



SMR 1829 - 27

Winter College on Fibre Optics, Fibre Lasers and Sensors

12 - 23 February 2007

Distributed sensing based on reflections and

Rayleigh backscatter

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Distributed sensing based on reflections and Rayleigh backscatter

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The basic plan: Distributed sensing using elastic (Rayleigh) scatter

- Sensing breaks and length measurement
- Sensing fibre lengths in sections
- Sensing distributed dynamic strain signals
- Polarimetric sensors
- Micro-bend based distributed sensor systems
- Coating based (chemical) distributed sensing systems
- (Sensing using the Sagnac interferometer)

Recapping the basic system



Measuring length...

- The <u>resolution</u> depends on the pulse length
- Or can also depend on the phase resolution of a sub carrier...
- Accuracies depend on timing stability



Subcarrier interferometry and pulse timing measurements for optical fibre delay measurement

Multiplexed Strain Sensor (RF Subcarrier)



(Crosstalk reduction using self-mixing)

OTDR Distance Measurement



FIBRE OPTIC DISTRIBUTED LENGTH MEASUREMENT SYSTEM



delays between partially reflective interfaces measured using precision time delay reflectometry or frequency domain analysis



Figure 10: A sacrificial optical fibre with an OTDR is a useful tool for locating anticipated gross damage

microwave sub-carrier interrogation for ac measurements:



For simple length and break location

- Resolution pulsed, ~100μm, phase ~10μm quasi static
- Resolution dynamic ~ 10nm phase, not achievable pulsed
- Stability ~mm pulsed and phase

Coherent OTDR – suppose *I_c* >> resolution length

- Interference sum of all scattering sites in the resolution length is detected, not the intensity sum
- Therefore sensitive to changes in the distribution of the scattering sites
- And remember can sample up to 10kHz for 10 km without range ambiguity – <u>*i.e acoustic*</u> <u>frequency fluctuations could be detected</u>

Coherent OTDR – the basics

- Coherent source
- External pulse modulation
- Adequate sampling rate and low integration time – therefore relatively high power levels
- Optical amplifier after modulator

A practical example



Fig. 1. Phase-sensitive OTDR (ϕ -OTDR) used for intrusion sensing.

- Juarez et al JLT vol 23 June 2005 p2061
- CW laser is highly stable – narrow line width and low drift
- basic approach take differences
 between sequential traces

Some sample results:





Output vs PZT drive at 2.4 km

An intruder - trial results....



80kgm man walking / standing on cable at about 2km

presence detected but little quantitative information

Coherent / phase sensitive OTDR in sensing

- Uniquely applicable to sensing
- Several demonstrations of variations on the basic idea
- Output is *qualitative* and only responds to changes over relatively small intervals (msec or less)
- Potential application as a first filter for intrusion detection etc...

Polarimetric distributed sensing systems

- Single mode fibre
- Birefringence depends on external parameters, especially anisotropic interactions
- Measure birefringence as function of position using POTDR

POTDR basics

- Measures Stokes parameters of backscattered light as a function of time – i.e of position
- Stokes parameters are...
 - Total intensity
 - Intensity through +45° polarizer
 - Intensity through -45°polarizer
 - Intensity through a right circular polarizer

Function of the POTDR

- Essentially a four channel OTDR so needs more backscatter for a given resolution
- Principal application is in PMD (polarisation mode dispersion) measurement rather than sensing

POTDR schematic





b)

a)

Typical POTDR traces



- Trace on Left includes PMD beat effects, trace on right is intensity / conventional POTDR
- Both axes in arbitrary units

Typical unperturbed birefringence distribution of communications grade SMF



 1psec/km equivalent to 1psec in 5µsec – 1 part in 5x10^{6.} Corresponds to approximately 1 radian per metre

Externally induced birefringence – relation to sensing

- Anisotropic strains will induce birefringence
- Most strain field do induce some anisotropy, especially bends and twists – which can be small
- BUT relationships are essentially qualitative.

Applications...

- Some demonstrations bending, shifting, twisting on pipelines and similar
- Essentially alarm based presence or absence of an event
- Little commercial penetration as sensor to date (though POTDR is used for PMD measurement)
- Same principle has been used to detect buried current carrying cables

Now to loss inducing distributed sensors

- Microbend physically induced perturbation through mechanical interfaces
- Variable lossy coatings, including chemical sensors
- Principally this is about distributed chemical sensing

Microbend Loss: the basics

Light Scattered at Bends





Microbend Strain Sensor

Use graded index multimode fibre for predictable coupling to radiative modes

Principles of microbend distributed sensors

- The mechanical fields induces loss through a periodic structure being caused to press upon the fibre
- The fibres should be graded index multimode, though single mode can be successful
- The relationship between the induced loss and the mechanical interaction is very loose

A micro-bend distributed fibre sensor OTDR trace



Liquid spillage detection: a cable which deliberately introduces microbend!





Microscope photographs of sensor

Polymers swelling in contact with liquids

• There are many:

- Hydrogels for water

 Many rubbers and other polymers for hydrocarbons and solvents

Trace of two 1m-long water spills



Moisture monitoring in and over soils



Hydrogel Grout (cement) Monitor





Distributed water ingress sensor used to monitor progressive drying of grout in duct. The high slope sections of the OTDR trace indicate wet regions

Hydrocarbon sensitive polymers: swelling behaviour



*Ethyl-Propyl-Diene Monomer

Spillage monitoring – a 1 metre Brent crude spill



Detecting leaks in pipelines



Trial installation on oil pipeline to detect oil leakage

Distributed spillage detection: technical peculiarities

- Fully protected cable must be porous to measurand and protect fibre from additional microbends
- Uses graded index multimode communications fibre – stability of supply?
- Fibre coating in contact with measurand
- Microbend helix winding process induces inevitable additional loss – maximum range <~ 10(?)km

Distributed spillage detection: market and applications features

- Who wants this?
 - Pipeline operators (water and oil)
 - storage system operators
 - Irrigation and distribution networks
- Who'll use this and why:
 - Pipeline manufacturers for legislation and/or market edge if additional cost minimal
- What's needed:
 - Assured manufacture of sensor cable
 - Operators to be willing to be trial users

Other distributed loss based chemical sensors

• Chemically active coatings on PCS (plastic clad silica) fibres



• Mukamal et al. Proc SPIE vol 6004 2005

Coating parameters

- Cause absorbance over lengths of few metres at hazardous levels of selected chemicals – e.g. H₂S, Cl₂ etc
- Coatings typically ~ 10 μm thick: response times in minutes
- Selected dyes for selected species can respond to different wavelengths
- Some dyes can be reset using UV radiation guides via fibres
- Again excess losses reduce ranges to ~km

Some typical results:



Figure 4 Response time of Cl2 fiber to 0.01 absorbance at 650 nanometers.



Figure 7 Response time of H₂S fiber to 0.01 absorbance at 532 nanometers.

Coating based distributed chemical sensors

• Field trials under way

 Sensitivity appears adequate for some security alarm applications

An overview on Rayleigh and reflection based distributed sensors

- Many demonstrations, few possibly no product as yet
- Serious potential for chemical alarm systems
- Intruder detection appears feasible too
- None is easy to accurately calibrate repeatedly
- Probably applications are as on / off or few resolvable points alarm systems