

Laboratory measurement guide to

# Optical Time-Domain Reflectometry

to the subjects of

## Building Block of Optical Networks

(Neptun code: BMEVIHVMA05)

and

## Lightwave Systems and Applications

(Neptun code: BMEVIHVMA06)



**BME** Budapest University of Technology and Economics

**VIK** Faculty of Electrical Engineering and Informatics

**HVT** Department of Broadband Infocommunications and Electromagnetic Theory



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## Radiation safety

**Never look directly into LASER source, into optical connector or into fiber end !!!**



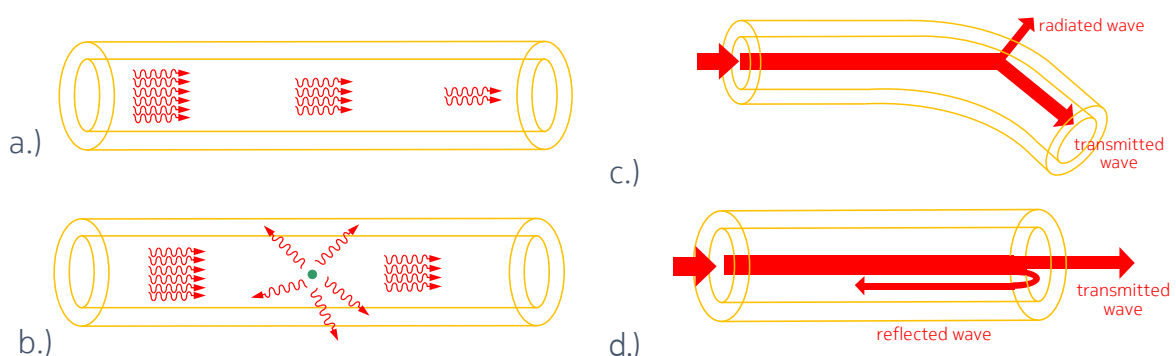
If you look into a **LASER beam** then your eye may focus the light onto a very small spot on your retina. Depending on the energy absorbed by the retina, the **eye may be damaged** temporarily or permanently. The optical wavelengths used in today's fiber-optic telecommunication links are **invisible**. This makes even small optical powers more dangerous than bright visible light. Because you cannot see it, you may look much longer into a LASER beam.

- The wavelengths of the visible light:  $\lambda = 380 - 750 \text{ nm}$
- The optical communication windows:  $\lambda_1 = 850 \text{ nm}$ ,  $\lambda_2 = 1310 \text{ nm}$ ,  $\lambda_3 = 1550 \text{ nm}$
- General rules:
  - Never not look directly into the end of optical fibers!
  - Put caps onto unused fiber ends!
  - Visualize invisible the light with infrared sensor card!
  - Use safety glasses whenever it is necessary!

## Optical fiber loss mechanisms

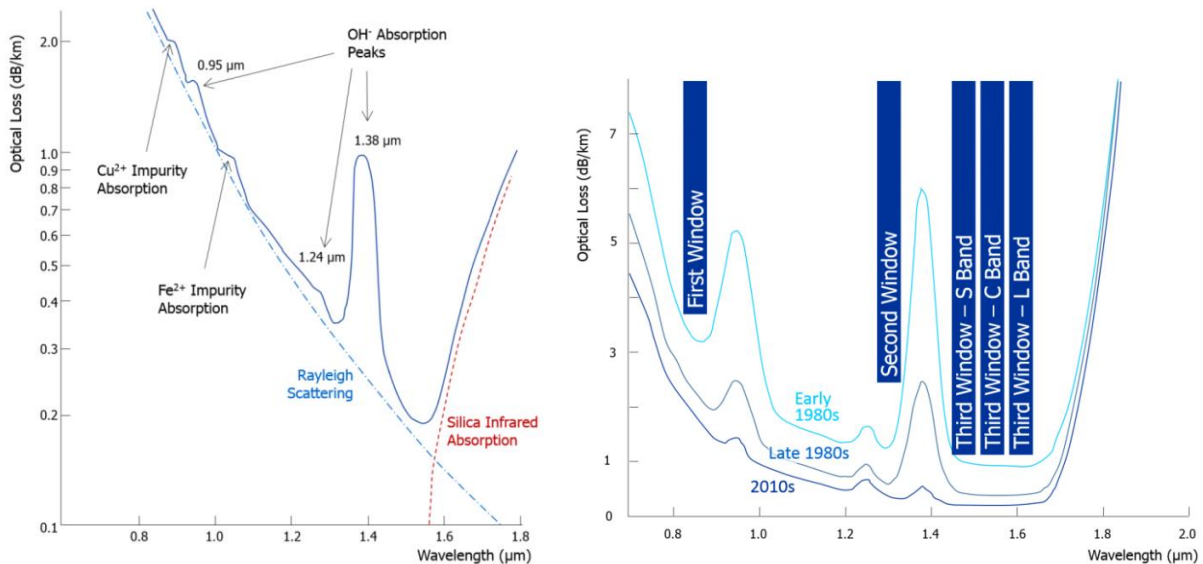
The major loss mechanisms in optical fiber connections are due to:

- absorption,
- scattering,
- radiation and
- reflection (air-to-glass and glass-to-air interfaces at the fiber ends and at bubbles).



**Figure 1.** Losses in optical fiber: a.) absorption b.) scattering c.) radiation d.) reflection [10]

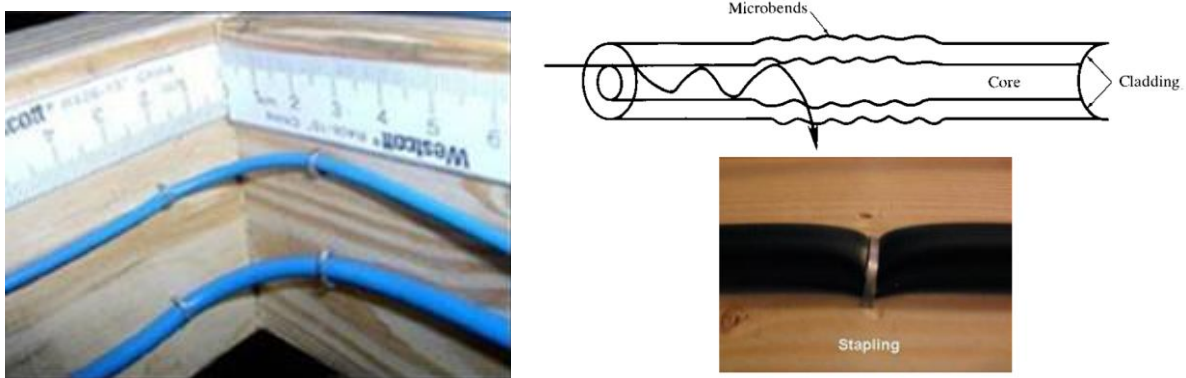
**Intrinsic material absorption** is caused by interaction of the propagating lightwave with one (or more) major components of the fiber material. Such an interaction is the infrared absorption band of  $\text{SiO}_2$  shown by the red line in the Figure 2.a. This loss represents a fundamental minimum to the attainable fiber loss and can be overcome only by changing the fiber material.



**Figure 2.** a.) Fiber loss and the absorption peaks  
 b.) Fiber attenuation as a function of wavelength and the telecom windows, [5].

**Extrinsic absorption:** extrinsic impurity ions absorption is caused by very small quantity of metallic ions (such as Cr<sup>3+</sup>, Cu<sup>2+</sup>, Fe<sup>2+</sup>) and the OH<sup>-</sup> ion from water dissolved in glass. The attenuation peaks caused by Cu<sup>2+</sup>, Fe<sup>2+</sup> and OH<sup>-</sup> ions are shown in the Figure 2.a too.

**Radiation** loss occurs when the geometrical parameters of the fibre change abruptly, or a mechanical tension is present in the fibre material due to fabrication failure or mechanical impact. Considering proper fabrication technology, protecting fibre jacket and proper cable installation, the radiation loss can be minimized. Similarly to absorption, radiation does not cause reflections. From OTDR measurement point of view, radiation losses can be handled as absorption losses. High-level discontinuities e.g., shown in Figure 3., originated by strong folding or stapling, can be detected by OTDR as they result in a high losses.



**Figure 3.** a.) radiation caused by fiber folding below the recommended radius  
 b.) mechanical tension due to improper cable installation

**Scattering:** Rayleigh scattering is the main type of linear scattering. It is caused by small-scale (small compared to the wavelength of the lightwave) inhomogeneities that are produced through the fiber manufacturing process. Examples of inhomogeneities are glass

composition fluctuations causing tiny changes in the material refractive index and density fluctuations. The composition fluctuations have been constantly improved over time. Rayleigh scattering accounts for about 95% of attenuation in the optical fiber.

With modern fiber manufacturing technology, material impurities are kept at a relatively low level. Such, as shown in Figure 2.b, the linear fiber loss is relatively small within the main telecommunication windows :

- 0.3 dB/km                    at 1300 nm,
- 0.15-0.2 dB/km            at 1550 nm.

In practice, the 1300 nm and 1550 nm wavelengths are used as the fiber loss has minimum at these wavelengths. The fibre loss increases strongly for the wavelengths above 1700 nm.

**Reflection:** Fresnel reflection occurs when the electromagnetic wave propagates through the border of materials having different dielectric constants (Figure 1.d). A certain portion of the power is reflected back according to Fresnel's law. Such a reflection occurs at the terminations of the fibre and at optical connectors. Here the dielectric constant changes abruptly due to glass-to-air transition. The power reflection coefficient of a polished fibre termination (considering perpendicular incidence) is typically 0.04 that corresponds to -14 dB. It means that a fibre termination can be detected even at far distances, where the Rayleigh scattered signal is already below the Noise Equivalent Power (NEP). Sharp peaks of reflections can be seen at the distances of the Fresnel reflections.

### Linear fiber attenuation

The total optical attenuation or transmission loss of a fiber section can be calculated as the power ratio of output and input optical power levels:

$$A = \frac{P_{\text{out}}}{P_{\text{in}}} \quad (1.)$$

As  $P_{\text{out}} < P_{\text{in}}$ , the attenuation is usually  $A < 1$  in linear scale. (For  $P_{\text{out}} > P_{\text{in}}$  cases we talk about Gain (G), that means there is amplification in the fiber optical link). In Figure 4  $P_{\text{out}}$  is measured at O2 port,  $P_{\text{in}}$  is measured at O1 port (Figure 5). In engineering practice equation (1.) is used in its logarithmic form. The attenuation is measured in decibels:

$$A[\text{dB}] = 10 \cdot \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \quad (2.)$$

(In dB scale attenuation is negative, gain is positive.) The total attenuation is proportional to the length of the optical fiber. This is why in dB scale it is often called 'linear attenuation'. The specific fiber attenuation  $A_{\text{sp}}$  is given in dB/km unit, that means decibel/kilometer, see Figure 1.a. The loss of a fiber section can be quickly calculated as:

$$A_{\text{fiber}}[\text{dB}] = L[\text{km}] \cdot A_{\text{sp}} \left[ \frac{\text{dB}}{\text{km}} \right] \quad (3.)$$

Microwave and optical instruments usually display the measured power and power spectral density (PSD) in logarithmic scale therefore it is important to practice calculations using decibels. In dB calculations -thanks to the logarithmic scale- instead of multiplications, we simply add numbers to each other. Similarly, instead of divisions we simply subtract the numbers. As an example, if one fiber optical connector has a loss of 0.5 dB and we have connectors at both ends of the fiber, then Equation (3.) can be written as:

$$A_{\text{link}}[\text{dB}] = A_{\text{fiber}}[\text{dB}] + A_{\text{connectors}}[\text{dB}] = L \cdot A_{\text{sp}}[\text{dB}] + 2 \cdot 0.5[\text{dB}] \quad (4.)$$

Naturally, as plotted in Figure 4, the fiber loss that is linear in logarithmic scale, is exponential in linear scale:

$$A_{\text{fiber}} = 10^{-L \cdot A_{\text{sp}}/10} \quad (5.)$$

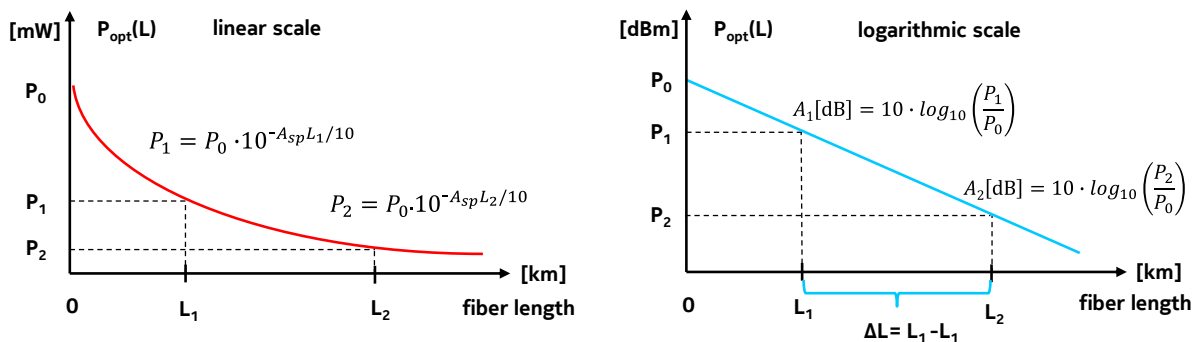


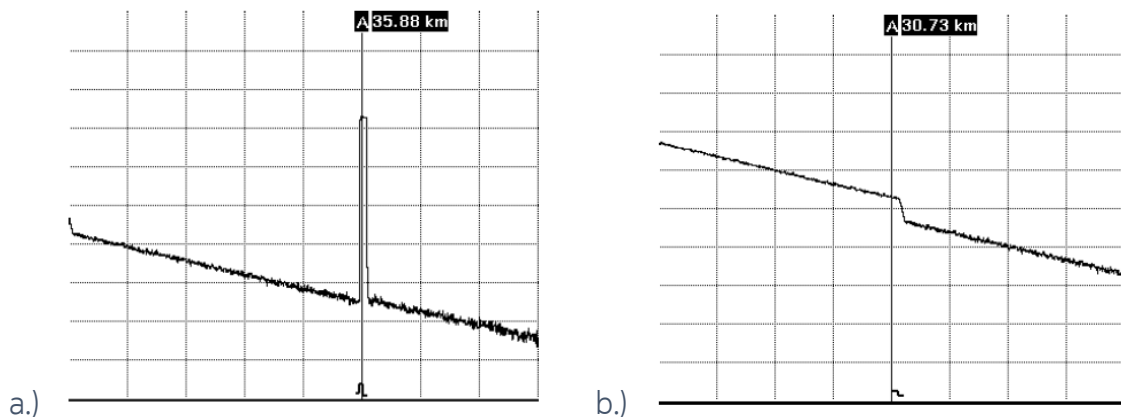
Figure 4. Attenuation as a function of fiber length, a.) linear scale, b.) logarithmic 'dB' scale

### OTDR as a one-port test instrument

The Optical Time Domain Reflectometer (OTDR) is one of the most important instruments for characterizing optical fibers. The OTDR can detect and measure various discontinuities in an optical fiber connection, for example splices, optical connectors, fiber cut or other fiber irregularities. This makes the OTDR instrument a very valuable tool for telecommunication when manufacturing, installing, or maintaining fiber-optic cables. OTDR is especially useful outside in the field. Engineers can use a field OTDR to check regularly if the fiber-optical link meets the required specifications.

With OTDR the characteristic properties of a single fiber section or an entire fiber optical link can be evaluated. With an OTDR instrument we can investigate fiber attenuation, fiber uniformity, splicing losses, possible faults, and distances between these fiber 'events'. Events are changes in the fiber causing the trace to deviate from a straight line. Events can be reflective or non-reflective. Reflective events occur when some of the pulse energy is reflected, for example at a connector. Reflective events produce a spike in the trace, a steep rise and fall in the graph, as seen in Figure 5.a. Non-reflective events occur at parts of the fiber where there is some loss, but no light is reflected. Non-reflective events produce a dip

on the trace, as shown in Figure 5.b.

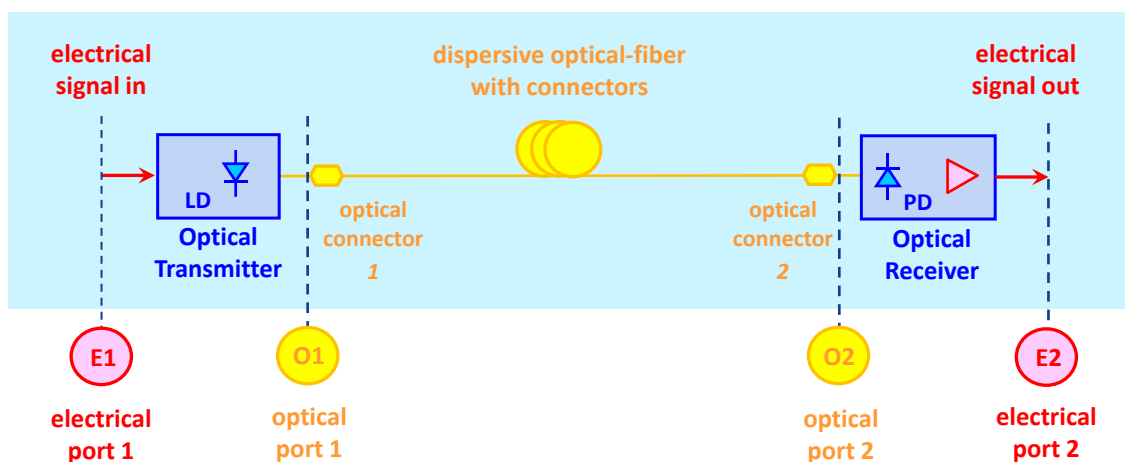


**Figure 5.** Fiber event types: a.) reflective b.) non-reflective. [3]

The OTDR instrument shows the irregularities in the fiber, can measure their distances, the attenuation between them, the loss due to them, as well as the linearity of the fiber attenuation. Even fiber dispersion can be measured with OTDR using suitably short pulses. The main advantage of OTDR is its one-port operation at the fiber input. There is no need to access the fiber output, that may be several kilometers far away from the input.

### One and two port measurements

The difference between one-port and two port measurements is illustrated in Figures 5 – 7. In both cases the Device Under Test (DUT) is the optical fiber. Figure 5 shows the principle of the two-port optical measurement. As seen in Figure 5, the optical input is at the beginning of the optical fiber. The optical output is at the end of the optical fiber. The LASER source provides the optical signal that is launched into the fiber input. The photoreceiver receives the optical output signal at the fiber end and converts to an electrical signal. The photoreceiver is composed of a fast photodiode (PD) and a wideband electrical amplifier.



**Figure 5.** Two-port optical measurement test setup.



into the optical fiber and its reflection is measured at the same port, at the beginning of the fiber. We do not need to connect the test instrument to the other end of the optical fiber. To separate the sent and the reflected optical signals, an optical coupler or a beam splitter is required, as it is shown in Figure 7.

**The measurement principle of the OTDR**

The typical OTDR measurement setup is shown in Figure 8. A pulse generator drives a LD which launches short optical pulses into the optical fiber. The optical power is typically 10 mW or more. The pulse-widths range from nanoseconds to microseconds at repetition rates of 1 kHz for long fiber lengths. For short fiber lengths the repetition rates are up to 20 kHz. The division by 2 at the oscilloscope inputs is required since both the vertical and horizontal scales correspond to the ‘one-way’ length of the fiber. The vertical axis shows the ‘one-way’ optical loss in dB and the horizontal axis shows length  $L$ , the distance measured from the fiber input.

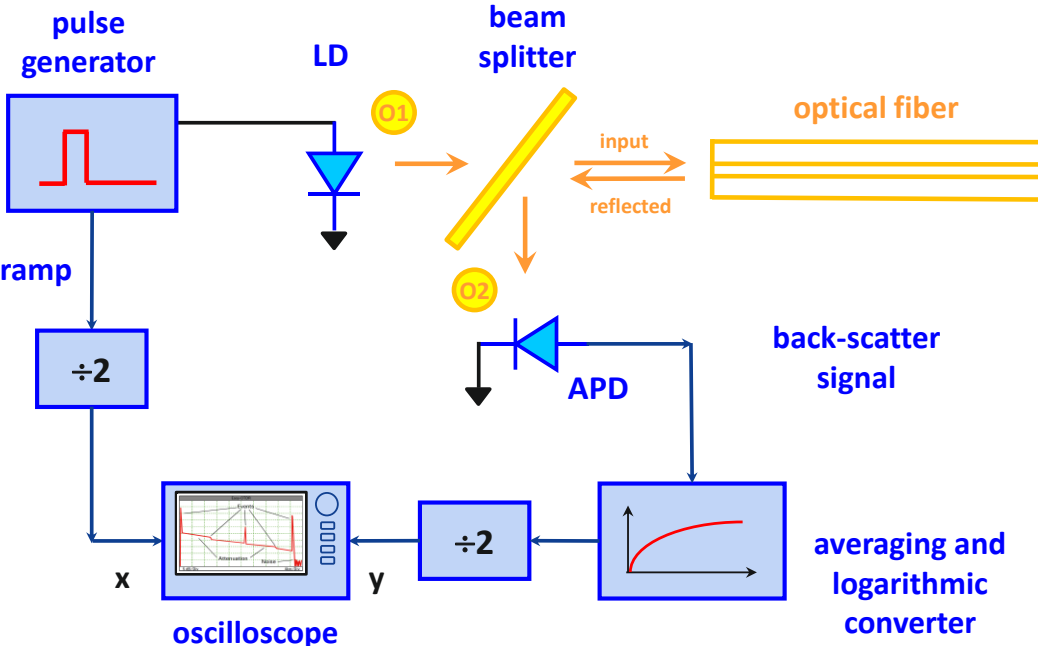


Figure 8. OTDR measurement principle [2]

A single optical fiber test yields the trace shown in Figure 9.a. We can observe a slightly decreasing power level due to the attenuation of the fiber. The reflections at the beginning and at the end of the optical fiber are seen as strong reflection peaks. The trace of an entire fiber optical link, for example between two cities, may look like as shown in Figure 9 b.). Besides the normal attenuation slope we see ‘events’, and noise after the end of the link.

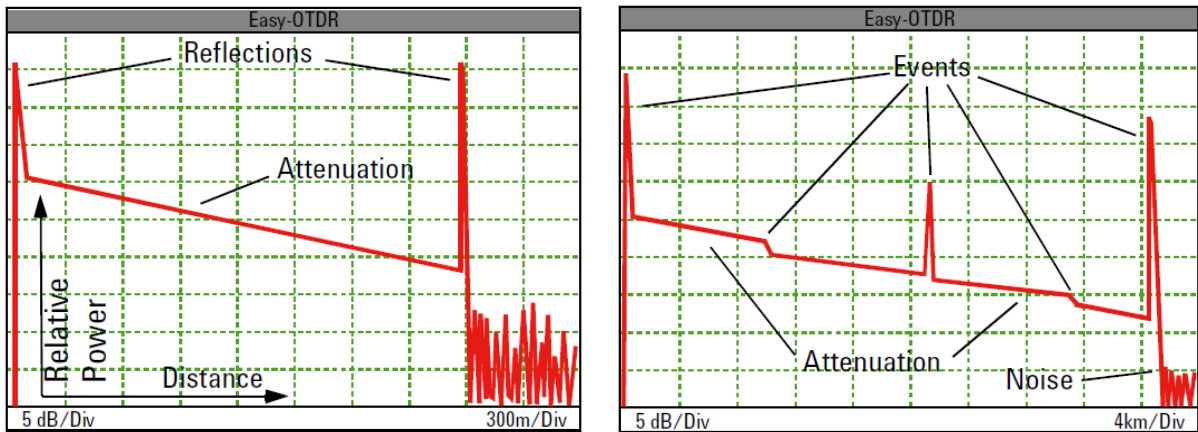


Figure 9. a.) OTDR plot of a single optical fiber,  
 b.) OTDR plot of an entire fiber optical link [1].

If we are using a normal straight connector, the beginning of a fiber always shows a strong reflection at the front connector as shown in Figure 10.a. In most cases you see a strong reflection at the end of the fiber before the trace drops down to noise level, as shown in Figure 10.b.

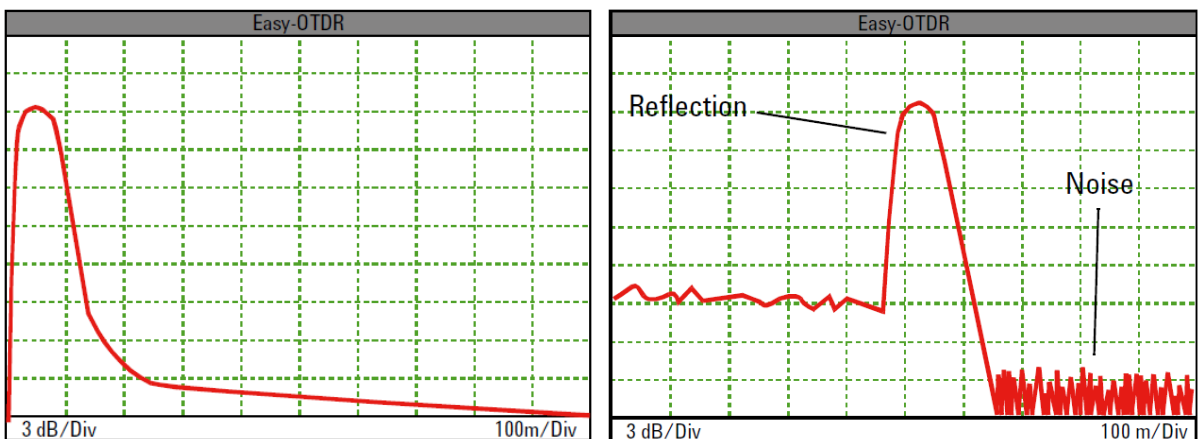


Figure 10. Connectorized fiber ends shown in OTDR plot:  
 a.) a fiber beginning with straight connector,  
 b.) a fiber end with straight connector [1].

Compared to connectorized fiber ends, fiber breaks do not show reflection. Breaks are non-reflective 'events'. The OTDR trace drops down to noise level (Figure 11.a). Connectors within a link cause reflection and loss at the same time (Figure 11.b).

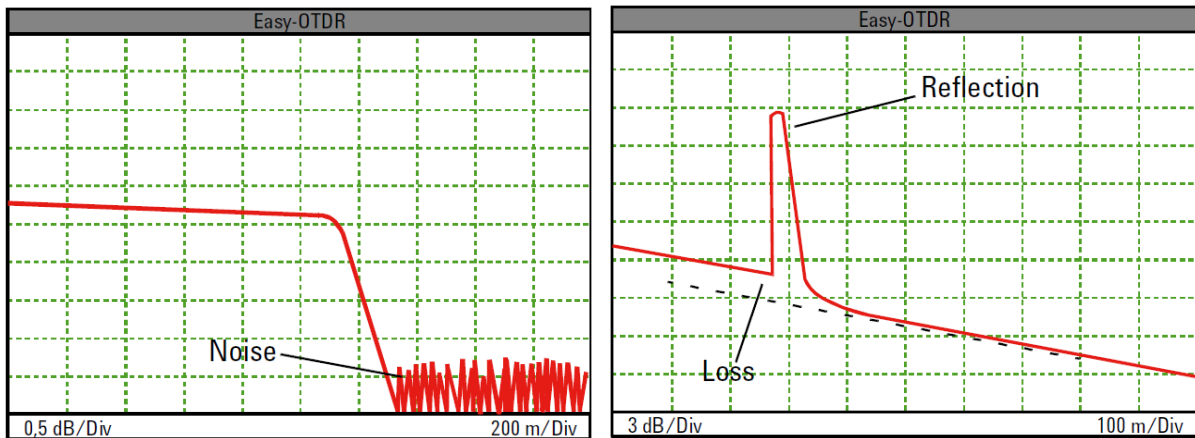


Figure 11. a.) Fiber break b.) Connector or splice [1]

A fusion splice is a non-reflective event, only loss can be detected. Modern fusion splices are so good, they may be nearly invisible (Figure 12.a). Bends in a fiber cause loss, but they are non-reflective events (Figure 12.b). To distinguish bends from splices, we can check the installation and maintenance records. Bending losses are at unknown locations. On the contrary, splices are at documented and well-known distances.

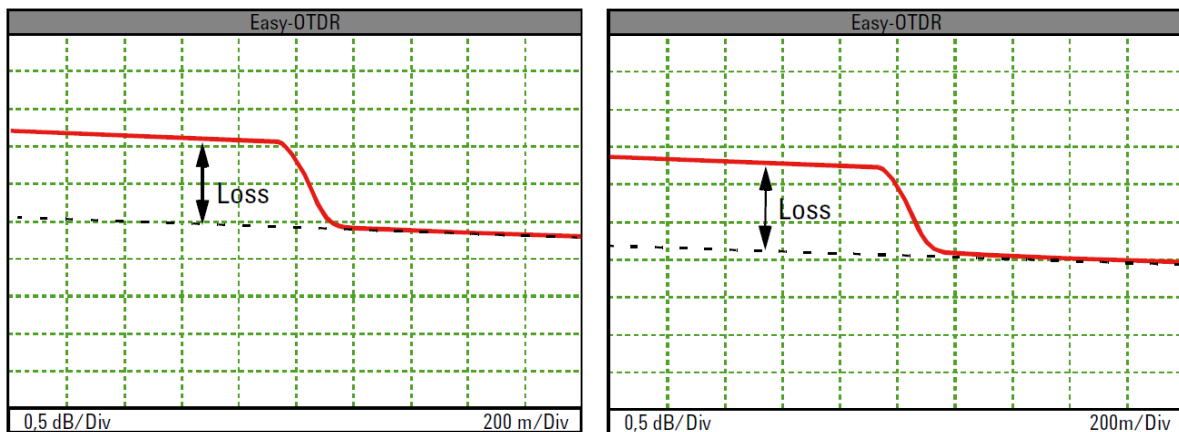
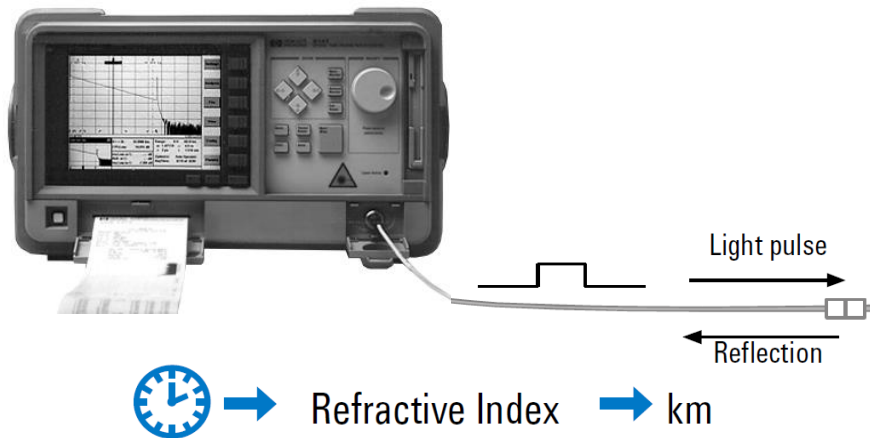


Figure 12. a.) Fiber fusion splice, b.) Fiber bend [1].

### Distance measurement based on the refractive index

The OTDR calculates the distance to an ‘event’ by measuring the time elapsed between transmission of the light and reception of its reflection. This can be, for example, the rising edge of the reflection of the front panel connector, or the reflection from a connector. The distance displayed and the time measured are linked by the refractive index. This means that changing the refractive index causes a change of the computed distance. The effective refractive index of the fiber is:

$$n_{\text{eff}} = \frac{\text{speed of light in vacuum}}{\text{speed of light in the fiber}} = \frac{c}{v} \quad (6.)$$



**Figure 13.** Time between transmitted and reflected light-waves calculated to distance [3].

The refractive index depends on the used fiber material and is usually provided by the fiber manufacturer. The distance displayed in OTDR plot is:

$$\begin{aligned}
 \text{distance} &= \text{measured time} \cdot \text{speed of light in the fiber} = & (7.) \\
 &= \text{measured time} \cdot \frac{\text{speed of light in vacuum}}{n_{\text{eff}}} = \text{measured time} \cdot \frac{c}{n_{\text{eff}}}
 \end{aligned}$$

Please note, that there is a factor 2 between ‘one-way’ and ‘two-way’ distances. The OTDR plots indicate ‘one-way’ distance, that is the real physical length of the DUT fiber, supposed the effective index is correctly set in the OTDR.

The effective refraction index values of unshifted fiber are around 1.4675 at 1300 nm and 1.4681 and 1550 nm wavelengths. The values for dispersion-shifted fiber are 1.4718 and 1.4711 at 1300 and 1550 nm, respectively, according to [9].

### Choice of pulse width

One key parameter to obtain good measurement results is the width of the light pulse emitted into the fiber. Pulse width determines the distance resolution, which is very important to separate ‘events’ clearly. Depending on the goal of the measurement, a proper trade-off between high-resolution and high dynamic range is needed. Short pulse widths are required when we measure the loss of splices or connectors that are close to each other. But long pulse widths are necessary if we want to detect a fiber break far away.

Shorter pulse means smaller energy:

- better resolution, but
- smaller dynamic range,
- more noise.

Longer pulse means higher energy:

- better dynamic range,
- less noise, but

- worse resolution.

Figure 13 illustrates how a wide pulse can cover two nearby events. Figure 14 shows the OTDR plot of the two events when short and long pulse widths are used.

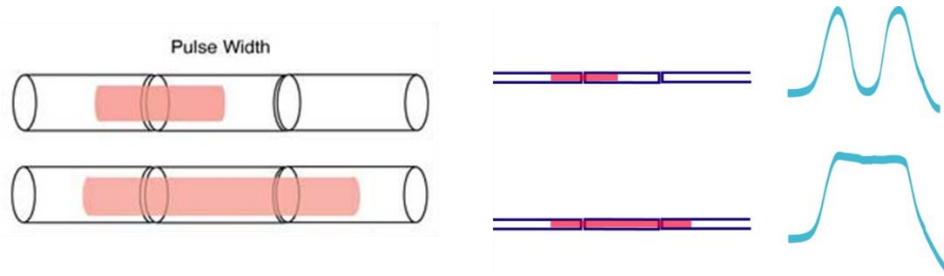


Figure 13. Selection of pulse width [8]

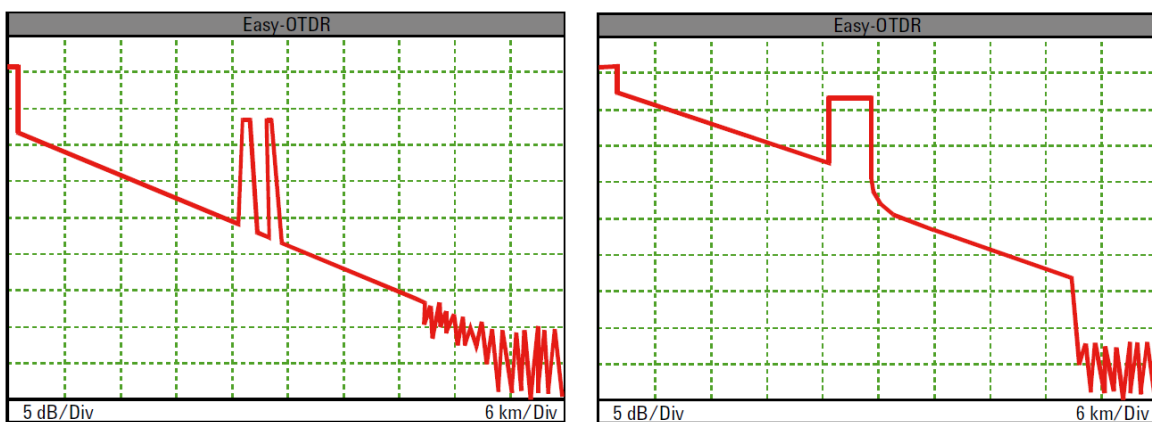


Figure 14. Selection of pulse width a.) short pulse width b.) long pulse width [1]

$$\Delta z = \frac{c \cdot T}{2 \cdot n_{eff}} \quad (8.)$$

Let us calculate the spatial resolution of OTDR when the pulse width  $T$  is given in the table below. For simplicity, we can approximate  $c \approx 300\,000$  km/s and  $n_{eff} \approx 1.5$ .

link span	long fiber links							
	short fiber links							
pulse width, $T$	5 ns	10 ns	30 ns	100 ns	300 ns	1 $\mu$ s	3 $\mu$ s	10 $\mu$ s
resolution, $\Delta z$								

## Averaging

OTDR sends light pulses repetitively into the optical fiber. Averaging reduces the random noise in the receiver. Longer averaging time increases the dynamic range by decreasing the noise floor of the OTDR. The best improvements for the trace are achieved within the first three minutes. The difference due to averaging can be seen in the OTDR plots of Figure 15.

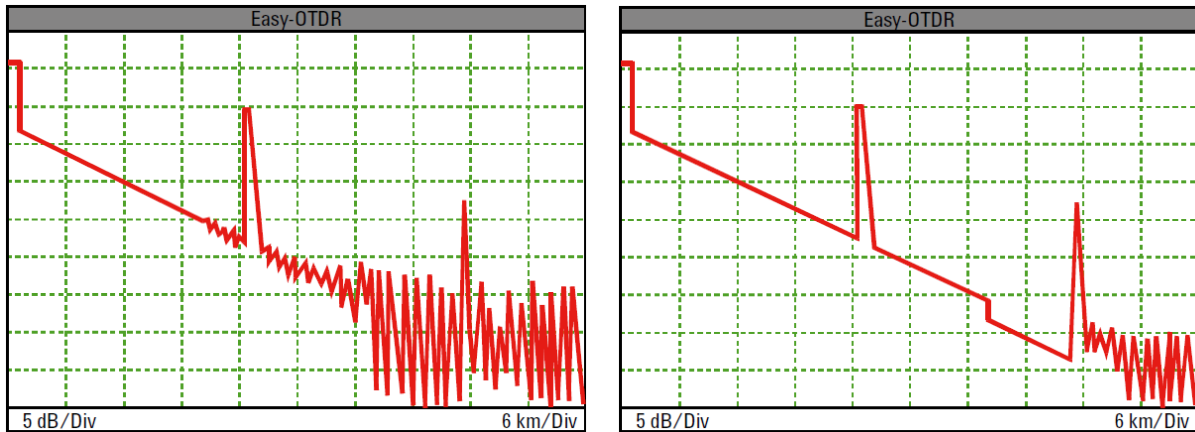


Figure 15. OTDR plots in case of tests: a.) without averaging b.) with averaging [1].

### Measurement tasks:

- Measure the length and attenuation of the optical fibers given in the test setup. Use the HP 8147 OTDR instrument.
- Measure the attenuation at both wavelengths: at  $\lambda=1310$  nm and at  $\lambda=1550$  nm.
- Write a test report with properly documenting the test setup and your results.
- Make a drawing of your measurement setup, and also include photos of the test instrument and the test setup.

The test report must show the names of the group members, their Neptun code, date in DD-MMM-YYYY format, and time when the test was performed. The final submitted report must be written with computer and saved in PDF form.

### References

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## Acronyms

A	A	attenuation
	APD	avalanche photodiode
	$A_{sp}$	specific fiber attenuation in dB/km
C	c	speed of light in vacuum: $2.9979 \cdot 10^8$ m/s $\approx$ 300 000 km/s
	$Cu^{2+}$	copper is a chemical element with the symbol Cu
D	dB	decibel, logarithmic unit
	/Div	/division
	DUT	device under test
E	E	electrical
F	$Fe^{2+}$	iron is a chemical element with symbol Fe (from Latin: ‘ferrum’).
G	G	gain
H	HP	Hewlett-Packard company
	$OH^-$	hydroxide is a diatomic anion. $OH^-$ consists of an oxygen and hydrogen atom
I	IM	intensity modulation
K	kHz	kiloHertz = 1000 Hz
	km	kilometer = 1000 m
L	L	fiber length
	LASER	light amplification by stimulated emission of radiation
	LD	laser diode
	$\lambda$	wavelength, in the optical domain $\lambda$ is given in nm or in $\mu$ m
M	mW	milliWatt = 0.001 W
	$\mu$ m	micrometer = $10^{-6}$ m
N	nm	nanometer = $10^{-9}$ m
	$n_{eff}$	effective refractive index
	NEP	Noise Equivalent Power
O	O	optical
	OTDR	optical time domain reflectometer
P	PD	photodiode
	PSD	power spectral density
S	$SiO_2$	silicon dioxide

## Notes

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