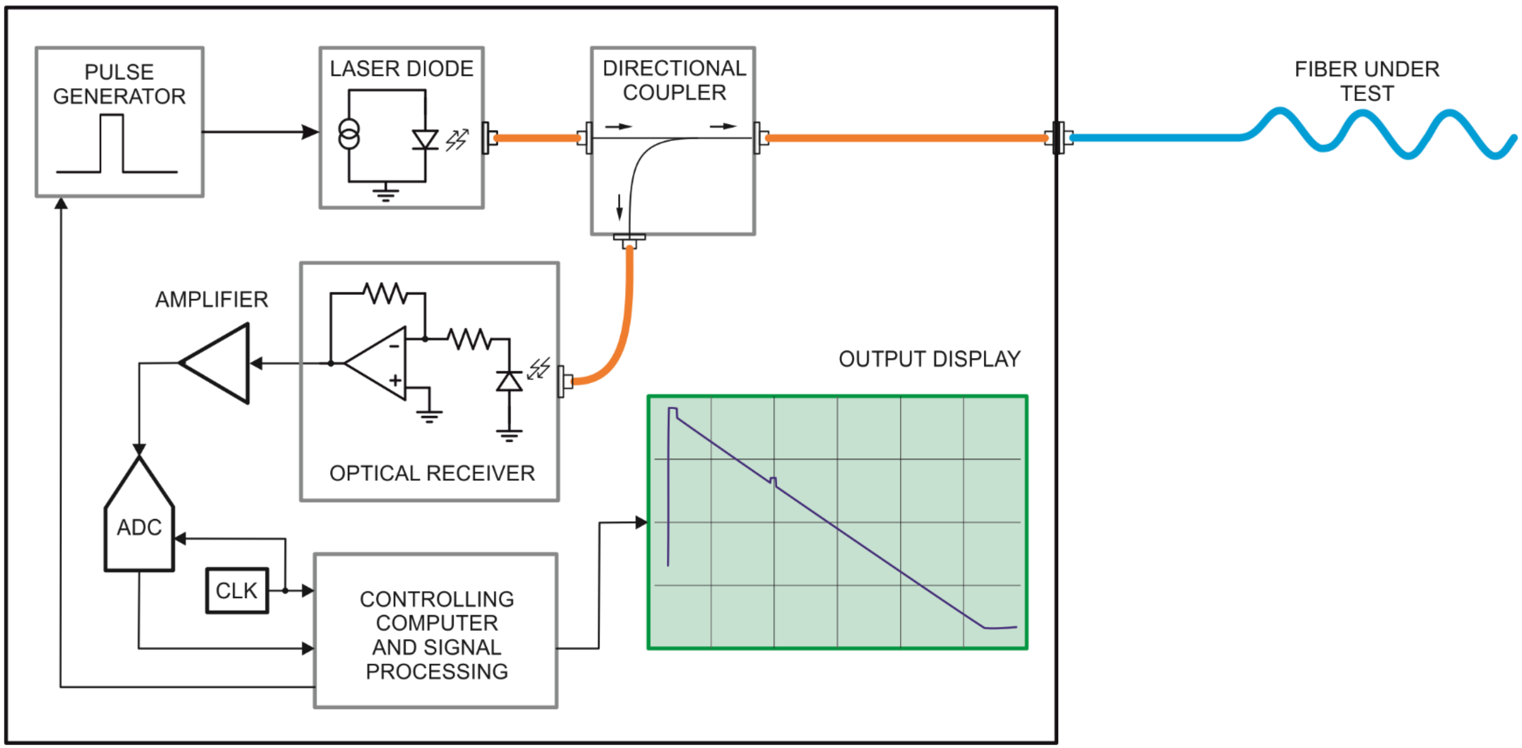
Monitoring of loss in installed fiber links

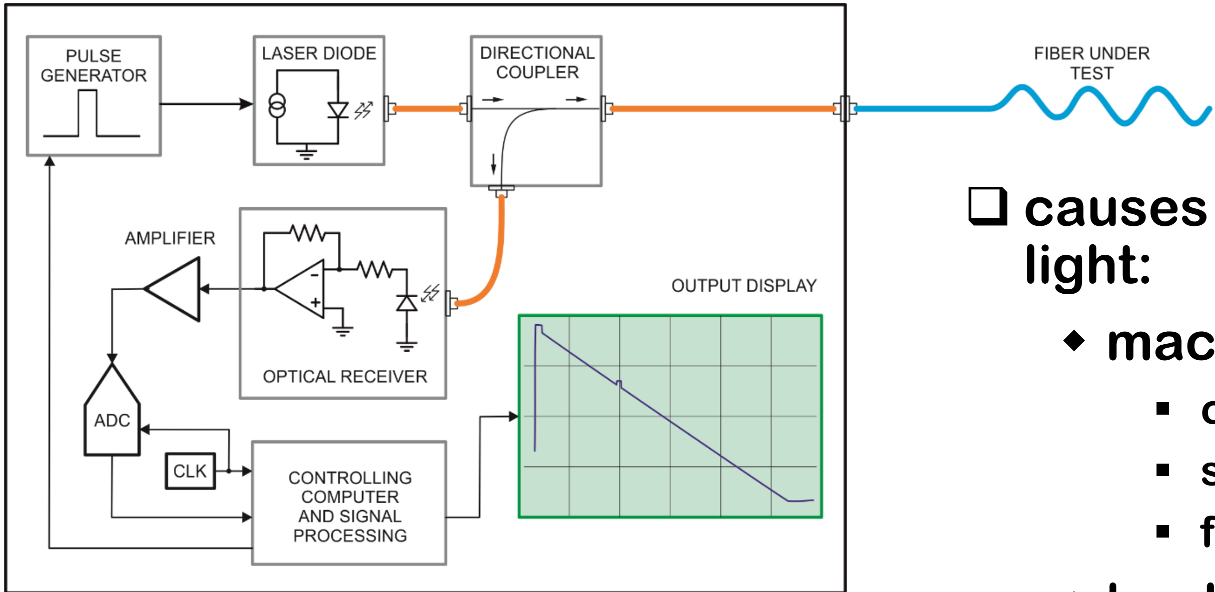
- the total loss of the fiber link determines the quality of the transmission system
- fiber loss and attenuation are subject to environmental influences, mainly:
  - humidity
  - temperature
  - physical stress
- a non-destructive method for measuring the loss is required
- the Optical Time Domain Reflectometer (OTDR) is the right solution for monitoring installed optical fibers

OTDR: principle of operation

- a short duration pulse is launched into the fiber
- the power of the light coming back to the fiber input end is recorded as a function of delay from pulse launch



OTDR: principle of operation



- ❑ causes of back propagating light:
  - macro discontinuities:
    - connectors,
    - splices,
    - fractures, bending, …
  - back scattering

- ❑ scattering:
  - linear:
    Rayleigh, it is due to density fluctuations in the fiber, inhomogeneities
  - nonlinear:
    Brillouin, due to acoustic waves inside the fiber
    Raman, due to molecular vibrations

Backscattering analysis

- given P_0 the optical power entering the fiber, the power at a distance z is:

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

  where α is the attenuation coefficient (km^{-1})

- expressing the attenuation in dB/km:

$$\alpha_{dB/km} = 10\, log_{10}\left(\frac{P_0}{P(z)}\right)\frac{1}{z} = 10\,\frac{1}{z}\, log_{10}(e^{\alpha z}) = 10\,\frac{1}{z}\ln(e^{\alpha z})\,\frac{1}{\ln(10)} = \frac{10\alpha}{\ln(10)} \cong 4.34\alpha$$

- the total attenuation is normally written as: $\alpha = \underbrace{\alpha_a}_{absorbance} + \underbrace{\alpha_s}_{scattering}$

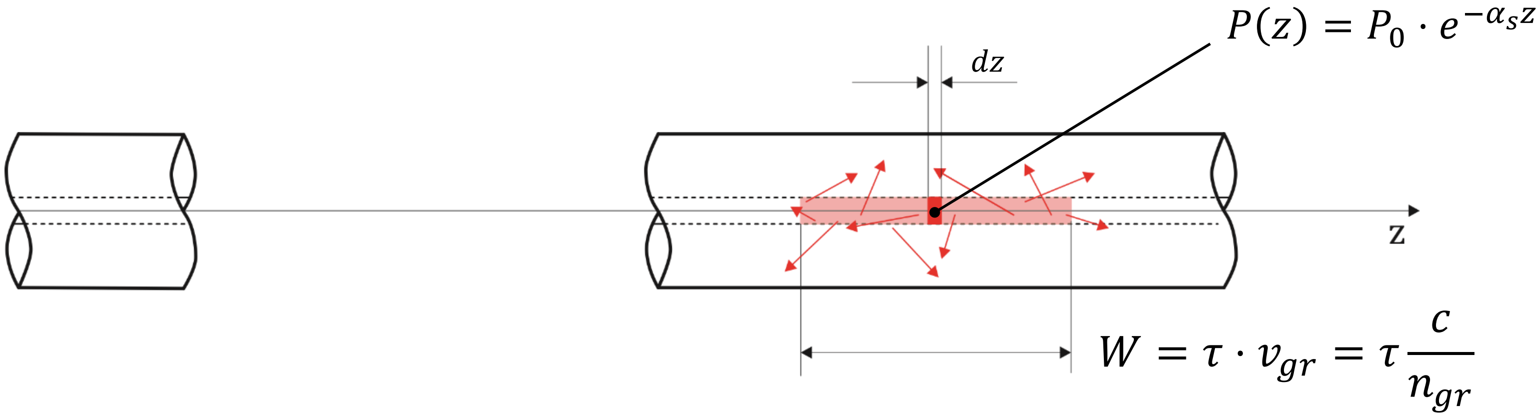
- in a good modern fiber, the scattering loss is predominant
- we can assume $\alpha_s \cong \frac{1}{\lambda^4}$

OTDR

- due to scattering, the pulse propagation is affected by losses both in forward and in backward direction
- the further the discontinuity from the input fiber end, the lower the power reaching back the photo-sensor

- at a given delay from the pulse launching what is the level of the power measured by the photodetector?

Backscattering analysis



τ is the temporal duration of the pulse, v_{gr} is the group velocity and n_{gr} is the group refractive index of the glass

- the optical power dP_s scattered by an infinitesimal length of fiber dz is equal to the power lost in that fiber length:

$$dP_s = P(z) - P(z+dz) = -P'(z)dz = \alpha_s \cdot P_0 \cdot e^{-\alpha_s z} dz = \alpha_s \cdot P(z)dz$$

- only a small fraction dp_s of dP_s will be coupled backward in the fiber and guided towards the fiber input, that is toward the photodetector

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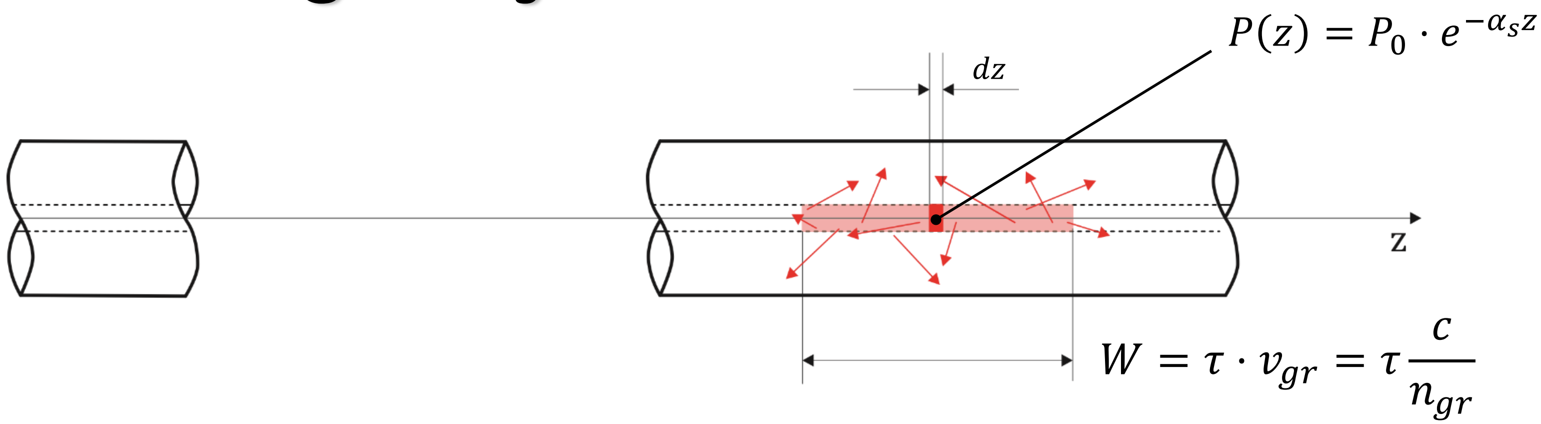
Backscattering analysis



- the fraction of the optical power scattered that returns to the photo-sensor is:

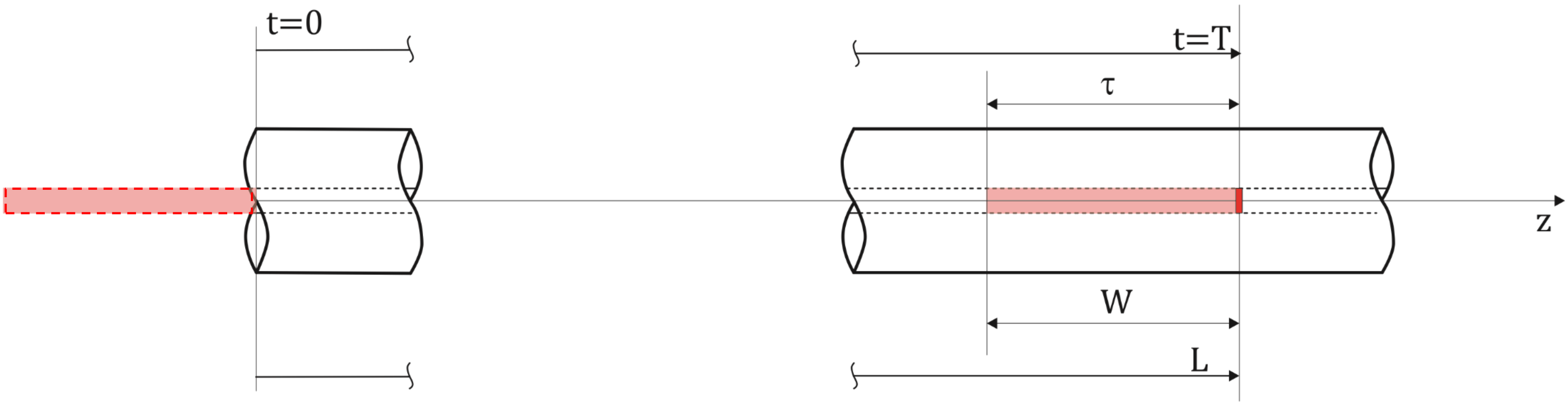
$$dp_s = S \cdot dP_s = S \cdot \alpha_s \cdot P(z) \cdot dz \qquad \alpha_s \cong \frac{1}{\lambda^4}$$

- where S, representing the fraction of the light scattered in all directions that is captured by the fiber core and guided back, is given by:

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

- where NA is the numerical aperture of the fiber, n_0 is the refractive index at center of the fiber core, and m is a correcting parameter depending on the refractive index profile of the fiber

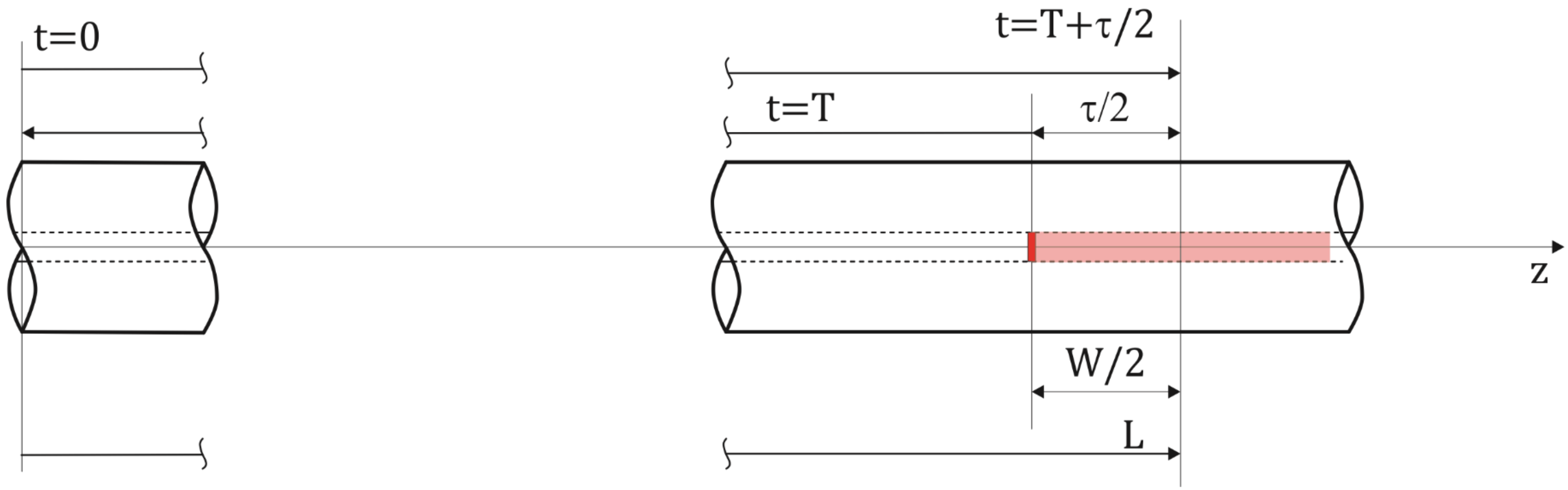
OTDR



- the light scattered at the leading-edge position of the travelling pulse reaches the photo-detector after the round-trip time equal to:

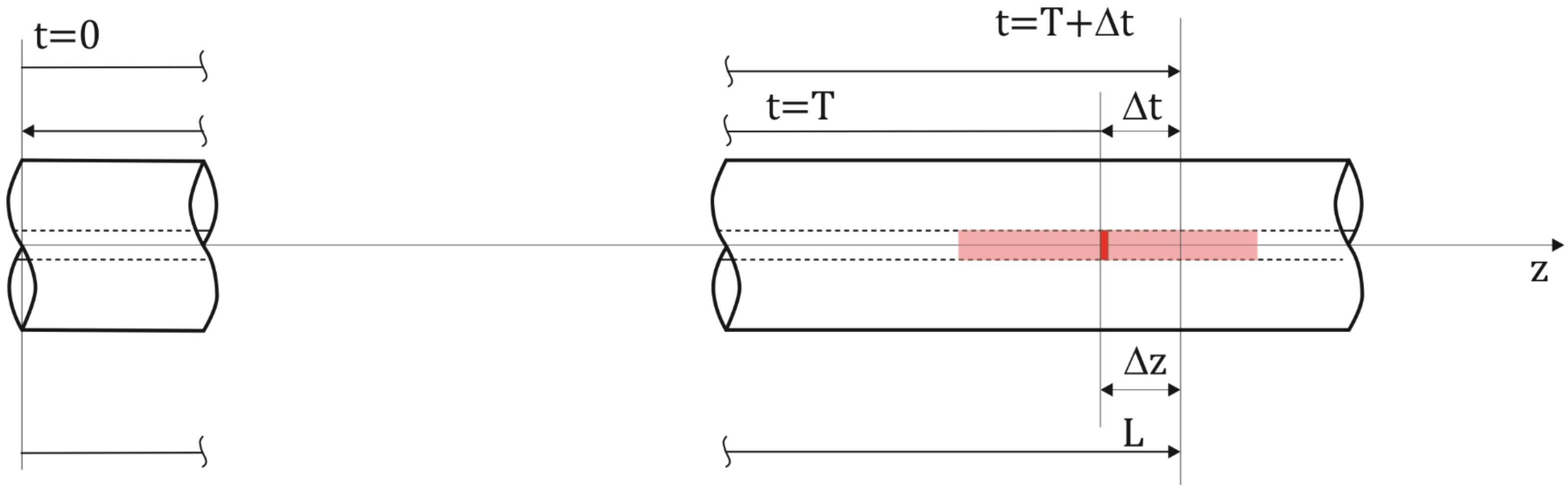
$$T_{forward} + T_{backward} = 2T$$

OTDR



- after a further delay of $\tau/2$ the trailing edge is at $L - W/2$
- the light scattered by this trailing edge will reach the photo-detector at the time $T + \frac{\tau}{2}\ (forward\ trip) + T - \frac{\tau}{2}\ (backwardtrip) = 2T$
- exactly together with the light scattered by the leading edge at time T

OTDR

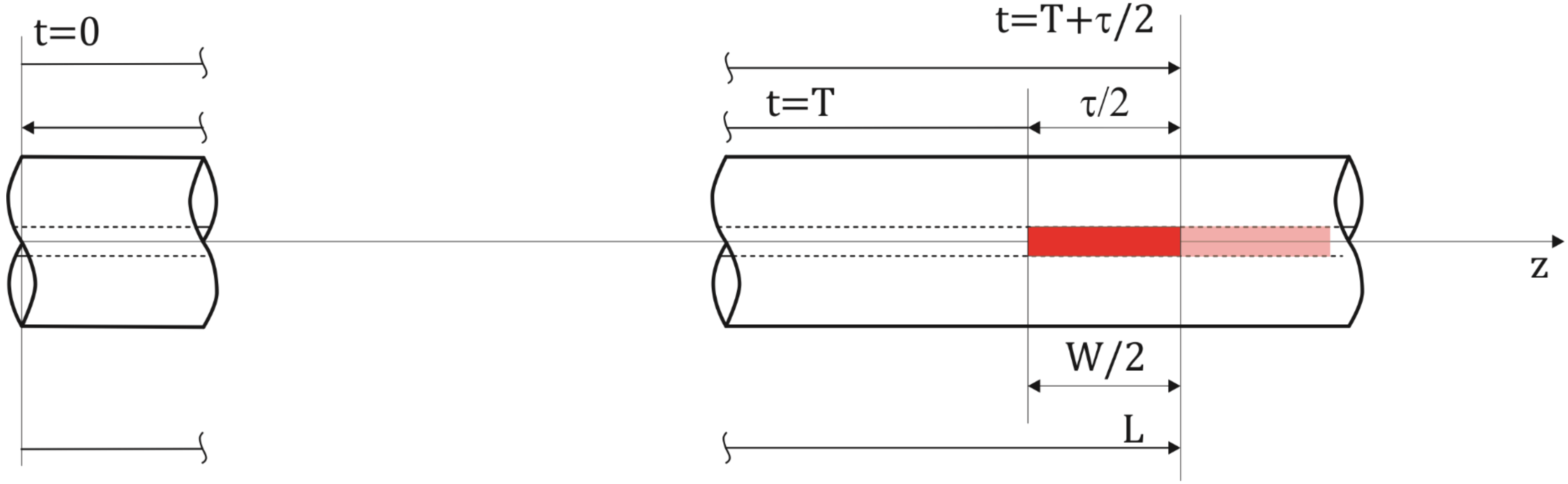


- for any time delay $\Delta t \leq \tau/2$, the light scattered at position

  $L - \Delta z = L - \Delta t \cdot v_{gr}$ takes the same time $2T$ to reach the photo-detector

OTDR

- the light collected at the photo-detector at time $2T$ is, therefore, the integral of the light scattered by the fiber section located from $z = L - W/2$ to $z = L$ (W is the pulse width)



$$P_s(L) = \int_{L-W/2}^{L} \underbrace{e^{-\alpha z}}_{\text{loss in return trip}} dp_s = \int_{L-W/2}^{L} S \cdot \alpha_s \cdot (P_0 \cdot e^{-\alpha z}) \cdot e^{-\alpha z} dz = \frac{S\alpha_s P_0}{2\alpha} \cdot e^{-2\alpha L}(e^{\alpha W} - 1)$$

for $L \geq W/2$

OTDR

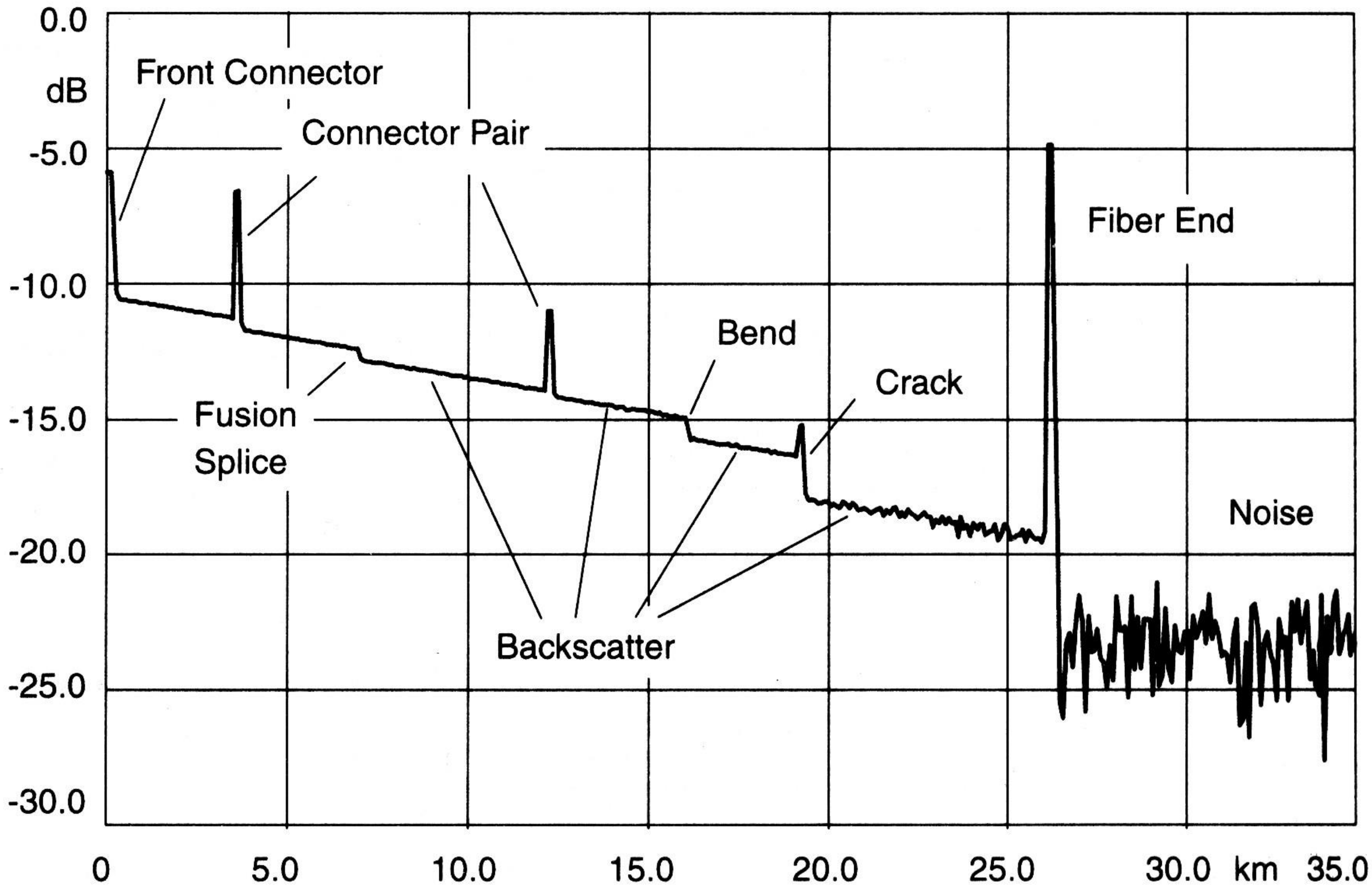
- for short pulses the losses inside the piece of fiber illuminated by the pulse can be neglected, we can assume:

$$P_s(L) = \underbrace{P_0 \cdot e^{-\alpha L} \cdot {}^{W}\!/_{2} \cdot S \cdot \alpha_s}_{\text{scattered power at position L coupled backward}} \cdot e^{-\alpha L} = P_0 \cdot k \cdot W \cdot e^{-2\alpha L}$$

- we define the backscatter factor as $\sigma = 10 \log \frac{P_0}{P_S(0)} = -10 \log(k \cdot W)$

  it can be measured, given W, it is a parameter characterizing the fiber

OTDR: measurement example



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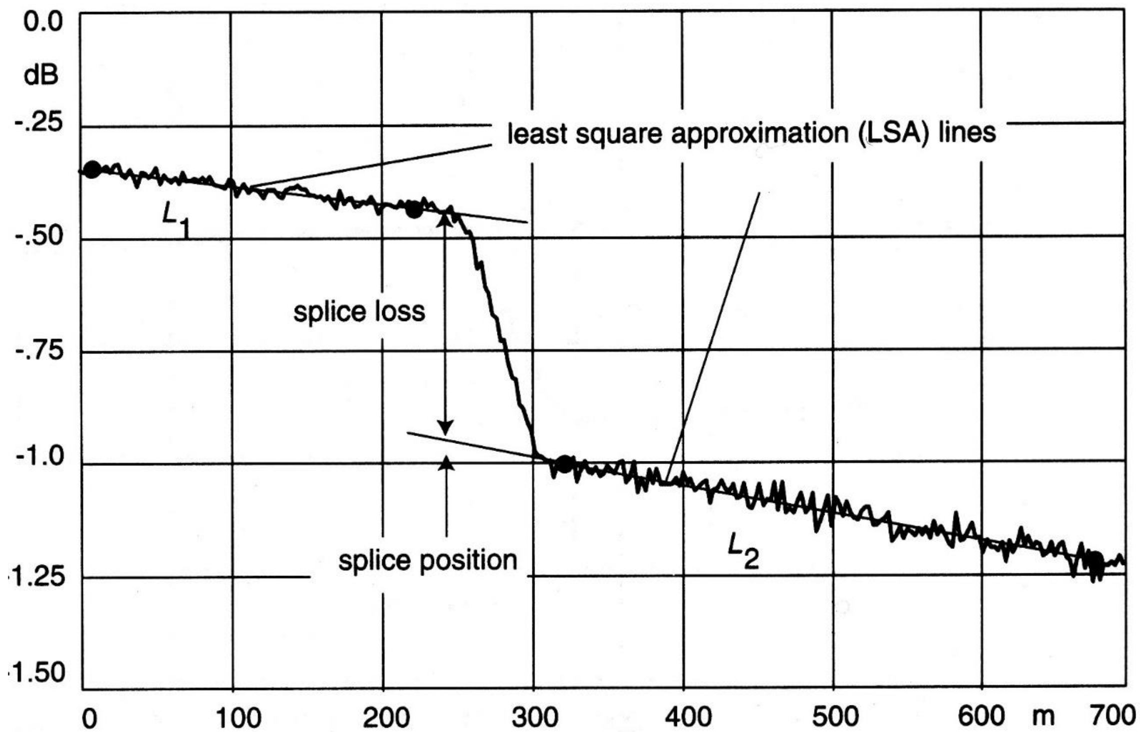
OTDR

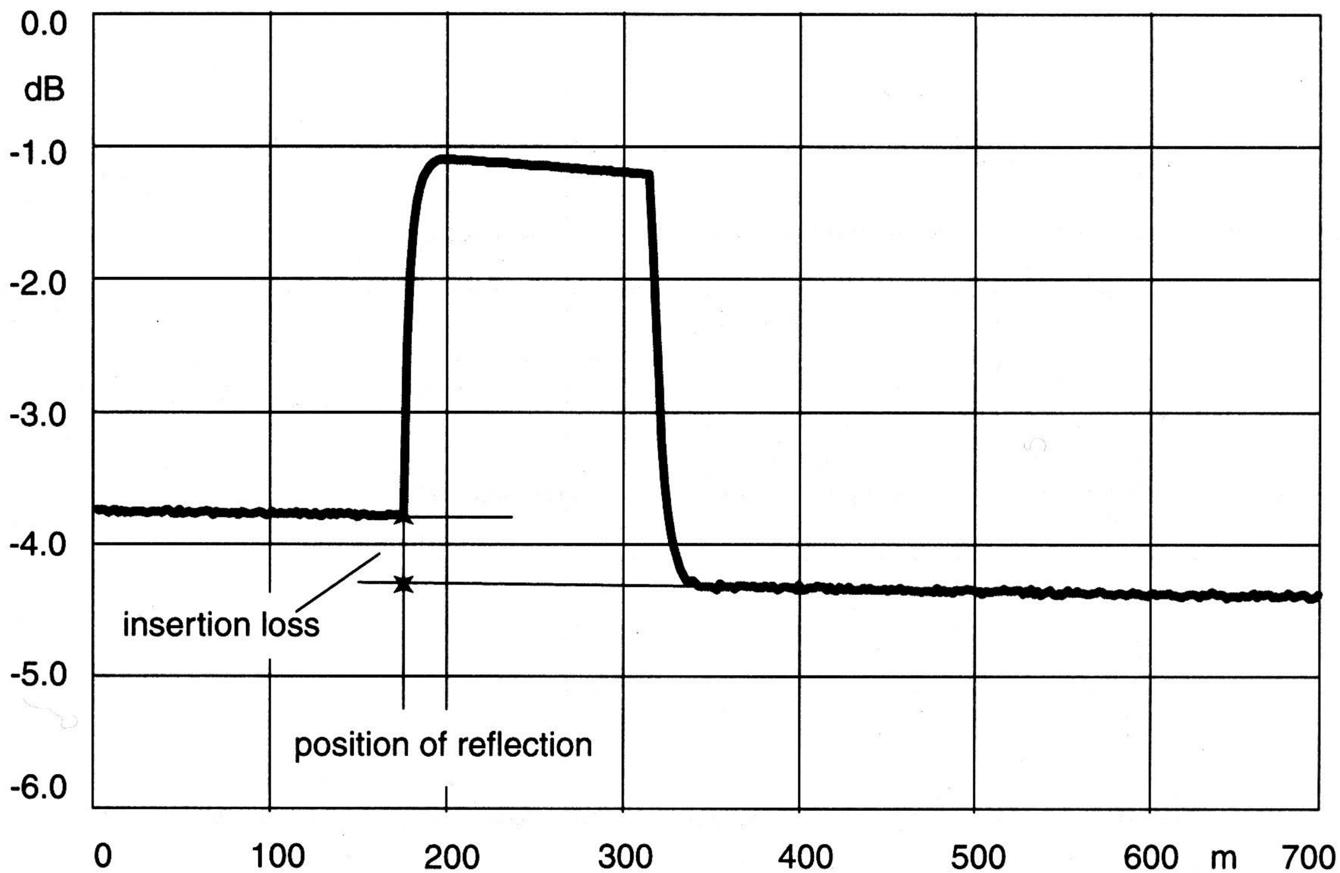
- the pulse propagation is affected by losses both in forward and in backward direction
- the further the discontinuity from the input fiber end, the lower the power reaching back the photo-sensor
- the OTDR works in the time-domain
  - the time-to-distance conversion is based on the knowledge of the light propagation velocity
  - for the round-trip time we can assume: 10 μs/Km
- the distance uncertainty is mainly defined by the uncertainty of the refraction index of the fiber
- a dual wavelength is usually available: 1310 and 1550 nm
- typical pulse duration from 5 ns to 10 μS
- the signal to noise ratio of the measurement is improved by averaging the acquisition over a great number of pulses

Splicer loss measurement

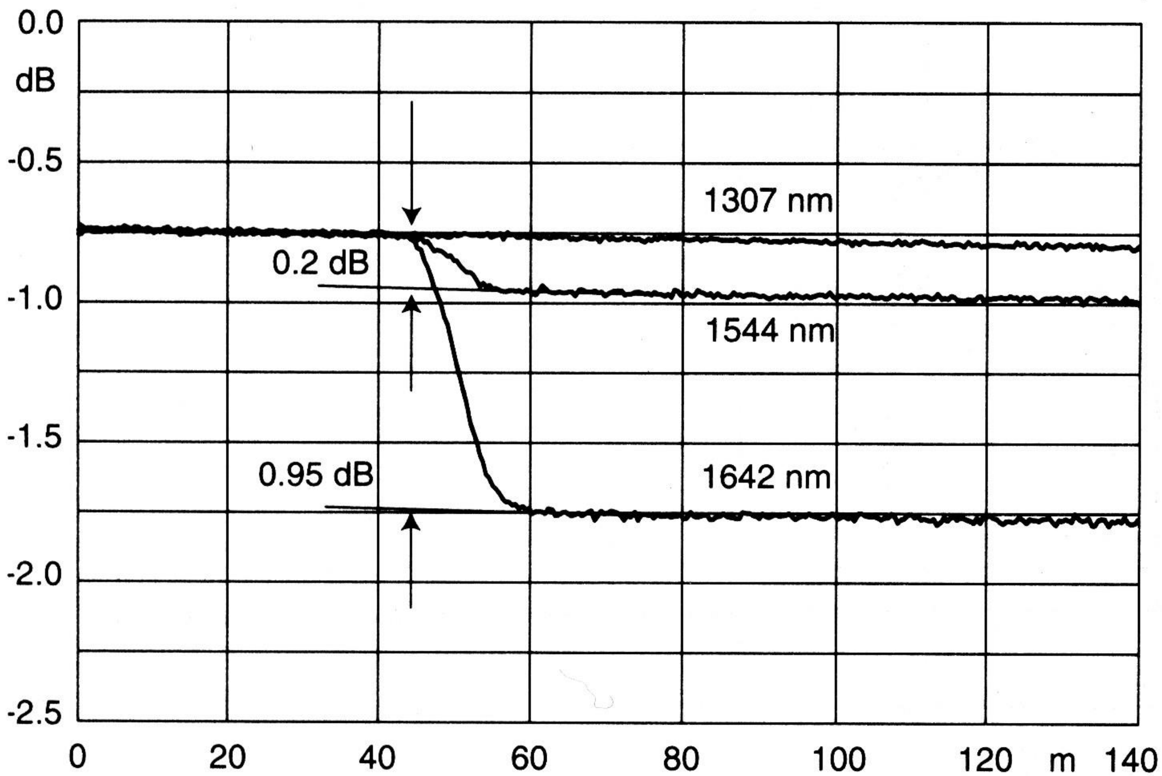


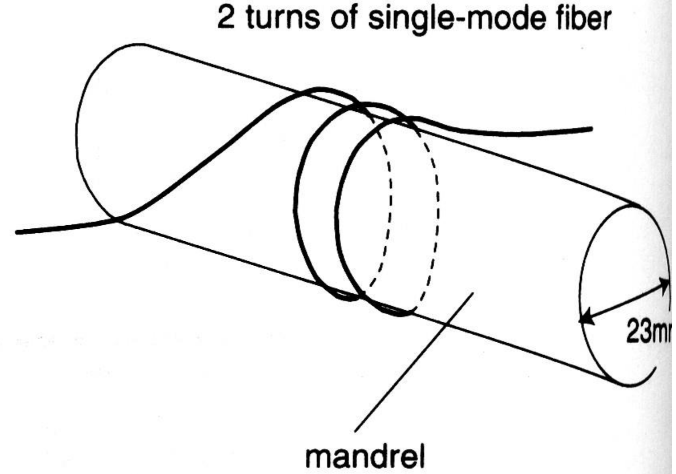
- the OTDR provides both the splicer loss and the splicer location

Measurement of a connector insertion loss

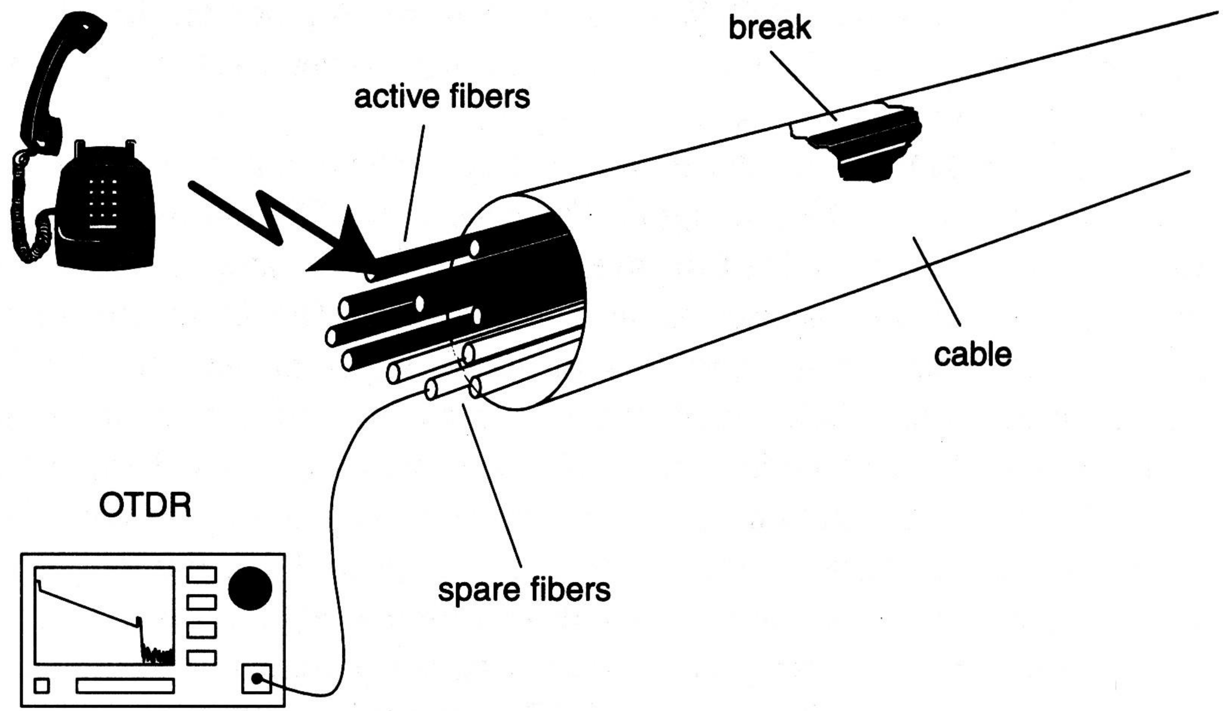


Bending losses



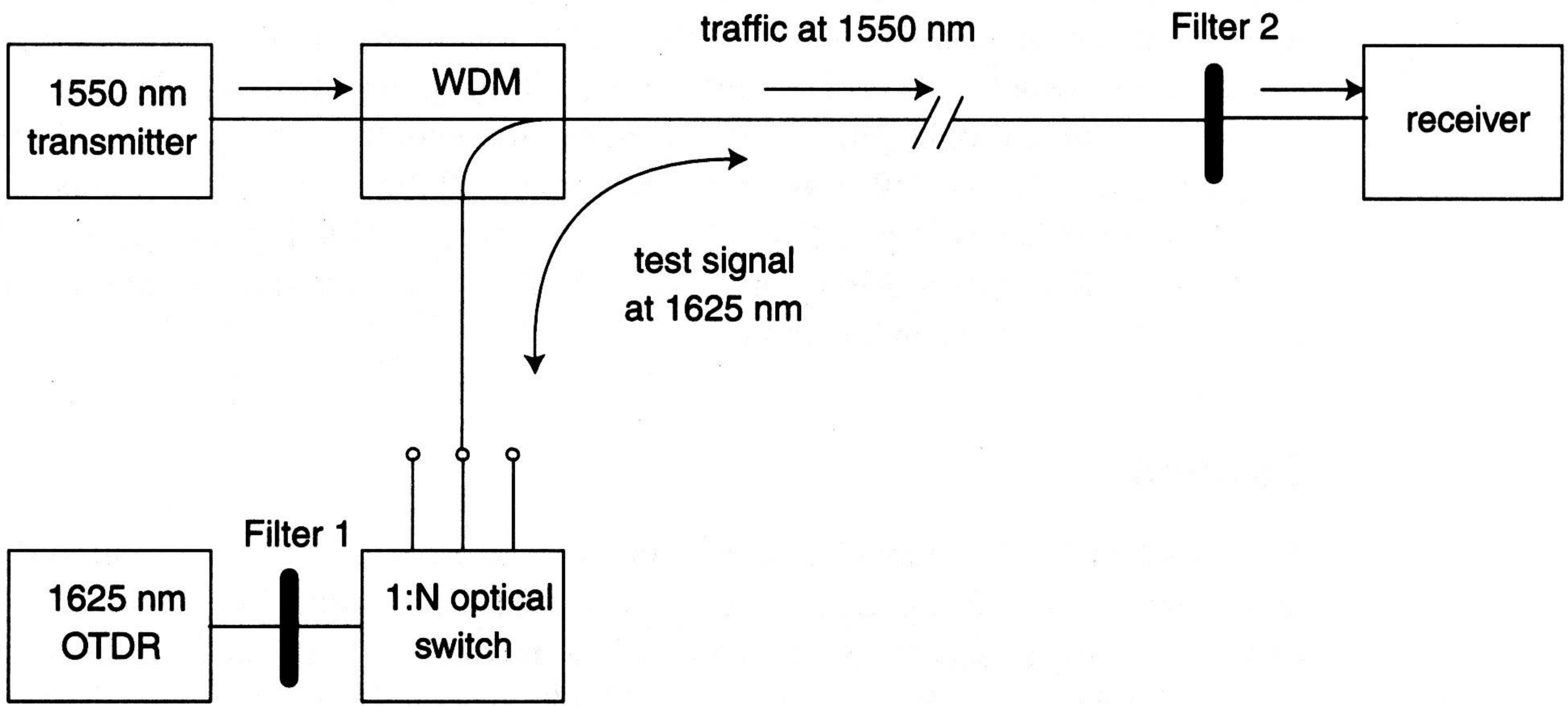


Dark fiber testing



- the measurement is carried out on spare fibers
- the hypothesis is that the eventual cable brake damages all fibers of the cable

Active fiber testing



- the optical filters play a very important role:
  - f1 to guarantee that the OTDR measurement is not influenced by the data traffic
  - f2 to avoid that the OTDR pulses interfere with the data traffic at the digital link receiver