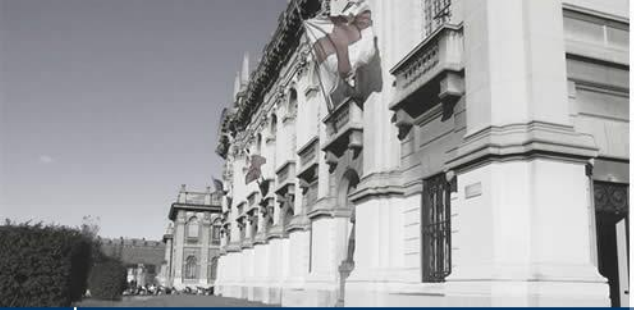


DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA

POLITECNICO DI MILANO





Lecture 12
Endoscopes
Fiber Optic Sensors

Fiber optics endoscopy

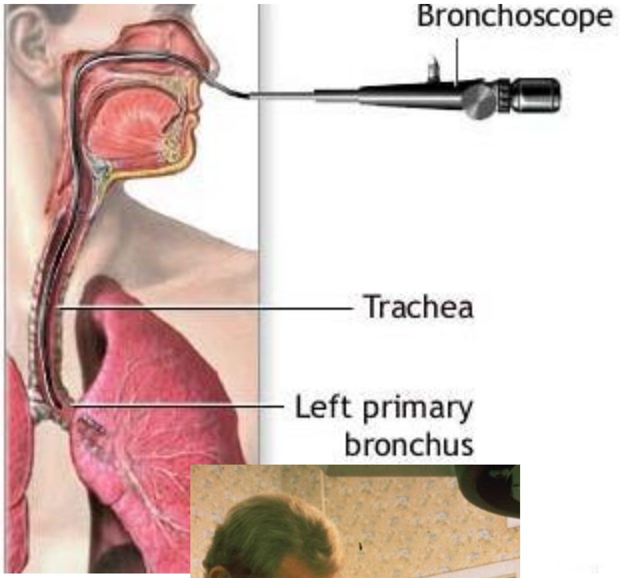
Endoscopy = from greek ενδομ (inside) and σκοπειν (seek).
Endoscope = optical instrument used to see inside the body through natural openings (ear, throat, rectum) or through small incisions in the skin.
A flexible endoscope is called fiberscope, which is fiber optic bundle with an eyepiece at one end, and a lens at the other. .
On the contary, in rigid endoscopes, a high number of lenses (up to 40-50) are used to convey light.

In practice, all flexible endoscopes are constituted by both incoherent (to transmit **light**) and coherent bundles (to transmit **images**).
There can be additional channels for passage of air, water or for remote controlling of devices like biopsy forceps or cytology brushes.

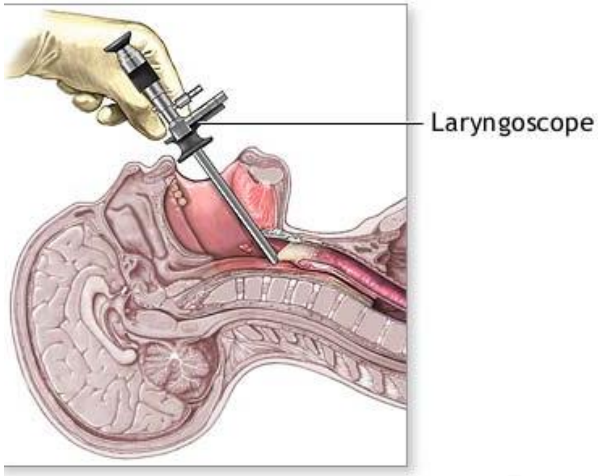
Endoscopy

Laparoscopy (abdomen, uterus, fallopian tube)

Bronchoscopy (lungs)

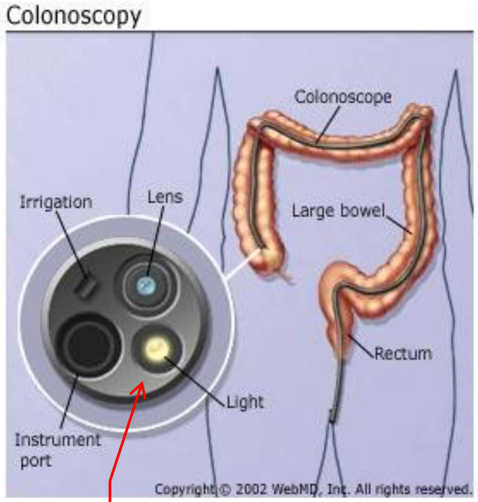


laryngoscopy (vocal cords)



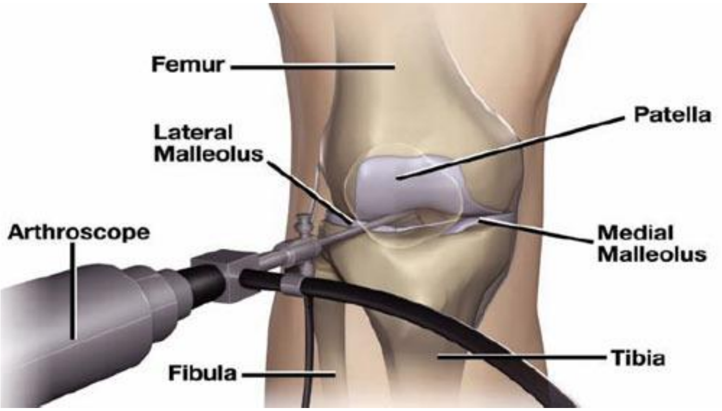
Endoscopy

colonoscopy (colon)

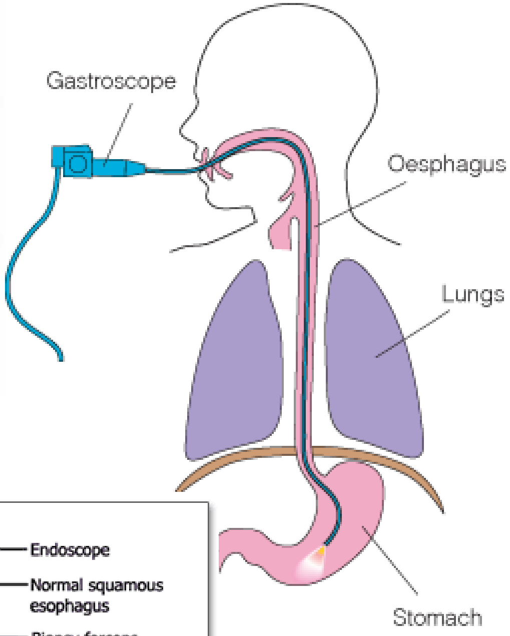


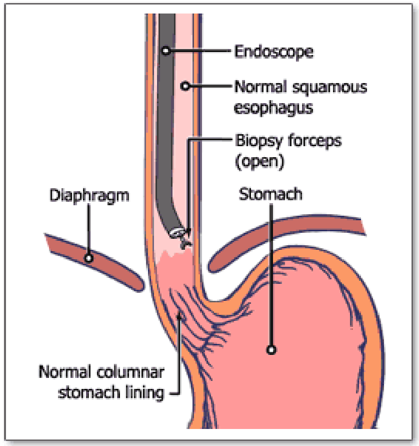
end of an incoherent bundle

arthroscopy (joint)

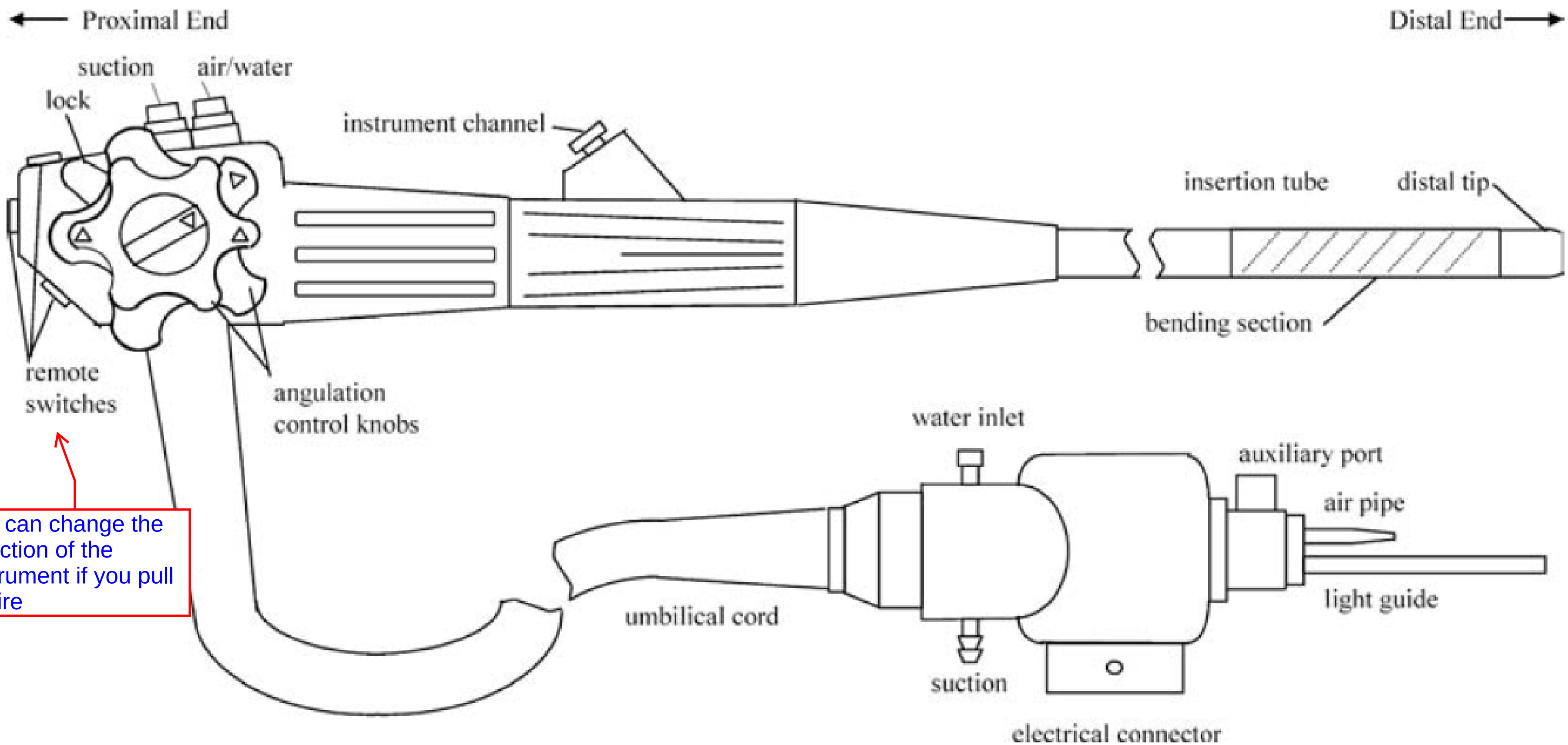


gastroscopy (GI, stomach, oesophagus)





Endoscope: basic components



you can change the direction of the instrument if you pull a wire

FIGURE 11.1 The basic components of a conventional endoscope is shown. The insertion tube is located on the distal end, and a short bending section connects to the distal tip. The proximal end contains the angulation control knobs, valves for suction, air, and water, and remote switches. The instrument channel is used to deliver accessories to the distal tip.

Endoscope: distal tip

end part of the instrument which is controllable

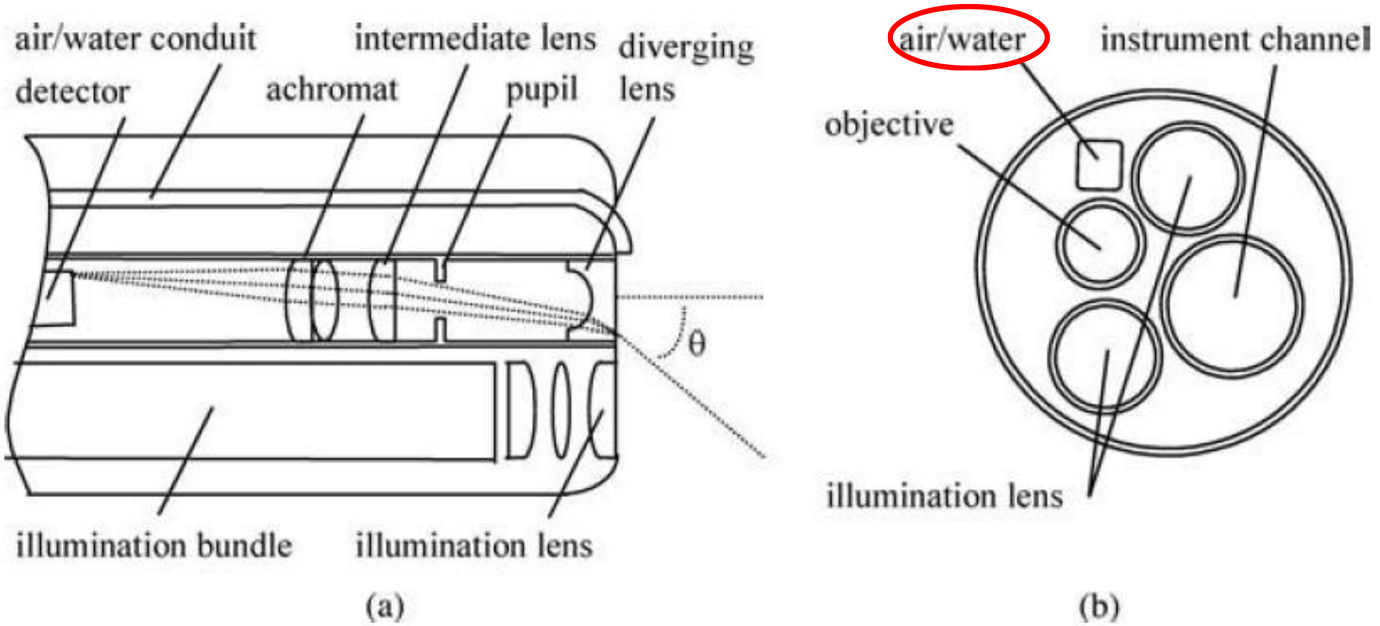


FIGURE 11.2 A detailed view of the distal tip. (a) A cross-section view shows the design of the optics, detector, and air/water conduits; (b) the end-view shows the relative location of these elements.

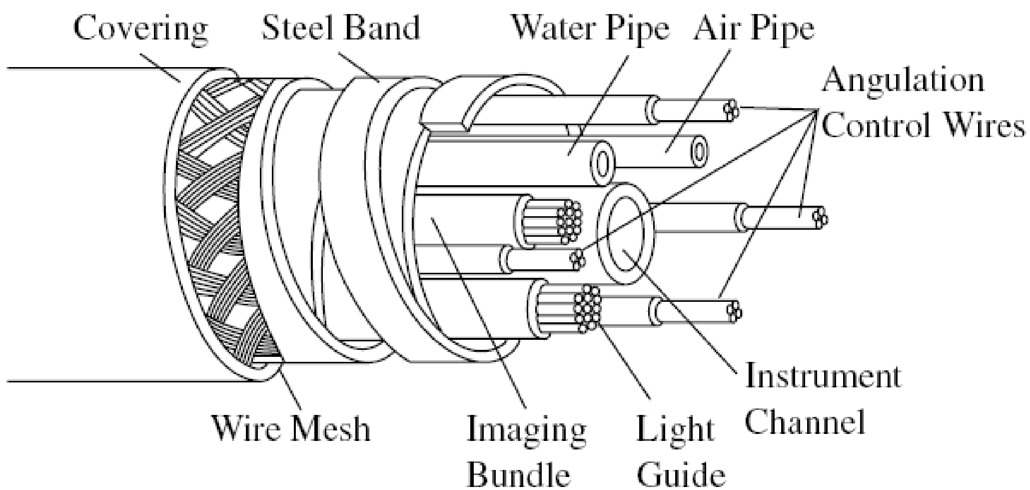


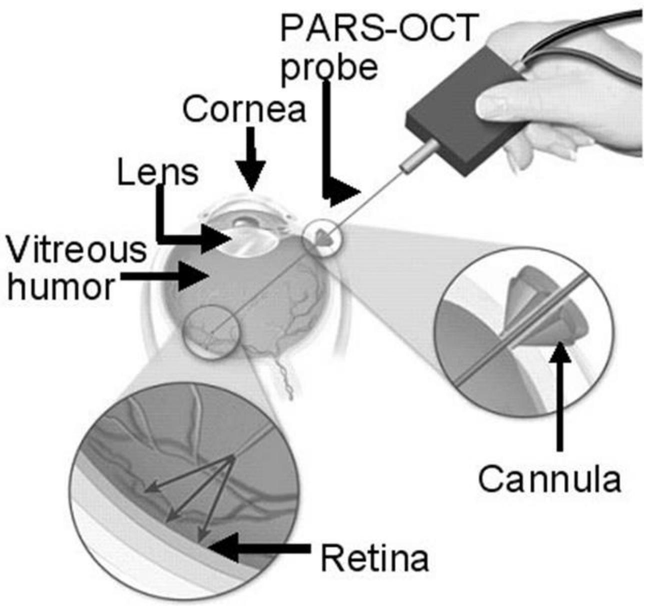
FIGURE 11.4 The contents of the insertion tube include the light guide, imaging bundle, angulation control wires, air and water pipes, and instrument channel, and are protected by a wire mesh and steel bands for mechanical protection.

Ultra-thin endoscopes

Angioscope

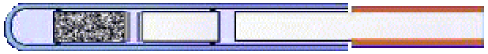
Opthalmic endoscope

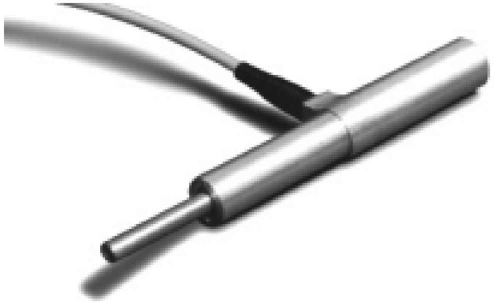
(Outer diameter of the probe only 820 µm –small)



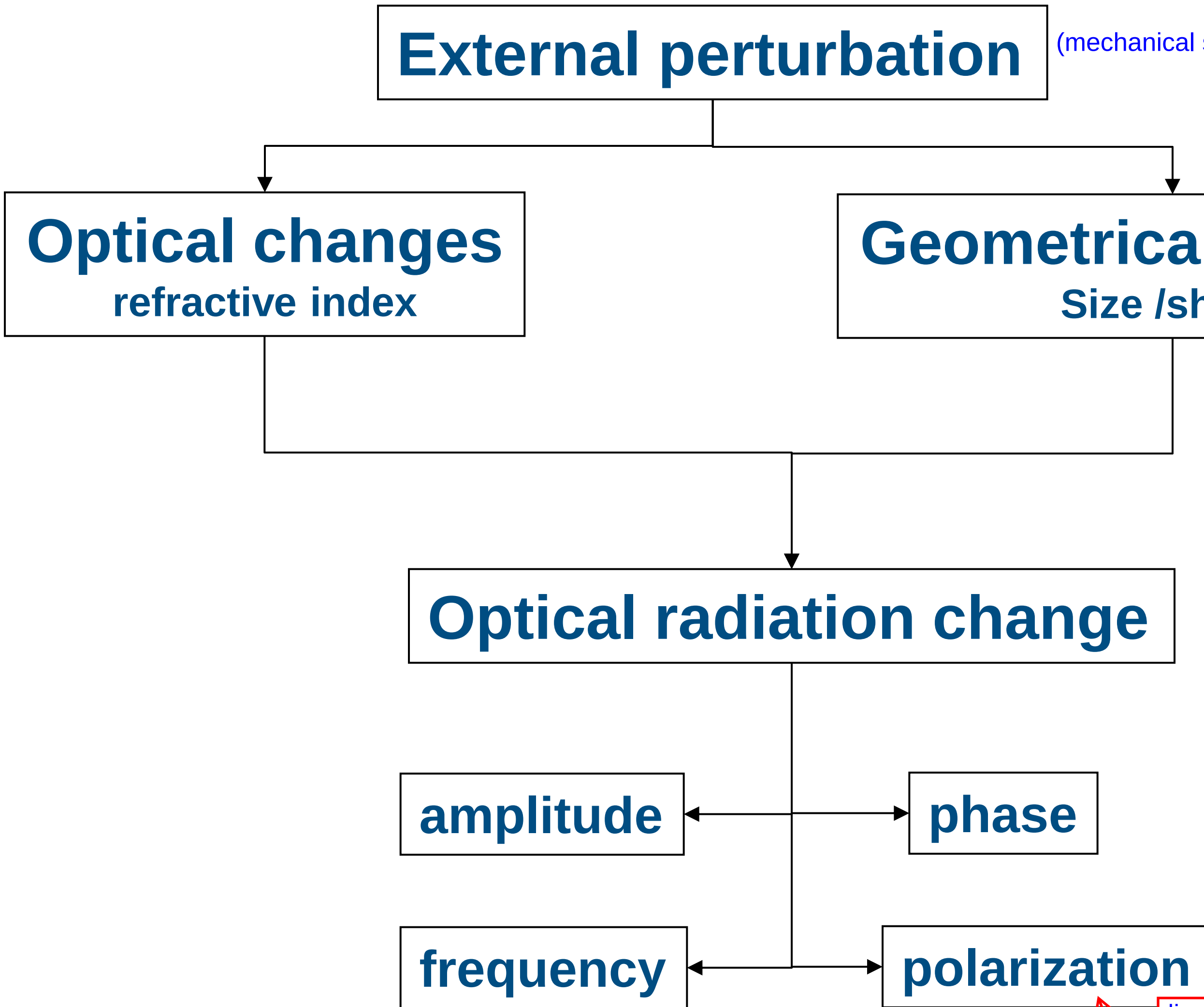
Needle scope

Any device in which variations in the transmitted power or the rate of transmission of light in optical fiber are the means of measurement of physical parameters such as strain, temperature, pressure, velocity, and acceleration





Fiber Optic Sensors (FOS)



(mechanical stress, temperature ...)

example: I have a substance that can go inside the fiber, and thus it can change a physical part of the fiber changing its refractive index. Or maybe I have a strain in the fiber, which changes the amount of light that goes from one point to the other (to respect the rest point). Btw generally speaking what I try to detect is optical radiation change. It could be more attenuated, increasing tempereature. Or I could change the frequency of the radiation wave, freq., polarization ... .

direzioni delle oscillazioni, le onde acustiche non le hanno, le onde delle corde di una chitarra sì: può oscillare verticalmente, orizzontalmente oppure in inifinite altre direzioni

FOS: Main Advantages (reason to produce and develope fiber optics sensors)

- Non-electric (immune to electromagnetic and radio-frequency interference) we don't need electrical current
- withstand high temperature and harsh environments (corrosion) for example If I put a sensor in a stomach I don't want it to be corroded
- high shock survivability (explosion or extreme vibration)
- high accuracy and sensitivity
- light weight and small size (human hair?)
- high capacity and signal purity
- multiplexing capacity
- can be easily interfaced with data communication systems

Fiber Optics Sensors (FOS): application areas

- **physical sensors** (measurement of temperature, stress, etc)
- **chemical sensors** (measurement of pH content, gas analysis, spectroscopic studies, etc.)
- **biomedical sensors** (measurement of blood flow, glucose content, etc.)

Measured Parameters by FOS

- Light intensity
- displacement (position)
- pressure
- temperature
- strain (rotation and displacement)
- flow
- magnetic and electrical fields
- chemical compositions
- velocity, acceleration and vibration
- force and stress

Fiber optics sensors: intrinsic and extrinsic

FOS use different physical-chemical phenomena that alter the parameters that determine light propagation in the fiber.

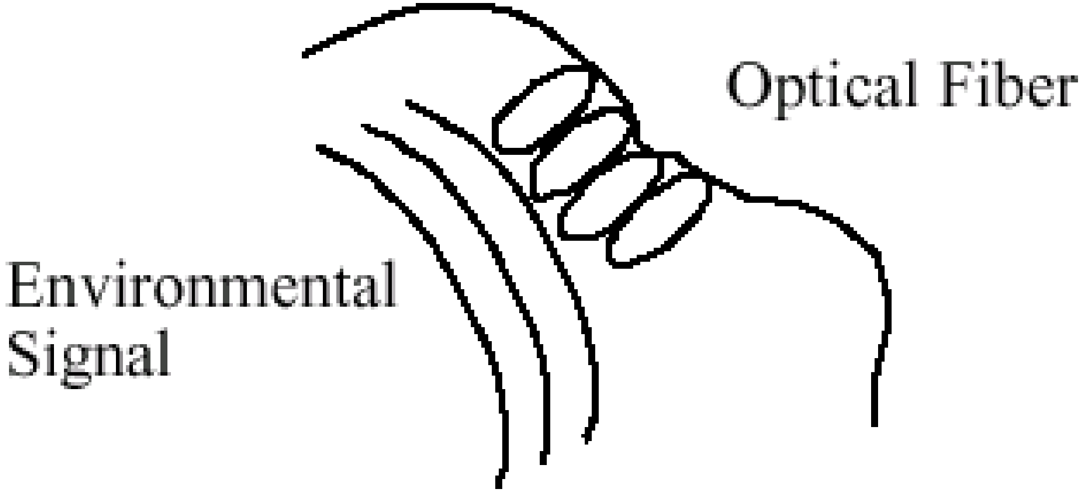
They can be divided into two categories, according to the place where sensing happens:

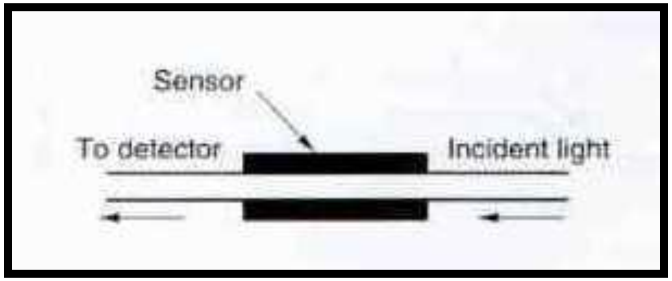
1) **Intrinsic (or all-fiber):** the measurand determines the variation of the transmission properties of the fiber
2) **Extrinsic (or hybrid):** the fiber simply acts as a light conductor from/to the sensor fibers are used ""as a tool""

Intrinsic or All-Fiber Optic Sensors

- Sensing takes place within the fiber itself (fiber itself performs the measurement)

- The sensors rely on the properties of the optical fiber itself to convert an environmental action into a modulation of the light beam passing through it.





Intrinsic FOS
"core-based"

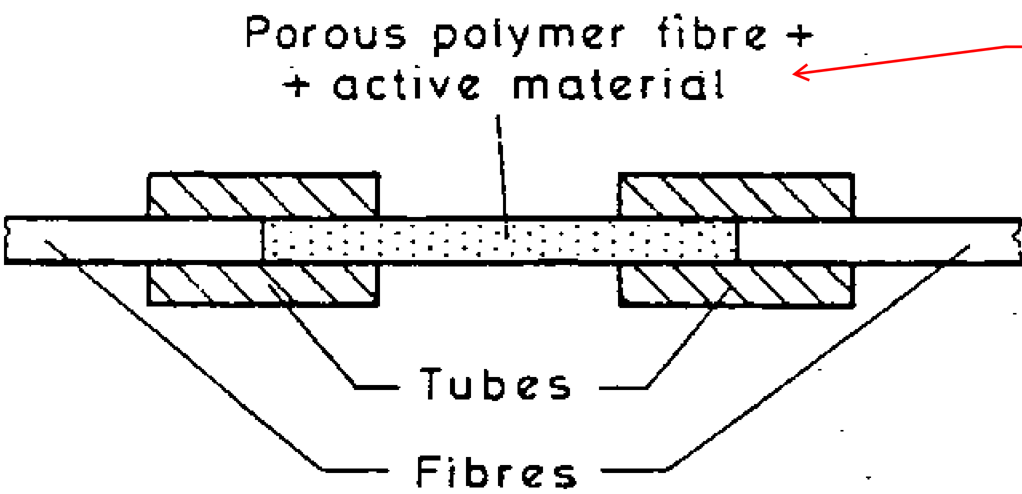
In questo caso cambiamo il livello di attenuazione

Porous fibers treated with selective chemical reagents. They can have a high gas permeability and liquid impermeability, and therefore can be used to detect a given gas concentration inside the sample according to Beer's law:

$$I = I_0 \exp\left(-hLc\right)$$

concentration, for exaple of O2, of where the FOS is inserted

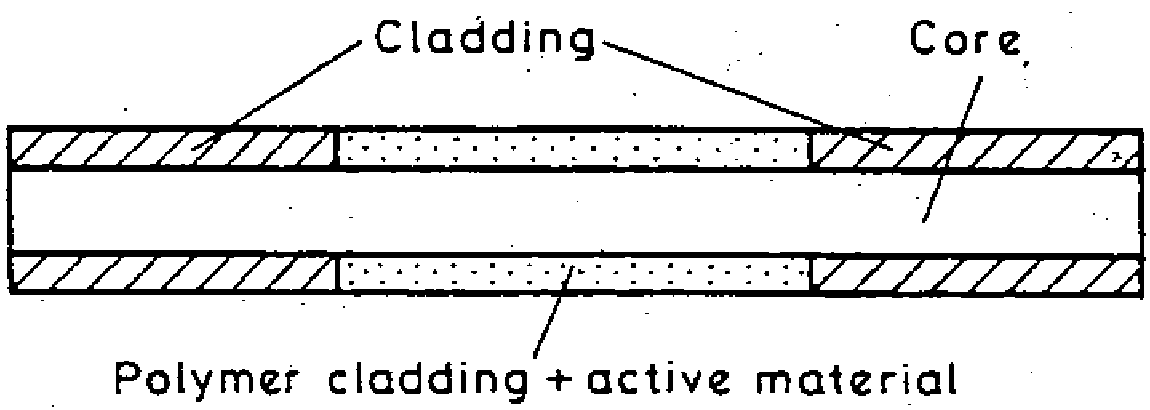
h=extinction coefficient (both light absorption and scattering)



the fiber is made of a particular material that is able to absorbe in a selective way substances (because of the chemical reaction that can happen within the material). So in the end this part acts with more, or less, attenuation

Intrinsic FOS alternative
"cladding-based"

The cladding of the fiber is made, in a given tract, with polymeric material and selective chemical reagents able to absorb the substance whose concentration has to be measured.
This determines variations of the cladding refractive index and therefore of the light transmitted throughout the fiber.
This kind of sensors can be used to measure humidity. The amount of vapor absorbed by the porous cladding depends on the humidity of the gas where the fiber is.

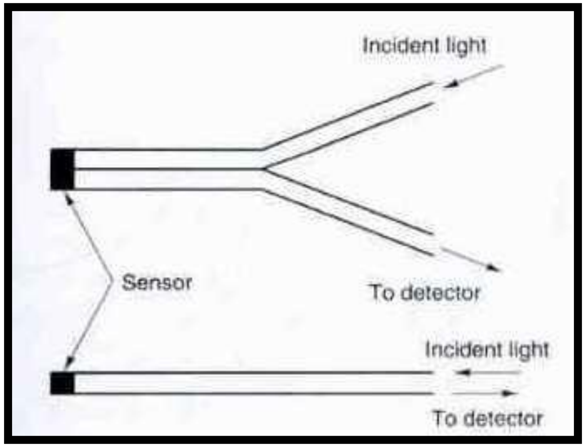


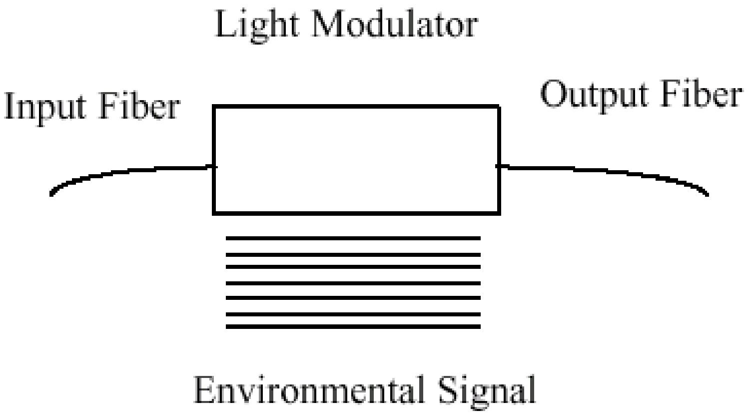
changes the refractive index of the cladding material

Extrinsic (or Hybrid) Fiber Optic Sensors

- Consist of *optical fibers* that lead up to and out of a "*black box*" that modulates the light beam passing through it in response to an environmental effect.

- Sensing takes place in a region **outside** the fiber. (in the blackbox, the light modulator)





FOS based on modulation and demodulation processes

FOS can be classified also according to the characteristics of light modulated by environmental effect

- Intensity-based

  Light is required to exit the fiber at the sensor (optical loss)

- Spectrally (or wavelenght)-based

  measures the changes in the wavelength of the light due to the environmental effects

- Phase-based (Interferometric) we measure the destructive/constructive interference

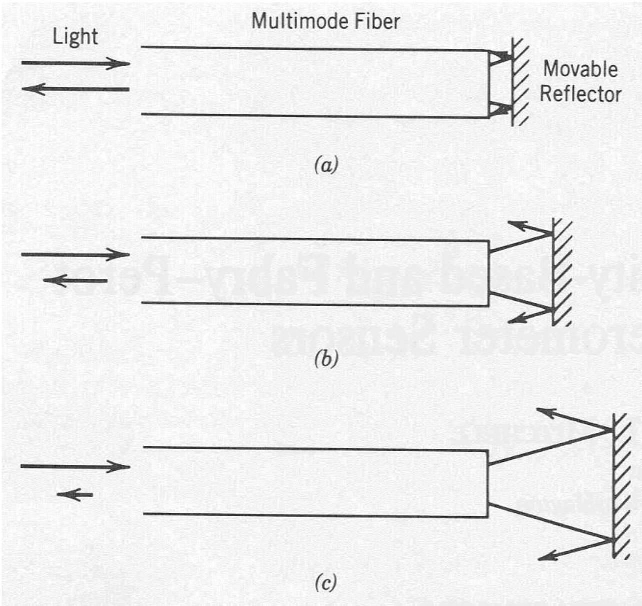
  compare the phase of light in a sensing fiber to a reference fiber in a device called interferometer (no optical loss)

Intensity-based Fiber Optic Sensors

Depend on the principle that light can be modulated in **intensity (amount)** by an environmental effect.

Single fiber reflective sensor

- Light leaves the fiber end in a cone pattern, and strikes a movable reflector.
- The relationship between fiber-reflector distance and intensity of returned light

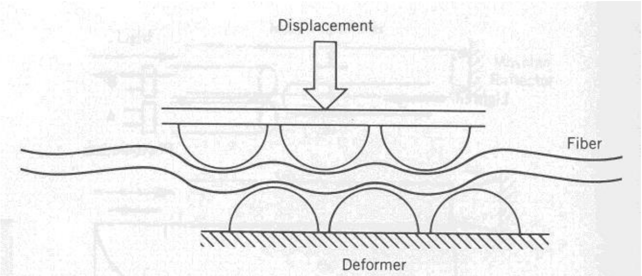


way to measure a distance

Bending the fiber

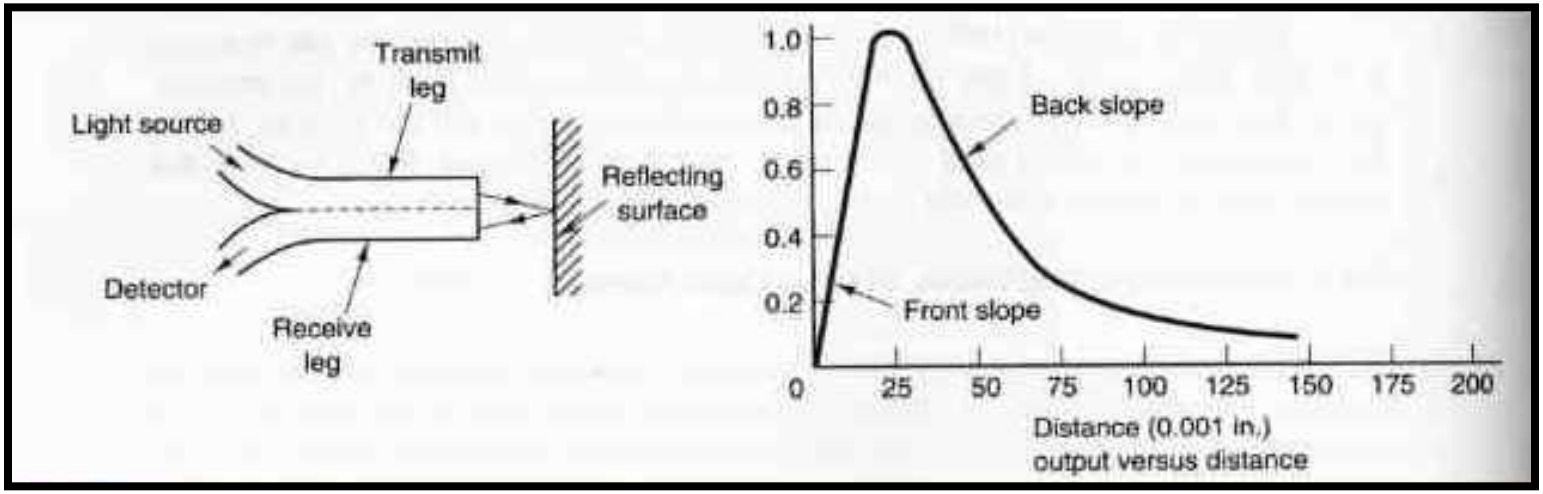
- As the deformer closes on the fiber, radiation losses increase and the transmitted light decreases.

changes the ratio between the input and the output light



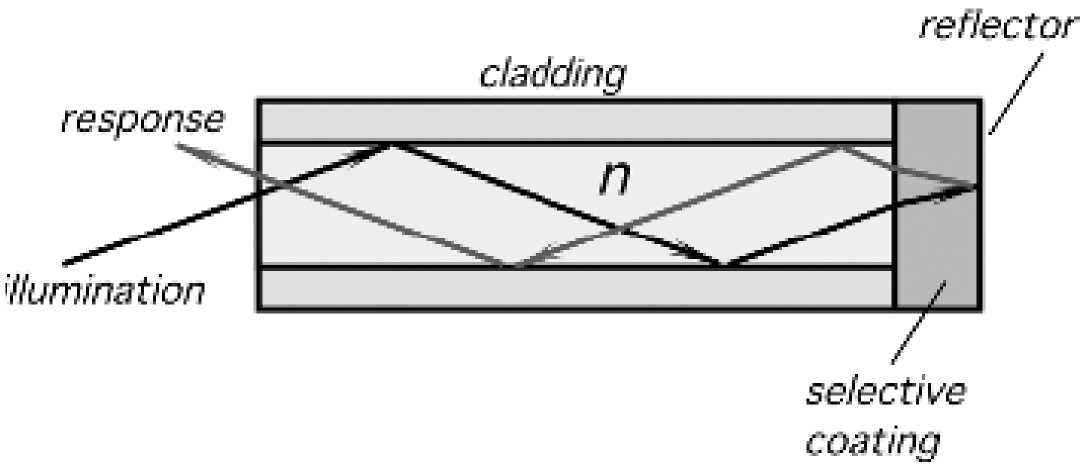
Reflective sensors

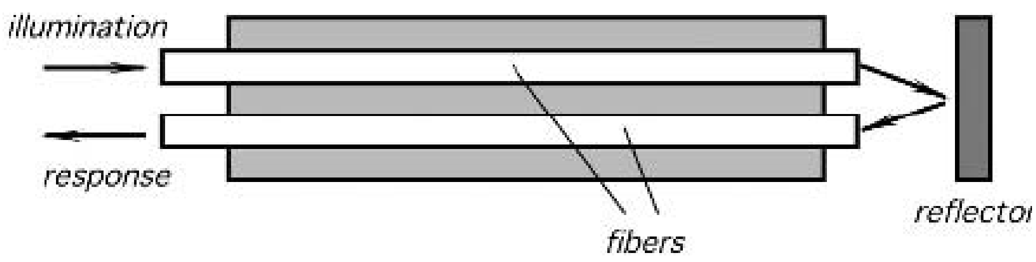
- One bundle is used to transmit the light to a reflecting target
- Other collects the reflected light and transmits to a detector
- Any movement of the target will effect the intensity of the reflected light.



FOS: single / double fiber

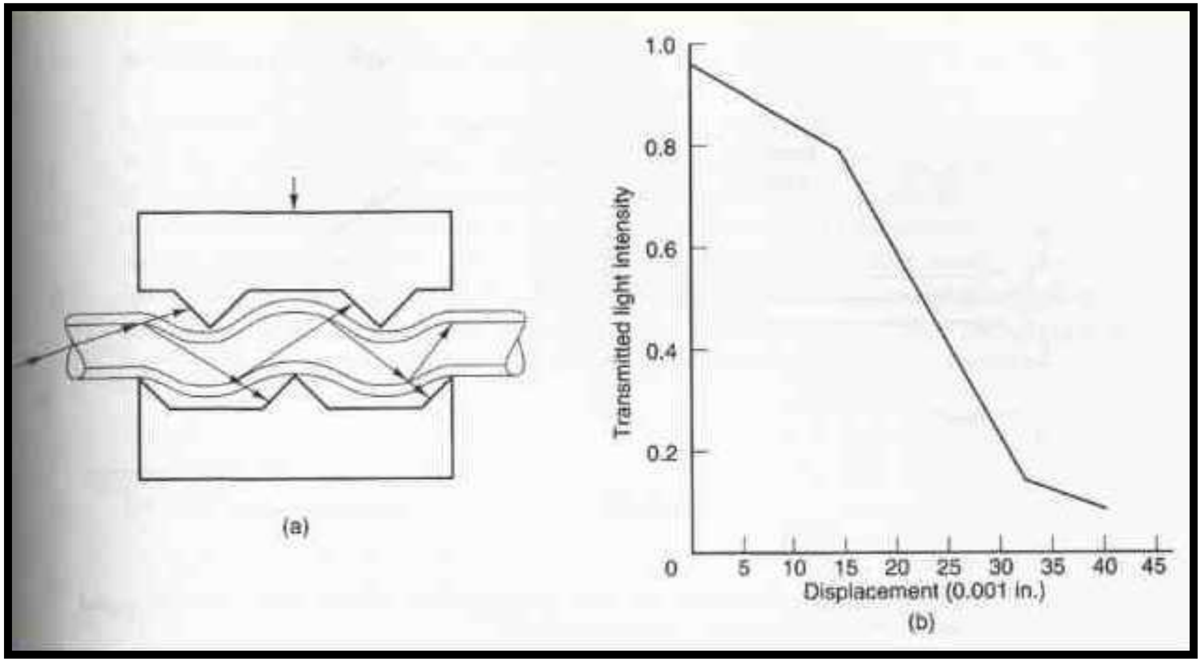
we can have single or double fiber



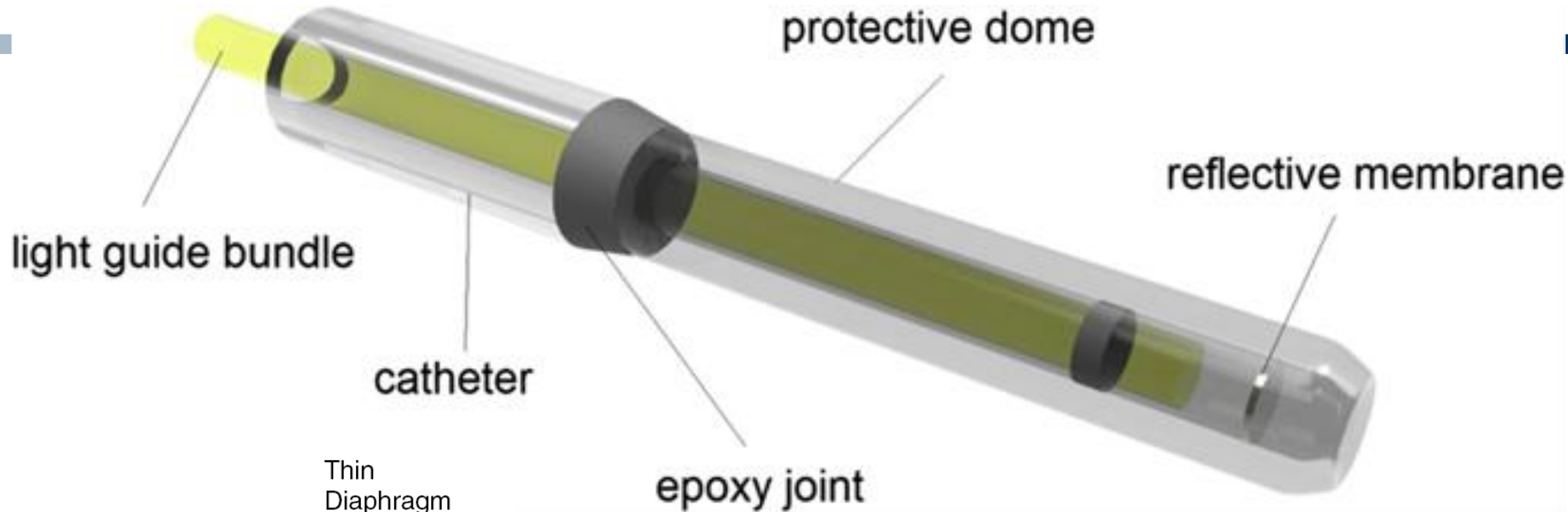


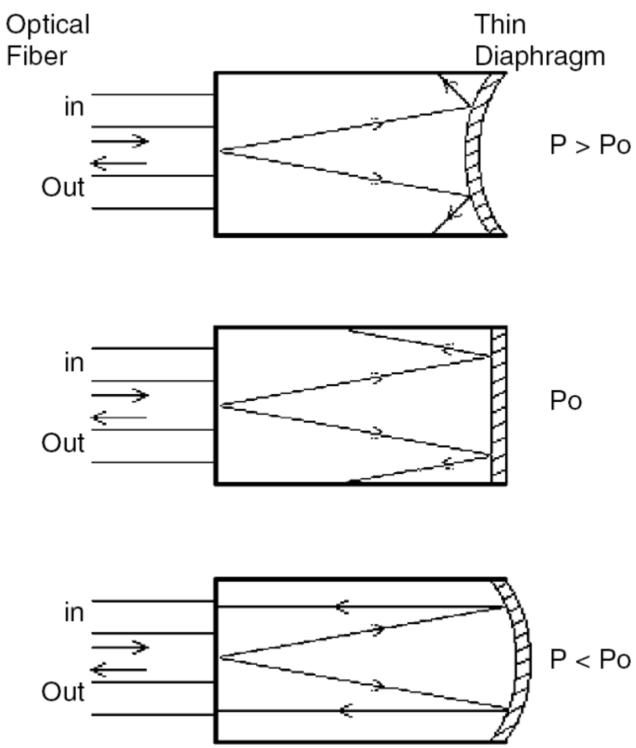
Fiber Optic Intensity Modulated Strain Gages

Micro-bend Sensors If a fiber is bent, a portion of the trapped light is lost through the wall.

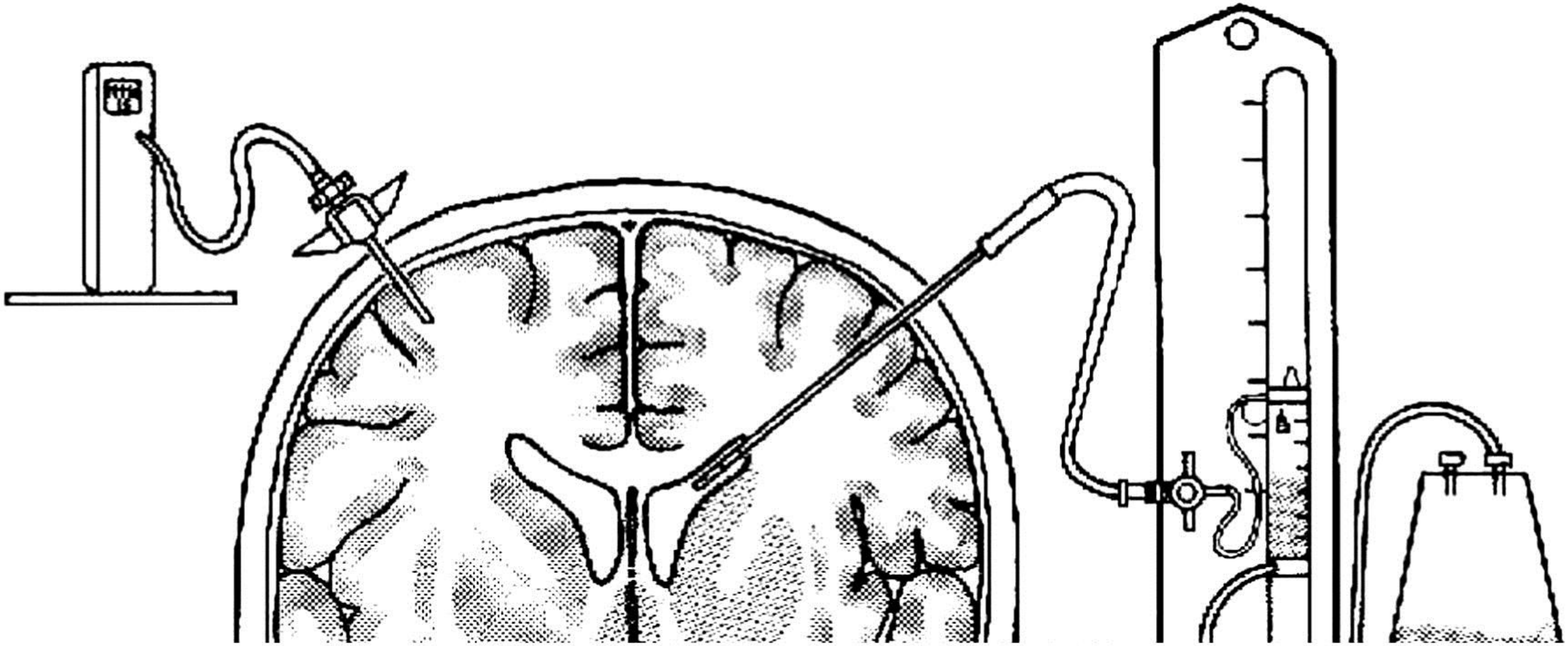


Catheter-tipped pressure sensors



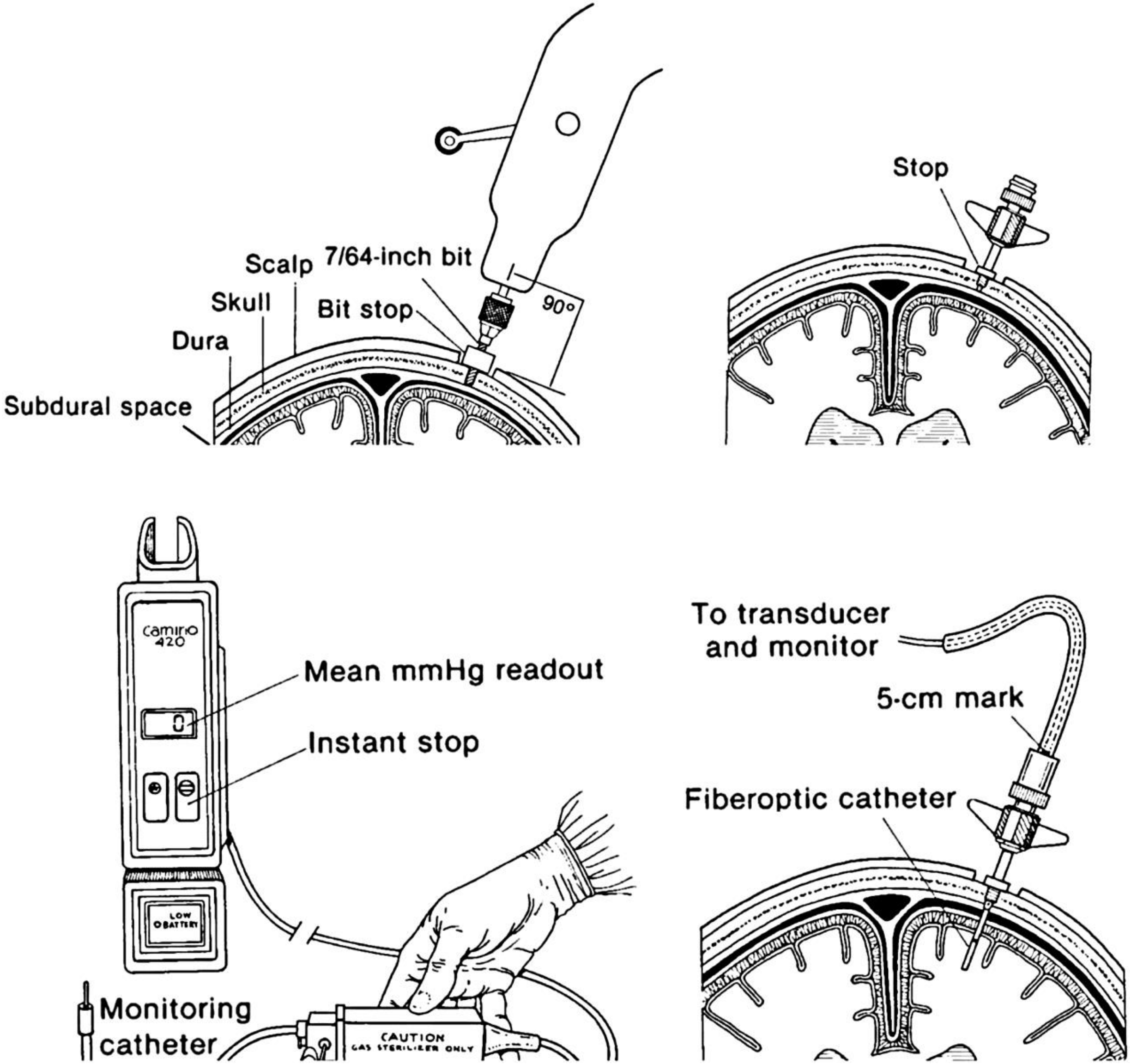


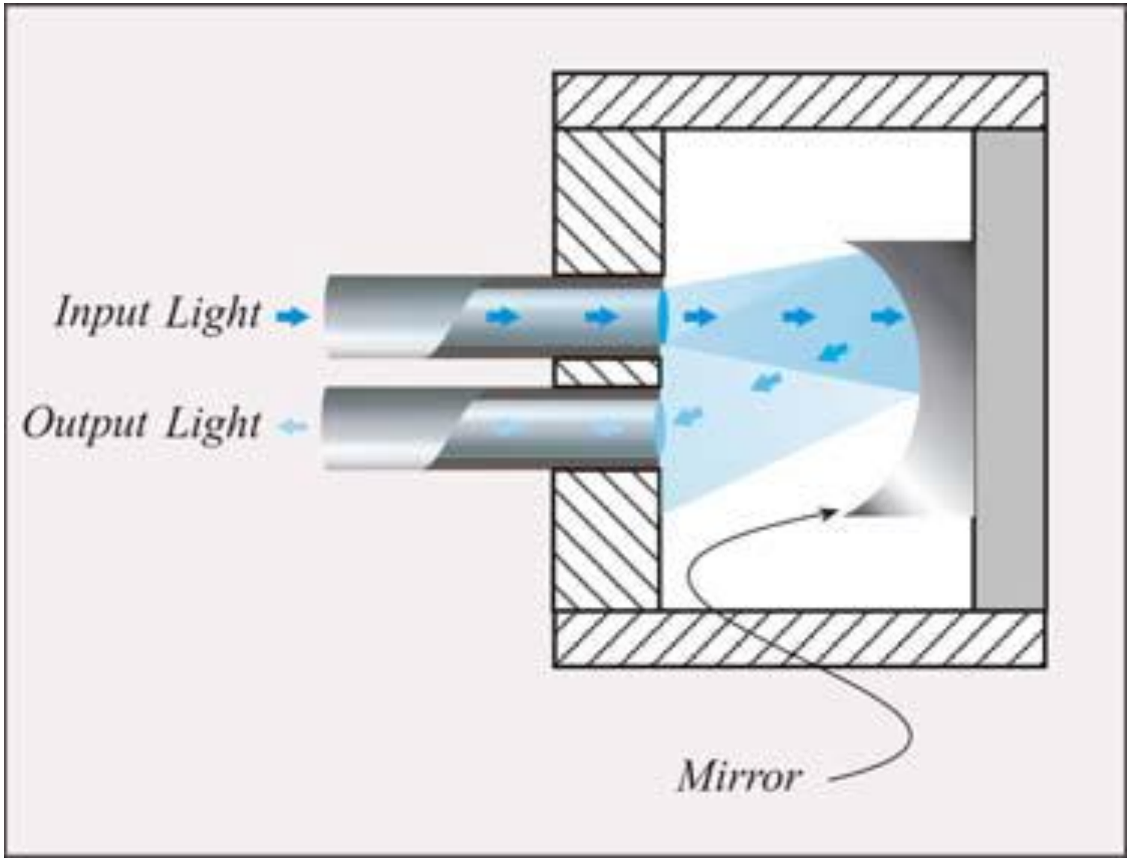
Application:
Intracranial pressure (ICP) monitoring



Contemporary techniques of intracranial pressure (ICP) monitoring. Parenchymal probe (left), ventricular catheter (right). From Schweitzer JS, Bergsneider M, Becker DP: Intracranialpressure monitoring.

ICP by fiberoptic catheter (Camino® Laboratories)

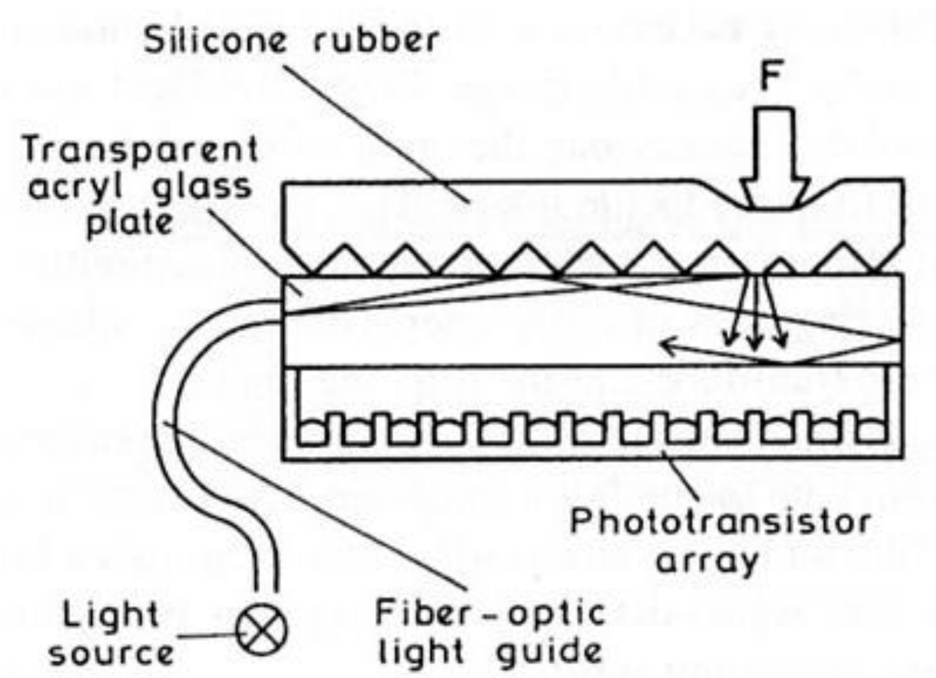




Schematic representation of the sensing element of the FOS made by Camino Laboratories: the output light variation is related to the pressure that causes a mirror displacement.

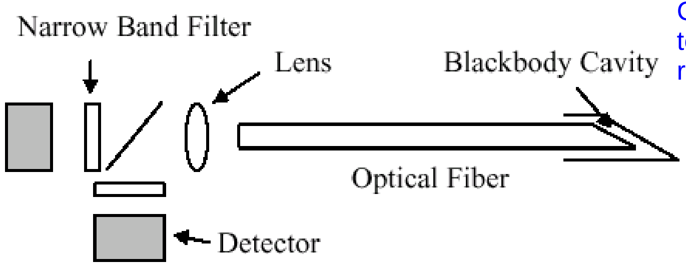
In presence of an applied force onto the silicon rubber surface, within the transparent glass plate local phenomena of diffused reflection occur instead of TIR. This allows to map the applied force.

Toatal Internal Reflection



Depend on the principle that a light beam can be modulated in **wavelength** by an environmental effect.

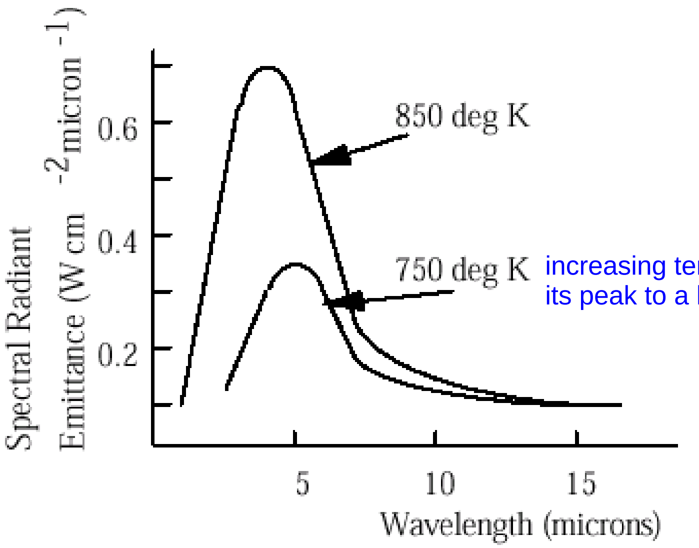
Example: Black body radiation



Changing temperature the radiation changes

When the cavity rises in temperature, it starts to glow and act as a light source.

Detectors in combination with narrow band filters are then used to determine the profile of the blackbody curve and in turn the temperature



increasing temperature it shifts its peak to a higher frequency!

Interferometeric Fiber Optic Sensors

The *optical phase* of the light passing through the fiber is modulated by the field ~~to be detected~~.

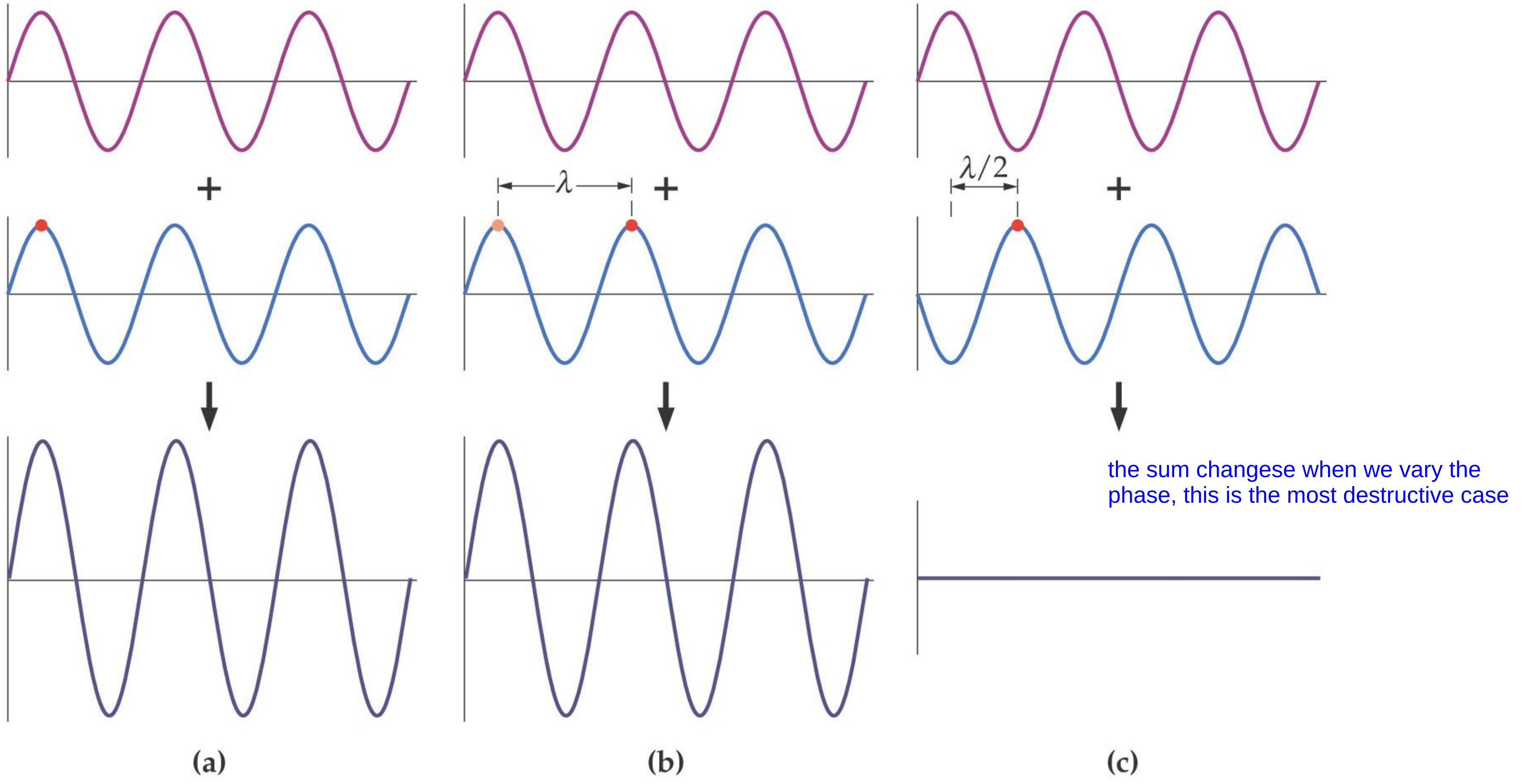
- This phase modulation is then *detected interferometerically*, by comparing the phase of the light in the signal fiber to that in a reference fiber.
- *Light is not required to exit the fiber* at the sensor ~~to interact with the field~~ to be detected.

In intensity based fiber optic sensors, *light has to leave the optical fiber* to interact with the optical sensor at the end of the fiber, leading to substantial optical loss.

~~Fabry-Perot, Sagnac, Mach-Zehnder and Michelson, polarimetric, and grating interferometers~~

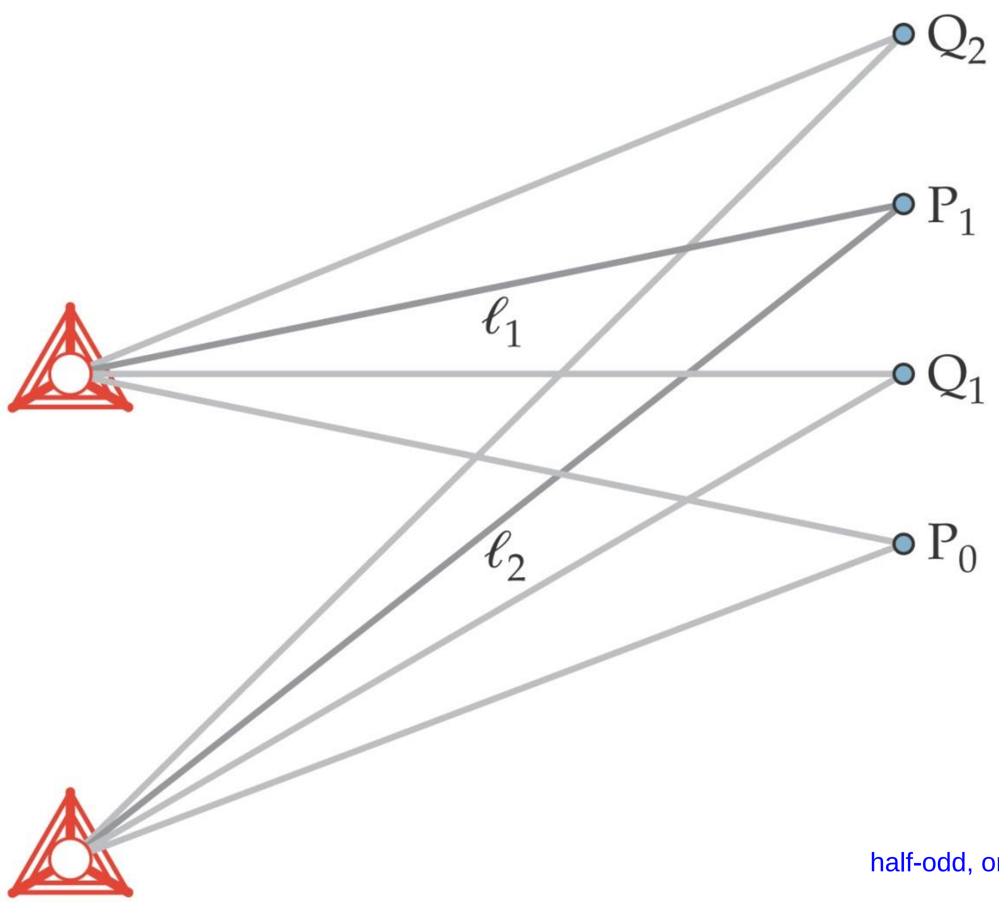
Superposition and Interference

If two waves occupy the same space, their amplitudes add at each point. They may interfere either constructively or destructively.



Interference is only noticeable if the light sources are monochromatic (so all the light has the same wavelength) and coherent (different sources maintain the same phase relationship over space and time).

If this is true, interference will be constructive where the two waves are in phase, and destructive where they are out of phase.



In this illustration, interference will be constructive where the path lengths differ by an integral number of wavelengths, and destructive where they differ by a half-odd integral number of wavelengths

half-odd, or half-integer: 1.5, 2.5, and so on. N+0.5

Superposition and Interference

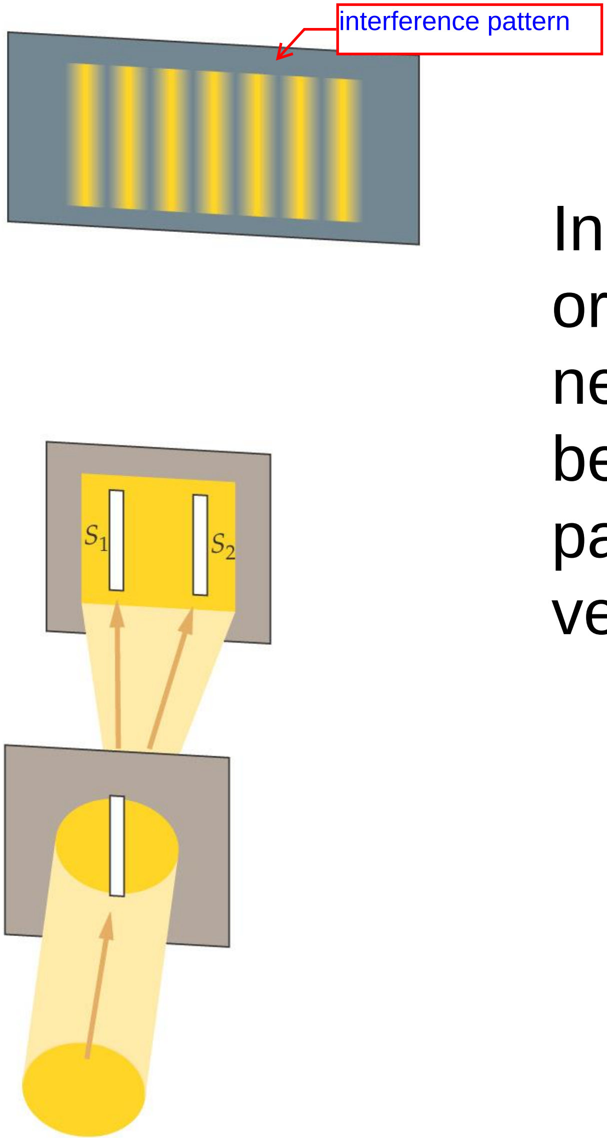
To summarize, the two path lengths l_1 and l_2 will interfere constructively or destructively according to the following:

$$\ell_2 - \ell_1 = m\lambda \qquad \text{(constructive interference)}$$

$$\ell_2 - \ell_1 = (m - \tfrac{1}{2})\lambda \qquad \text{(destructive interference)}$$

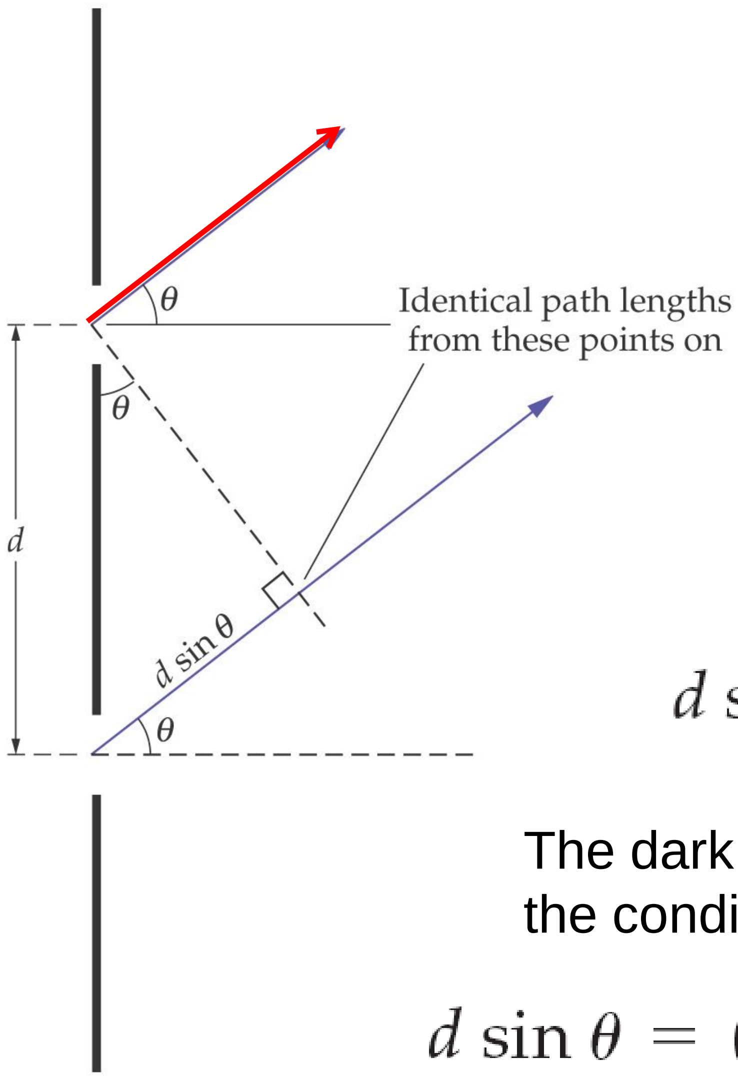
Sececondo me comunque questi due casi sono il massimo, cioè il primo è il picco di costruttività, il secondo è che si annulla, cioè picco di distruttività (si annullano se sono della stessa ampiezza)

Young's Two-Slit Experiment



In this experiment, the original light source need not be coherent; it becomes so after passing through the very narrow slits.

Young's Two-Slit Experiment



As the pattern on the screen shows, the light on the screen has alternating light and dark fringes, corresponding to constructive and destructive interference.

The path difference is given by:

$$\Delta\ell = d \sin\theta$$

Therefore, the condition for bright fringes (constructive interference) is:

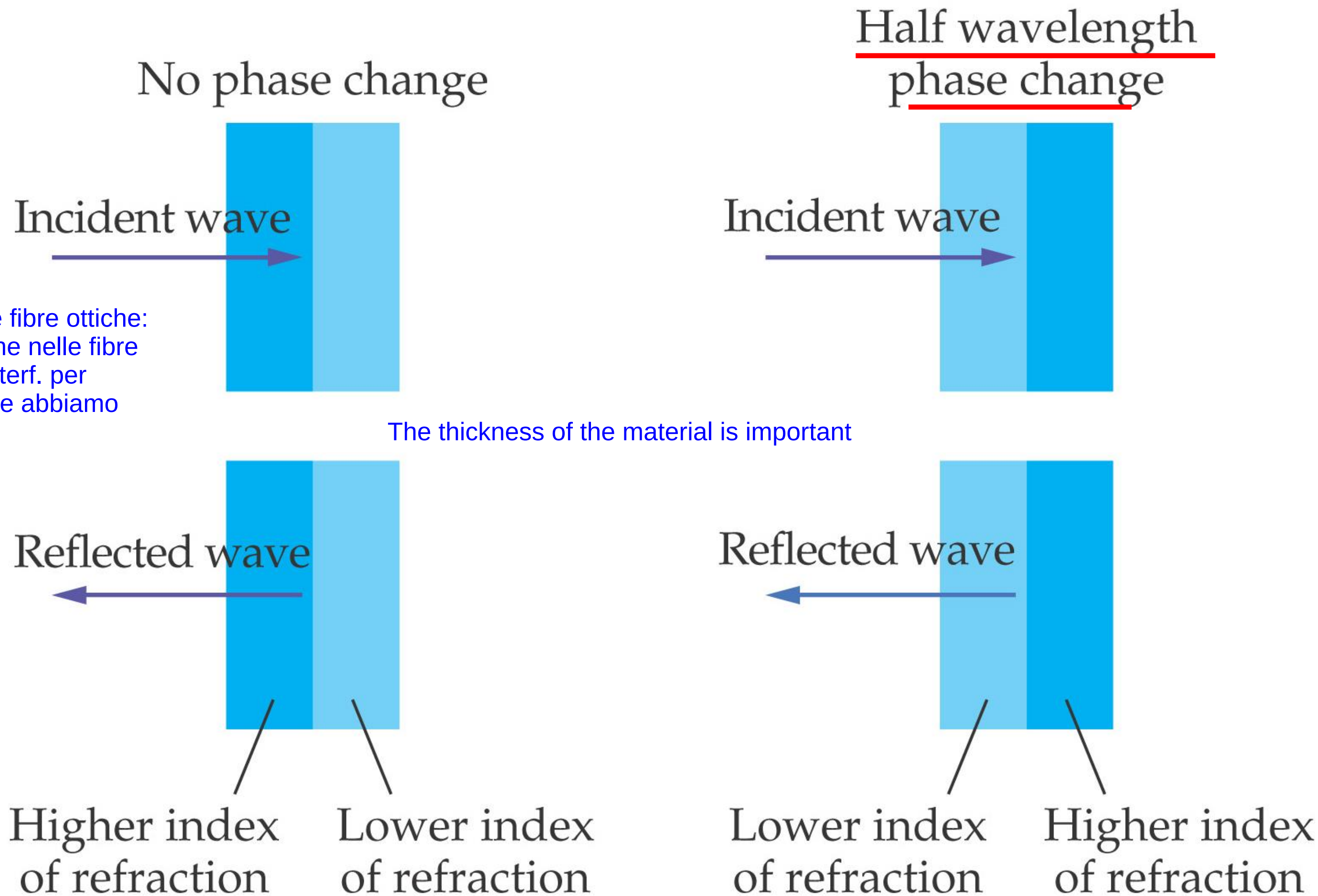
$$d \sin\theta = m\lambda \qquad m = 0, \pm 1, \pm 2, \ldots$$

The dark fringes are between the bright fringes; the condition for dark fringes is:

$$d \sin\theta = (m - \tfrac{1}{2})\lambda \qquad m = 0, \pm 1, \pm 2, \ldots$$

Interference in Reflected Waves

Reflected waves can interfere due to path length differences, but they can also interfere due to phase changes upon reflection.



condizione tipica delle fibre ottiche: per ricordarti pensa che nelle fibre ovviamente non c'è interf. per riflessione, e nelle fibre abbiamo na>nb>nc e così via

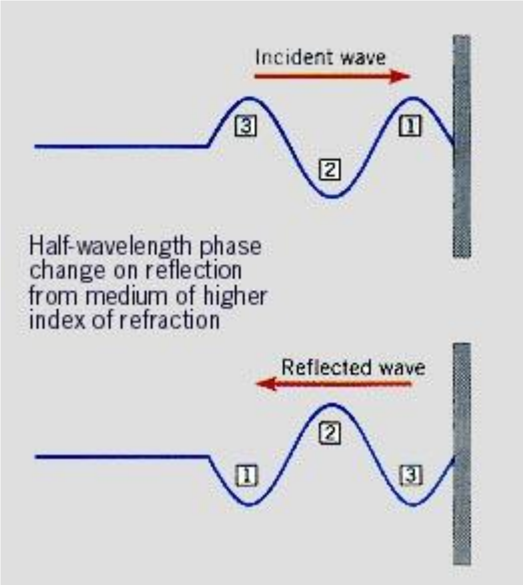
The thickness of the material is important

Interference in Reflected Waves

There is no phase change when light reflects from a region with a lower index of refraction.

There is a half-wavelength phase change when light reflects from a region with a higher index of refraction, or from a solid surface.

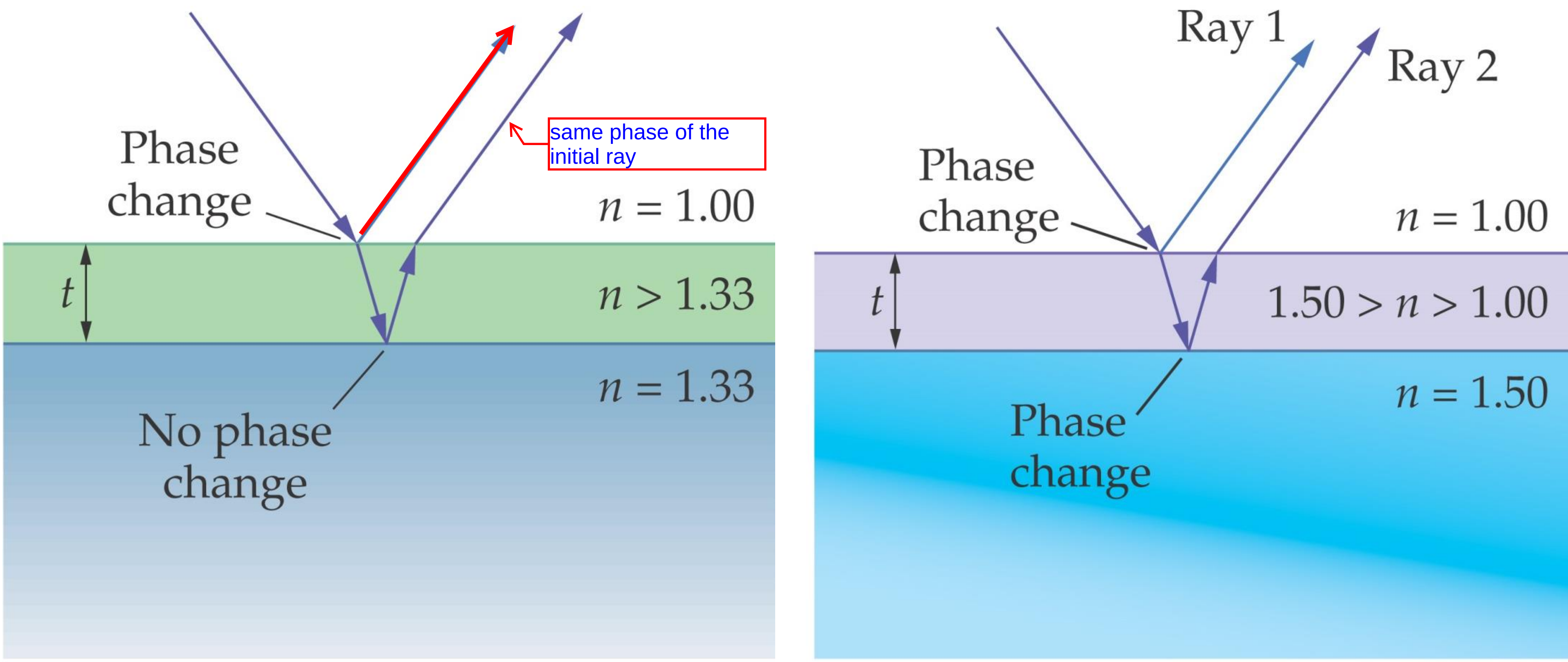
There is also no phase change in the refracted wave.



penso generalmente

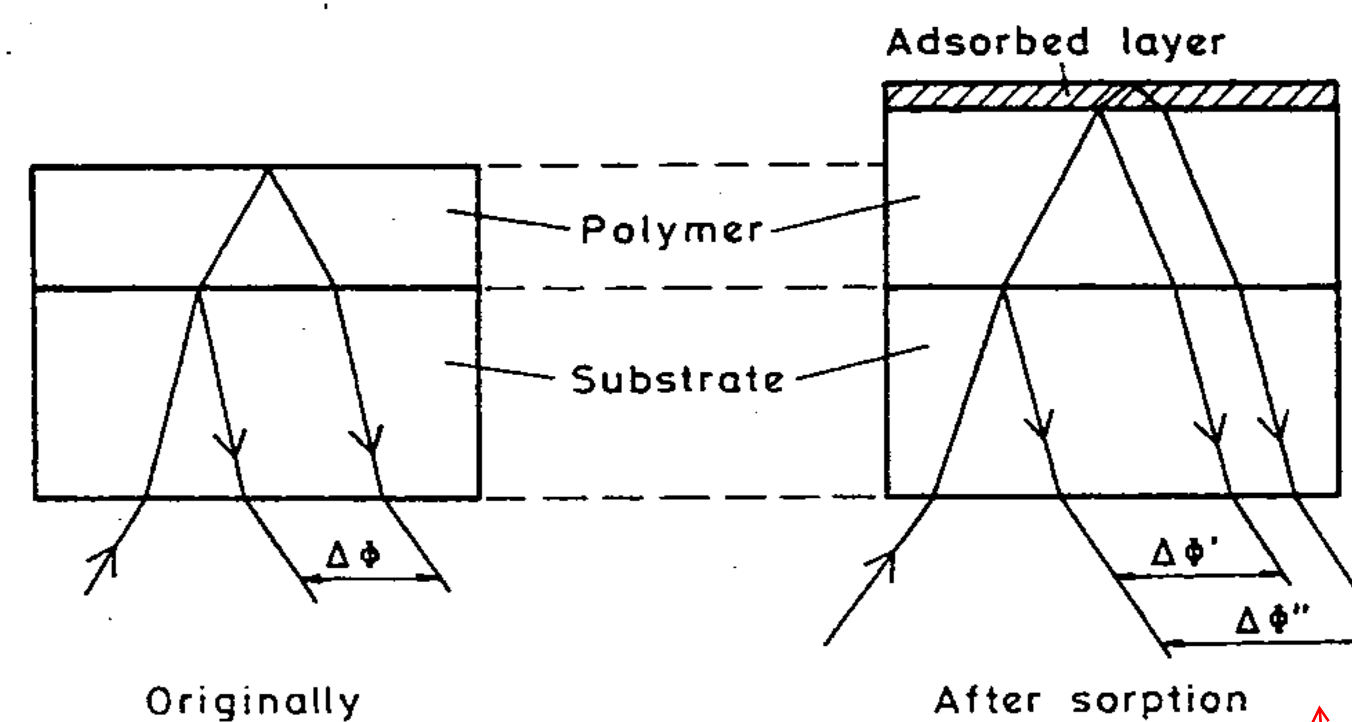
The phase changes upon reflection depend on the indices of refraction of the film and the surrounding media:

I guess these two should have the same phase?



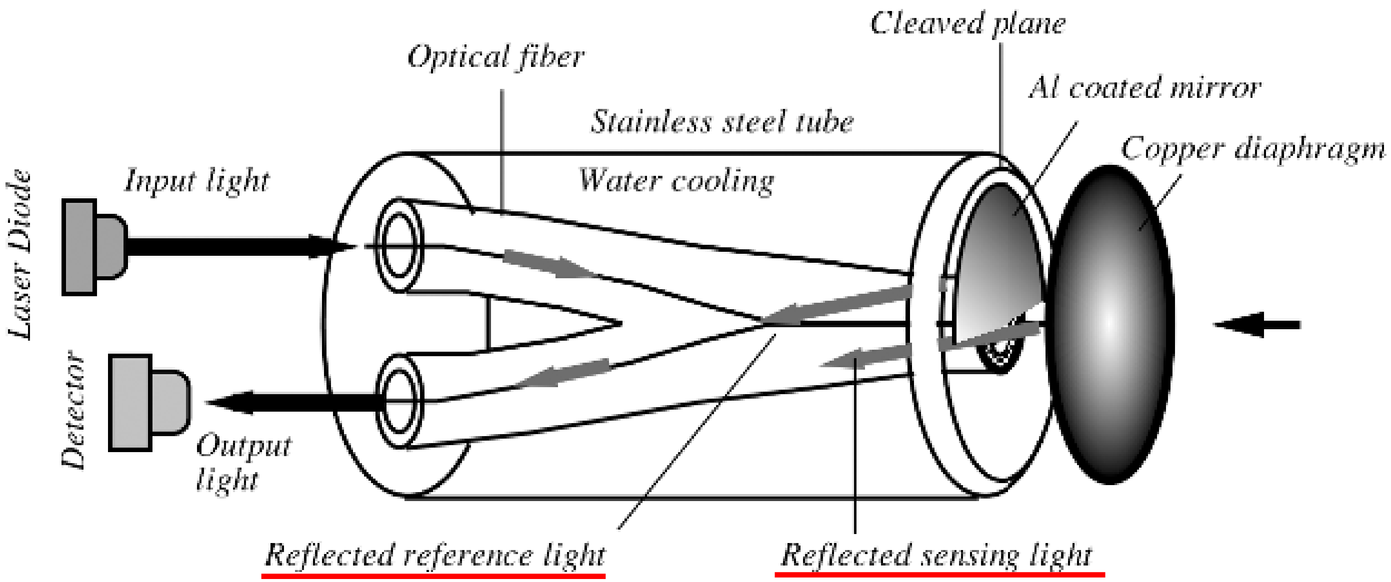
Reflective interferometric sensors

Figure 3.10(e) illustrates the operation of reflection-type interferometer sensors (Gauglitz et al., 1993). The superposition of the two partial beams reflected from the waveguide/polymer and polymer/air interfaces, respectively, can be influenced either by swelling of the film caused by permeation of gases and liquids or by adsorption of particles on the top of the film, which will introduce an additional reflection. Moreover, the introduced analyte can interact with the polymer film, thus influencing the value of the refractive index. Spectral interferometry allows these effects to be discriminated to a certain extent.



dal momento in cui cambia la distanza cambia anche il punto in cui fanno interferenza costruttiva/distruttiva..? Ma comunque non dovrebbero già cambiare fase (quella iniziale rispetto a quella che arriva) dato che c'è un materiale "absorbed layer" che suppongo con reflessive index maggiore?

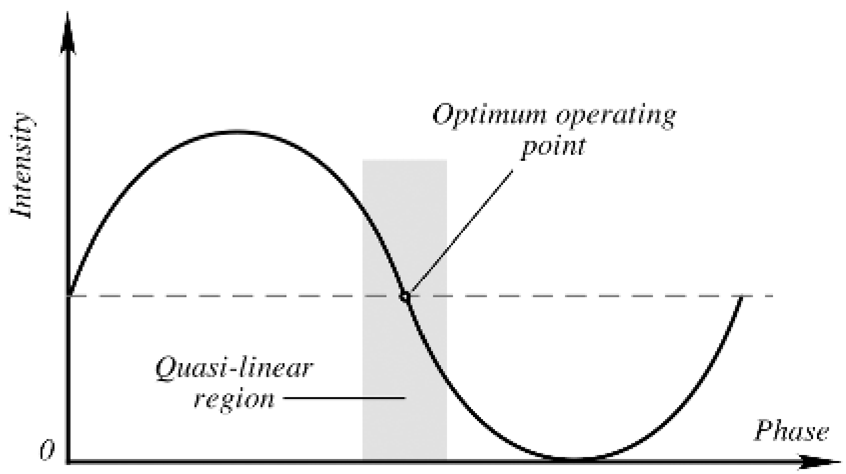
Fiber-optic interferometric microphone



Depending on the position of the diaphragm, the phase of the reflected light will vary, thus becoming different from the phase of the reference light. **While traveling together to the output detector, the reference and sensing lights interfere with one another, resulting in the light-intensity modulation.** Therefore, the microphone converts the diaphragm displacement into a light intensity.

Theoretically, the signal-to-noise ratio in such a sensor is obtainable on the order of 70–80 dB, thus resulting in an average minimum detectable diaphragm displacement of 1 Å (10^{-10} m).

To assure a linear transfer function, the operating point should be selected near the middle of the intensity, where the slope is the highest and the linearity is the best.
The slope and the operating point may be changed by adjusting the wavelength of the laser diode. It is important for the deflection to stay within one-quarter of the operating wavelength to maintain a proportional input.

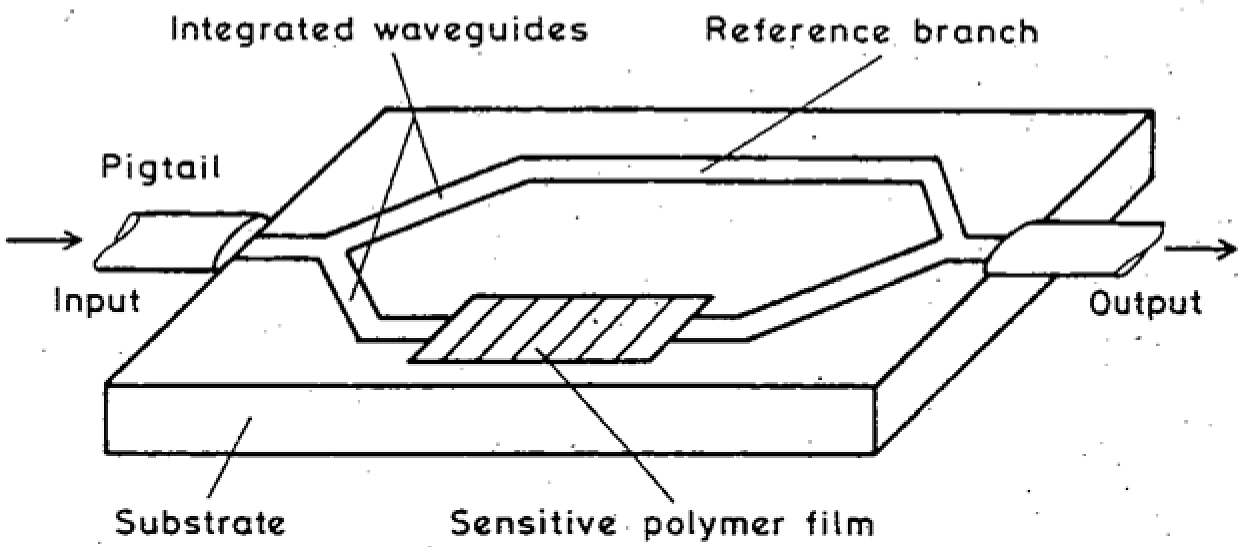


Interferometric transmission sensors

The principle of measurement is based on light propagation in a Y-guide. At the output, the resulting intensity will be function of the difference of the two optical paths depending on interference phenomena.

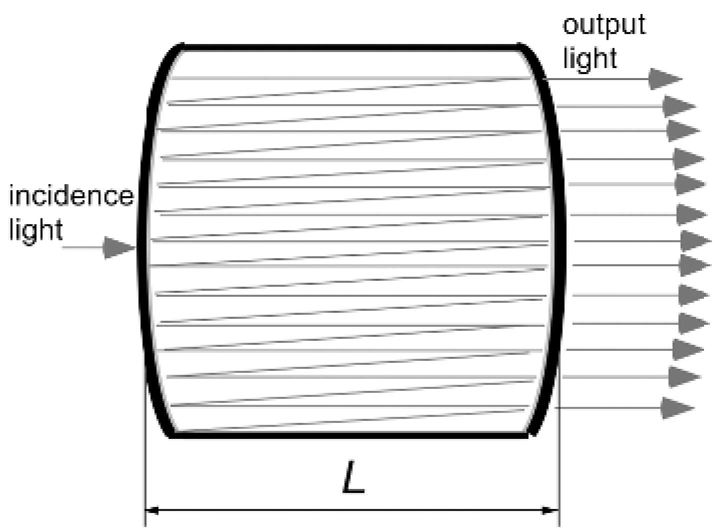
Light at the input is split into two paths, one reference, one covered by a polymeric film whose refractive index is dependent on the surrounding medium (and therefore of the chemical-physical variable that must be measured).

associated with the propagation velocity

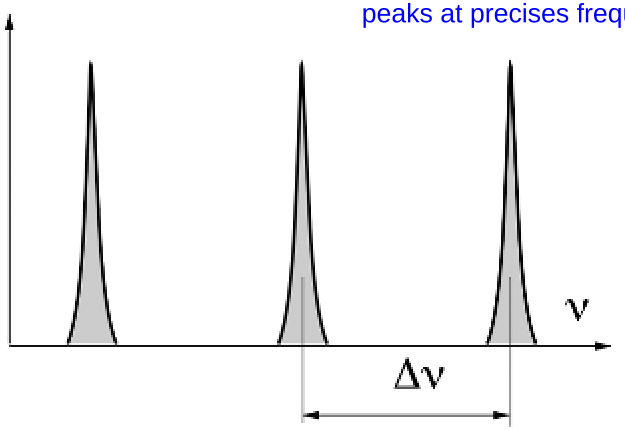


Fabry–Perot Sensors (1)

For measuring small displacements with high precision in a harsh environment, the so-called **Fabry–Perot optical cavity** can be employed. The cavity contains two semi-reflective mirrors facing each other and separated by distance *L*. The cavity is injected with light from a known source (a laser, e.g.) and the photons inside the cavity bounce back and forth between the two mirrors, interfering with each other in the process. In fact, the cavity is a storage tank for light. At some frequencies of photons, light can pass out of the cavity.



spectral analysis of the output light in terms of frequencies is characterized by peaks at precises frequencies



misuriamo il movimento della membrana calcolando la variazione di DeltaV

$$\Delta\nu = \frac{c}{2L}$$

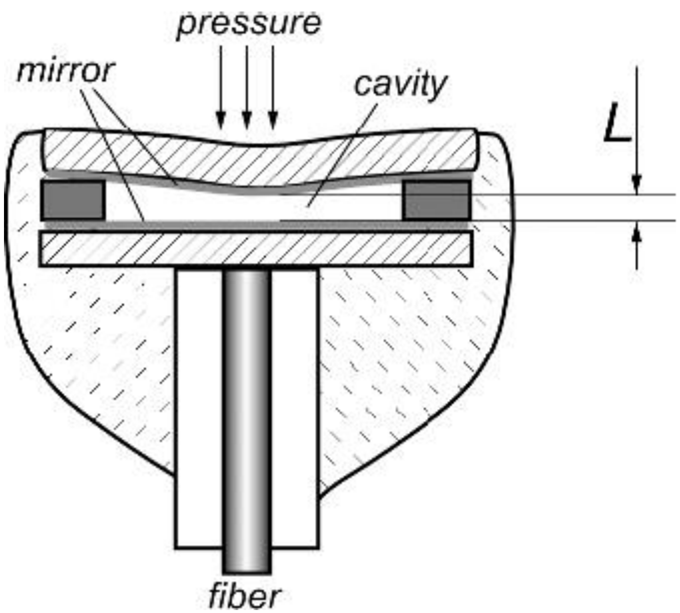
Fabry–Perot Sensors (2)

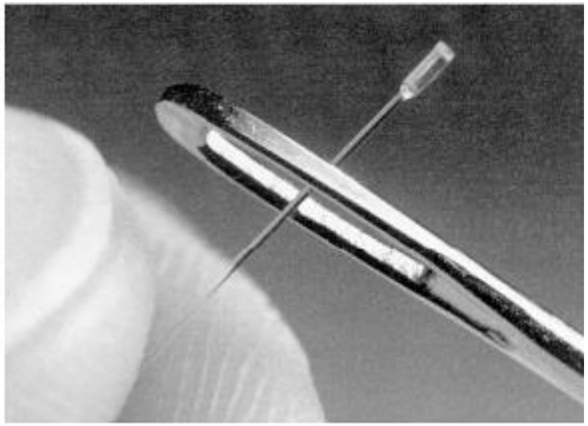
A Fabry–Perot interferometer is basically a **frequency filter** whose transmission frequency is intimately related to the length of the cavity. As the cavity length changes, the frequencies at which it transmits light change accordingly. By making one of the mirrors movable, by monitoring the optical transmission frequency, very small changes in the cavity length can be resolved. The narrow bands of transmitted light are separated by frequencies that are inversely proportional to the cavity length:

$$\Delta \nu = \frac{c}{2L}$$

Fabry–Perot Sensors (3)

For practical cavities with a mirror separation on the order of 1 µm, typical values of ν are between 500 MHz and 1 GHz. Thus, by detecting the frequency shift of the transmitted light with respect to a reference light source, changes in the cavity dimensions can be measured with the accuracy comparable with the wavelength of light. Whatever may cause changes in the cavity dimensions (mirror movement) may be the subject of measurements. These include **strain, force, pressure, and temperature**.





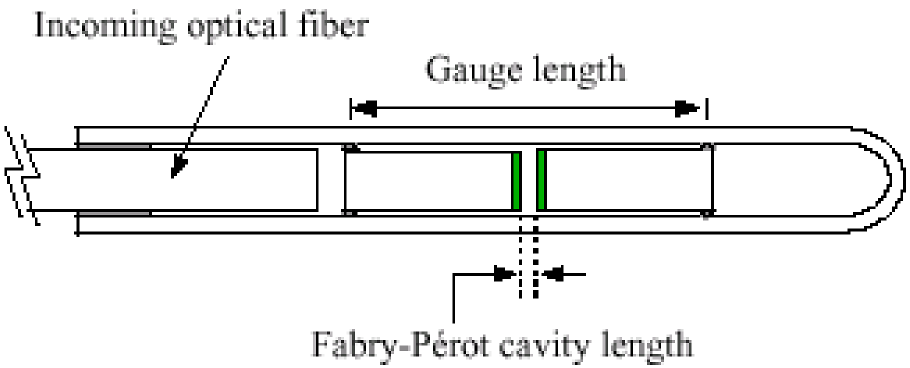
Interferometric Fiber Optic Sensors: Fabry-Perot interferometers (FPI)

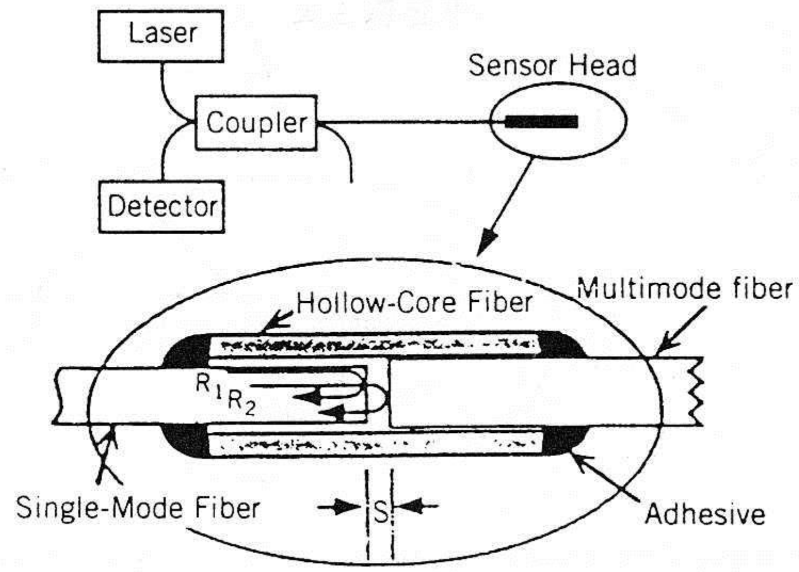
veloce

Constructed of two reflectors deposited on either side of an optically transparent medium, and on the tips of two optical fibers inserted into a micro-capillary

Gage length: the distance between the spots where the optical fibers are welded

The transmittance of the interferometer changes with respect to spacing of the reflectors



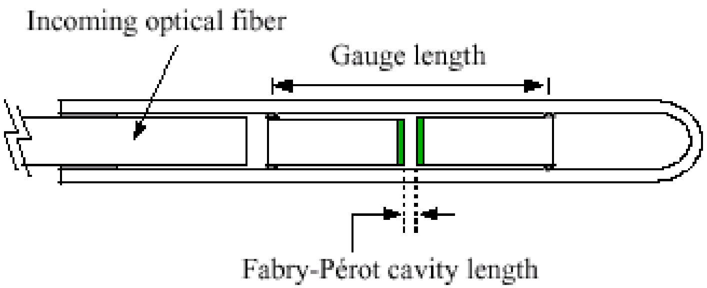


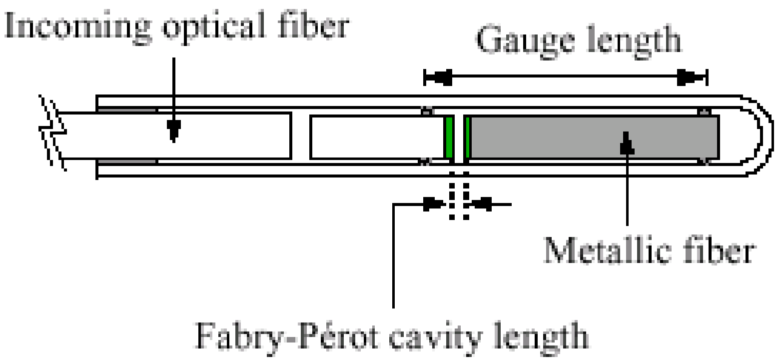
(b)

Fabry-Perot interferometers (FPI): Fiber Optic Strain Gauge

NO

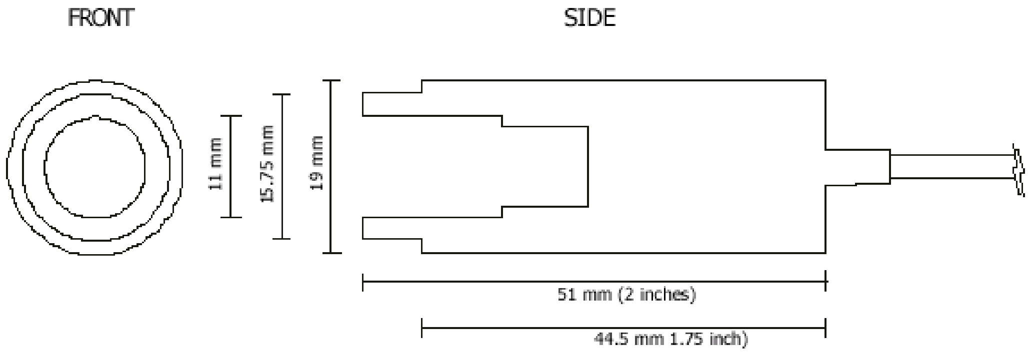
- Strain range: From -10000 to +10000 microstrains (1 %)
- Resolution: Less than 0.01%
- Transverse sensitivity: Less than 0.1%
- Operating temperature: Up to 350 °C (adhesive dependent)
- Gauge dimensions: Diameter 180 μm, length 1 to 10 mm
- Fiber optic cable: Braided fiberglass, length 1.5 m, dia. 0.9 mm
- Special gages: Embeddable gage, Surface-weldable gauge





Fabry-Perot interferometers (FPI): Fiber Optic Pressure Transducer NO

- Pressure range: From 0-0.3 bar (5 psi) up to 0-700 bar (1000 psi)
- Resolution: 0.01% of FS
- Precision: 0.1% of FS
- Operating temperature: -20 to 350 C (650 F)
- Thermal sensitivity: 0.01% of reading/ 1 C
- Gauge dimensions: O.D. 19 mm, length 51 to 102 mm depending on pressure range
- Fiber optic cable: Length 10 m, Custom length up to 5 km



Fabry-Perot interferometers (FPI): Fiber Optic Temperature Transducer

NO

- Temperature Range: FOT-L: -40 to +250 C, FOT-H: -40 to +350 C
- Resolution: 0.1 °C
- Accuracy: 1 °C or 1% of FS (whichever is greater)
- Response time: Less than 1.5 second
- Gauge dimensions: Sensitive zone length 10 mm, Probe O.D. 1.45 mm
- Fiber optic cable: Length 1.5 m, Custom up to 5 km

Fiber Bragg Grating (FBG) sensors

grating = griglia

An optical fiber core characterized by periodic refractive index changes constitutes a FBG.
- fiber Bragg gratings (FBGs): the grating spatial period has the order of magnitude of hundreds of nanometers,
- long period gratings (LPGs): the spatial period has the order of magnitude of hundreds of micrometers.

When light propagates through a fiber with a Bragg grating, a phenomenon of radiation reflection happens only for a narrow range of wavelengths, other wavelengths are transmitted. The wavelength placed in the middle of the reflected range is called Bragg wavelength λ_B, and can be expressed by the following equation:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

where Λ is the spatial period of the grating, and n_{eff} is the effective refractive index of the fiber core.

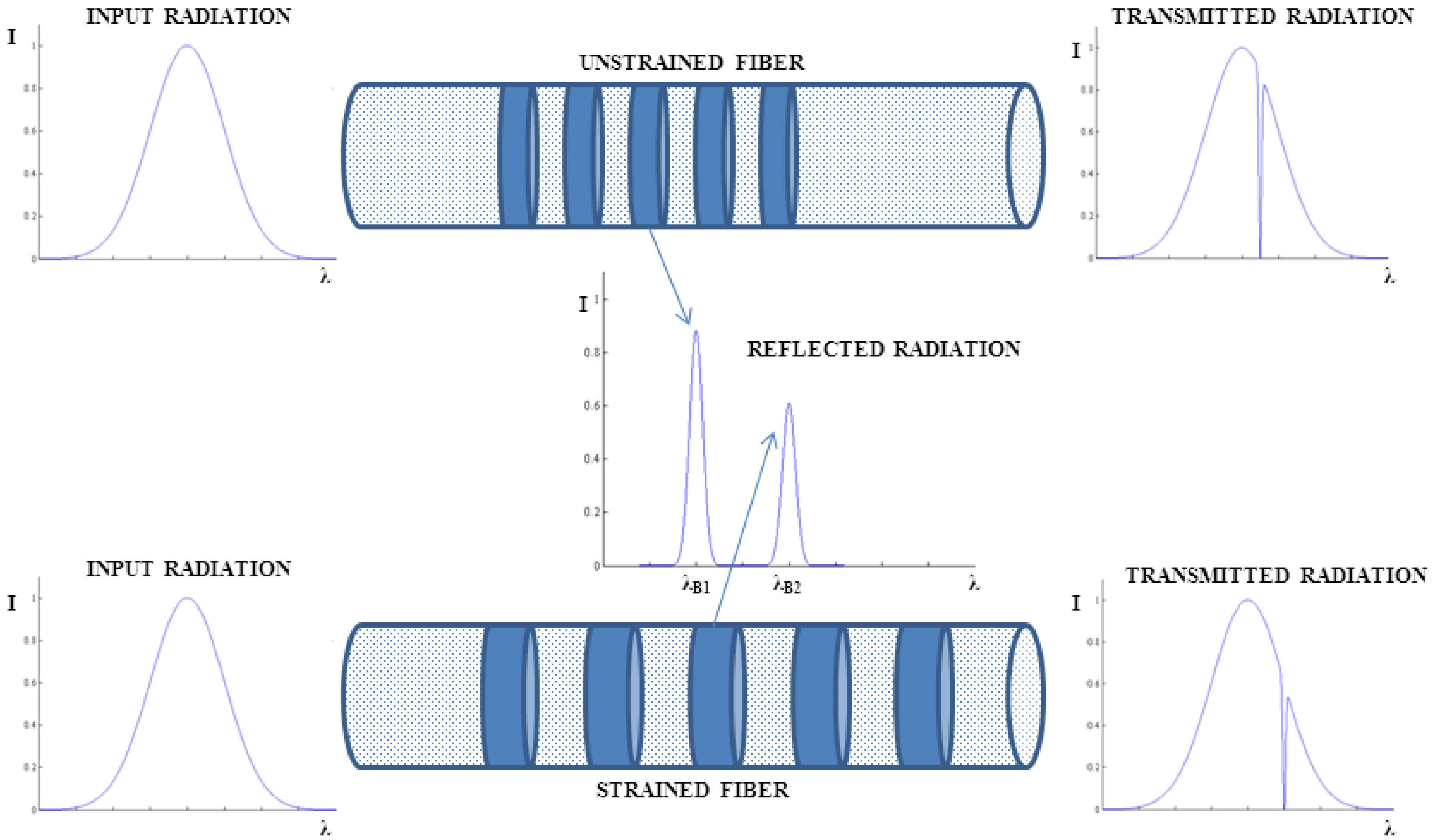
Working principle used in FBG sensors:

- λ_B shift due to a variation of the spatial period of the grating
  (es: measurement of **STRAIN ε**)
- λ_B shift due to a refractive index variation of the core
  (es: measurement of **TEMPERATURE change, ΔT**)

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e \cdot \varepsilon + \left[P_e \left(\alpha_s - \alpha_f \right) + \varsigma \right] \cdot \Delta T$$

Where P_e is the strain-optic coefficient α_s and α_f are the thermal expansion coefficients of the fiber bonding material and of the fiber respectively, and ς is the thermo-optic coefficient

Fiber Bragg grating sensors



Shift of Bragg wavelength due to fiber optic strain

FBG-based sensors: medical applications

temperature sensors

- cardiac monitoring estimating the stroke volume with thermodilution technique,
- *in vivo* blood temperature monitoring

monitoring heart muscle activity (the sound generated by the heartbeats causes vibrations of a membrane).

minimally invasive surgery to provide a feedback of the forces applied to the tissue during the surgery

- laparoscopic surgery
- robotic surgery (e.g., Da Vinci)

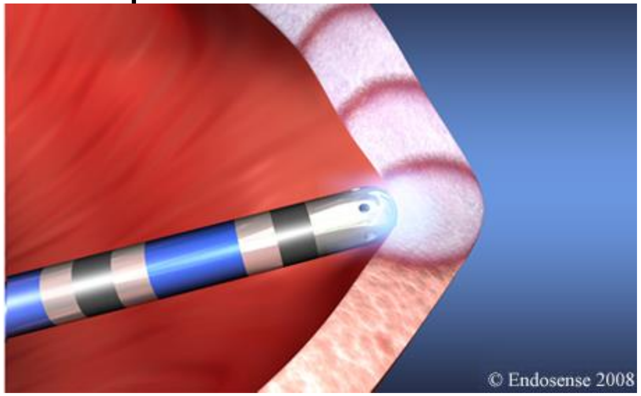
microsurgery

- monitoring force between tool and tissue during retinal microsurgery
- tumors removal (laser-induced thermotherapy, LITT)

FBG-based sensors in cardiac RF ablation system

NO

Atrial Fibrillation = cardiac arrhythmia that typically causes poor heart blood pumping.



Treatments for AF

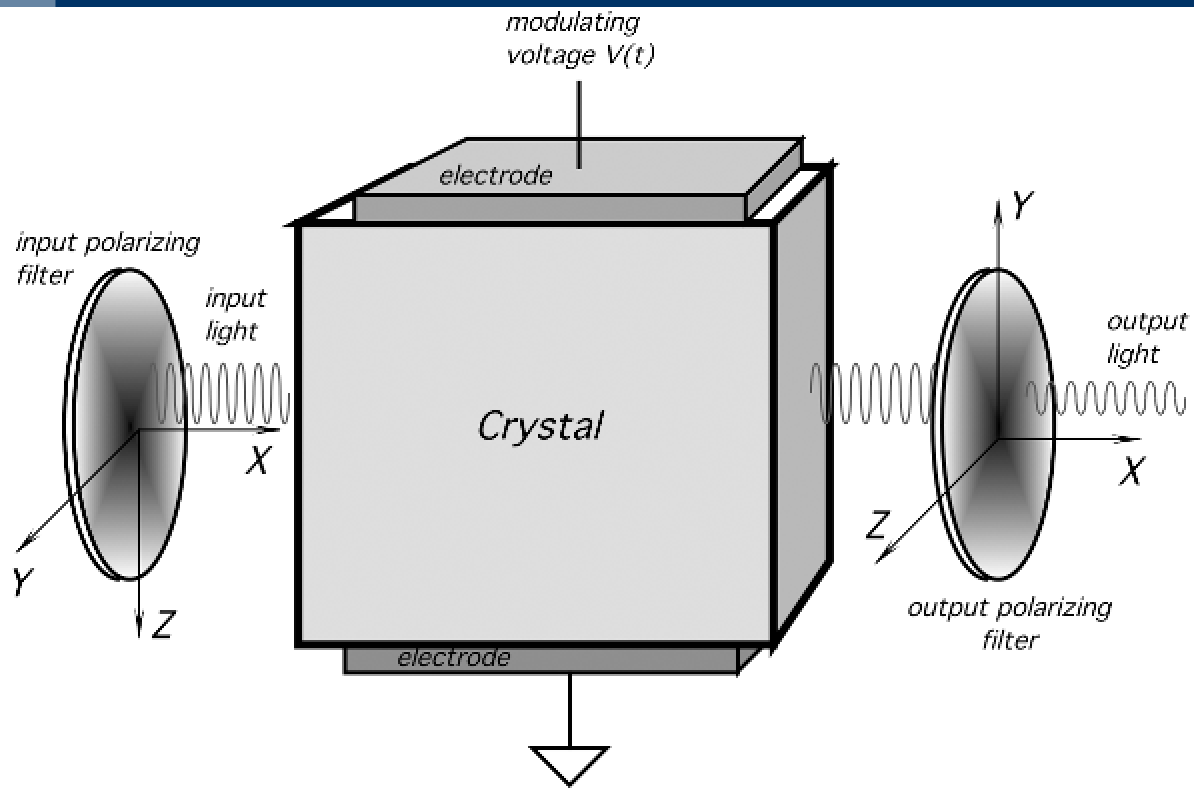
- pharmaceutical drugs
- electrical defibrillation (cardioversion)
- invasive ablation surgery

Surgical ablation is performed mostly by radiofrequency (RF) waves conveyed in an invasive probe. Lesions caused by RF ablation are related to **electrode-tissue contact force**.

A FBG-based sensor has been developed to perform a real time monitoring of the contact force. The sensor (TactiCath, Endosense SA), incorporated in the ablation catheter, is composed of three optical fibers to monitor the deformation of the catheter tip. Three FBGs, mounted on the deformable body, allow to relate the body deformation with the applied force representing the contact force between the ablation catheter and the tissue. The system allows to measure contact force along three different directions (parallel, perpendicular, and at 45° with the tissue) at frequency of 10 Hz, the discrimination threshold is better than 10^{-3} kgf ($9.8 \cdot 10^{-3}$ N)

Light modulation by electric signals: electro-optic modulator

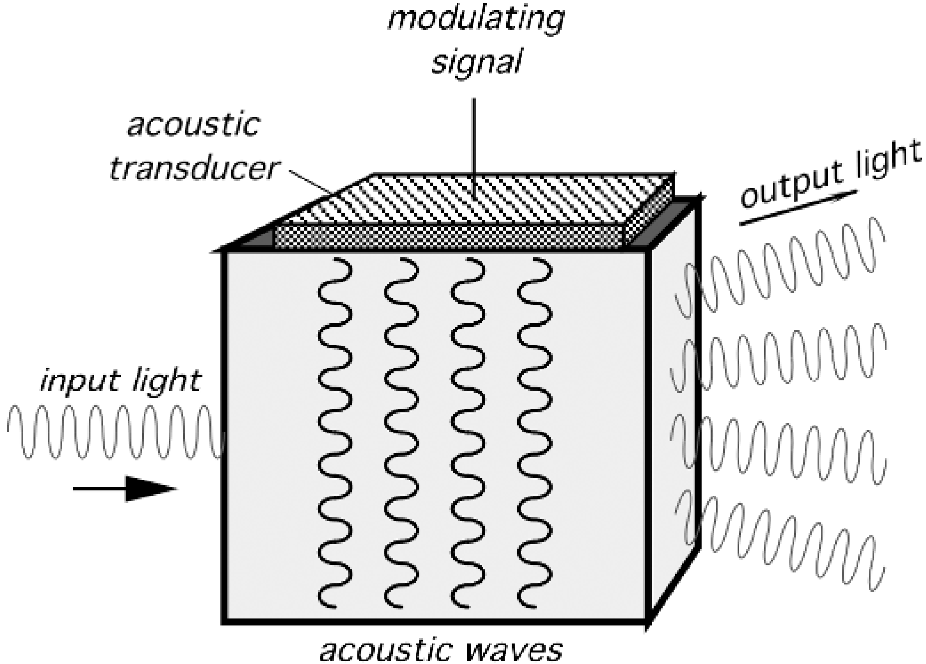
NO



In some crystals, the refractive index can be linked to an applied electric field. The effect is characterized in the context of the propagation of a light beam through a crystal. For an arbitrary propagation direction, light maintains constant linear polarization through a crystal for only those polarization directions allowed by the crystal symmetry. An external electric field applied to a crystal may change that symmetry, thus modulating the light intensity. Lithium niobate ($LiNbO_3$) is one of the most widely used materials for electro-optic devices. A crystal is positioned between two polarizing filters which are oriented at 90° with respect to one another. The input polarizer is oriented at 45° to the axis of the modulating crystal. The crystal modulator has two electrodes attached to its surface. By changing the modulator voltage, the polarization of the light incident on the output polarizer is varied, which, in turn. leads to the intensity modulation.

Light modulation by acoustic waves: acousto-optic modulator

NO



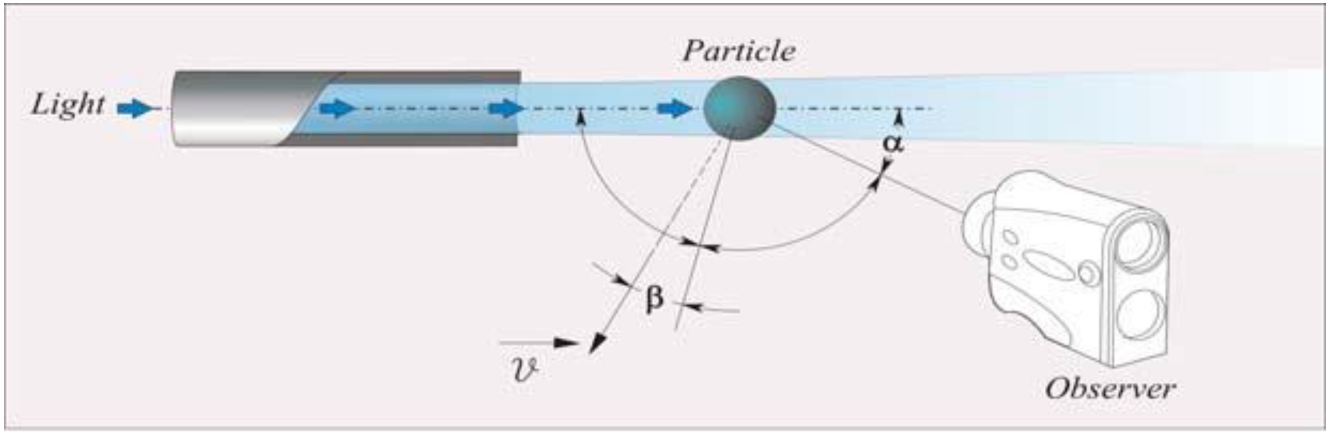
A similar effect can be observed when the crystal is subjected to mechanical effects—specifically, to acoustic waves. However, acousto-optic devices are used most often in fiber-optic applications as optical frequency shifters, and only to a lesser extent as intensity modulators. In the modulator, the light beam propagating through a crystal interacts with a traveling-wave index perturbation generated by an acoustic wave. The perturbation results from a **photoelastic effect**, whereby a mechanical strain produces a linear variation in refractive index. This resembles a traveling wave diffraction grating, which, under certain conditions, can effectively deflect an optical beam. Acousto-optic devices are often fabricated from lithium niobate and quartz, because acoustic waves can effectively propagate through these crystal over a frequency range from tens of megahertz to several gigahertz. The acoustic velocity in lithium niobate is about 6×10^3 m/s; thus a 1-GHz acoustic wave has a wavelength of about 6 μm, which is comparable to light in the infrared spectral range.

Fiber optic sensors for laser Doppler velocimetry (LDV) NO

Doppler shift: if an electromagnetic or acoustic wave is reflected back by a moving object the frequency of the reflected wave is different from the frequency of the incident one. This frequency difference (Δf) is related to the speed of the moving object and can be expressed by the following relation:

$$\Delta f = \left(\frac{2V}{\lambda}\right) \cdot \cos\beta \cdot \sin\left(\frac{\alpha}{2}\right)$$

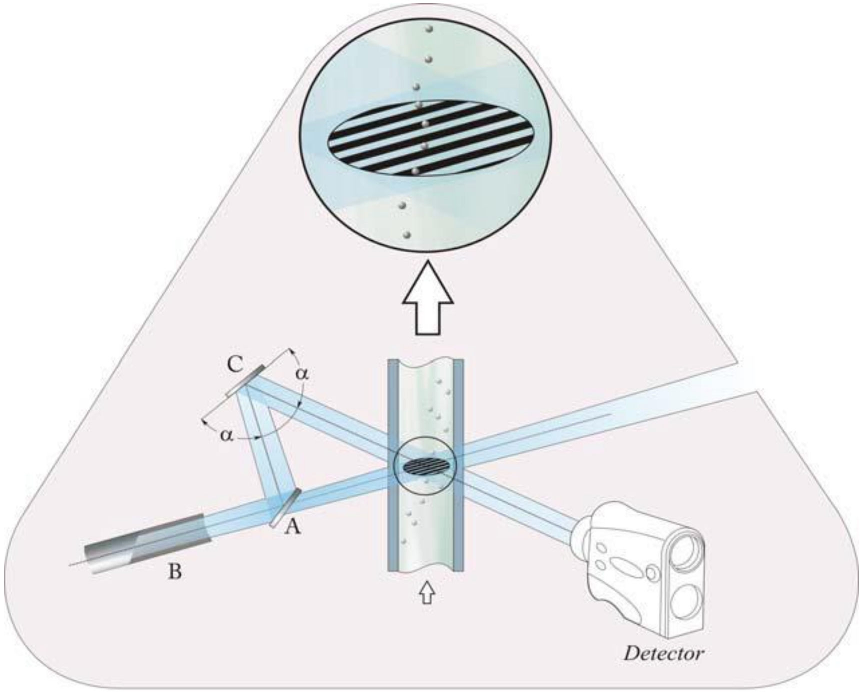
V the moving object speed, λ the wavelength of the incident wave, α the angle between the axis of the incoming wave and the observer, and β the angle between the moving object velocity direction and the bisector of the angle between the axis of the incoming wave and the segment connecting the object and the observer



Fiber optic sensors for LDV: dual-beam approach

NO

The performances of these sensors are improved through the **dual-beam approach** The radiation B is split into two beams, through a beam splitter A, successively crossed into an intersection region through a mirror C. This region defines a sampling volume, placed into the fluid flow, where the particle velocity is measured. In the intersection region, an interference pattern, characterized by alternating interference fringes, is produced. When a particle passes through the fringes, it causes periodic variations of the intensity of the scattered light.



The particle speed (V) is related to the frequency fluctuations (f_r) of the scattered intensity and to the distance between two contiguous fringes (γ) as follows:

$$V = \gamma \cdot f_r = \frac{\lambda}{2 \cdot \sin\left(\frac{\theta}{2}\right)} \cdot f_r$$

where θ is the angle between the two beams

The light penetrating the tissue is backscattered by red blood cells moving in different directions and with various velocities. Therefore, the backscattered light shows a frequency shift, measurements are based on the changes of the power spectrum of the backscattered light.

measurements of blood flow rate (**perfusion**)

- skin
- optical nerve head, sub-foveal choroid, and the iris (*in vivo* monitoring)
- intestinal mucosal
- cerebral
- hepatic
- renal
- gingival
- bone