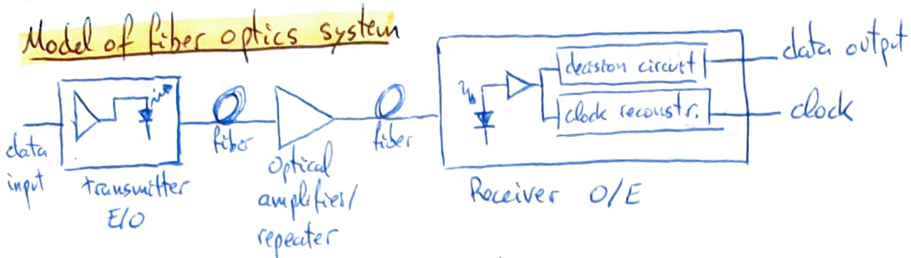
Lecture 3: Fiber Optics Systems

Model of fiber optics system

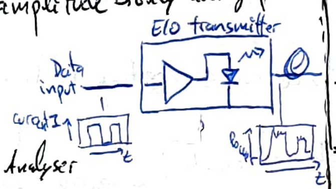


Kind of measurements
- Power losses along the fiber link
- Time-domain Reflectometry:
  - ↳ we find a break in the fiber

More required measurement for modern fibers
- Wavelength Division Multiplexed (WDM): Multiple channels in the same fiber need measuring:
  Power, SNR, and optical wavelength for each channel
- Very High Transmission Rates (10th GHz): Is needed to
  - ↳ monitor emission spectrum of transmitter lasers
  - ↳ and chromatic dispersion of the fiber
  - ↳ BW of transmi and receivers optimized
- Use of Optical Amplifier (OA): Make possible to introduce very lossy components → MUX, DEMUX
- Short Range Links:
- Increasing complexity

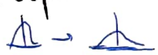
Basic Components characterization

Transmitter: (elec) current to power (opt) converter
→ Optical signal is NOT amplitude signal but a power signal
→ Too fast so no detector can detect amplitude → only average power
→ { Laser → Long range transmi
  LED source → Short range transmi



→ Two possibilities for output signal
- ↳ We want Optical signal → Optical Spectrum Analyser
- ↳ We want Power signal as function of time { oscilloscope / spectrum anal
  - ↳ First convert to electronic signal then

Optical Fiber:
→ Measure attenuation: dB/Km
→ Chromatic Dispersion: velocity inside the fiber depends on λ
the pulse will be broader



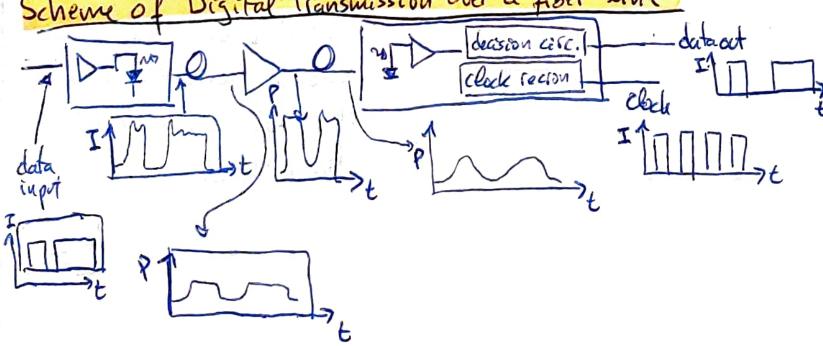
→ Losses: 0,2 dB/Km @ λ=1550nm

Amplifier:
→ To compensate losses
→ Worse SNR, signal distortion
→ High Output power

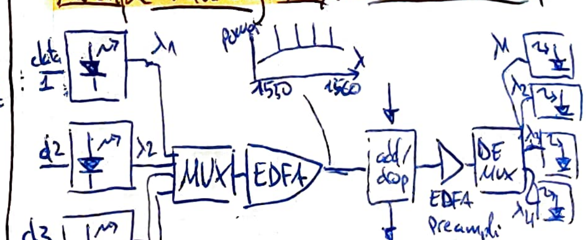
Repeater:
→ Convert Optical signal to Electrical signal
It is reshaped and retrasmitted
→ Is a receiver combined with a transmitter

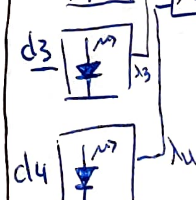
Receiver:
→ Power (optical) to Current (elect) converter
↳ Uses: PIN diode or APD (Avalanche - Photo-detectors)
→ Automatic Gain Control: to solve the fluctuations
→ Clock Reconstruction: It is transmitted along with the signal.
→ To test the receiver we need high velocity electronic instruments

Scheme of Digital transmission over a fiber link



Multiple Wavelength System → WDM





Specific measurements
- → Absolute measurement of λ with accuracy 0,01nm
- → Measur. laser-source λ stability of 0,001nm
- → Loss measurement as a function of λ

Characterization of an Optical fiber digital link

→ We use a signal, put the fiber under test and check at the receiver (comparing with original pattern) if there are errors by computing Bit-Error-Rate (BER)

↳ Pseudo Random Binary Sequence ⇝ length: $2^{23}-1$

↳ BER values ⇝ 10^{-9} to 10^{-13}

↳ BER as function of fiber loss

Waveform Analysis

→ BER only tell us that there is a problem but not where.

→ We analyse the waveform at the output to know what is happening

Clock Jitter Measurements

→ It is the unwanted clock variation. We have to keep it in control to do not make errors when sampling the signal.

→ Jitter tolerance: The max. level of input jitter that can be tolerated at receiver for a given BER

→ Jitter generation: The measurement that let us know how much jitter is generated by the device we are testing

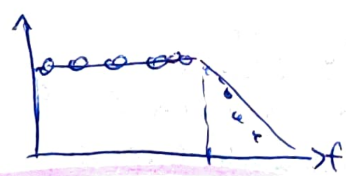
→ Jitter transfer: The capability of the device we are testing to transfer the input jitter to the output.

To do: at input measure jitter + clock
at output measure jitter + clock } Comparing → get transfer jitter

→ Slide 18 – Optical PDF 1

We have the input clock and we induce or modulate with a jitter.

We use a phase detector input clock → $\boxed{PD}$ → output clock and we get the transfer function



We have here kind of cut-off freq.
We can reconstruct the jitter when is slow enough, when the receiver stops following we have the attenuation

Optical Power Measurements

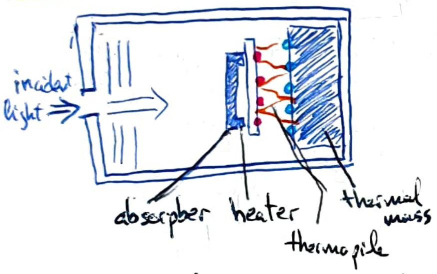
o) Absolute measurement
→ I want to know (the power) in International System Units
→ It has to be traceable
→ When we do?
optical sources charact., detectors/receivers charact. / safety measurement

o) Relative measurement
→ I just want to know the ratio
→ NOT necessarily traceables
→ When we do?
loss / attenuation
gain
insertion loss

o) Optical power measurements are based on electrical power measure
There are two kind: Thermoelectric detectors or electronic photo-detectors

o) Features:	Dependence on λ	auto-calibration	sensitivity	Uncertainty
Thermoelectric	very low, wide range	yes	low	$\pm 1\%$
Electric	very high, short range	no	very high	$\pm 2\%$

Thermoelectric Detectors



① A) The light enters, we want to measure power
B) Absorber temperature increase
The temp. difference between absorber and thermal mass is $\Delta T \propto P_{opt}$
C) Measure ΔT using thermopile

② D) Close the hole so no more light comes the absorber cooldown.
E) Start the heater until get the same ΔT as before
F) Now we measure the electrical power needed for the heater and $P_E = P_{opt}$

o) It is a slow measurement (few secs)

P-I-N photo-detectors

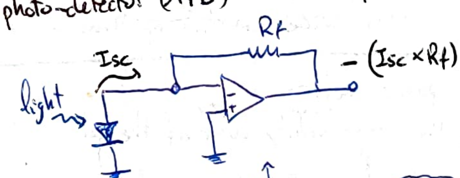
o) Basic idea: incident photons are absorbed by the intrinsic layer and it is converted in an electron.

o) Responsivity: Ratio between the photo-current produced by the optical power $r(\lambda) = \frac{I}{P_{opt}} \left[\frac{A}{W}\right]$
↳ It is dependent of λ
↳ There is threshold and a range of λ where we can use
↳ Halving (-3dB) the optical power ⟶ current reduced by -6dB
↳ Also depend of temperature (shift the cut-off)

o) Materials: Si, Ge, InGaAs → the different materials are used to absorb different λ

o) Very fast response, BW ~ 100 GHz

o) Avalanche photo-detector (APD) → Lower speed (few $\frac{GHz}{BW}$), higher sensitivity



Optical Power emitted by a broadband source

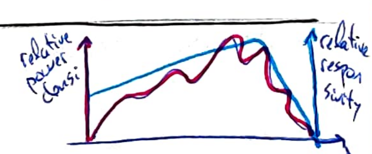
↳ Slides 10, 11
↳ We cannot use a photo-diode to measure the emitted total power because we need to know the power spectral density $I_{tot} = \int r(\lambda)\, p(\lambda)\, d\lambda$ → total photo-current

o) Relative responsivity: $r(\lambda) = r_{\lambda_0} \cdot r_{rel}(\lambda)$
r_{λ_0} → responsivity at reference λ
$r_{rel}(\lambda)$ → the graph

↳ Total photo current $I_{tot} = \underbrace{r_{\lambda_0}}_{\text{scaling factor representing the sensitivity}} \underbrace{\int r_{rel}(\lambda)\, p(\lambda)\, d\lambda}_{\text{form factor}}$

characterization (of family) by
→ shame relative responsiv.
→ different sensitivity

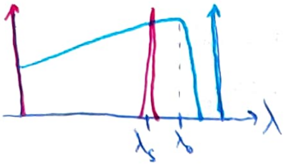
o) Relative power spectral density
$p(\lambda) = p(\lambda_0)\, f(\lambda) = P_{\lambda_0} \underbrace{f(\lambda)}_{\text{relat. power densi.}}$



total photocurrent $I_{tot} = \underbrace{P_{\lambda_0}}_{\text{absolute power of light source}} \underbrace{r_{\lambda_0}}_{\text{sensitivity of detector}} \int \underbrace{f(\lambda)}_{\text{light source}}\, \underbrace{r_{rel}(\lambda)}_{\text{kind of photodiode}}\, d\lambda$

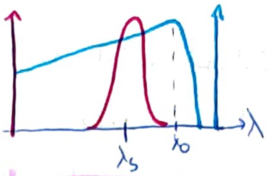
depends on the type of photodiode and on the type of light source

o) Optical power emitted by monochromatic source



$$P_{tot} = \frac{I}{r_{\lambda_0} r_{rel}(\lambda_s)}$$

o) Optical power emitted by a LED



$$P_{LED} = \frac{1}{r_{\lambda_0}} \frac{\int f(\lambda) d\lambda}{\int r_{rel}(\lambda) f(\lambda) d\lambda}$$

→ If emission simmetric respect λ

→ If responsibility linearly changes with λ

$$P_{LED} = \frac{I}{r_{\lambda_0} r_{rel}(\lambda_s)}$$

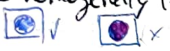
Power Meter with photo-detectors

o) For accurate measurements we need:

→ Correction for each λ (know the relative responsibility for each λ)

→ Temperature stable (Peltier cooler)

→ Space homogeneity (Active area, intrinsic light absorber material



→ Minimize reflections (tilt the glass (back to laser source)

o) Non linearity of the power meters

→ Very large dynamic range

$\frac{I_{max}}{V_{noise}} \sim 10^{-6}$ (6 decade)

→ Detector non-lin.

↳ With low optical power → noise effect (electronic) on the current

↳ Medium optical power → supra-linearity

↳ High optical power → saturation

→ Electronic non-lin.

↳ Low power → offset

↳ High power → saturation

Photo-detector noise

We represent current noise in terms of noise equivalent (optical) power (NEP)

↳ We think about an ideal photo-detector having no noise, and a source of noise reported at the input with an equivalent power producing the same level of the noise at the output

$$NEP = \frac{1}{r}\sqrt{2 e B_n (2 I_{dark} + r \cdot P_{opt})} \quad \left[\frac{W}{\sqrt{Hz}}\right]$$

responsivity; noise equivalent power; current when no light; incoming optical power

$$SNR = \frac{P_{opt}}{NEP}$$

o) Applications of power meter

→ Do absolute measurements: Power level at a certain λ

use optical attenuators for high power levels

when wide emission spectrum → do a correction

→ Do a calibration of power meter: we have to determine the relative responsibility curve of the sensing head.

We do for many λ and using a reference system (standard sensor)

We know the responsivity of the standard sensor

We do $\frac{P_{read}}{P_{ref}}$ → and do the responsibity of the power meter

Uncertainty of optical power measurements

→ Fluctuations of power of light source (feedback)

→ Power meter calibration (accuracy +/- 2%)

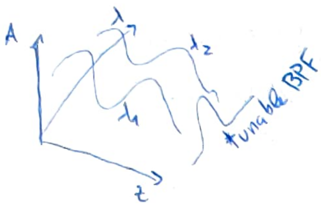
→ Systematic errors

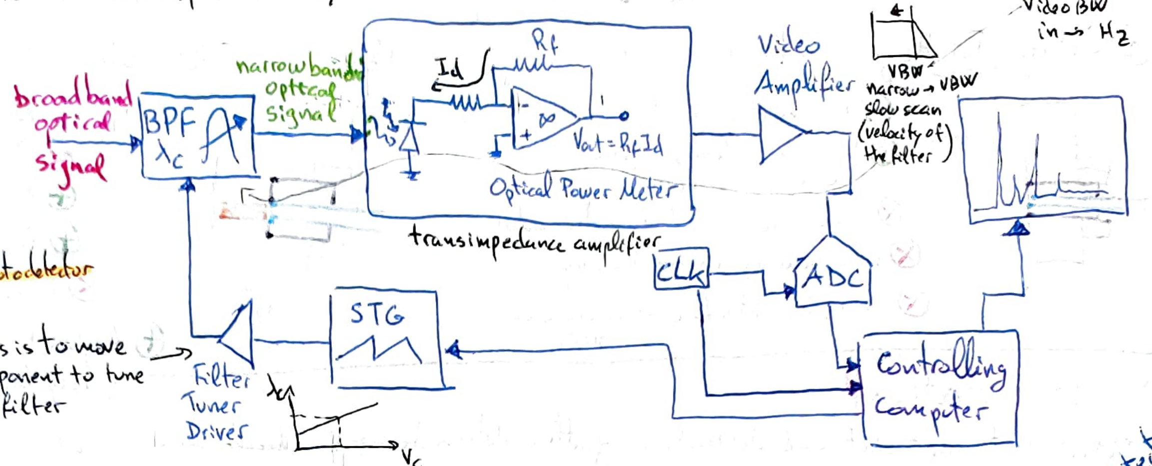
Optical Spectrum Analysis (OSA)

→ Reminder: The reading (i.e. $-3{,}8\,dBm$) is normalised along the BW of $1nm$ → $\frac{-3{,}8\,dBm}{1\,nm}$ | Resolution BW → in nm

Video BW in → Hz

The scheme is similar to the radio spectrum analyser





this is to move a component to tune the filter

Spectrometer: Monochromator + Photodetector

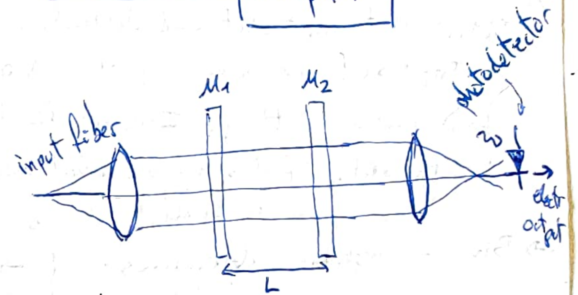
OSA: Automatic Spectrometer

•) Fabry-Perot Filter

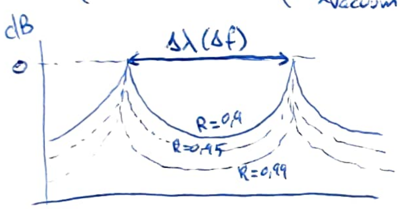
→ It is based in a resonant cavity formed by two mirrors

→ Only the resonant λ will pass through the filter (constructive interference)

→ We can tune the filter by changing the space between the mirrors.



$$T = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2\left(\frac{2\pi L n\cos\theta}{\lambda_{vacuum}}\right)}$$



•) We can see that the filter let pass through those two λ. so we cannot use the filter for broad bands

•) The selectivity (width of peaks) → $\delta f_{1/2}$ depends on the reflectivity R

•) Spacing between the peaks: $\Delta f = \frac{c}{2Ln\cos\theta}$

↳ in term of λ (free spectral range FSR) $|\Delta\lambda| = \frac{\lambda^2}{2Ln\cos\theta}$

•) Finesse: Express the quality of Fabry-Perot filter

It is related to the reflectivity R

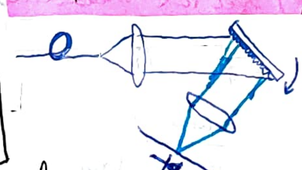
•) Main characteristics

→ Very high wavelength resolution

→ Narrow wavelength range

→ Use mirrors with reflectivity in regions to reduce periodicity

•) Diffraction-Grating



We use a collimated lens to create a plane wave

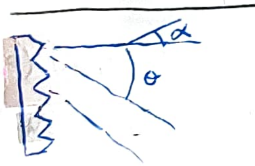
We illuminate the diffraction grating at an angle

So it reflects at an angle depending on d, λ

We put another lens to makes the light beam focus onto the photodiode's aperture.

If another ligh with other λ comes it won't be alligned with the photodiode ⇒ Filtering

By rotating the diff. grating we allign for a different λ



•) We have to avoid the overlapping of different orders n. But the band is broader than Fabry-Perot

•) Diverge angle $\Delta\theta_{min} = \frac{\lambda}{N d\cos\theta}$

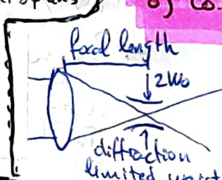
↳ kind of diameter of lens

$n\lambda = d(\sin\theta - \sin\alpha)$

•) Dispersion of different λ $D = \frac{\Delta\theta}{\Delta\lambda} = \frac{n\,(\text{ref index})}{d\cos\theta}$

•) Best resolution $\Delta\lambda_{min} = \frac{\lambda}{N \cdot n}$

•) Collimating Optics



→ We can use mirrors or lenses to build it

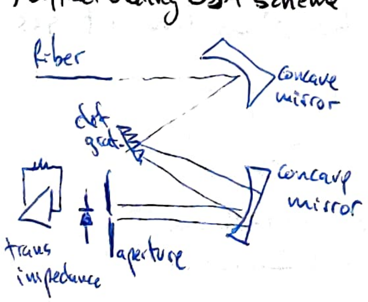
→ The collimator focal length should be independent of wavelength λ. Mirrors are not dispersives so we prefer over lenses

→ Diameter large as possible to achive wavelength resolution

→ Performances limited by diffraction

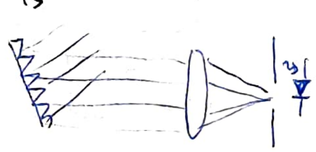
$W_0 = \frac{2\lambda F}{\pi D}$

•) Diffract Grating OSA scheme



•) Focusing Optics

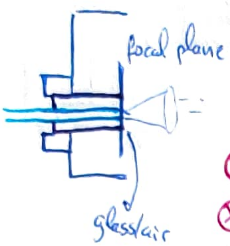
Converts the diffraction angle into a position of the light spot on focal plane where detector is



Input Stage of OSA

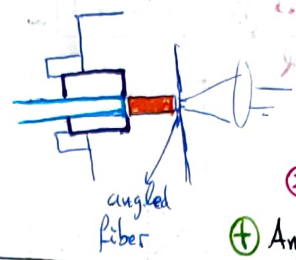
: It is the input aperture of monochromator, so we have to put the optical signal exactly in the focus of collimating optics.

① Option: Put the fiber in the focal point



- ⊕ No insertion loss
- ⊕ No risk to damage input of monochromator
- ⊗ Risk pollution of monochromator
- ⊗ Low accuracy in positioning
- ⊗ Air/glas interface → return loss 14dB

② Option: Put a short optical fiber in between



- ⊗ No predictable insertion loss
- ⊗ Risk of damaging
- ⊕ No pollution risk
- ⊕ Perfect positioning
- ⊗ Fiber/Fiber interface → return loss 28dB
- ⊕ Angled fiber makes reflections back very low

Light Detection

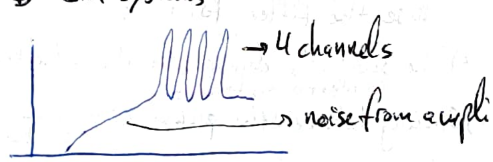
→ Output slit, input slit and diffraction gratting determine ⇒ Wavelength resolution of OSA
- ↳ Input slit: depending on positioning λ resol better or not
- ↳ Diffraction gratting: Inherent limit of λ resol.
- ↳ Output slit: If it is big we collect more power but worse λ resol.
- " " " small " " less power " better λ resol.

→ BW of amplifier determines:
- ↳ sweep velocity
  

- ↳ instrument sensivity
  - ↳ increase sensi ⇒ slow scan ⇒ reduce BW ⇒ reduce noise BW ⇒ better SNR
  - ↳ low sensitivity ⇒ fast scan

⇒ BW has to match with scan velocity

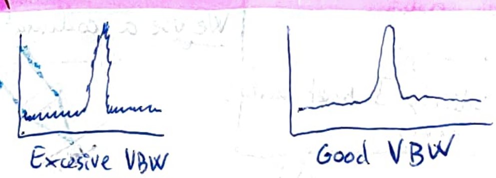
→ Dynamic range very important for DWDM systems



Sensitivity

→ Limiting Factors
- ↳ Monochromator is lossy (3 to 8 dB)
- ↳ Detector sensitivity
- ↳ Electronic BW of photodetector (Video BW)

Spectral measurements on modulated signals

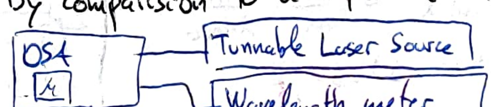


Triggered-Sweep mode

- ↳ ADC trigger mode
- ↳ ADC-AC mode

Wavelength calibration of OSA

→ By comparision to a reference λ meter



→ By comparision with known absorption lines of gas

↳ We know the absorption is at $\lambda = 1530\,nm$ and we receive another readout → correct

Monitoring of loss in installed fiber links

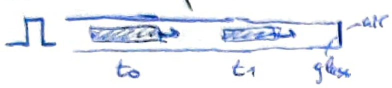
→ Necesity to verifying if the installation works well ⇒ The total loss determine the quality of the transmission

→ Fiber loss and attenuation: due to:
↳ humidity, temperature and mechanical stress ⇒ Measure the loss not only in the lab, but in the installation

→ We use **Optical Time Domain Reflectometer (OTDR)**

•) Principle of Operation

① Launch a pulse into the fiber



② At the end of the fiber, reflection

③ After a given time the pulse will reach the input of the fiber.
And we see at this pulse.

→ Why the light comes back? Causes:

↳ Macro discontinuities
connectors, splices, fractures

↳ Back scattering
linear: Rayleight due to inhomogeneities
non-linear: Brillouin, Raman

→ Attenuation of power along the distance:

↳ Optical power at dist. z ⇒ $P(z) = P_0 e^{-\alpha z}$

↳ attenuation $\alpha_{dB/km} = \frac{10 \log\left(\frac{P_0}{P(z)}\right)}{z} \simeq 4{,}34\alpha$

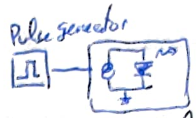
↳ Total attenuation

$\alpha = \alpha_{absorbance} + \alpha_{scattering} \simeq \alpha_{scattering} \underset{\text{Rayleigh}}{\simeq} \frac{1}{\lambda^4}$

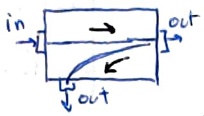
↳ Remember that pulse propagation is affected by both foward and backward direction.

→ Components

⊛ Pulse generator + Laserdiode

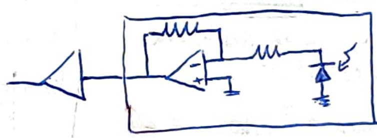


⊛ Directional Coupler: We want to launch the pulse into the fiber under test and we also to catch the light coming back from the fiber

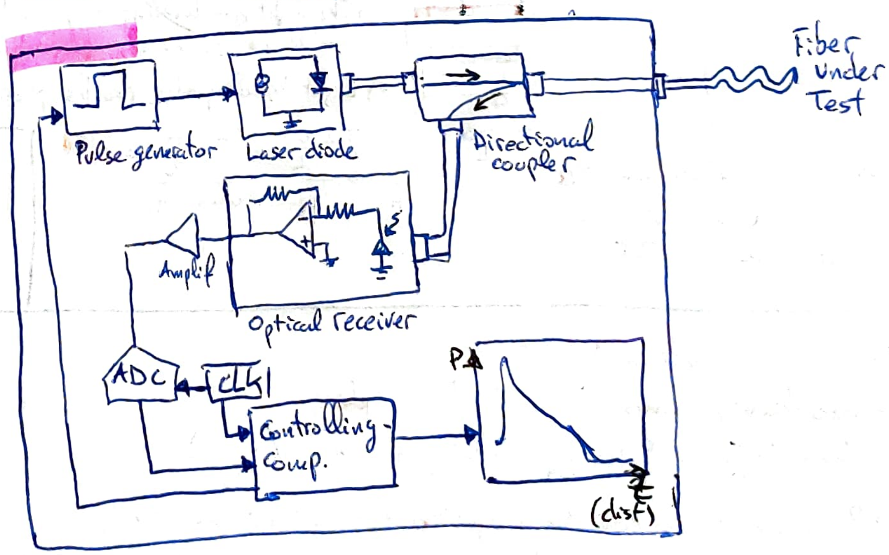


⊛ Optical power meter + Amplifier: We use the photodiode and the transimpedance amplifier to convert photocurrent into voltage
And then amplify the signal

The receiver must be very sensitive bc the pulse back is low

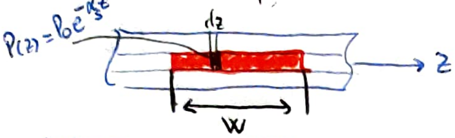


⊛ ADC and Computer: We converter to digital form to obtain the trace
We know the velocity of light inside the fiber
so we convert time (t) $\xrightarrow{\text{to}}$ distance (dist)



•) Bakscattering Analysis: What is the power level I am expecting at photodector as function of the time delay from pulse injection into the fiber.
(At given time t which is the level of the power reaching the photodetector?)

① We have the pulse inside the fiber



$\tau \to$ pulse duration
$v_{gr} \to$ group velocity
$n_{gr} \to$ group refractive index

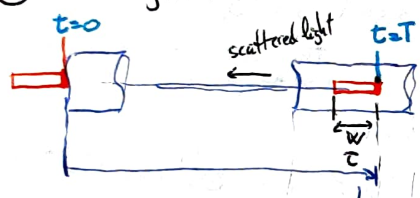
$W = \tau \cdot v_{gr} = \tau \dfrac{c}{n_{gr}}$

② Scattered power is coincident with loss power
$dP_s = \alpha_s P(z) dz$ ⇒ Only a small fraction of dP_s will enter back into the fiber and guided to the photodector

③ The fraction can be represent through S
$dP_S = S \cdot dP_s = S \cdot \alpha_s P(z) dz \simeq S \dfrac{1}{\lambda^4} P(z) dz$

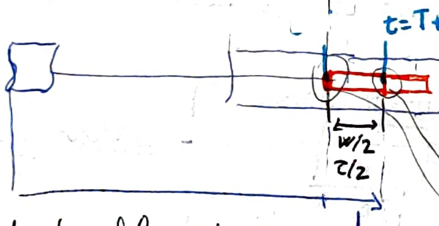
↳ S is the fraction represented by $S = \left(\dfrac{NA}{n_0}\right)^2 \dfrac{1}{m}$

④ At a given T:



The light scattered in this position will reach the photodetector
$T_{forward} + T_{backward} = 2T$

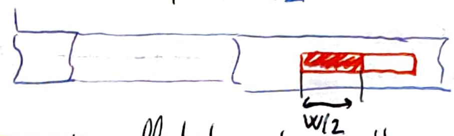
⑤ After $t = \tau/2$



$t = T + \tau/2$
•) Trailling edge at $L - W/2$
•) The light at trailling is generate at time $t = T + \tau/2$ (light backwards)
•) Light trailling edge reachs photodect at:
$\underbrace{T + \frac{\tau}{2}}_{\text{forward trip}} + \underbrace{T - \frac{\tau}{2}}_{\text{backward trip}} = 2T$

→ Any time delay $\Delta t \leq \tau/2$ will reach the photo sensor at same time 2T

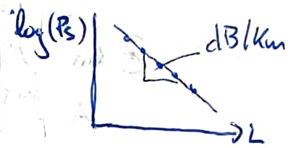
⑥ The light collected at photodector at time 2T will be all from W/2



The power collected is due to the scattering of a region of the fiber, not only from a point

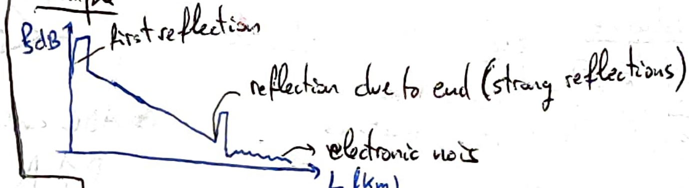
$$P_s(L) = \int_{L-W/2}^{L} e^{-\alpha z} dP_s = \int_{L-W/2}^{L} S\alpha_s \left(P_0 e^{-\alpha z}\right) e^{-\alpha z} dz = \frac{S\alpha_s P_0}{2\alpha} e^{-2\alpha L}\left(e^{\alpha W} - 1\right)$$

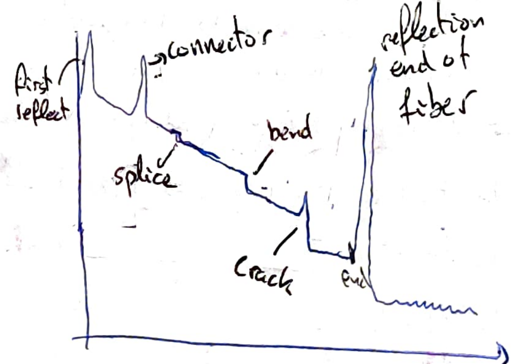
↳ For short pulses simplify:
$P_s(L) = P_0\, k \cdot W\, e^{-2\alpha L}$



Backscattered factor: Injected power over the measured power at position zero
$\sigma = 10 \log \dfrac{P_0}{P_s(0)} = -10 \log(k \cdot W)$

Example





•) Some Conclusions

→ Uncertainty comes from refraction index
$W = \tau \cdot \dfrac{c_0}{n} = 5\,ns \cdot \dfrac{1}{1{,}5} \cdot 3 \cdot 10^8 \dfrac{m}{s} = 1\,m$ (resolution)

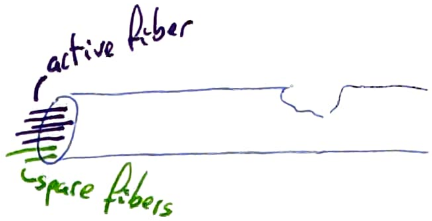
→ Pulse duration can be adjusted: It affect sensitivity
↳ Longer pulse: High sensitivity (High Power) ⇒ Worse distance resolution → Use for long fiber
↳ Short pulse: Low power (maybe it doesn't reach photodetector) ⇒ Better resolution → Use for short fiber

→ Increase SNR by averaging with great number of pulses
↳ Distance between two pulses must be greater than roundtrip time

• Use OTDR to monitor fiber installations

→ Technique: Dark fiber testing

To see if there is something wrong along fiber cable.
Do the measurement on spare fibers
We avoid interferences with data traffic



→ Technique: Active fiber testing

To avoid disturb data traffic we use two different wavelengths. We use filters.