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Optical Fiber Sensors
Basic Principles

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Basic Principles

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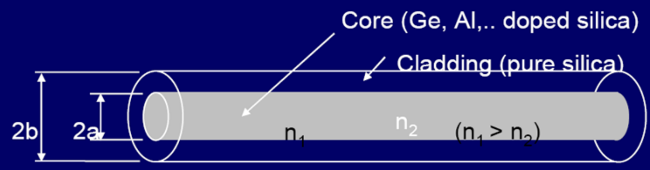
Outline

- ***Basic of optical fibers***
- ***Basic of optical fiber sensors***
- ***Principles of photonic sensors***
- ***Multiplexed and distributed sensors***
- ***Introduction to Fiber Bragg Grating (FBG) sensors***
- ***Introduction to distributed optical fiber sensors***
- ***Optical Time Domain Reflectometry (OTDR)***

Basic of Optical Fibers

Optical fibers are cylindrical dielectric waveguides



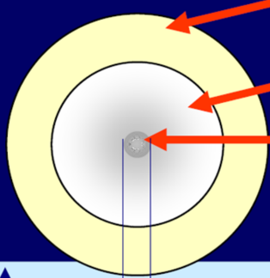
Typical dimensions

Core diameter	2a = 9 to 62.5 μm
Cladding diameter	2b = 125 μm

Typical values of refractive indices

Core:	$n_1 = 1.461$
Cladding:	$n_2 = 1.460$

Refractive Index Profile



Protection cladding

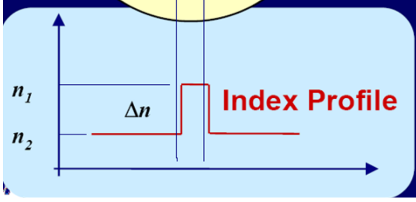
Plastic (250 or 900 μm)

Cladding

pure silica (125 μm)

Core

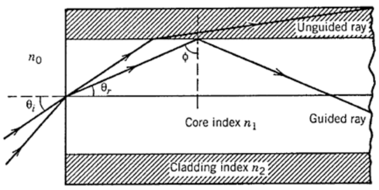
Doped silica (9 – 62.5 μm)

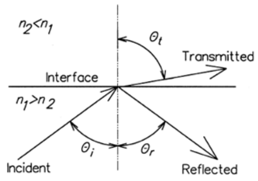


Index step typical values:

$\Delta n = 0.001 - 0.01$

Total Internal Reflection





Snell's Law: $n_0 \sin\theta_i = n_1 \sin\theta_r$ $\quad n_0 = 1$ for air

For angles Φ greater than the critical angle Φ_c defined by: $\sin\phi_c = \dfrac{n_2}{n_1}$
the ray experiences total internal reflection at the core-cladding interface.

All rays characterized by $\Phi > \Phi_c$ remain confined to the fiber core.

The maximum angle θ_i that the incident ray should make with the fiber axis to remain confined inside the core can be obtained as: $\theta_r = \pi/2 - \phi_c \Longrightarrow \sin\theta_r = \cos\phi_c$

$$n_0 \sin\theta_i = n_1 \sin\theta_r = n_1 \cos\phi_c = n_1(1-\sin^2\phi_c)^{1/2} = (n_1^2 - n_2^2)^{1/2}$$

$NA = n_0 \sin\theta_i = \sqrt{n_1^2 - n_2^2}$ NUMERICAL APERTURE

$$NA = \sqrt{n_1^2 - n_2^2} = n_1(2\Delta)^{1/2}$$

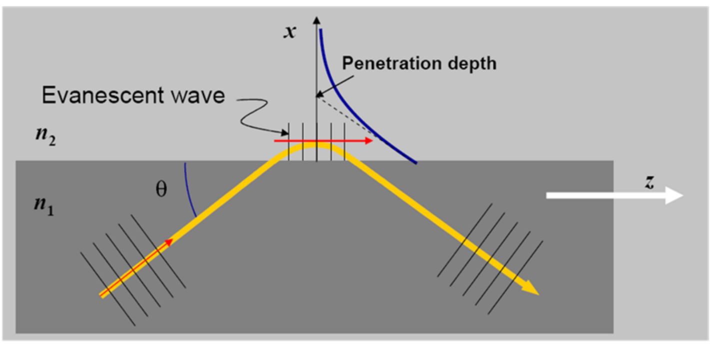
$$\Delta = (n_1^2 - n_2^2)/2n_1^2 \approx (n_1 - n_2)/n_1$$

Total Internal Reflection

Wave penetrates the lower index medium in total internal reflection

$n_2 < n_1$

$\theta < \theta_c$

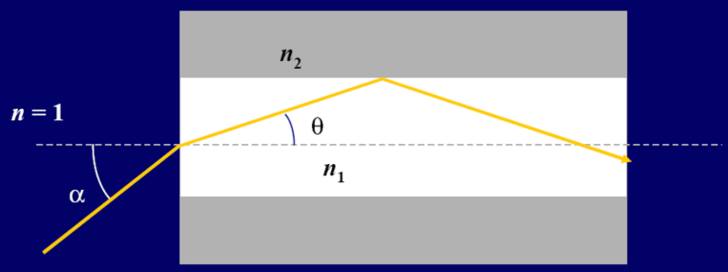


Cladding material must be highly transparent in low loss fibers

Evanescent waves can be used to couple light from one fiber to another

Numerical Aperture

Acceptance angle for a ray to be guided



Total internal reflection $(\theta \leq \theta_c) \Rightarrow \sin\alpha \leq NA$

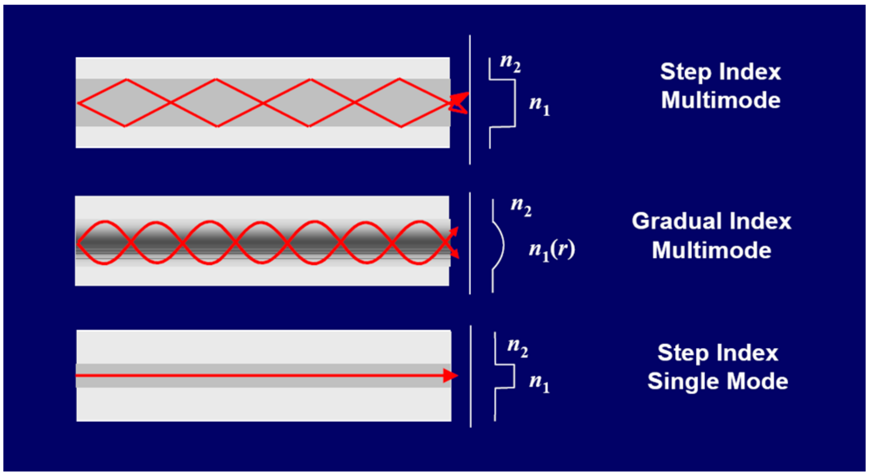
where:

$$NA = \text{Numerical Aperture} = \sqrt{n_1^2 - n_2^2}$$

$$\sin\theta_c = NA / n_1$$

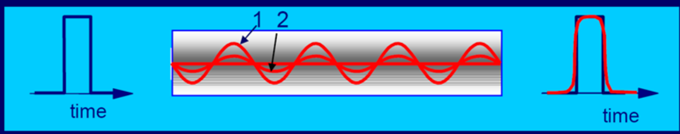
Ex: $n_1 = 1.47$ and $n_2 = 1.46 \Rightarrow \alpha = 9.9^\circ$ and $NA = \mathbf{0.17}$

Multi-mode and Single Mode Fibers



Graded-Index Multi-mode Fibers

Input pulse Graded Index MM fiber Output pulse

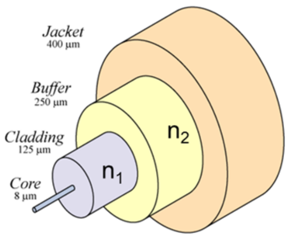


- Mode 1 travels a longer *physical* path than mode 2, but through regions of lower index (higher speed);
- The *propagation delay* is approximately the same for both modes.

Capacity of MM-graded index fibers ≈ 2 Gb/s×km

Single-mode Fibers

Inner dielectric or core (r<a): n_1
Outer material or cladding) (r>a): n_2 $n_1>n_2$
The cladding is assumed of inifinite outer radius



Core diameter ~ 9 µm

Cladding diameter ~ 125 µm

Normalized index difference: $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx (n_1 - n_2)/n_1 = \frac{\delta n}{n_1}$

The approximation is based on the assumption that n_1 is very closed to n_2

Numerical aperture NA: $NA = \sqrt{n_1^2 - n_2^2} = n_1(2\Delta)^{1/2}$

$\Delta = (n_1 - n_2)/n_1$

Dispersion Characteristics
Step Index Optical Fiber

Relation between the propagation constant and frequency is called the Dispersion Relation: $\beta = \beta(\omega)$

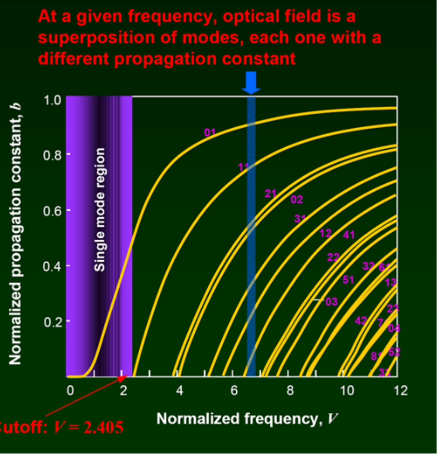
Normalized Propagation Constant

$$b = \frac{(\beta / k_0)^2 - n_2^2}{n_1^2 - n_2^2}$$

Normalized frequency

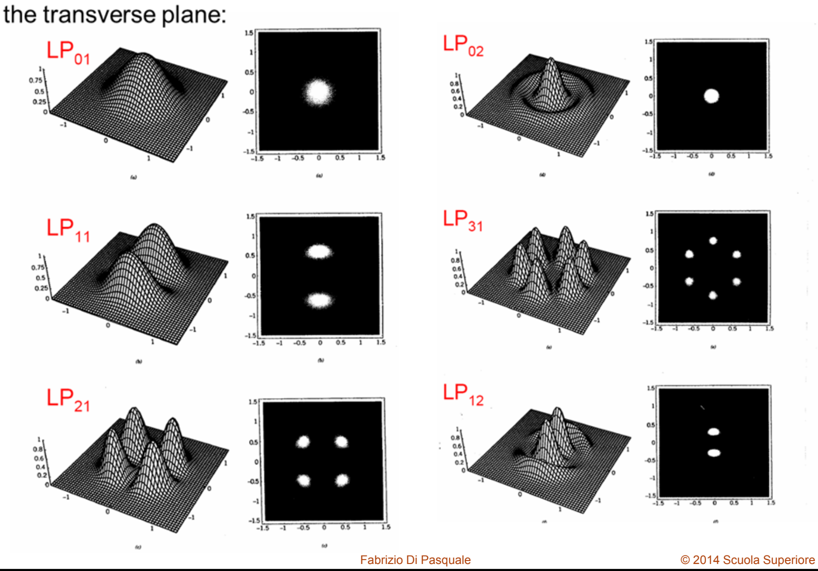
$$V = ak_0(n_1^2 - n_2^2)$$

$$[k_0 = \omega / c = 2\pi / \lambda]$$

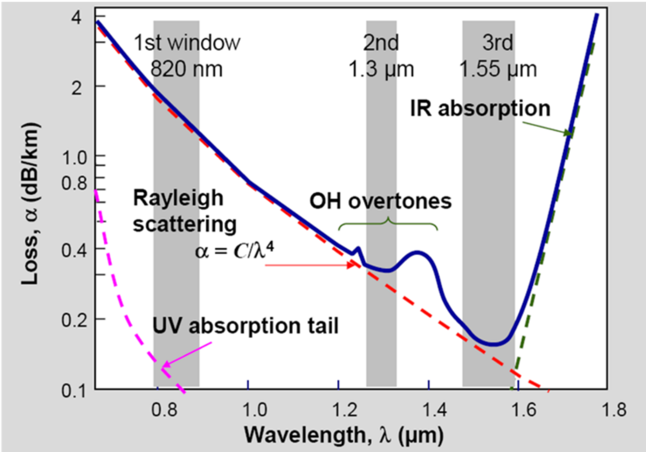


Intensity Distributions
LP_{lm} Modes

LP modes are experimentally observed as intensity patterns (proportional to EE*) in the transverse plane:



Fiber Attenuation



Attenuation due to:

- Material absorption
- Bending losses
- Rayleigh scattering

Evolution of optical power along fiber length *z*:

$$P(z) = P_0 \cdot e^{-\alpha_\lambda z}$$

Loss coefficient

$$P_{\text{dBm}}(z) = P_{0\_\text{dBm}} - \alpha_{\text{dB/km}} \cdot z\,(\text{km})$$

$$\alpha_{\text{dB/km}} = \alpha \cdot 10\log_{10} e = 4.343 \cdot \alpha \quad (\text{Km}^{-1})$$

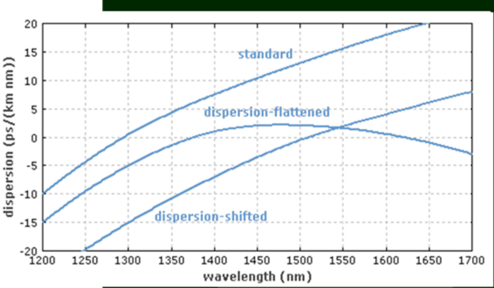
Chromatic dispersion

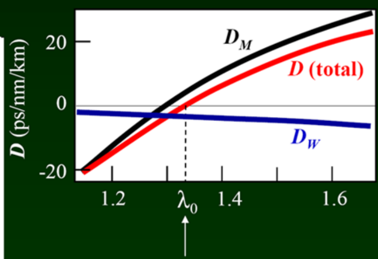
Group velocity (v_g) depends on λ

Dispersion parameter:

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2}$$

$$D = D_M + D_W$$



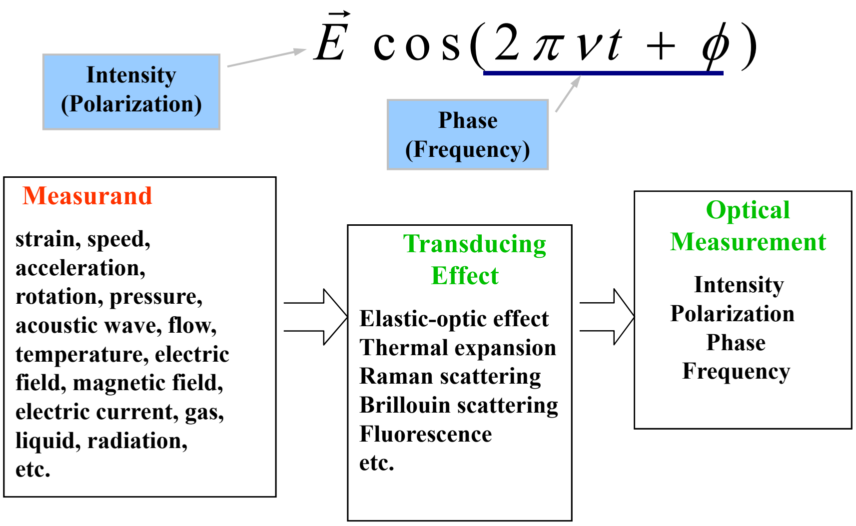


Zero dispersion wavelength

Optical Fiber Sensors Basics

- Fiber-transmission and fiber-sensing systems
- Intensity, polarization, phase and frequency modulated sensors
- Individual-, multiplexed-, and distributed-sensors

Principle of Photonic Sensing



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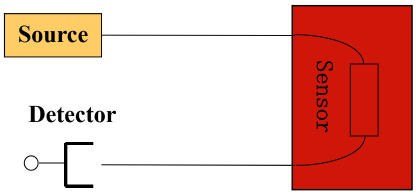
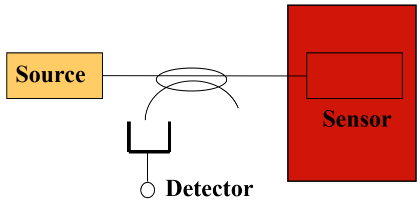
Principle of Photonic Sensing

Transmission



Voltage
Current
Magnetic field
Temperature
Acceleration, etc.

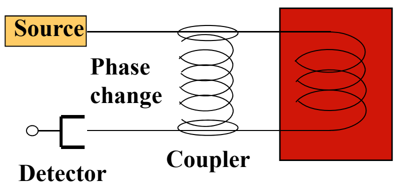
Reflection



Sound
O_2 in Blood
Micro wave power
Temperature, etc.

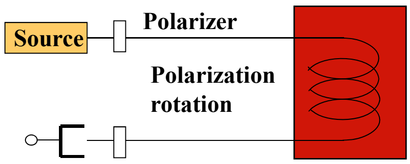
Principle of Photonic Sensing

Interferometer



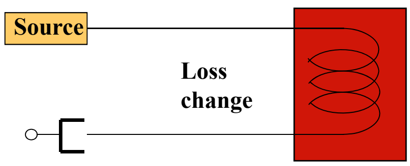
Temperature
Pressure
Strain
Magnetic field
Sound, etc.

Polarimeter



Current
Magnetic field, etc.
(Faraday effect)

Power Meter

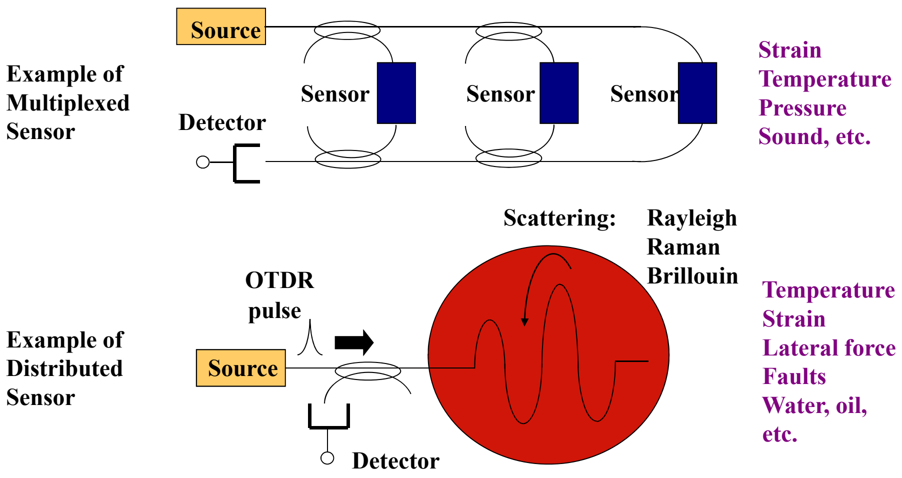


Sound (Micro bending)
Gas concentration
(Evanescent wave)
Radiation, etc.

Why Fiber Optic Sensors ?

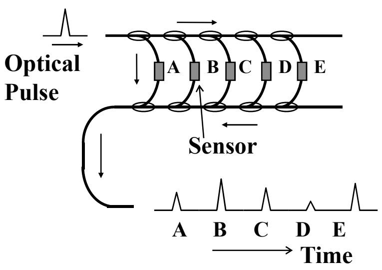
- Light properties in fiber are sensitive to environmental disturbance
- Optical fiber easily to be configured into host material or structure and not degrade the host
- Optical fibers are not sensitive to EMI
- Multiplexed OFS (WDM, TDM, SDM)
- Distributed sensing (long sensing distances)
- No electric power requirement at the sensing point
- High temperature values can be reached

Multiplexed and Distributed Sensors

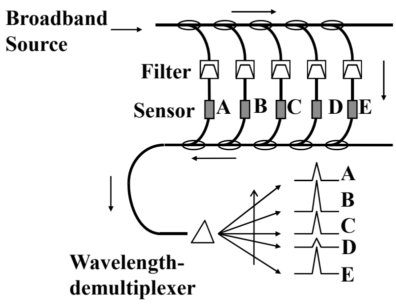


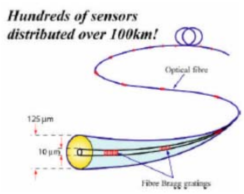
Approaches for Multiplexed Fiber Sensors

Time Division Multiplex (TDM)



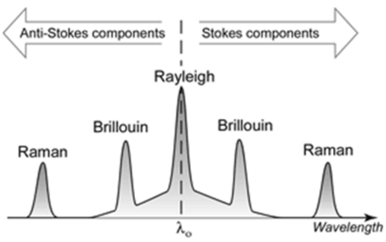
Wavelength Division Multiplex (WDM)





Examples of Fiber Sensors

- ❑ **FBG-based sensors**
- ❑ **Distributed backscattering-based sensors**
- ✓ ***Raman scattering*** based distributed sensors
- ✓ ***Brillouin scattering*** based distributed sensors
- ✓ ***Rayleigh scattering*** based distributed sensors



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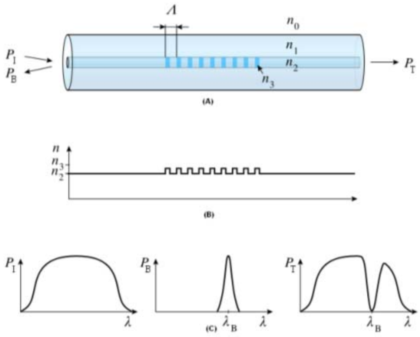
Fiber Bragg Grating Sensors

- ❑ Periodic refractive index variations within the optical fiber core lead to light reflection at specific wavelength
- ❑ FBG couples the forward propagating core modes to backward modes at the wavelength λ_B corresponding to resonance condition:

(n is the effective index of the core mode and Λ is the period)



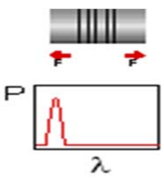
$$\lambda_B = 2n\Lambda$$

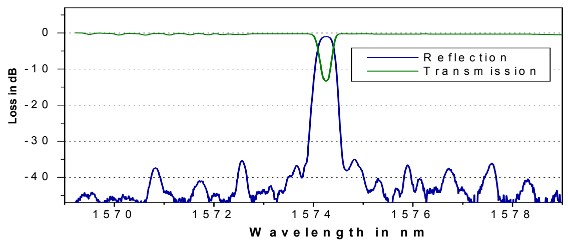
Typical structure of a uniform Fiber Bragg Grating

FBG for strain & temperature sensing

Physical Mechanisms

- ❑ Changes induced in the periodic refractive index variations of the FBG will lead to wavelength variations in the reflected light
- ❑ Temperature and strain variations induce changes in the refractive index periodicity of the FBG





- ❑ Strain & temperature cross-sensitivity $\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = (1-p_e)\epsilon + (\alpha_\Lambda + \alpha_n)\Delta T$

P_e: strain optic coefficient
α_Λ: thermal expansion coefficient
α_n: thermo-optic coefficient

Introduction to distributed optical fiber sensors

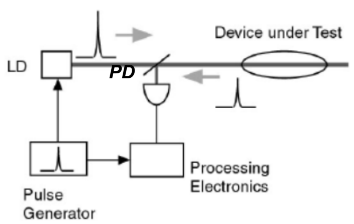
Distributed fiber sensors allow the measurement of physical properties along fiber length (temperature, strain, etc.)

based on optical reflectometry

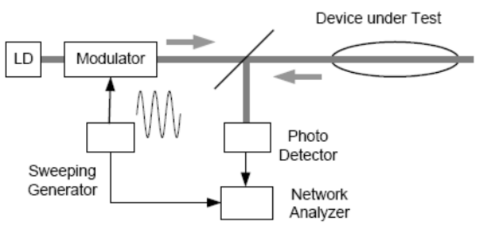
- ✓ ***Optical Time Domain Reflectometry (OTDR)***
- ✓ ***Optical Frequency Domain Reflectometry (OFDR)***
- ✓ ***Coherent Optical Frequency Domain Reflectometry (C-OFDR)***
- ✓ ***Optical Low Coherence Reflectometry (OLCR)***

Direct Detection: OTDR & I-OFDR

Optical Time Domain Reflectometry OTDR

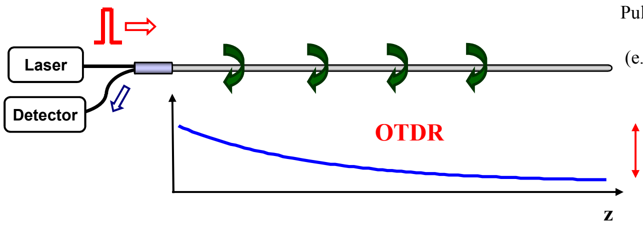


Optical Frequncy Domain Reflectometry OFDR



$$I = R \cdot P_{ref}$$

Optical time-domain reflectometry



Pulse width determines the spatial resolution (e.g. 10 ns 1 m sp. res.)

Dynamic range limited by receiver sensitivity

Low SNR at long distances

- To increase SNR at the receiver:
  - Use higher peak power → limited by nonlinear effects
  - Use longer pulses → degrades the spatial resolution

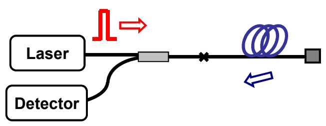
Trade off between distance range and spatial resolution

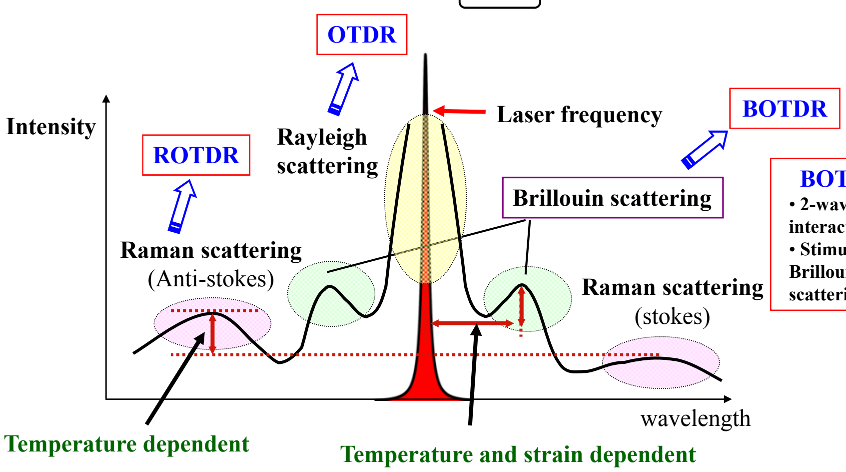
- To overcome the limitations
  - Use receiver with higher sensitivity (e.g. coherent detectors)
  - Use of optical pulse coding

Coded-OTDR techniques:
- Spreading signal in time domain
- More optical input power
- It avoids to use high peak power pulses (nonlinearities)
- It allows to improve the SNR with no impact on the spatial resolution

Scattering phenomena used in DOFS

Distributed optical fiber sensors based on optical-time domain reflectometry (OTDR)

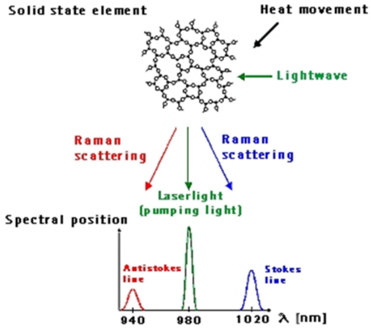


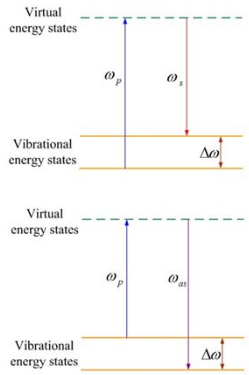


BOTDA
- 2-waves interaction
- Stimulated Brillouin scattering

Spontaneous Raman Scattering and Phonons

Raman scattering is generated by light interaction with resonant modes of the molecules in the medium (vibrational modes)





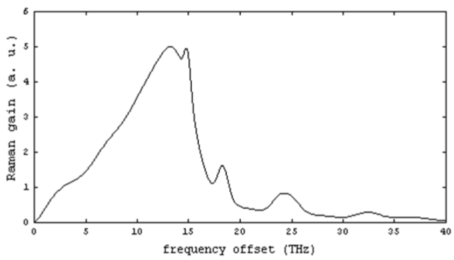
Raman Stokes

Raman Anti-Stokes

- **Phonons interact with photons in inelastic scattering**
- **Stokes line → photon energy is given to phonon**
- **Anti-Stokes line → phonon gives energy to photon**

Spontaneous Raman Scattering and Phonons

- *The high energy of vibrational modes induce a large Raman frequency shift (~ 13 THz in silica fibers)*



- *For each molecular vibration two Raman components are observed:*

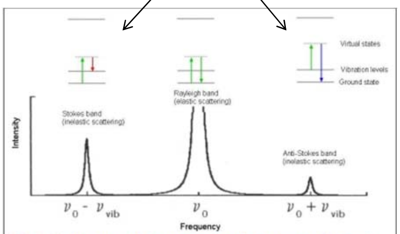


Fig. 4.1.2: Spectrum of photon transition from elemental ground level to virtual states.

© Mascarós et al., in: "Handbook on the Use of Lasers in Conservation and Conservation Science", 2008.

- *At different increasing temperature thermal excitation increases both Raman S and AS (asymmetry between Raman S and AS !)*

Spontaneous Raman Scattering and Phonons

- ***Transition rates and propagation equations due to thermal excitation:***

$$W_S \propto N_0(1+N_\Omega) \quad \textbf{Stokes} \quad dP_S(z) = (1+N_\Omega)\Gamma_S P_o dz$$

$$W_{AS} \propto N_0 N_\Omega \quad \textbf{Anti-Stokes} \quad dP_{AS}(z) = N_\Omega \Gamma_{AS} P_o dz$$

N_0 is the incident photon flux (proportional to pump intensity)
Γ_S and Γ_{AS} are the Raman Stokes and Anti-Stokes capture coefficients

N_Ω is the Bose-Einstein thermal population factor:

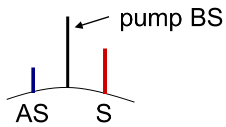
$$N_\Omega \propto \frac{1}{\exp\left(\frac{h\Delta\nu_R}{K_B T}\right)-1}$$

h: Plank constant
K_B: Boltzman constant
$\Delta\nu_R$: vibration frequency
T: absolute temperature

$$\frac{W_{AS}}{W_S} \propto \exp\left(-\frac{h\Delta\nu_R}{K_B T}\right)$$

$W_{AS} \sim W_S$ at high T
$W_{AS}/W_S \longrightarrow 0$ for $T \longrightarrow 0$ K

Raman based distributed temperature sensors

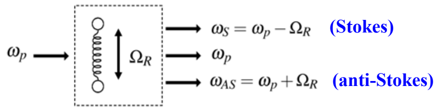


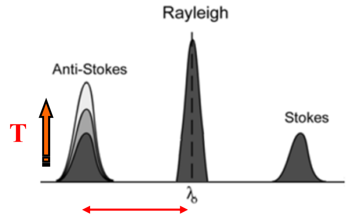
T dependence of phonon population → T dependence of SRS light

Ratio $R(T)$: P_{AS}/ P_S (or P_{AS}/ P_{BS}) is usually used

Raman temperature sensitivity: 0.8% K^{-1}

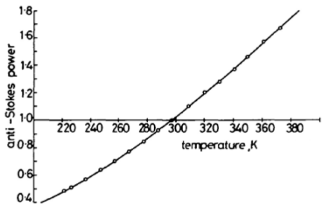
Spontaneous Raman Scattering





12.5 THz
(100 nm @1550 nm)

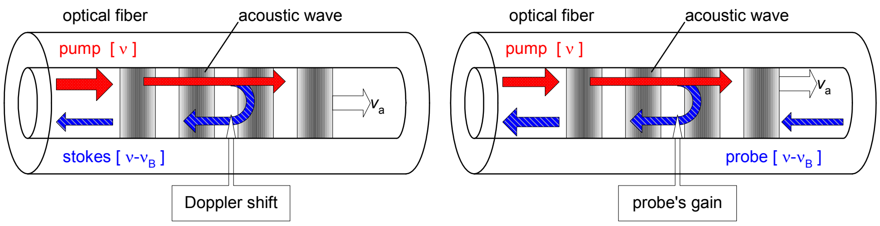
Suitable for **Temperature Sensing** only



Advantages	*Disadvantages*
Easy detection	Low backscattered power
High sensitivity	High input power required

Sensitivity: 0.8 % /K

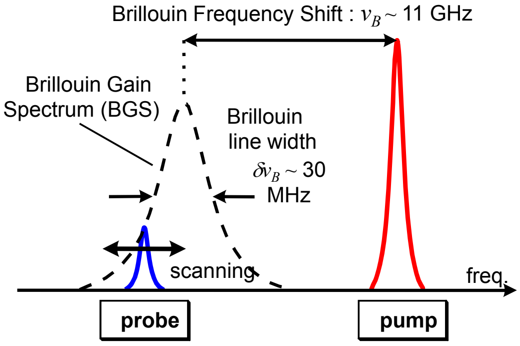
Brillouin Scattering



Spontaneous Brillouin Scattering ***Stimulated Brillouin Scattering***

- Acoustic wave works as a diffraction grating
- Stokes wave's frequency is down-shifted by Doppler shift
- Probe's gain profile is called Brillouin gain spectrum (BGS)

Utilization of BGS for Sensors



Brillouin frequency shift

$$\nu_B = \frac{2nV_a}{\lambda_p}$$

n: refractive index

V_a: acoustic wave velocity

λ_p: pump wavelength

- Brillouin **frequency shift** and **intensity** change linearly against tensile strain and temperature

$$\begin{bmatrix} \Delta\nu_B \\ \Delta P_B \end{bmatrix} = \begin{bmatrix} C_{\nu_B\varepsilon} & C_{\nu_B T} \\ C_{P_B\varepsilon} & C_{P_B T} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix}$$

$C_{P_B T} = 0.36\,\%\,°C^{-1}$

$C_{P_B\varepsilon} = -9\times10^{-4}\,\%\,\mu\varepsilon^{-1}$

$C_{\nu_B T} = 1.07\,MHz\,°C^{-1}$

$C_{\nu_B\varepsilon} = 0.048\,MHz\,\mu\varepsilon^{-1}$

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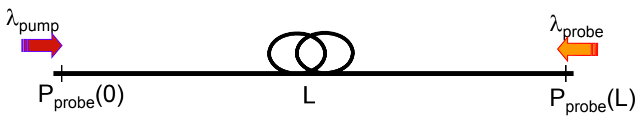
Stimulated Brillouin Scattering

A pulsed pump and a CW signal are counter-propagating along a single mode optical fiber



The probe power at $z = 0$ is maximum when the frequency difference between pump and signal is equal to the Brillouin frequency shift $\Delta f = \nu_B$ ($\approx$ 10 GHz)

ν_B is a linear function of the **temperature** T and **strain** ε with the coefficients:
$C_T \approx$ 1.1 MHz/°C, $C_\varepsilon \approx$ 0.048 MHz/με

$$\Delta\nu_B = C_T\Delta T + C_\varepsilon\Delta\varepsilon$$

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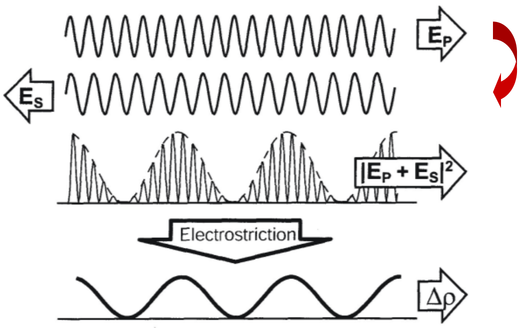
Stimulated Brillouin Scattering



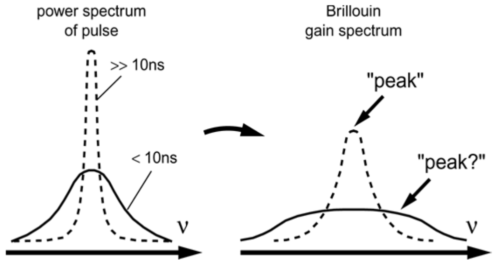
Generation of a pressure wave by electrostriction

❑ The two counter-propagating waves generate an acoustic wave through **electrostriction** effect

❑ The acoustic wave induces energy transfer from pump (lower wavelength) to signal (longer wavelength)

Limitations in conventional time domain techniques

◆ Use of a pulsed lightwave



Pulse width is set to be shorter than acoustic dumping time

Gain spectrum obtained is flattened

◆ Spatial resolution in BOTDR is limited to *~ 1m*

◆ Integration is required to obtain S/N ratio: *only static sensing*

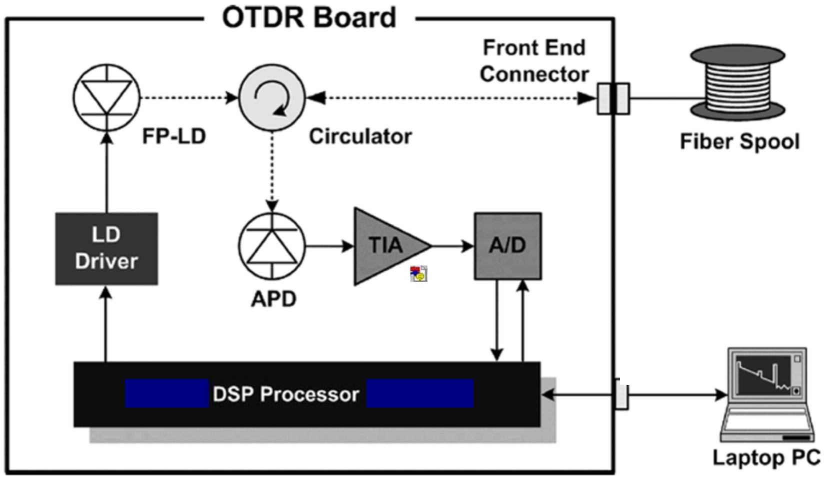
- Separating pump from Brillouin line: FBGs, coherent detection

Optical time-domain reflectometry

Optical Time Domain Reflectometry

- Overview of OTDR
- Dynamic range, dead-zones and resolution
- OTDR signal analysis
- OTDR measurements
- Use in optical communication systems

Typical OTDR Scheme

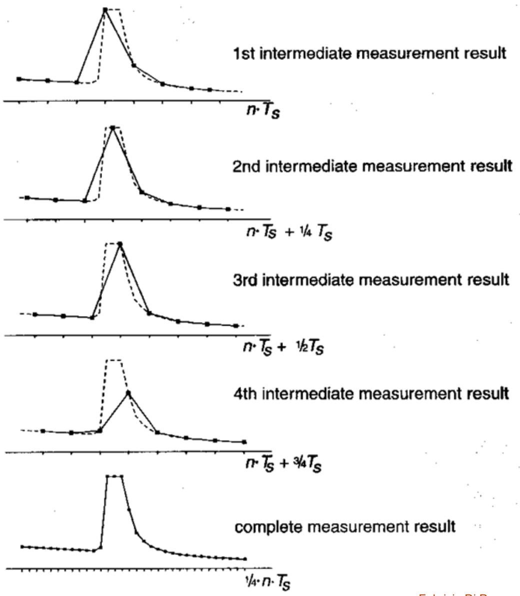


- ❑ Pulse widths between 5 ns and 1 μs (0.5 m to 100 m spatial resolutions)
- ❑ Circulator, 3 dB coupler, optical filters for detecting backscattered light
- ❑ Pin or APD photoreceiver, 1310 nm or 1550 nm, 1620 nm wavelengths

OTDR principles

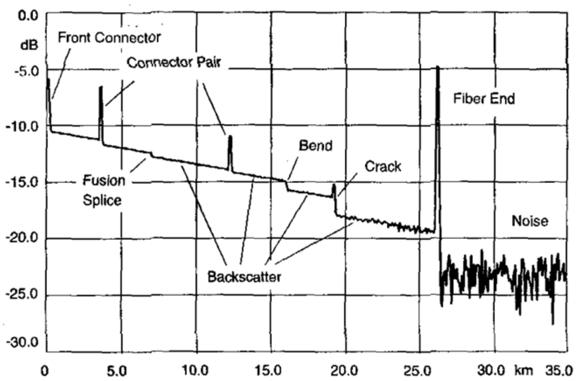
- ❑ Analog-to-digital-converter (**ADC**) is the interface from analog to digital signals
- ❑ The ADC sampling rate determines the **spatial resolution** of adjacent data samples (50 MHz sampling rate corresponds to a data spacing of ~ 2 meter)
- ❑ It is not practical to increase the resolution by increasing the sampling rate
- ❑ **Interleaved processing** schemes are usually used to improve the spatial resolution
- ❑ **High bandwidth** is required in the signal processing to avoid smoothing of the final results
- ❑ As the backscattered signal is usually weak **averaging** is used to improve the SNR

ADC interleaved sampling



- ❑ For good shape resolution, pulses should be short
- ❑ ADC sampling rate should be high
- ❑ Common use of interleaved data acquisition (longer acquisition time necessary)

Example of OTDR trace



- ❑ **Time delay with respect to pulse launch is converted into distance:**

$$T = \frac{2L}{v_g}$$

$$v_g = \frac{c}{n} \approx \frac{3\times10^8 m/s}{1.5} = 2\times10^8 m/s$$

→ **Round trip propagation delay T:** $\sim 10\,\mu s/km$

- ❑ **One-way OTDR diagrams: 5·log$_{10}$(P)**
- ❑ **X-axis accuracy: exact timing, group index, cabling factor** $\Delta T_{acc} \sim 0.01\%$

Main features of OTDR traces

- **Distributed Rayleigh backscattering gives rise to straight lines in OTDR traces**
- **Non-reflective events give rise to positive or negative steps**
  - **fusion splices**
  - **bends**
- **Reflective events give rise to positive spikes**
  - **mechanical splices**
  - **connectors**
  - **cracks**
- **Fresnel reflection at fiber end connector is about 4% of incident light**

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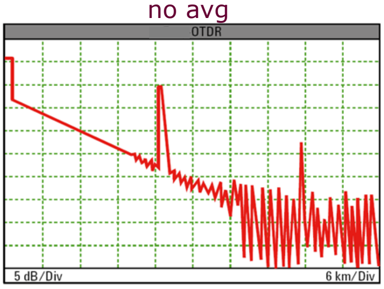
Time averaging

- SNR improved with time averaging
- Longer acquisition time
- Noise amplitude depends on number of acquired samples N as: $1/\sqrt{N}$

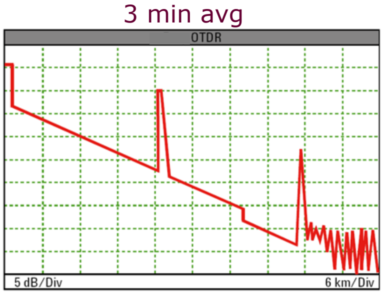
σ_{noise}	$\dfrac{\sigma_{\text{noise}}}{\sqrt{N}}$
Not averaged	Averaged

- SNR improves with averaging samples proportionally with $\sqrt{N}$
- SNR specified typically after 3 min averaging time

no avg



3 min avg



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Time averaging

Reflectivity R(z) as a function of distance is measured with OTDR (optical power reflected back is converted into electrical currents or voltages, referred as signal amplitudes)

The process is repeated many times and the measurments are averaged

R'(z) is the measured value of R(z)
R'(z)=R(z)+e where e is the noise amplitude in the measurment

Variance in the measurement: $\langle [R'(z) - R(z)]^2 \rangle = \langle e^2 \rangle = \sigma^2$ electrical noise power in the measurement

Suppose the measurement is repeated N times and $R_i'(z)$ is the i-th measurement. Assuming the noise e_i uncorrelated and zero-mean random variables, the mean value of R'(z) is:

$$\langle R'(z) \rangle = \left\langle \frac{1}{N} \sum_{i=1}^{N} R'_i(z) \right\rangle = \left\langle R(z) + \frac{1}{N} \sum_{i=1}^{N} e_i \right\rangle = R(z)$$

Time averaging

The variance (noise power) of the measurement is:

$$\langle [R'(z) - R(z)]^2 \rangle = \left\langle \left[R(z) + \frac{1}{N} \sum_{i=1}^{N} e_i - R(z)\right]^2 \right\rangle = \frac{1}{N^2} \left\langle \underbrace{\left(\sum_{i}^{N} e_i\right)^2}_{=N\sigma^2} \right\rangle = \frac{\sigma^2}{N}$$

The noise power in the measurement is reduced by 1/N and the noise amplitude by $1/\sqrt{N}$

Example of time averaging

A 20 km fiber link is tested with an OTDR at 1300 nm. Compute the noise reduction that can be achieved by signal averaging compared to a single shot measurement within the fist second and after 3 min, considering that 10% of the time is needed for processing overhead.

Round trip time for a 20 km fiber: $T = 10\frac{\mu s}{km} \times 20km = 200\mu s$

Number of averages in 1 sec: $N_{1s} = \frac{1}{200 \times 10^{-6}} \times 0.9 = 4500$

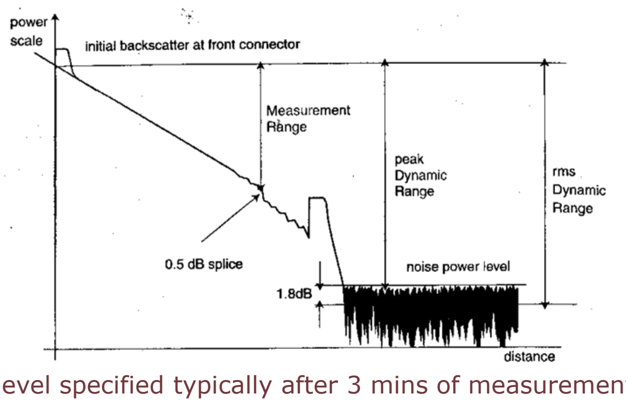
Number of averages in 3 min: $N_{3\min} = 4500 \times 180 = 810000$

The noise reduction is proportional to the square-root of N:

$$\Delta SNR_{1s} = 10 \times \log(\sqrt{N_{1s}}) = 5 \times \log(4500) = 18.3dB$$
$$\Delta SNR_{3\min} = 10 \times \log(\sqrt{N_{3\min}}) = 5 \times \log(810000) = 29.5dB$$

Dynamic Range

❑ DYNAMIC RANGE: difference between initial backscatter level and noise level in 'one-way' decibel

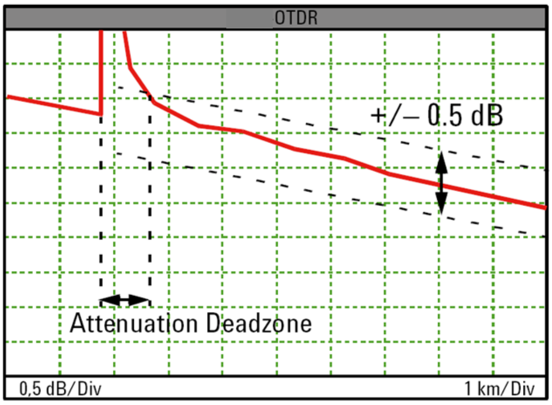


Noise level specified typically after 3 mins of measurement time

Measurement range ≠ dynamic range (measurement range deals with identification of events: 0.5 dB splice is usually chosen as the event to be identified). It is the maximum attenuation that can be inserted between the OTDR and an event for which the OTDR is still able to measure the event.

Attenuation Deadzone

❑ Reflective events cause saturation of the receiver, with recovery time inversely proportional to the receiver bandwidth



❑ ATTENUATION DEADZONE: distance from start of a reflective event and recovery within 0.5 dB of backscatter trace

Dynamic Range and Resolution

Spatial resolution: ability to detect two different events with a given distance spacing

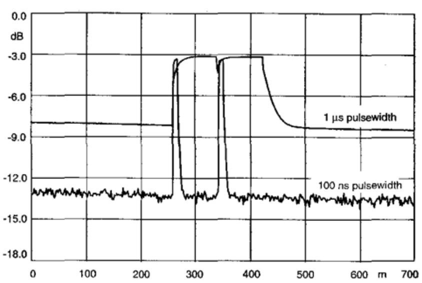
Spatial resolution typically defined as one-way distance from 10% to 90% power increase for a reflective event

RISE TIME
RESPONSE TIME

Trade-off between dynamic range and resolution: $s(t) = p(t) \otimes f(t) \otimes r(t)$

Received signal as convolution of the probing pulse p(t), **backscattering impulse response of the fiber** f(t) **and impulse response of the receiver** r(t)

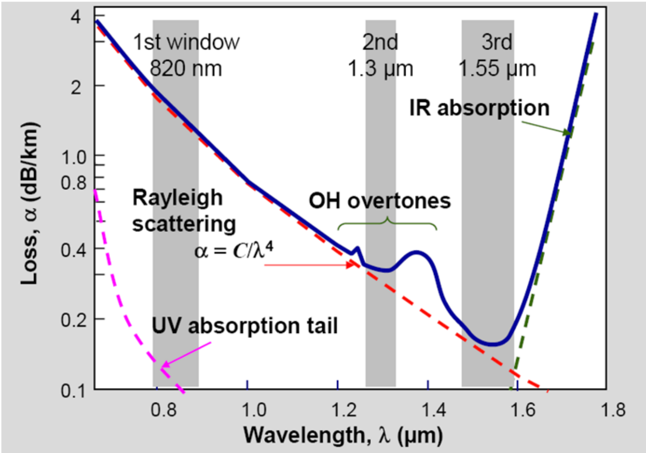
EXAMPLE



Longer pulses → higher dynamic range

→ less spatial resolution

Fiber attenuation and Scattering



Attenuation due to:

- ❑ Material absorption (intrinsic+extrinsic)
- ❑ Bending losses
- ❑ Rayleigh scattering

$$\alpha = \alpha_R + \alpha_M + \alpha_{MB} + \alpha_{mB}$$

Evolution of optical power along fiber length *z*:

$$P(z) = P_0 \cdot e^{-\alpha_\lambda z}$$

In dB: $P_{\mathrm{dBm}}(z) = P_{0\_\mathrm{dBm}} - \alpha_{\mathrm{dB/km}} \cdot z$

Loss coefficient

$$\alpha_{\mathrm{dB/km}} = \alpha \cdot 10 \log_{10} e = 4.343 \cdot \alpha$$

Rayleigh Scattering

Rayleigh scattering:

Microscopic variations of refractive index n with a spatial scale << than signal λ
cause
scattering of lightwave signal in all directions → power loss

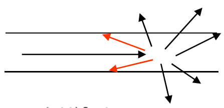
Rayleigh scattering absorption coefficient in Silica fibers:

$$\alpha_s = \frac{(0.76 + 0.51 \cdot \Delta n)}{(\lambda/\mu m)^4} \left[\frac{\mathrm{dB}}{\mathrm{km}}\right] \longrightarrow \alpha_s = \frac{C}{\lambda^4}$$

C: constant

3rd window: $\alpha_s = \alpha_R \sim 0.1$ dB/km, **absorption is dominated by Rayleigh scattering**

Signal backscattering: **A fraction of scattered signal is collected by fiber NA in backward propagating direction**



$$S = \left(\frac{NA}{n_0}\right)^2 \cdot \frac{1}{m}$$

m~4.5 for SMF, S~10⁻³

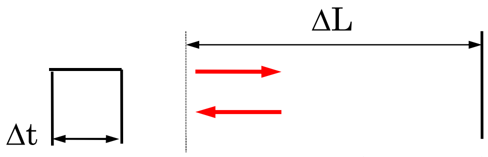
Rayleigh back-scattering coefficient γ :

$\gamma = S \cdot \alpha_R$ *S*: capture factor (fiber geometry, NA)

$\gamma \sim 10^{-4}$ 1/km

Measuring Distance with Light Pulses (OTDR) Spatial Resolution

Optical Time-Domain Reflectometry



$$\Delta L = c\Delta t/(2n)$$

Spatial resolution is basically determined by the pulse-width.

In glass (fiber):

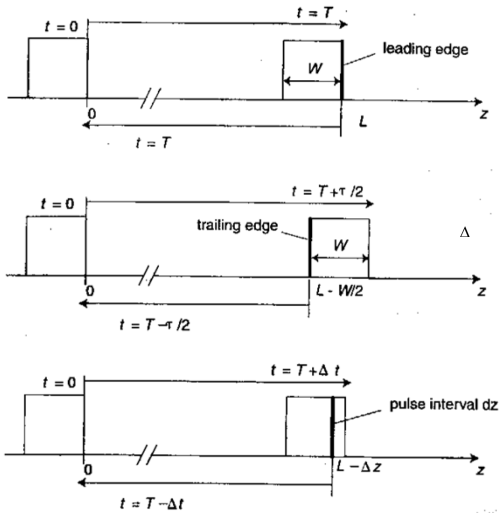
10 ns ➡ 1 m

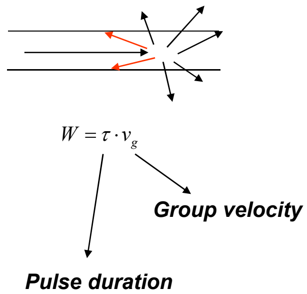
1 ns ➡ 10 cm

1 ps ➡ 0.1 mm

$c = 3\times10^{8}$ m/s

Analysis of OTDR traces





$\gamma = S\alpha_s$

α_s: backscattering coeff. ~$1/\lambda^4$

S: capture factor

Scattered power at position z with infinitesimal length interval dz:

$$dP_s(z) = \gamma \cdot P(z) \cdot dz$$

Analysis of OTDR traces

❑ Integrating on pulse spatial width W we obtain total received power at time T, corresponding to the distance L :

$$P_s(L) = \int_0^W S \cdot \alpha_s \cdot P_0 \cdot \exp\left(-2\alpha\left(L + \frac{z}{2}\right)\right) dz \qquad W = \tau \cdot v_g$$

❑ For short pulses $\alpha W << 1$ ($W<<1/\alpha$) we can simplify the expression at fiber distance L:

$$P_s(L) = S \cdot \alpha_s \cdot W \cdot P_0 \cdot e^{-2\alpha L} = \overbrace{S \cdot \alpha_s \cdot \tau \cdot v_g}^{\sigma} \cdot P_0 \cdot e^{-2\alpha L}$$

For short pulses the backscattered power is proportional to the pulse duration τ

Backscatter factor σ **:**

$$\sigma(dB) = -10\log(S\alpha_s W) = -10\log(S\alpha_s \tau v_g) \text{ [dB/}\mu\text{s]}$$

Analysis of OTDR traces

❑ Backscattered power proportional to pulse duration

$$P_s(L) = S \cdot \alpha_s \cdot W \cdot P_0 \cdot e^{-2\alpha L} \qquad W = \tau \cdot v_g$$

❑ BACKSCATTER FACTOR is typically specified for optical fibers:

TYPICAL VALUES

$$\sigma = -10 \cdot \log(S \cdot \alpha_s \cdot W)$$

λ [nm]	Fibertype	α_s [km^{-1}]	S	σ [dB/1 μs]	η [W/J]
850	MM-SI 50μ	$3.5 \cdot 10^{-1}$	$1.1 \cdot 10^{-2}$	31	385
1300	MM-GI 62.5μ	$6.5 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$	38	65
1300	MM-GI 50μ	$6.5 \cdot 10^{-2}$	$5.0 \cdot 10^{-3}$	41	32
1310	SM 9μ	$6.3 \cdot 10^{-2}$	$1.0 \cdot 10^{-3}$	49	6.3
1550	SM 9μ	$3.2 \cdot 10^{-2}$	$1.0 \cdot 10^{-3}$	52	3.2

Analysis of OTDR traces

Example: 100 km fiber is probed with an OTDR having a peak output power of 13 dBm and the pulsewidth is 10 μsec.

Calculate the backscattered power returning from the far end of the fiber having attenuation of 0.33 dB/km, a scattering coeff. α of 0.3 dB/km and capture factor S=10^{-3} at 1300 nm.

$$P_s(L) = S \cdot \alpha_s \cdot W \cdot P_0 \cdot e^{-2\alpha L}$$

$$P_s(100km) = 0.001 \times (0.3 \times 0.23) \times 2 \times 20mW \times e^{-2\times(0.33\times0.23)\times100} =$$

$$= 35.3 \times 10^{-12} \times 20mW = 0.75\,pW = -91.5dBm$$

$$W = \tau \cdot v_g = 2km$$

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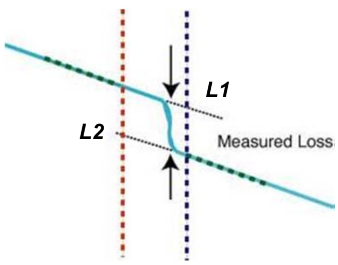
Measurement of splice and connector losses

OTDR can be used to measure loss from splices, bending and connectors

Different Rayleigh backscattering coefficients before and after an event can affect the inserction loss measurement accuracy



Least-square-approximation is usually used to determine the slopes and positions of the two lines L1 and L2

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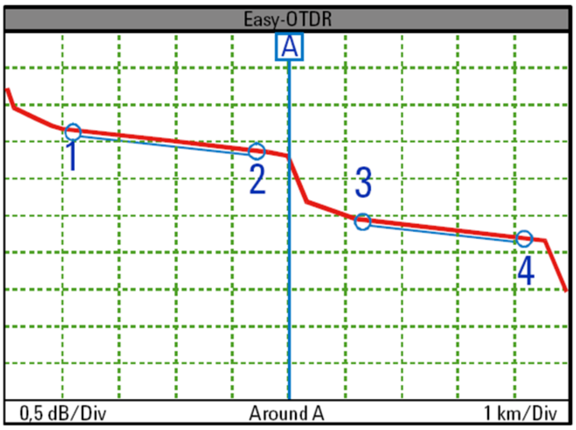
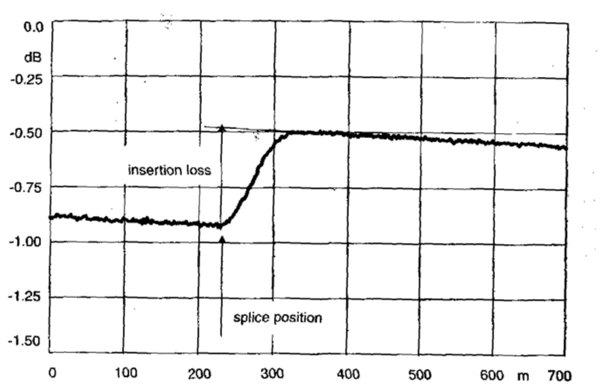
Splice Loss Measurement



- Least mean square approx of attenuations
- Backscatter coefficients should be the same for the two fibers

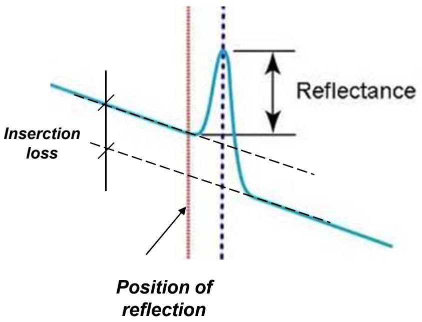
Splice Loss Measurement

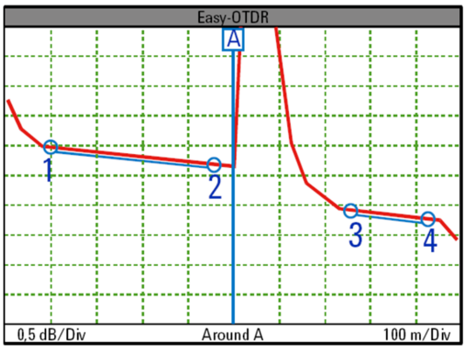


- If BS coefficients are not the same, then 'gain' can be seen by OTDR

Insertion Loss Measurement

Air gap of a tiny crack, a mechanical splice, a connector are examples of reflective events.
Also misalignement of connectors, mismatch in core dimensions or NA can induce additional losses





Extrapolation of reflection point for IL measurement in a reflective event