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"Optical Fibre Sensors: Technology and Strategy"

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Optical fibre sensors
Technology and Strategy

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General outline

- Fibre sensors - the basic ideas
- Some examples of the predominant applications
- Current strategic view of the technology *(mine!)*
- The future, technologies and applications

The fibre sensor:

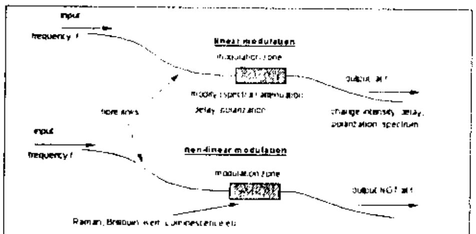


Figure 3.17 Linear and non-linear optical processes for measurement

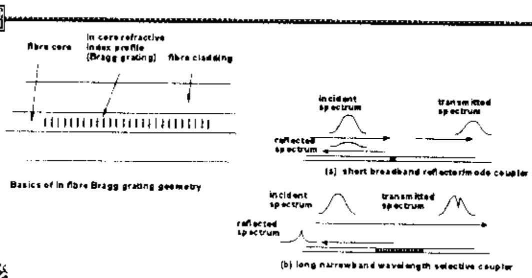
Which optical parameter to measure?? - *the modulation ?*

- Spectral content - no new spectral components
- optical phase / delay
- non linear mechanisms - new spectral components
- intensity *(sometimes via polarization)*

Spectral content modulation

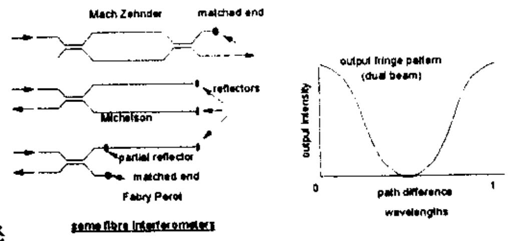
- Bragg gratings:
  - *physical measurements, temperature, strain*
- Colours of dyes:
  - *chemical measurements - pH, oxygen etc*
- Needs:
  - *known source characteristics and adequately precise spectral monitoring*

Bragg gratings



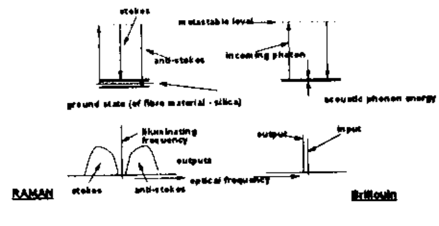
Functions performed by in fibre Bragg gratings

Optical phase/delay



same fibre interferometers

Non linear mechanisms



Non-linear scattering processes in optical fibre

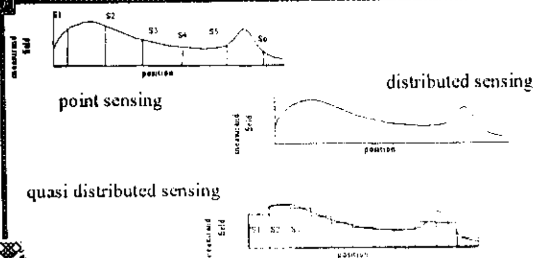
Optical fibres as a sensing and measurement technology

- Have many unique features:
  - *distributed, quasi distributed and point measurement capability*
  - *compatibility with many new (and old!) functional materials*
  - *can operate over long distances, wide areas*
  - *electromagnetically passive, intrinsically safe*
- But must take their technological place

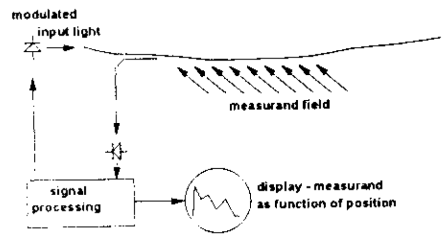
Fibre optic sensors - some applications

- Medical, biomedical, environmental and chemical
- structural monitoring
- measuring electromagnetic fields
- gyroscopes and hydrophones
  - *but first - some of the other features....*

Optical fibres : point, distributed quasi-distributed sensing..



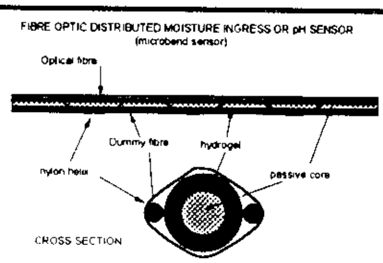
Optical fibres : distributed sensing is unique..



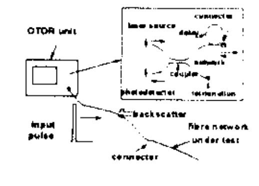
Optical fibres : distributed sensing applications..

- Raman scatter - distributed temperature sensing - *commercial instruments*
- Brillouin scatter - distributed temperature and strain - *commercial instruments*
- Microbend - experiment instruments for moisture detection

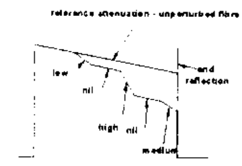
Distributed moisture ingress



OTDR sensing - the basic idea:

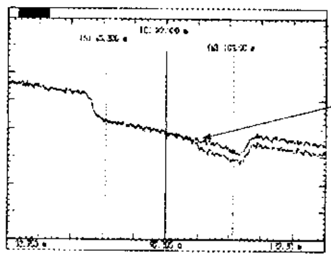


The Optical Time Domain Reflectometer (OTDR) illustrating the essential basic features



Representative OTDR trace for microbend sensor High, low etc refer to value of imposed measurand

Moisture sensing - results:

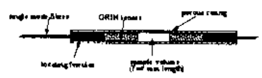


Chemical and Environmental sensing - *some observations*

- many indicator based optrodes *(fibre is light guide)*:

- some special systems using unique features of fibres e.g attenuation for distant measurements

Fibre optic gas measurement: *Methane detection*



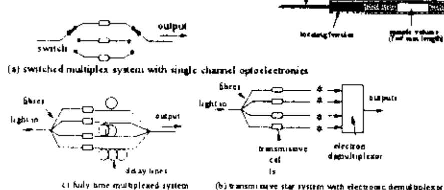


Figure 1 Multiple cell system configuration

Structural monitoring:
Bragg grating arrays

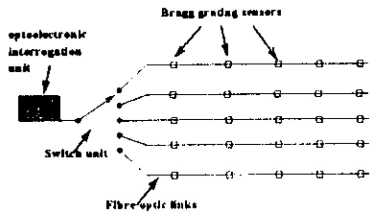
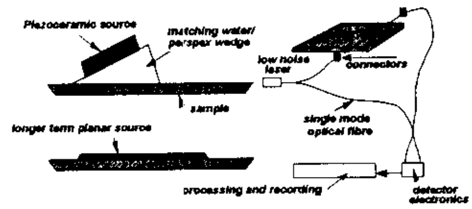


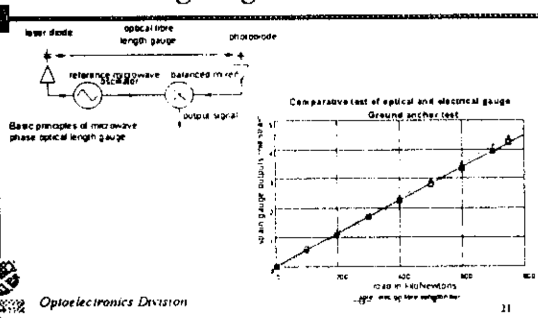
Figure 8: The basic format of the fibre Bragg grating array based on a switched addressing architecture.

Structural monitoring:
another way - optics and ultrasound

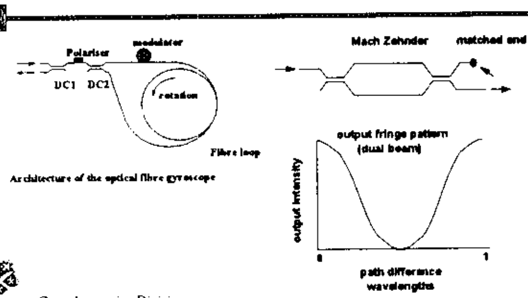


Source and detector configurations for proof of principle ultrasonic/fibre optic test system for composite panels

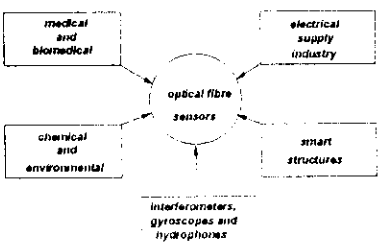
Structural monitoring:
measuring length: microwaves



Gyroscopes and hydrophones:
defence interferometers



Fibre sensors:
applications areas:



Fibre sensors: Strategic points:

- Technology is relatively mature
  - *(first patents in mid 1960's)*
- Sensors is an applications specific art
  - *small companies, niche oriented*
- Applications engineering to specific need is both challenging and time consuming but..,
  - *"glues"*

Fibre sensors: Some future thoughts

- Incorporate the combinations of:
  - new technologies from fibre optic communications
  - old physics from spectroscopy and optics
  - microengineering
  - applications analysis: *identifying the gaps and needs*

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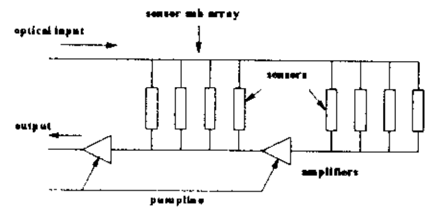
Fibre sensors - multiplexed arrays and amplifiers



Schematic of one architecture for amplified sensor array. The location of the amplifiers can be varied to optimise noise performance

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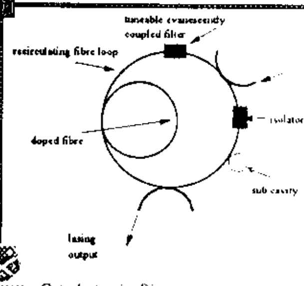
Tuneable fibre laser



- *Convenient architecture*
- *narrow lines, low noise*
- *fibre or semiconductor gain block*
- *mode hopping inevitable*

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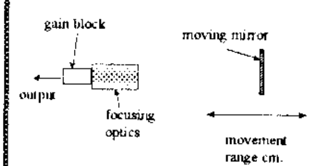
Air path tuneable laser



- *Mechanical tuning*
- *precision engineering*
- *possible to avoid mode hoping*
- *any gain block*
- *good noise and linewidth*

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Tuneable lasers
some general characteristics

- power outputs 1-10mW
- tuning range typically 5% depending somewhat on gain medium (50 to 100nm)
  - *tuneable DFB only few nm*
- wavelengths 1.3, 1,55 micron ranges typical. Can also use Nd at 1.06 microns
- tuning speed usually slow (msec to sec) limited by filter, cavity tuning capability

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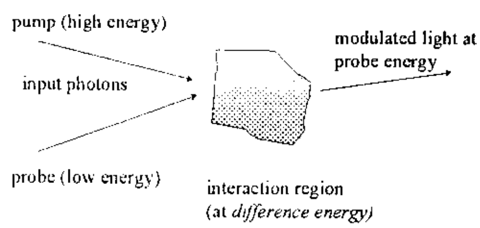
Multiphoton spectroscopy:



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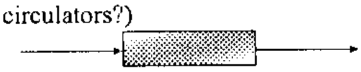
Multiphoton spectroscopy in fibres:

- overlap assured (and this is very important)
  - *even in an open path cell - spatial coherence*
- can use the fibre windows for long range transmission
  - *but can detect at wavelengths outside these regions*
- but the process is non-linear and calibration is an issue - *little used to date*

Non reciprocal effects

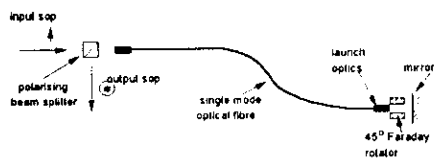
- established components such as isolators (and circulators?)



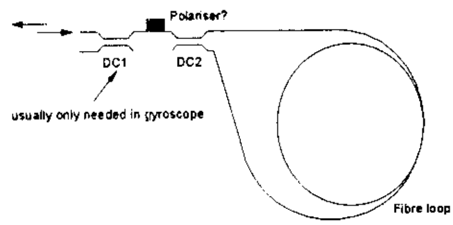
- new components such as non reciprocal mirrors

Non reciprocal mirrors

- Ensure exact replication of returned polarisation
  - A self adjusting polarisation controller
    - *always gives back the orthogonal state*

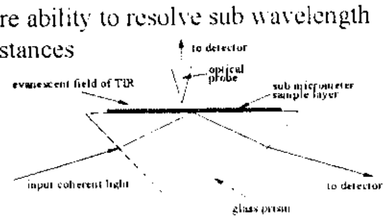


Loop mirrors - *also known as gyroscopes...*



Near field devices

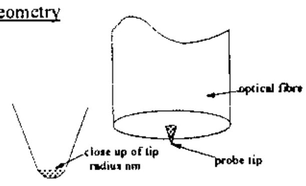
- Feature ability to resolve sub wavelength distances



Principle of photon tunnelling microscope

Tapered fibre probe

Etched geometry



Probe for photon tunnelling microscope

Near field devices

- Some actual and potential applications:
  - surface characterisation complementing scanning tunnelling microscopy
  - chemical probes into biological cells and similar nanometre to micrometre scale objects

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And other technologies??

- LIGA offers its own unusual dimension
- silicon MEMS has demonstrated switches, mirrors etc.........
  - ***implications for sensing??***
- a new guiding and manipulating sub micro-optics scale technology, not yet really exploited

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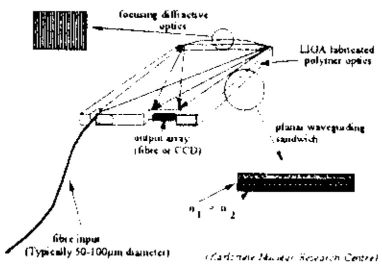
LIGA spectrometer - an example



(Carlsruhe Nuclear Research Centre)

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Other odd ball detection systems:

- Four wave mixing in detection crystal for multipath interferometry (e.g... from multimode fibres)
- Time gated source acting also as detector
  - etc. etc. ....
- But few used in earnest as yet

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And what does the sensor engineer do about it

- We can't be expert in all (or probably any!) of these *(and other)* techniques!

so..

- We need to be aware of the potential offered by the wide range of available techniques

and...

- We need to be able to apply as necessary

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Fibre optic Sensors - some conclusions

- Most of the techniques are well established
- Applications engineering is the principal activity
- Some new technologies from other domains will be important
- The skill lies in fitting the need to the technology and making everything cost-effective

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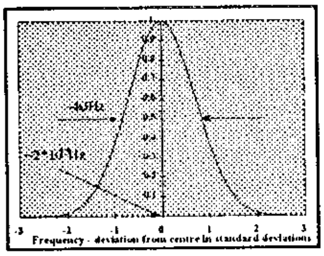
Fibre Optic Systems for Remote Gas Spectroscopy - *possibilities and pitfalls*

Brian Culshaw,
Strathclyde University,
Glasgow
Scotland

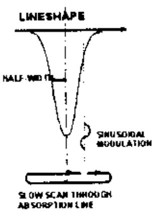
Fibre Optic Systems for Remote Gas Spectroscopy

- Gas spectroscopy - the basics
- Where do fibres come in?
- Mid IR or near IR - some comparisons
- System concepts using fibres
- Some examples
- Where next??

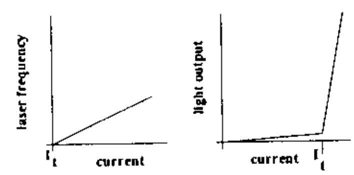
Gas Spectroscopy - *the basics*



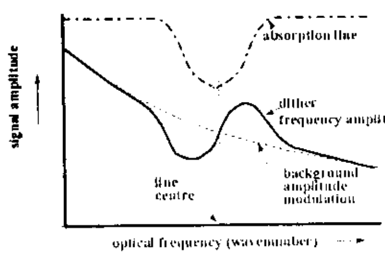
Gas Spectroscopy - *the basics* *Modulation techniques*



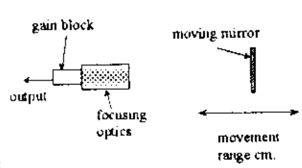
Diode laser characteristics



Gas Spectroscopy - *signal output*

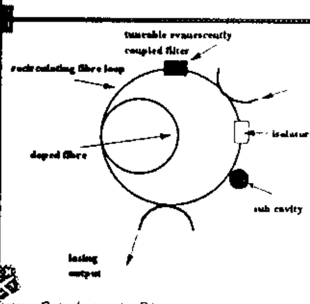


Air path tuneable laser



- *Mechanical tuning*
- *precision engineering*
- *possible to avoid mode hoping*
- *any gain block*
- *good noise and linewidth*

Tuneable fibre laser



- *Convenient architecture*
- *narrow lines, low noise*
- *fibre or semiconductor gain block*
- *mode hopping inevitable*

Fibre Optic Techniques remote spectroscopy - Why use optics?

- Electro chemical detectors, while well known, have their limits:
  - *poisoning, safety, range limits, vulnerability*
- Optics:
  - *with fibres have range to km., intrinsic safety, no local power supply, ruggedised sources*
  - *but: cost, confidence, producability???*

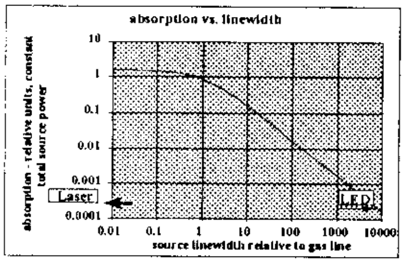
Fibre Optic gas spectroscopy Detection SNR - near *vs.* mid IR

- mid IR has much stronger lines

But:

- near IR has components and infrastructure, especially ***lasers***
- source spectral density is the ultimate SNR factor

Varying source linewidth vs. gas line width - the near IR contrast



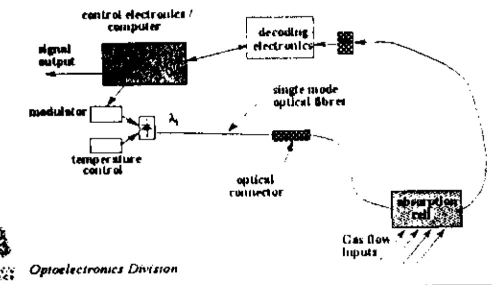
Fibre Optic Techniques for gas Detection SNR - near *vs.* mid IR

- The laser linewidth is <<0.1 of the gas linewidth
- An LED linewidth is typically many times 10^4 the gas linewidth, ***so that:***
- *a mid IR line can be several thousand times stronger but still practically overwhelmed by a near IR line*

Fibre Optic Gas Spectroscopy *where do the fibres come into it?*

- Optical fibre components can be modified to accommodate near IR measurement systems ***but***
- semiconductor and other lasers are special *(market for semiconductor gas spectroscopy lasers= 1000 compared to 200,000,000 for CD reading laser!!)* :**laser is expensive and influences system concept**

Fibre Optic Gas Spectroscopy
basic fibre architectures



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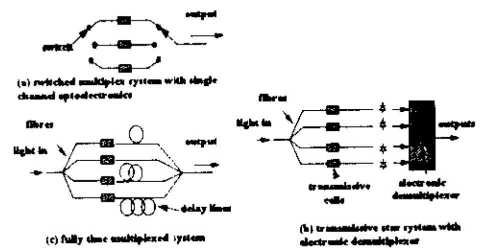
Fibre optic (remote) system architectures



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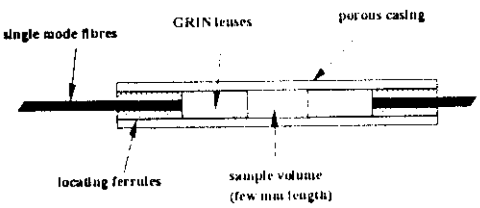
Gas cell design for remote systems - as simple as possible



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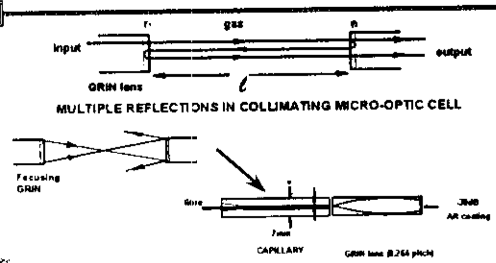
Gas cell design: some other factors



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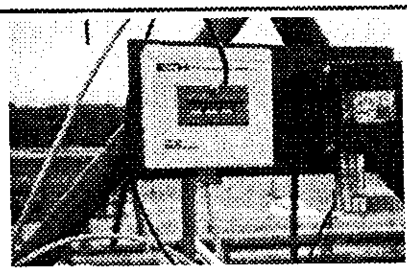
Remote cells - a practical version
designed for methane



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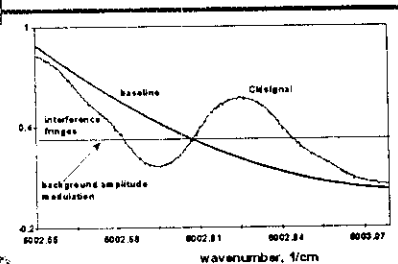
Signals from methane



Typical results - OMEGA system showing signals dither frequency at 20% LEL

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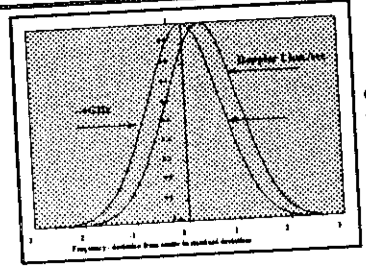
Signals from - other gases??

This is a selection.........

Gas	Absorption Line Wavelength, nM	Line Strength [illegible]	Estimated Sensitivity [illegible]	[illegible]
Acetylene C_2H_2	1530	[illegible]	[illegible]	
Hydrogen Iodide HI	1541	0.775	0.34	
Ammonia NH_3	1544	0.925	[illegible]	
Hydrogen Cyanide HCN	1530	[illegible]	[illegible]	
Carbon Monoxide CO	1567	[illegible]	1	
Carbon Dioxide CO_2	1573	[illegible]	[illegible]	
Hydrogen Sulphide H_2S	1578	0.165	[illegible]	
Methane CH_4	[illegible]	[illegible]	[illegible]	
Hydrogen Fluoride HF	1330	32.5	[illegible]	
Hydrogen Bromide HBr	1341	[illegible]	1	
Water H_2O	[illegible]	32.5	[illegible]	
Oxygen O_2	761	[illegible]	[illegible]	
Nitrogen Dioxide NO_2	[illegible]	[illegible]	[illegible]	

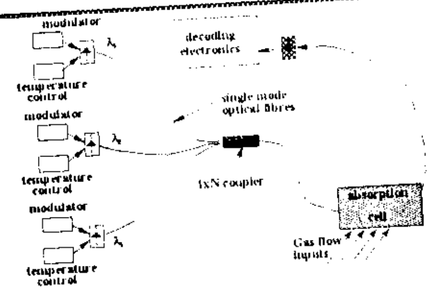
- Numerous possibilities for optical fibre addressing of gas species

Fibre Optic Techniques for gas spectroscopy - *other prospects*



Gas velocity from spectral shift

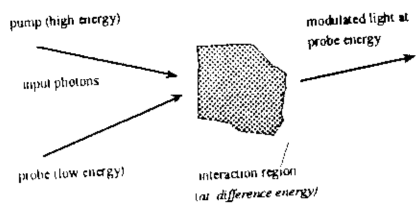
Multiple gas spectroscopy - *more prospects*



Measurements in Gas Turbines

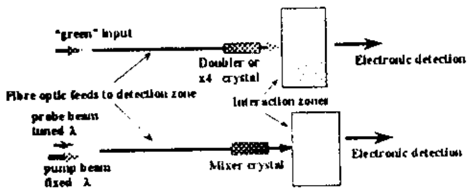
Measurements in Gas Turbines *Doppler shifts - oxygen lines*

Fibre optic remote spectroscopy - some other concepts



Multiphoton spectroscopy - keeping it in the fibre....

Interrogating using a fibre..
Local frequency conversion



Fibre optics in remote gas spectroscopy

- The possibilities:
  - immensely flexible implementation at useful sensitivity levels for toxic and hazardous species in remote / difficult environments
- The pitfalls
  - there are almost always other approaches which are better established
- Finally - very competitive when applied to the appropriate problem in the appropriate way

Fibre optic techniques for structural measurements - an introduction

Brian Culshaw
Department of Electronic and Electrical Engineering
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Glasgow
Scotland

General outline

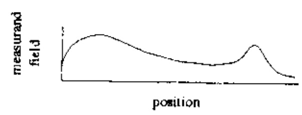
- An idea of the general principles:
  - *length, strain and temperature*
- Exploiting optical delay in strain measurement, the benefits and pitfalls
- Using other optical properties of fibres
- Introducing some of the techniques
- Comments on where, when and how
- Other techniques to be introduced later

Here we concentrate on *Optical fibre strain measurement systems:*

- **Optical fibre strain measurement can:**
  - operate over extreme strain ranges (to a few%)
  - be configured in gauge lengths from μm to km
  - be embedded into many materials, GRP, CRP, concrete
  - operate over wide temperature ranges (to >500°C)
  - interrogate over long lengths (to 100km!) without EMI

and, functionally fibre strain measurement can:
- provide new functions multiplexed, integrating and distributed
- work from dc to 100MHz or thereabouts

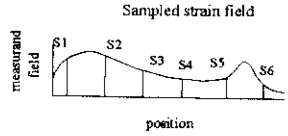
Different measurement functions with fibre optic strain gauges….



Original field as a function of position

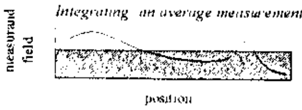
Sampled strain field

Point sensing: ***electrical strain gauges, Bragg gratings, EFPI in fibres***



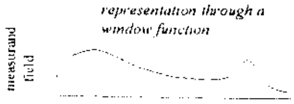
Different measurement functions : integrating, quasi distributed, distributed

Integrating: an average measurement

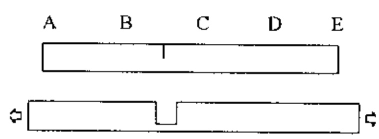


Quasi distributed: sectional averages

Fully distributed: continuous representation through a window function



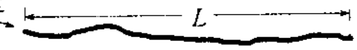
Integrated vs. point strain measurements: Sensitive to different parameters….



Point train sensors at A, B , C , D will miss the crack - and will show the same stress as if the crack were absent…..

Measuring length and strain using optical fibres: Length measurement

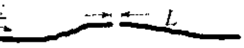
– *in the fibre:*



optical phase change ~ $(L.\Delta T.\delta n_{eff}/\delta T + \Delta L.n_{eff}).(2\pi/\lambda)$

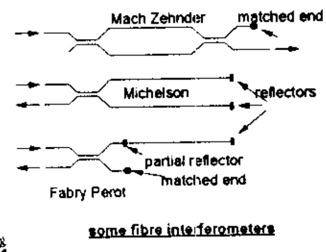
Note: temperature about -10ppm/K
strain about +1ppm-με

– *outside the fibre:*

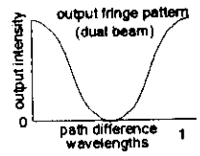


Same relationship, but now applied to material in the gap

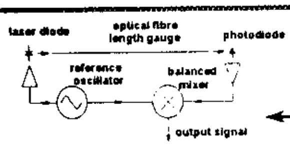
Measuring optical delay: *the laser as a clock and light as a tape measure - optical interferometry*



- *Measure changes of small fraction of λ (to 10^{-6})*
- *periodic in λ*

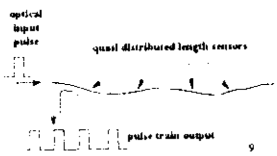


Measuring optical delay: *using sub carriers...*

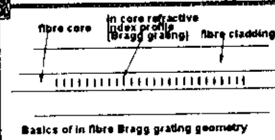


microwave sub-carrier phase (same basic response!!) sub micron dynamic, sub mm static resolution

time domain reflectometry picosecond pulses give sub mm resolution

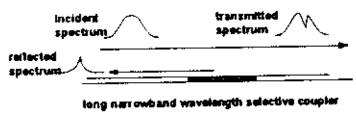


Measuring optical delay: *the Bragg grating as a reflection wavelength modulator*



- *gratings introduced by photorefractive damage via UV laser:*
- *proven stability, repeatability*
- *used in telecommunications*

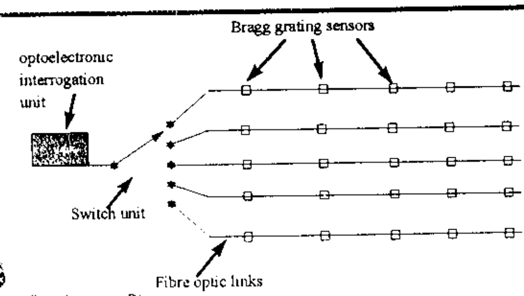
Reflected spectrum when grating period is $\lambda_{light}/2$



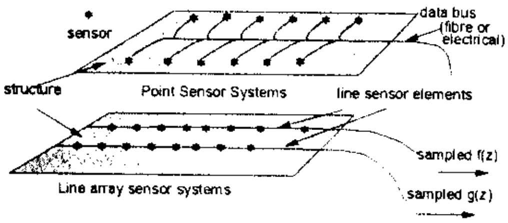
Some comments on Bragg gratings.....

- Commercially available components
- Response is intrinsically that of the fibre
- Precision wavelength measurement and calibration is essential
- can multiplex to around 16 per string
- temperature: strain crosstalk must be accommodated:
  - *temperature reference, ac measurements*
- packaging must be designed for application

Multiplexing Bragg gratings: strings of sensors in a single fibre



Multiplexing Bragg gratings: simple installation architecture



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Bragg gratings: some examples of trials under way...

Graphics of test sites and installations to be added

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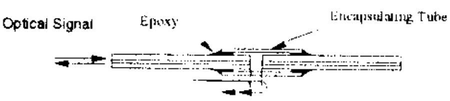
Measuring length outside the fibre The 'EFPI'



The flexibility in the encapsulating tube is important

Simple, mechanically versatile, commercially available

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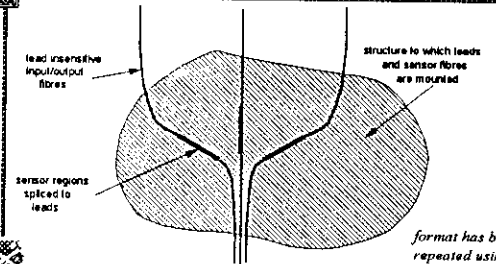
The EFPI: First optical fibre strain rosette



format has been repeated using Bragg gratings...

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Point strain measurement using optical fibres

- Some overall comments:
  - Bragg gratings most common format
  - EFPI principal alternative
- do same job as strain gauges but
  - can multiplex onto single fibre (Bragg to about 16, EFPI to about 4)
  - and temperature crosstalk is an issue (as with ALL strain sensors)

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Fibres in Composites - embedded sensors though none of these is a Bragg grating......

pictures of embedded fibres with conectors, cross section, with flying leads to come

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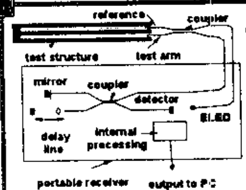
To integrated, distributed measurements:

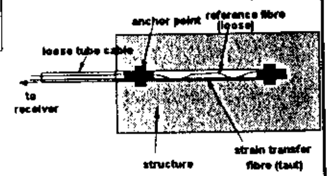
- SOFO : an integrated measurement system-
  - gauge lengths from about 30cm to 100m
  - proven stability to 5μm over years
  - commercially proven over 1000 installed
  - use - sensing bridges, tunnels, dams etc.
  - compatible with building site use and installation in concrete

The SOFO operating principles:

overall system diagram



the sensor itself



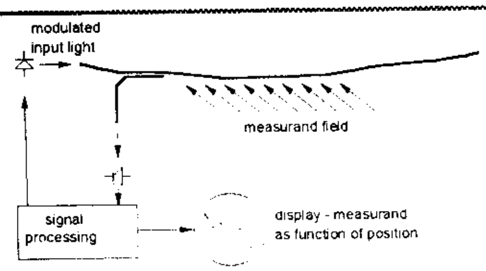
The SOFO - some results:

results from SOFO including equipment pic, site pic, graphs

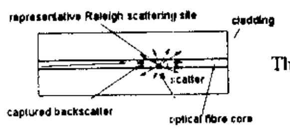
The SOFO for ac measurements: microwave sub-carrier interrogation

dynamic measurements - this will be mainly graphs

Optical time domain reflectometry: Basic ideas of distributed measurements

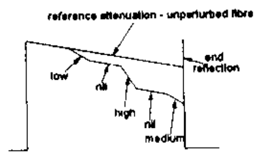


Distributed measurements using loss modulation introduced in the fibre

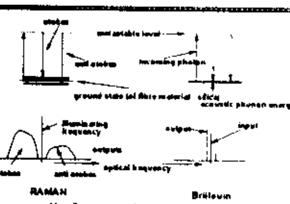


guided backscatter in fibres

The OTDR (optical time domain reflectometer) trace



Stimulated Brillouin scatter: distributed measurements using frequency modulation



- *Stimulated Brillouin scatter depends on STRAIN (and, of course, temperature)*
- *Measures microwave frequency offsets - tricky instrumentation*
- *Commercially available (Japan and Switzerland)*
- *10με, 1K over few metres*
- *range to 100km*

Measuring length and strain using optical fibres: Strain measurement

- Stimulated Brillouin Scatter:
  - measures acoustic velocity via optical wavelength (assumed known and fixed)

$$\Delta v_{ac} = K_{\varepsilon}.\varepsilon + K_T.\Delta T$$

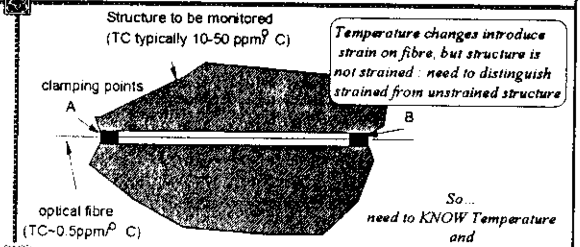
$$\Delta f_{SBS} = \Delta v_{ac} / \lambda_{light,fibre} + \Delta\lambda_{light,fibre} v_{ac} / \lambda_{light,fibre}^2$$

$\Delta f_{SBS} \sim$ *1.2MHz/K and 58kHz/με at* $\lambda_{light,air} = 1.3\mu m$*.*
from a starting frequency of ~ 13GHz

Stimulated Brillouin scatter: - a sensor application in marine ropes with a very advanced OTDR

Brillouin OTDR tests on marine ropes - NEL pictures, include some graphs too

Some final thoughts on temperature:



So...
need to KNOW Temperature
and
model, not only thermally compensate!!

Later you will hear about other techniques to measure:

- Chemical effects in structures using distributed loss modulation optical fibre sensors:
  - *water, pH changes, liquid hydrocarbons*
- Some mechanical probes based on ultrasound and similar techniques for detecting structural deterioration
- Need to fit the technique to the need...

Optical fibres for strain measurement: finally, some overall observations

- Diverse range of fibre based technologies available *(more than I've mentioned here!)*
- Most measure LENGTH, some measure STRAIN
- All need temperature compensation and / or temperature measurement for low frequency
- All need to be tailored to a specific requirement
- some available commercially (SOFO, Brillouin, some Bragg, EFPI)
- major issues, packaging, application compatibility