MEASUREMENT GUIDE

OTDR - Optical Time Domain Reflectometer

(OTDR)

V2, 620.
Optical Telecommunications Lab

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<u>The architecture and the operation of the OTDR system</u>

The OTDR is the most important investigation tool for optical fibres, which is applicable for the measurement of fibre loss, connector loss and for the determination of the exact place and the value of cabel discontinuities. By means of very short pulses it is also possible to measure the modal dispersion of multimodal fibres. The structure of a typical OTDR equipment is shown below:

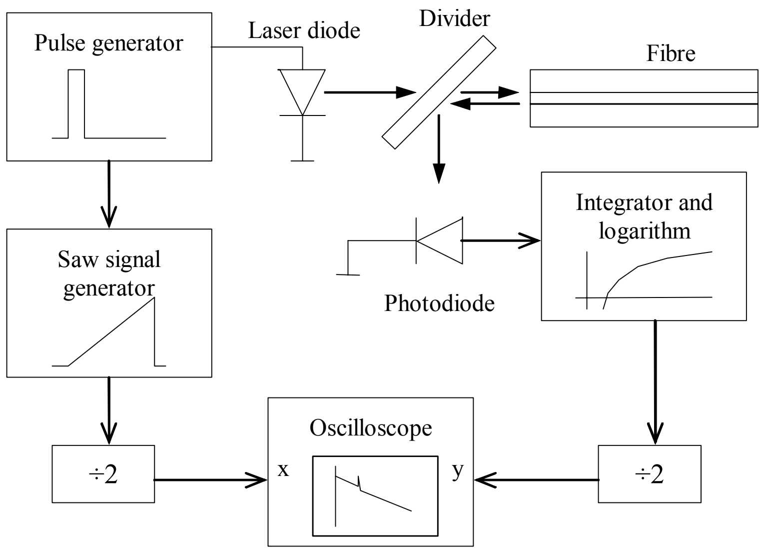

Figure 1. The structure of the OTDR instrument.

The principal of the OTDR analyzer is the following: a short light pulse is transmitted into the fibre under test and the time of the incidence and the amplitude of the reflected pulses are measured. The commonly used pulse width ranges from nanosecs to microsecs, the power of the pulse can exceed 10 mW. The repetition frequency depends on the fibre length, typically is between 1 and 20 kHz, naturally it is smaller for longer fibres. The division by 2 at the inputs of oscilloscope is needed since both the vertical (loss) and the horizontal (length) scales correspond to the one-way length.

<u>The components of the fibre loss and their importance in the OTDR measurements</u>

There are three reasons for the fibre loss:

- absorption
- radiation loss
- Rayleigh scattering

The absorption creates 10-20% of the fibre loss. It mainly originates from the OH^- ions inside the fibre material (impurities). With modern technologies the number of these contaminants, so the loss can be kept at relatively low level. The fibre loss increases dinamically for wavelengths above 1700 nm, thus this is the lowest frequency for optical telecommunications. In practice the 1300 and 1550 nm wavelengths are used as the insertion loss shows minimal values at these wavelengths. Naturally, absorption does not induce reflection, so if this would be the only physical phenomena, the fibre loss could be measured by the means of OTDR only with a well known, calibrated termination.

In practice, the fibre continuously radiates backwards due to the Rayleigh scattering, which will be described later, so the absorption loss is measured together with the other losses.

Radiation loss occurs when the geometrical parameters of the fibre abruptly change, or a mechanical tension is present in the fibre material due to fabrication failure or mechanical impact. Considering appropriate fabrication technologies and fibre jacket, the radiation loss can be neglected and, like absorption, it does not create reflections, so from the OTDR measurements point of view it can handle as absorption losses. A high level discontinuity originated by e.g. strong folding, can be shown by OTDR as it produces high loss.

During OTDR measurements the most important loss is the one caused by Rayleigh scattering. It generates the 80-90% of the total loss. The scattering is induced by the microscopic inhomogenity of the refractive index of the fibre. These inhomogenities cause diffraction, so a certain part of the light energy is radiated isotropically. The level of the diffrection reaches its maximum when the wavelength is in the same range as the dimensions of the microscopic inhomogenities. Thus the level of the scattering decreases when the wavelength is increased. Among others this is the reason for using the 1300 and the 1550 nm ranges instead of the 850 nm. A certain part of the diffracted light propagates backwards in the fibre which is, when measured, carries important information. In the following, we calculate the ratio of the diffracted and the backward propagating light.

Its known that the light intensity in the fibre in the function of the distance is the following:

$$P_t(z) = P_0\left(10^{\frac{-z\alpha}{10}}\right) \qquad (1)$$

where $\alpha = \alpha_s + \alpha_a$, the sum of the scattering and absorption losses in dB/km.

The total scattered power at distance of *z:*

$$P_s(z) = \alpha'_s \Delta z P_t(z) \qquad (2)$$

Where:

Δz impulse length in the fibre,

α'_s scattering loss, is given in ratio/km [1/km]. α'_s can be easily calculated with: α'_s [1/km] = 0.23α_s [dB/km].

The impulse length in the fibre can be expressed with the group velocity:

$$\Delta z = w v_{gr} = wc/n_{gr} \approx wc/n \qquad (3)$$

Where:

w the impulse duration,

v_{gr} the group velocity in the fibre,

n_{gr} the group refractive index that now is estimated with the normal refractive index,

c the speed of light in vacuum.

Since the numerical aperture of the fibre is finite, only a certain part of the scattered light can travel backward in the fibre (S). This also faces losses during the propagation in the fibre and it reaches the input of the fibre, where the total backscattered power is:

$$P_{bs}(z) = S\alpha_s^{,}\Delta z P_0\left(10^{\frac{-2z\alpha}{10}}\right), \qquad (4)$$

where:

$z=tv_{gr}/2$, where t is the two-way propagation time of the impulse

$S=(NA/n)^2/4.55$ in case of a single mode fibre

Based on this, the scattered power from the input of the fibre that can be measured at t=0, can be easily determined:

$$P_{bs}(0) = S\alpha_s^{,}\Delta z P_0 T_s \qquad (5)$$

where T_s is the transmission of the light divider. Similarly, the scattering-amplitude generated at the end of the fibre (distance of L):

$$P_{bs}(L) = T_s S\alpha_s^{,}\Delta z P_0\left(10^{\frac{-2L\alpha}{10}}\right) \qquad (6)$$

So, the backscattered power shows an exponential fall in the function of the distance (i.e. in the function of time during the measurement). Now, calculate the maximum values of the backscattered power at 1550 and 1300 nm applying (5) considering some typical parameters (table 1.):

Wavelength	1300 nm	1550 nm
$\alpha=\alpha_s+\alpha_a$	0.4 dB/km = 1.092/km	0.2 dB/km = 1.046/km
$\alpha_s^{,}$	0.074/km	0.036/km
w	1 µs	1 µs
n	1.485	1.485
NA	0.1	0.1
T_s	1	1
S	$9.8\cdot10^{-4}$	$9.8\cdot10^{-4}$
$P_{bs}(0)/P_0$	-48.4 dB	-51.5 dB

Table 1.

When measuring such low level signals, when the power of the signal is close to the own noise of the receiver, i.e. the NEP (Noise Equivalent Power) parameter, the signal to noise ratio is increased by averaging (see Figure 1.). Thus the NEP decreases:

$$NEP_{eff}=NEP/n^{1/2}, \qquad (7)$$

where n is the number of the averaged samples

The dynamic range

The maximal fibre length that can be measured by OTDR is the function of the most important parameter of the instrument, namely the dynamic range. The definition of this parameter is:

$$\frac{P_{\max back}^{[dB]} - NEP_{eff}\left[dB\right]}{2} = \frac{P_{bs}(0) - NEP_{eff}\left[dB\right]}{2} \qquad (8)$$

where the /2 factor is due to the two-way measurement.

The effect of Fresnel reflection

Another important phenomena from the OTDR point of view is the Fresnel reflection. Fresnel reflection occurs when the electromagnetic wave propagates through the border of materials with different dielectric constants. A certain part of the power is reflected that can be calculated according to Fresnel's law. Such a reflection occurs at the terminations of the fibre and at connectors, where the dielectric constant changes abruptly (e.g. glass-air transition). The power reflection coefficient of a polished fibre termination (considering perpendicular incidence) is tipically 0.04 that corresponds to -14 dB. If we compare this with the values in Table 1. (ca. -50 dB), it is clear that it bigger by 3 orders of magnitude. It means that a fibre termination can be detected even at a distance, where the Rayleigh scattered signal is already below the NEP_{eff}. Normally, sharp peaks can be seen at the distances of the Fresnel reflections.

Measurement of attenuation by means of OTDR

Based on equation (6), it is possible to localize abrupt attenuation changes and to determine its value. This way, it is possible to localize fibre welds and connectors as well their attenuations. This abrupt attenuation change generates a step on the OTDR display. Its height is proportional to the attenuation. When there is a Fresnel reflection as well, a sharp edge can be found before the step.

Finally, it is important to emphasize that the OTDR attenuation measurements radically differ from the two-port measurements. So, it is also possible that positive steps can be found, as the fibre would amplify. This can be experienced when the numerical aperture of the fibre changes (so S changes). This problem can be solved by measuring the fibre from both ends and averaging the two attenuations.

The resolution of the OTDR – the dead zone

The resolution of the OTDR system is the distance of two reflecting points that still can be distinguished by the instrument. This depends on the width of the transmitted impulse, since the impulse must not overlap. Let us consider two reflecting points that are close to each other and an impulse (with length of Δz) propagating towards them. When the impulse reaches the first point, a certain part of its power is reflected. This reflection lasts as long as the impulse travels through the reflecting point, i.e. the length of the pulse. It means that the reflected pulse is also Δz long. Meantime, the non-reflected part of the transmitted pulse reaches the second reflection point. If the front of the second reflected pulse, also with Δz length, reaches the end of the first reflected pulse, then the two pulses cannot be distinguished as they overlap. It means that the locations of the two reflections cannot be distinguished either. So, the theoretical limit of the resolution is the half of the length of the impulse ($\Delta z/2$). The decrease of the pulse length increase the resolution, however the signal power decreases, too. Thus, the good resolution results narrow dynamic range. This problem can overcome by means of code modulation which is commonly used in radar technology.

The dead zone closely connects to the resolution: the instrument cannot measure accurately during the transmission of the test impulse as the width of the pulse at the input of the fibre changes continuously. Besides, during the transmission there is a strong reflected signal at the input of the instrument from the Fresnel reflection at the input of the fibre, which overloads the receiver.
The detector needs some time after the transmission for accurate measurements (on the display the reflection peak covers the real signals). During this time only very high level signals (e.g. other reflection peaks) can be detected. In practice, the dead zone is a multiple of the resolution.

Required equipments:

- HP 8146 optical reflectometer (OTDR)
- 2 pcs 2m monomodal patch cord
- 1 pc 4 m monomodal patch cord
- 6 km monomodal loop
- 18 km monomodal loop
- infrared sensor card for 1300 nm wavelength

Measurements:

1. Calculate the values of the dead zone and resolution belonging to different impulse widths (w = 10, 30, 100, 300 ns and 1us, and use n_{gr}~1.5). At the calculation of the dead zone, approximate it by four times the resolution. Write the results in chart 3.

2. Compare some results obtained in the previous task to the data in the help content of the instrument.

3. Calculate the reflected light power – transmitted light power ratio (P_{bs}/P_{out}) in dB at the input plane of the fibre connecting to the instrument (Z = 0) for all pulsewidths given in the first task. The wavelength is 1300 nm. For the calculation, consider the values given in Table 2. The results have to be written in Table 3.
The same procedure has to be done for the other wavelength. Compare the results and comment the meaning of it.

Wavelength	1300 nm	1550 nm
α [dB/km]	0.4	0.2
α_s [dB/km]	0.35	0.25
α'_s [1/km]=0.23α_s [dB/km]	0.0805	0.0575
n	1.485	1.485
NA	0.1	0.1
T_s	1	1
S	$9.8\cdot10^{-4}$	$9.8\cdot10^{-4}$

Table 2.

4. Let us assume the maximum output power coupled into the fibre is 1 mW (0 dBm) and NEP = -70 dBm. Write these values into the corresponding heads of chart 3. By the use of the results already obtained in the previous tasks calculate the dynamic reserve of the measurement (P_{din}[dB] = (P_0[dBm]+$P_{bs}(0)/P_0$[dB]-NEP[dBm]/2). Recalculate it in case of an averaging using n = 10 000 ($NEP_{eff} = NEP/n^{0.5}$)

Wavelength	1300 nm					1550 nm				
w (ns)	10	30	100	300	1000	10	30	100	300	1000
Resolution [m]										
Dead zone [m]										
$P_{bs}(0)/P_0$ [dB]										
P_0 [dBm]										
NEP [dBm]										
Pdin [dB]										
NEP_{eff} [dBm] n = 10 000										
$Pdin_{eff}$ [dB] n=10000										
L [m]										
L_{eff} [m]										

Table 3.

5. Knowing the dynamic reserve, calculate the maximal length of section on the line. Take into account the followings:
- the attenuation of the line (Rayleigh scattering and the absorption together) per kilometer
- the attenuation of fibre weldings and backloops (generally 0.1 dB/km)

Recalculate the task in case of an averaging using n = 10 000 points.

6. Power on the instrument and get familiar with the basic features and the user interface.

7. Connect a 4 meters long patch cord fibre to the input of the instrument. Set the following parameters:
- wavelength: 1310 nm
- impulse width: 10 ns
- start position: 0 km
- span: 2 km
- averaging time: 5 sec

Activate the laser. It is forbidden to look into the fibre while the laser is in operation!
Check if the laser is in operation by the use of the infrared sensorcard. With the aid of markers find and enlarge the reflection corresponding to the end of the fibre, and read the length of it.

8. Study the picture of the connection between universities placed on the wall in the laboratory. Connect the 7 km loop (third and fourth connector in the light –cabel cupboard) so that one of its end stays open. Set the following parameters:
- wavelength: 1550 nm
- impulse width: 10 ns
- start position: 0 km
- span: 7 km
- averaging time: 5 sec

a, Activate the laser and search for the dominant reflections. To determine the positions of the reflections follow the way of light along the fibre, between the lab 620 in building V2, Horticultural University and the R building.

b, Increase the width of the impulse so that the whole 7 km section gets over the noise level.

c, Determine the attenuations at each connectors, and the attenuation of the fibre per kilometer.

Repeat the measurement at λ = 1550 nm, and compare the results with the previous values at 1310 nm.

9, Repeat the previous measurements on the loop of length equal 18 km. What sort of odd phenomenon do you observe during the measurement?

Questions:

1. Give the wavelengths of the three optical window.
2. What is the physical background of the Rayleigh scattering?
3. What is Fresnel reflection? How much is the general value of it in case of polished fibre?
4. How does the absorption attenuation affects the whole fibre attenuation being measured?
5. At 1550 nm, or at 1300 nm would be the fibre attenuation bigger? Why?
6. What sort of factors affects the resolution?
7. What is dead zone?
8. When can radiation loss appear?
9. What is the definition of the dynamic range?
10. Draw the block scheme of OTDR.

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