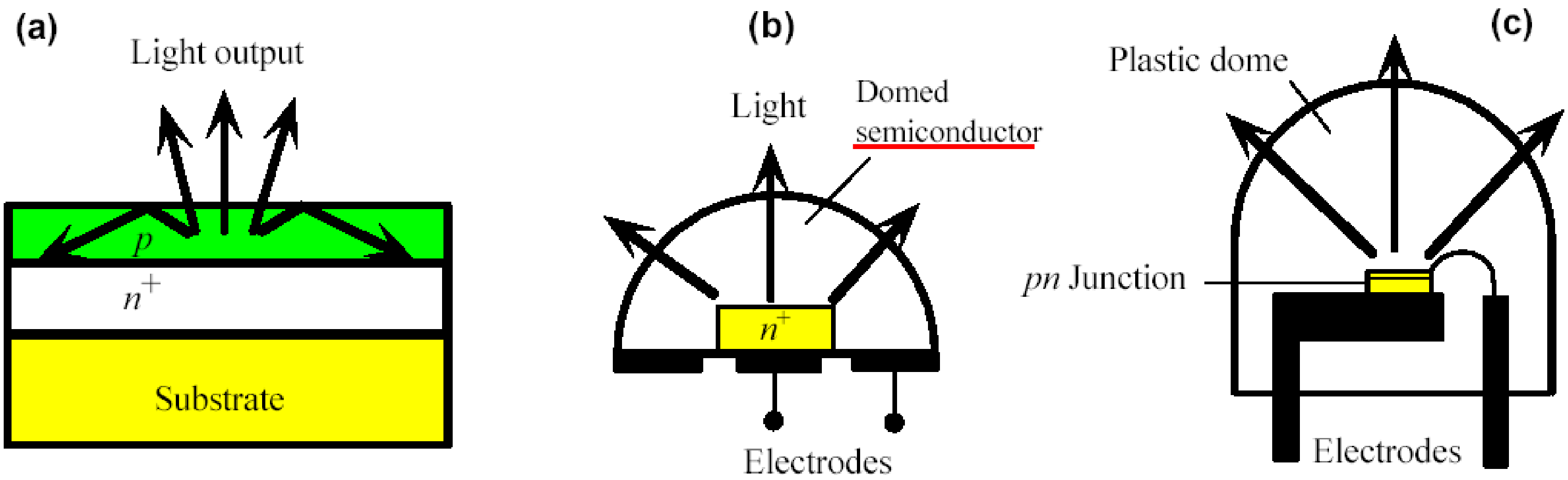


Snell's law



We can have situations in a planar system, in which we have reflections, and so the light stays confined in the device, thus the optical power output is not optical, because genearted photons do not exits the device. One possibility is to shape the semiconductor (for example the p part) curved. Like a semisphere

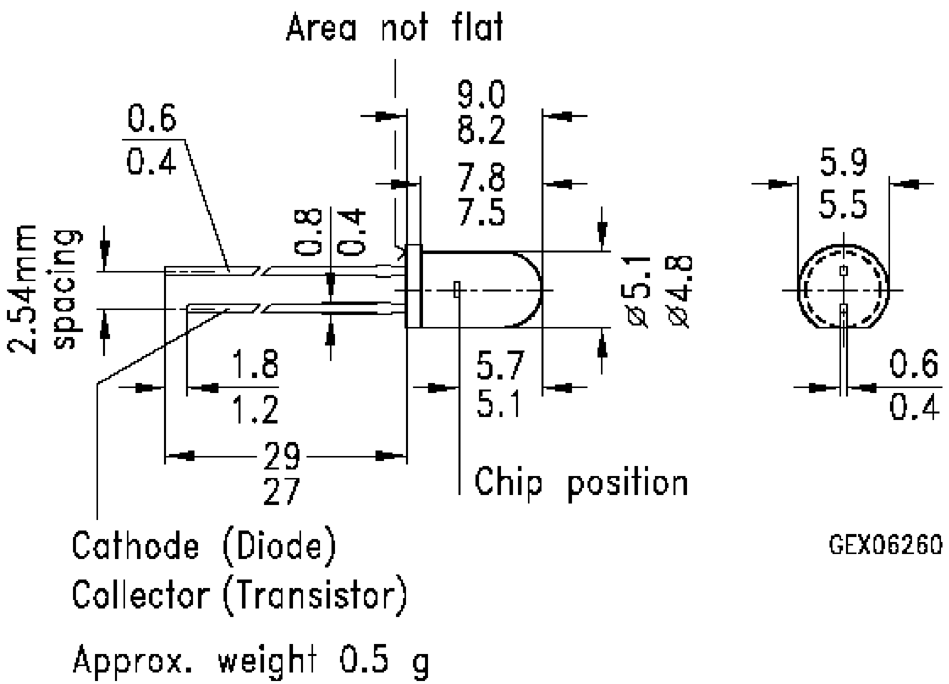
Losses for reflection



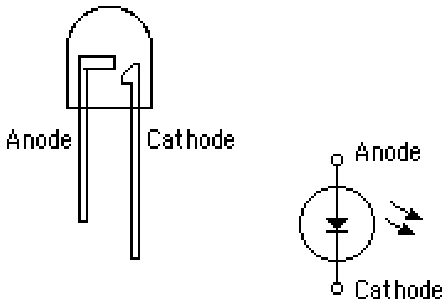
(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

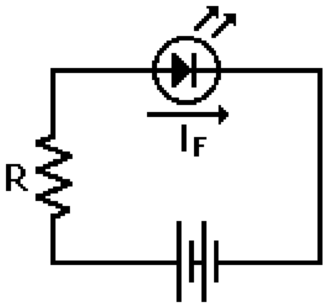
Now in this situations, all the direction will be normal to the superface! This means that all direction have a very low incident angle! For sure below the critical angle, and so the light is transmitted. This can be the solution in order to have most of the photons exit the device. The problem is that this is very expensive. An intermediate solution is to encapsulate the device in a plastic material, like a dome, this way we still have the problem, but all the photons leaving the material are not further lost (??) (it's better than nothing).

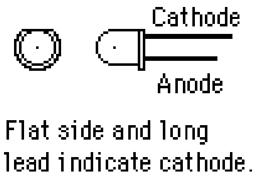
LED: characteristics (1)



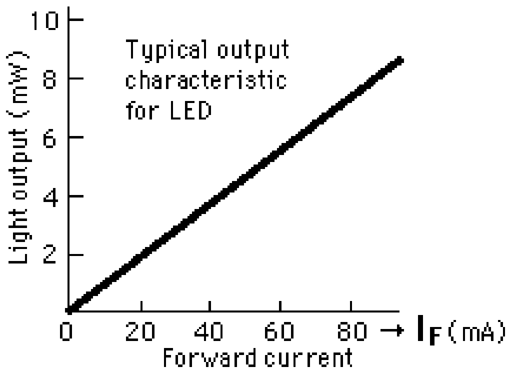
LED: characteristics (2)

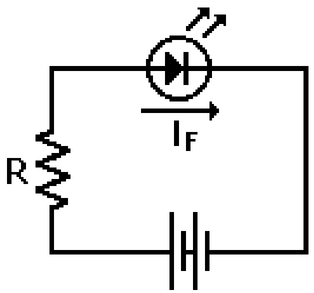




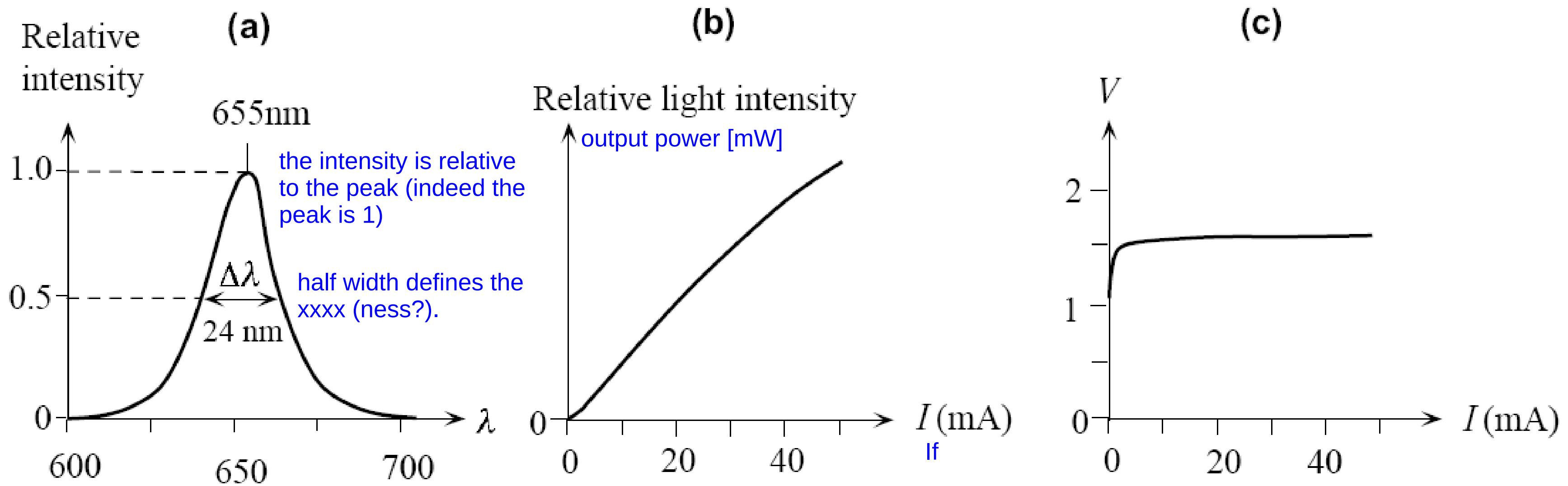


We can modulate the light intensity chaning the amount of current





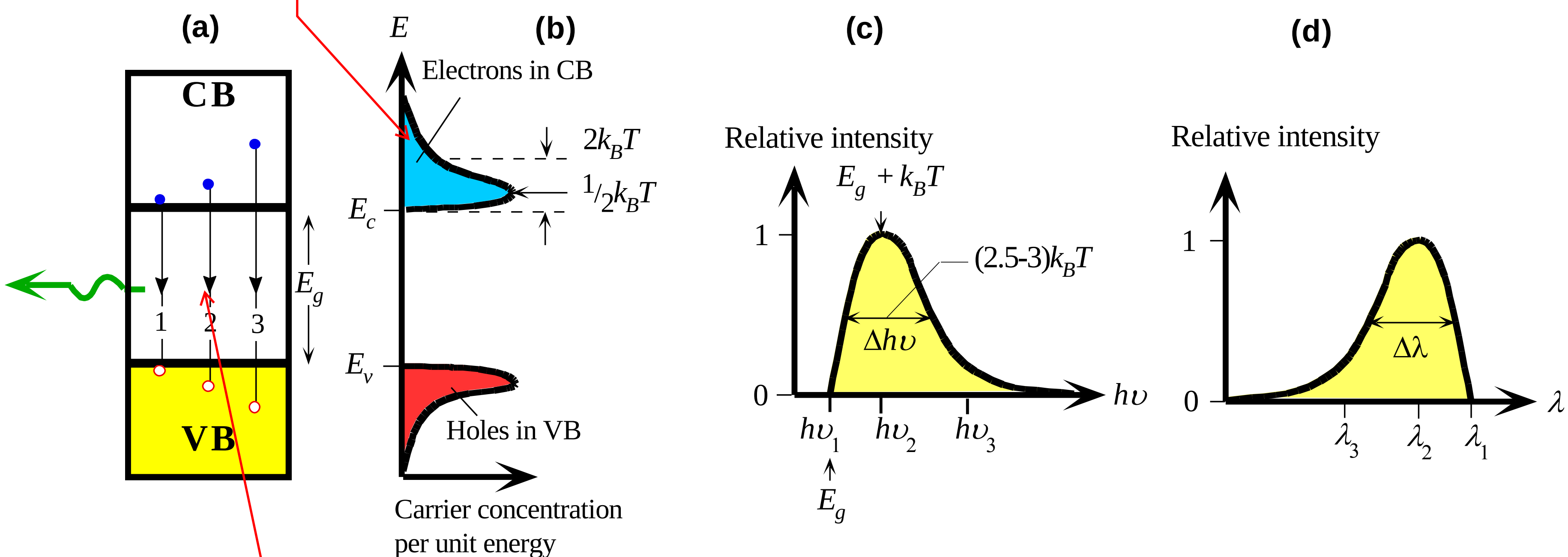
LED: characteristics (3)



The most probable wavelenght is 655nm. This is due small imperfection in material, and slightly different energy level in the material. 600nm is red.

(a) A typical output spectrum (relative intensity vs. wavelength) from a red GaAsP LED. (b) Typical output light power vs. forward current. (c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.

there's a distribution of
the electrons like this

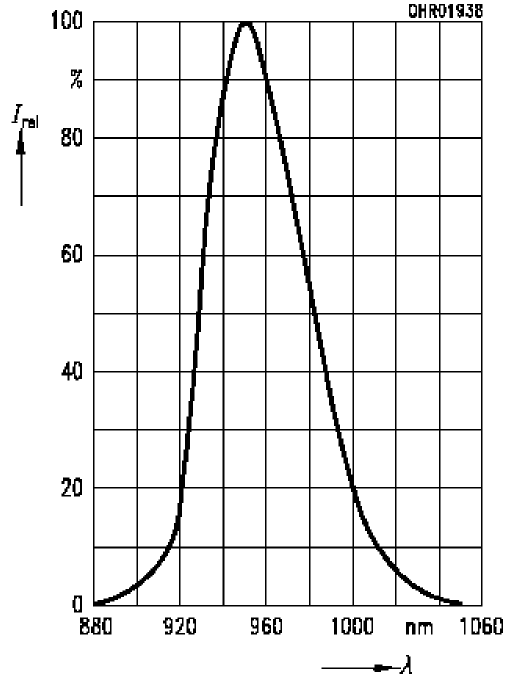


(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is $(1/2)k_BT$ above E_c. (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c).

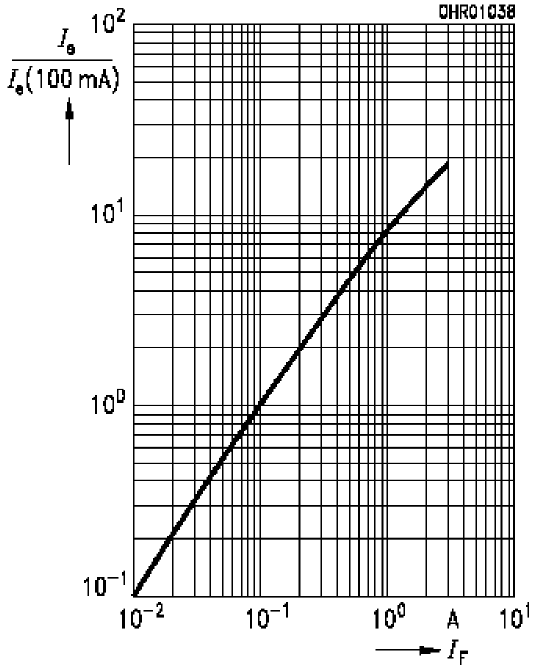
So basically you can also have different travels. Meaning
that most are "1" but there are others

LED: characteristics (4)

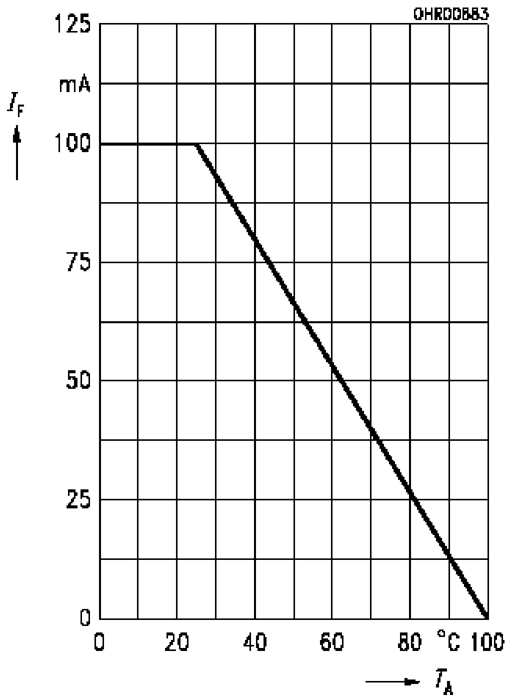
Relative spectral emission
$I_{rel} = f(\lambda)$



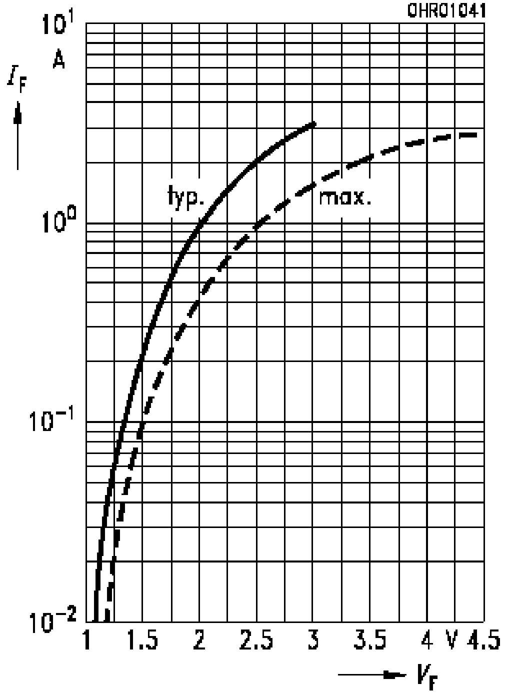
Radiant intensity $\frac{I_e}{I_e\ 100\ mA} = f(I_F)$
Single pulse, t_p = 20 µs



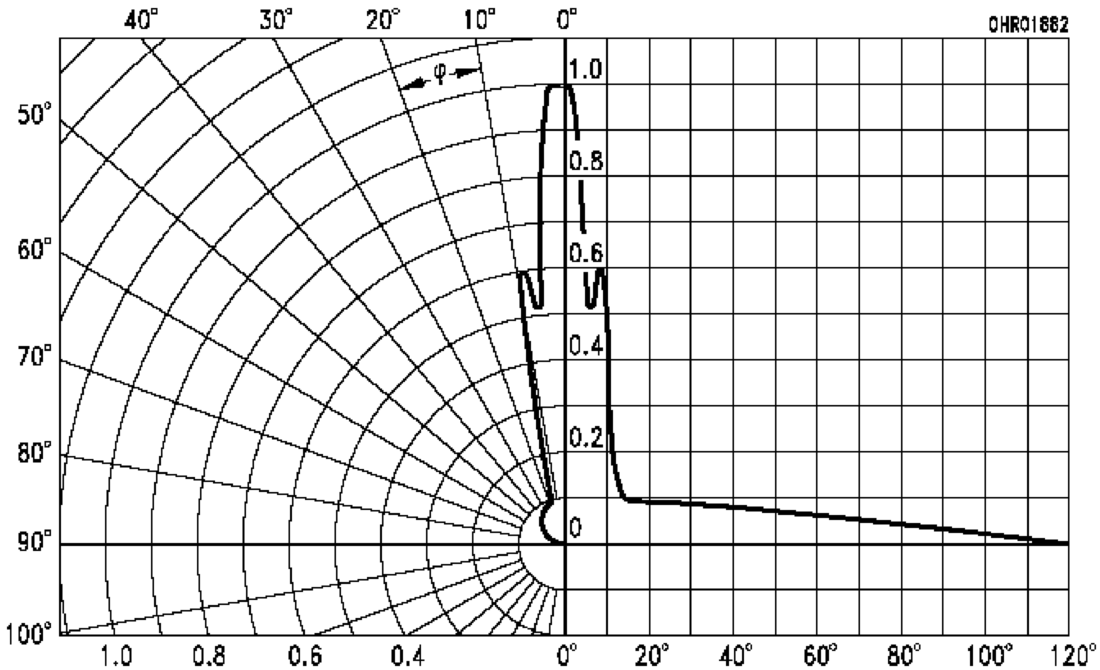
Max. permissible forward current
$I_F = f(T_A)$



Forward current
$I_F = f(V_F)$, single pulse, t_p = 20 µs

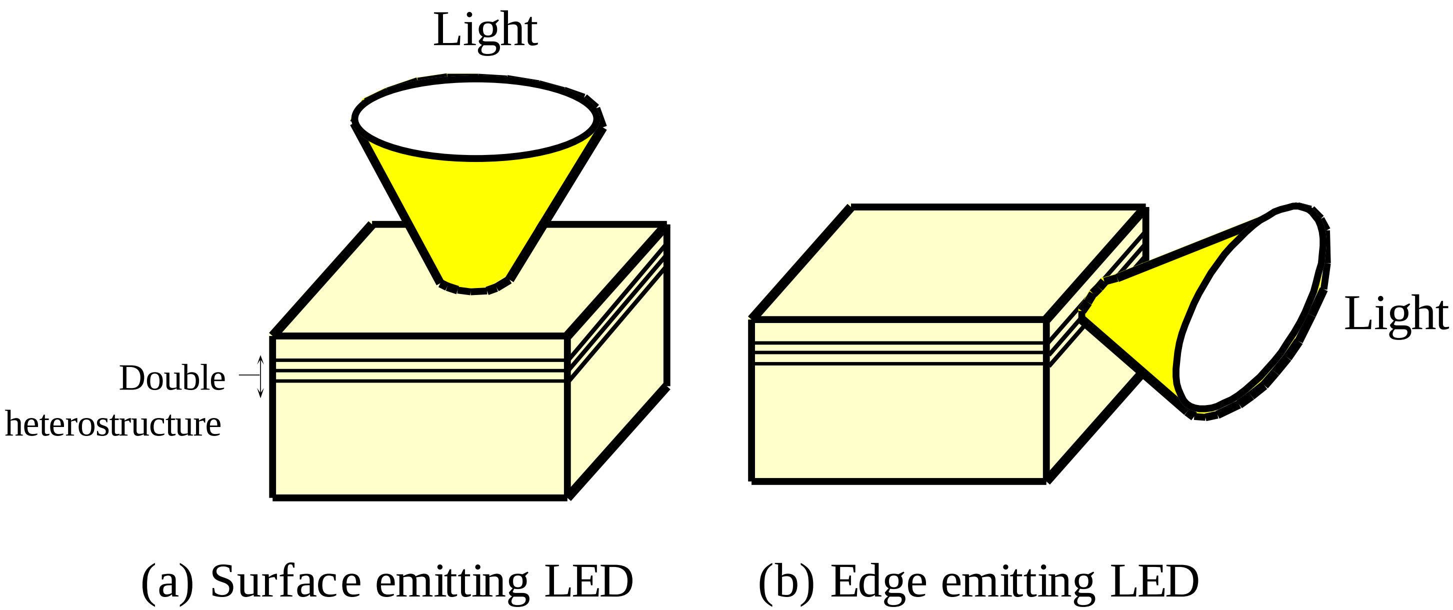


Radiation characteristics, $I_{rel} = f(\varphi)$



all the light generated is confined in a very narrow region! like 10 degrees.

We can have different shapes, like surfaces LDS, or from the lateral surface

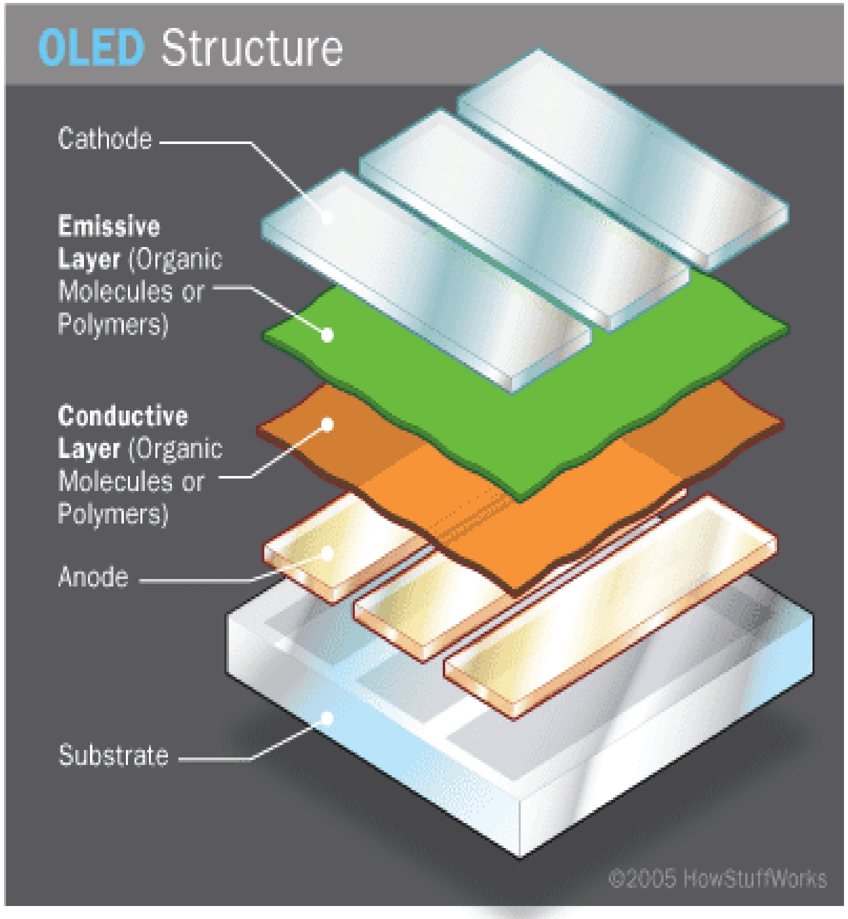


Organic Light Emitting Diode (OLED)

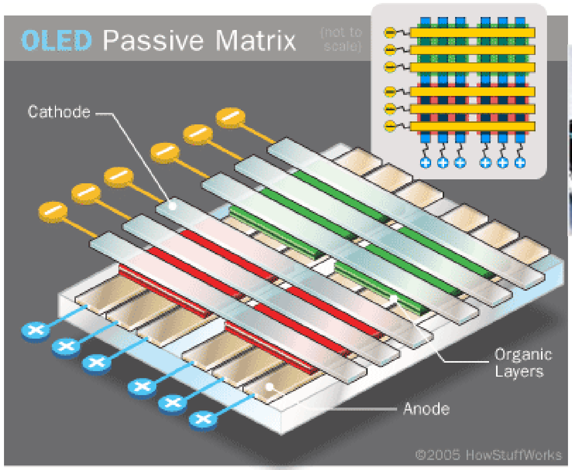
you can create transparent and flexible devices

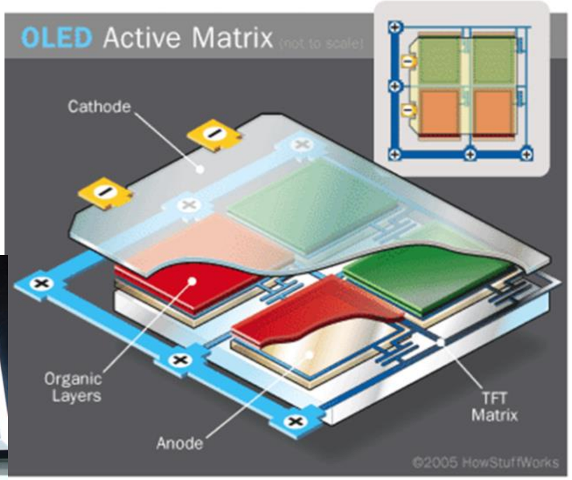
- An OLED is an electronic device made by placing a series of organic thin films between two conductors. When electrical current is applied, a bright light is emitted.

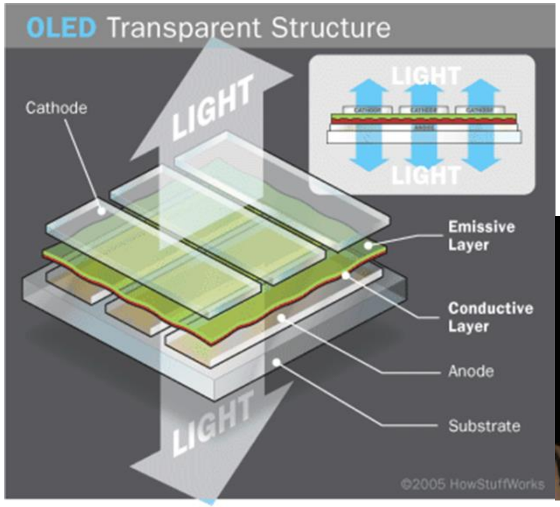
- This device is 100 to 500 nanometers thick or about 200 times smaller than a human hair.

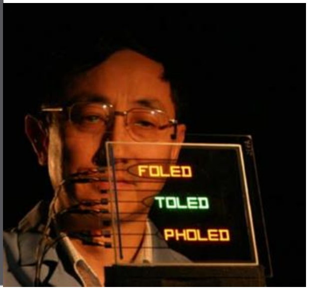


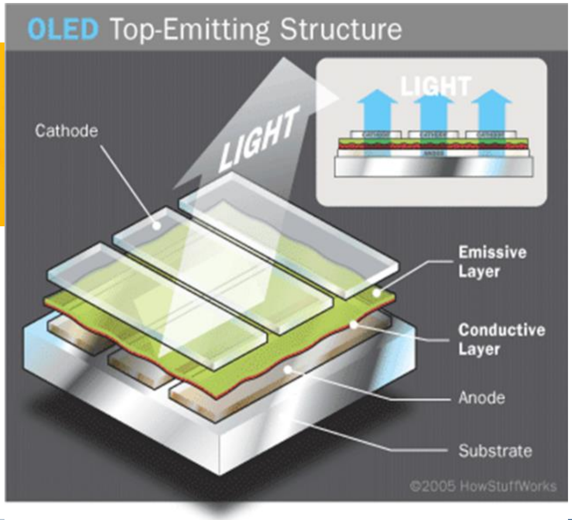
Organic Light Emitting Diode (OLED): types and structures



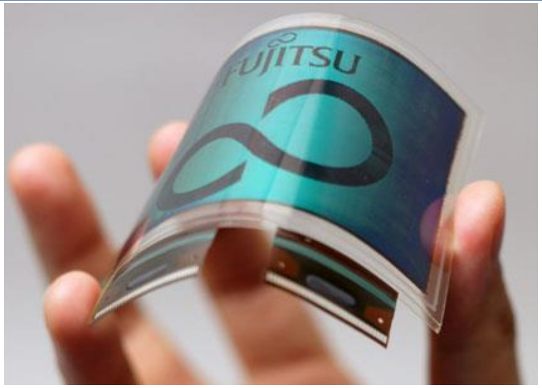








Organic Light Emitting Diode (OLED)



Advantages

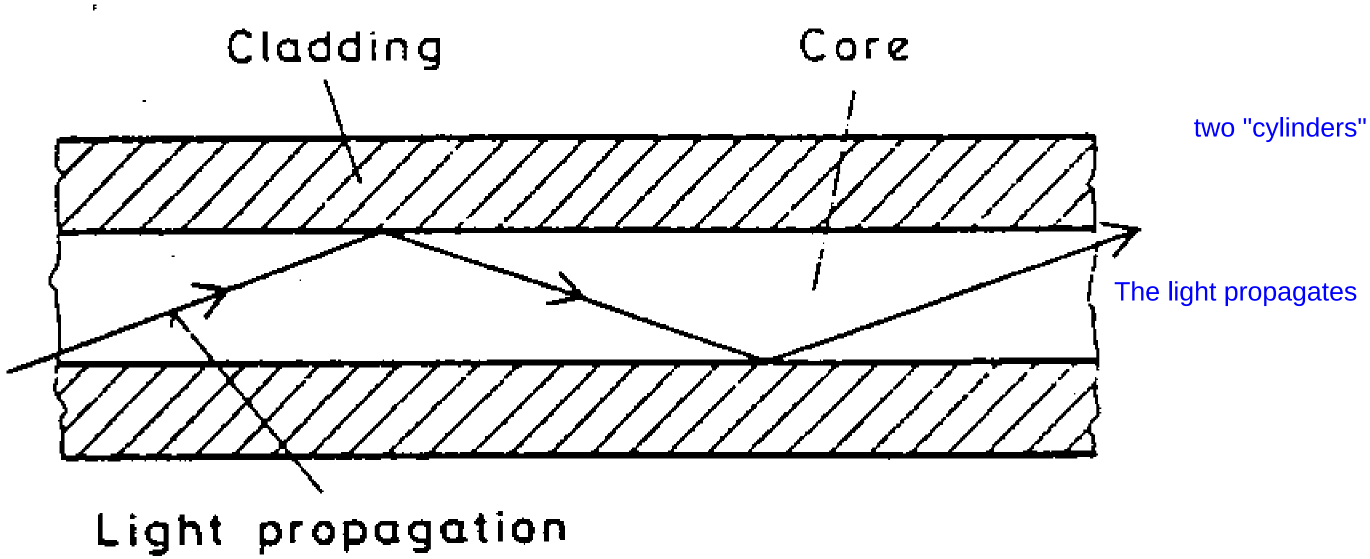
- Thinner, lighter and more flexible
- Brighter
- Consume much less power
- Easier to produce and make into larger sizes
- Large field of view

Disadvantages

- Lifetime
- Manufacturing
- Water

Optical fibers

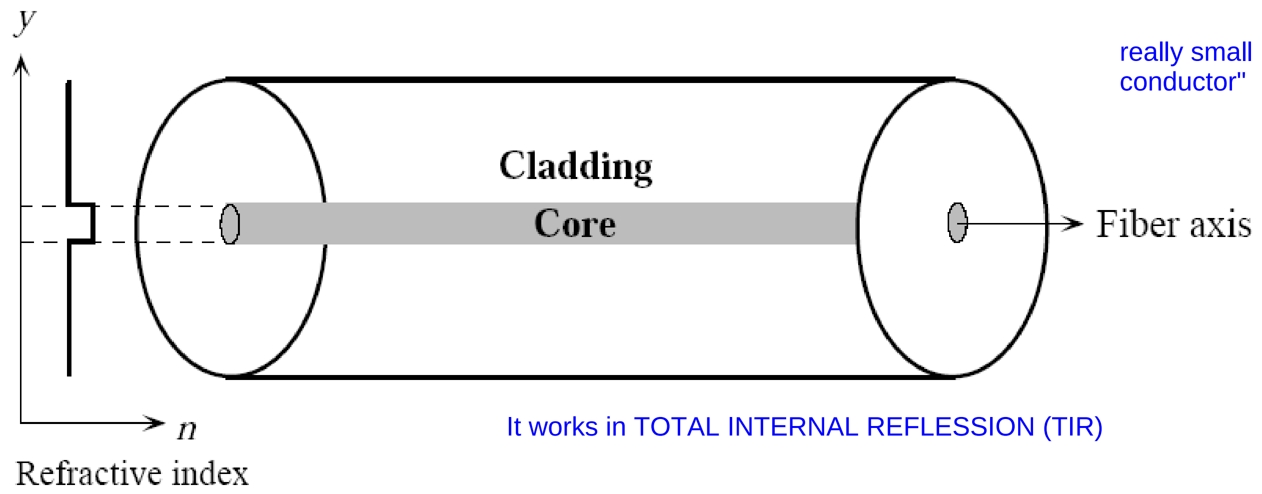
Optical fibers are small cylindrical fibers (diameter ~100 μm), that works as dielectric waveguides able to carry light (electromagnetic waves) from one side to the other.
An optical fiber is composed by an inner part (‘**core**’) with higher refractive index and an outer part (**‘cladding’**) characterized by a lower refractive index.



In case of “step index” fibers (in which the refractive index varies stepwise from core to cladding, see later), the variation of the refractive index is very small, of the order of about 1%.

The core must be characterized by the lowest possible optical attenuation, in order to allow light transmission through the fiber.

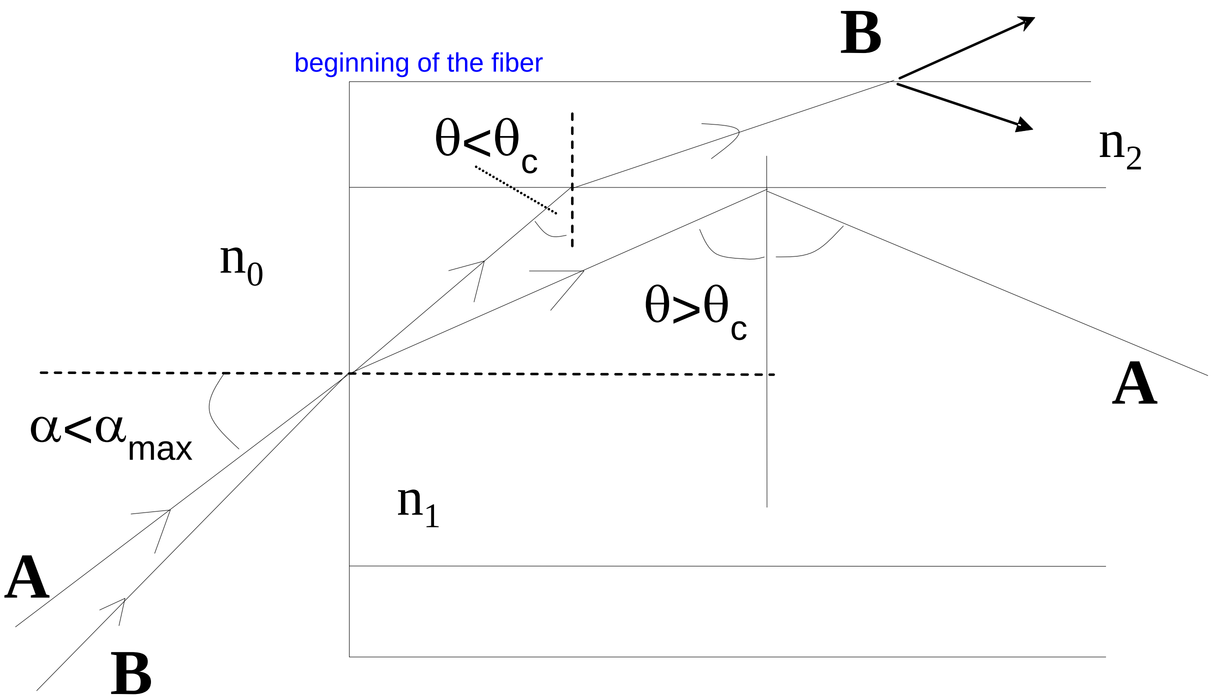
really small losses! in this sense it's a "light conductor"



It works in TOTAL INTERNAL REFLESSION (TIR)

Acceptance angle of the fiber (α_{max}) = maximal angle below which all rays propagate in the fiber with **total reflection**

It's important: the relative nclabbin-ncore, we can have two different types of material, step or graded. Also the deree of light incident is important

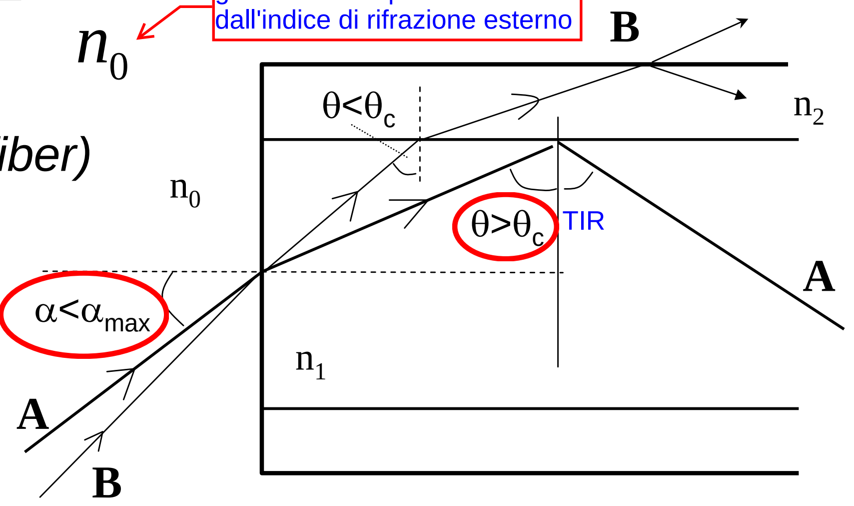


$$\frac{\sin\alpha_{max}}{\sin\left(90°-\theta_c\right)}=\frac{n_1}{n_0} \qquad \sin\theta_c=\frac{n_2}{n_1}$$

$$\sin\left(90°-\theta_c\right)=\cos\theta_c=\sqrt{\left(1-\sin^2\theta_c\right)}=\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}=\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

$$\Rightarrow \quad \sin\alpha_{max}=\frac{\sqrt{n_1^2-n_2^2}}{n_0}=\frac{N.A.}{n_0}$$

giustamente dipende dall'indice di rifrazione esterno

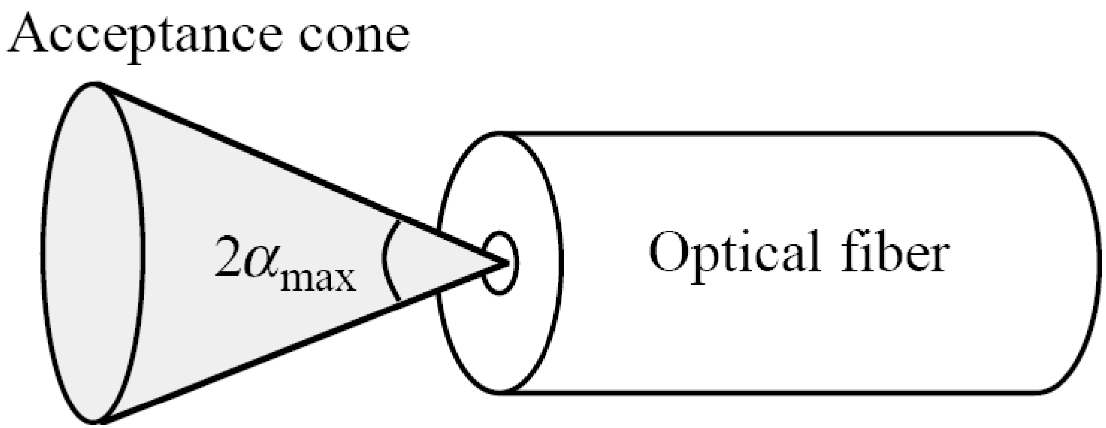


(N.A.= numerical aperture of the fiber)

(it defines completely the fiber)

Acceptance cone

Acceptance cone is the cone whose axis is aligned with the longitudinal axis of the fiber and whose angle is equal to the double of the fiber acceptance angle

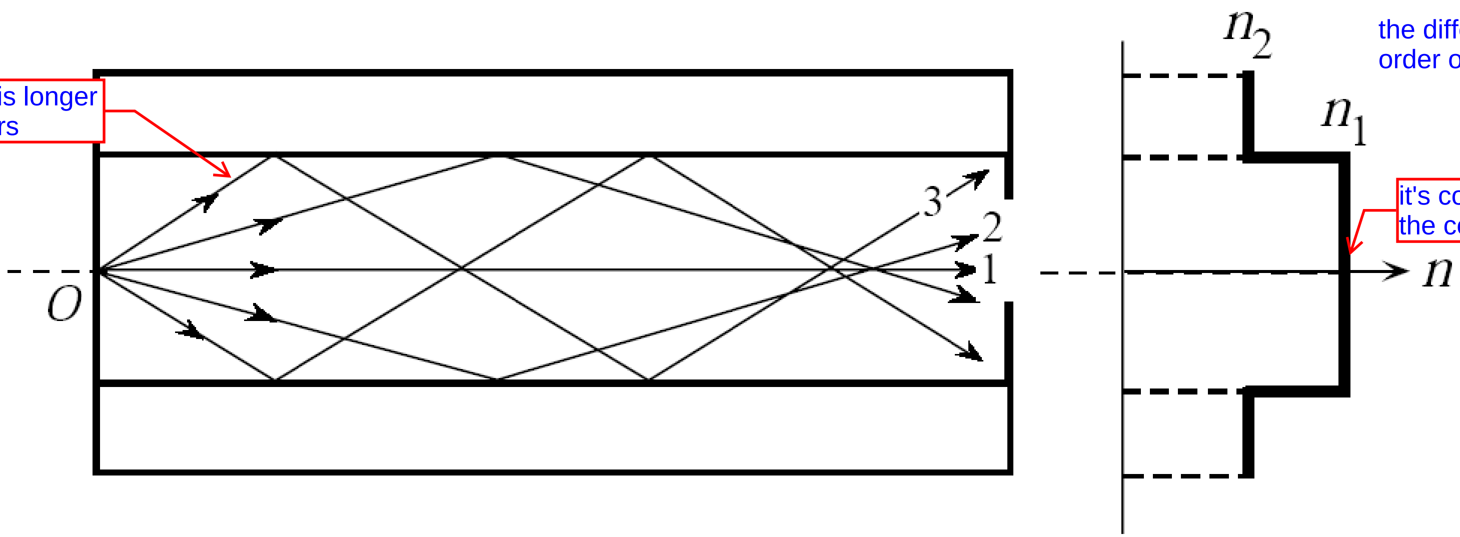


Fibers “step index”

The light rays travel through optical pathways of different length, therefore they reach the end of the fiber at different times (so the path is different from ray to ray according to the angle of incident) we need longer reading times, so a slower connection speed

the difference is in the order of 1%, not a lot

this pathway is longer than the others



it's constant through the core

Possiamo dire direttamente che il percorso è "Più lungo" inteso anche di tempo di percorrenza, perché n è costante in tutto il core, significa che anche la velocità dei rays sarà costante in tutto il core

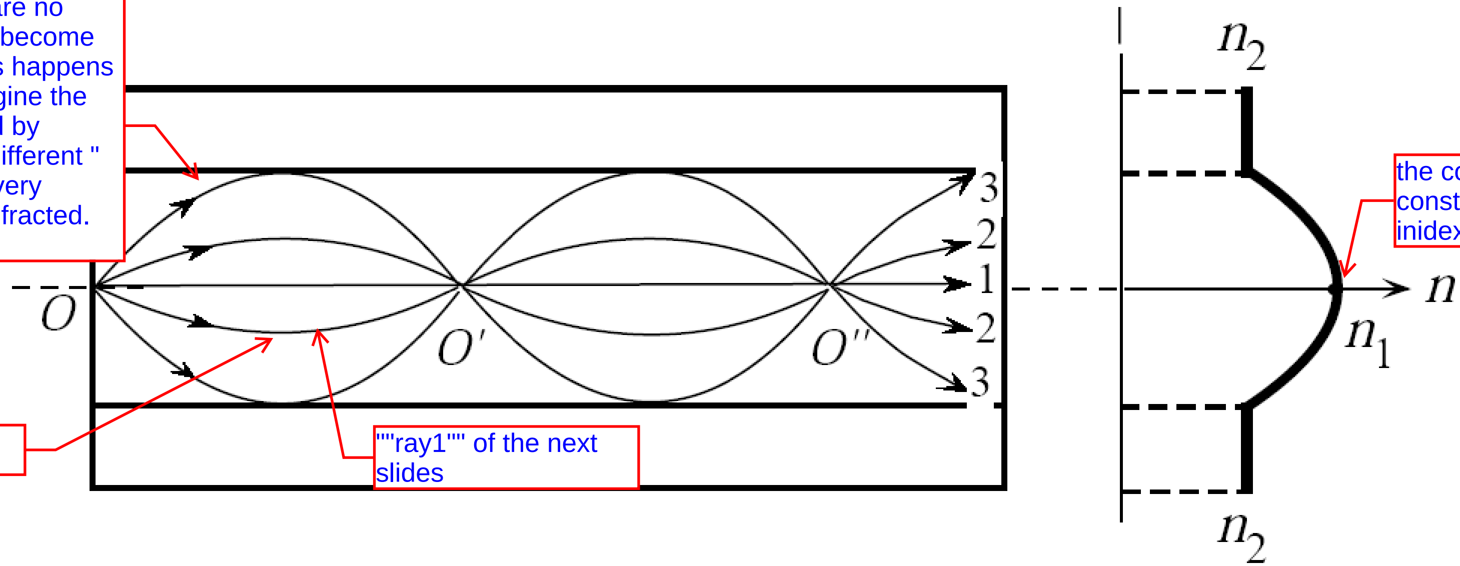
Fibers “graded index” (GRIN)

"sort of solution of the problem just encountered"

"gradually"

The light rays, again, travel through optical pathways of different length, however, also their velocities (equal to c/n) are different because of the refractive index profile (usually parabolic), so they arrive arrive at the fiber end a the same time.
(E.g., ray 2 travels through a longer pathways compared to ray 1, however, the latter has in average a lower velocity)

this way the pattern are no more linear, but they become more curvilinear. This happens because we can imagine the core being composed by different layers with different "n", so the ray is, at every change get slighlty refracted. (changes its angle).

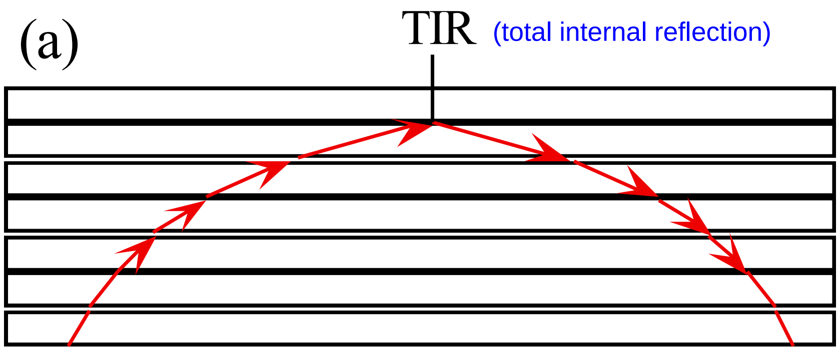


the core has not a constant reflaction inidex

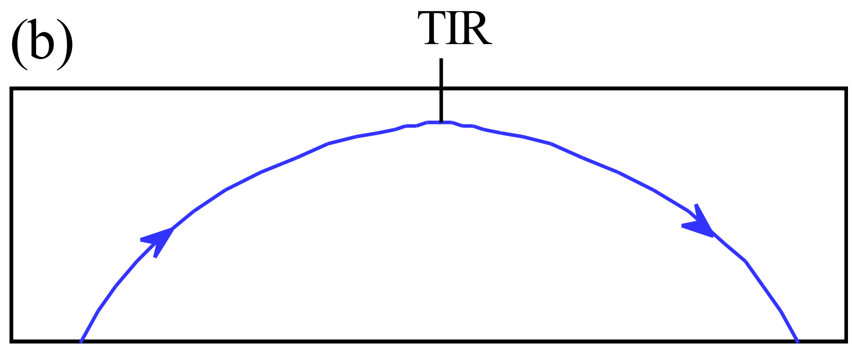
here it satisfies TIR

""ray1"" of the next slides

Fibers "graded index"



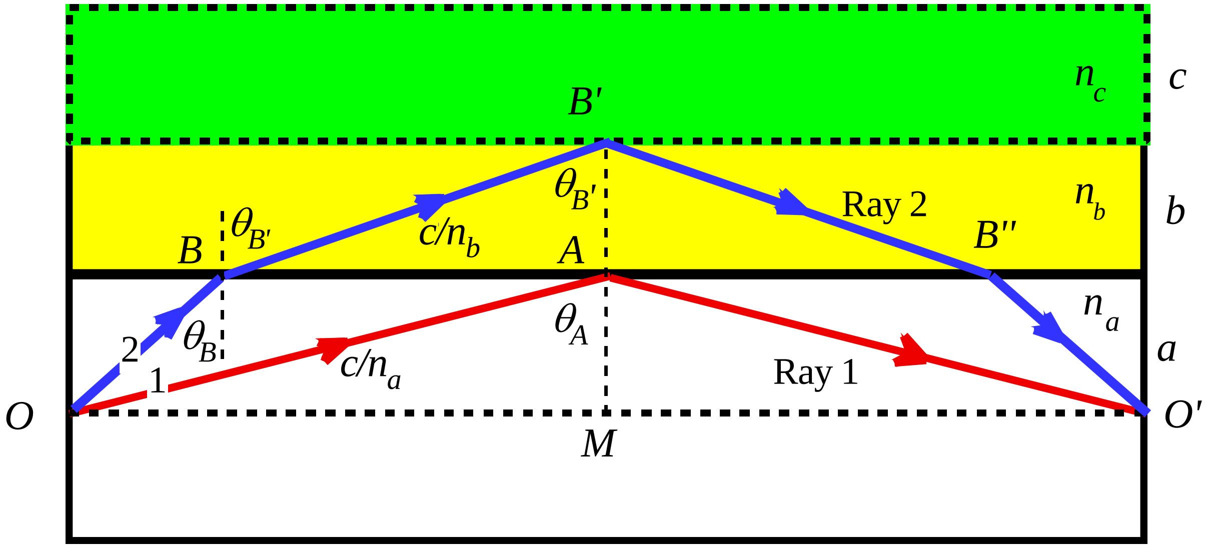
n decreases step by step from one layer to next upper layer; very thin layers.



Continuous decrease in *n* gives a ray path changing continuously.

(a) A ray in thinly stratifed medium becomes refracted as it passes from one layer to the next upper layer with lower *n* and eventually its angle satisfies TIR.
(b) In a medium where *n* decreases continuously the path of the ray bends continuously.

Fibers “graded index”



We can visualize a graded index fiber by imagining a stratified medium with the layers of refractive indices $n_a > n_b > n_c$ ... Consider two close rays 1 and 2 launched from O at the same time but with slightly different launching angles. Ray 1 just suffers total internal reflection. Ray 2 becomes refracted at B and reflected at B'.

Ray1 spends more time inside the core, while Ray2 spends more time in the outer circle. For R1 means spending most of the time in a region where n is high. Using the definition of the refractive index 'n', this means that the velocity of the wave in the core is equal to c/n. So, high n means low velocity, thus Ray1 spends more time in a layer with a slower velocity, but it travels over a short path! So we have a sort of equalization. shortpath-slow; longpath-fast. In the end we have much shorter difference in time.

Attenuation = loss of optical power of a wave travelling in the fiber in the longitudinal direction, due to absorption and scattering phenomena.

Absorption coefficient α = fractional decrease of optical power per unit of distance *dx*:

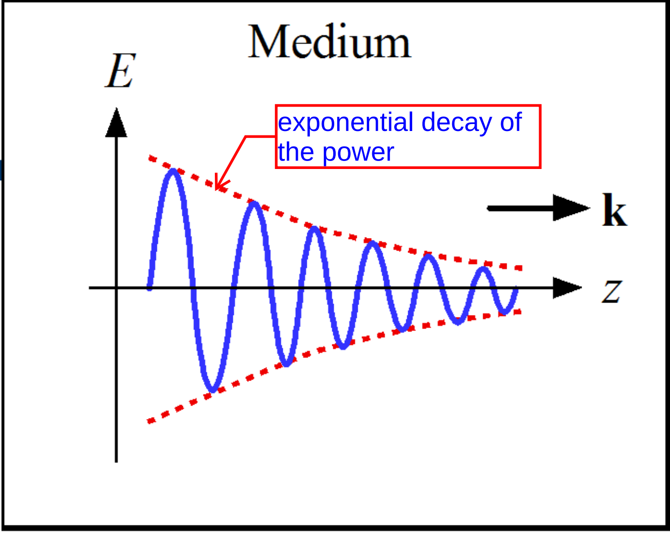
we can just change the order of the equation with dP/dx = is proportional to the power: lower power, lower attenuation, high power high attenuation. It's a sort of linear relationship. For example if we have the power as a funcion of x, and we want to know what happens after it enters a zone (where we know there's a fiber), we just have to integrate. And it results ln(p(x)) - ln(Pin) where Pin is the starting power

$$\alpha = -\frac{1}{P}\frac{dP}{dx}$$

we have a loss in power but want a positive coefficient

like if it's 1W at a 1km the power is """a little bit""" lower. Btw power is really important in fiber optics

Attenuation



Integrating along distance L:

If the wave exits after a certain point, expressed by pout, we can have the attenuation described by alpha (meaning that instead of p(x) we put P(out) = Pout

$$\alpha = \frac{1}{L} ln\left(\frac{P_{in}}{P_{out}}\right)$$

$$\Rightarrow \quad P_{out} = P_{in}\, exp(-\alpha L)$$

(absorption coefficient)

The attenuation of optical power in an optical fiber is often expressed in terms of decibel per unit of fiber length (typically dB/km). In terms of base-10 logarithm :

Perdita di potenza per lunghezza, chiaramente dato che è potenza e decibel allora è il rapporto fra Pin e Pout con 10 davanti rapportato alla lunghezza

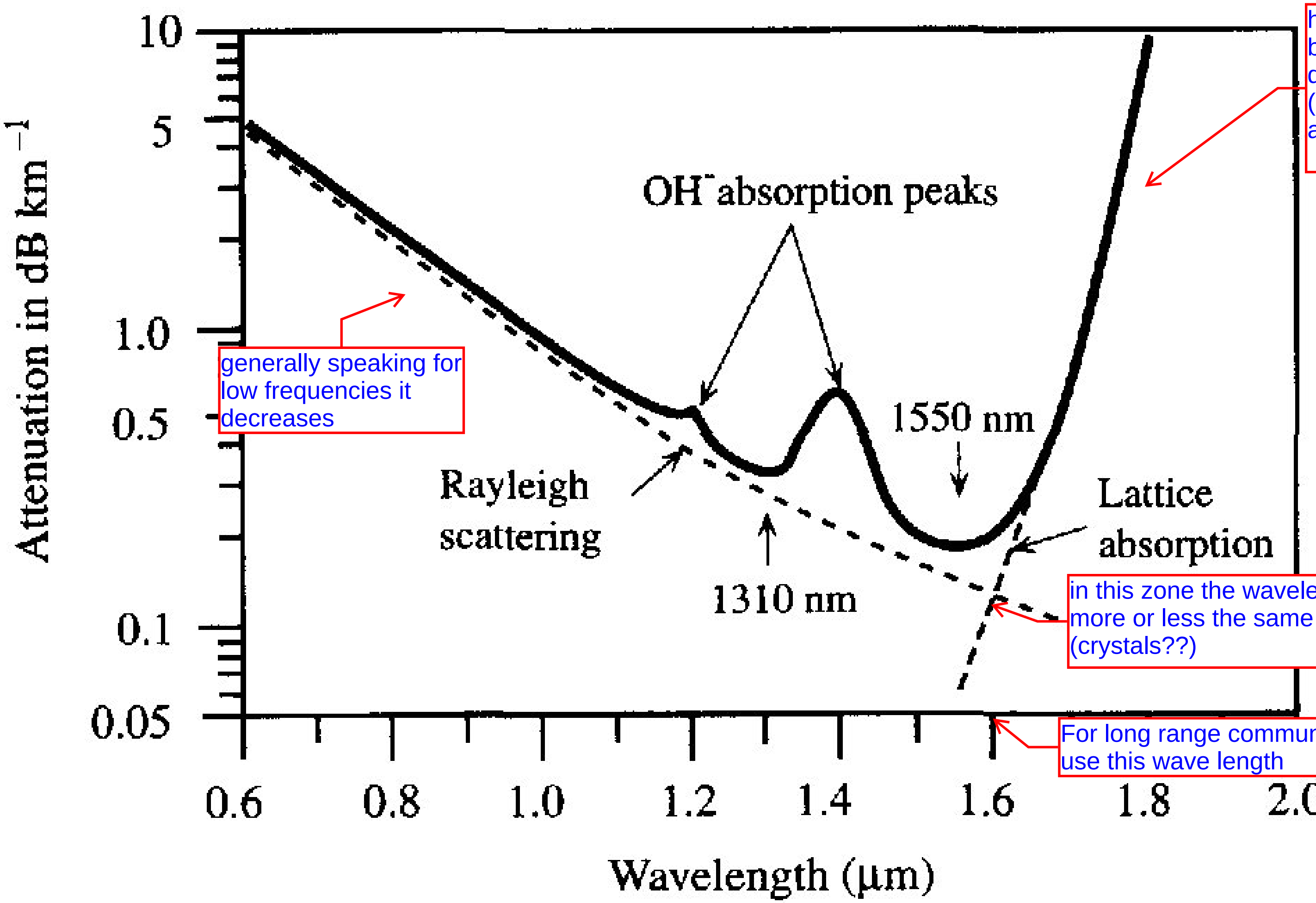
$$\alpha_{dB} = \frac{1}{L} 10\, log\left(\frac{P_{in}}{P_{out}}\right)$$

BTW in optical fibers alpha is not constant but depends on the wavelength. (it would be constant with a monochromatic source, like a laser diode, it's almost one wavelength)

$$\alpha_{dB} = \frac{10}{ln(10)}\alpha = 4.34\,\alpha$$

Attenuation of Si optical fibers

the core is Silicon



generally speaking for low frequencies it decreases

here it's different, because we have different phenomena (in this case Lattice absorption)

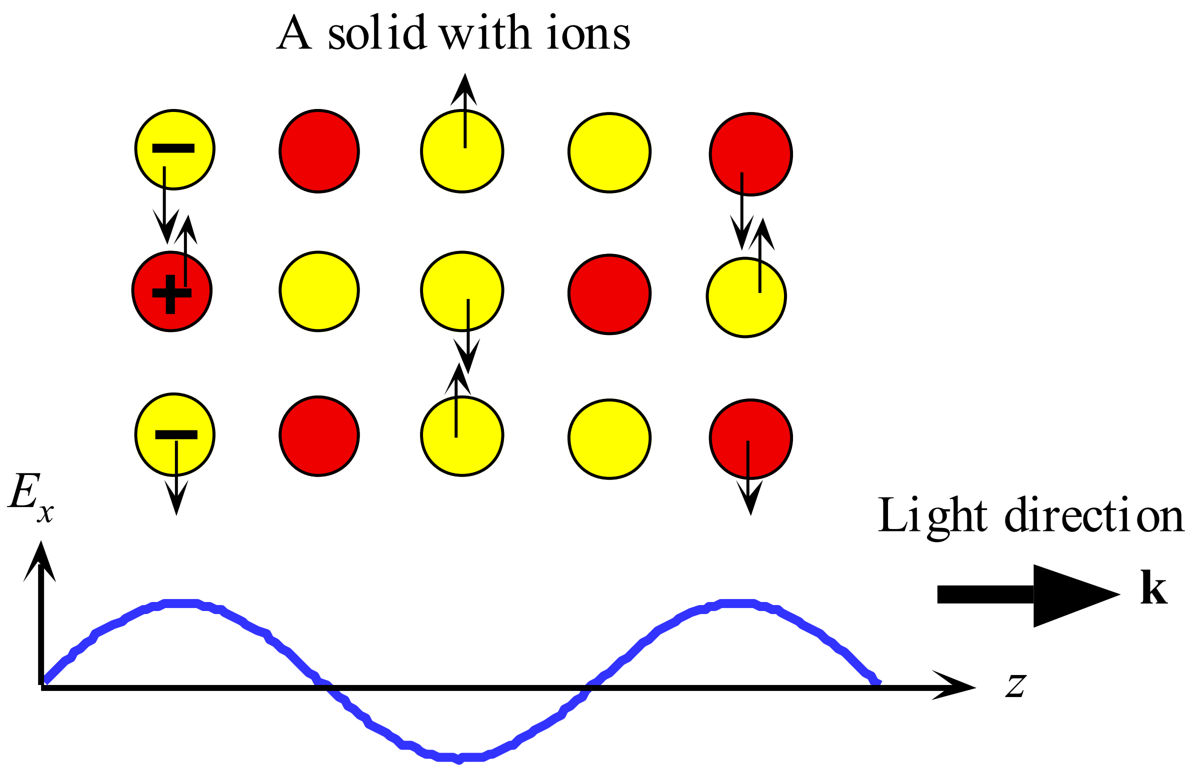
Lattice=Reticolo

in this zone the wavelenght is more or less the same as the.... (crystals??)

For long range communication I would use this wave length

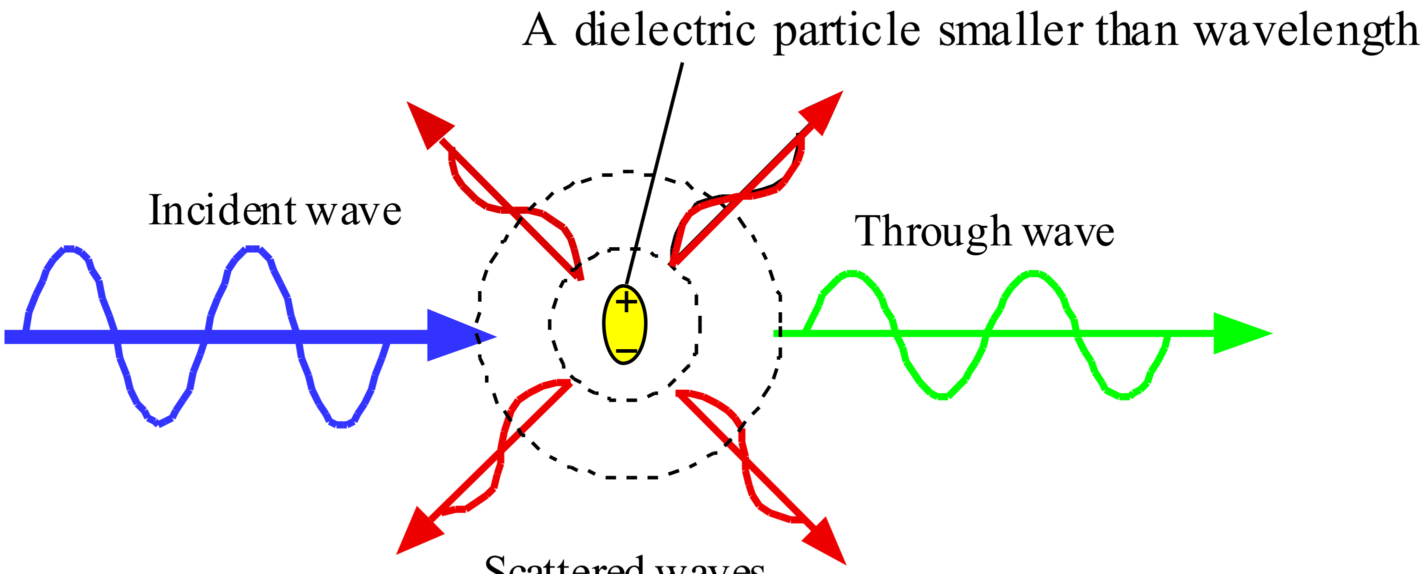
When the wave is short what is important is the interaction of the wave with local atoms, groups of atoms. Attenuation means loss of energy. Indeed the scattering, which is dispersion of energy along different direction, happens when the wave interacts with single atoms, because we are considering SHORT length. If the wave l. is greater than these groups of atoms, it's more important the idea that the wave makes vibrate the crystal itself.

Lattice absorption



Lattice absorption through a crystal. The field in the wave oscillates the ions which consequently generate "mechanical" waves in the crystal; energy is thereby transferred from the wave to lattice vibrations.

Rayleigh scattering



Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength. The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

Attenuation of Si optical fibers

• Lattice absorption in the infrared region (λ > 1.6 μm), i.e absorption of energy by the vibrations of ions constituting the crystal

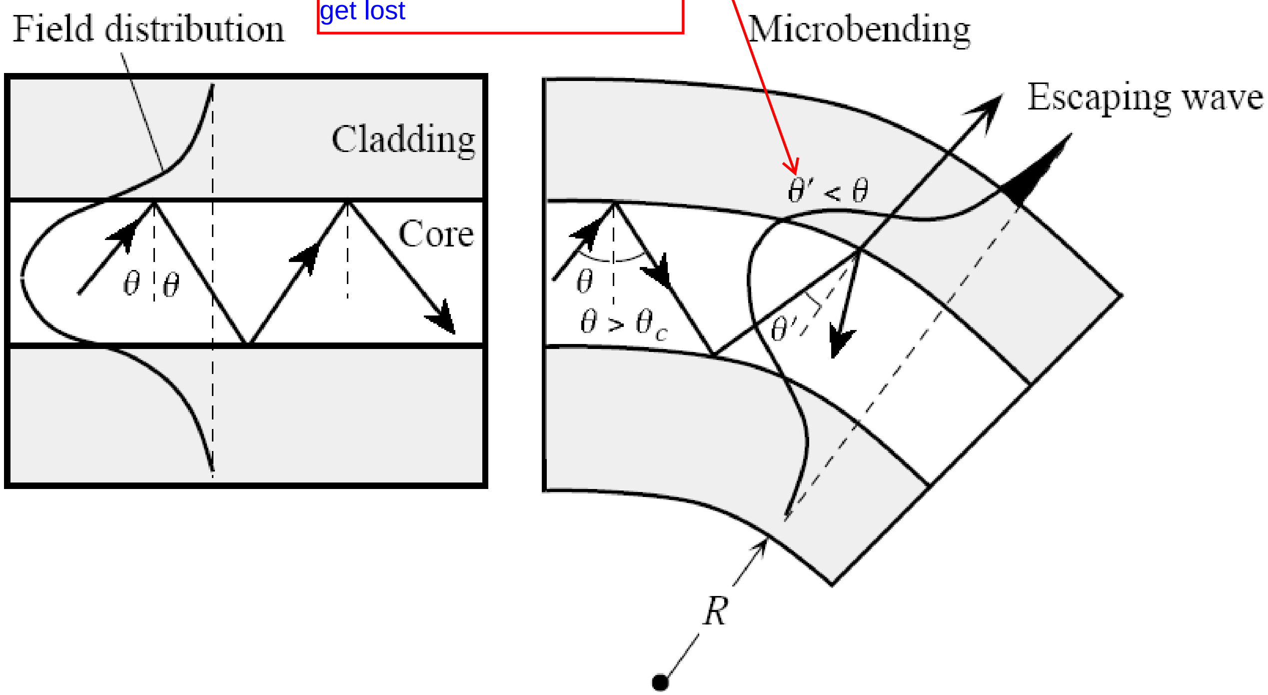
• Rayleigh Scattering (proportional inversely to λ^4): local variations of the refractive index

• Absorption peaks at 1.24 and 1.4 μm, due to impurities (OH- ions) in the lattice structure

$\Rightarrow$ 2 low attenuation windows

Bending losses

holy shit it could be lower than the critical angle. If it happens it's lost. And generally a small proportion of the incident light get lost

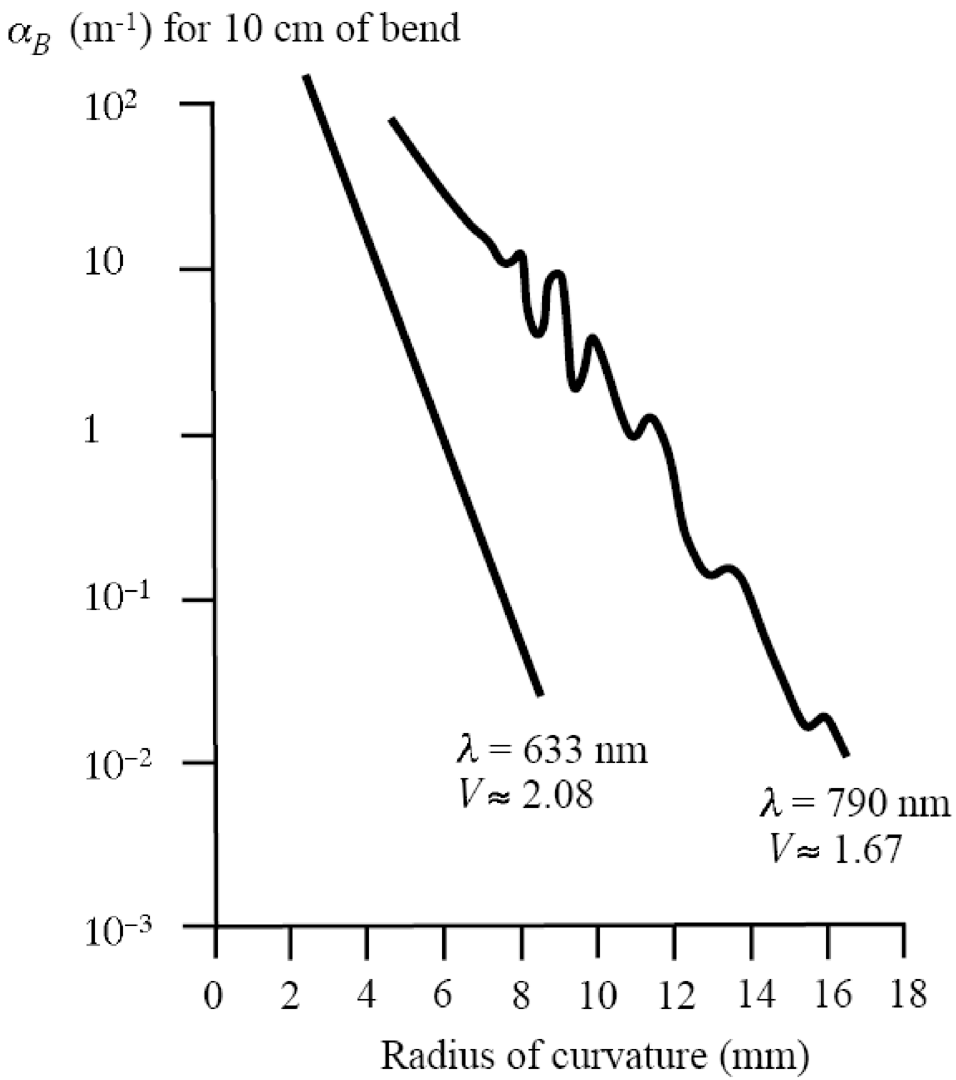


Sharp bends change the local waveguide geometry that can lead to waves escaping. The zigzagging ray suddenly finds itself with an incidence angle θ' that gives rise to either a transmitted wave, or to a greater cladding penetration; the field reaches the outside medium and some light energy is lost.

loss of energy due to bending, not only macro but ALSO micro bending. But you could also use this phenomen... as a mechanical sensor.

Bending losses

losses as a function of beding



Measured microbending loss for a 10 cm fiber bent by different amounts of radius of curvature R. Single mode fiber with a core diameter of 3.9 μm, cladding radius 48 μm, $\Delta = 0.00275$, $NA \approx 0.10$, $V \approx 1.67$ and 2.08 (Data extracted and replotted from A.J. Harris and P.F. Castle, *IEEE J. Light Wave Technology*, Vol. LT14, pp. 34-40, 1986; see original article for discussion of peaks in α_B vs. R at 790 nm).

Optical fibers: manufacturing techniques

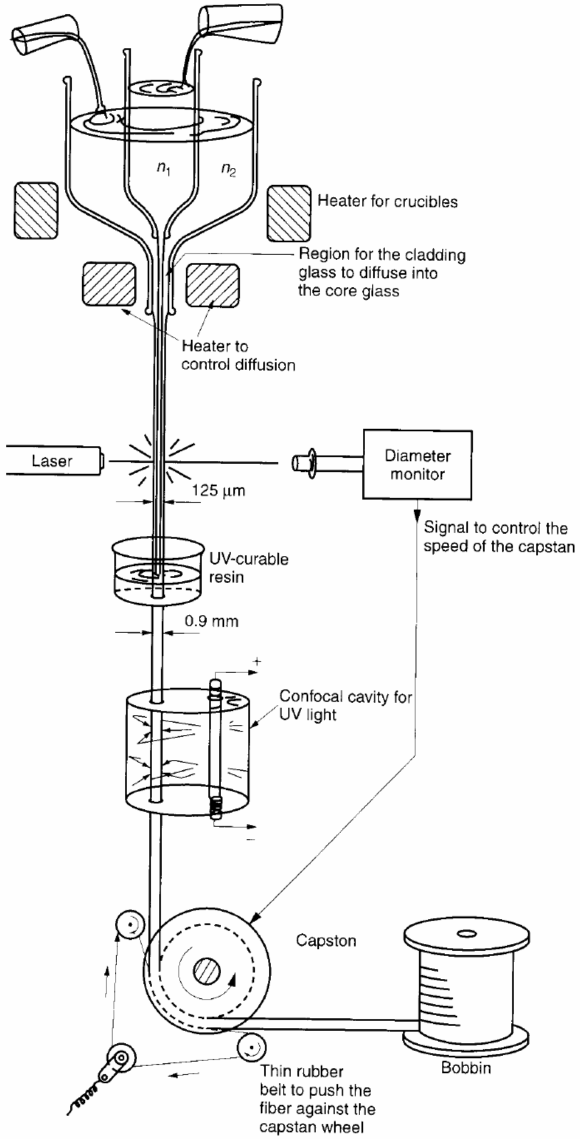
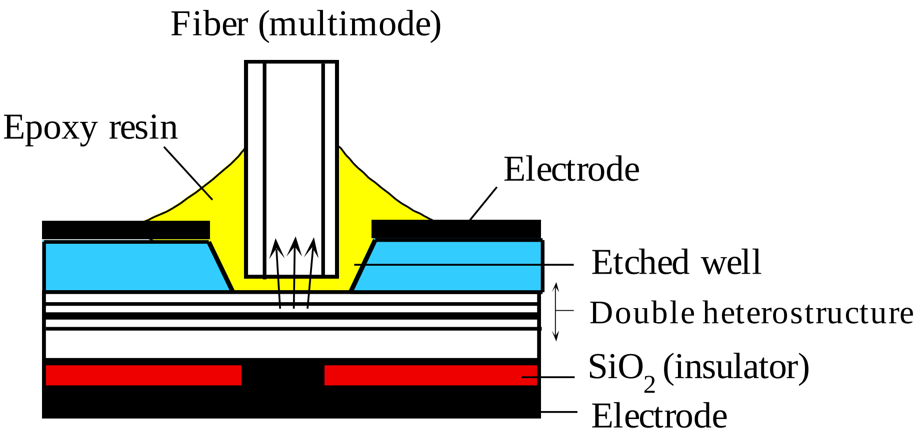


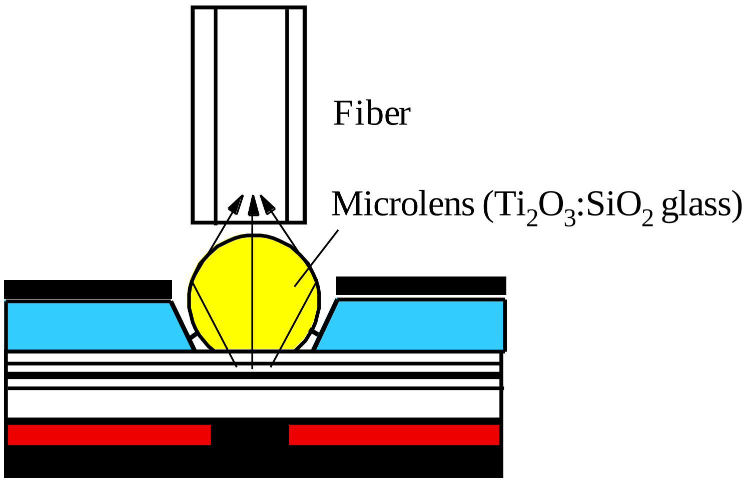
Figure 11.45 Fabrication of optical fiber by the double-crucible method.

LED-optical fiber coupling [produzione]



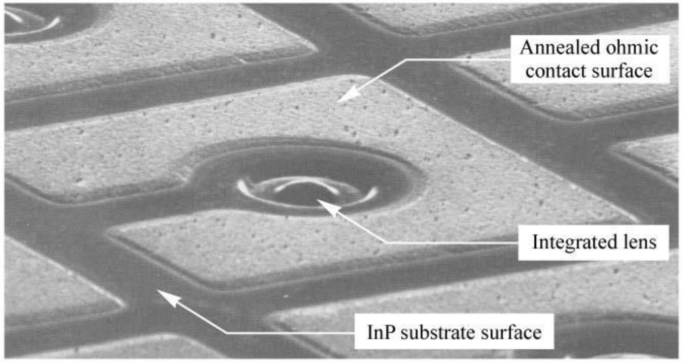
(a)

Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.

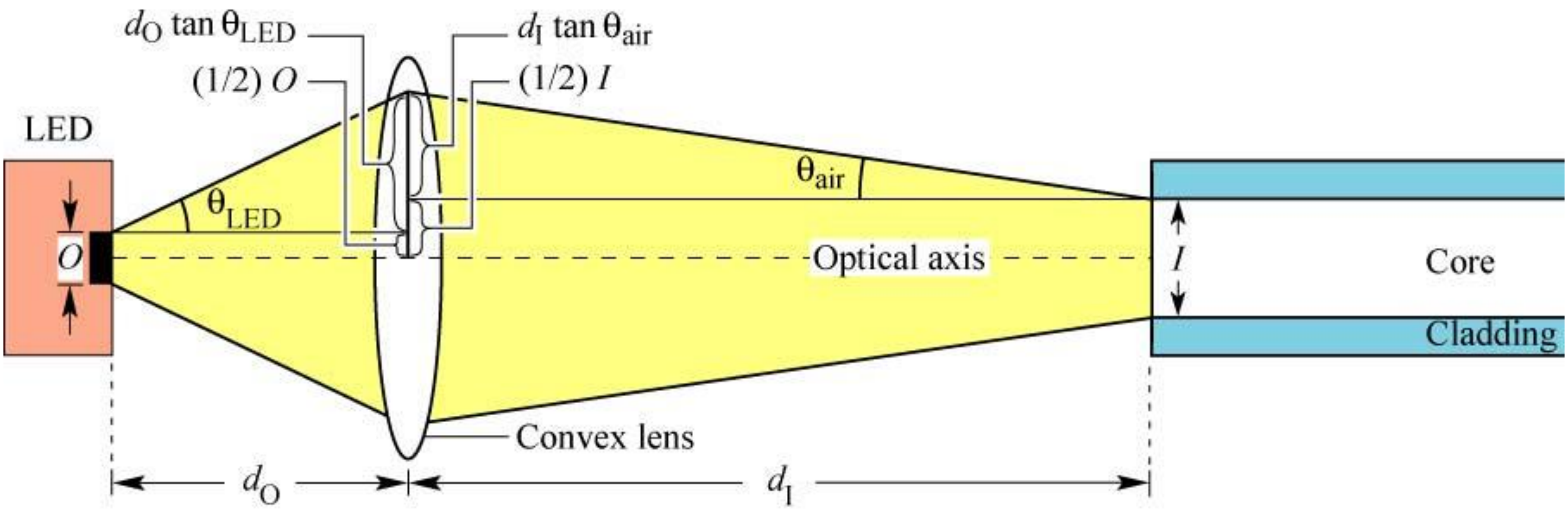


(b)

A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.



LED-optical fiber coupling



Schematic illustration of coupling with a lens by imaging the light-emitting region of an LED onto the core of an optical fiber. The LED has a circular emission region with diameter O (Object). The emission region is imaged onto the fiber core with diameter I (Image) using a convex lens with focal length f.

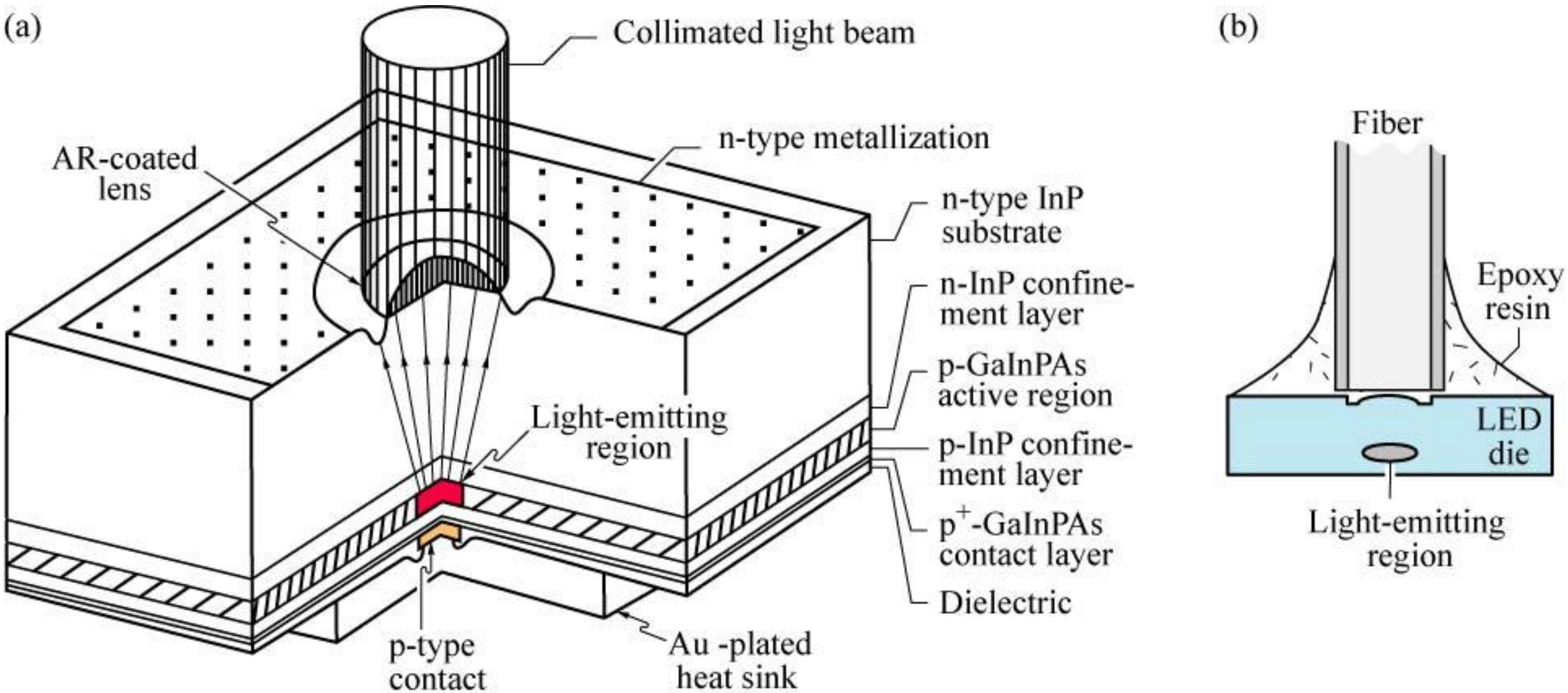


Fig. 23.2. (a) Structure of a communication LED emitting at 1300 nm with a GaInPAs active region lattice-matched to InP. The light generated in the active region is transmitted through the transparent InP substrate. The lateral dimension of the light-emitting region is defined by current injection under the circular ohmic contact with a diameter of 20 µm. An anti-reflection-coated (AR) lens, etched into the substrate, collimates the light beam. (b)Illustration of LED-to-fiber coupling using epoxy resin.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Fiber bundles

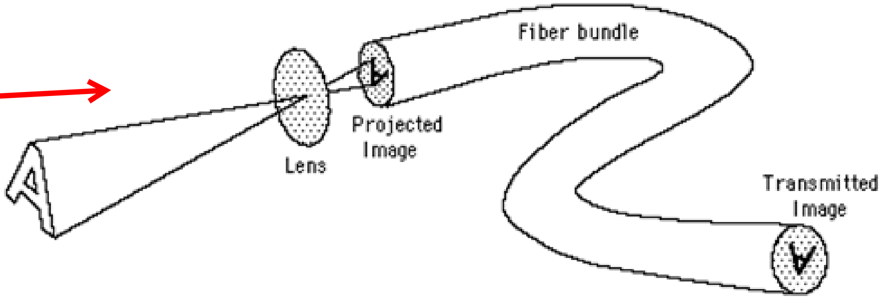
In most cases not single optical fibers, but sets (several hundreds) of optical fibers, to form **bundles**, are used.

We have two types of fiber bundles:

it's not taken care of the relative position of one fiber to the other

In **incoherent bundles**, the fibers are not arranged in any particular way and can transmit only illumination (e.g. in surgery, illumination of internal organs, determination of oxygen saturation in the vessels). Many microscopes use incoherent fiber-optic light sources to provide intense illumination of samples being studied.

In **coherent bundles** of fibers, the relative position of the fibers is the same at the two terminals.
So they are used in **imaging**.



A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures. Industrial endoscopes (see fiberscope or borescope) are used for inspecting anything hard to reach, such as jet engine interiors.

ofc easiest way is if the fibers are parallel

Coherent bundles of fibers

if we use the bundle to transmit an image

• resolution increases with increasing number of fibers in the bundle

• it is very important to avoid evanescence (*) among contiguous fibers (this can be neglected in incoherent bundles)

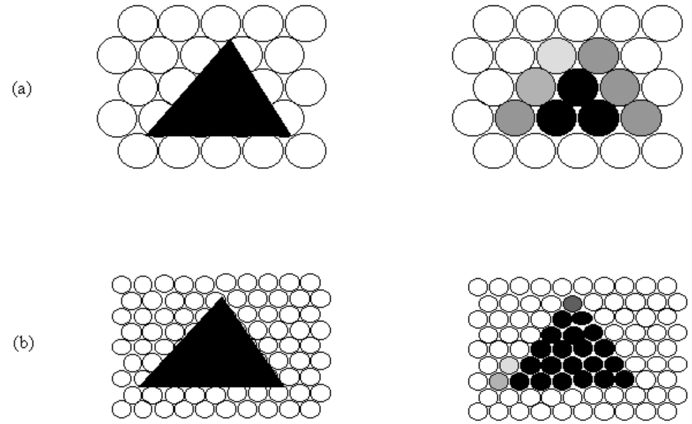


Image projected on the distal face of the fiber bundle
Image seen on the proximal face of the fiber bundle

(*) close to the contact point of two adjacent fibers there is a zone where distances are of the order of the wavelength, and there is transfer of radiant energy (evanescence).

To minimize evanescence:

• Metal Coated Silica (MCS) Fibres

• fiber coating with materials with lower refractive index and thickness of the same order of the wavelength.

We can't have high number of fibers because of the evanescence.. which happens if I want to compress many different fibers, basically one wave enters a different fiber and we have noise. We have to insulate each single fiber. ofc insulating means covering with another material, but this increases a little bit the size of a single fiber.