# Measuring Optimal Length of the Amplifying Fiber in Different Working Conditions of the Amplifier

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***Abstract.*** *The aim of this article is to highlight possible unwanted behaviour of an EDFA optical amplifier during temperature changes. After a brief introduction dealing with amplifiers and doped fibers in general we focus on the assembly of our own EDFA amplifier with standard construction and the IsoGain I-6 amplifying fiber, and on the parameters of its individual components. Since an erbium doped fiber has usually no direct thermal stabilization, temperature changes can affect performance of the entire amplifier. The next part of the article therefore describes the impacts of such changes on behaviour of our amplifier. At the very end we performed a measurement of the amplifier deployed in the actual WDM-PON the description of which can be found in the last chapter.*

## Keywords

***EDFA, erbium, optical amplifier, PON, rare earths, thermal stress, WDM.***

## 1. Introduction

The crucial thing in optical telecommunication systems is the need to span long distances between the endpoints of a topology. The optical signal from a transceiver must pass through an optical fiber and then must be detected by a receiver. However, we can encounter certain problems the biggest one of which is the attenuation.

The attenuation originates in optical fibers as well as in other optical components such as couplers, splitters, AWGs, etc. It can make a signal very weak for detection. That is why, the main objective in the optics in the last decade has been to find a method to regenerate or amplify the signal so it can be easily detectable. Devices performing such regeneration and amplification are the so called regenerators and optical amplifiers, respectively. [1].

As far as differences between the two devices are concerned, the former “only” receive the optical signal, convert it to the electric domain, repair it and then convert it back, while the latter, i.e. amplifiers, work similarly, plus their main advantage is their versatility. Optical amplifiers do not need to know the network settings, modulation, bitrate etc., they do not depend on them, so the systems which use the amplifiers can be easily upgraded. [2].

Over the last few years, optical fiber amplifiers have experienced enormous development, especially as far as their properties are concerned. These properties are influenced not only by the material they are made of but also by the way the material is utilized.

A doped fiber is made of a host matrix, i.e. the material to which a dopant is added. Rare earth ions are used as dopants. In the case of erbium-doped fibers, the silica glass is used with aluminium as a codopant. However, there are also other options such as oxide glass, halide glass, chalcogenide glass, etc. [3], [4].

Other important fiber components are admixtures that are added to the $SiO_2$ in order to improve its characteristics. We can e.g. increase the refractive index using $GeO_2$, $TiO_2$, $Al_2O_3$ or $P_2O_5$. On the other hand, decrease in the refractive index can be achieved by using $B_2O_3$ or F. As far as dopants are concerned, the most important one is erbium because it is the main substance of EDFA amplifiers. Various types of dopants cause higher absorption in a fiber, which allows us to use shorter lengths of doped fibers.

Another way to change the properties of a doped fiber is to apply a strain. In our experiment we have focused on thermally induced strain that results in change in cooperative upconversion. Cooperative upconversion is an energy transfer between two excited electrons where one of them gets higher energy and ascends to a higher level, whereas the other one loses energy and rapidly drops to a lower level. The erbium-doped medium is represented by a two-level system to which the Boltzmann distribution law is applied. The signal level decreases when temperature and cooperative upconversion increase. The increasing noise is a secondary phenomenon [5], [6]. Thermal strain influences not only the signal power of the amplifier but also directly affects the time when electrons remain in the excited state. Intrinsic saturation power increases with temperature, but excited state lifetime decreases [7].

However, there are also other ways how to apply stress, for example by the electron radiation. Results of such experiment show that when the intensity of the electron radiation increases, the gain of the amplifier as well as the susceptibility of the whole system to the temperature or input signal power change decreases [8].

Mechanical strains occurring in a fiber do not always have a negative effect, as shown by experiments with Macro-bends. When used properly, macro bends can be very useful. The problem of uneven amplification of the whole spectrum is usually solved by using a gain-flattening filter. Unfortunately, these filters are difficult to manufacture and therefore are very expensive. In this case, macro bends can be a useful solution. They cause higher loss at longer wavelengths and thus flatten the gain spectrum of the proposed C-band EDFA [9]. The right combination of macro bends and EDF lengths enables us to achieve a balanced amplification of the whole spectrum.

## 2. Concept of Erbium Doped Fiber Amplifier

This chapter is focuses on the construction of an amplifier and properties of the individual components. As a model, we used a conventional erbium-doped fiber amplifier schematic diagram.[10] This scheme can be seen in Fig. 1.

Instead of components used in standard amplifiers much bigger components were used, so it was impossible to achieve at least partial integration. For that reason, the entire amplifier was placed on a mounting plate covered by a soft foam protecting individual components and optical fibers. Since we expected it would be necessary to move the amplifier from one place to another, we have built a two-storey construction that is easy to manipulate and at the same time is "component-friendly". The assembly can be seen in Fig. 2.

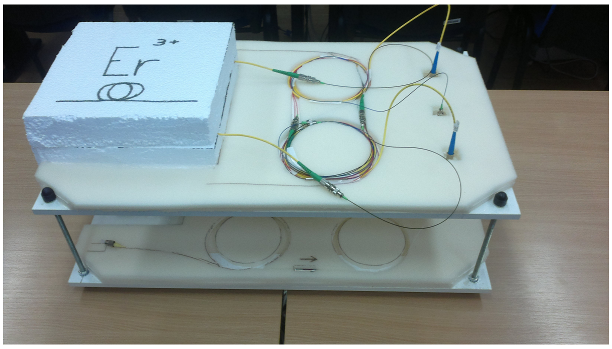


**Fig. 2:** Construction of the erbium doped fiber amplifier.

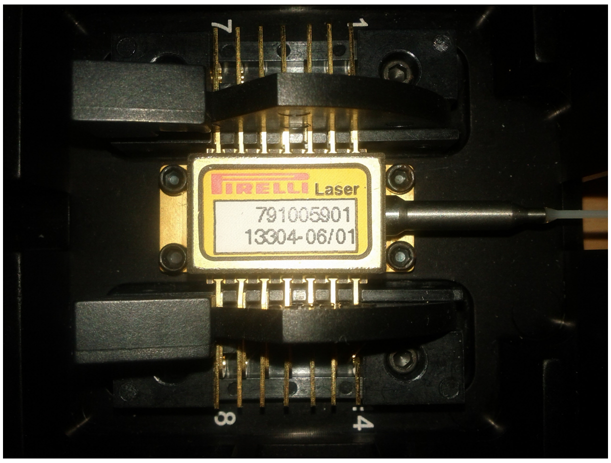


**Fig. 3:** Pump laser placed in the butterfly laser diode mount Thorlabs LM14S2.

### 2.1. Used Components

The first important component of an EDFA amplifier is a pumping laser. In setup we used a butterfly-type semiconductor laser together with an adapter from Thorlabs. Another component is the erbium doped fiber. For our measurement we used a fiber from Fibecore. The most suitable one for our purposes was a fiber from the IsoGain series, the IsoGain I-6 type in particular.

For the construction the optical source from Pirelli was chosen; its parameters at 25 °C are given in Tab. 1. Fig. 4 shows $P/I$ characteristics of the pump laser, and Fig. 5 shows its spectral characteristics.

The main advantage of the IsoGain I-6 fiber is its absorption which enables us to use shorter fiber length and thus lower power of the pumping source. The information provided in the datasheet for this type of fiber state that the optimal fiber length at the 115 mW pumping power and the 977.1 nm wavelength is

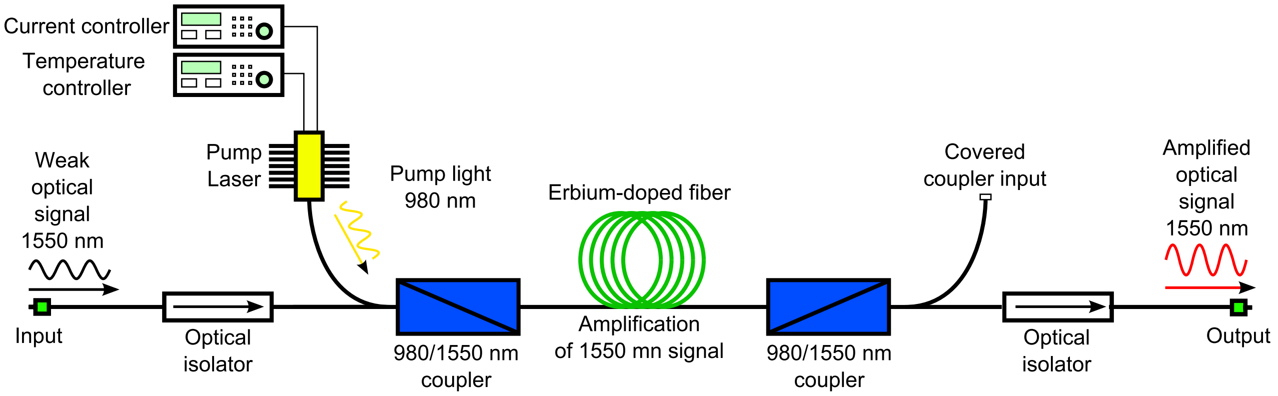


**Fig. 1:** Circuit of the constructed amplifier.

**Tab. 1:** Parameters of the pump laser.

| Parameter | Value |
|---|---|
| Rated power | 125 mW |
| Threshold Current | 20,4 mA |
| Forward Current | 21,56 mA |
| Kink current | 258 mA |
| Peak Wavelength | 976,6 nm |

**Tab. 2:** Parameters of the erbium doped fiber IsoGain I-6.

| Parameter | Value |
|---|---|
| Cut-off wavelength | 870-970 nm |
| Numerical Aperture | 0,22-0,24 |
| MFD @ $\lambda$ nominal | 3,5 @ 980 µm |
| Absorption at 980 nm | 4,5-5,5 dB·m$^{-1}$ |
| Attenuation at 1200 nm | $\leq$ 10 dB·m$^{-1}$ |
| PMD | $\leq$ 0.005 ps·m$^{-1}$ |
| Fiber diameter | 125 $\pm$ 1 µm |
| Core concentricity | $\geq$ 0.3 µm |
| Coating diameter | 245 $\pm$5% µm |
| Coating type | Dual acrylate |

approximately 14 m. Other components involved in the construction were isolators and couplers. A list of parameters of the WDM coupler and the isolator can be found in Tab. 3 and Tab. 4.

A component which is essential for the amplifier but is missing in the list of the used components because of its high cost is the gain flattening filter. Its task is to flatten a gain spectrum of the amplifier. As we know from the previous chapters, the EDFA can amplify an optical signal in its entire optical gain spectrum. However, such amplifiers do not amplify the band evenly. That is why, gain flattening filters are usually used. Their downside is their high cost.

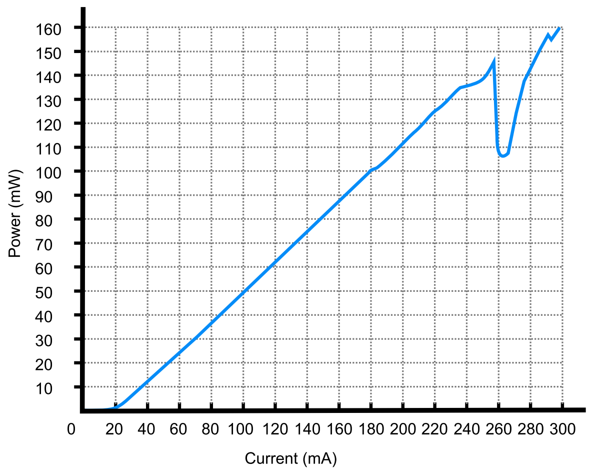


**Fig. 4:** $P/I$ characteristics of the Pirelli pump source.

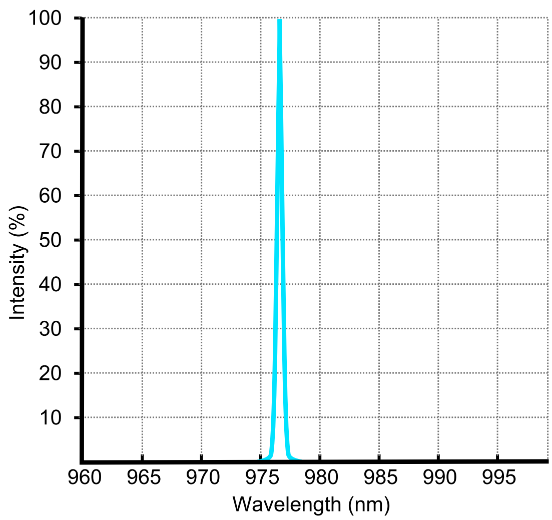


**Fig. 5:** Spectral characteristics of the Pirelli pump laser.

**Tab. 3:** Parameters of the WDM coupler.

| Parameter | Value |
|---|---|
| Operating Wavelength | 980/1550 nm |
| Insertion Loss at 980 nm | 0,02 dB |
| Isolation Loss at 980 nm | 24,3 dB |
| Insertion Loss at 1550 nm | 0,06 dB |
| Isolation Loss at 1550 nm | 33,7 dB |
| Directivity | >60 dB |
| PDL | 0.01 dB |
| Fiber Type | OFS 980 Coupler |
| Fiber Length | 1.0 m |
| Connector Type | FC/APC |
| Operating Temperature | -20∼+70 °C |

**Tab. 4:** Parameters of the isolator.

| Parameter | Value |
|---|---|
| Fiber type | SMF-28 |
| Operating Wavelength | 1550 nm |
| Insertion Loss | 0,26 dB |
| Isolation | 31,56 dB |
| Polarization dependent loss | 0,08 dB |
| Polarization mode dispersion | <25 ps |
| Return loss, input / output | >60/55 dB |

# 3. Measuring Optimal Length of the Amplifying Fiber in Different Working Conditions of the Amplifier

This chapter deals with the measurement of the ideal length of fiber in various temperature conditions. The length of fiber has a significant effect on the gain of the amplifier. Figure 8 and Fig. 9 illustrate the construction diagram that was designed for this measurement. We used the oilbath model ONE 7 from Memmert in order to achieve high temperatures, and the snow for cooling and achieving low temperatures. For the measurement at 25 °C, the fiber was loosely placed on the table.

For the experiment, we selected three basic temperature conditions - 1 °C, 25 °C and 50 °C - because we wanted to achieve three basic states: hypothermia, standard state and hyperthermia. As already mentioned above, according to the producer's datasheet, the ideal length of fiber is 14 m. Since we had 20 m at our disposal, we decided to start measuring at 20 m and then successively cut off 2-metre-long pieces and, thus, measured 20 m, 18 m, 16 m, 14 m, etc. of the fiber. Another step consisted in splicing pigtails to both ends of the fiber. Particular emphasis was placed on maximum precision of the work so that each weld had the lowest possible attenuation. Due to this accuracy, the highest attenuation achieved was 0.01 dB. The spliced fiber was then put in a plastic foil and carefully sealed in order to prevent penetration of water to the fiber when it was placed in a temperature bath. Along with the fiber there was also the PalmSence FTC-PALM-ST fiber thermometer. Fig. 6 and Fig. 7 illustrate placing the fiber in the thermal and snow bath. A disadvantage of this solution was condensation of water inside the plastic foil. For that reason the measurement had to be performed quickly.

**Fig. 6:** Testing erbium doped fiber IsoGain I-6 at 1 °C temperature.

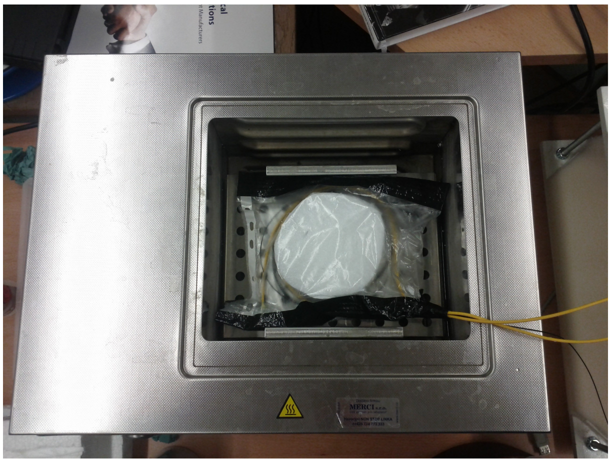

**Fig. 7:** Testing erbium doped fiber IsoGain I-6 at 50 °C temperature.

Due to high output power of the amplifier the variable EXFO $FV - 60b$ digital attenuator was placed between the amplifier and the spectrometer in order the prevent damage of the latter. The attenuation of EXFO $FV - 60b$ was set to 1.55 dB, and the internal attenuation of the digital attenuator was set to 2.5 dB. This attenuation was sufficient for the protection of both devices.

The following charts (Fig. 10, Fig. 11 and Fig. 12) show the ideal fiber length at the pumping power of 10 mW, 50 mW and 125 mW. For the amplified signal we chose the parameters with the 1553 nm wavelength and 1 mW power. It is obvious from the chart that the power for the sufficient excitation of erbium ions is up

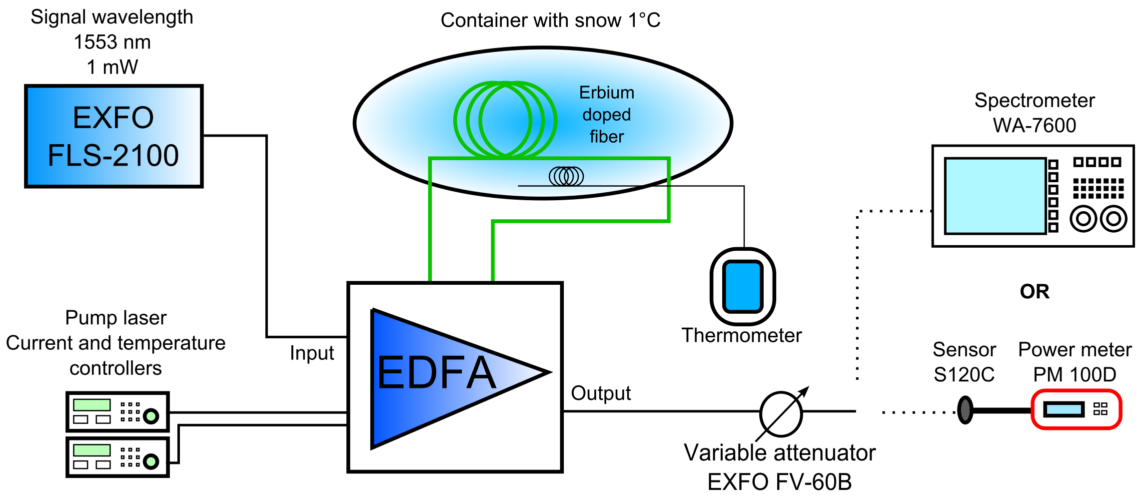


**Fig. 8:** Measurement construction for testing different lengths of EDF at 1 °C temperature.

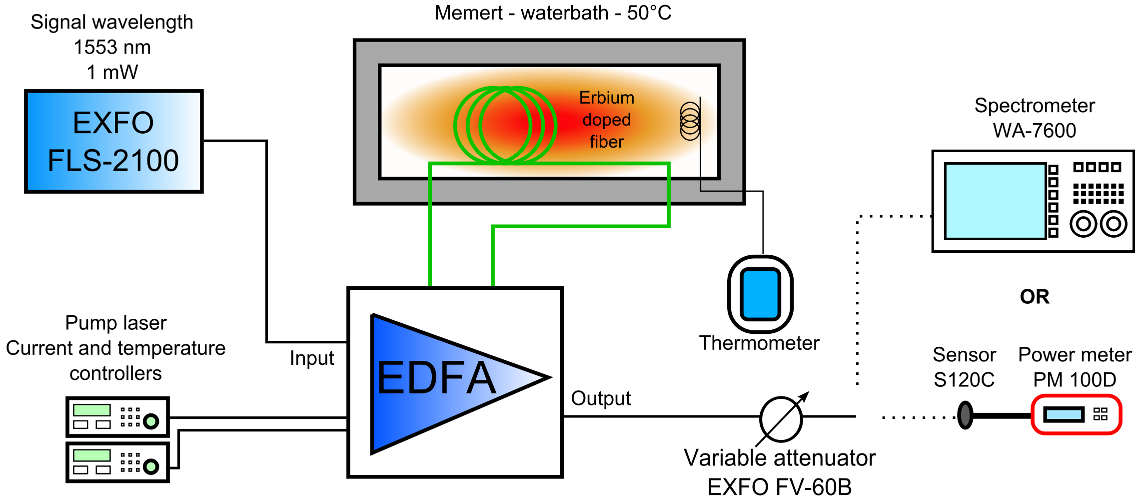


**Fig. 9:** Measurement construction for testing different lengths of EDF at 50 °C temperature.

to 125 mW. At lower powers the fiber was attenuated or amplified only partially.

The optimal fiber length at all three temperatures was 16 m. The conclusion resulting from the measurements is that the change in temperature of the fiber did have an impact on the power of the amplifier. The lowest power of the amplifier could be observed at 50 °C. The change in temperature causes a change in the stimulated emission cross section: with the temperature increase the cross section of erbium decreases, which affects the overall gain of the amplifier. The measurement also shows that the temperature stress does not have a significant influence on the change of the spectrum of the output signal of the amplifier as such. This fact can be caused by low resolution and spectral range of the used spectrometer. In fact, power fluctuations can also be caused by moving the energy among parts of the spectrum that the spectrometer possibly have not measured at all [11].

## 4. Measuring Function of the Amplifier in the WDM-PON

The final part of the measurement consisted in connecting the amplifier into the optical network. Our

**Tab. 5:** LG-Nortel EAST 1100 – WDM-PON parameters.

| Parameter | | Value |
|---|---|---|
| PON interface | Wavelength band | 1573-1600 nm |
| | Mean launch power | 19 dBm |
| | Minimum sensitivity | -29 dBm |
| | Channel interval | 100 GHz |
| | Transmission distance | 20 km |
| | Transmission speed | 125 Mbps |
| WPF | AWG insertion loss | 5 dB |
| Ethernet Access units | Wavelength band | 1533 -1560 nm |
| | Mean launch power | -12 dBm |
| | Minimum sensitivity | -36 dBm |

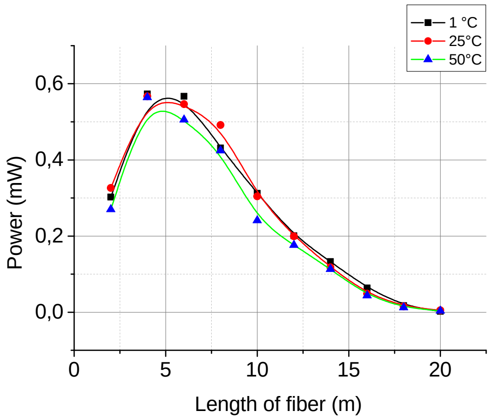


**Fig. 10:** Measuring different lengths of doped fiber at 10 mW pump power and dissimilar temperatures.

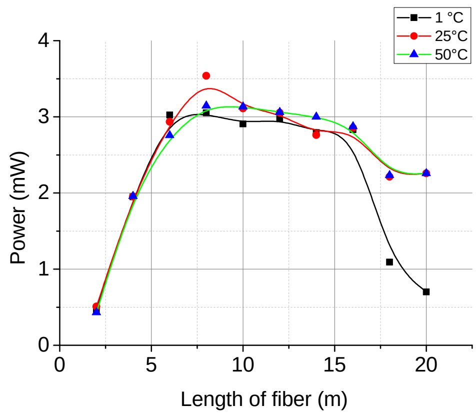


**Fig. 11:** Measuring different lengths of doped fiber at 50 mW pump power and dissimilar temperatures.

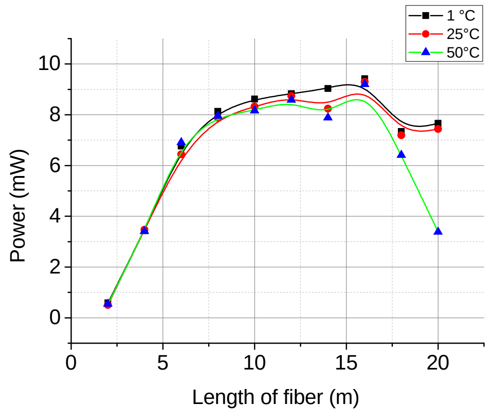


**Fig. 12:** Measuring different lengths of doped fiber at 125 mW pump power and dissimilar temperatures.

designed solution of EDFA amplified only the C-band, which had to be taken into account. As for the Optical Line Termination (OLT), we chose the LG-Nortel EAST 1100 with WDM-PON service card whose parameters can be found in Tab. 5. The ONU unit parameters are to be found in Tab. 6.

**Tab. 6:** LG-ERICSSON EARU 1112 parameters.

| Parameter | Value |
|---|---|
| Wavelength band | Colorless |
| Bands Tx @ Rx | C-band @ L-band |
| Input fiber type | SMF ITU-T G.652 |
| Connector | SC/APC |

Figure 13 describes the whole schematic diagram of the amplifier connection into the WDM-PON. Using a circulator, the original signal had to be divided into two parts: the L-band for downstream and the C-band for upstream. Such system was needed because the EDFA amplified only the C-band, and the L-band would not have passed through it. This could have resulted in non-functioning of the whole construction because the ONU units would have not been tuned to the required wavelengths. Therefore, the L-band branch was just connected using an ordinary single-mode patch cord. In the opposite direction, there was the digital attenuator and the amplifier connected in a line.

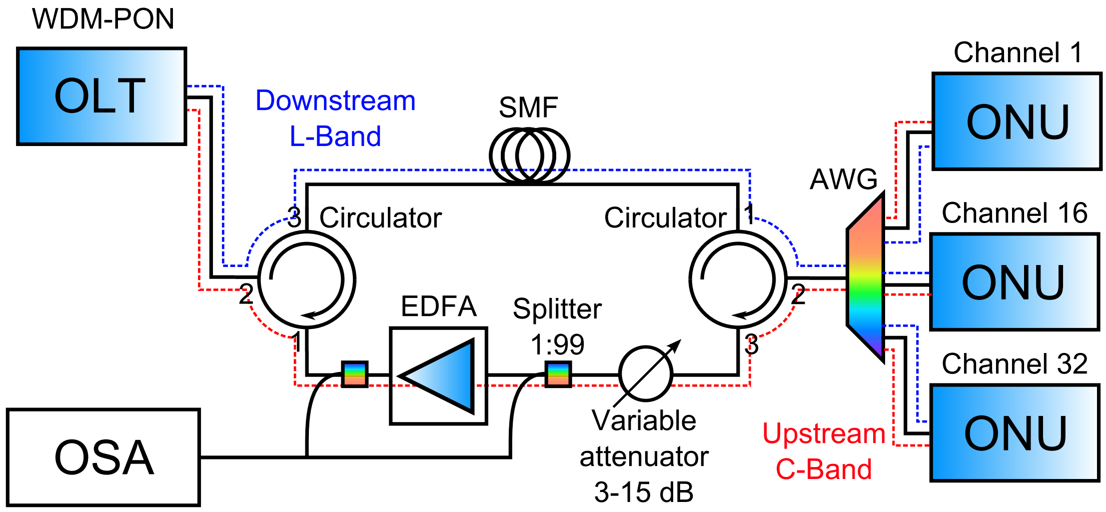


**Fig. 13:** Diagram of connecting the amplifier into the WDM-PON.

Other components were two splitters; one of them was connected in front of the amplifier and the other one behind it. The split ratio of these splitters was 1:99, where 99 % of the power was connected in front of the amplifier, or behind it, as the case may be and the remaining 1 % of the power into the spectrometer, which was necessary for measuring the spectrum that entered and subsequently left the amplifier. At the input/output of the circulator n. 2, AWG was connected, and it divided the individual signals for particular ONUs. The testing number of ONUs was set to 3 and they were tuned at 1$^{st}$, 16$^{th}$ and 32$^{nd}$ wavelength channel.

Frequencies of all channels were based on ITU-T G.684.1 standards. As for the variable FVA-60B digital attenuator, we gradually set the attenuation from 3 up to 15 dB. The main deficiency of using the digital attenuator was the fact it simulated only the attenuation of the path. The real path, in contrast, would exhibit scattering and nonlinear effects, which represent highly undesirable phenomena.

The following charts (Fig. 14, Fig. 15 and Fig. 16) illustrate the measurement of the input and output spectra of the amplifier. In the figures, there are always two lines; the black one stands for the input signal routed into the amplifier, while the red one represents the output signal routed from the amplifier. The graph clearly shows that the apparatus amplified the whole C-band containing 3 channels. The disadvantage of our construction resided in using the splitters 1:99 due to which a really low power entered the spectrometer. This is the reason why there were no channels in higher power levels. Nevertheless, the individual channels are still recognizable in the particular charts.

At the 3 dB attenuation, the channel 1 had the power of -27.82 dBm, the channel 16 the power of -29.70 dBm and the channel 32 the power of -25.89 dBm. We could recognize already from the first measurement that the amplifier does not amplify the whole spectrum evenly. As already mentioned, this problem could be solved using the gain flattening filter. It can be observed that when increasing the attenuation on the attenuator, the level of individual channels decreases. The ONU units stopped communicating with OLT after exceeding the value of 12 dB.

Another finding was a noticeable untune of OLT. This phenomenon was characterized by tuning randomly different channels in the OLT interface. A reason for this behaviour is wrong filtering of the pumping laser from the output of the amplifier, which is caused by an inappropriate selection of isolators. Another possible reason for this could be four-wave mixing.

The conclusions resulting from the last part of our measurements are very satisfactory. The amplifier was successfully connected to the WDM-PON. Its utilization enabled us to go through the path with the 12 dB attenuation. Assuming that the optical fiber with the 0.25 dB.$km^{-1}$ attenuation was used, we could span a distance of nearly 50 km.

## 5. Conclusion

The aim of this article was to highlight negative impacts of temperature strain on erbium-doped fiber amplifiers. Since EDFA amplifiers represent the most important components used in optical WDM networks, it is necessary to keep improving them constantly.

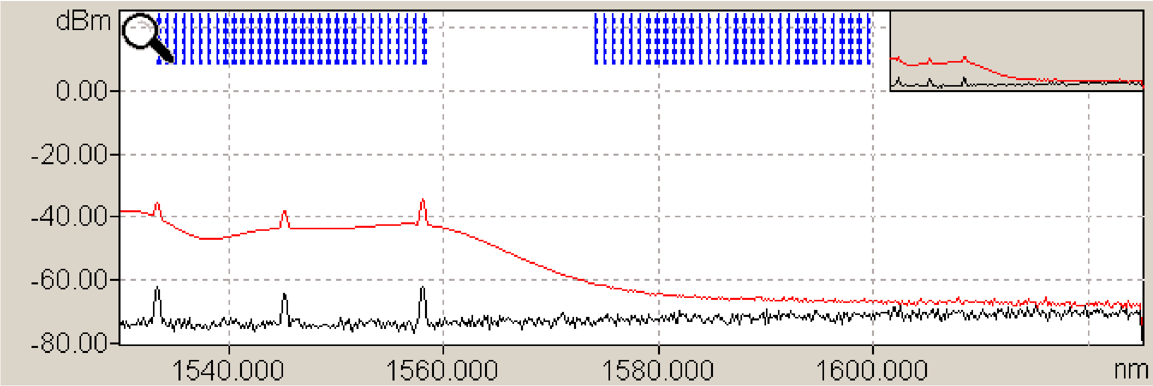


**Fig. 14:** Signal at input (black) and output (red) of the amplifier with the attenuator set to 3 dB.

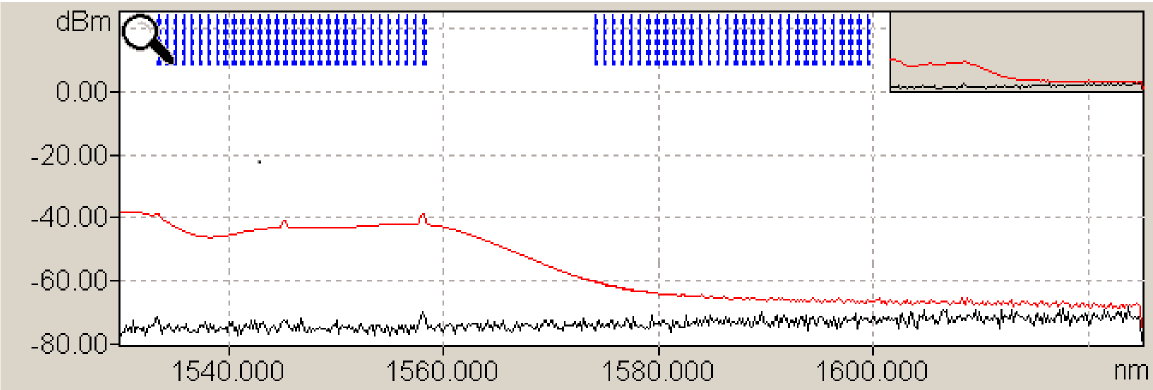


**Fig. 15:** Signal at input (black) and output (red) of the amplifier withthe attenuator set to 9 dB.

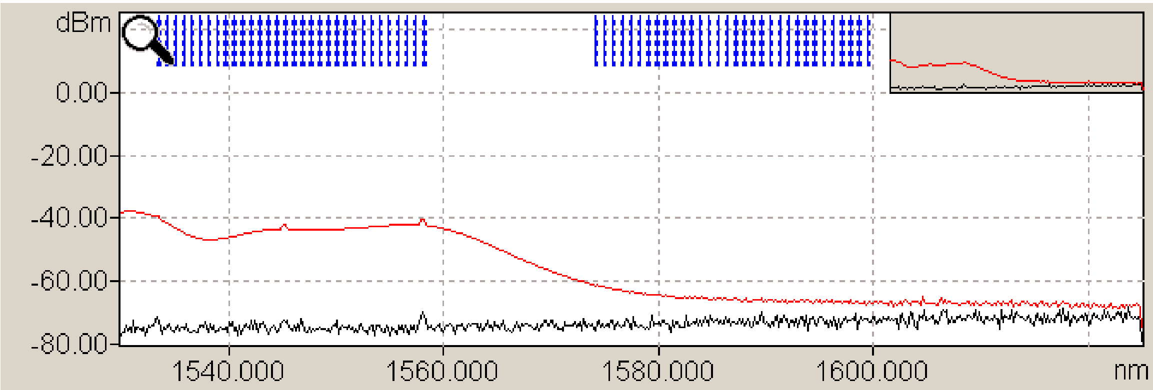


**Fig. 16:** Signal at input (black) and output (red) of the amplifier with the attenuator set to 12 dB.

The first task was to test an ideal length of the fiber in different temperature conditions. This measurement has not confirmed that the temperature fluctuation had any significant effect on the ideal fiber length. However, the results indicate that temperature influences the output power of the amplifier, which directly depends on the state of the pumping laser. What can be read from the charts is e.g. the amplifying fiber characteristics in various power levels of the pumping source. The last chart concerning the 125 mW pumping power indicates the influence of temperature on the power of the amplifier depending on the amplifying fiber length. At all the testing temperatures, the optimum fiber length was 16 m, which corresponds with higher pumping powers and partly also with theoretical assumptions based on the datasheet provided by the fiber manufacturer.

The second part of our measurements was focused on connecting the assembled EDFA amplifier to a real WDM-PON network topology. The results of this measurement clearly show that our designed apparatus amplified the whole C-band. Thanks to the gain of the amplifier, which was nearly 30 dB, we have managed to span the distance of approximately 50 km. If we take into consideration other additional attenuations on the path caused by welds, connectors, patch cords and other components, this result is very satisfying.

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