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Winter College on Fibre Optics, Fibre Lasers and Sensors

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<u>Distributed fibre optic sensing</u>

(Part 1)

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Distributed fibre optic sensing: Part 1

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Indicative plan for the three lectures:

- Lecture 1:
  - The concept of distributed sensing
  - Basics of backscatter
  - Elastic scatter processes: Rayleigh
  - Timing: time domain and frequency domain
  - Power budgets, detection and basic integration and averaging processes etc…
  - The optical time domain reflectometer (OTDR)
  - Basic sensing through elastic processes
  - Inelastic scattering processes: Raman and Brillouin
  - Distributed sensing using the Sagnac interferometer

And to Lecture 2:

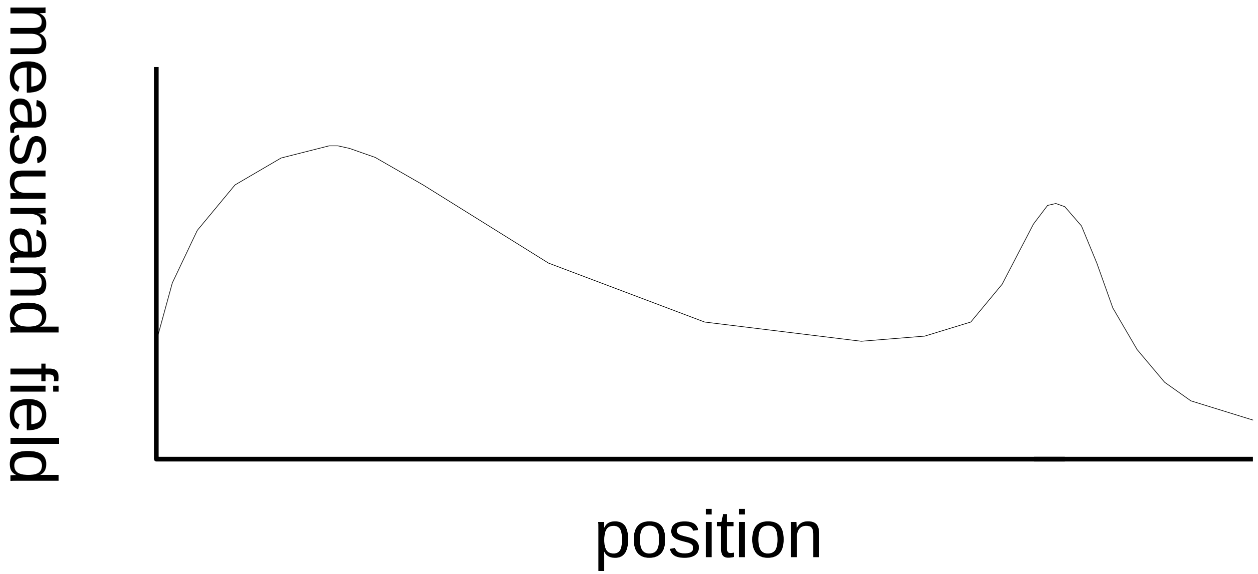
- Distributed sensing using elastic (Rayleigh) scatter:
  - Sensing breaks and length measurement
  - Sensing fibre lengths in sections
  - Sensing distributed dynamic strain signals
  - Polarimetric sensors
  - Micro-bend based distributed sensor systems
  - Coating based (chemical) distributed sensing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

To Lecture 3:

- Inelastic sensing systems:
  - Raman scatter and its use in distributed temperature measurement
  - Brillouin scatter and its use in distributed temperature and / or strain monitoring
- Some thoughts on the market potential for distributed fibre optic sensor systems

All measurements vary in space and time…

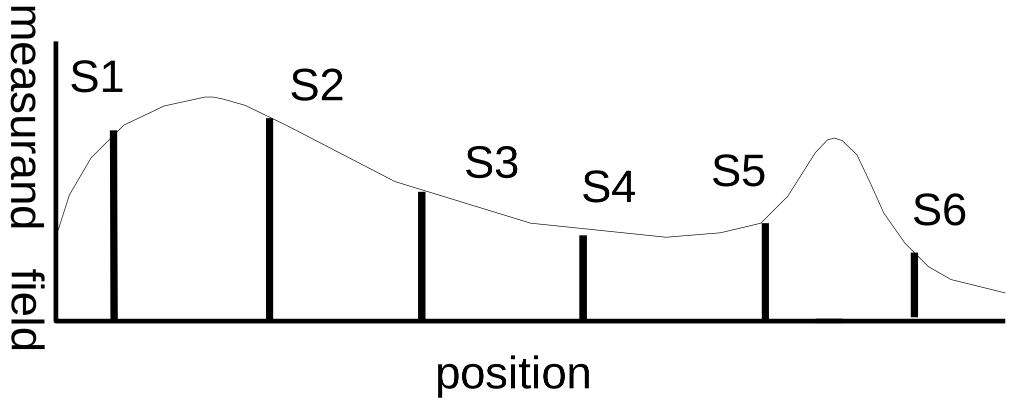
- Looking at a spatial sample in one dimension:



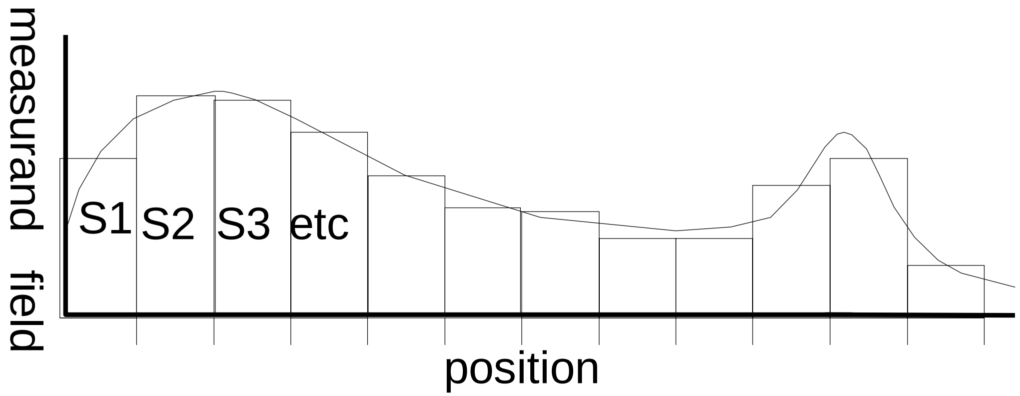
- How could we best estimate this measurement requirement??? ….

The concept of distributed sensing:

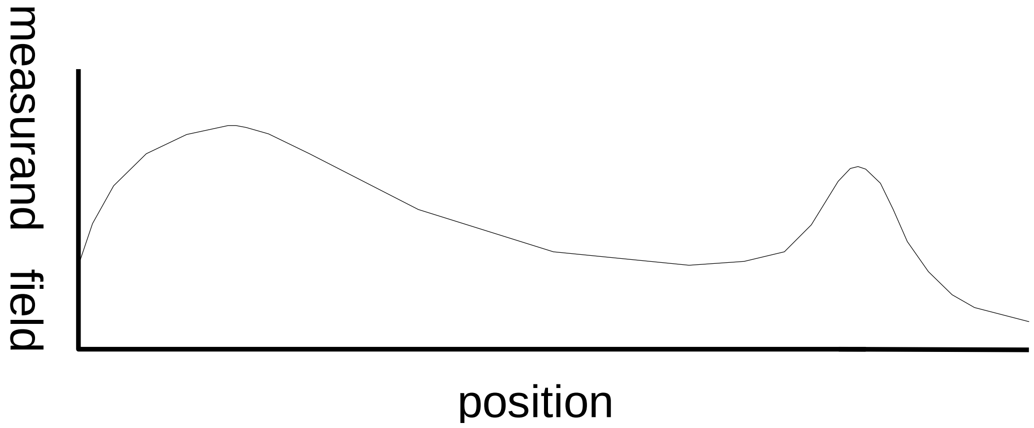
(a) sampling:
point sensors



(b) Averaging over
set sections:
integrating sensors



(c) Distributed
measurements

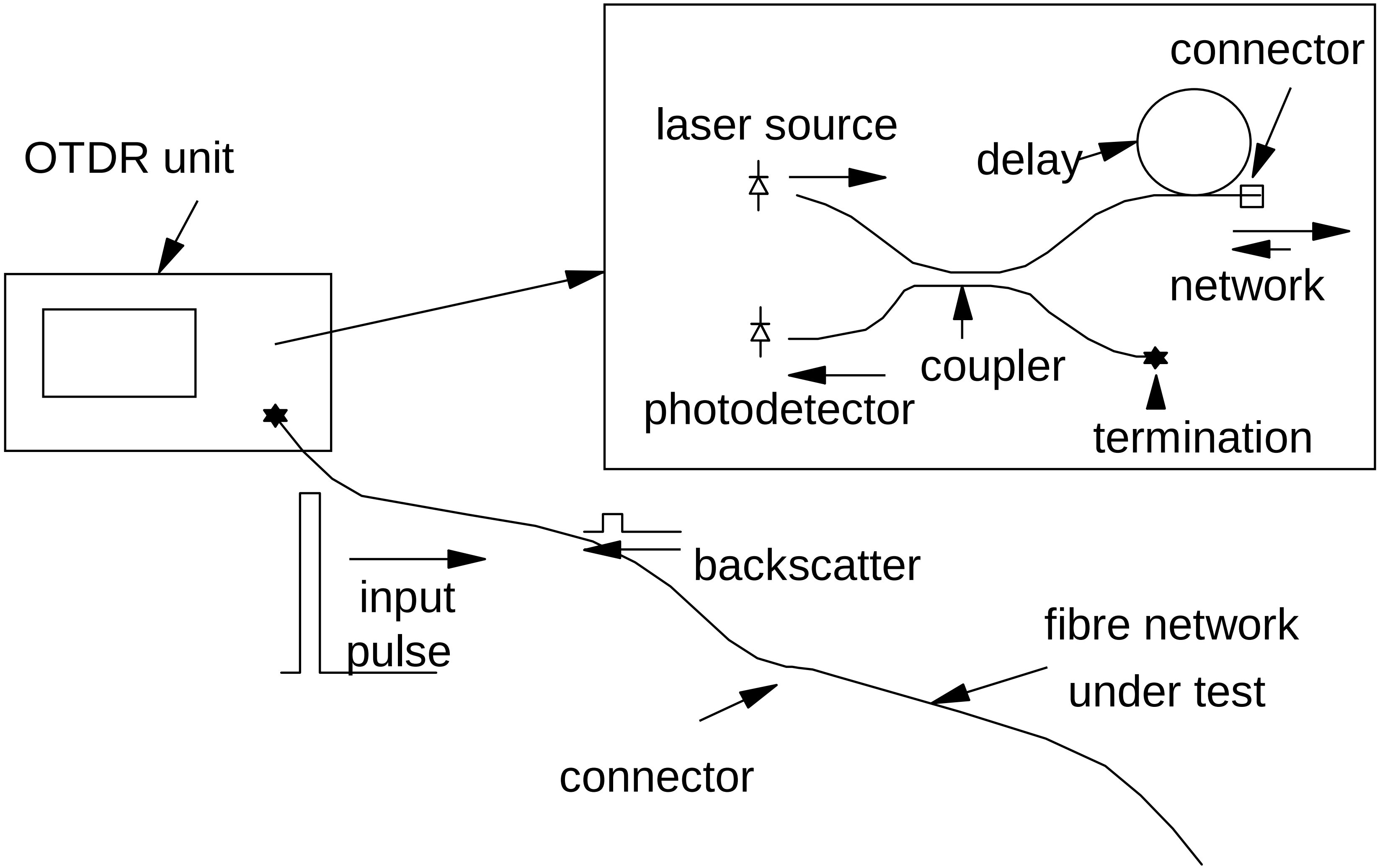


Observations on scatter based distributed measurements

- Time domain reflectometry is the key
  - Excellent reference – *P. Healey - 'Instrumentation Principles for Optical Time Domain Reflectometry' J Phys E Sceintific Instruments* ***19*** *pp334-341 (1986)*

- Based on elastic (Rayleigh scatter) or inelastic (Brillouin, Raman scatter) measurements

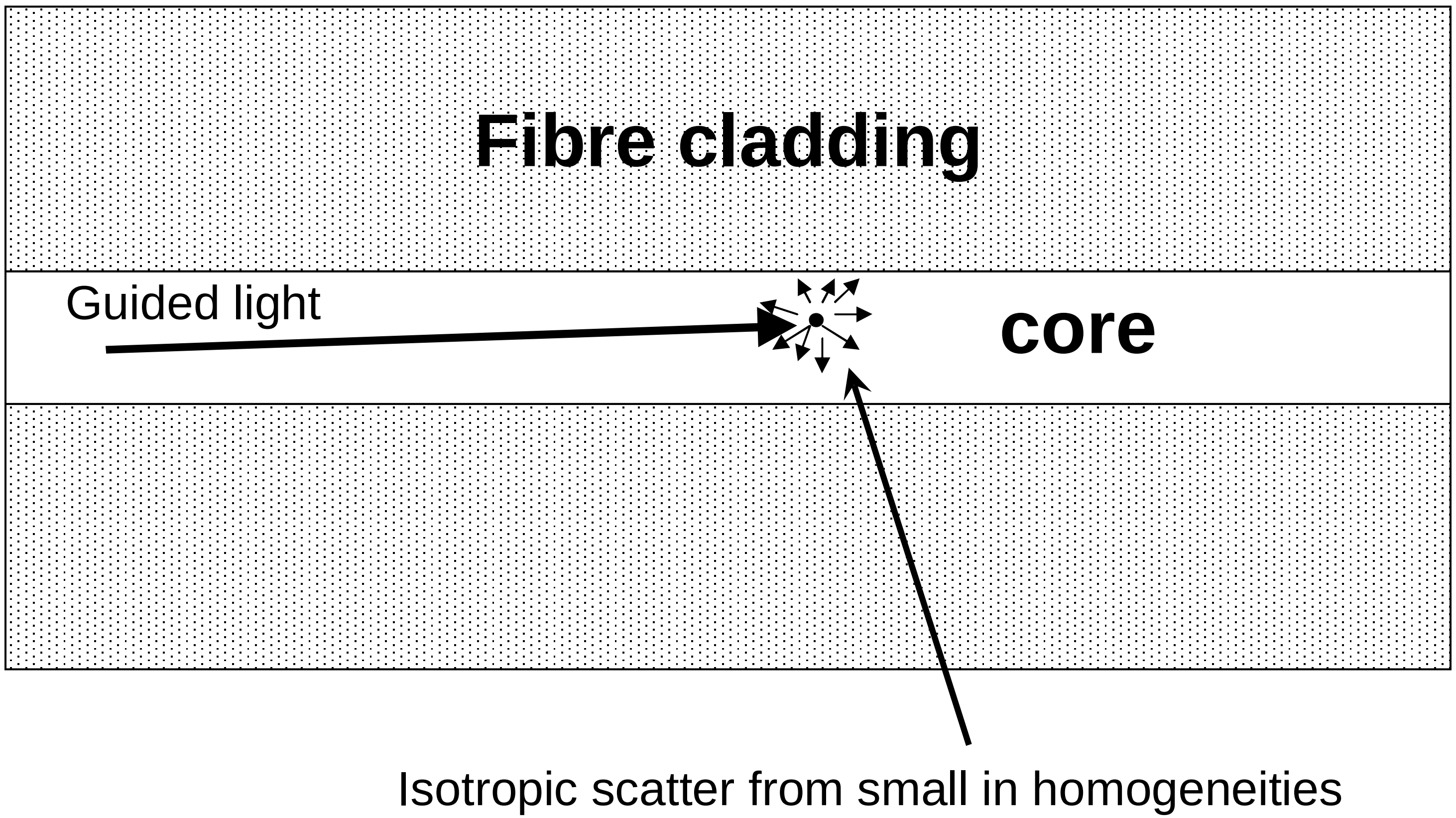
- ***A technique unique to fibre optics***



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

Scattering in optical fibres: the basics

- Rayleigh Scatter:



Relating backscatter to reflected and on going power

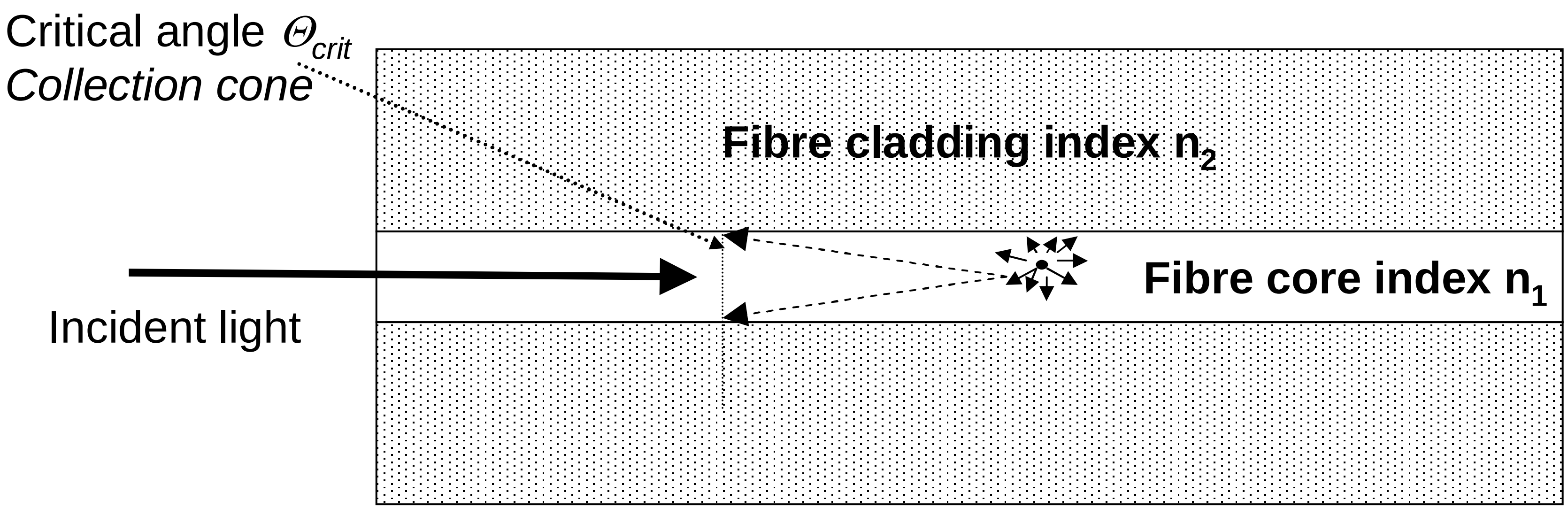
- Assume:
  - All attenuation is due to Rayleigh scatter, with a loss coefficient α_s per unit length
  - The Rayleigh scatter is uniform over 4π solid angle
- So what is the total backscatter power?

The collected backscatter is…

- Total Rayleigh backscatter over length *dl*..

  $= \alpha_s \cdot dl$

- Of this, a fraction determined by the numerical aperture of the fibre is collected:



Collected fraction??

- Critical angle: $\Theta_{crit} = \sin^{-1}(n_2/n_1)$
- Collection half angle $\Theta_{coll} = \pi/2 - \Theta_{crit}$

- $n_1 = n_2 + \Delta n$ where Δn is the (assumed small) index difference between core and cladding

- Using these relationships and the definition of fibre NA ~ $n_1(2\Delta)^{1/2}$ gives:
  - collection fraction ~ **$(NA)^2/4n_1^2$**

Collected Rayleigh backscatter power??

- Collected backscatter power per unit length is:

$$P_{coll.,\, backscatter} = P_{input} \,.\, \alpha_s \,.\, dl \,.\, (\mathrm{NA})^2/4n_1^2$$

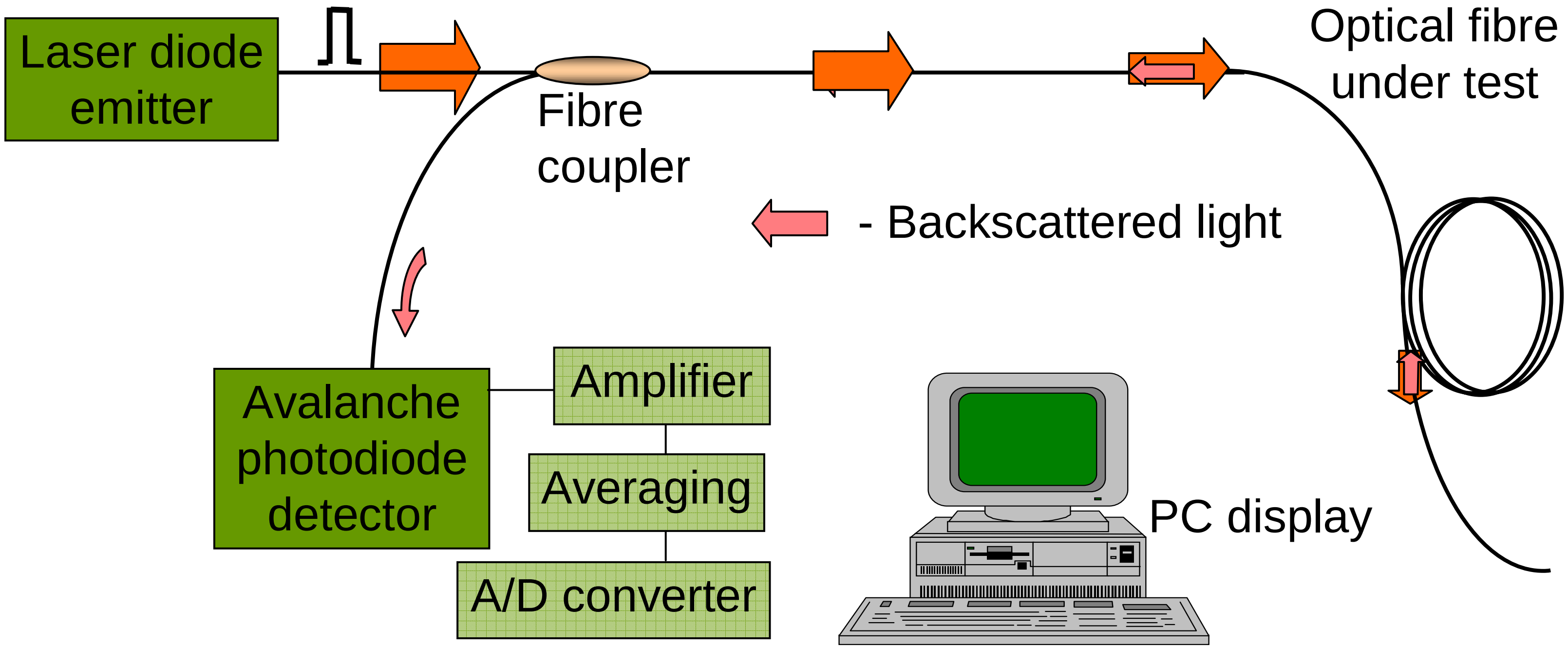
- *For 1 metre fibre at 1 dB/km the backscatter is about 56dB down on the incident power. (assume NA=0.1)*

There's another important assumption..

- The powers backscattered add – rather than amplitudes.

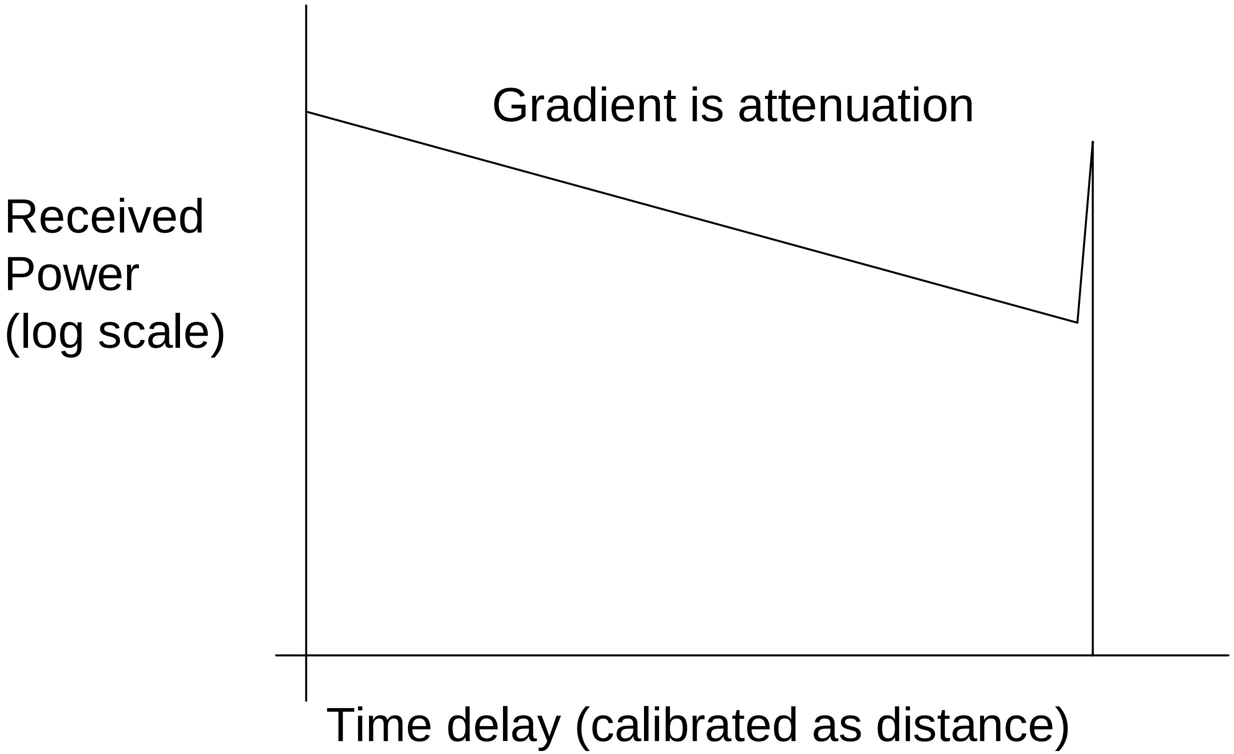
- i.e. The coherence length of the optical source is short compared to the resolution length of the system.

Optical Time Domain Reflectometer: (OTDR)

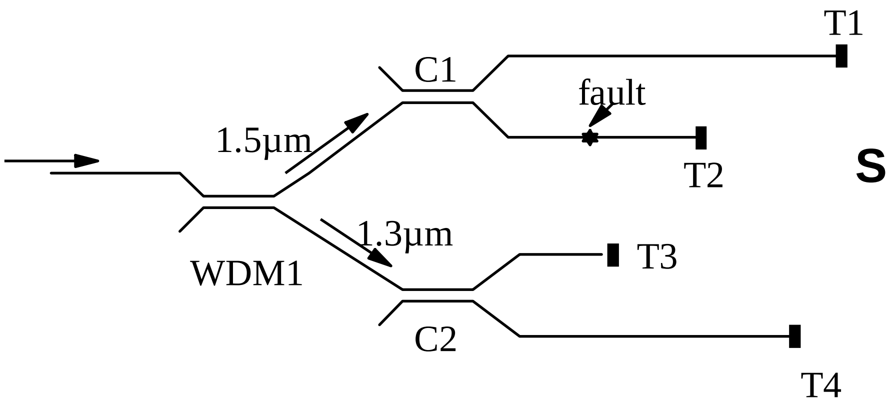


Light scattered back to the detector is plotted as a function of distance down the fibre

The OTDR trace – single fibre

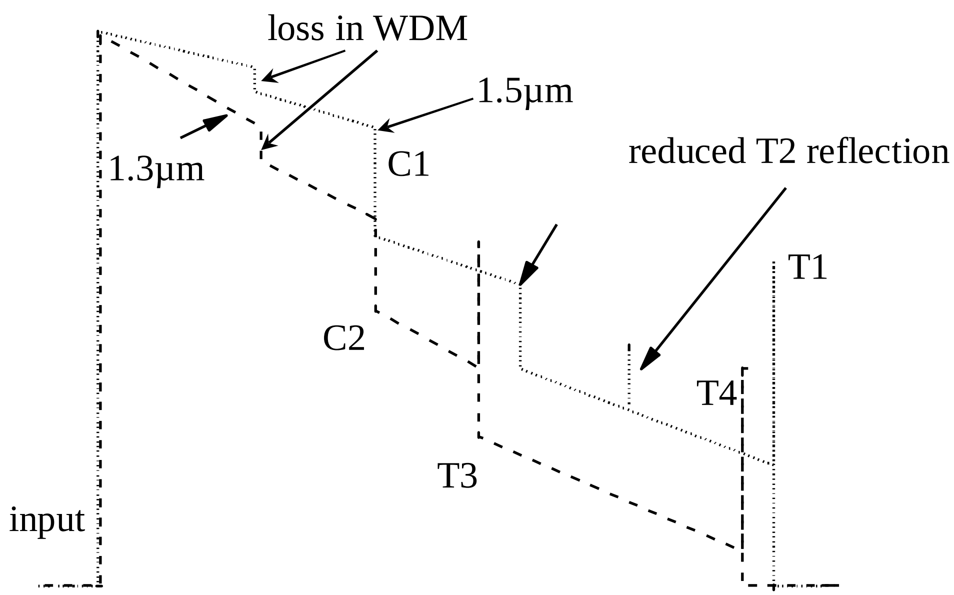


OTDR – network testing

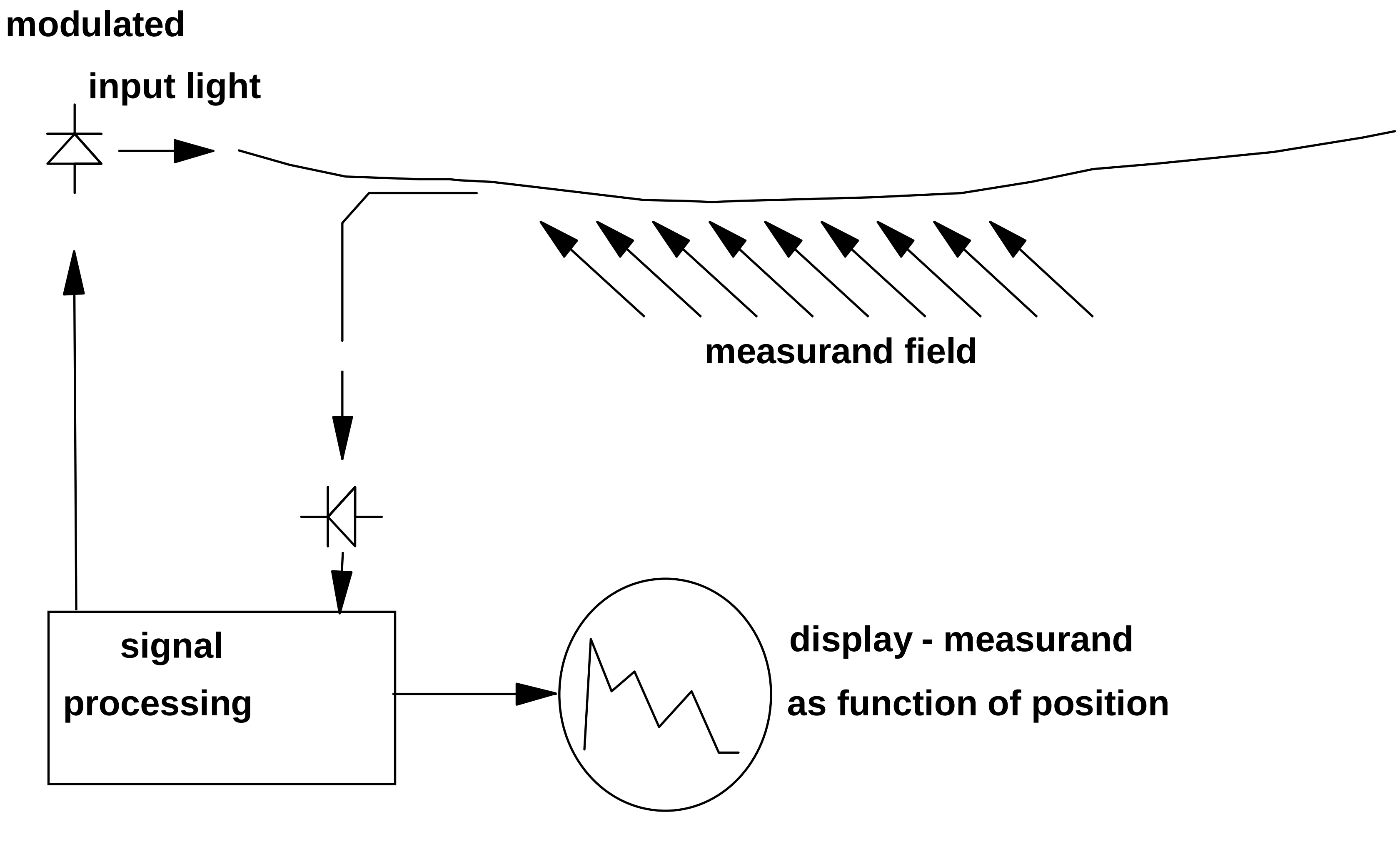


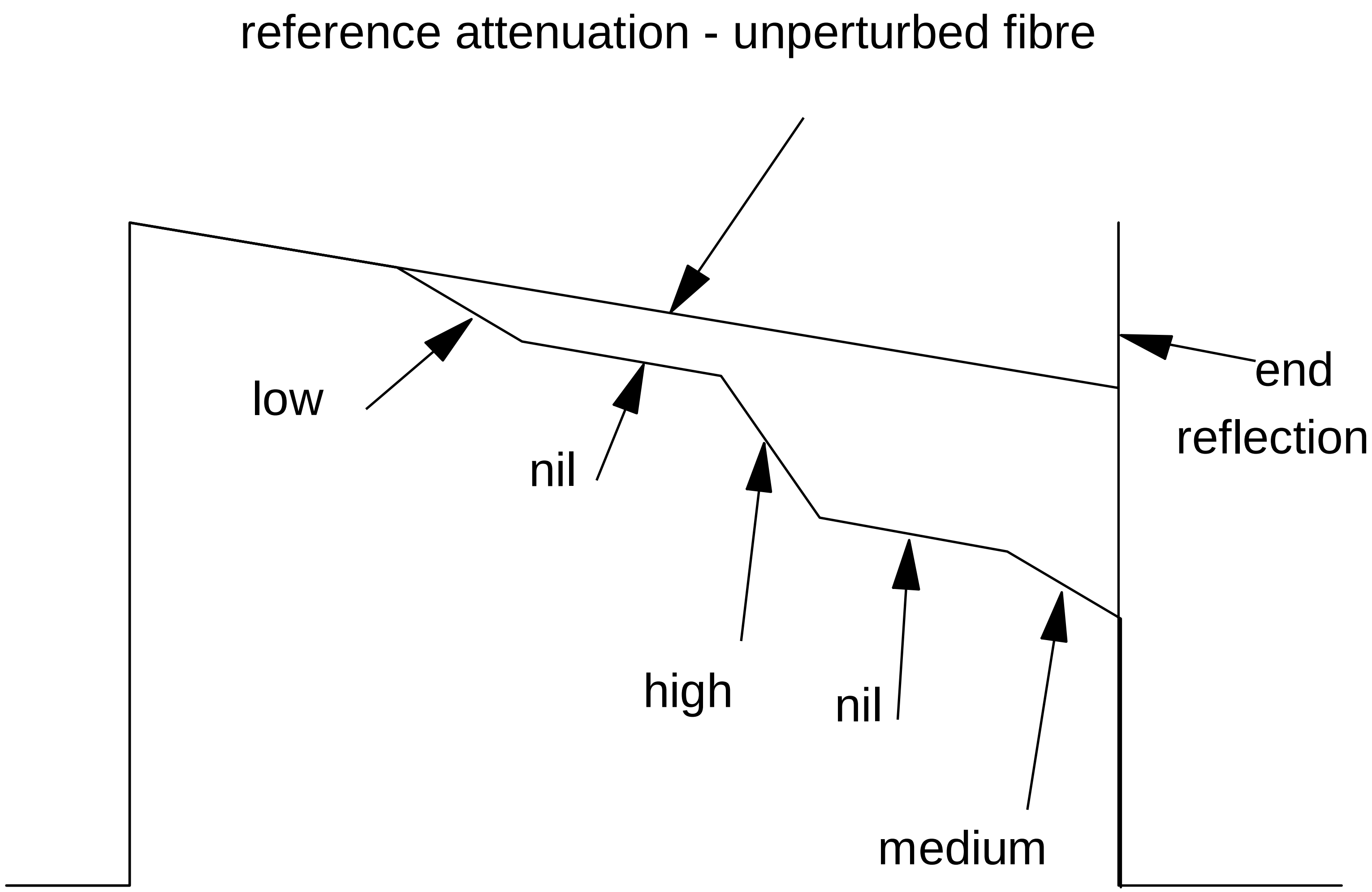
Simple network with hypothetical fault

OTDR traces at two λ from network after fault introduced



As a distributed sensor…





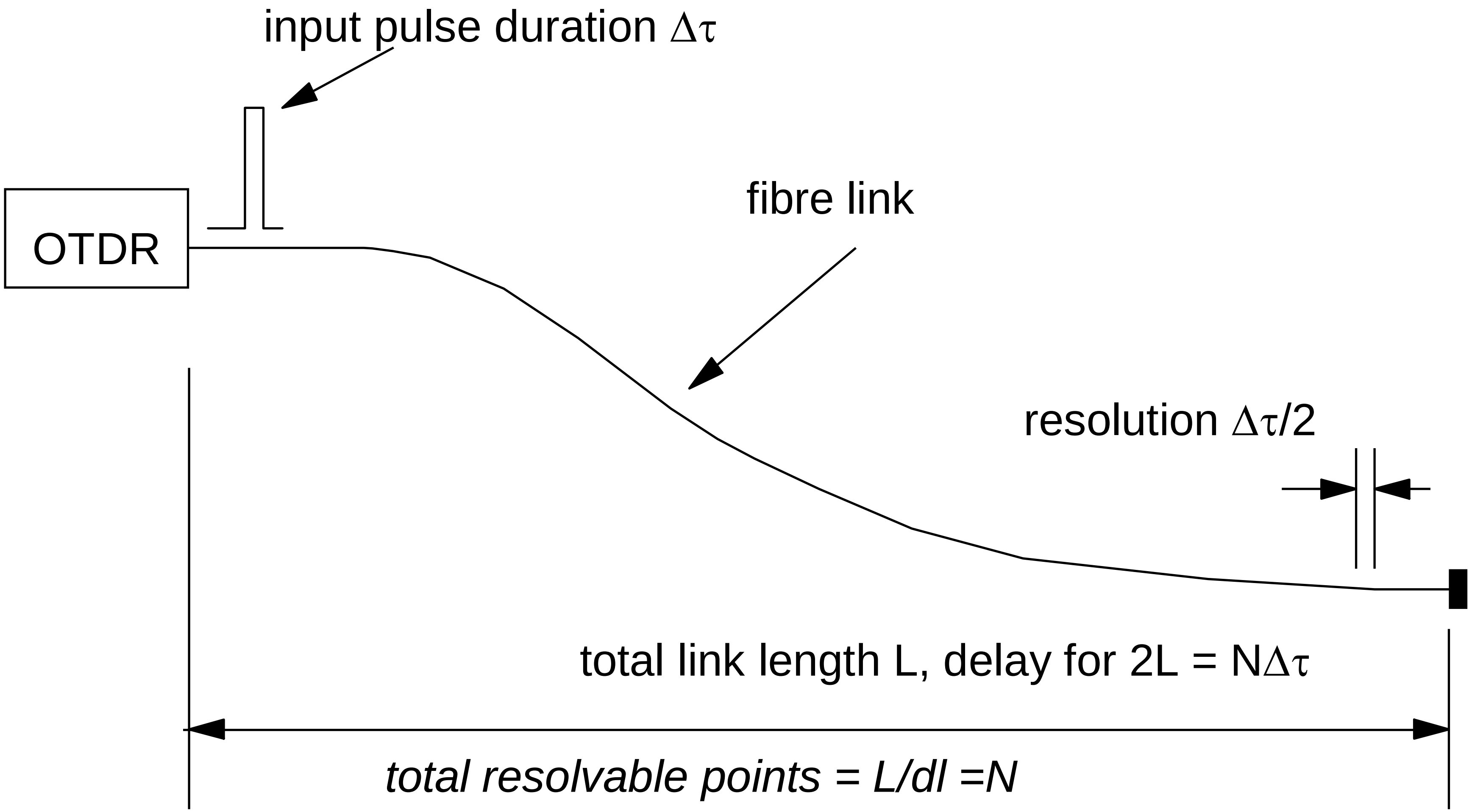
Representative OTDR trace for microbend sensor

High. low etc refer to value of imposed measurand

Pulse lengths, resolutions and timing:

- Relating the time resolution and duty cycle for the OTDR unit to spatial resolution along the fibre

- Also – as an aside remember that anything done in the time domain can also be achieved in the frequency domain – the *OFDR…* is an equivalent (though rarely used) instrument



Number of resolvable points, duty cycle, resolution and total range in OTDR

Rough estimates of returned power levels: more on the pulsing…

- Timing issues:
  - Delay is 5nsec / metre in typical silica fibre so…
  - Assume wish to look at 1 metre of fibre, pulse length must be <10nsec
  - Assume 10km total length, then time between pulses must be >100μsec.
  - *i.e.* pulse rate = 10kHz.

Detecting pulses: some estimates for the shot noise limit…

- Suppose we wish to resolve our returned pulse power for each pulse to 1 part in 1000 and also suppose we wish to update every second.

- Total number of returned photons required per pulse in 1 second is then >~ 2 x 10^6 assuming shot noise limited detection *from each one metre section of the fibre*.

Detecting pulses: some estimates for the shot noise limit…

- Energy per photon ~ 1eV =1.6 x 10 $^{-19}$ Joules (*energy in eV ~1.24/λ for λ in microns)*

- Energy per returned pulse per second is then ~3x10^{-13} Joules.

- We've assumed 10^4 pulses per second. Energy backscattered per pulse is then ~ 3x10^{-17} Joules

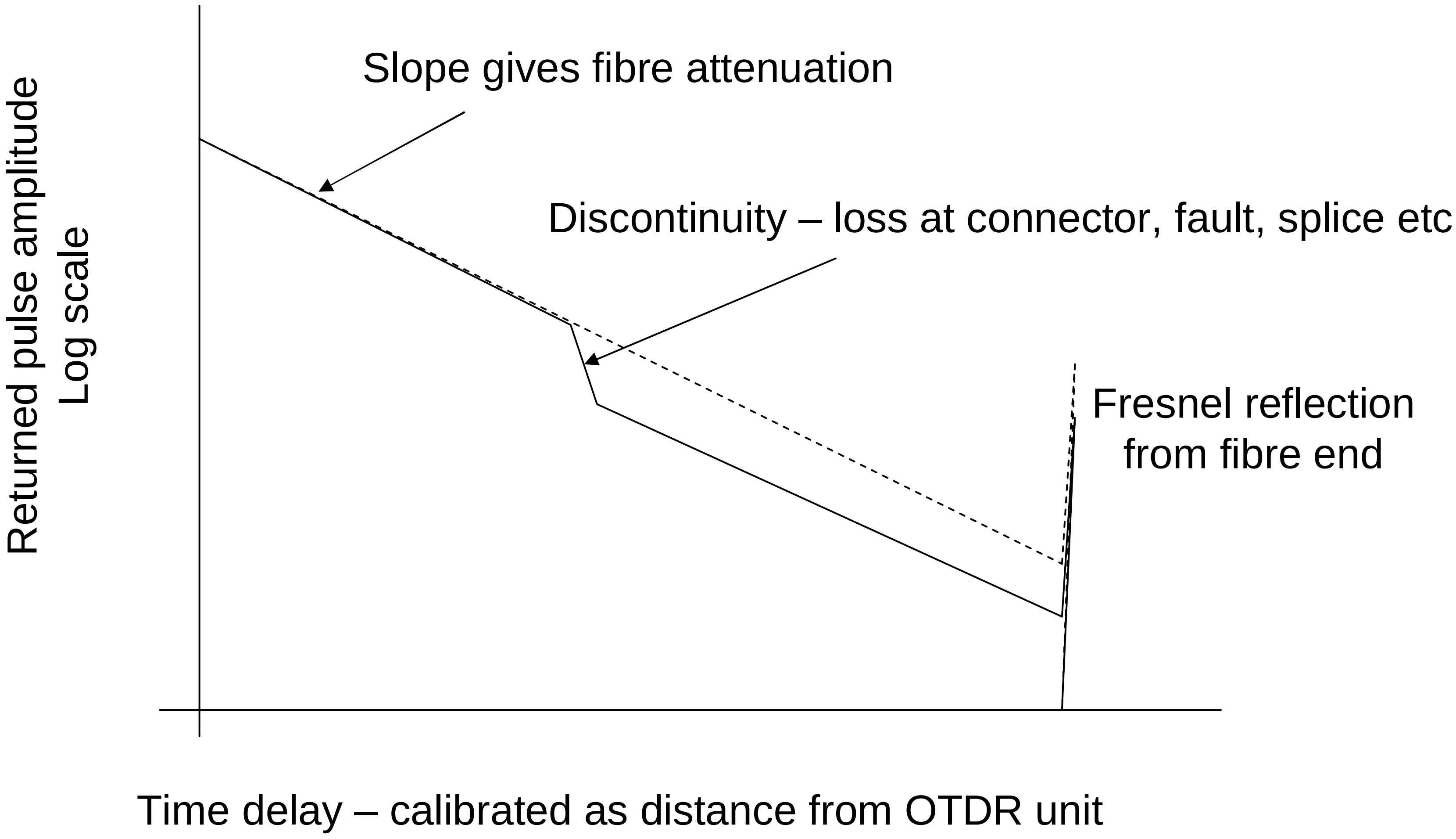
Detecting pulses: some estimates for the shot noise limit…

- Assume 55 to 60dB backscatter loss on one metre, this corresponds to input energy of ~ 3 x 10^{-11} Joules per pulse. Peak power in the pulse of duration 10^{-8} seconds ~ few milliwatts.

Conclusion… backscatter power requirements

- In round figures:
  - From whatever backscatter process is invoked… - elastic or otherwise
  - Around 10^6 photons per second is more than adequate from each sensing section
  - For Rayleigh backscatter – around 10mW peak power is all that is needed
  - For other processes, can estimate from the physics of the non linear effects *(Aggrawal, Non Linear Fibre Optics is an excellent text)*

The basic OTDR trace

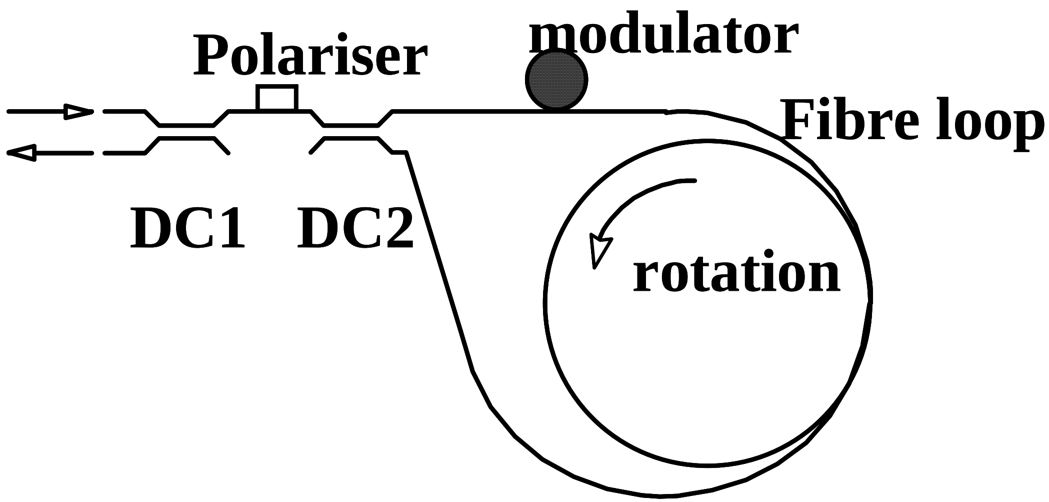


Elastic scatter in sensing:

- The basic processes…
  - The parameter to be sensed changes one of the ***optical power***, ***phase*** or ***state of polarization*** of the backscattered light.
- These changes are read as a function of distance using a suitable form of OTDR

The Sagnac interferometer as a distributed *(direct disturbance)* sensor

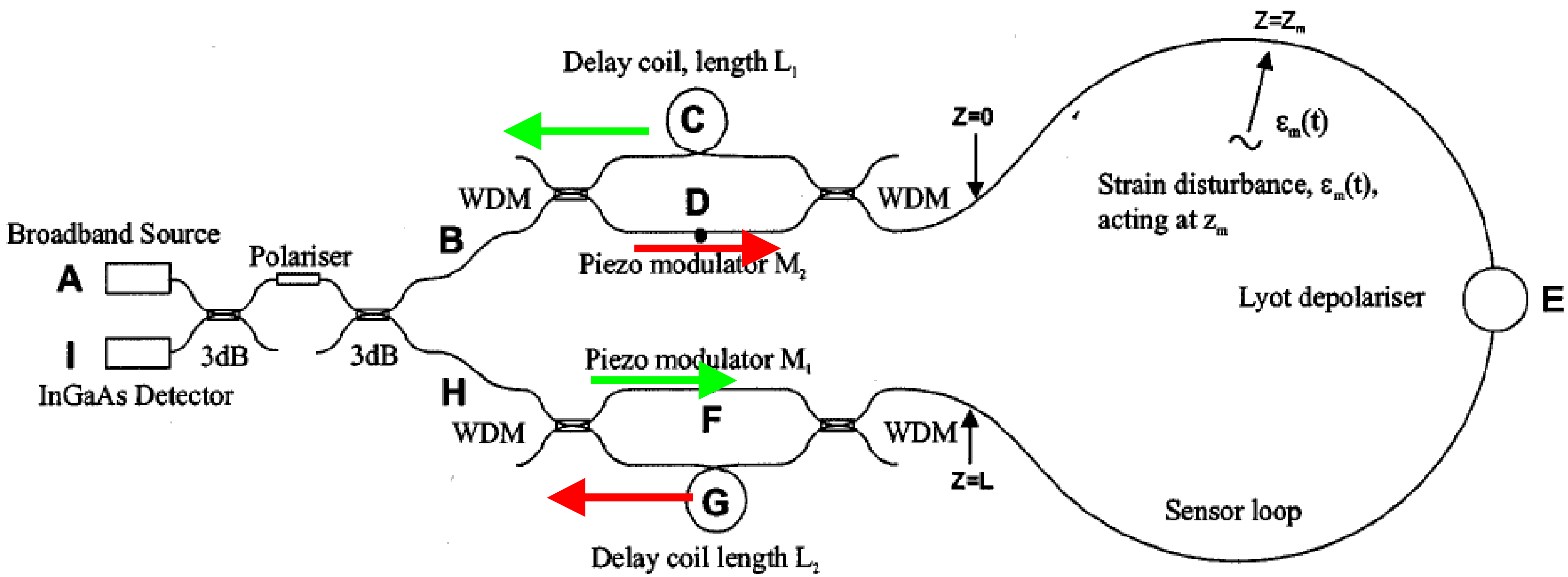
- The Sagnac interferometer:



Architecture of the optical fibre gyroscope

- Usually configured as the fibre gyroscope

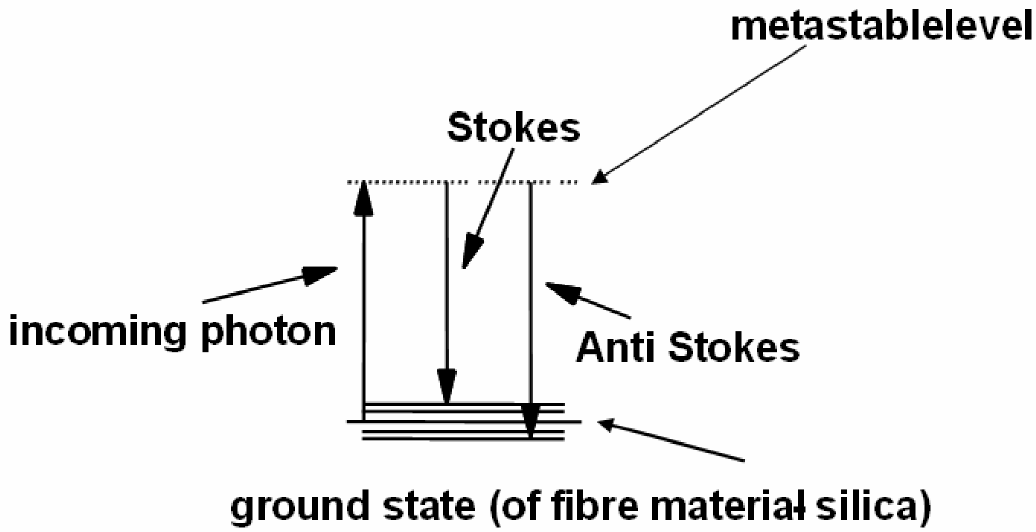
Sagnac interferometer as a distributed disturbance position monitor

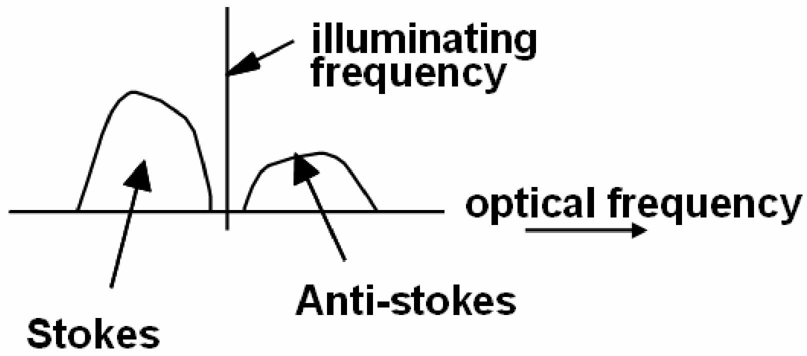


- The basic idea – two separate Sagnac interferometers with a common sensing section *(at RHS in diagram)*

Russel et al JLT 19 2 2001 pp 205 -213

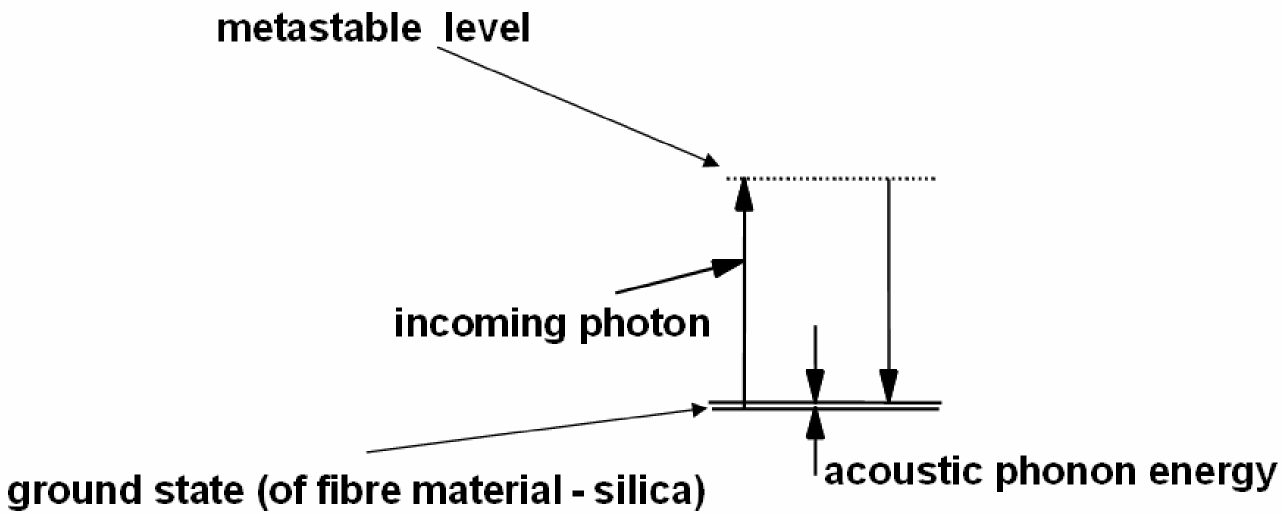
Non-linear effects – the basics



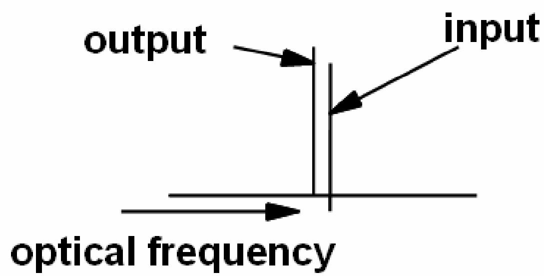


RAMAN: power ratio in Stokes and anti-Stokes f(T) alone equidistant from carrier

Non-linear effects – the basics



BRILLOUIN *(stimulated)* –
Output frequency offset depends on $\nu_{acoustic}$ i.e. temperature and strain



Summarising the prospects for fibre non- linearity in sensing:

- Raman backscatter power ratio taken equidistantly from the excitation wavelength gives temperature fields.

- Stimulated Brillioun scatter offset frequency gives a value of acoustic velocity in the fibre – i.e a combination of temperature and strain.

To recap from – distributed sensing basics:

- Distributed sensing is a powerful tool in fibre optic sensor system – it is genuinely unique to this technology
- Time domain reflectometry is the key to implementations relying on changing backscatter cross signals (Rayleigh, Raman or Brillouin)
- Sagnac interferometers have also been used as distributed sensors – relatively minor applications compared to backscatter