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Fibre Optic Sensors: basic principles and most common applications

(PART 1)

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"OFS technology is really about modulation – about making light interact with the environment in a controlled repeatable and, finally, useful fashion. The stimulus was originally scientific curiosity coupled to the glimmer of application."

Brian Culshaw, 1998

Outline

- Part I : Overview
  - Fibre Optics Sensors: General Aspects
  - Components and Devices
  - Standard Examples
  - Detection Techniques
  - Applications
- Part II: Components & Devices
- Part III: Detection Techniques & Applications

Light Sensing

Fibre Optic Sensor

- Sensor: transducer + communications channel + processing sub-system.
- Any process or part uses a fibre optic ⇨ Fibre Optic Sensor (FOS)
  - Transducer (Sensing Device)
  - Communication (Transport of light)
  - Processing (Detection, imaging, ...)

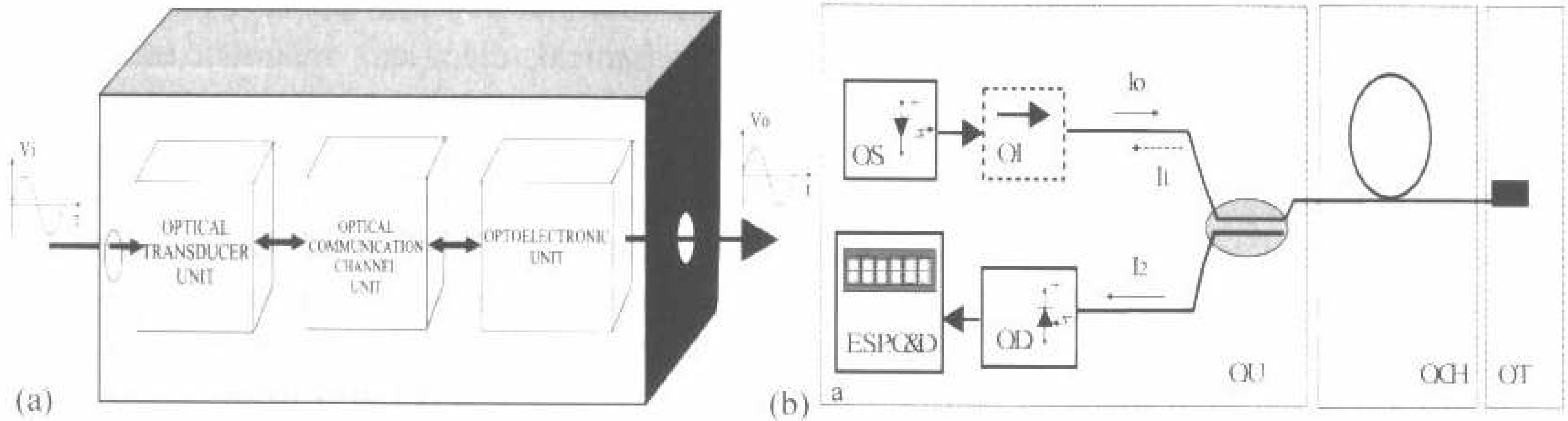
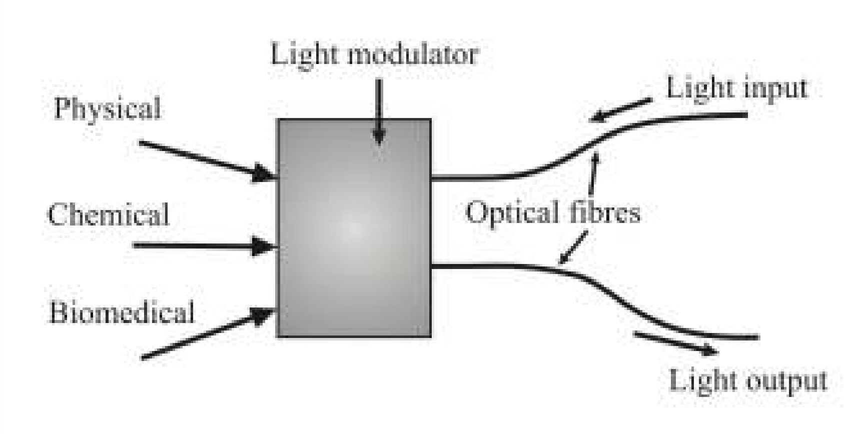


Figure 1.1 a) Conceptual block diagram of a general Optical Sensor System; b) example of an OFS architecture. (OU: optoelectronic unit; OCH: optical channel; OT: optical transducer, OI : optical insulator, OS : optical source, OD : optical detector, ESP.C&D : Electronic signal processing conditioning and display unit).



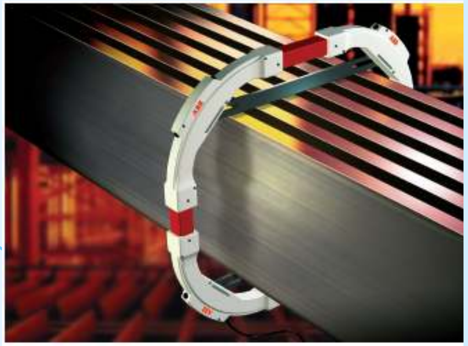
Domain of Measurement

- Mechanical Sensors: displacement, vibration, velocity, acceleration, ...
- Thermal: Temperature
- Electromagnetic: Electric and Magnetic fields, current, ...
- Radiation: X-rays, γ-radiation, neutron flux, ...
- Chemical Composition
- Fluids: Flow, turbulence, ...
- Biomedical: acidity, oxygen, carbon dioxide, blood flow...

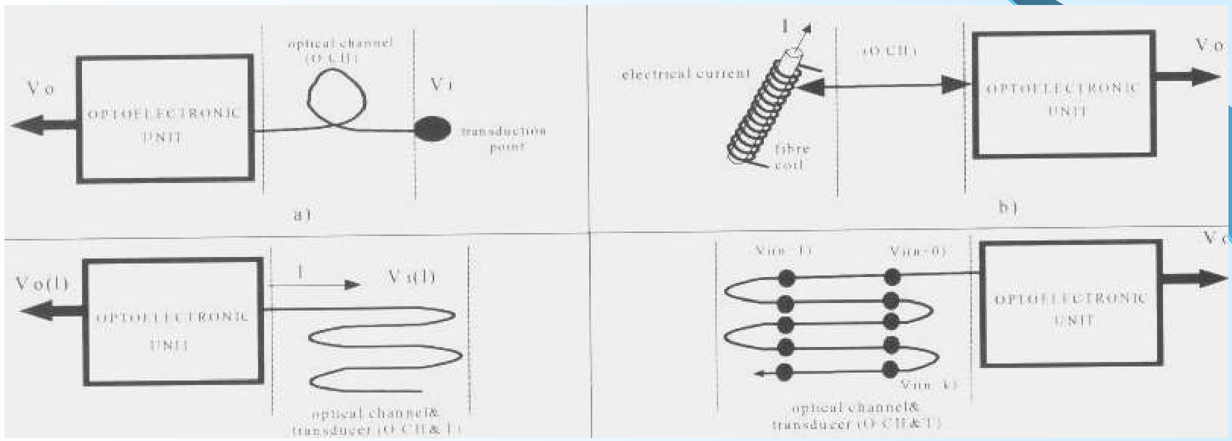
Spatial Positioning

- Point sensors: discrete points, different channels for each sensor/measurand.
- Distributed: measurand can be determined along a path, surface or volume (optical link).
- Quasi-distributed: variable measured at discrete points along an optical link.
- Integrated: measurand is integrated along an optical link giving a single value output.

Point

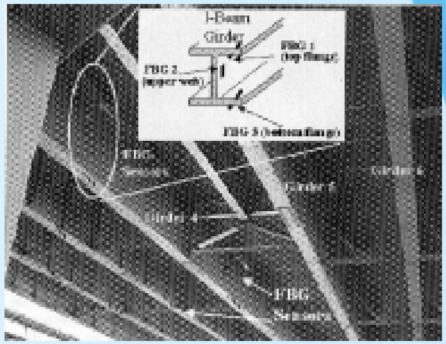


Integrated



Distributed

Quasi-distributed

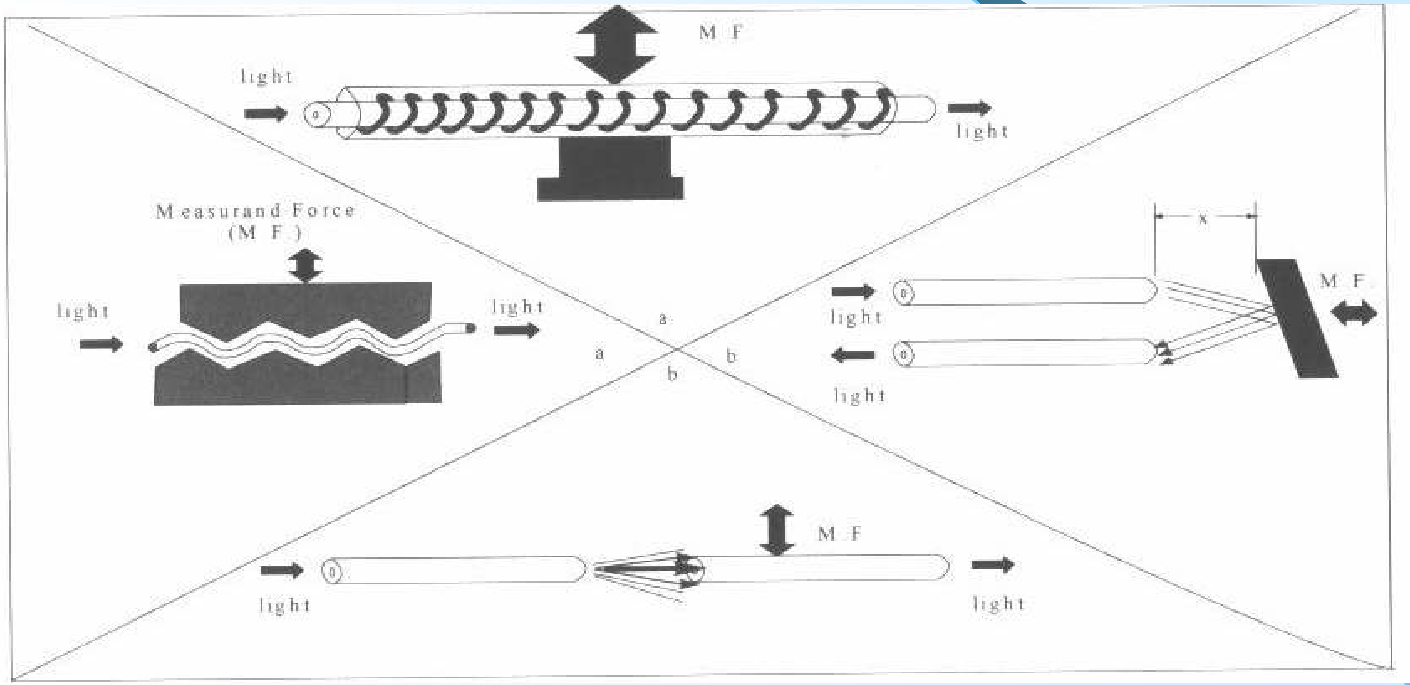


Interaction with Light

- Intrinsic: measurand affects directly a selected characteristic of light propagation into the fibre, e.g.,
  - Absorption from dopants in the fibre
  - Evanescent field interaction
  - Microbend induced leakage
  - Bragg gratings
  - Faraday rotation
- Extrinsic: interaction with light in an external device, light is originated/returned through an fibre optic, e.g.
  - Active optical filters
  - Moveable mirrors
  - Butt coupled fibres

Nature

Intrinsic



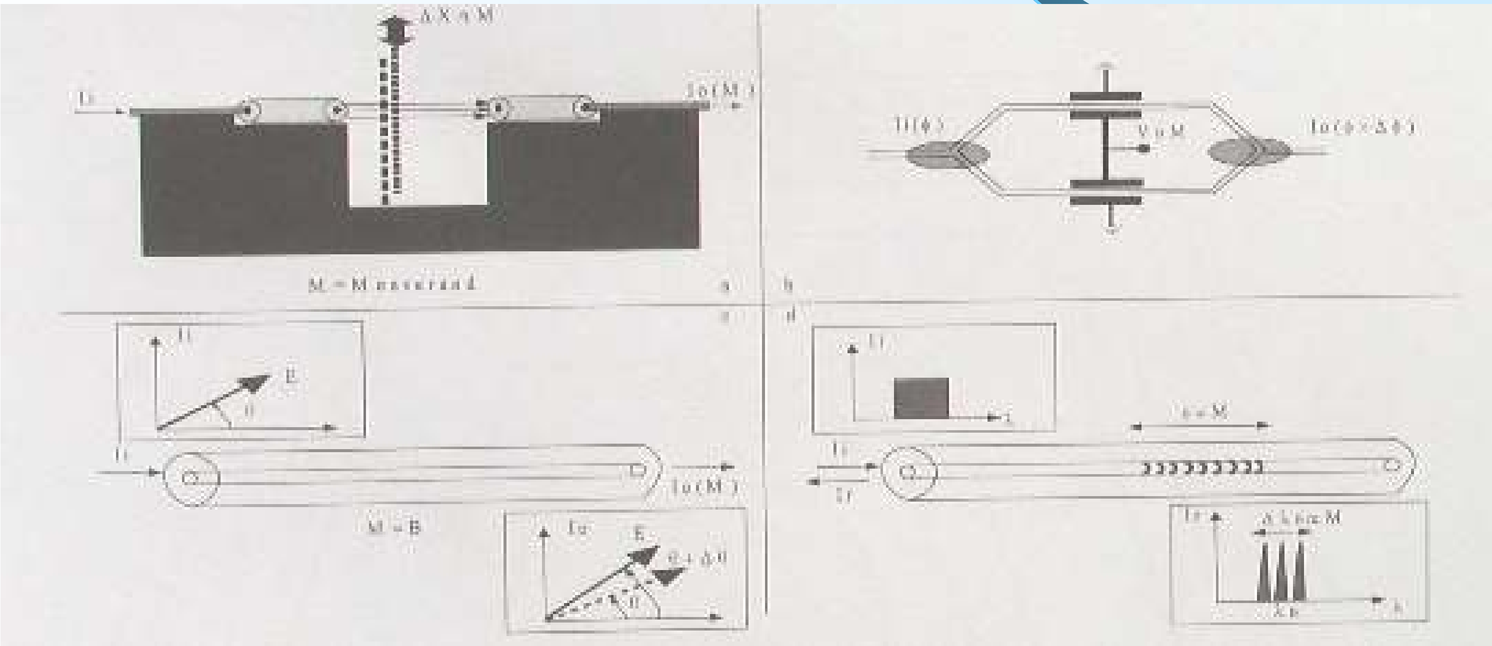
Extrinsic

Light Modulation

- Amplitude (Intensity) modulated sensors
  - Detection thru light power
- Phase modulated (Interferometric) sensors
  - Detection using the phase of the light beam
- Polarimetric sensors
  - Detection of changes in the S.O.P. *(State of Polarisation)*
- Spectroscopic sensors
  - Detection of changes in the spectrum of the light

Intensity

Phase



SOP

Spectrum

Manufacture

- Fibre Optic Technology
  - Uses fibre optic and fibre based devices
- Integrated Optic Technology
  - Fibre + IO devices (phase modulators, e.g.)
- Integrated Opto-electronic
  - Semiconductor (modulation, source, detectors…) integrated devices
- Hybrid Optic Technology
  - Mixes fibre/IO with standard (discrete) optic devices

Advantages

- Dielectric Fibre (integrated optical waveguide)
- Immunity to electromagnetic interference
- Small, lightweight
- Long distance access through an optical link
- Potential high sensitivity, resolution or dynamic range
- Multiplexing, Distributed sensing,
- Biocompatibility
- Chemical Inertness

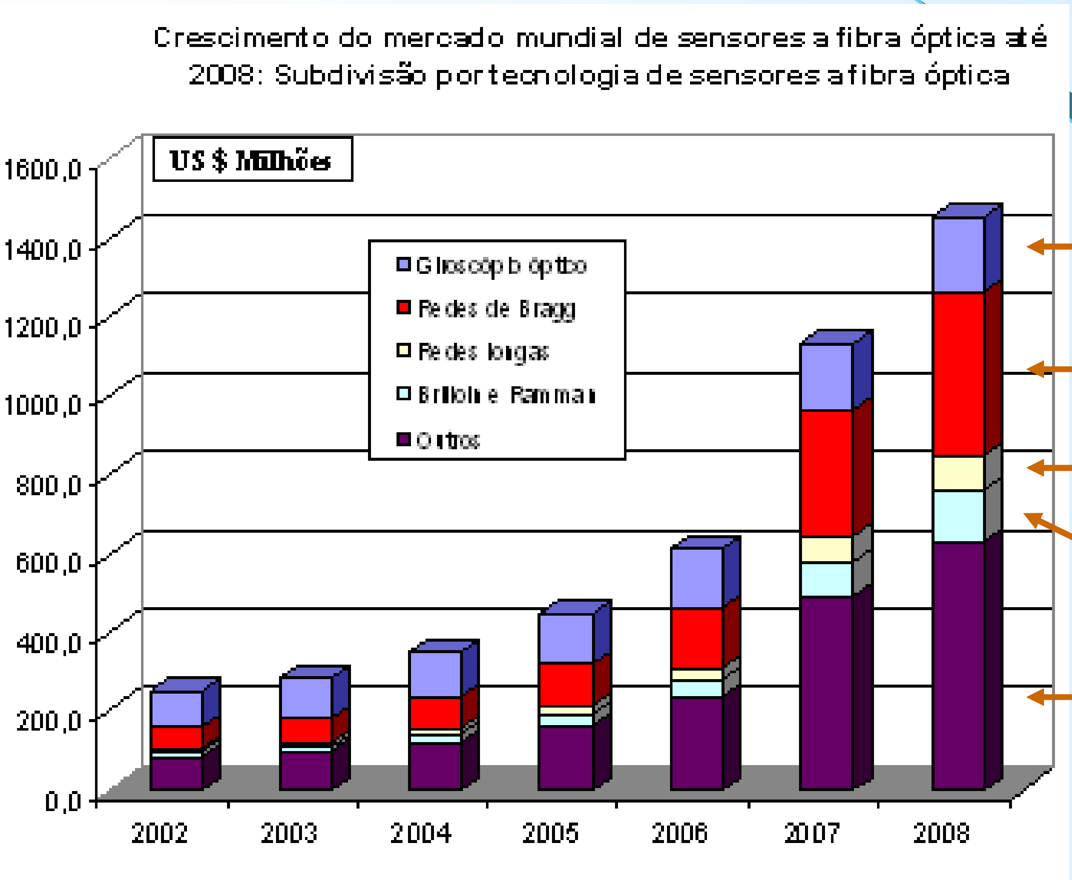
Drawbacks

- Cross-sensitivity
  - The fibre optic is sensible to several common agents, sometimes difficult to isolate the effects of the measurand
- Cost (sometimes) ?
  - Usually FOS does not compete with standard, well-established sensor technologies
- Current powered optical sources (most common)
  - Battery life can be an issue for 'stand-alone' applications

Applications

- Aggressive electromagnetic environment
- Inflammable or Explosive Areas
- Air & Aerospace Transport
- Distributed monitoring in large areas (buildings, dams, power plants)
- In-vivo medical and biological measurements
- Chemical detection

Market



Fibre gyroscope

Fibre Bragg grating

Long period grating

Brillouin & Raman

Other

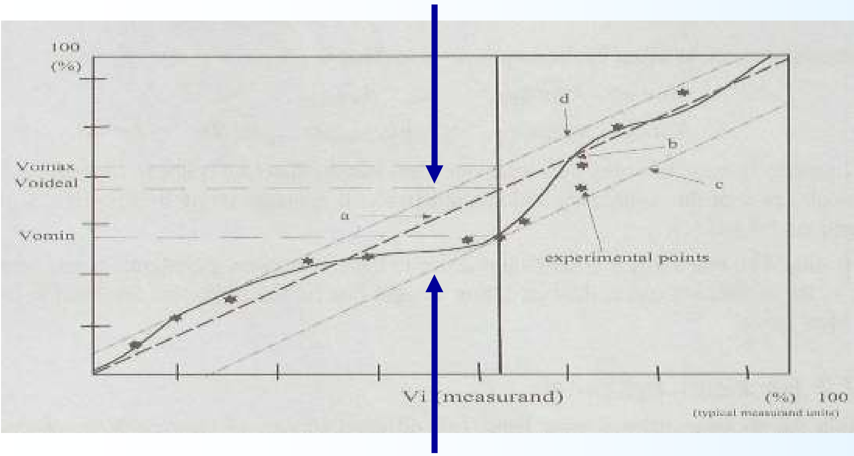
Remark

Fibre Optic Sensors are promising in terms of Research, Development and Investment in areas where a *niche* can be found, where conventional sensing techniques are unavailable, too expensive or have not enough resolution, sensitivity or dynamic range.

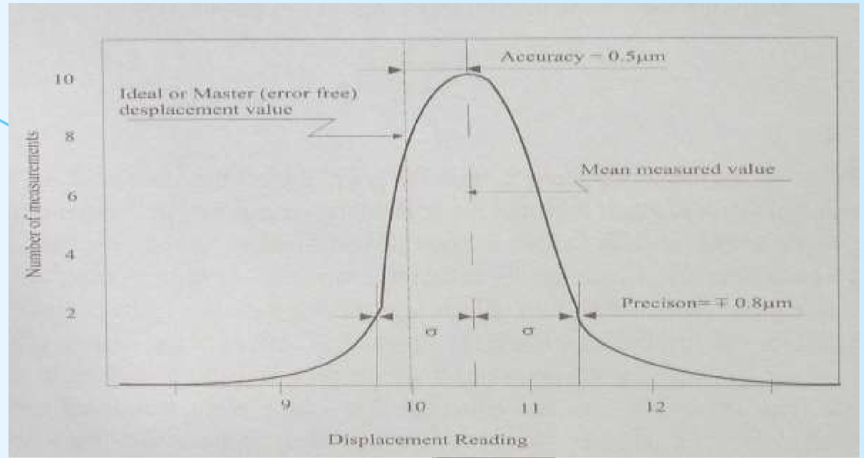
Required Characteristics

- Errors (margin, bands)
- Conformity and linearity
- Backlash, Hysteresis
- Stability & drift
- Sensitivity
- Detectivity
- Accuracy, precision, resolution
- Ranges
- Reliability

$$d_+ = \left| V_{o\,\max} - V_{o\,\mathrm{ideal}} \right|$$



$$d_- = \left| V_{o\,\min} - V_{o\,\mathrm{ideal}} \right|$$



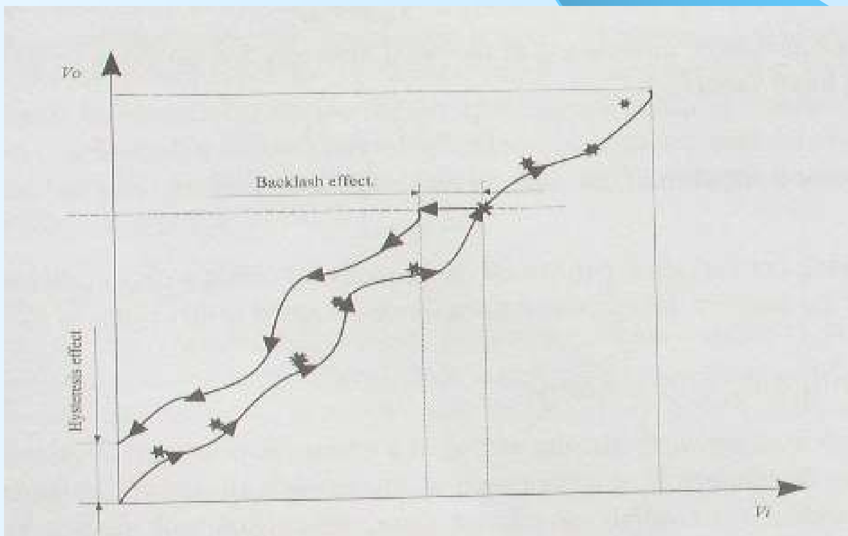


Figure 1.8 Backlash versus hysteresis.

- Fibre Optics Sensors: General Aspects
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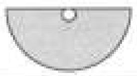
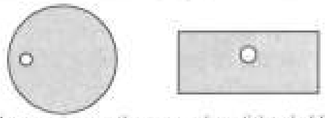
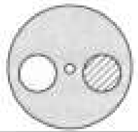
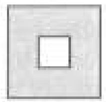
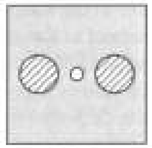
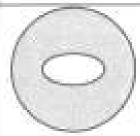
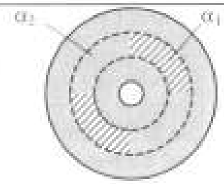
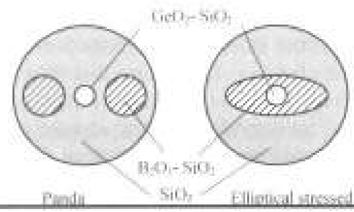
Fibres

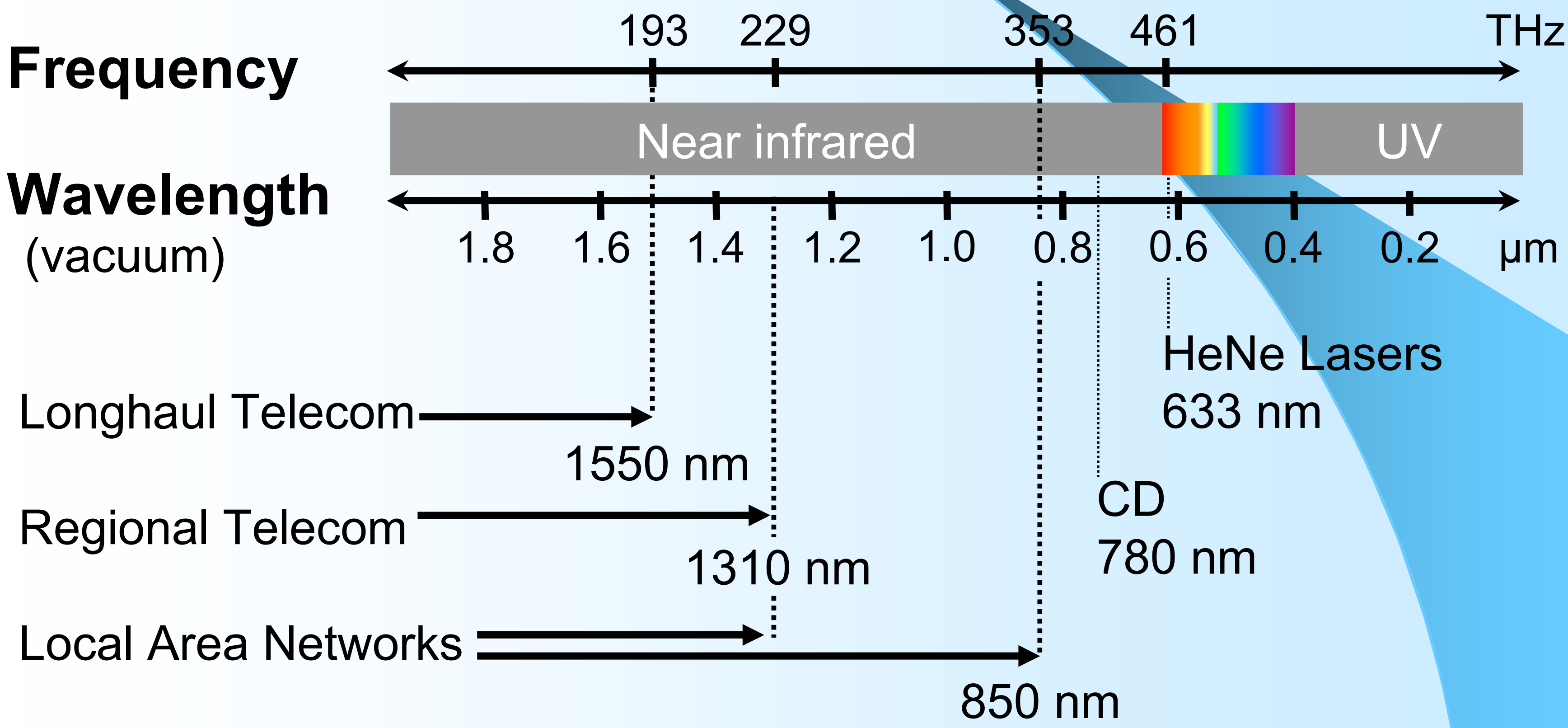
- Standard Fibre Optic (Telecommunications)
  - Multimode
  - Single-mode
- High Birefringence Fibre Optic
  - Low birefringence (spun fibres)
  - High birefringence (bow-tie, PANDA, …)
- Doped Fibres
  - Erbium doped fibres, specially doped fibres…
- Plastic Fibres (& Plastic Clad Fibres)

Most Common Commercial fibre types

Table 4.6 Special shape fibres and their applications.

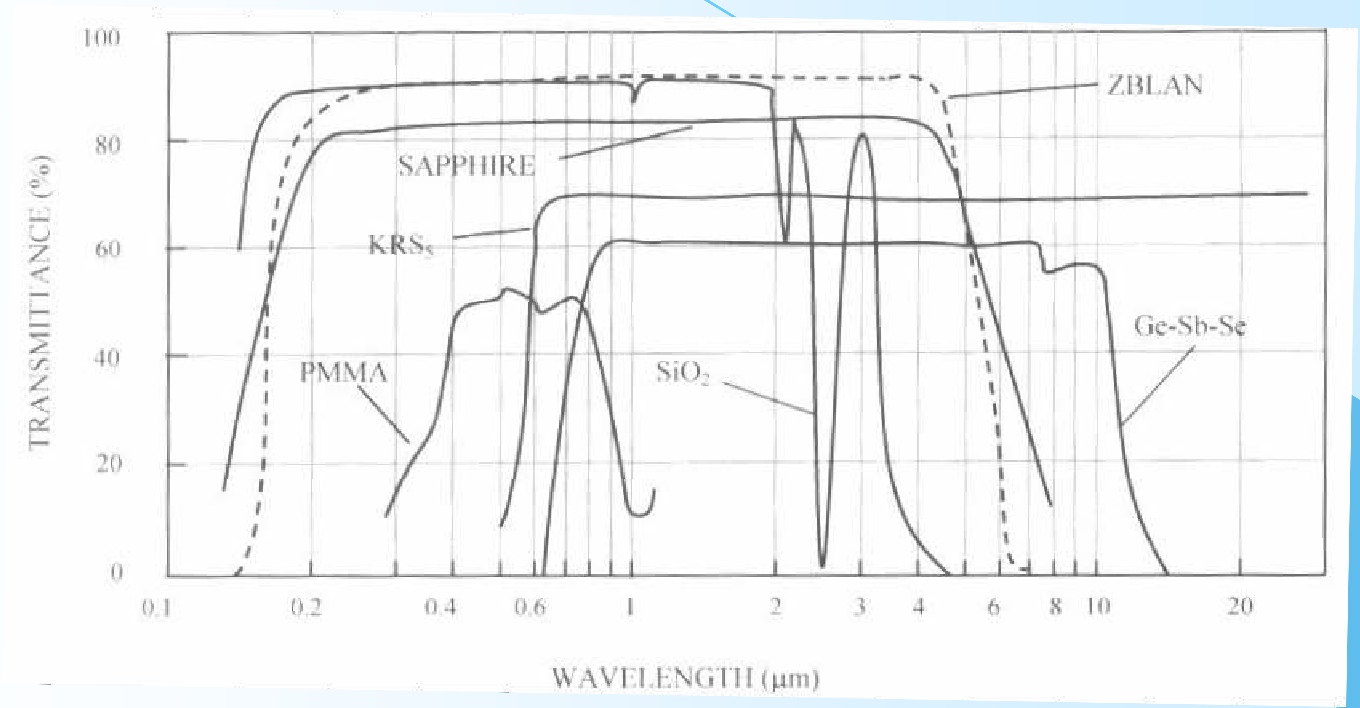
Special shape fibre	Description	Application
Cladding-like D-shape		Distributed liquid sensing
Eccentric core fibre	 The core is near the outer edge of the cladding	Distributed liquid sensing (oil, gasoline, jet fuel, methane gas...) Gas and liquid sensing (ammonia)
Twin core fibre	 Twin hole fibre with two hollow portions in its cross section at both sides of the core	Spectroscopic analysis (content of salt or O_2, blood) Electric field sensor by inserting two metal leads into the holes
Square fibre	 Square-core square-cladding fibre  Square-cladding with twin holes and a circular core	Power applications; two dimensional distribution sensing Polarisation maintaining fibres
Elliptical core and bow tie	 Elliptical core  Bow-tie They are well suited to high performance interferometric and polarimetric sensors.	Polarisation maintaining fibres Elliptical core: Birefringence is obtained because of core ellipticity. The birefringence is a function of the ratio between the two axes of the ellipse (a/b), as well as of the difference in the refractive index between core and cladding. Bow-tie: Birefringence is induced by two different expansion coefficients: α_1 for the silica and α_2 for the doped silica. The beat length is less than 2 mm.
Panda and elliptical stressed inner cladding		Polarisation maintaining fibres Panda: Its name comes from the shape of the doped silica (B_2O_3-SiO_2). The core is graded-index. Elliptical stressed: The birefringence comes from the difference between the thermal expansion coefficient of the core (high) and that of the elliptical cladding (low).

Optical Spectrum



Using a standard optical window can bring advantage with low cost components

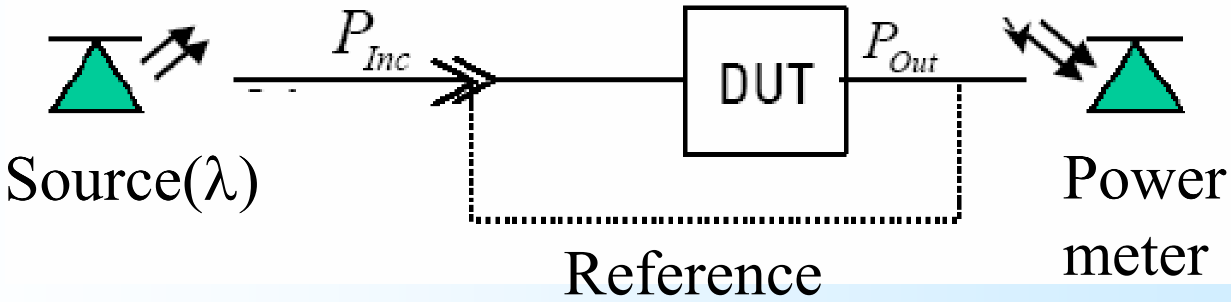
Fibre Transmission



- Signal spectral characteristics can determine the fibre material to be used.
- Fibre loss reduces dynamic range, sensitivity & resolution.
- Mandatory for spectroscopic sensing & measurement.

Attenuation

Light power drops through fibre and optical devices due to intrinsic absorption of the medium, waveguide characteristics and scattering.



$$AT = -10\log\frac{P_{out}}{P_{in}}$$

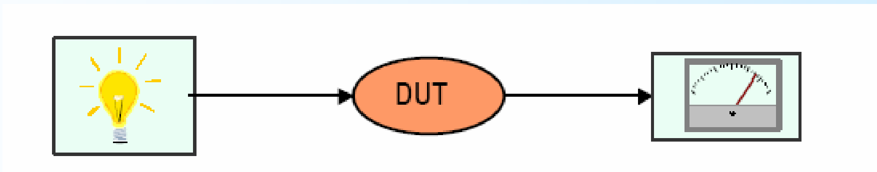
For fibres:

$$\alpha(\mathrm{dB/m}) = -\frac{10}{L}\log\frac{P_{out}}{P_{in}}$$

Insertion loss

Loss induced by the insertion of a device in the optical link, includes intrinsic attenuation + coupling losses.

Emiter Receiver



$$IL = -10 * \log\left[\frac{P_{Out}}{P_{Inc}}\right] (dB)$$

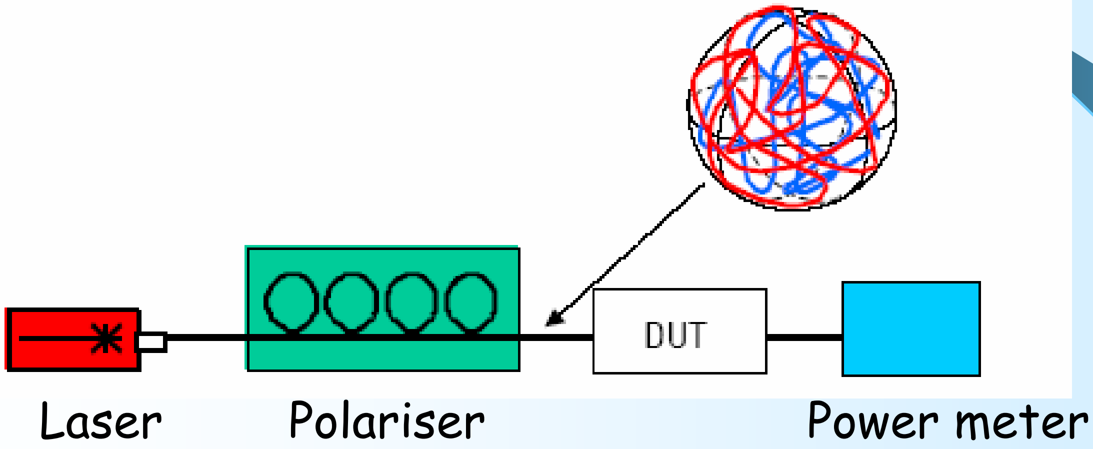
Emiter	Receiver
Tunable spectrum (Laser)	Large spectrum (Power meter)
Large spectrum (ELED, ASE)	Tunable spectrum (OSA)
Tunable spectrum (Laser)	Tunable spectrum (OSA)

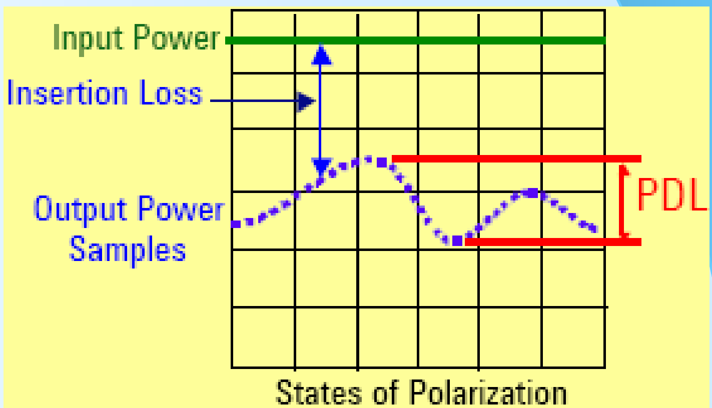
Return loss

- Power reflected from devices (generally undesirable)
- Return loss = $\dfrac{P_r}{P_i}$

Polarization Dependent Loss

PDL – Polarization Dependent Loss: Maximum change in the insertion loss when the State of Polarization is changed.





Optical Sources

- LEDs
  - Low cost, broad spectral band, low operational current
- Lamps
  - Most common optical source, can have wide spectral band
- Lasers
  - Narrow spectral band, higher spectral power density
- ASE (Amplified Spontaneus Emission) from EDF (Erbium Dopped Fibre) sources
  - Centred at the C-band (~1530-1565 nm) (L-band already available), good spectral power density, less sensitive to polarization

Required Characteristics

- Optical Spectrum
  - Wavelenght
  - Spectral Width
- Emitted Power & Directivity
  - Coupling to fibre optic
- Packaging, dimensions, weight, power supply, …
- Cost

Detectors

- Photodiodes / Photoconductive
- Photomultipliers
- CCDs
- Photoresistive

- Spectral Band
- Spectral Responsivity
- Noise
- Fidelity, Stability
- Reliability
- Size, weight, cost, power supply

Devices

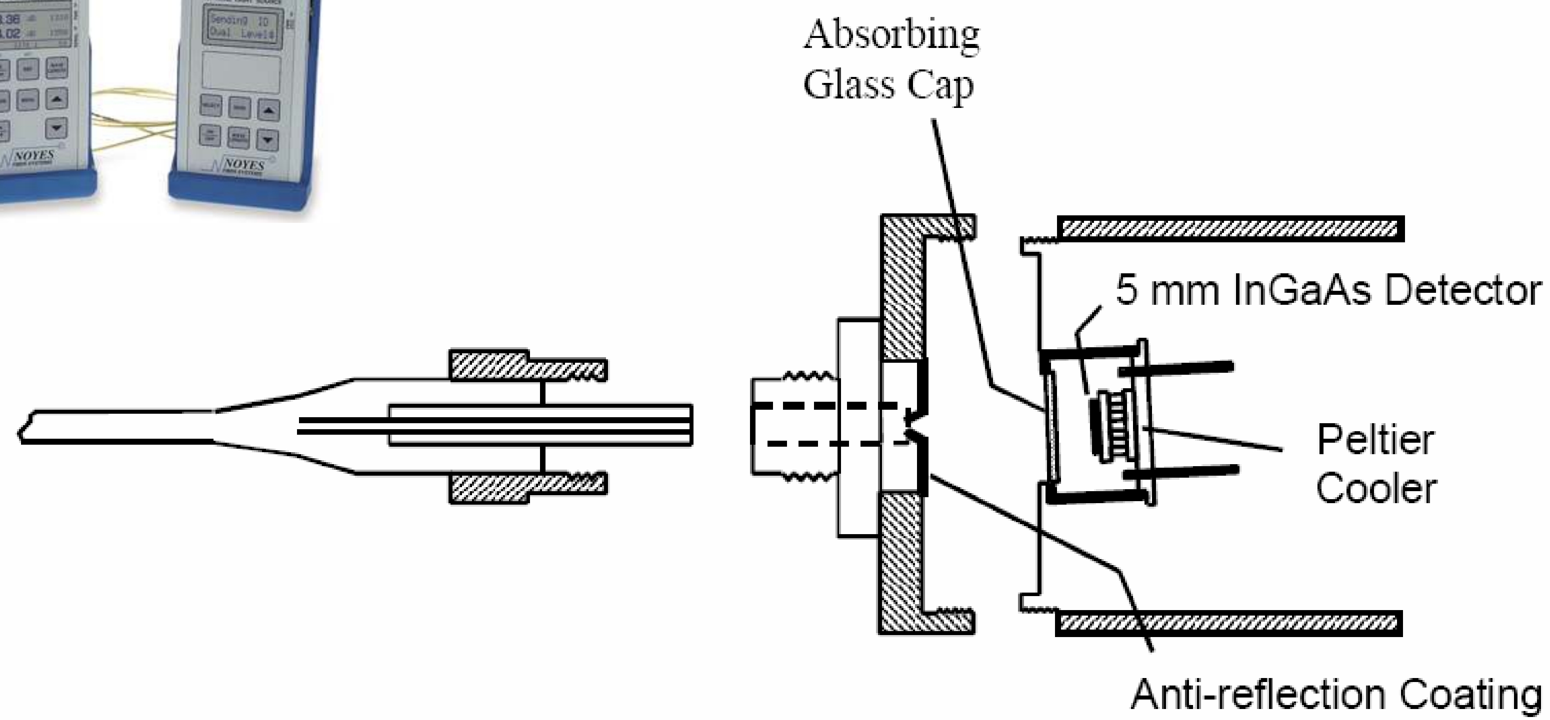
- Fibre based devices:
  - Couplers
  - Wavelength Multiplexers
- Hybrid devices (have fibre transition):
  - Isolators
  - Polarisers
  - Electro-optic modulators
- Optical Measuring Instruments

Optical Instruments

- Optical Power Meters
- Optical wavemeters
- Optical Spectrum Analysers (Monochromators)
- Optical Network Analysers
- OTDR (Optical Time Domain Reflectometers)
- …

Power meters

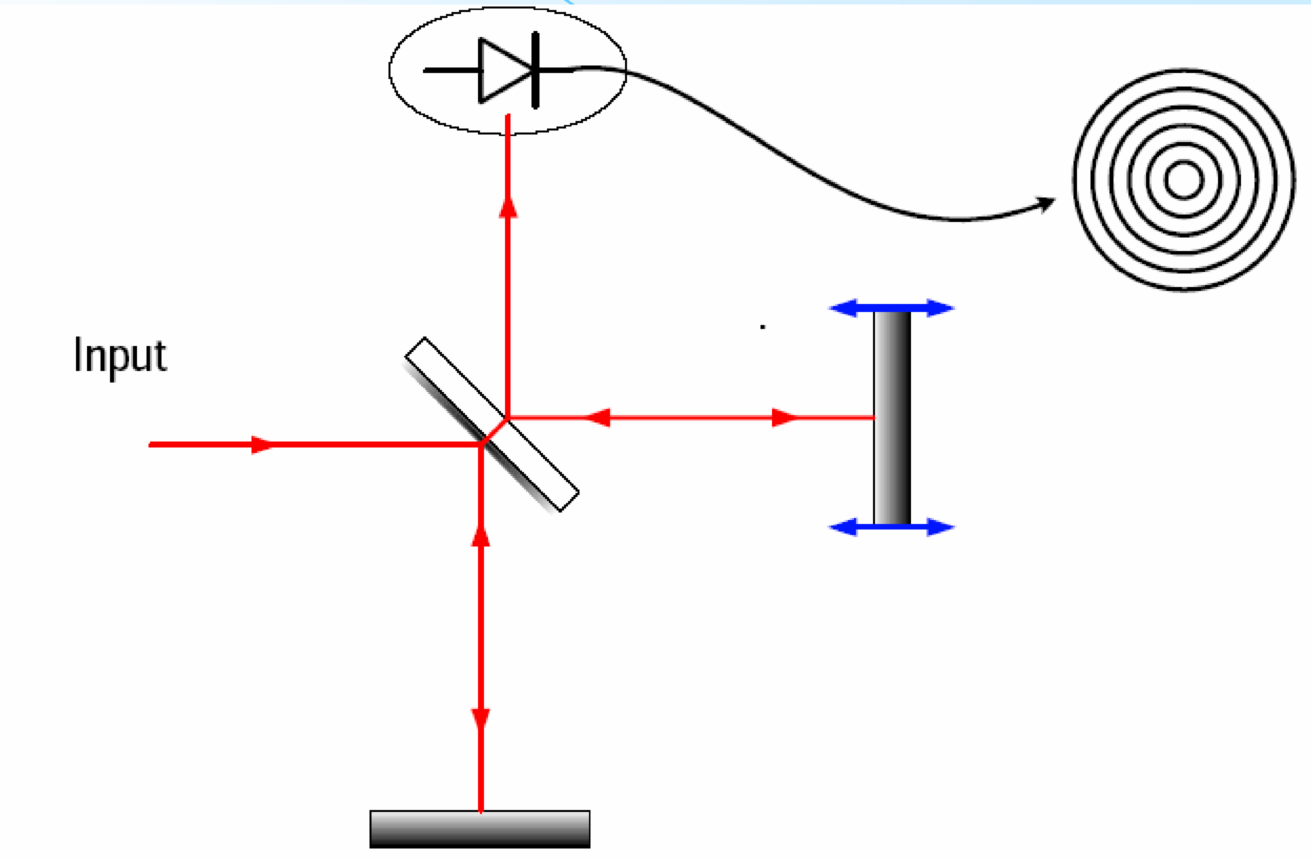
Detectors based on PINs, dully callibrated.



Wavelength Meter

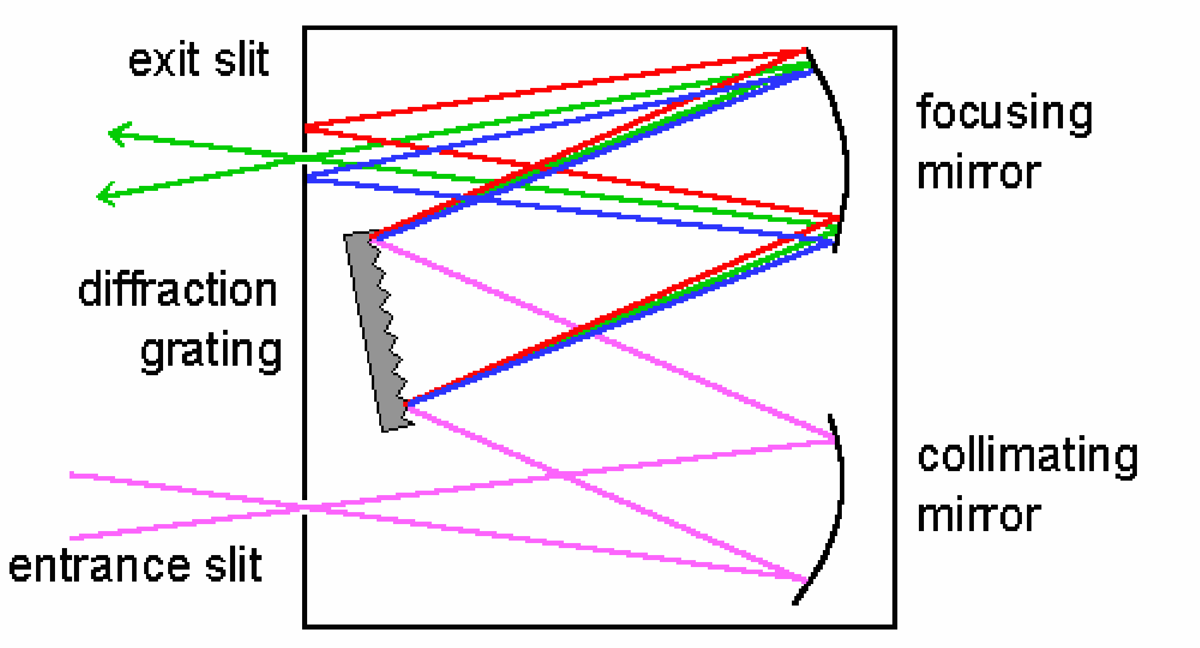
Based on the Michelson interferometer

The distance between fringes is proportional to the wavelength



Optical spectrum analyser

Based on a movable diffraction grating and monochannel detectors OR fixed gratings and CCD



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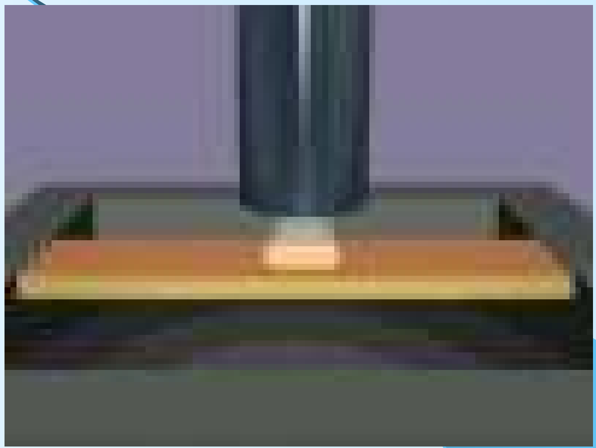
Intensity Modulated Sensors

- Measurand affects the intensity of the optical signal
  - Moveable parts
  - Fresnel Reflection
  - Absorption
  - Fluorescence
  - Evanescent field



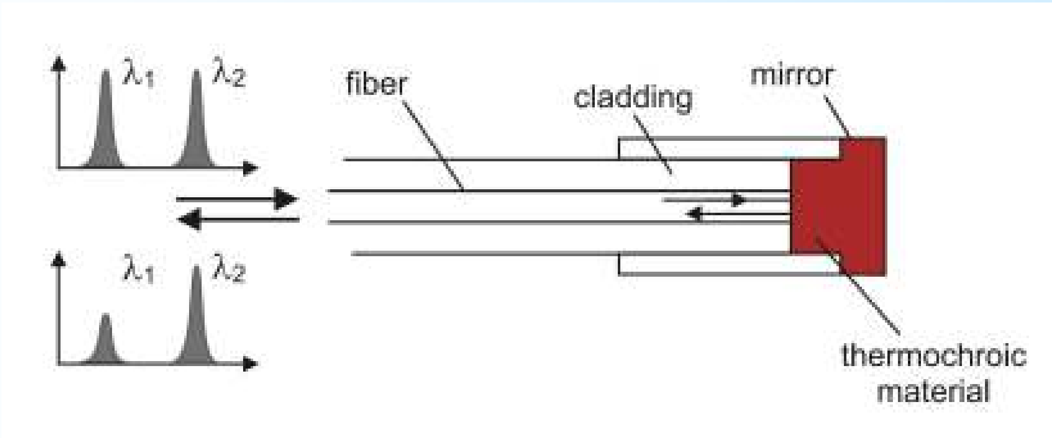
Light reflected by membrane is collected by the same fibre (or others, single or bundle)

Distance to membrane defines solid angle for light acceptance

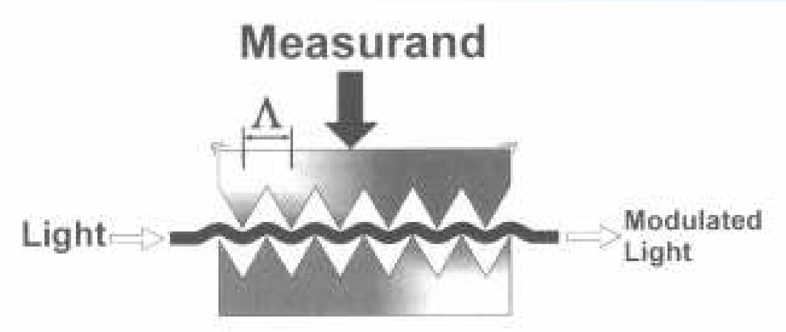
Can measure displacement (amplitude), frequency (vibration) or pressure (chamber)

Thermochroic Thermometer

- Thermochroic material changes band intensity as function of temperature
- Filtering the λ_1 component it is possible to associate the band intensity to the temperature



Microbend Sensor

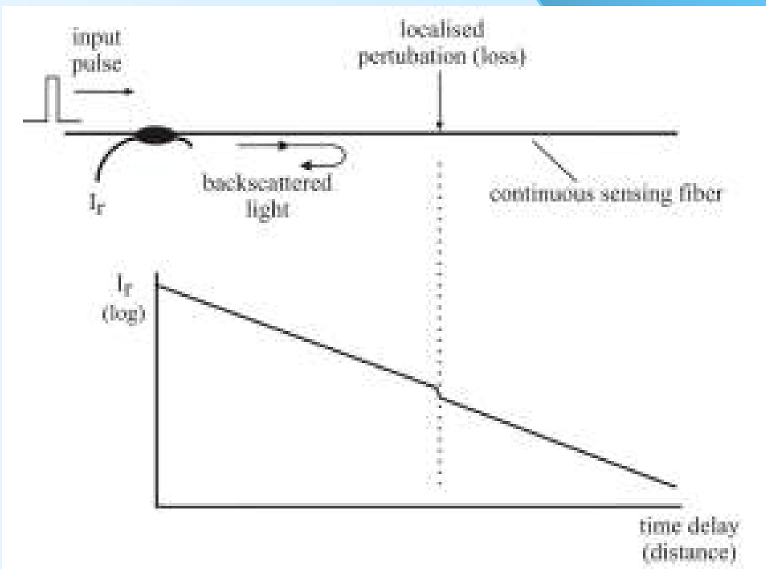


Light leakage from fibre optic depends on the applied force

- -Force (Pressure)
- -Displacement
- -Vibration
- -Acceleration

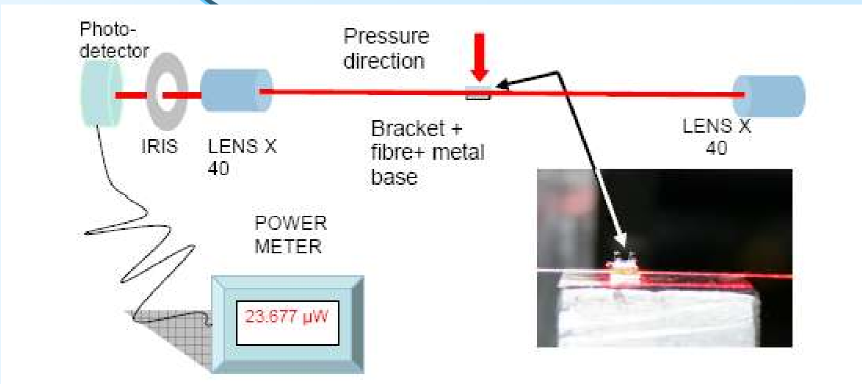
Intruder detection can be sensed by an OTDR (Optical Time Domain Reflectometer) within the spatial resolution.

Using an adequate jacket, continuous (distributed) sensing can be implemented.



"Microbend" Polymer PCF Loss Sensor

Losses from Polymer Photonic Crystal Fiber used to determine forces of orthodontic appliances



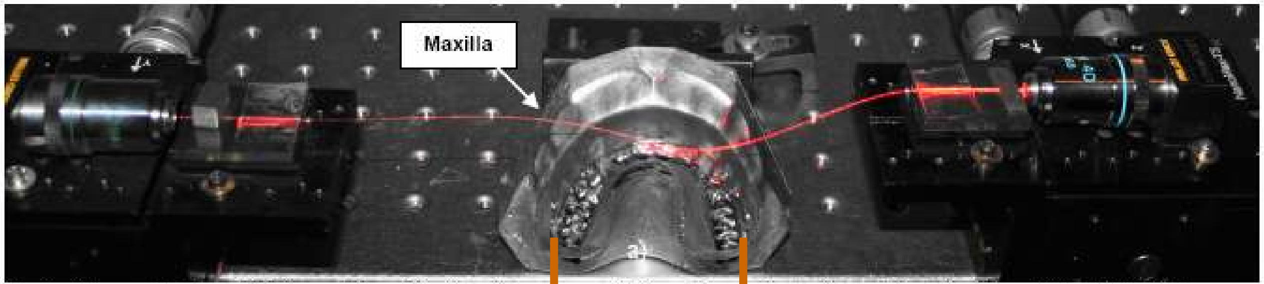
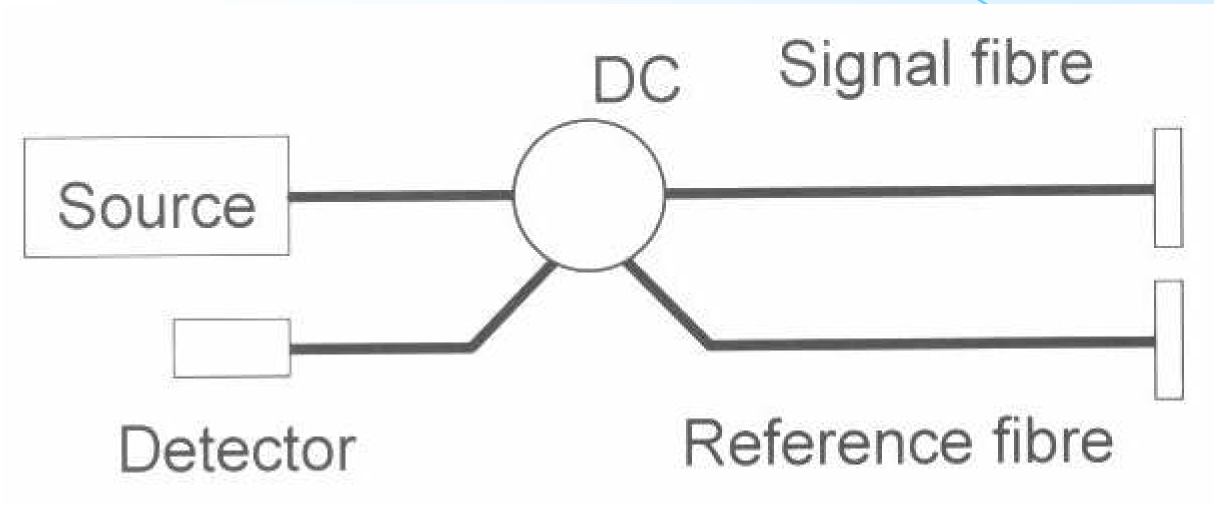
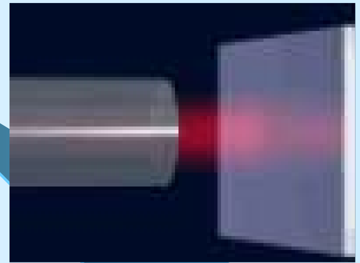


Fig. 3. Set up with the artificial maxilla and the Bracket sensor with the polymer photonic crystal optical fibre. HeNe light lights up the fibre.

Load

Interferometric Sensor





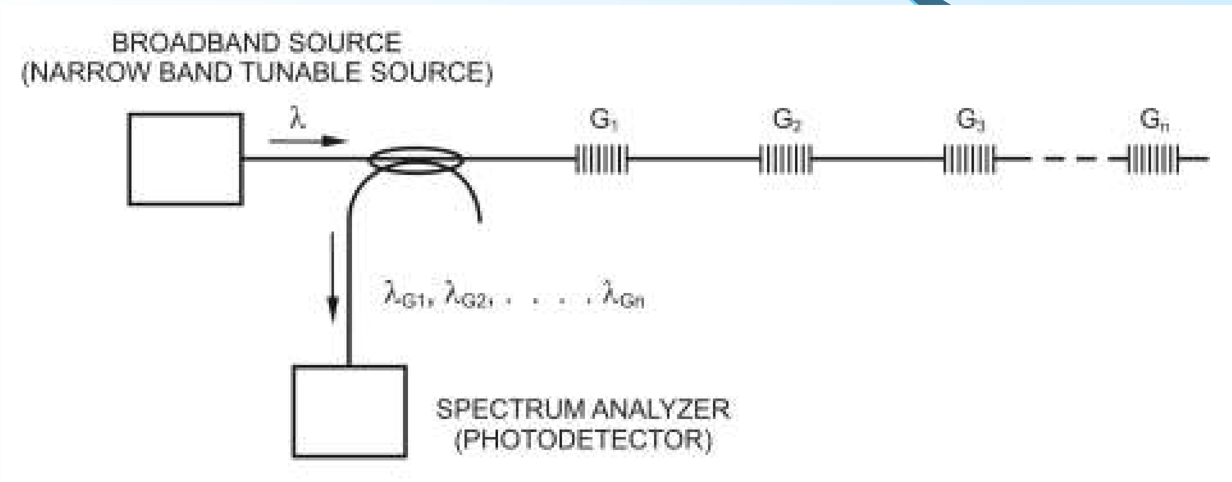
Measurand induces phase changes in the optical path

Fringe counting or phase detection can demodulate measurand

Very sensitive

Care shall be taken in order to avoid spurious phase changes, particularly on long fibre links

Multiplexed Bragg Grating Sensors



Quasi-distributed spectroscopic sensing, each grating reflects it's own spectrum and their spectral changes can be correlated to the measurand at the grating's position.

Monitoring of large structures (bridges, dams, aircraft, ...)

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