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Winter College on Fibre Optics, Fibre Lasers and Sensors

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Fibre Optic Sensors:
basic principles and most common applications

(PART 3)

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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."

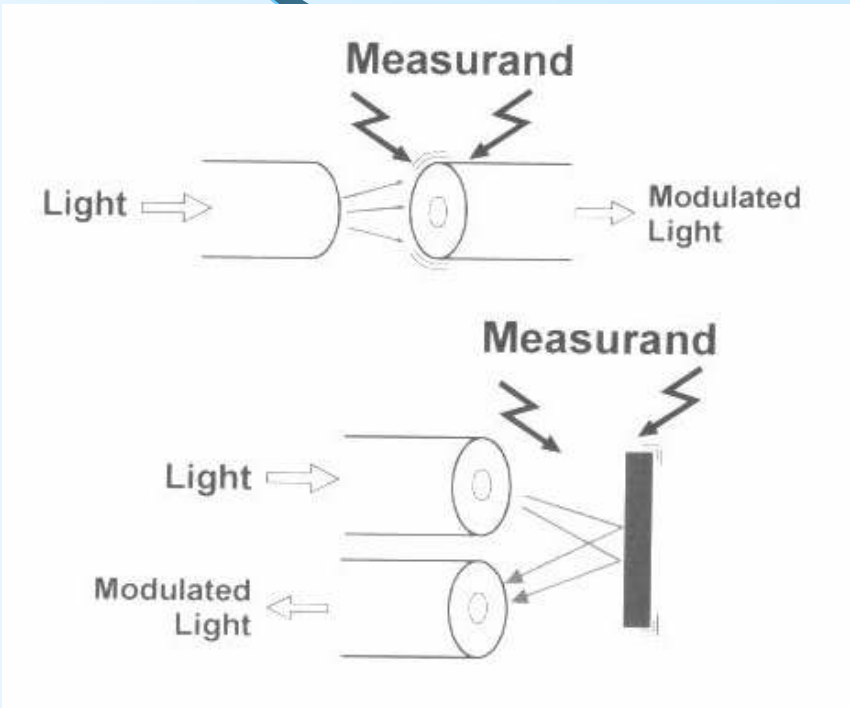
Brian Culshaw, 1998

Outline

- Fibre Optics Sensors: General Aspects
- Components and Devices
- Standard Examples
- Detection Techniques
- Applications

Intensity Modulated FOS

- Simplest models made by mechanical modulation of coupled light
  - two butt coupled fibres
  - fibre(s) and mirror
  - reflective membrane
  - in between gratings
  - obstacles (on-off switch)
- Light attenuation
  - Absorption
  - leakage
- Fluorescence
  - emission spectrum
  - temporal quenching



Compensation Techniques

Change of power caused by measurand but also due to other factors like

- aging of components (sources / detectors)
- operational conditions (temperature)
- cross-sensitivity of fibre

Referencing is mandatory for intensity modulated sensors

Compensation techniques:

- path diversity
  - two similar optical paths, one sensitive (dummy fibre)
- balanced bridge
- wavelength referencing, one sensitive to measurand
- frequency division in the electrical domain
  - AC component (measurand affected) compared to DC one (other effects)

Balanced Bridge

- Symmetrical fibre links with two modulation frequencies
- Measurand acts on one path
- Ratio of combined frequency signals used to determine measurand

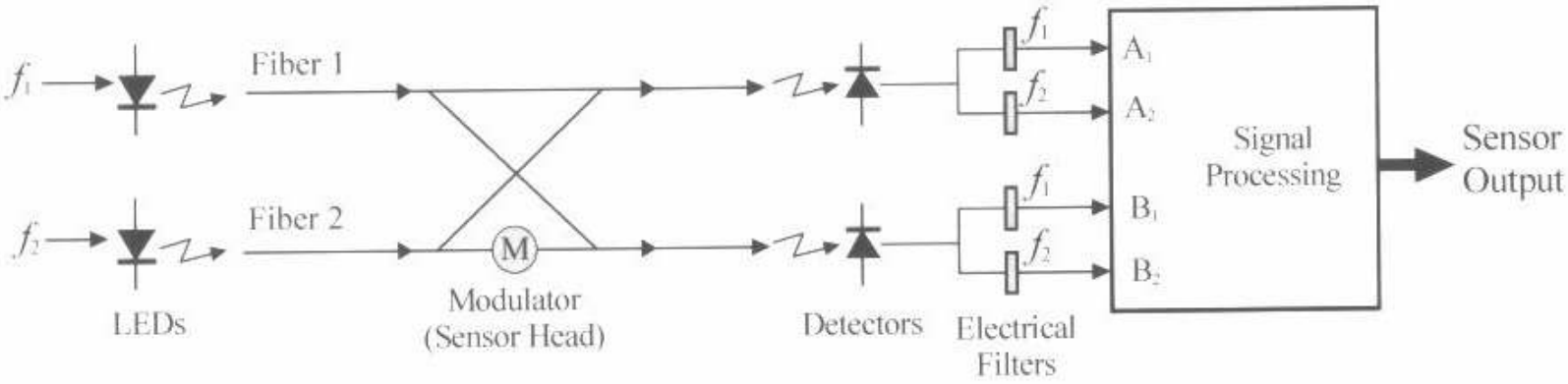
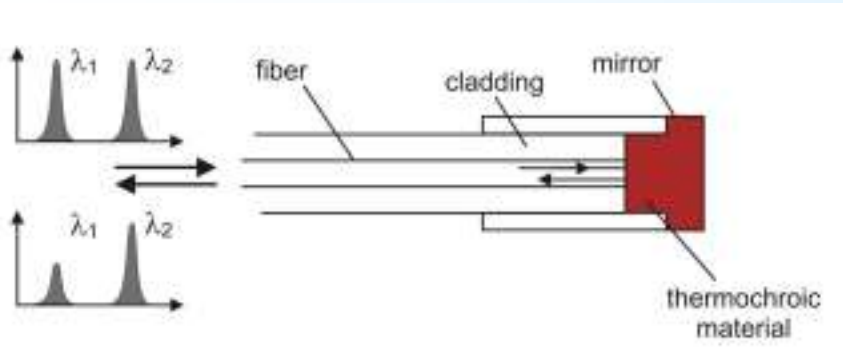
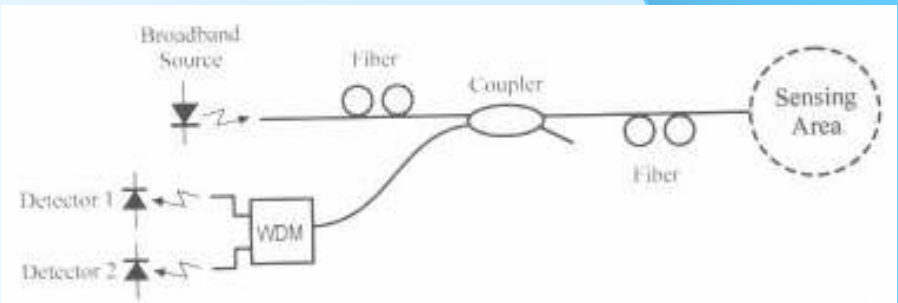


Figure 11.9 Compensation technique based on a balanced bridge.

Wavelength Referencing

- Two (or more) wavelengths (bands)
- Filtering the λ_1 component it is possible to associate the band intensity to the measurand, whereas changes in λ_2 serve to compensate for other effects
- Does not account for spectral changes in the source or along the optical path to/from sensor material





FO Thermometer

- Loss on fibre U-turn embedded in polymer
  - n(T) dependent
- Simple power referencing with coupler
- Calibration curve for detected signals (ratio) vs temperature
  - EPROM storage for microprocessor

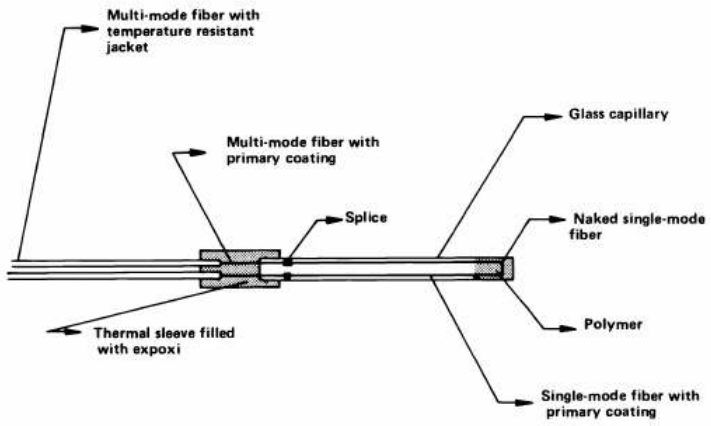


Figure 1: Schematic drawing of the probe.

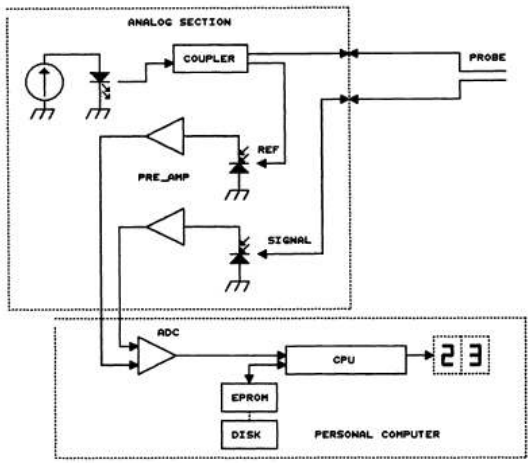
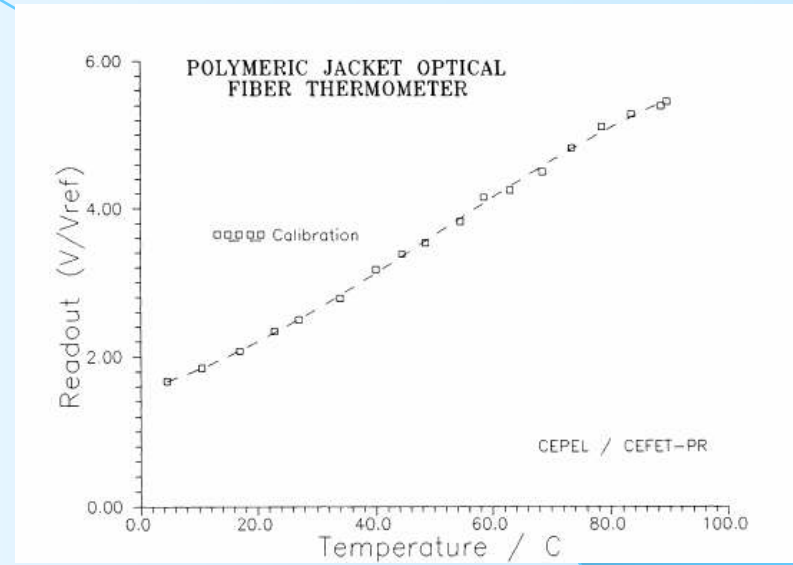


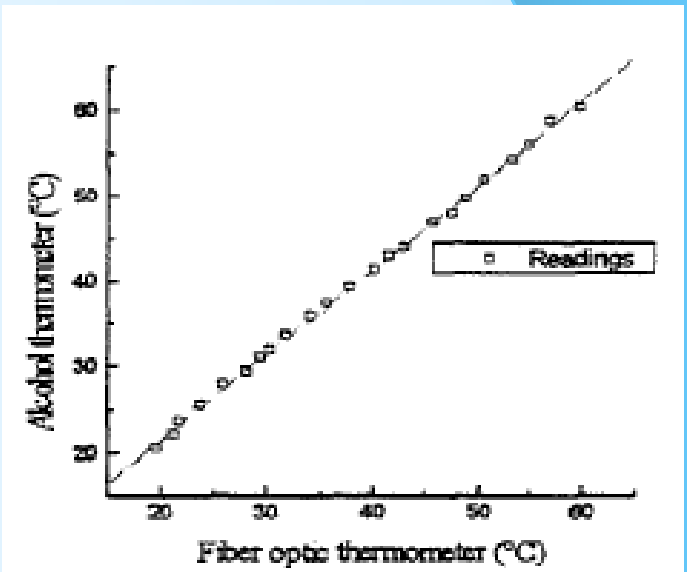
Figure 2: Block diagram of the instrument.

H.J. Kalinowski et al., Proc. SPIE 1795, 261 (1992)

Performance

- Industrial grade (±1 °C) easily achieved
  - stability ± 0.3 °C / 20 h
  - one fixed point calibration (three-month interval)
- Medical use (hypothermia)
  - single lock-in (on chip) circuitry
  - 0.25 °C accuracy, 0.1 °C resolution
  - 0.2 °C deviation from linearity





H.J. Kalinowski et al., Proc. SBMO/IEEE IMOC'97, 16 (1997)

Fibre Optic Oil Leak Detector

- Simple reflective fibre – air interface.
- Reflection coefficient depends on refractive index of medium.
- Threshold detection for "off-on" status due to presence of petroleum compounds.

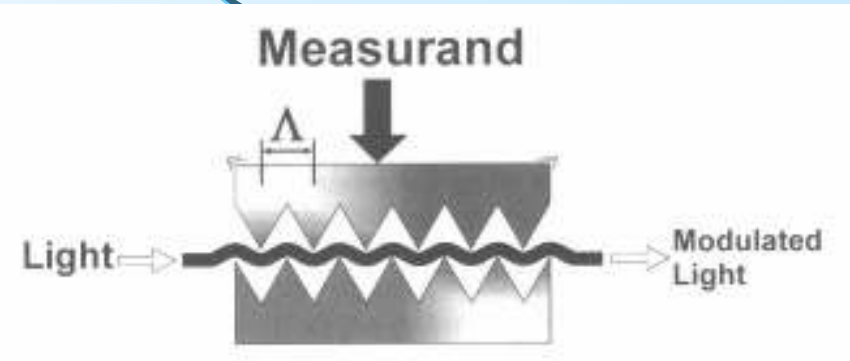
Fibre optic tip sensor can be calibrated to identify the compound or to measure a mixture

www.gaveasensors.com

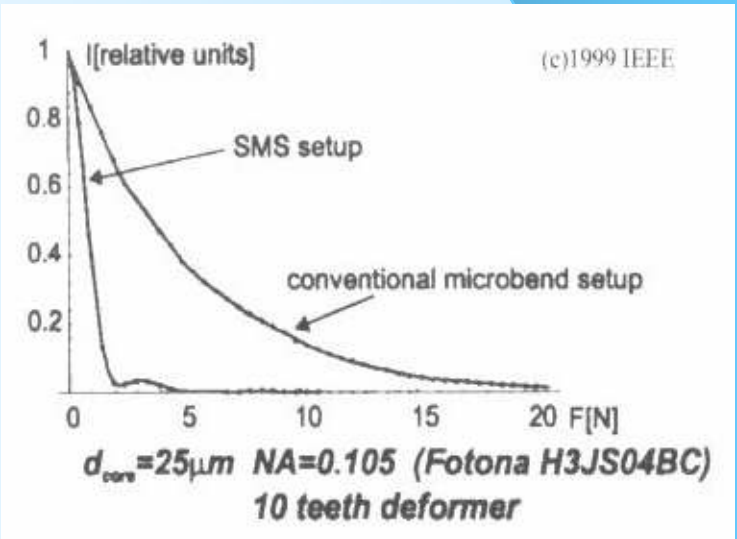
Micro-bending FOS

- Mechanical modulator or proper fibre jacket

$$\beta - \beta' = \pm \frac{2\pi}{\Lambda} \qquad \Lambda_{th} = \frac{\pi a}{\sqrt{\Delta}}$$



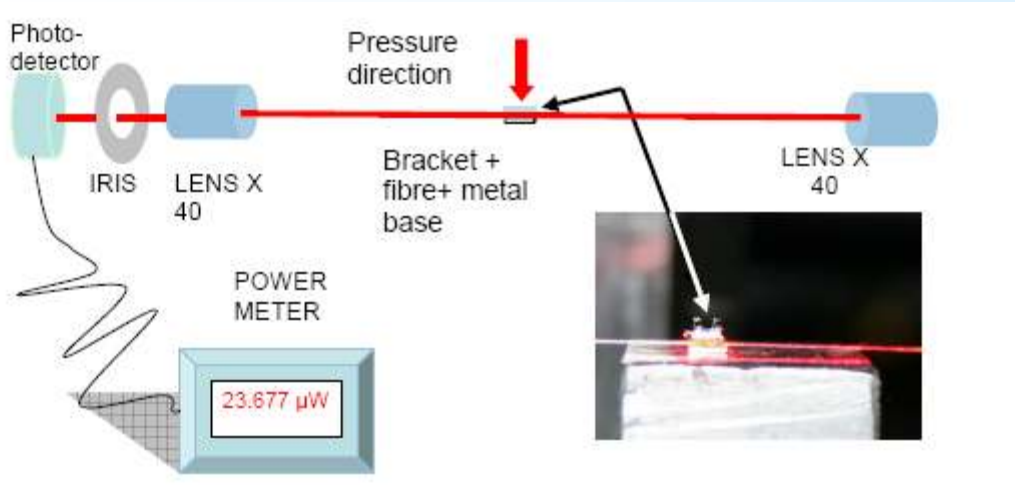
  - 10^{-10} $m/\sqrt{Hz}$ sensitivity
  - 40 dB dynamic range
  - < 1% non linearity
  - Accuracy limited by thermal sensitivity, ~0.5%



Microbending losses on Polymer PCF

Microbend losses on Polymer Photonic Crystal Fibre used to monitor the load applied by orthodontic apparatus

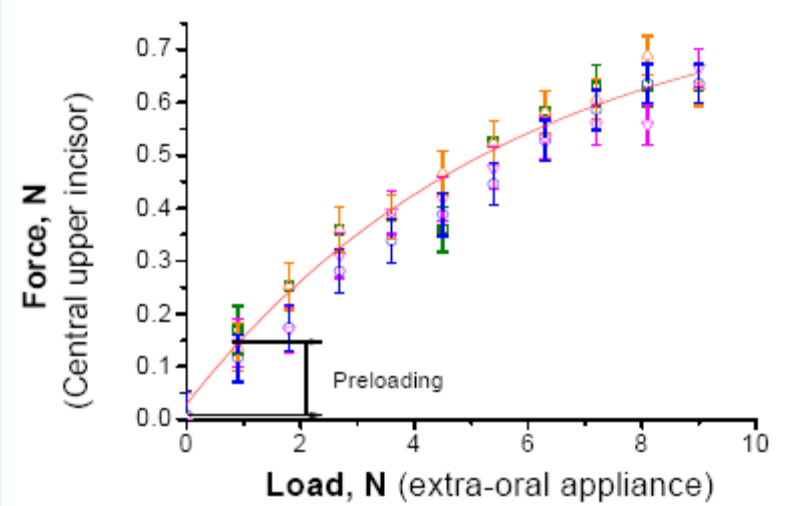
- small sensor formed by the “bracket” and tooth surface
- load induced loss
- previous calibration with weight or load cells (repeatability)



M.S. Milczewski et al., EWOFS (Naples) (2007) - submitted

Results

- Sensor mounted on maxilla model + appliance
- Load applied by weights to the wire arch of appliance (extra-oral)
- Loss determines the normal component of the force on the teeth



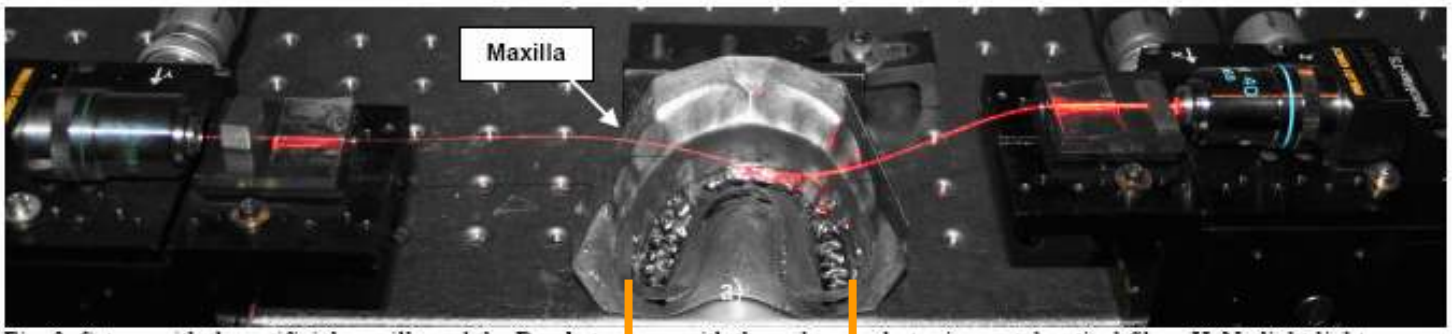
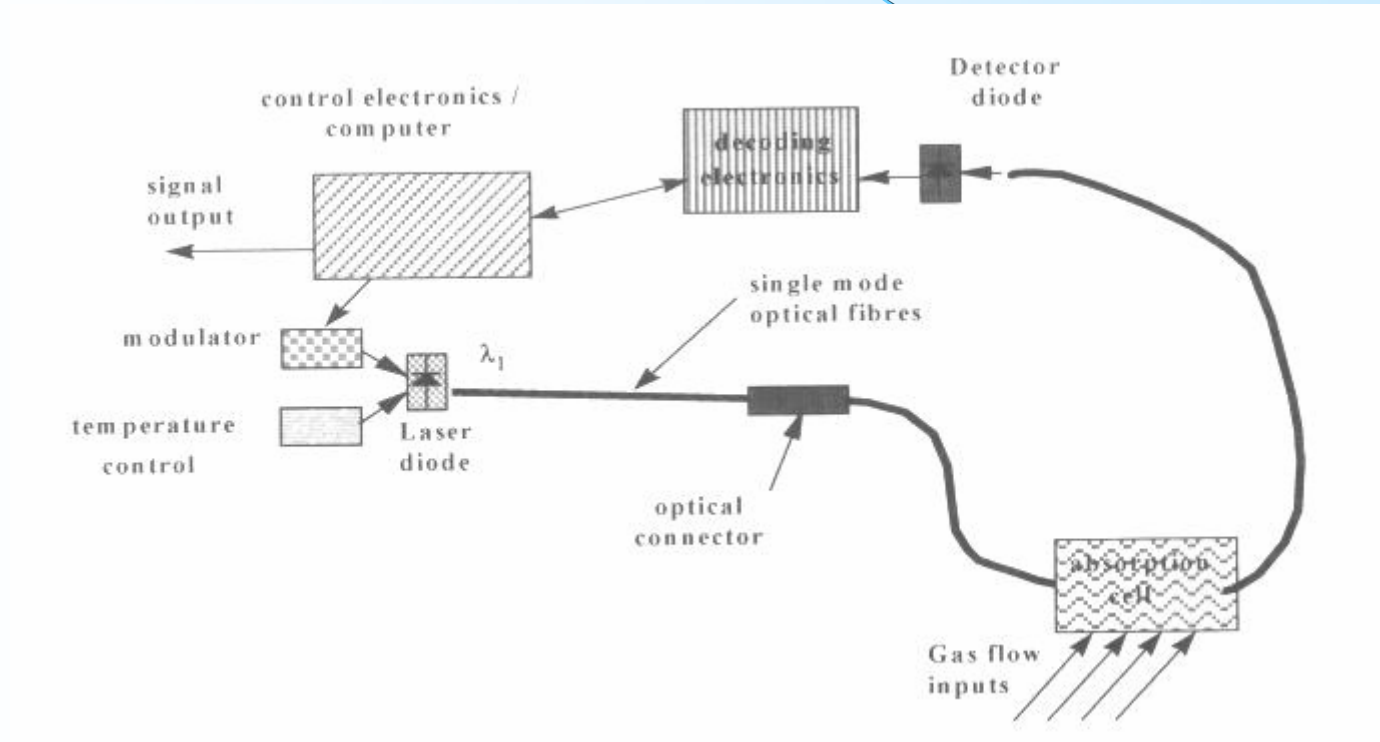


Fig. 3. Set up with the artificial maxilla and the Bracket sensor with the polymer photonic crystal optical fibre. HeNe light lights up the fibre.

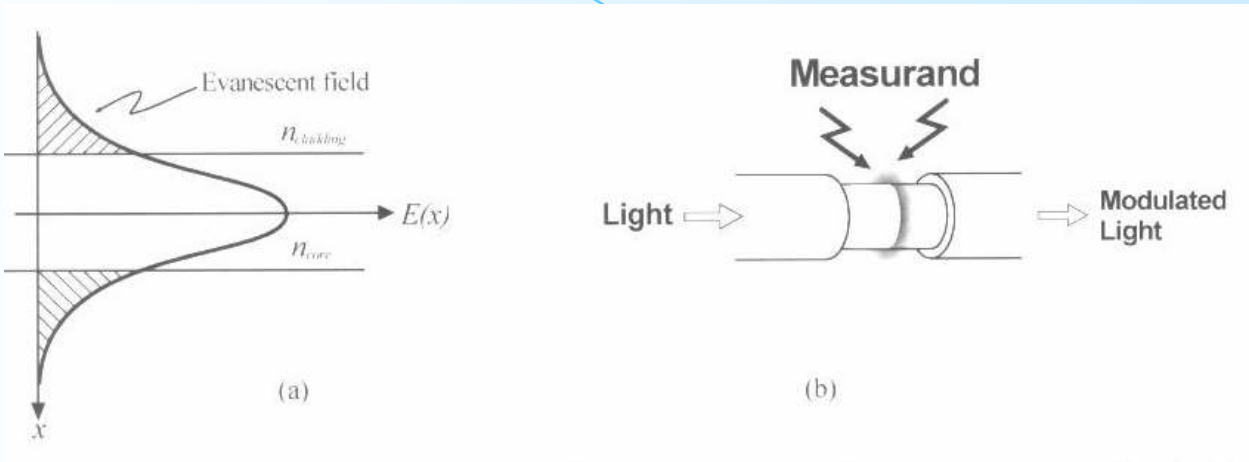
Load

Absorption Spectrometry using Fibre Optics



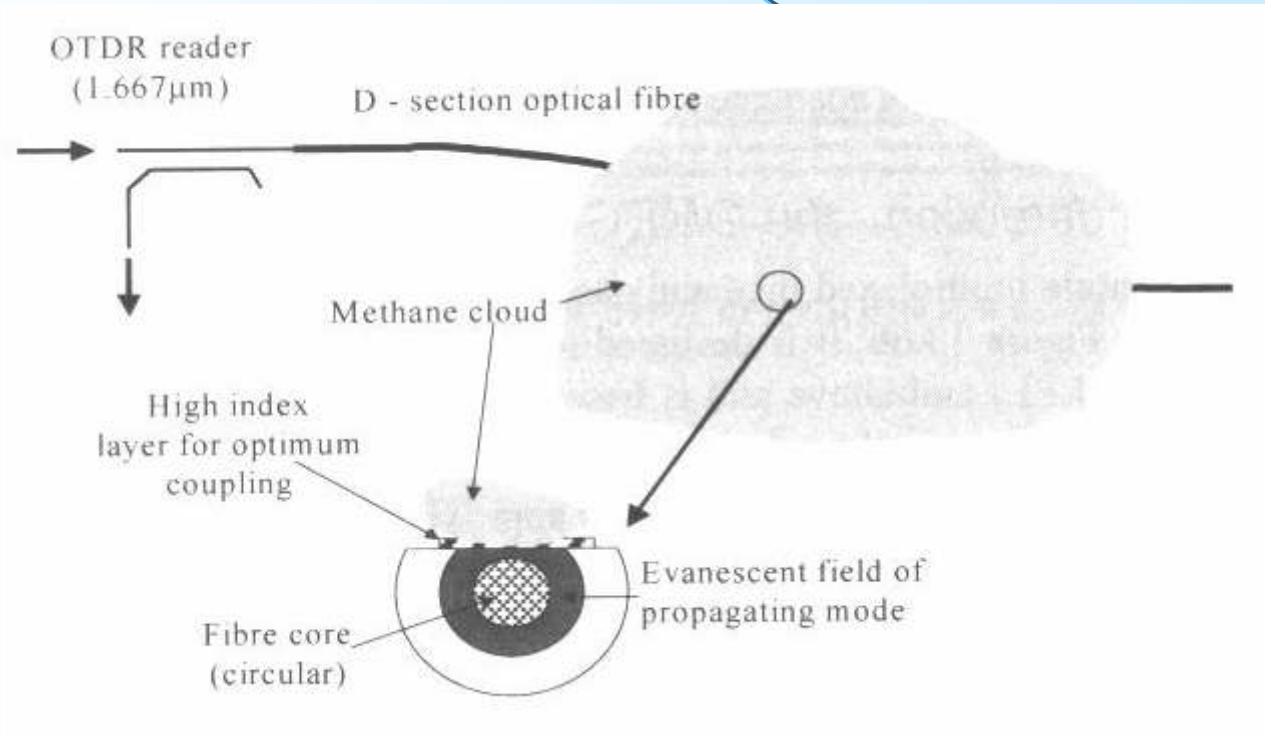
Fibre is used only as light guide to and from the sample (absorption cell)

Evanescent Field FOS



- Exposed evanescent field interacts with measurand
- Absorption (power monitoring)
- Fluorescence (spectral monitoring, temporal analysis)
- Micro & macro curvature (power monitoring)

Absorption of Evanescent Field

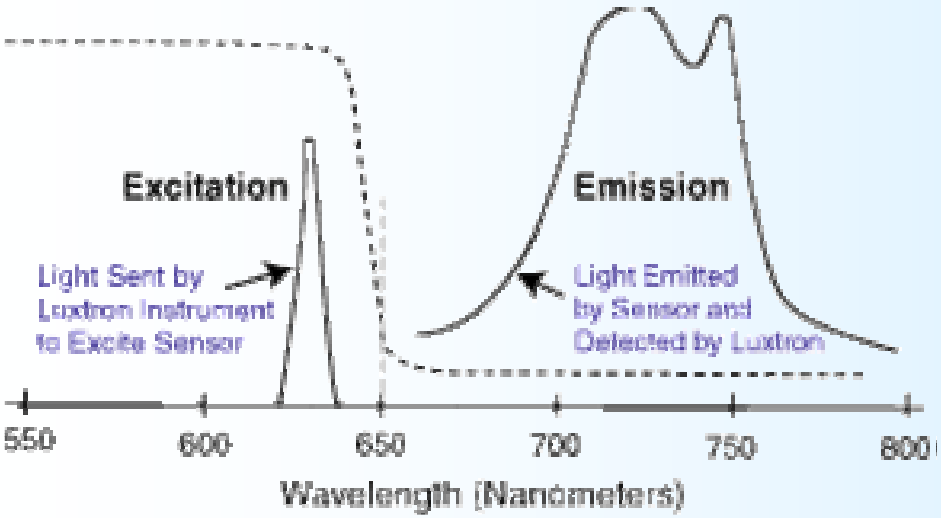


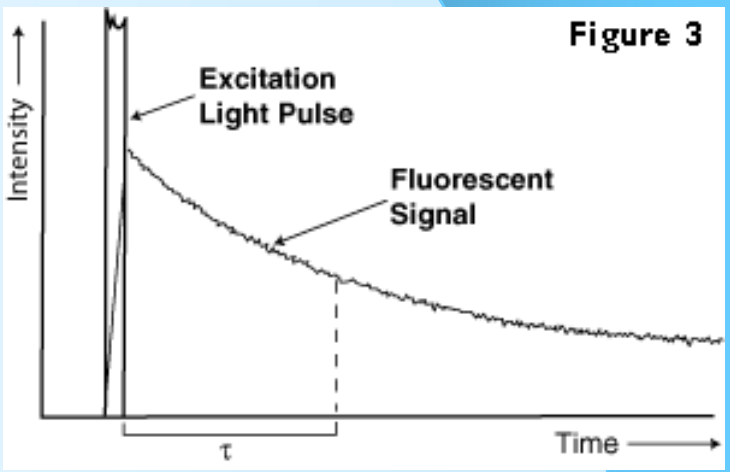
Interaction can be enhanced by close exposition of fibre core by chemical etching or D-shaped fibres.

Fluorescence Sensors

A fibre optic can illuminate a suitable fluorescent material on its tip

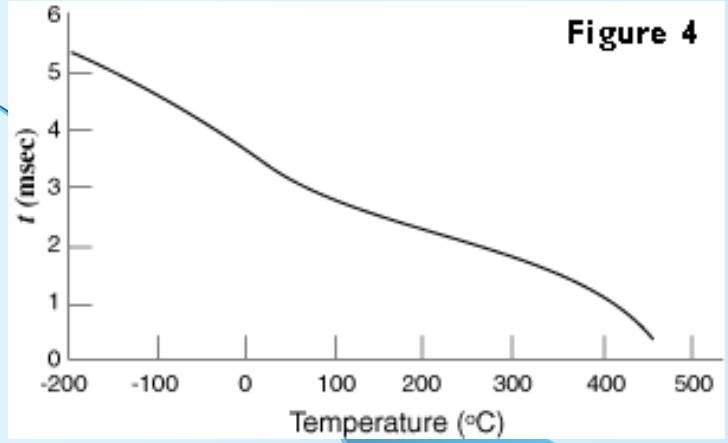
- spectral analysis through changes in the emission band
- measure of fluorescence quenching time





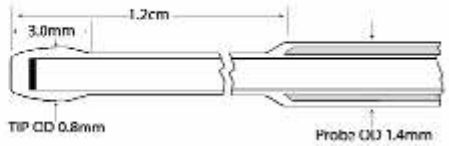
Luxtron Thermometer

Fluorescence decay related to temperature
Time resolved signal intensity
avoids power referencing problems



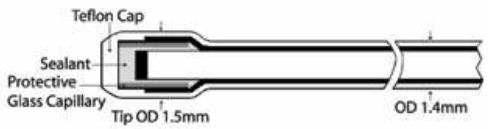
STF - fast response Immersion

Temperature Range	0 to 295 °C
Response Time	1.25 seconds in still air, 250 milliseconds in water
Connector Type	ST



STM - general purpose immersion

Temperature Range	-25 to 250 °C
Response Time	5 seconds in still air, 0.7 seconds in stirred water
Connector Type	ST



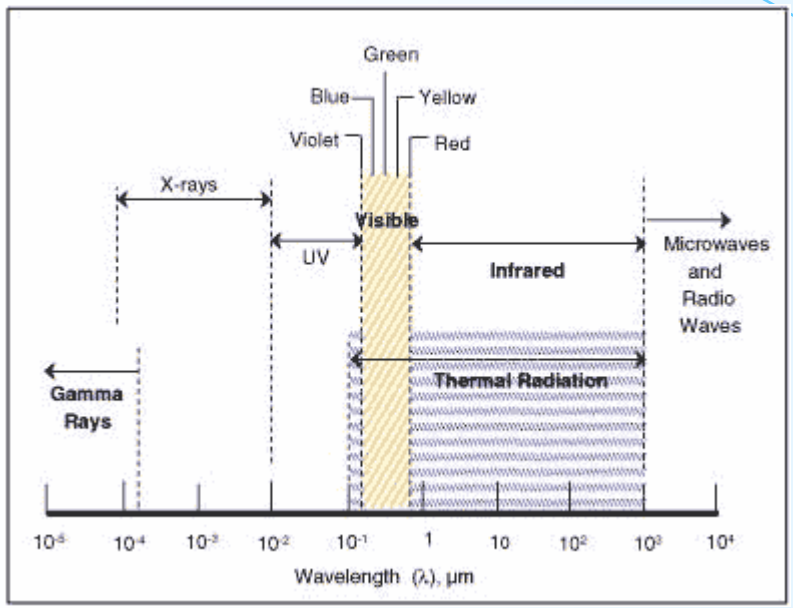
Measurement Range	-100 to 330°C
Electrical Interference	Probe Immune to EMI, RF, Magnetic and Microwave
Accuracy (Calibrated)	±0.5°C within 50°C of Calibration Point
Repeatability (Precision)	0.5°C RMS @ 8 Samples per Measurement
Output Resolution	0.01°C
Measurement Rate	1 to 4 Hz per Channel, Configurable

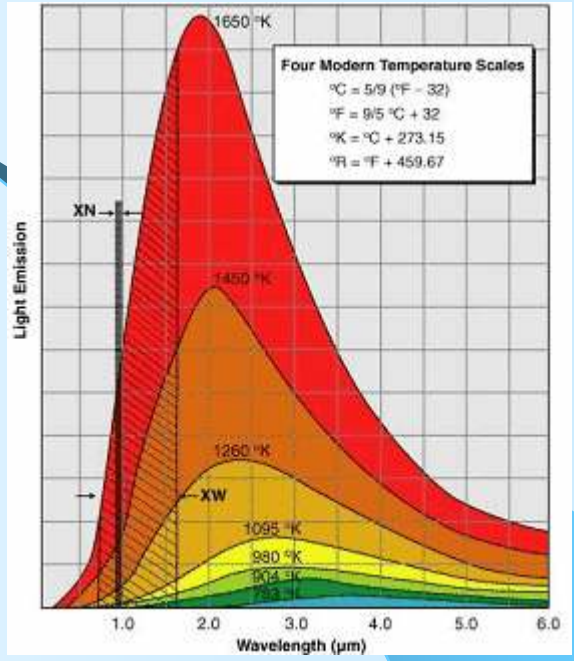
Several probes design

Similar developments (UCL):

phosphorescence of metallo-proteins to detect oxygen mixtures

Thermo Emissive Sensor





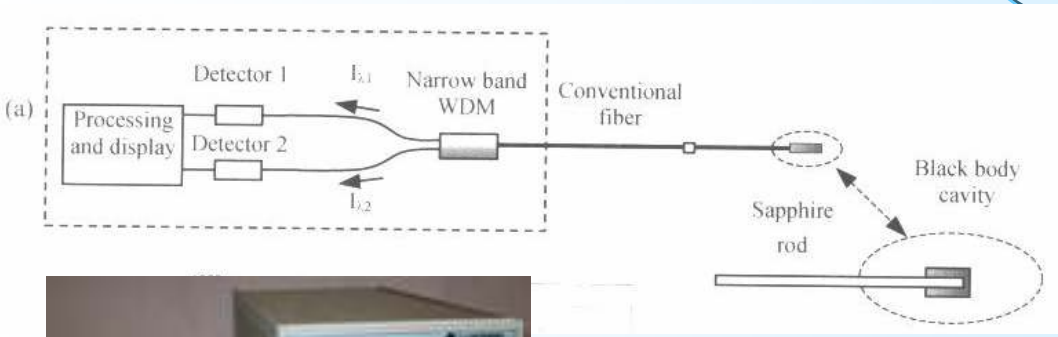
Detection of the thermal radiation emitted by a heated body

Spectral analysis (optical pyrometer) comparing intensities at different wavelengths of collected light from heated body

Detection of reflected intensity by an opaque body

Temperature sensor using a small blackbody cavity at the fiber tip

Blackbody Cavity Sensor



Total power emission $P_T = \varepsilon \sigma T^4$

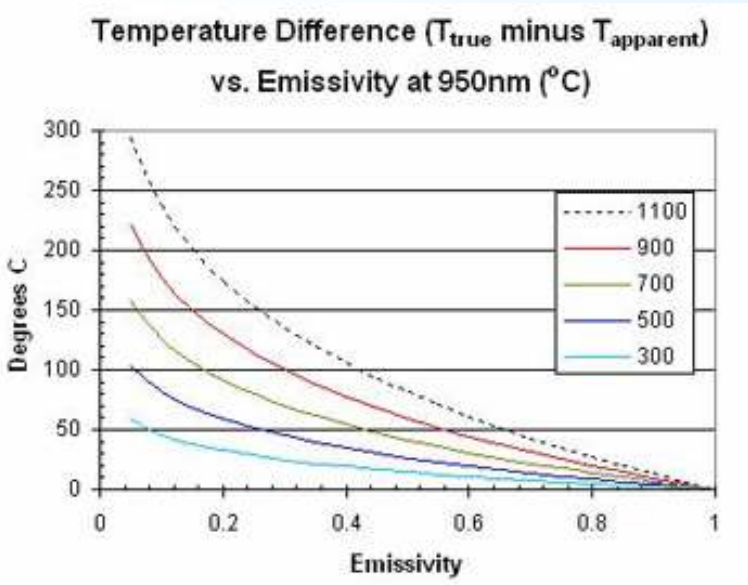
$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc/K}{\lambda T}} - 1}$$

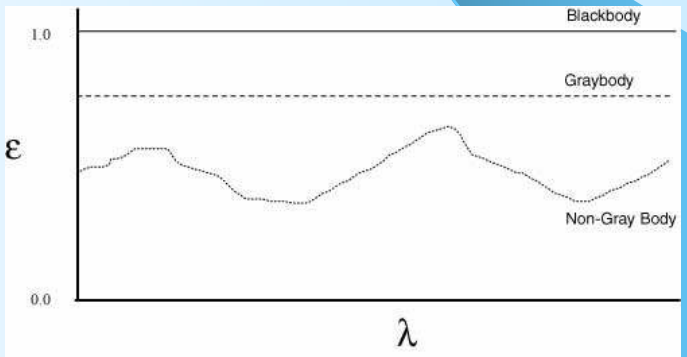
Sapphire light pipe with metallic coating

Hollow tip Sapphire rod

Thermo Emissive Detection

Blackbody has unitary emissivity: e = 1
Real objects are either graybodies or non-graybodies
— Graybodies have constant e < 1
— Non-graybodies have e varying with wavelength and temperature.
Most objects are non-gray-bodies.





For an opaque surface: $t + \alpha + \rho = 1$ where t is the transmission
α is the absorptivity
ρ is the reflectivity

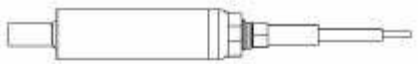
From Kirchhoff's law: $\alpha = \varepsilon$ when $t = 0$

So that using a reflectometer that measures ρ we can obtain ε

from: $\varepsilon = 1 - \rho$ where ε is emissivity

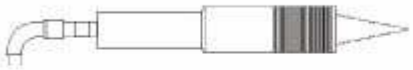
Probe Models

LP



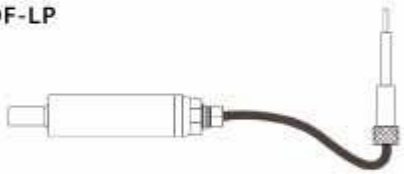
Dectector electronics module (DEM) with lightpipe optical input

PY



DEM with lens optical input

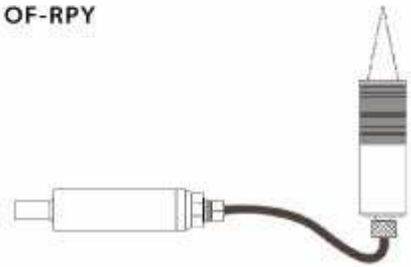
OF-LP



DEM with optical fiber input connecting to light-pipe probe. This is a three line item system consisting of:

(1) DEM
(2) Optical fiber cable
(3) Lightpipe

OF-RPY



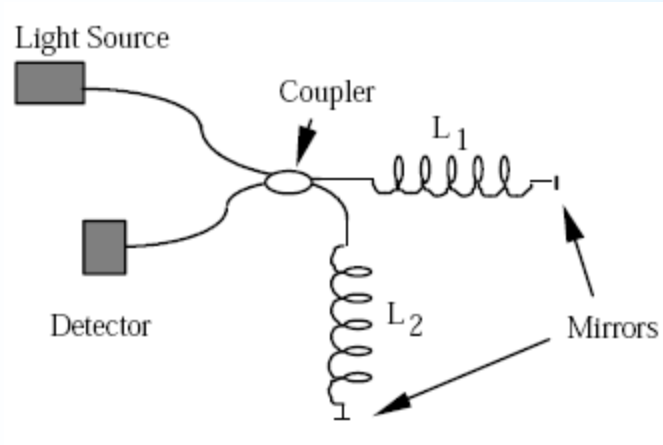
DEM with optical fiber input connecting to lens assembly. This is a three line item system consisting of:

(1) DEM
(2) Optical fiber cable
(3) Remote lens assembly

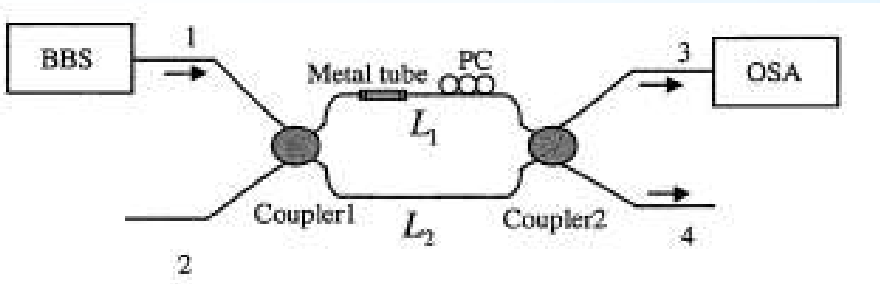
Specifications

Temperature Range	Standard Spot	Mini-Spot
Minimum	65°C	125°C
Maximum	1100°C	2800°C
Wavelength	700 - 1650nm	
Resolution	0.01°C Above 150°C	
Accuracy	± 1.5°C or 0.15 % of Reading	
Speed	Up to 1 kHz	
Repeatability	< 0.15 °C per Year Drift	

Interferometric FOS



Michelson Interferometer



Mach-Zehnder Interferometer

All fiber interferometers

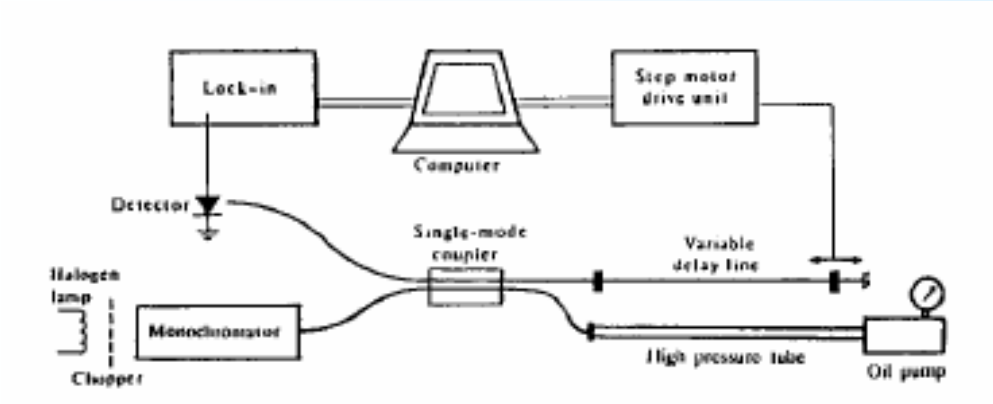
- Michelson
- Mach-Zehnder
- Fabry-Perot
- Sagnac

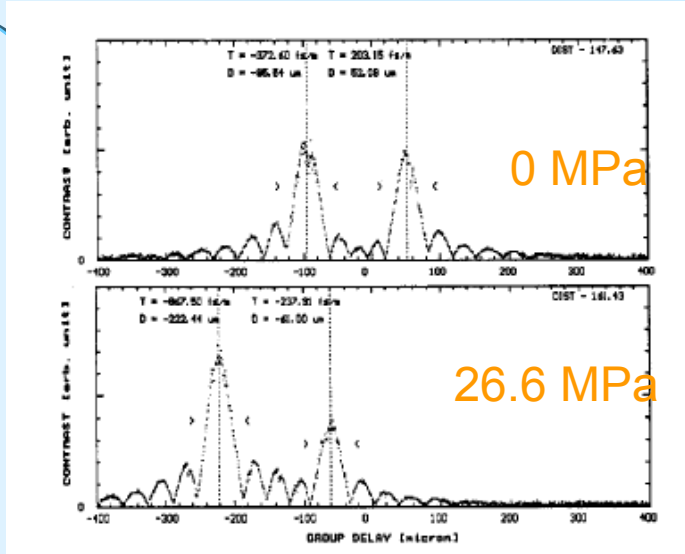
High sensitivity (cross sensitivity)

Care with fibre path (temperature, vibration, turns, ...)

Easily implemented with fibre couplers or circulators

Pressure monitoring through the Group Delay





Fibre interferometer, changes in the modal group delay causes shift in the fringe position (& visibility)

HiBi fibres (not necessary, particular case)

Pressure increase changes group velocities and PMD of sensing fibre

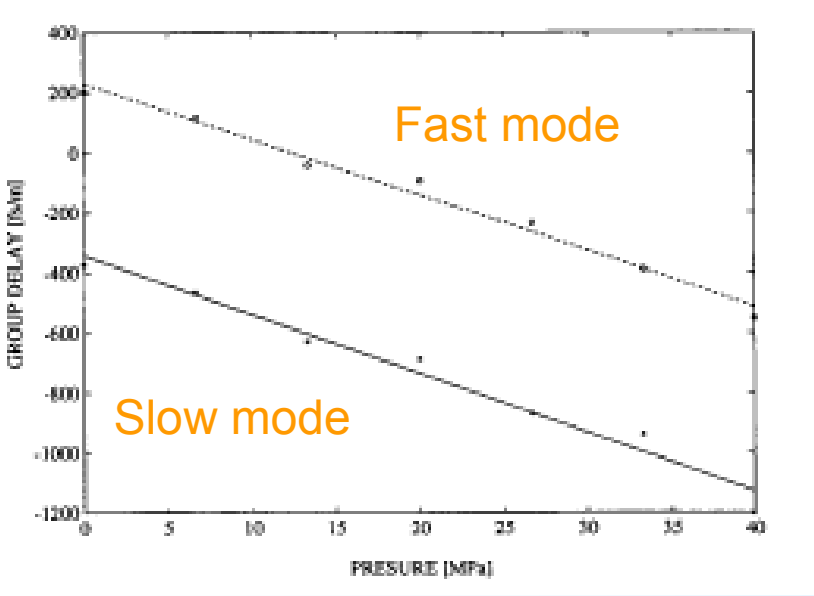
R. Passy et al. J. Lightwave Technol. 10, 1527 (1992)

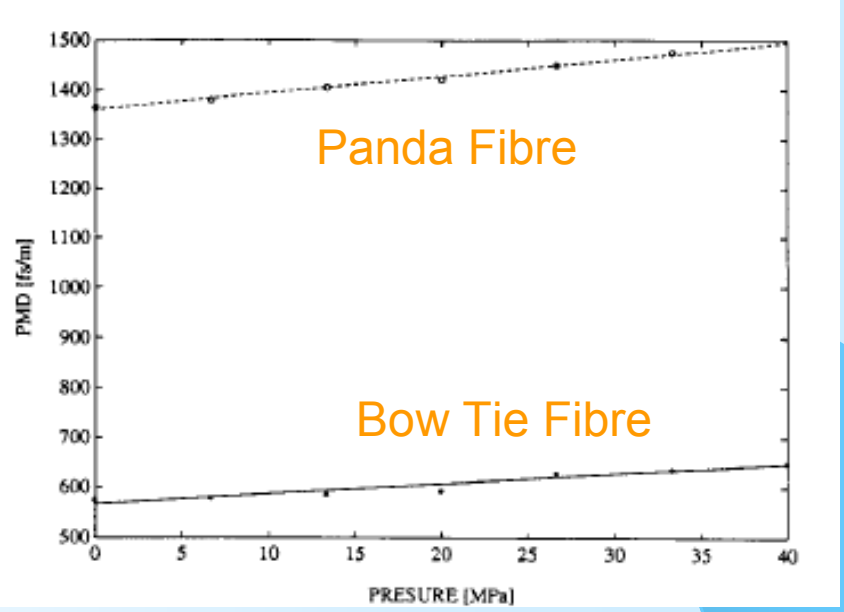
Overall shift of interference pattern related to pressure induced changes in group delay

Pressure induced change of PMD shifts relative position of interference patterns

Results

Bow Tie Fibre



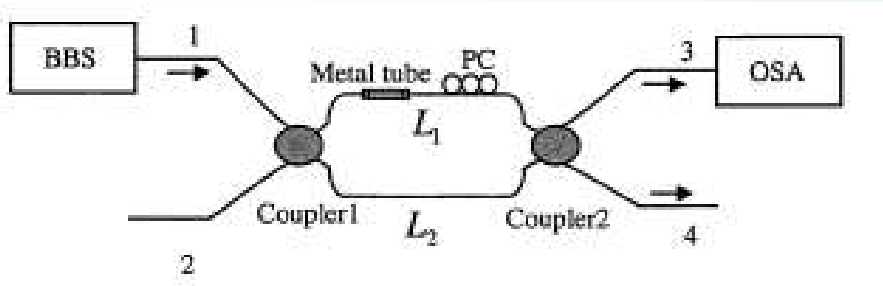


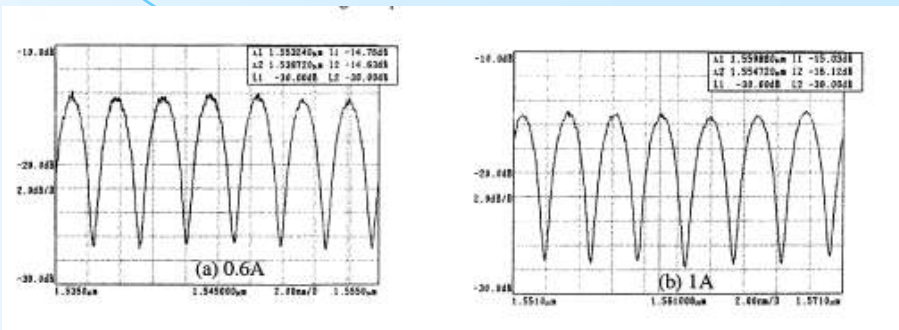
Change of group delay vs. pressure

Relatively easy implementation with standard single mode fibre

Change of PMD vs. Pressure

Mach Zehnder Current Monitoring





Asymmetrical Mach Zehnder Interferometer

Light phase modulated by current flow on thin metal tube over fibre

fibre length and refractive index depends on temperature

0-1.8A <-> 22.5π (32 nm)

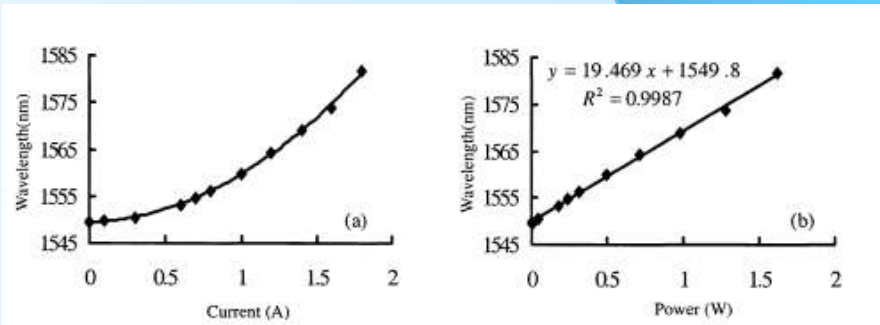
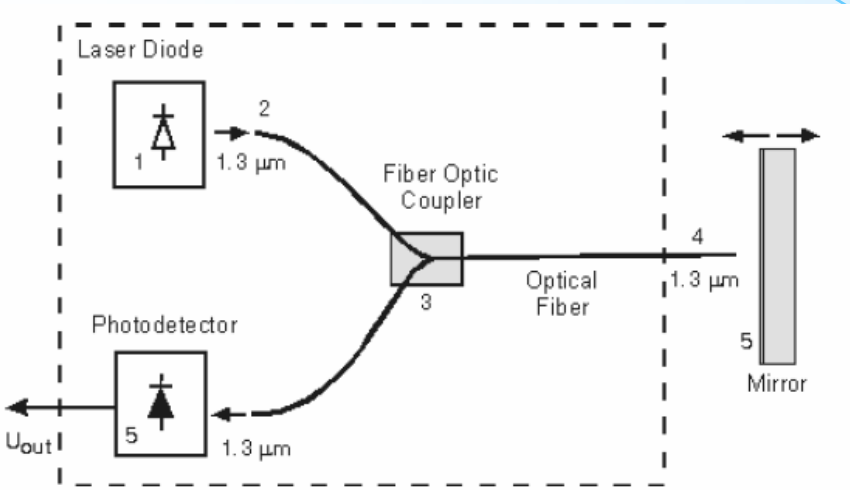
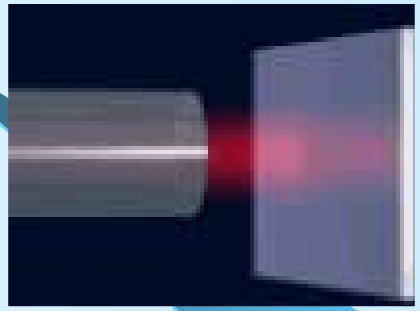


Fig.4 Dependence of Mach-Zehnder interferometer wavelength on (a) current and (b) power

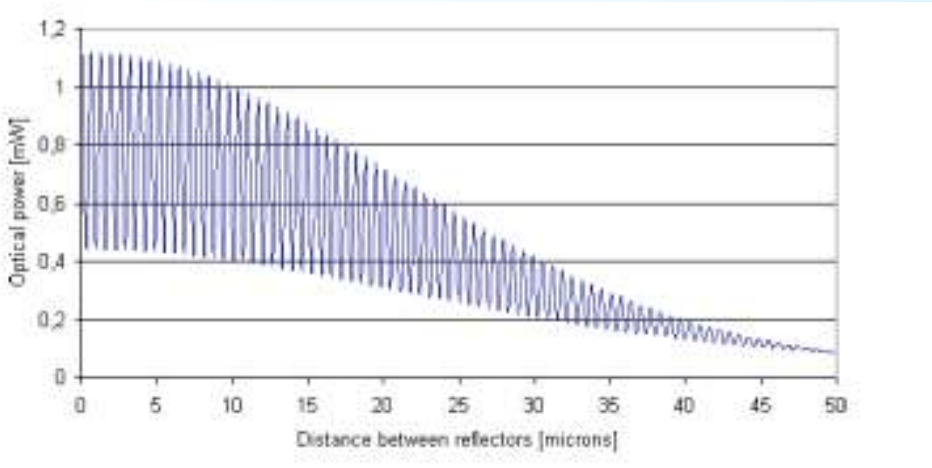
Z. Tong et al., Proc. SPIE 4920, 487 (2002)

Fabry Perot Interferometric FOS





$$\Delta\varphi(t) = (4\pi/\lambda)\, x_0 \sin(\omega t - \eta) = \varphi_\omega \sin(\omega t - \eta)$$



$$I(t) \cong \cos\left\{\frac{4\pi}{\lambda} x_0 \sin(\omega t - \eta) + \varphi_0\right\}$$

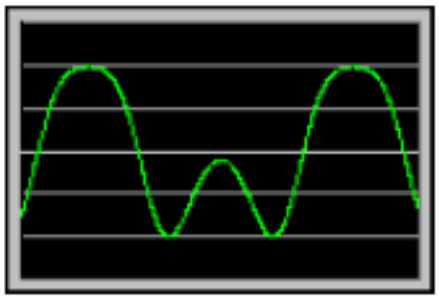
http://physics.nad.ru/sensors/English/interf.htm

Result

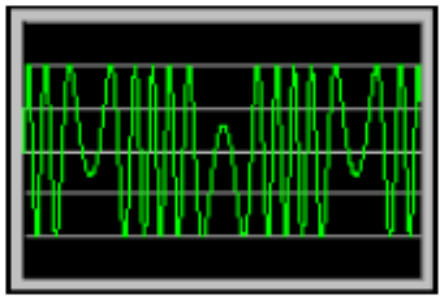
$$I(t) \cong J_1(\varphi_\omega)\sin(\omega t - \eta)\sin\varphi_0 - J_2(\varphi_\omega)\cos(2\omega t - 2\eta)\cos\varphi_0 + \ldots$$

$$\text{when } \varphi_\omega << 1 \text{ and } \varphi_o = (k + \frac{1}{2})\pi$$

$$\Rightarrow J_i(\varphi_\omega) \approx \frac{\varphi_\omega}{2} \Rightarrow I_\omega \approx \sin(\omega t)$$



Change of interferometric signal during linear increase of the mean separation between mirrors



Change of interferometric signal with linear increase of the amplitude of vibration

Faraday FOS – Electrical Current

Electrical current changes SOP on low-birefringence fibre optic
- linear input polarisation
- output polarisation changes by

$$\Phi = N\ Ve\ I$$

- usually limited by phase folding

Peak detection of both orthogonal components allows to measure large currents in AC regime (60 Hz), using fast sampling electronics

Field prototype (with semi-conductor lasers) tested up to ~100 kV

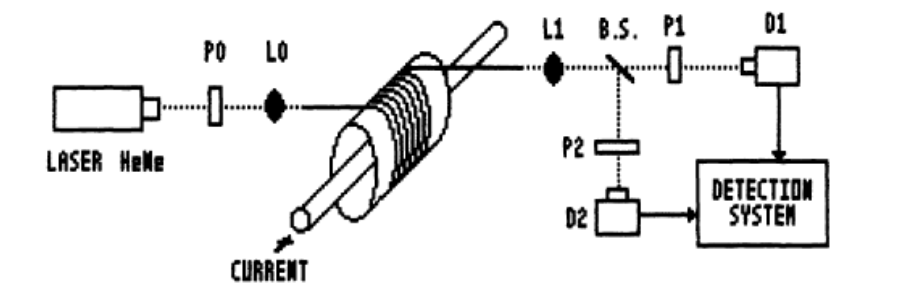
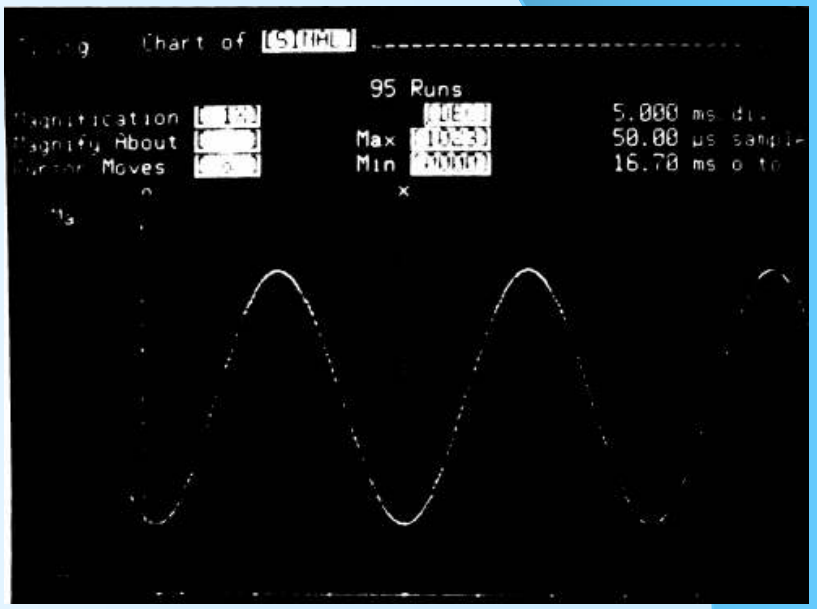


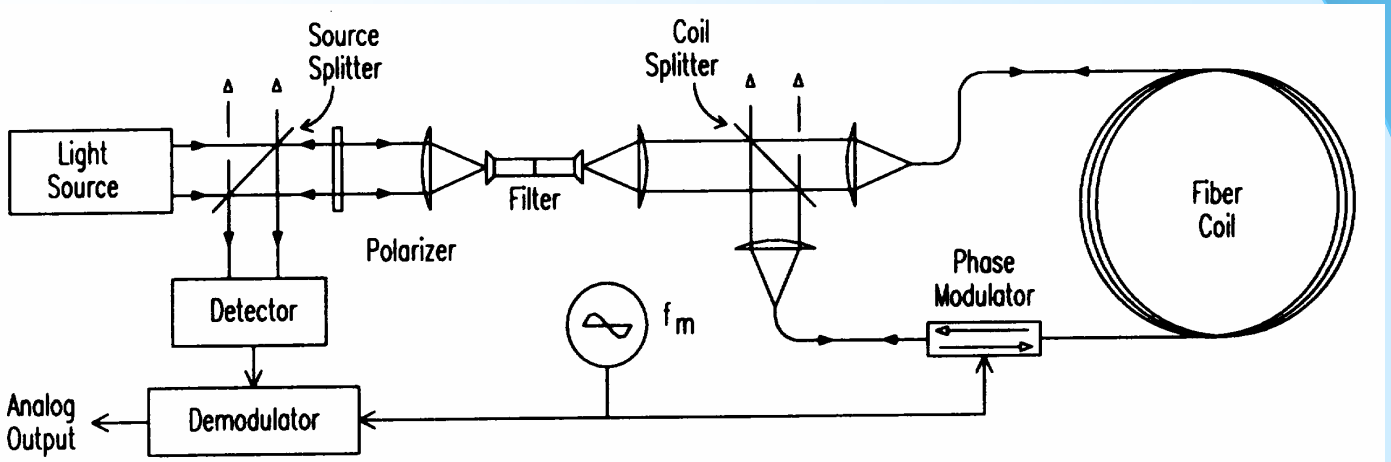
Figure 1 - Schematic diagram of the current sensor.



L.C. Guedes Valente et al., Proc. SPIE 1584, 96 (1991)

Sagnac Interferometric Fibre-Optic Gyro

- Sagnac Interferometer (counter propagating beams on same fibre coil)
- Polarisation maintaining single-mode fibre is employed to ensure the two counter-propagating beams in the loop follow identical paths in the absence of rotation
- When gyro is rotated the rate of rotation is proportional to the phase shift between the beams (Sagnac phase shift)



Open-Loop Interferometric Fibre-Optic Gyro

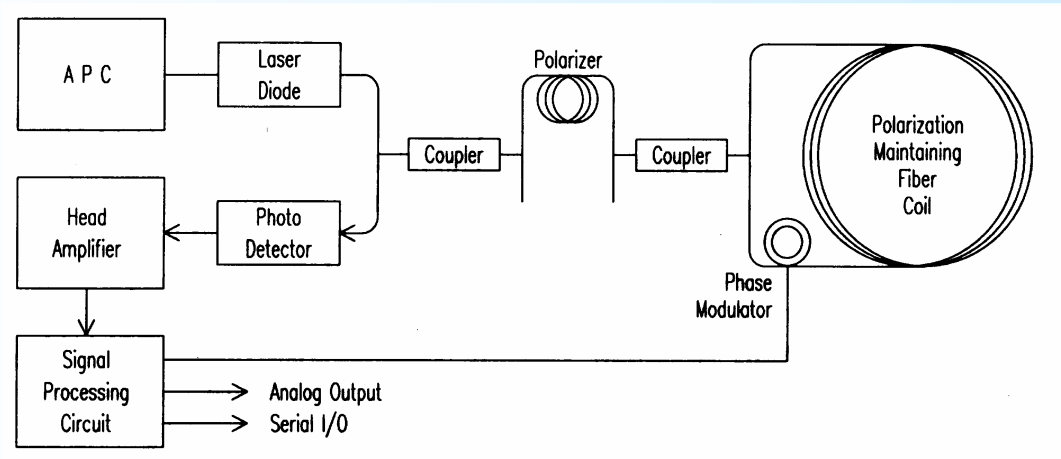
- low-price
- not sensitive to shocks and vibrations
- not sensitive to gravity nor accelerations
- short initialization time
- good sensitivity
- the geometry of the fibre coil is not critical
- no need to control the length of the optical path

- very long single mode fibre
- the dynamic area is small comparing to ring-laser gyros
- drift caused by the analog components

- Suitable for low-cost applications where best performance is not required
  - Heading of (robots, cars)
  - Tilt and roll sensing

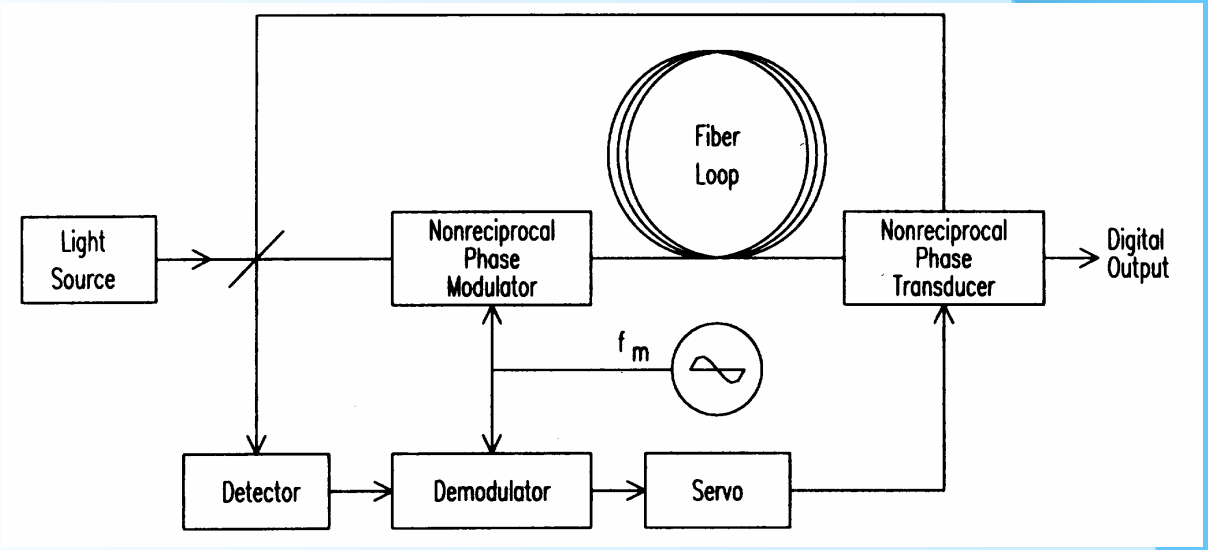
Hitachi Fibre-Optic Gyro

- Hitachi Cable Ltd. is manufacturing one-axis open loop fibre optic gyroscopes
  - used in mobile robotics and automotive applications
  - demonstrated Gyro Hitachi FOG-X
  - Drift ~ 5 deg/hour



Closed - Loop Interferometric Fiber - Optic Gyro

- For more sophisticated applications like aircraft navigation
- Digital signal processing is more complicated than analog, which is used in open – loop systems
- Benefit comparing to open – loop systems:
  - Not sensitive to light source intensity variations
  - Not sensitive to gains of single components=>very small drift ~ 0,001 – 0,01deg/h
  - Linearity and stability depend only from the phase transducer



Summary

- Fibre optic sensors can be implemented in several useable configurations by adding the proper components blocks
- Can be adapted to measure a large number of measurands in different applications
- However, success in terms of a final product depends heavily on engineering aspects like (apart cost) packaging, stabiliy, conformity, ...
- It is not a light work !