Introduction to Optical Amplifiers OA1

Interactive learning module

University Program
Photonics Curriculum Version 8.0

Preface

In this module, the effects of optical amplifier noise on the performance of a long distance transmission link will be explored. It also shows the motivation for using optical amplifiers with a flat gain vs. λ curve.

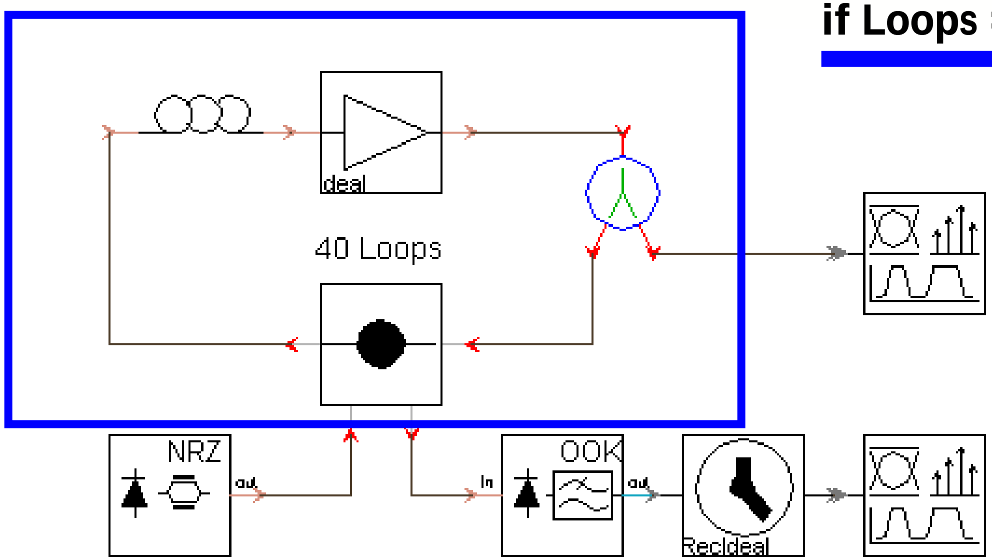
- A long distance optical link may stretch over several thousands of kilometers. For such applications, optical amplifiers are mandatory in order to ensure that the signal arrives at the receiver at a level that is detectable at an acceptable BER.
- Optical amplifiers add amplified spontaneous emission (ASE) noise to the amplified signal. Over many fiber spans, the ASE noise will accumulate and degrade the BER of the received signal.
- How far can a signal be transmitted over a cascade of noisy optical amplifiers before its BER becomes unacceptable? For a link of fixed distance and span length, how noisy can the optical amplifiers be before the BER of the received signal becomes unacceptable?
- Practical optical amplifiers do not have a gain vs. λ curve that is flat. This is not a big issue for transmission links that use a single wavelength channel, but what about transmission links that use many wavelength channels (e.g. WDM systems)?

Note:

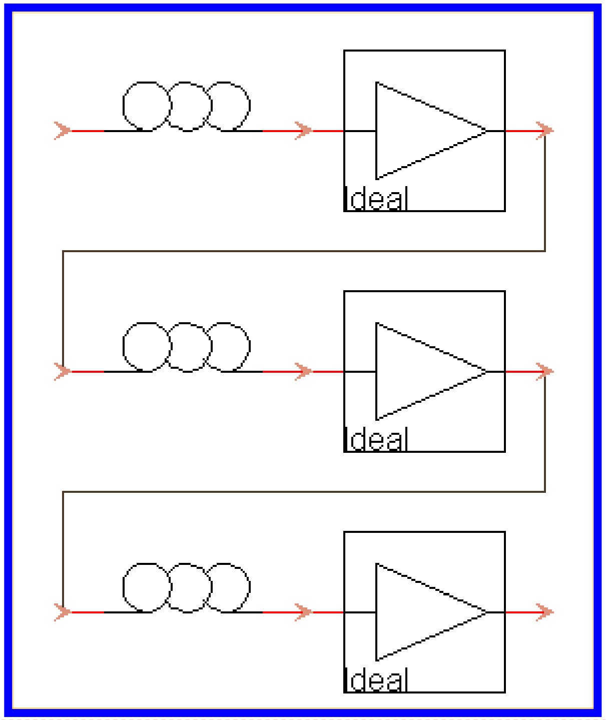
For details on the handling of VPItransmissionMaker / VPIcomponentMaker please read the *Simulation Guide* before starting this unit.

Optical Fiber Amplifiers in IMDD Systems

- Open setup OA1_1. The schematic is shown in the diagram on the bottom left.
- The loop structure (highlighted by the blue box) is used to efficiently represent a transmission link that consists of several identical spans of fiber (with an amplifier to compensate for the fiber attenuation), as shown on the right. The number of spans to be simulated may be defined by setting the global variable ***Loops*** to the desired number.



For example, if Loops = 3

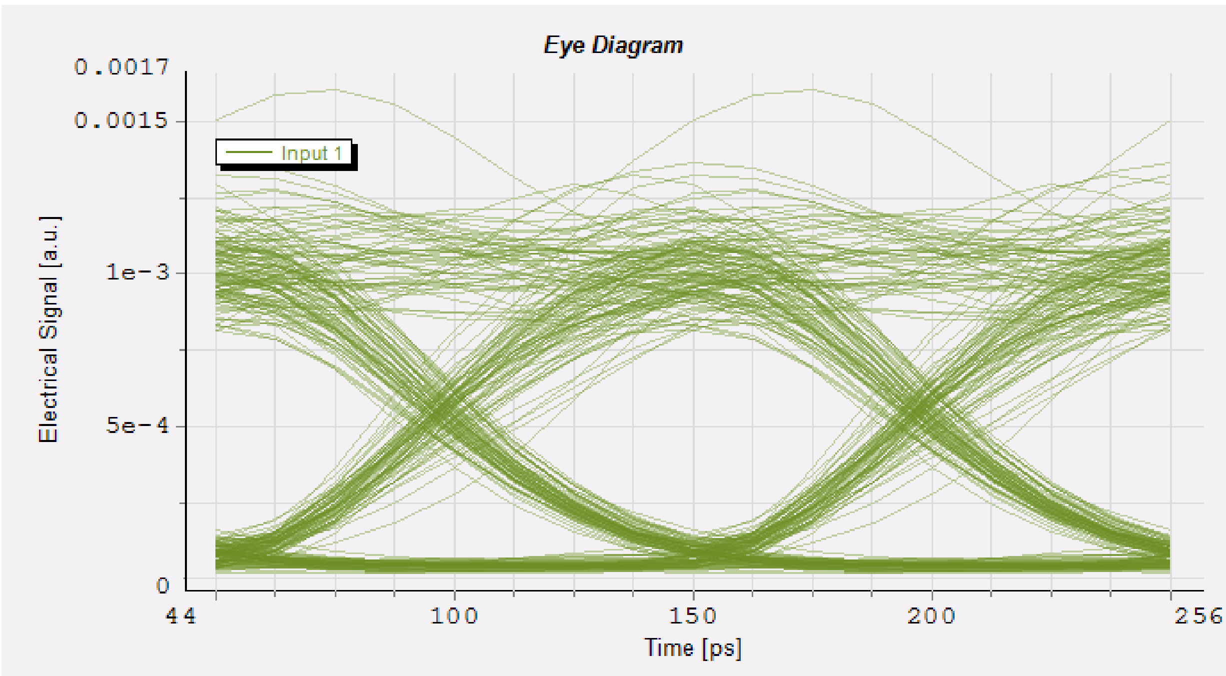


Optical Fiber Amplifiers in IMDD Systems

- The nonlinear and dispersion effects of the optical fiber are turned off. This enables us to concentrate on how the characteristics of an optical amplifier affect the performance of the optical transmission link.
- As it stands, the parameters of the setup are set to simulate a transmission link that is 4000 km long. This link is divided into 40 spans, each span being 100 km long.
- The fiber attenuation in each span is fully compensated for by an optical amplifier.
  Question 1: What should be the gain of the optical amplifier in order to fully compensate for the fiber loss within each span? How is the gain calculated?
- The noise figure of each optical amplifier is initially set at 3 dB.
  Question 2: What is the significance of this value (3 dB) of the noise figure for an optical amplifier?

Noise Figure of Optical Fiber Amplifiers

- Run the simulation. The received eye diagram and optical spectrum after each loop should appear when the simulation is finished.
- The transmitted data is fully recovered at the receiver, as shown by the eye diagram of the received data below. The eye is open, and the BER is ~ 10^{-11}.

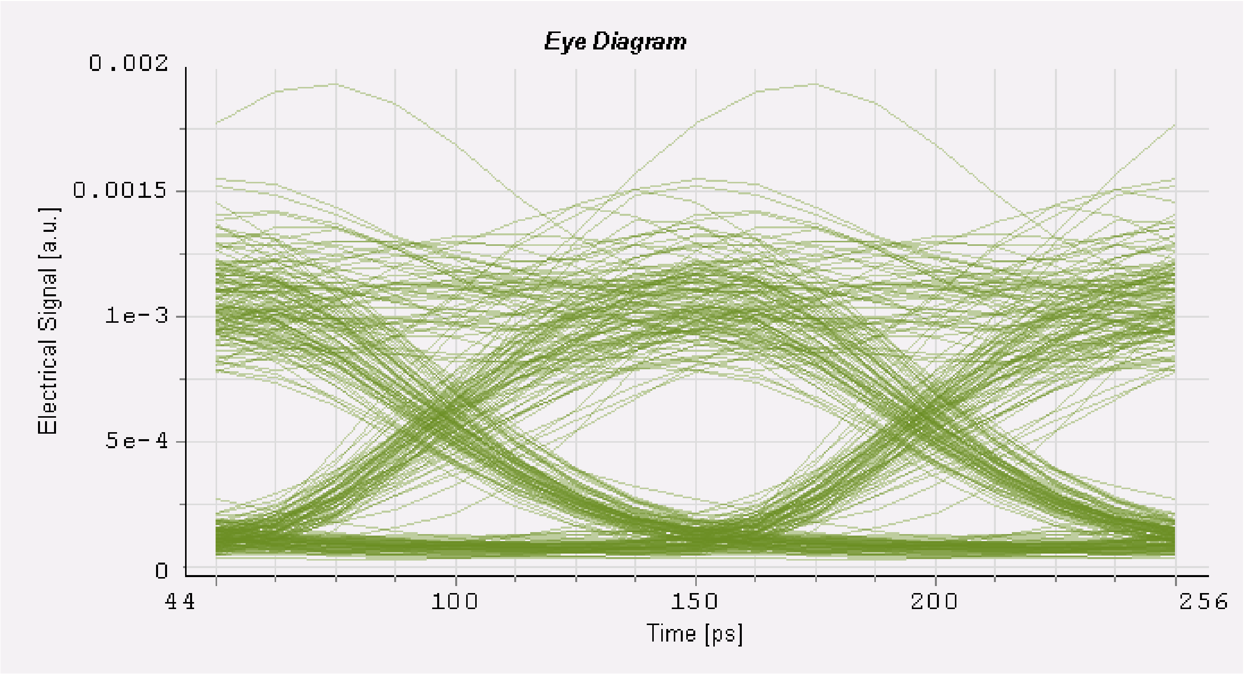


BER

Signal Type	Input 1	Unit
BER	5.98211033531839e-11	None
Q	6.4059895447099	None

Noise Figure of Optical Fiber Amplifiers

- The typical noise figure of a practical optical amplifier is 4.5 to 6 dB.
- Set the noise figure of the optical amplifier to 6 dB and rerun the simulation. Examine the received data waveform. Now, examine the Eye-diagram of the received data (which should be similar to the one shown below) and find the BER.
- **Question 3**: Compare the received optical power level in this case with that obtained from the previous simulation (when the noise figure was 3 dB). Explain the resultant BER in this case.



Noise Figure of Optical Fiber Amplifiers

- **Exercise 1**: Open setup OA1_1a, and make a plot of the BER of the received data signal vs. the noise figure of the optical amplifier. Do this for noise figures from 3 to 6 dB inclusive, with a step size of 1 dB. For the 4000 km long link that is being simulated, what is the maximum allowable noise figure in order to ensure that the BER of the received signal is acceptable (i.e. not greater than 10^{-9})?

- **Exercise 2**: Make sure the noise figure of the optical amplifier is set to 6 dB. Reduce the length of the optical transmission link that is being simulated by reducing the number of fiber spans and find the BER. Make a plot of the BER of the received signal vs. the length of the link. What is the maximum length of the optical transmission link that will still result in an acceptable BER ($< 10^{-9}$)?

- **Exercise 3**: Repeat Exercise 2, but this time for optical amplifiers with a noise figure of 4.5 dB.

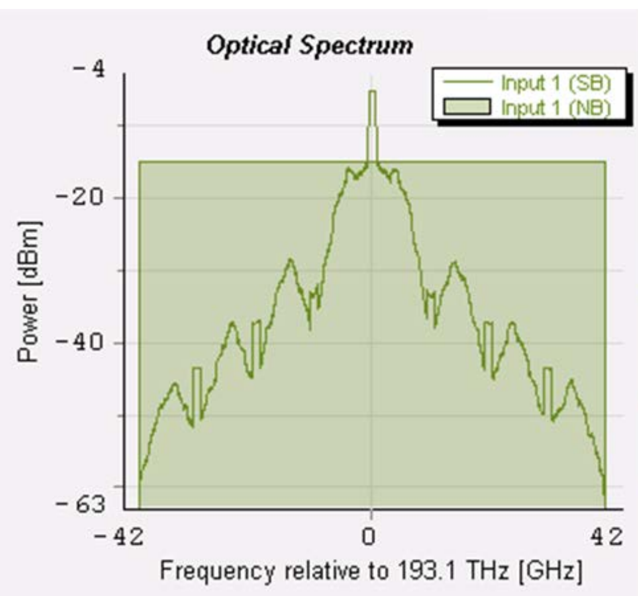
Optical Amplifiers with Higher Gain

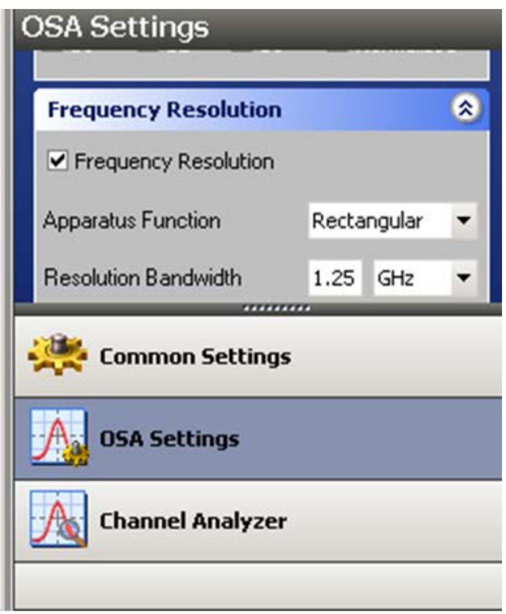
- Optical amplifiers are expensive. Therefore, in the design of long distance transmission links, one way of decreasing costs is to consider using fewer optical amplifiers.
- However, in order to decrease the number of amplifiers needed in a link of a given length, the length of each amplified fiber span must be increased. Accordingly, the gain of each amplifier must be increased to account for the increased fiber span.
- Physical limitations preclude this method of reducing costs to be taken to the extremes. But within these physical limits, what are the ramifications of using fewer amplifiers, each with higher gain, as opposed to using a greater number of amplifiers, each with lower gain?

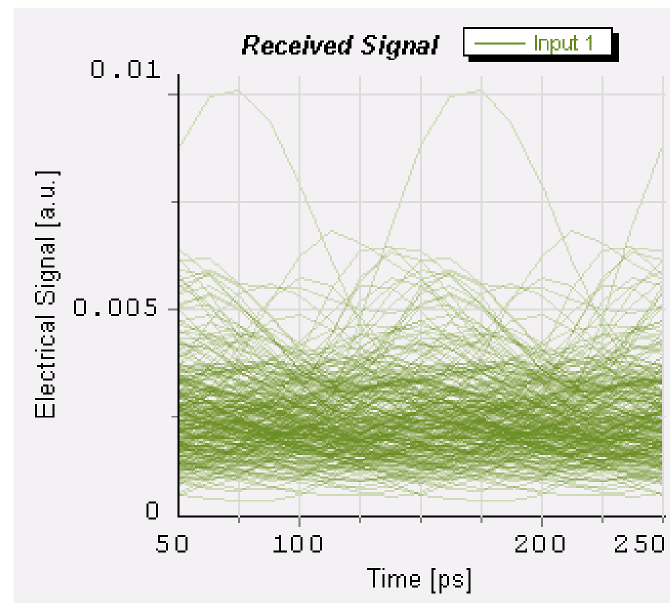
- Open setup OA1_1b. Here, the schematic used previously is modified slightly to investigate the use of fewer optical amplifiers with higher gain in a long distance optical transmission link.
- Reduce the value of the global variable ***Loops*** from 40 to 20, so that the number of amplifiers used is reduced accordingly (i.e. halved).
- With this setting, the length of each fiber span is increased from 100 km to 200 km and the gain of the amplifier is increased from 20 to 40 dB. Keep the noise figure at 3 dB for the time being.

Number of Optical Amplifiers in a Link

- When the modifications have be completed, run the simulation.
- An inspection of the Eye-diagram of the received signal (which should be similar to the diagram shown below) indicates that the BER will be unacceptable.
- **Question 4**: Explain why the received signal is so badly degraded, bearing in mind that the noise figure of each amplifier is only 3 dB?
- **Question 5**: Would optical amplifiers with higher gain have higher or lower noise figures?







Number of Optical Amplifiers in a Link

- **Exercise 4**: In the previous simulation, we have established that using 20 amplifiers, each having a 40 dB gain, did not work. In a systematic way, investigate the dependence of BER on the number of amplifiers used in the link (i.e. make a plot of BER vs. number of amplifiers). Check that the gain and fiber span length are being automatically changed accordingly.
- From the exercise above, determine the maximum gain of the amplifier (and the corresponding maximum fiber span length) permissible whilst still keeping the BER to an acceptable (i.e. 10^{-9}) level.

Optical Fiber Amplifiers in WDM Systems

- The gain spectrum of an Erbium-Doped Fiber Amplifier (EDFA), an optical amplifier that is widely used, has several peaks and valleys. It is obvious that such an amplifier will not amplify signals of different wavelengths with the same gain.

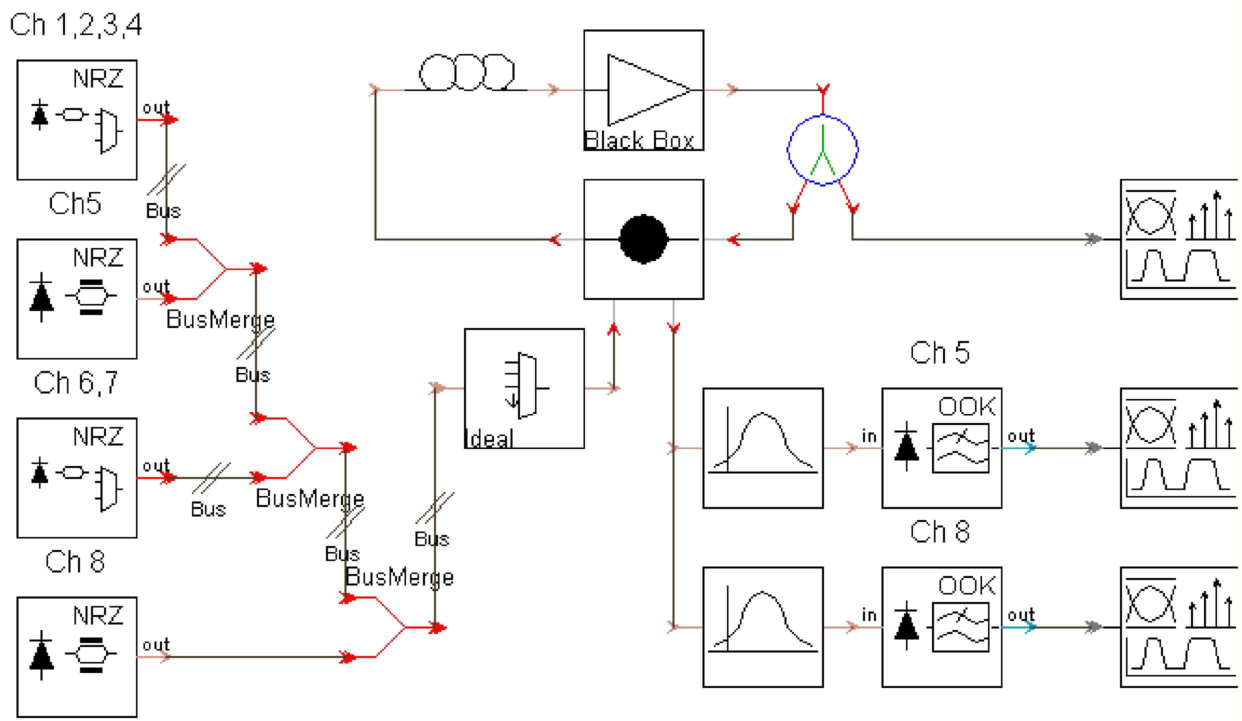
- When transmitted through a cascade of EDFAs, the signals near the peak of the gain curve will grow at expense of the other signals. This can be a limitation if the receiver at the end of the transmission link does not have a dynamic range that is sufficient to cover the spread of powers in the signals at different wavelengths.

- One way to combat this effect is to keep all wavelength channels in a limited bandwidth region where the gain is, more or less, flat. This is restrictive in terms of available bandwidth and overall channel capacity given for a minimum channel spacing.

- Gain flatness is a difficult goal to achieve in a system of cascaded EDFAs, without the help of external gain-shaping and gain-flattening elements. Simulations of amplifier behavior in a WDM system provide a guide for optimizing the transmission characteristics of the system, both in terms of the choice of amplifiers and possible external gain shaping filters.

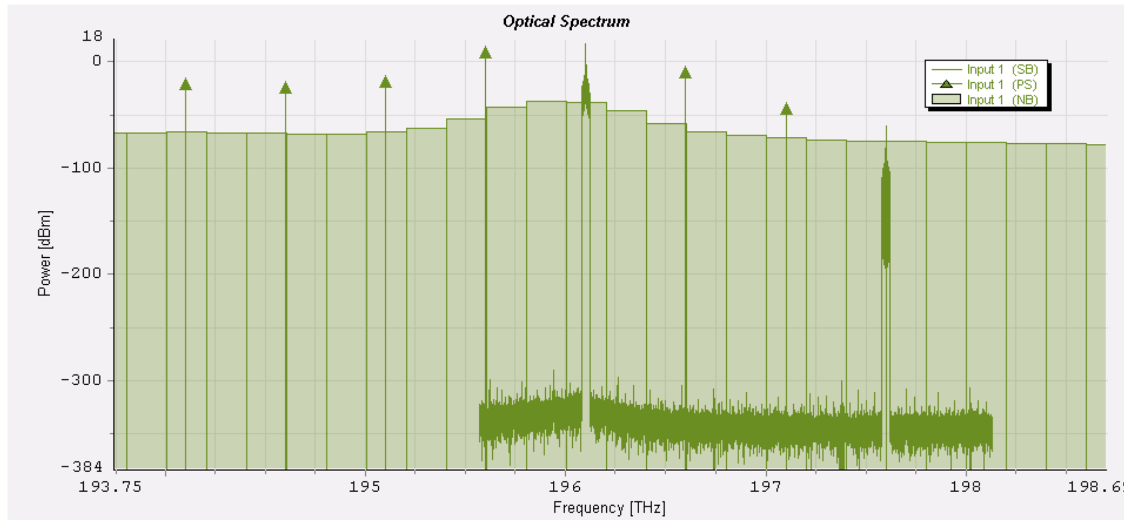
Optical Fiber Amplifiers in WDM Systems

- In this example, we will investigate the limitations imposed on WDM systems due to the non-flat shape of amplifier gain vs. λ.
- Open the setup OA1_2. Shown below is the schematic. Signals at eight wavelengths are multiplexed and transmitted through many amplified fiber spans. Again, a loop structure is used to conveniently represent multiple fiber + amplifier spans.
- A more detailed optical amplifier model is used here. In particular, it models a more realistic gain vs. λ curve instead of a flat gain that is independent of λ.



Gain Flatness of Optical Amplifiers

- Set global parameter ***Loops*** = 1 and run the simulation.
- An OSA plot appears, showing the eight wavelength channels. The input power of the eight channels are initially all equal (check this by placing an OSA at the appropriate spot in the schematic and rerun the simulation).
- **Question 6**: What is the difference in power level between the strongest and weakest channel?
- Inspect the scope trace of the signal in channels 5 and 8.

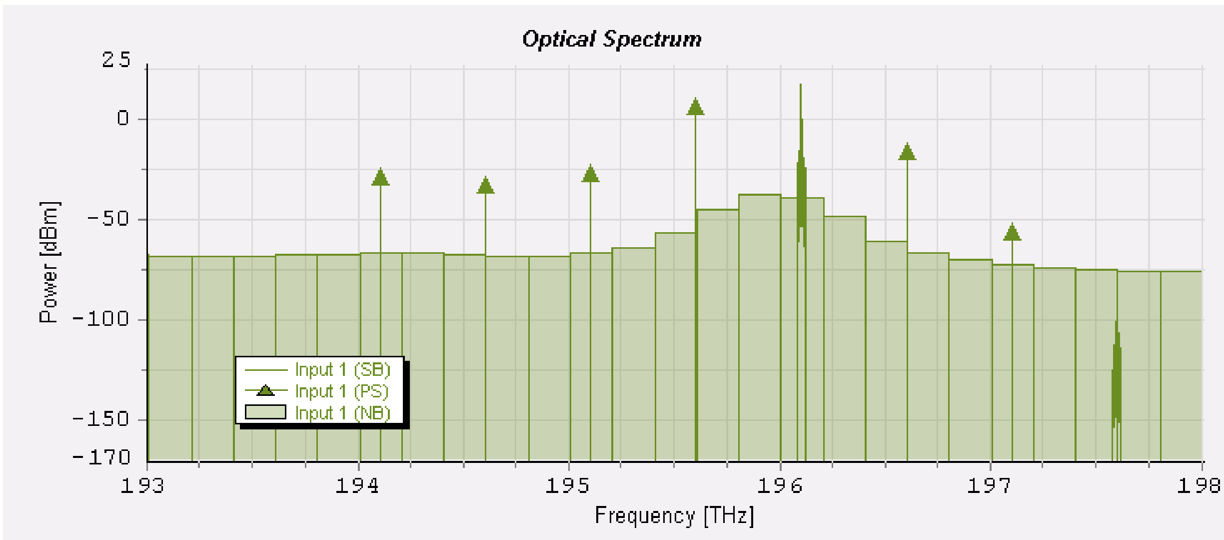


Results (Input 1)

Signal Type	Frequency, THz	Power, d Bm	Noise Power, d Bm	OSNR, d B	OSDR, d B
PS	194.1	-21.3091204631279	-41.6074192791741	20.2982988160462	—
PS	194.6	-24.645168461725	-42.6782463213971	18.0330778596721	—
PS	195.1	-19.3381248249077	-41.6137323302528	22.2756075053451	—
SB	195.6	-308.513408576541	-21.136324800284	-287.377083776257	—
PS	195.6	8.91436287550942	-21.136324800284	30.0506876757934	—
SB	196.1	19.3973008249478	-13.3448246394774	32.7421254644252	—
SB	196.6	-312.764227162015	-36.1178180344749	-276.64640912754	—
PS	196.6	-10.1264503484817	-36.1178180344749	25.9913676859932	—
SB	197.1	-313.230391400948	-47.2683277243472	-265.962063676601	—
PS	197.1	-44.3317864576064	-47.2683277243472	2.93654126674076	—
SB	197.6	-59.0115834790161	-50.0406566228651	-8.97092685615098	—
SB	198.1	-312.995461383509	-51.3749313703836	-261.620530013125	—

Gain Flatness of Optical Amplifiers

- Now, set ***Loops*** = 5 and rerun the simulation again. This simulates a transmission link with five amplified fiber spans.
- The OSA plot (shown below) shows the spectral intensity after the signals have been transmitted through the cascade of amplifiers.
- **Question 7**: Compare this result with that of the previous result (when ***Loops*** = 1). What is the difference?

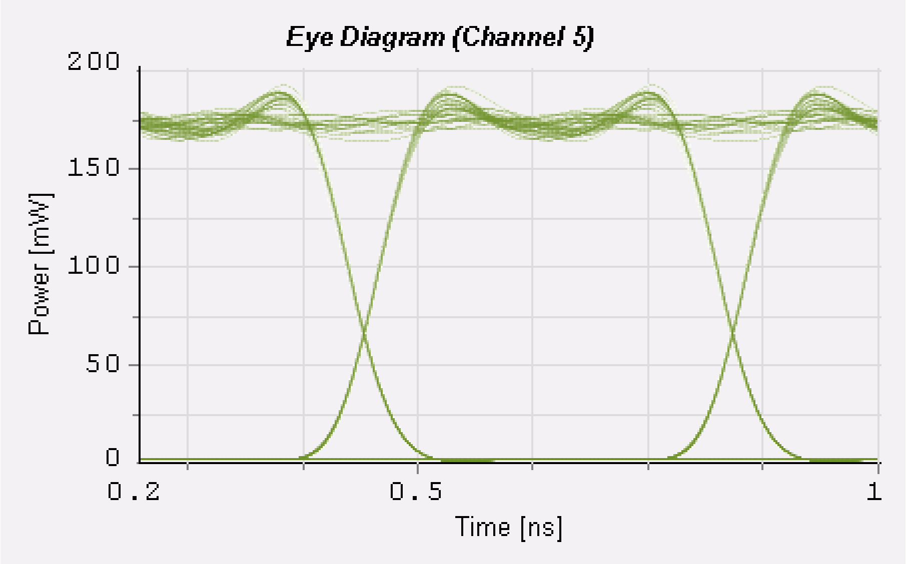


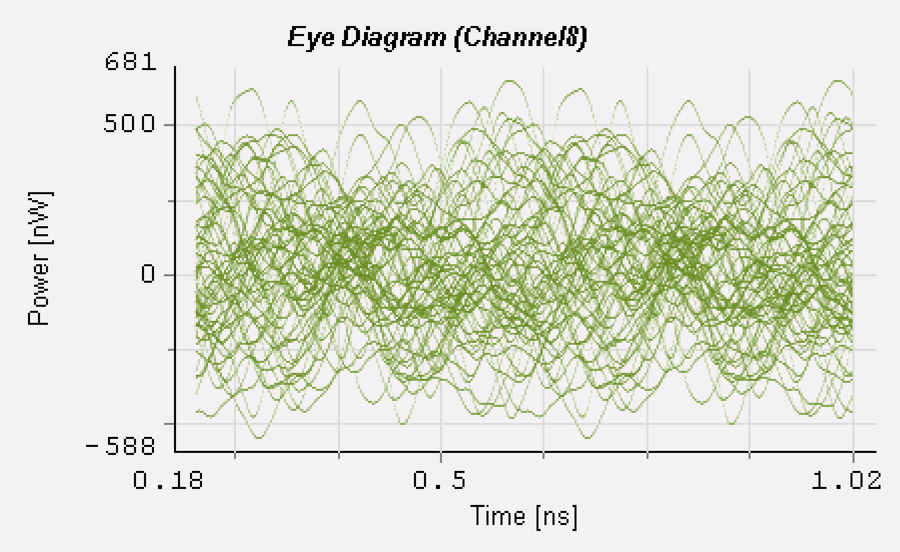
Results (Input 1)

Signal Type	Frequency, THz	Power, dBm	Noise Power, dBm	OSNR, dB
PS	195.6	6.40733768612814	-27.6386560080256	34.0459936941538
PS	196.6	-16.1817520744703	-36.7114427808459	20.5296907063756
PS	197.1	-55.7626525687464	-47.3422983356376	-8.42035423310876
PS	194.1	-28.1477586815089	-41.8593527718764	13.7115940903675
PS	194.6	-32.364354470256	-42.6309531032243	10.2665986329683

Gain Flatness of Optical Amplifiers

- Once again, inspect and comment on the scope traces of channel 5 and 8.
- Shown on the left is the eye of channel 5, which, by virtue of its location near to the peak of the gain spectrum of the optical amplifier, is the strongest channel.
- Shown on the right is the eye of channel 8. As can be seen, system performance in this channel is severely degraded.
- **Question 8**: Why is the degradation so severe in channel 8?





- **Exercise 5**: Open the setup OA1_2b. In a systematic way, investigate and find the maximum distance that the WDM signals can be transmitted such that all eight channels can be detected at an acceptable BER (i.e. 10^{-9}). To vary the transmission distance, set the fiber length to a small value (for example, 30 km), and use a relatively large number of loops (for example, 12 loops to calculate the BER from 30 to 360 km of total transmission distance).
- **Exercise 6**: Can the limitation caused by non-flat gain profiles of amplifiers be solved simply by increasing the transmitted power of each channel? Investigate this by changing the power of the transmitters for all 8 channels from 0 to 12 dBm (with a step of 3 dB for example). In this case, what is the maximum distance that the WDM signals can be transmitted whilst still enabling all 8 channels to be detected by the receivers at an acceptable BER?
- **Question 9**: Are there better ways of countering the effect of the non-flat gain profiles apart from the one proposed in Exercise 6? List two different ways.

Summary

- In this introductory module on optical amplifiers, their main characteristics (gain, flatness, noise and noise figure) have been explored.
- A long transmission link comprising multiple spans of fiber, with an amplifier to compensate for fiber attenuation in each span, forms the basis for investigation.
- The impact of the noise figure of optical amplifiers on their spacing in an transmission link is investigated.
- The trade-off between using fewer amplifiers of higher gain (and hence large amplifier spacing) and more amplifiers of moderate or lower gain (and hence small amplifier spacing) is investigated. It is found that attenuation of the fiber and receiver sensitivity dictates how large the amplifier spacing can be.
- The use of optical amplifiers in an WDM transmission link is introduced. In particular, the issue of the flatness of amplifier's gain vs. wavelength curve is explored. The problem of unequal amplification of different WDM channels and the problems that arise as a result are highlighted.