Measuring and evaluation of single-mode fibers using optical time-domain reflectometry

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Contents

1 Introduction

Most of the international communication use fiber to transmit data [1]. To measure and evaluate if a fiber is working correctly is therefore of high importance. In this report some fibers are measured and evaluated. Characteristics which are handled in this report includes connector losses, bending losses and fiber attenuation at two wavelengths, 1555 nm and 1310 nm.

2 Background

2.1 Characterizing a fiber

To characterize a fiber some different metrics can be used. One of those is attenuation which is described by α in units of dB/km. This corresponds to a power loss of α dB per km.

Another important metric is connector loss. For a single-mode fiber (SMF) designed for a wavelength of some μm it can be approximately 10 µm [2]. A small misalignment can therefore give rise to losses. If the core of to fibers are not equal it can also create losses. Splices which change the core diameter can give rise to losses, production faults such as varying core diameter and bending of fiber are also sources of losses [3]. The losses between point A and B are defined as the power at B divided by the power at point A. The unit dB is often used for these kinds of losses.

For collecting data about fiber losses and characteristics of some SMF fibers a OTDR device was used (Agilient/HP 8147 OTDR). The device exerts a high power laser pulse into the fiber and measures the back-scattered light [4]. The back-scattered light is directly proportional to the pulse power [5]. Therefore the device can calculate the power of the pulse relative to the pulse power. The back-scattered light is calibrated in time to also measure at what time back-scattered light is detected at the instrument [5]. This allows for calculation of distance that the back-scattered light has travelled.

2.2 The OTDR instrument Agilient/HP 8147 OTDR

Some important settings of the Agilient/HP 8147 OTDR (OTDR instrument) are pulse length and laser wavelength [4]. The pulse length is the length of the laser pulse inserted into the fiber by the instrument. It affects the resolution of the instrument and the pulse power. A high pulse power is needed when examining a longer fibre. Because of the attenuation in the fiber for long fibers the back-scattered power will be to small for the instrument to detect. However with a longer pulse length the resolution will get worse [5]. A pulse which is 15 meters of length will have back-scatter from all parts of the pulse. If a pulse of length 15 meters passes two connectors which are 1 meter apart, they will both affect the back-scattering at almost the same time. Therefore a limiting factor of the resolution is the length of the pulse.

Another feature of the OTDR is the average mode and the refresh mode. The average mode averages over many pulses and will therefore make some noise cancel out [4]. However the refresh mode refreshes the measurement so that it is possible the set up the measurement [4].

2.3 Bending losses

Bending losses can be divided into macro and micro bending losses [3]. The micro bending losses are generally very small bends in the fiber and macro bends are larger bends [3]. Bending can occur because of environmental properties, production defects, or large scale bending of the cable.

The bending loss can be explained by looking at total internal reflection. Total internal reflection is achieved in a SMF and can be explained by a ray model of light. If a light ray falls upon a surface with incident angle of θ, then it will be totally reflected if

$$\theta < \theta_C = \sin^{-1}\left(\frac{n_2}{n_1}\right), \tag{1}$$

where n_1 is index of refraction in material with incoming wave and n_2 is index of refraction behind the surface for the wave to be reflected upon (for a step index SMF) [6]. This is called total internal reflection [6].

In an idealized case a ray in a SMF is reflected between the two sides of the core of the fiber (in a step-index fiber) [6]. However if a bend in the fiber is introduced, also θ increase to some extend [3]. If $\theta > \theta_C$ still, there will be total internal reflection. However if the bending make $\theta < \theta_C$ then the ray will leave the fiber. In the ray model some of the rays propagating in the fiber will not be totally reflected and then leave the fiber [3], which explains the bending loss.

3 Measurement method

This report includes measurements of fiber length, fiber attenuation (α), optical connector loss and fiber bending loss. The length of two different fibers (later referred to as "fiber 1" and "fiber 2") have been measured. For measurement of connector loss a connector between fiber 1 and 2 put under measurement to determine optical connector loss. Lastly the bending loss of fiber 1 was tested.

3.1 Measurement of fiber length and attenuation

To measure fiber length the OTDR instrument sends out a pulse, measure the back-scattered light and also at which time different levels of light are

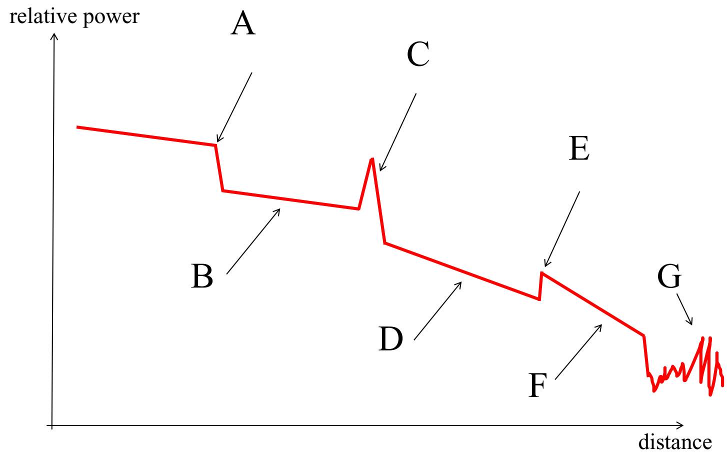

Figure 1: Plot of a typical display with some features, A, B, C, D, E, F and G. A corresponds to a splice, B to a fiber, C to a connector, D to a fiber with attenuation greater than B, E to a splice and F to a fiber with more attenuation than D. G indicates a noise floor.

detected [5]. It displays the power level versus time but converts time to distance and power to relative power compered to the pulse power. Such a graph is shown in figure 1. The distance (from instrument) is shown on the horizontal axis and relative power levels on the vertical axis. Features (marked A, C, E) in the graph corresponds to different so-called events in the fiber. The length of one cable is determined by looking at the features. The lines marked B, D and F are fibers. The back-scattering is linearly (appears as linearly in dB scale) decreasing. At A, C and E there are connectors between fibers. Therefore the length of the first fiber can be determined by looking at which distance point A is [4].

The attenuation of the fibers can be observed in figure 1. At point B the power is decreasing linearly in the plot. The OTDR displays the relative power in units of dB [4], so the power is actually decreasing exponentially [5]. The attenuation coefficient α can be determined by measuring the slope of B, D and F in figure 1. A steeper slope corresponds to a higher attenuation. The OTDR instrument does is described by

$$\alpha = \frac{P_2 - P_1}{d_2 - d_1} \tag{2}$$

where P_1 and P_2 are relative power levels at point 1 and 2. d_1 and d_2 are distances at point 1 and 2. In the OTDR the attenuation is calculated and displayed for intervals adjustable by placing markers [4].

Bending loss have been evaluated by bending a fiber under measurement a number of turns around a cylinder of diameter 9 mm. By using refresh mode of the OTDR instrument a attenuation of fiber first was noted without a bending of the fiber. Then by bending the fiber 1, 2 and 3 turns around the cylinder a decrease of back-scattered power was observed and noted.

3.2 Optical connector and splice losses

A connector connects two fibers together. An example of how that will be detected by an OTDR instrument is shown at point C in 1. A high power reflection is followed by more fiber of different characteristics [5].

How a splice in a fiber can look is shown at point A in figure 1. In point A the loss can be read from the vertical axis, however at point E the power seem to have increased after the optical connector. A passive element as a fiber does not have a gain [3]. What happens is that back-scattered power level at fiber F is higher than in fiber D. That means that the loss at E (which corresponds to a lower back-scattered power) will to some extent be canceled out by the additional back-scatter from the fiber at F. An error is therefore introduced and means that a coupling loss with fibers of different attenuation need to be measured from both ways [3][4][5].

The apparent loss (shown in the OTDR machine, L_{app}) can be described as

$$L_{app} = L_{coupling} + \Delta P_{back-scatter} \tag{3}$$

where $L_{coupling}$ is the actual coupling loss and $\Delta P_{back-scatter}$ is the difference in back-scattering level.

$$\Delta P^{A \longrightarrow B}_{back-scatter} = -\Delta P^{B \longrightarrow A}_{back-scatter} \tag{4}$$

where $A \longrightarrow B$ denotes that fiber A comes before fiber B. Therefore it is possible to measure the coupling loss combining equation 3 and 4 into

$$L_{coupling} = \frac{L^{A \longrightarrow B}_{app} + L^{B \longrightarrow A}_{app}}{2}. \tag{5}$$

This is the mean can be used to calculate the coupling loss.

4 Results

The results include length, attenuation, and loss measurements.

4.1 Length and attenuation

Length measurements where conducted for the two fibers. In figure 2 the display is shown under measurement of fiber 1. With markers places as in

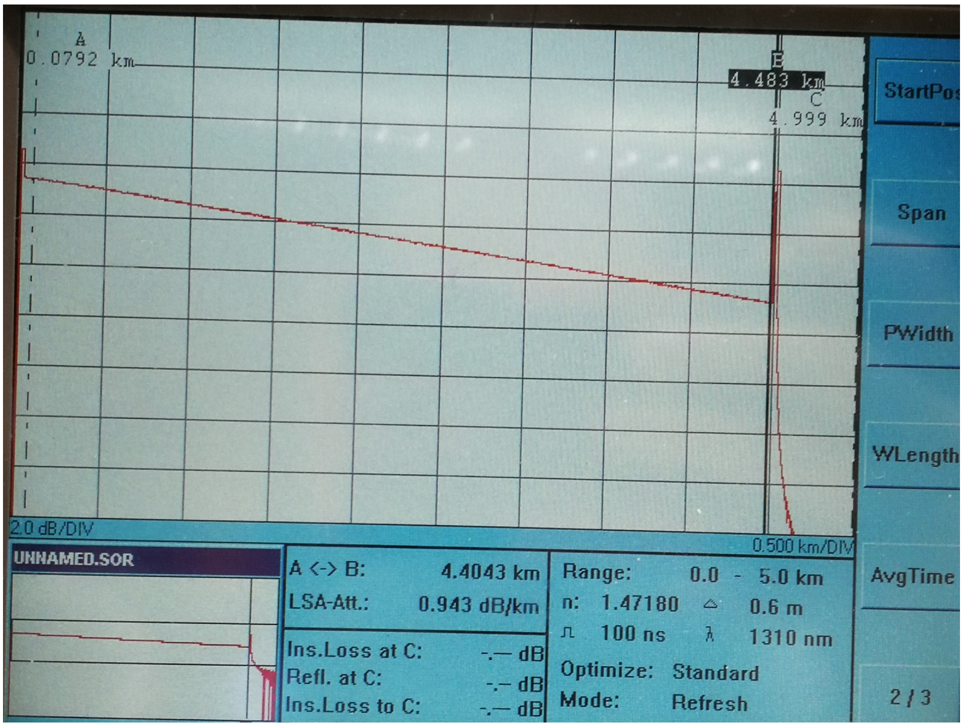

Figure 2: Fiber 1 under measurement.

	$\lambda = 1310\,\text{nm}$	$\lambda = 1555\,\text{nm}$
Fiber 1	$\alpha = 0.942\,\text{dB/km}$	$\alpha = 0.457\,\text{dB/km}$
Fiber 2	$\alpha = 0.332\,\text{dB/km}$	$\alpha = 0.197\,\text{dB/km}$
Corning SMF-28 fiber	$\alpha = 0.32\,\text{dB/km}$ [2]	$\alpha = 0.18\,\text{dB/km}$ at $1550\,\text{nm}$ [2]

Table 1

the figure the length of the fiber is approximately 4.4 km. A pulse length of 1 µs is used.

In figure 3 fiber 2 is under measurement. With markers places as in the figure the fiber length is approximately 49.5 km. A pulse length of 1 µs is used.

The attenuation in the two fibers where measured with wavelength 1310 nm and 1555 nm. Four measurements where carried out. In figure 4 fiber 2 is under measurement with a wavelength of 1555 nm. The results are summarised in table 1.

4.2 Bending loss

The bending loss was measured for some cases which are shown in table 2. The bending loss specified in the table is the percentage of the power that

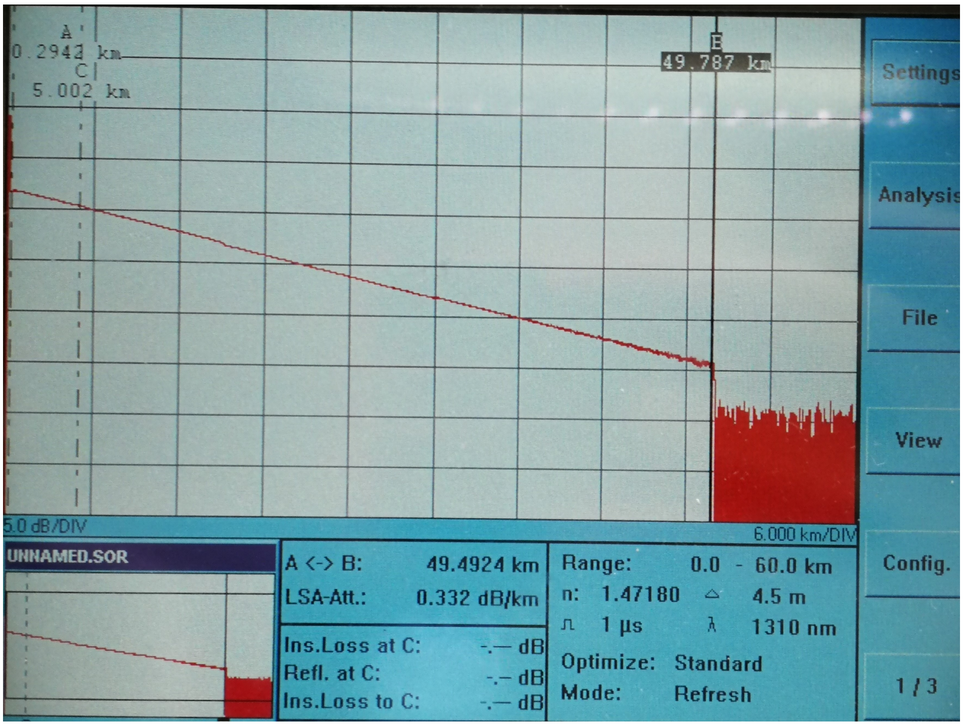

Figure 3: Fiber 2 under measurement.

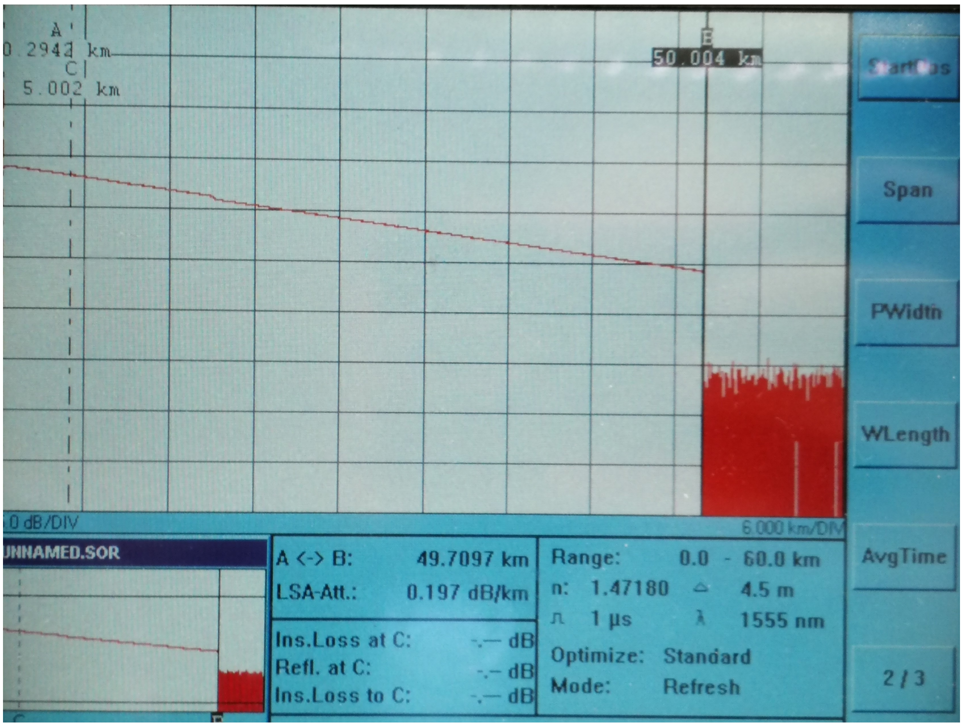

Figure 4: Fiber 2 under measurement.

is not lost in the bend.

Number of turns	Cylinder diameter	Bending loss
1 turn	9 mm	$-1\,\mathrm{dB} \approx 79\%$
2 turns	9 mm	$-4\,\mathrm{dB} \approx 40\%$
3 turns	9 mm	$-12.5\,\mathrm{dB} \approx 6\%$

Table 2

4.3 Connector loss

The connector loss was measured by doing two OTDR measurements, one from each fiber end. The measurement where fiber 1 (4.4 km) was connected to the instrument is shown in figure 5. Markers A and B where placed around the connector event and the apparent "loss" can be read off as 4.85 dB. With fiber 2 connected to the OTDR instrument figure 6 was obtained. With marker A and B placed as in the figure, a apparent "loss" of −3.11 dB can be observed. The actual loss is obtained by

$$L = \frac{-3.11\,\mathrm{dB} + 4.85\,\mathrm{dB}}{2} \approx 1.77\,\mathrm{dB} \tag{6}$$

using equation 5.

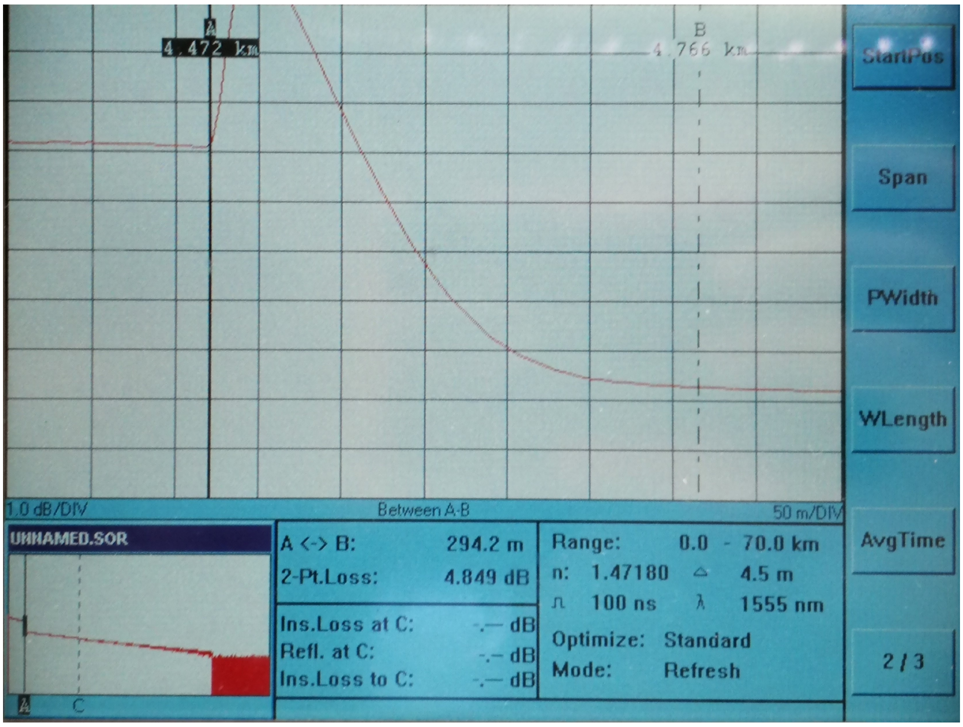

Figure 5: OTDR measurement of coupling loss with the instrument connected to fiber 1.

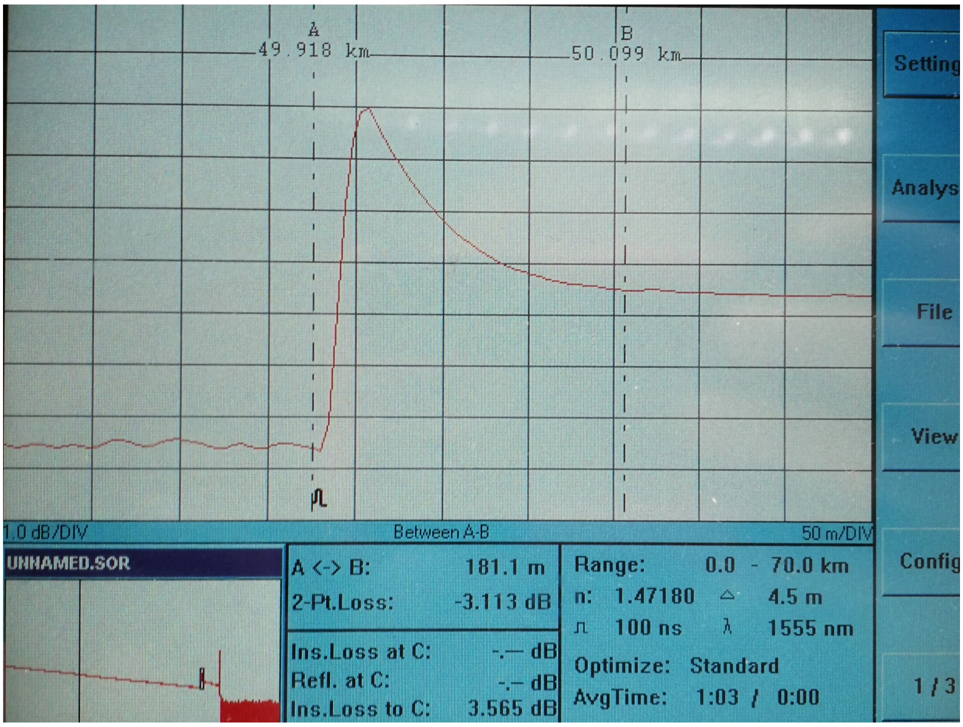

Figure 6: OTDR measurement of coupling loss with the instrument connected to fiber 2.

5 Discussion

Evaluation of fiber performance can be done with the results in this report. Attenuation in a fiber from Corning is 0.32 db/km for 1310 nm and 0.18 db/km for 1550 nm [2]. According to the values from measurements done on fiber 1, it can be noted that the attenuation is much higher than that of a Corning SMF-28 Ultra Optical Fiber [2]. However fiber 2 has a attenuation that is almost as low as for the Corning fiber. Therefore a conclusion could be that fiber 1 has a bad performance while fiber 2 has a acceptable performance. However a choice of fiber should also include considerations of cost, dispersion, type of usage and other system requirements.

For all three fiber (fiber 1, 2 and the Corning fiber) the attenuation at 1555 nm is lower than at 1310 nm. This fits well with other the loss spectrum for different wavelengths in SMF where there is a minimum in the loss at approxidamently 1550 nm [6].

The bending loss of fiber 1 was also evaluated. It can be seen that the loss is not proportional to the number of turns. After one turn a loss of 21% is present, however after three turns the transmitted power through the bend is only 6%. One turn could probably be tolerated in some fiber optic systems but three turns is probably unacceptable in most systems. An expression correlating the bending by degrees per meter to the loss could be useful to investigate in further research. In section 2.3 a model to describe the bending loss is presented. Using this model the bending loss will increase when bending occurs which is also observed in table 2.

Lastly, the connector loss can be evaluated. A connector loss from experiments described in this report are 1.77 dB. A typical optical connector loss is 0.3 dB (depending on type of connector) [7] [8]. The loss in the experiments conducted are therefore much larger than that of a typical connector. In the experiments some extra connectors where used to attach fiber 1 and 2 to the connector. This probably led to some extra losses which was not observable in the OTDR instrument because of the resolution being to low. However the number of extra connectors is not enough to support the conclusion that the connector has a loss of about 0.3 dB. The conclusion must be that the optical connector loss in this experiment was higher than normally seen in optical fiber systems.

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