Optical Amplifiers – Erbium Doped Fibers

1 Objective

Study the characteristics of EDFAs alone and in a system. Reanalyze the importance of receiver noise and the effect of amplification on the quality of an optical system.

2 Pre-Lab

Loss in optical fiber is a major limiting factor in optical system design. Before the advent of efficient optical amplifiers, electrical regenerators were used to reproduce the optical signal after a certain propagation distance, but these became too difficult to implement, especially when wavelength demultiplexed systems were introduced. Erbium doped fiber amplifiers (EDFAs) do not have this issue and soon replaced regenerators in optical fiber networks.

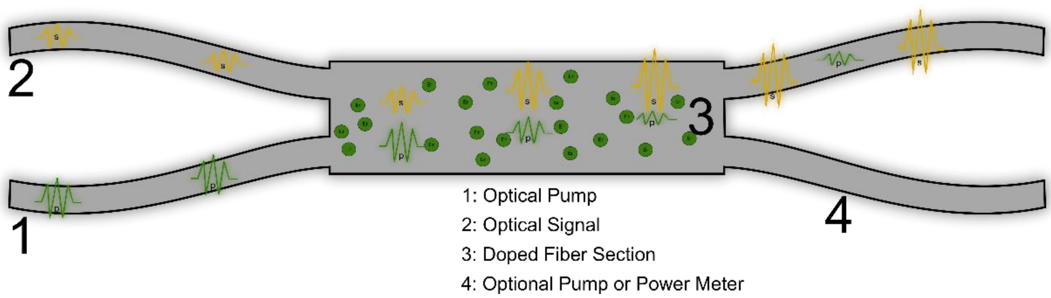

Figure 1: Schematic of an Erbium Doped Fiber Optical Amplifier

The basic principle of an EDFA is much similar to that of a semiconductor Laser, differing by the lack of feedback (the reflective end facets) and an electrical pump. An EDFA exploits the stimulated emission process from an excited ion, in this case Erbium, in a similar manner. The Erbium ions are excited by a high frequency optical pump into a higher unstable state and subsequently lose energy nonradiatively and drop to a slightly lower metastable state, and emit photons by stimulated emission that are direct copies of the incident signal and as a result the signal is amplified.

The importance of using Erbium ions becomes clear because of their particular energy states, which correspond to the range of wavelengths that experience the lowest loss in silica fiber, known as the C band 1530-1565 nm.

2.1 Energy Levels and Cross Sections

There are two main pumping schemes used for EDFAs: in the first method light at the wavelength 1450 nm is used to excite Er^{3+} ions to a sub-level of the $^4I_{13/2}$ state and the second method where light at a lower wavelength 980 nm is used to excite the Er^{3+} ions to a completely different state $^4I_{11/2}$. The first method has a higher power efficiency because of the smaller energy lost in the relaxation of the ion, however it also introduces more noise in to the signal.

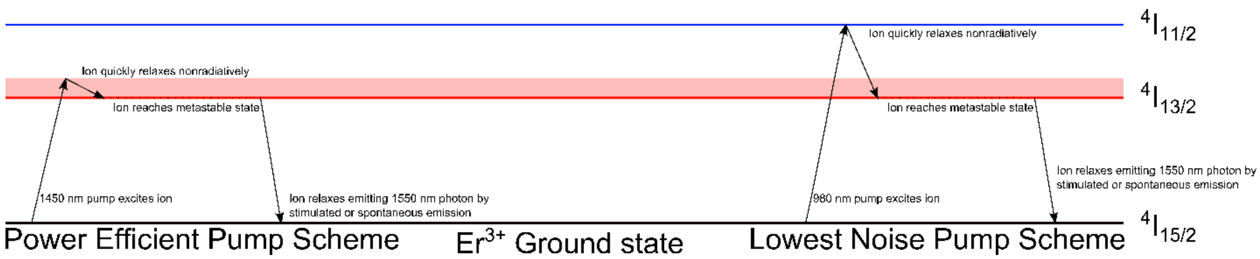

Figure 2: Energy levels of Er^{3+} ion and two popular pumping schemes

Since the lifetime of the higher energy state is much less than the metastable state this process can be modelled by a two-level system with rate equations:

$$\frac{dN_2}{dt} = -\frac{dN_1}{dt} = -\Gamma_{21}N_2 + (N_1\sigma_a - N_2\sigma_e)\phi_s - (N_2\sigma_e - N_1\sigma_a)\phi_p. \qquad (1)$$

Here N_1 and N_2 are the population densities of the first and second level respectively. Γ_{21} is the probability of a spontaneous transition from the second to first level and σ_a, σ_e are the absorption and emission cross sections, which together with the signal and pump light intensity fluxes ϕ_s, ϕ_p calculate the probability of a stimulated absorption or stimulated emission. The cross section data is very important for calculating the gain and the noise spectrum and so an accurate model will capture its wavelength dependence. The cross sections also depend not only on the dopant, but also the host material. This data is generally found experimentally and can then be loaded into OptiSystem as a text file. The default option is data from a silica host.

<u>Questions:</u>

2.1.1 Calculate the portion of energy lost due to nonradiative relaxation for both pump schemes, for this simple model.

Answer: Power Efficient

$$1 - {E_{1550}}/{E_{1450}} = 1 - {hc\lambda_{1450}}/{\lambda_{1550}hc} = 6.45\%$$

Lowest Noise

$$1 - {E_{1550}}/{E_{980}} = 1 - {hc\lambda_{980}}/{\lambda_{1550}hc} = 36.77\%$$

2.1.2 For a small signal flux what is the threshold condition for the pump flux to reach population inversion? $N_2 = N_1$

Answer:

$$0 = -\Gamma_{21}N_2 + (N_1\sigma_a - N_2\sigma_e)\phi_s - (N_2\sigma_e - N_1\sigma_a)\phi_p$$

$$0 = -\Gamma_{21}N_2 + (N_2\sigma_a - N_2\sigma_e)\phi_s - (N_2\sigma_e - N_2\sigma_a)\phi_p$$

$$0 = N_2(-\Gamma_{21} + (\sigma_a - \sigma_e)\phi_s - (\sigma_e - \sigma_a)\phi_p)$$

$$\phi_p = \frac{\Gamma_{21}}{\sigma_a - \sigma_e}$$

2.2 Amplified Spontaneous Emission Noise

Although population inversion allows for incoming optical signals to be amplified by stimulated emission, it also introduces the problem of spontaneous emission. Ions randomly relaxing radiatively lead to a source of noise that is also amplified throughout the fiber and ultimately limits the performance of the amplifier.

The amplified spontaneous emission (ASE) depends on the degree of population inversion as well as the particular cross sections of the fiber, as an example the ASE profile of common EDFAs look like Figure 3. Although the exact ASE can depend on the pump power, length of the EDFA, and even the incident signal itself due to broadening.

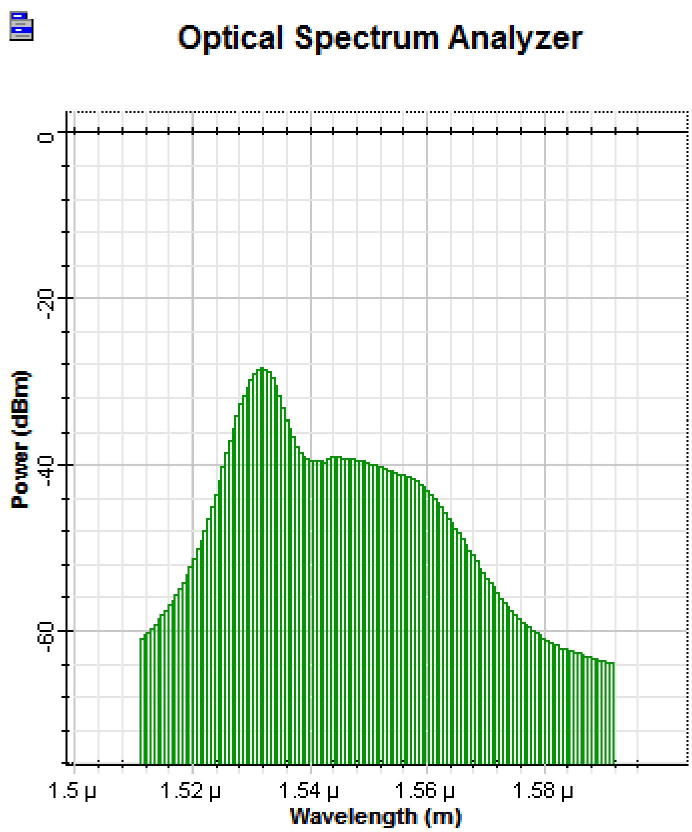

Figure 3: ASE spectrum from EDFA

ASE, along with some other sources of noise in OptiSystem are represented by noise bins. The noise bins themselves contain information about the power contained in a certain range of frequencies. This allows for very large bandwidths of noise to be represented without using a sampled signal, which would waste a lot of computer memory. Thus, in some sections of the simulation the noise bins are treated separately than the optical sampled signal, but the user can control this aspect with the convert noise bins parameter. For example, the following setup was simulated of a simple NRZ signal at 193.1 THz propagating through an EDFA with the above ASE. In the first case the noise bins are not converted and in the second they are.

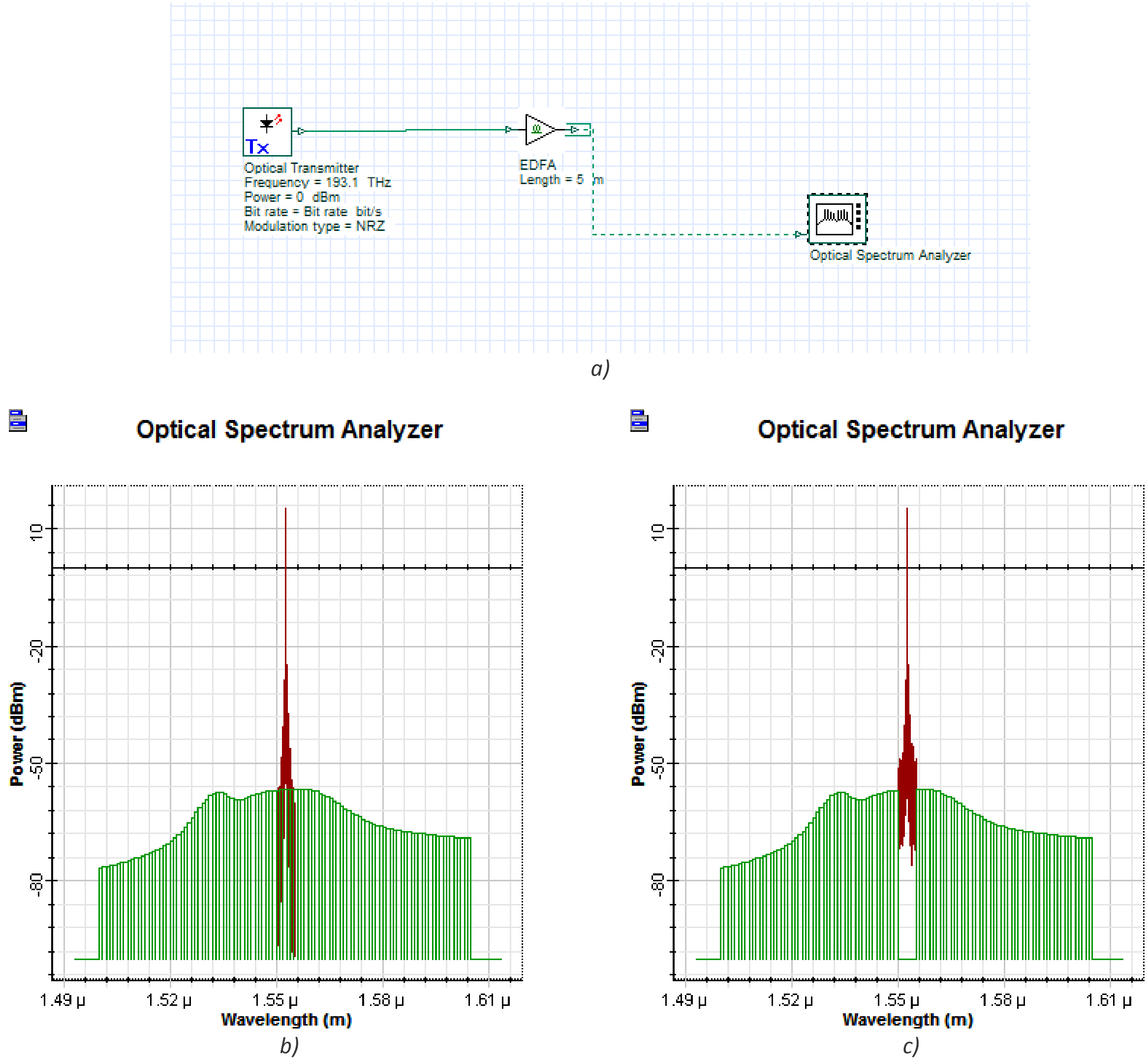

Figure 4: a) Layout of simulation b) Simulation without converting noise bins c) Simulation with converting noise bins

When the noise is added to the sampled signal it is then also converted to a random sampled signal and added as you would expect. The noise bins also allow the user to make easy calculations of the signal to noise ratio, because it explicitly separates the noise from the signal.

<u>Questions:</u>

2.2.1 Estimate the signal to noise ratio from the graphs in Figure 4.

Answer: SNR = 15 dBm + 56 dBm = 71 dB

2.2.2 Remove the Optical Transmitter component from the Layout in Figure 4 and replace it with an Optical Null. Explain the effect of increasing pump power on the ASE spectrum

Answer: The increase pump power creates a larger population inversion which not only increases the ASE but changes the shape as well.

2.3 Noise Figure

The ASE that is introduced to a signal results in degrading initial Signal to Noise ratio. It is characterized by the quantity known as the Noise Figure and is calculated by:

$$N_f = \frac{SNR_{in}}{SNR_{out}}, \qquad (2)$$

where SNR_{in} is the input signal to noise ratio and SNR_{out} is the output signal to noise ratio. Another useful quantity is called the optical SNR or OSNR. On account of the bandwidths in optical communications being very large and an even larger noise bandwidths. The SNR is calculated over a certain range of frequencies, most commonly a resolution bandwidth of 0.1 nm. For example, the OSNR would be given as:

$$OSNR = \frac{P_{s_{0.1\,nm}}}{P_{n_{0.1\,nm}}}. \qquad (3)$$

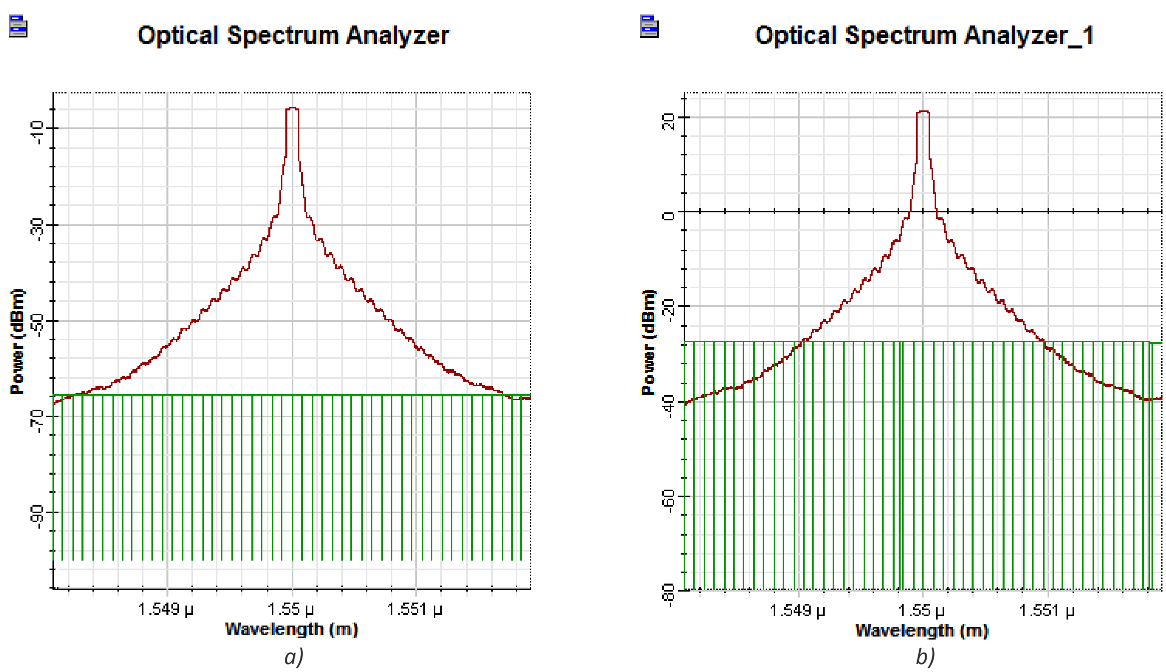

Figure 5: Comparison of the SNR before and after an EDFA

<u>Questions:</u>

2.3.1 Estimate the signal to noise ratio for the input and output signals in Figure 5.

Answer: SNR$_{in}$ = 60 dB SNR$_{out}$ = 48.7 dB

2.3.2 Calculate the noise figure of the amplifier tested in Figure 5.

Answer: $N_f = 60dB - 48.7dB = 11.3\ dB$

3 CHAINS OF EDFAS

In optical communication systems, EDFAs are equally spaced throughout the fiber links to counteract loss of the fibers. Numerous EDFAs of low gain are generally favored over less high gain EDFAs because the lower gain amplifiers introduce less ASE that can be exacerbated by subsequent amplifiers.

3.1 NOISE BUILDUP

Build the following layout to experimentally test the buildup of noise in amplifier chains. In this simulation the optical fibers will be replaced by simple attenuators to model the loss only. The loss of the attenuators will be set to 20 dB to model a fiber around 100 km in length. The EDFAs simulated will have a length of 1.9 m and a forward pump of 50 mW.

- Optical Transmitter — Transmitters Library/Optical Transmitters
- Optical Attenuator — Passives Library/Optical/Attenuators
- EDFA — Amplifiers Library/Optical
- Optical Spectrum Analyzer — Visualizer Library/Optical
- Dual Port WDM Analyzer — Visualizer Library/Optical

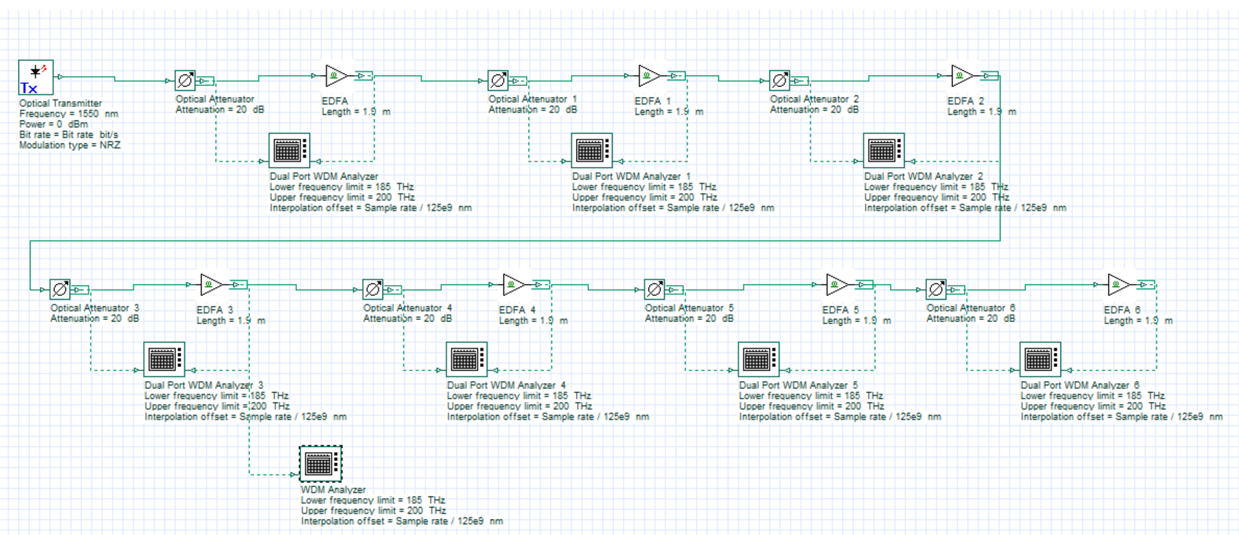

Figure 6: Layout of EDFA chain simulation.

As the original signal with no noise propagates through successive attenuator-amplifier pairs, the SNR degrades. Using a Path, quantities like signal power and OSNR can be plotted as the signal moves through the transmission link. Once the project above has been made click on the "Draw path" icon at the top right

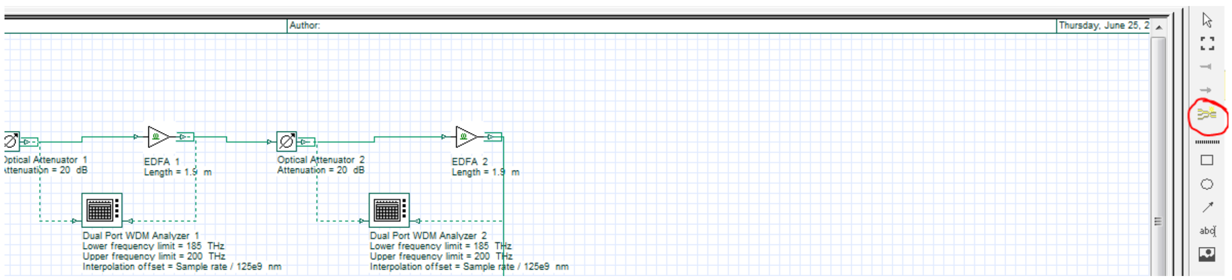

Figure 7: Finding the path tool.

Left-click on the Optical Transmitter and the final EDFA, then hit Accept on the Path Tool window and give your path the name "EDFAChain".

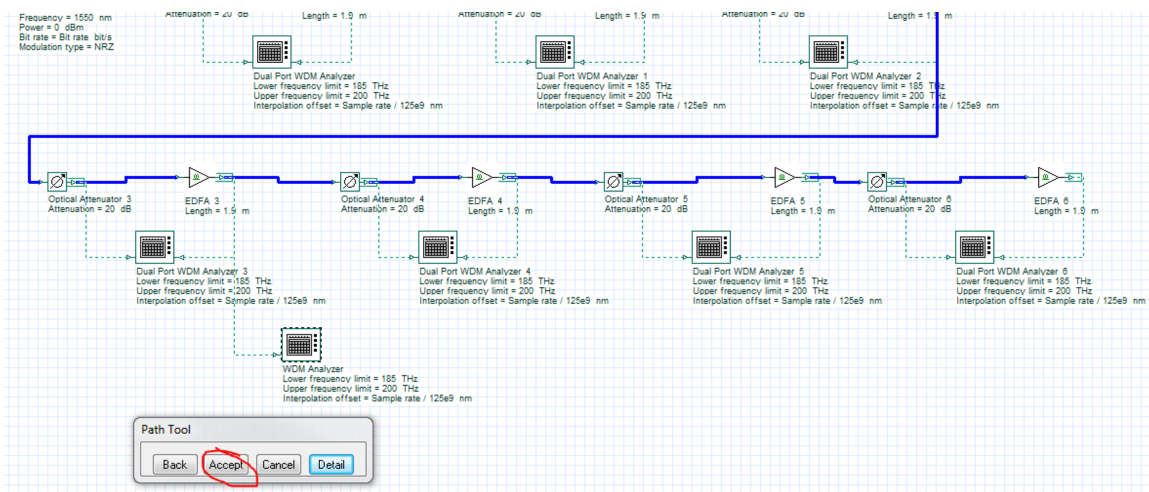

Figure 8: Creating a path through the EDFA chain.

Run the simulation, once complete the results are ready to view in the Project Browser. Find the folder Paths under Global in Layout 1 and right-click the path EDFAChain. Choose preview from the list of options and the Trace Display will open.

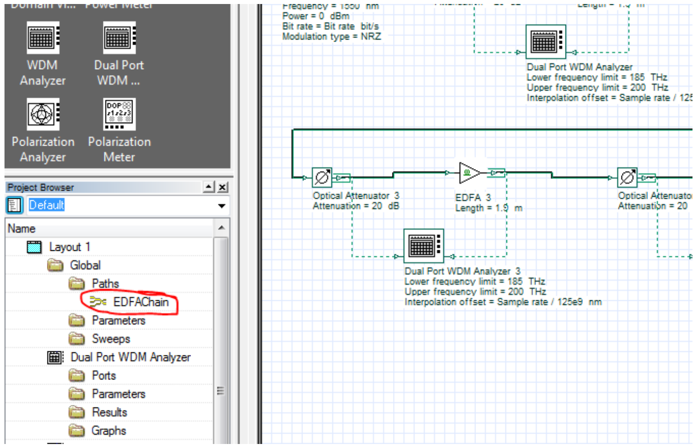

Figure 9: The created path can be found in the project browser.

From the Trace Display the quantities can be displayed as a function of distance, which is more useful for simulations involving more fiber, or by discrete components, choose the latter option. The OSNR is shown in the top portion of the graph starting very large from the lack of noise in the optical transmitter.

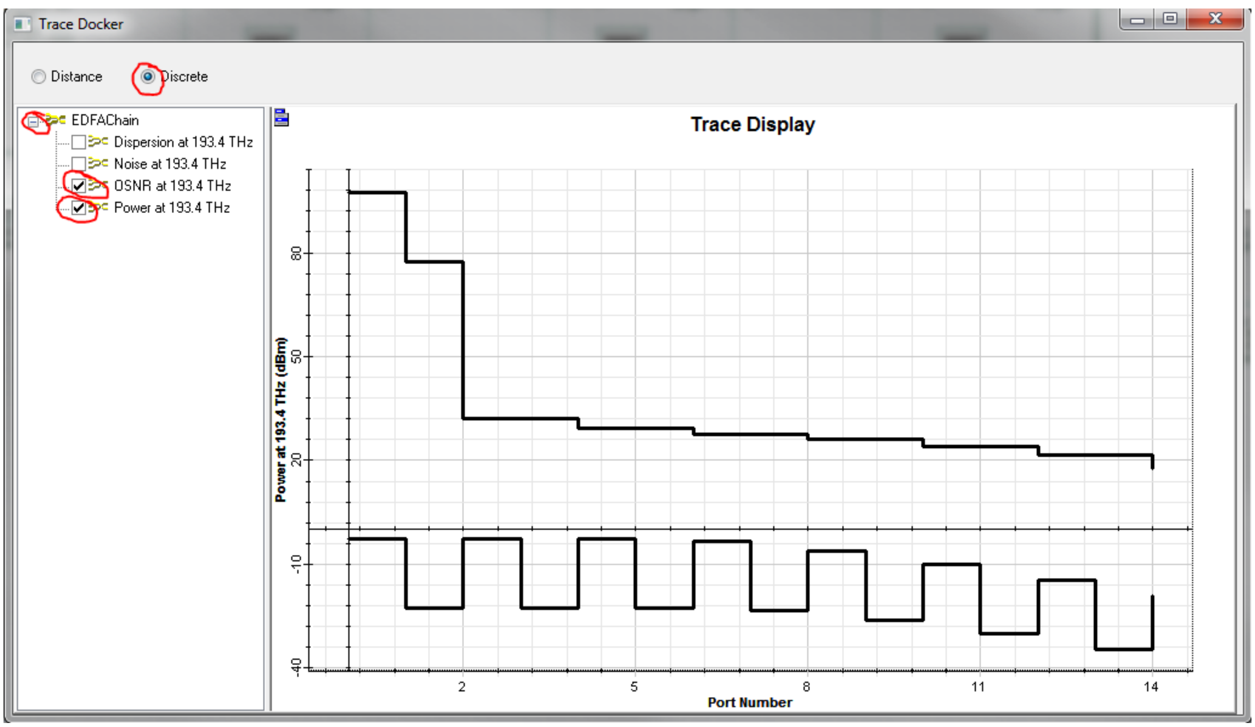

Figure 10: The trace plotting the power and OSNR of the signal as it propagates through the link.

Another useful tool is the Dual Port WDM Analyzer, double clicking the visualizer will allow the user to quickly find out many of the same quantities.

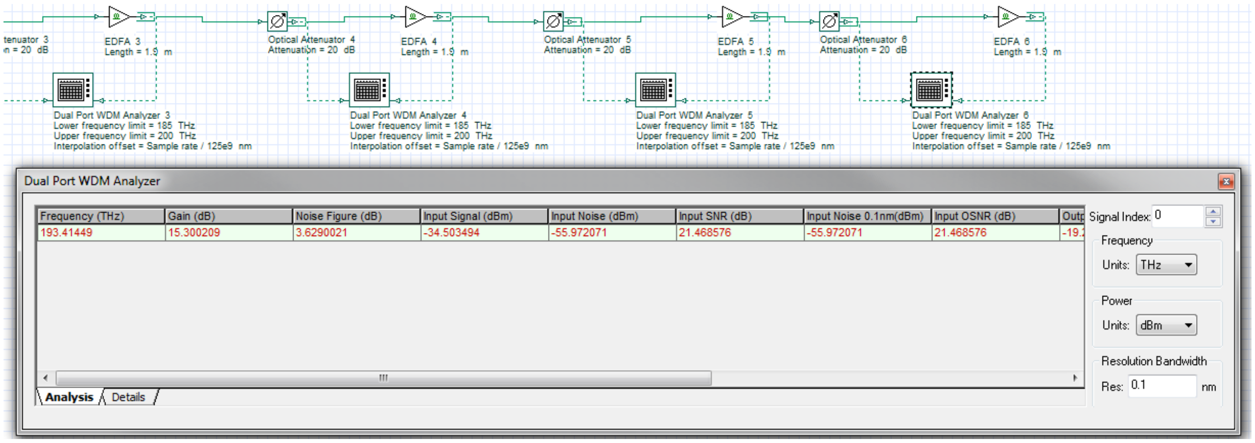

Figure 11: Viewing the results calculated by the WDM Analyzer.

The component automatically calculates the Gain, Noise Figure, SNR and OSNR both input and outputs. The calculation can also be refined over a bandwidth with the Resolution Bandwidth parameter.

<u>Questions:</u>

3.1.1 From this graph and using Markers estimate the OSNR before and after each attenuator-EDFA pair. Estimate the noise figure.

Answer: The noise figure is close to 3 dB for each amplifier.

3.1.2 For the first stages of the amplifier chain the gain is large enough that the signal power is brought back to its original value. However, in the later stages the signal power begins to drop. Explain why this happens. Hint: Look at the noise power as well.

Answer: The ASE from the EDFAs gets larger and larger until the input signals to the EDFAs begin to saturate the later stages. Thus the signal experiences less gain.

3.1.3 Explain how using optical filters the problem in the previous question can be mitigated.

Answer: Filtering out the noise out of the signal band using a bandpass filter will lead to less total noise power and slow down the gradual increase of noise power. This in turn reduced the saturation effect on the amplifier.

3.2 Maximum Length of EDFA Chains

Using the Path Trace or any other method find the proper length of the EDFA that compensates for 10 dB of loss at each attenuator with a 75 mw pump. Reproduce the system in the previous section but with these new parameters.

3.2.1 What is the optimal length to compensate 10 dB?

Answer: An EDFA of length 0.94 m gives roughly 10 dB of gain.

3.2.2 What is the effect of doubling the pump power on gain? What does this say about the ratio N_2/N_1 of the population densities?

Answer: The gain only increases by 0.25 dB or only about 6%. This means that the ions are already mostly excited and any additional pump power is not readily absorbed.

3.2.3 Duplicate these attenuator-EDFA pairs a number of times using the initial pump power and discovered optimal length. Then for a resolution bandwidth of 0.1 nm find the maximum number of attenuator-EDFA pairs that can be placed before the OSNR drops below 20 dB.

Answer: The signal can propagate through 17 attenuator-EDFA pairs before finally dropping below an OSNR of 20 dB.

3.2.4 Comparing the total loss over the entire link of these two different compensation schemes (high gain/low gain), which provides the better performance?

Answer: The low gain implementation can compensate for the same total loss of the system but introduces less noise to the signal. That is to say the OSNR stays larger of longer propagation distances.

4 Report

In your lab report include the following:

- Brief overview of the background and theory.
- Answers to all pre lab questions, clearly showing your work.
- Brief description of the simulation method and setup, including screenshots.
- Final results including figures and discussion.

5 References

[1] Agrawal, G. P. *Fiber-optic Communication Systems*. New York: Wiley, 1997. Print