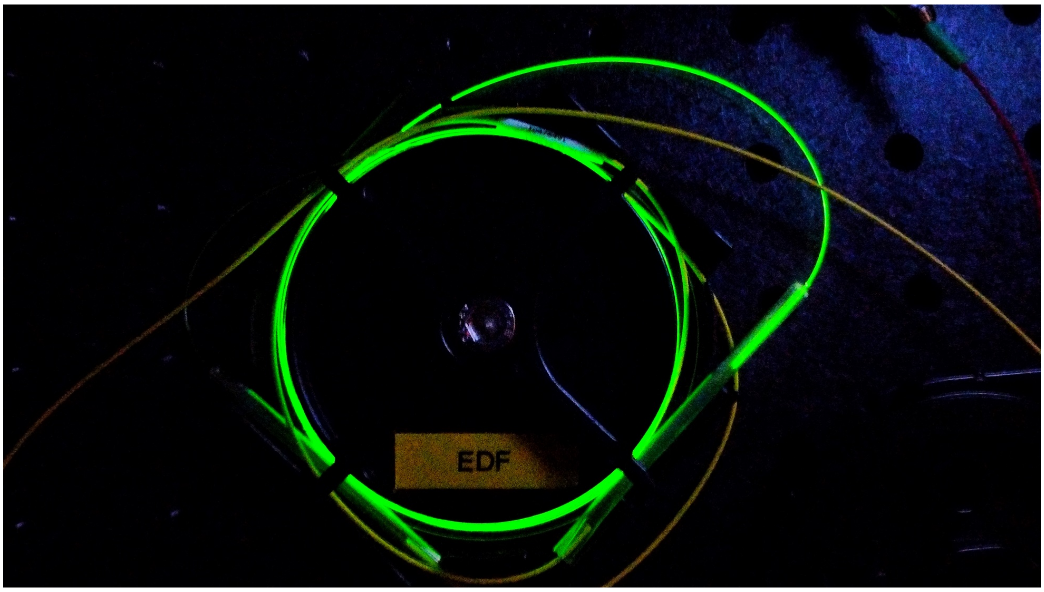
EPFL

Optics Laboratory Work

Erbium Doped Fiber Amplifier



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Index

Picture on the cover page: green fluorescence from an Erbium Doped Fiber pumped strongly with infrared light. The process is enabled by excited state absorption of infrared photons and relaxation processes, that bring Er^{3+} *ions to the state* $^4S_{3/2}$*, the upper level of the green transition* [1].

1 Objectives

The objectives of this optics laboratory session are:

- Understand the physical principle of optical amplification.
- Construct an EDFA and an erbium-doped fiber laser.
- Measure some basic EDFA characteristics.
- Understand the essential and critical parameters of an EDFA.
- Learn to use DFB telecom lasers, fiber connectors, pump lasers.
- Learn to operate an Optical Spectrum Analyzer (OSA).

It is essential that you prepare this lab session in advance by reading through the lab notes. The tasks denoted with the symbol “🏠” are short questions that require a written preparation before the lab (a handwritten draft is sufficient; the questions will be discussed in the beginning of the lab). In addition, there will be an oral examination during the first session about the methods described in these notes. Make sure to take notes and save images during the lab session, so that you can include this material in your final lab report. If you need more information about certain topics of this lab session, feel free to consult the references given at the end of this document.

2 Safety

The pump laser sources used in this lab are Class 3B lasers, emitting approximately 300 mW of light at 980 nm. A number of precautions have been taken for your safety, such as attenuation and expansion of the laser output. As a result, the experimental setup should therefore be eyesafe.

You should nonetheless observe the following rules:

- Do not disconnect the optical fiber connectors when the lasers are emitting. Fiber connection must be performed with the laser emission disabled.
- Optical fibers are made of glass; loose shards can be difficult to detect and quite harmful. Be careful during fiber manipulation.

Additionally, please note that the experimental setup is pre-built. Do not disconnect optical fibers or carry any other optics manipulation yourself, unless specifically instructed in these lab notes or by the teaching assistant. The assembly of the setup is simple but requires careful handling of the fiber and couplers.

3 Introduction

An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. The signal to be amplified and a pump laser are coupled at the same time into the doped fiber, and the signal is amplified through interaction with the doping ions. Since its invention in the late 1980s, the erbium-doped fiber has proved to be a versatile tool with a wide range of applications, including broadband optical sources, wideband optical amplifiers, and tunable lasers.

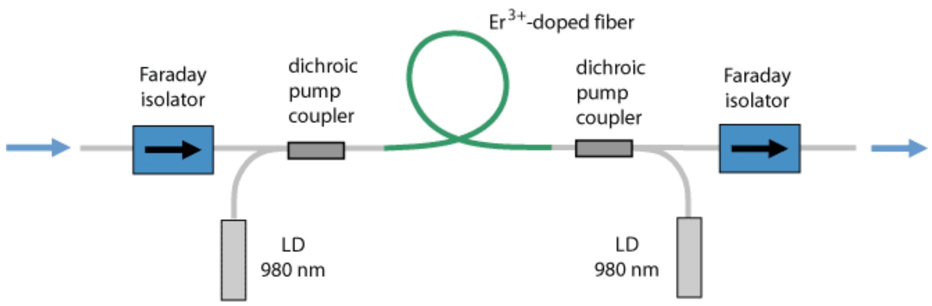

Figure 1: Diagram of an Erbium Doped Fiber Amplifier. The signal to be amplified and the pump beam are combined in the same fiber, and split at the output of the EDFA. Faraday isolators are inserted to prevent back-reflections from entering the amplifier and laser cavities. Source: RP Photonics.

3.1 Optical fiber

Optical fibers are cylindrical waveguides, usually made of silica glass. The glass in the core is doped with germania or alumina to increase the refractive index and guide the light

Silica is so widely used because of its outstanding properties, in particular its potential for extremely low propagation losses (realized with extremely pure starting material) and its amazingly high mechanical strength against pulling and even bending (provided that the surfaces are well prepared). They are the core components of fiber optics, and thus of this lab. Optical fiber communications utilize silica optical fibers mostly for long-range data transmission over thousands of kilometers. Here we will use typical fiber, SMF28, which are single mode in the telecom window.

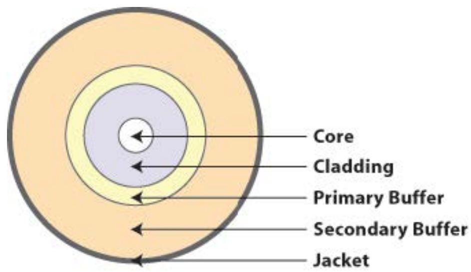

Figure 2: Schematic cross section of an optical fiber. Te jacket and buffers are polymeric layers for protection against mechanical stress and environmental factors.

3.2 Erbium dopants in glass: three level systems

An erbium-doped fiber is an optical fiber of which the core is doped with rare-earth element erbium ions, Er^{3+}. A simplified energy level diagram of the Er^{3+} ion is shown in Figure 4. The energy levels are broadened considerably by the insertion in an amorphous matrix, such as silica, and by the presence of other co-dopants such as germania and alumina within the fiber core. The broad spectral region covered by the gain of such fiber is a great advantage for wavelength division multiplexing applications (WDM).

In the case of erbium-doped fibers, the optical gain is supplied by the excited erbium ions (Er^{3+}) when the amplifier is pumped to achieve population inversion. Depending on the energy states of the dopant, pumping schemes can be classified as a three- or four-level scheme (Figure 5).

Erbium-doped fiber amplifiers make use of the three-level pumping scheme, as illustrated in Figure 5**(c)**. When only a 970 nm pump laser diode beam is fed into an erbium-doped fiber, Er^{3+} will be excited from the ground state E_1 to the higher level E_3. The excited Er^{3+} ions on E_3 will

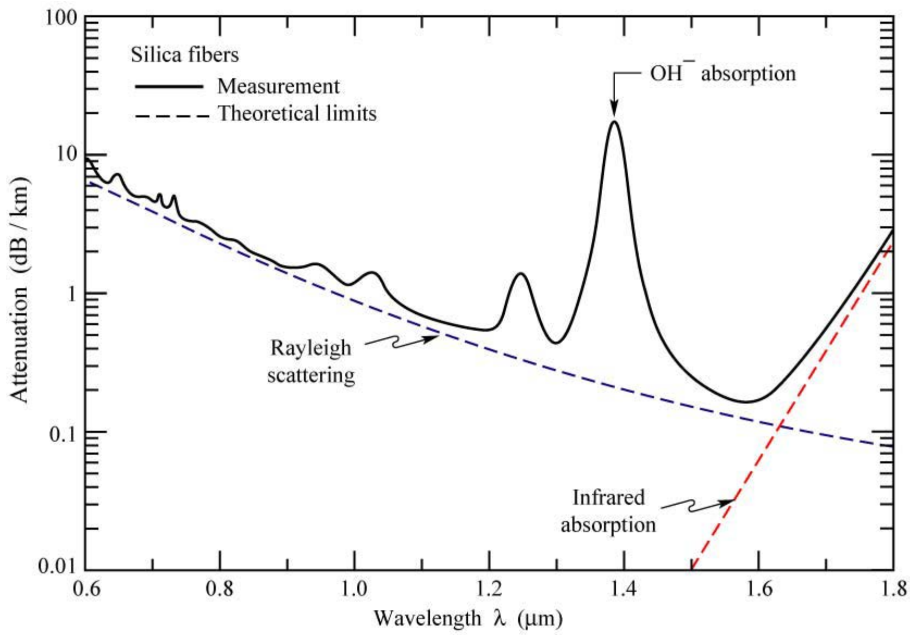

Figure 3: Measured attenuation of light propagating in an optical fiber versus its wavelength in the near infrared spectrum. The dashed lines represent two known causes of attenuation in silica.

rapidly decay to energy level E_2 through nonradiative processes. The excited ions on E_2 eventually return to ground state E_1 through *spontaneous emission*, which produces photons in the wavelength band 1520 – 1570 nm. The spontaneous emission will be amplified as it propagates through the fiber, especially when the pump laser power is increasing in the direction of propagation. As *Amplified Spontaneous Emission* (ASE) covers a wide wavelength range, 1520 – 1570 nm, we can use it as a broadband light source.

Optical amplifiers amplify incident light through stimulated emission, the same mechanism used by lasers. If a laser signal with a wavelength between around 1550 nm, and a 974 nm pump laser are fed into an erbium-doped fiber simultaneously as shown in Figure 5, there are three possible outcomes for the signal photon:

- stimulated absorption: signal photon excites an erbium ion from the state E_1 to a higher level E_2 and gets annihilated in the process;
- stimulated emission: signal photon stimulates an erbium ion at state E_2 to decay to E_1, producing another identical photon. Thus, the signal is amplified;
- signal photon can propagate unaffected through the fiber.

Meanwhile, spontaneous emission always occurs with a certain probability between level E_2 and level E_1. When the pump laser power is high enough such that the population inversion is achieved between the energy level E_2 and E_1, the input laser signal passing through the fiber is amplified. The spontaneous emission is also amplified at the same time. **Therefore, ASE is always present in EDFAs, and it is the main source of noise in these amplifiers.** Along the fiber, the

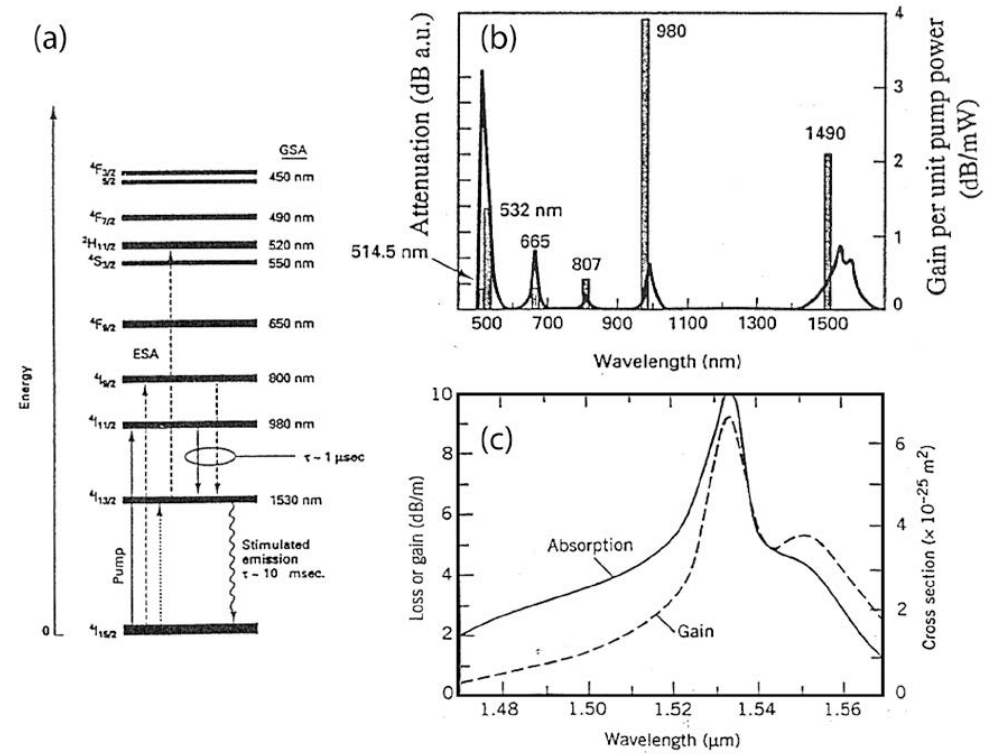

Figure 4: **(a)** Energy levels of the triply ionized erbium ion, Er^{3+} (GSA=ground state absorption). **(b)** Absorption bands of Er^{3+} (solid lines) and the pump efficiency (vertical bars). **(c)** Absorption and gain spectra magnified around 1.5 µm.

pump is absorbed and its energy converted into signal amplification and ASE. There is therefore a competition for gain between the ASE and the signal.

3.3 Gain saturation

The inversion level is established, primarily, by the power of the pump and the power of the signal. As the signal power increases, the inversion level will reduce and thereby the gain of the amplifier will be reduced. This is a result of the depopulation of E_2 due to an increasing number of signal photons. This effect is known as gain saturation. Conversely, beyond a certain pump power, almost all the dopant in the fiber will be excited. Therefore, the amplifier cannot produce more output power. In fact, along the fiber, the gain coefficient can be written as:

$$g(z) = \frac{g_0(z)}{1 + P(z)/P_S}, \tag{1}$$

where $g_0(z)$ is the small-signal gain coefficient per unit length at a given wavelength and pump power level, P is the signal power and P_S is the saturation power, defined as the power required for the gain coefficient to drop to half (or 3 dB below) its small-signal value. The integration of this expression over the fiber length yields an implicit, transcendental expression for the gain evolution [2]:

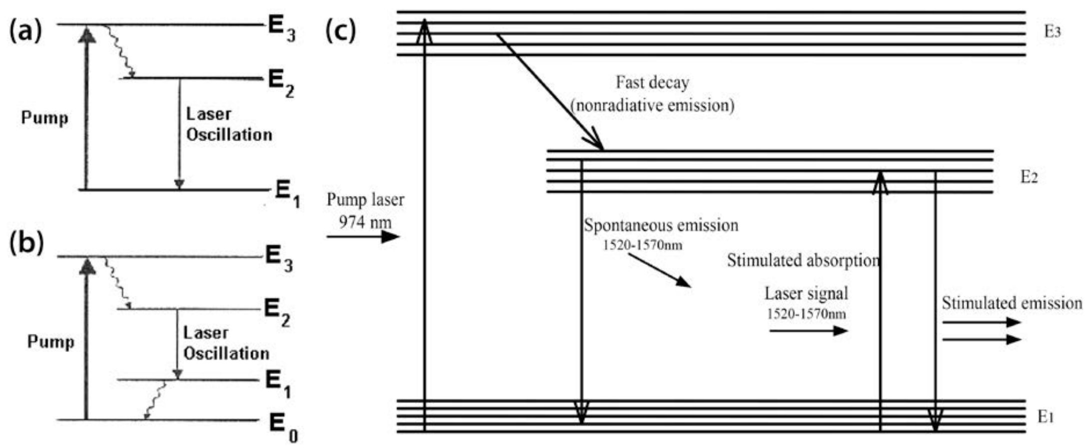

Figure 5: Schematic illustration of **(a)** three-level and **(a)** four-level pumping schemes. Wavy arrows indicate relaxation of the level population through fast nonradiative processes. **(a)** Simplified energy levels of Er^{3+} ions illustrating the three-level pumping scheme and the various radiative processes.

$$G = e^{-\alpha L} \cdot e^{\frac{\phi_{\text{in}} - \phi_{\text{out}}}{\phi_S}}, \tag{2}$$

where $\phi_i = P_i/h\nu_i$ are optical powers expressed as photon fluxes, α is the absorption coefficient of the unpumped EDF, L is the fiber length and

$$\phi_{\text{in,out}} = \sum_k \phi^k_{\text{in,out}} \tag{3}$$

are the total photon fluxes at the input and output of the fiber (accounting for pump and signal photons). This expression allows to model the decrease of the EDFA gain as the signal power approaches and surpasses P_S.

3.4 Noise Figure

Every amplifier, electronic or optical, has the side-effect of adding noise on top of the signal by the amplification process, thus degrading the **Signal-to-Noise Ratio** (SNR). This degradation of the signal quality by the amplifier is quantified by the **Noise Figure** (NF), which evaluates the change in SNR:

$$NF = \frac{SNR_{\text{in}}}{SNR_{\text{out}}} > 1 \tag{4}$$

Assuming a *shot-noise limited* input signal, the noise figure due to spontaneous emission (after electrical detection) can be expressed as [3, 4]:

$$NF \approx 2n_{\text{sp}} \frac{G-1}{G}, \tag{5}$$

where G is the amplifier gain and n_{sp} the *spontaneous emission factor*:

$$n_{\text{sp}} = \frac{N_2}{N_2 - N_1} \tag{6}$$

N_2 and N_1 are the population densities in the excited and ground states of the amplifying medium. In practice, the NF of an EDFA is around 3 - 8 dB (depending on the gain), and determined mostly by incoherent photons generated by ASE.

In the present lab, we will consider only the optical signal to noise ratio ($OSNR$). It can be determined experimentally by looking at the optical spectrum of a signal and measuring the contrast between the peak of the source and the adjacent noise level, as illustrated in Figure 6.

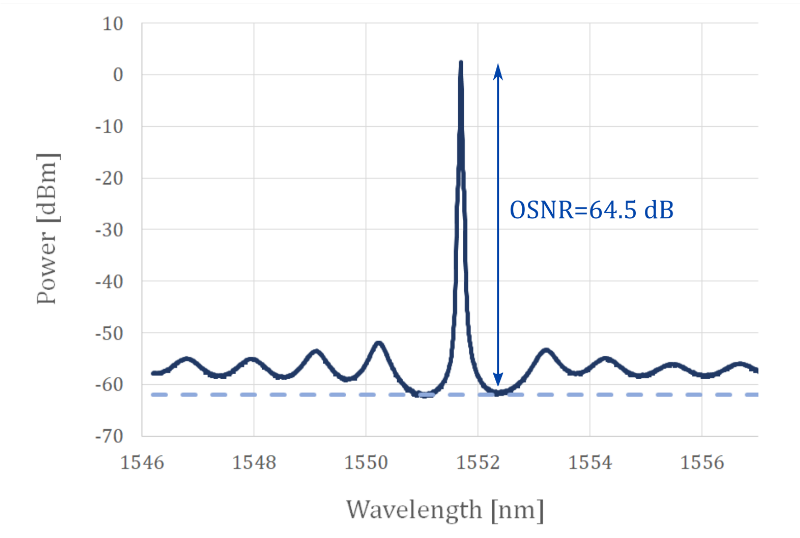

Figure 6: OSNR determination from a laser spectrum acquired with an optical spectrum analyzer. The secondary peaks are side-modes of the DFB laser.

3.5 EDFA configurations

Figure 7 shows three EDFA device configurations. Pump beams are coupled into the doped fiber via the fiber coupler (dichroic combiner). Pump coupling can be in the forward direction (co-propagating pump and signal), the backward direction (counter-propagating pump) or both directions (bidirectional pump).

4 Preparatory questions

Answer the following questions before the first lab session:

1. Based on the graph in Figure 3, what is the best wavelength to transmit an optical signal over a long distance?
2. Briefly describe what is Wavelength Division Multiplexing. Why was the EDFA key to the development of this technology? Why was Erbium selected as a doping material for telecom signal amplification?

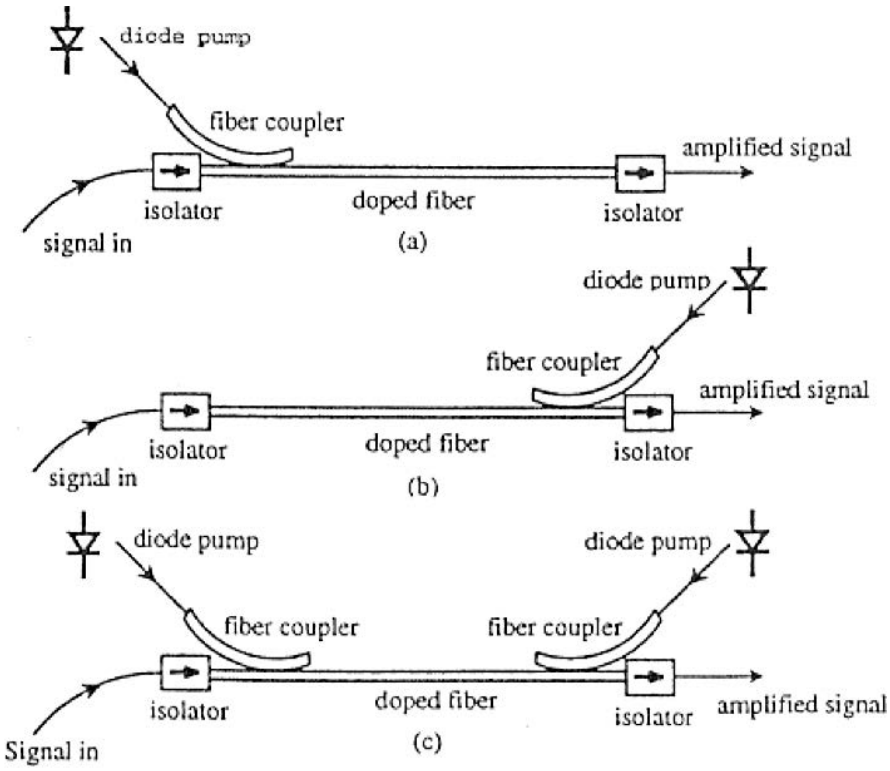

Figure 7: Schematic EDFA configurations utilizing **(a)** forward pumping **(b)** backward pumping and **(c)** bi-directional pumping.

3. What are the differences between the three- and four-level pumping? Which one is the most efficient as gain medium? To which class does an erbium-doped fiber belong, in its most common operation?

4. Instead of 980 nm, what other wavelength could be used to pump Er^{3+}?

5. What is theoretically the best noise figure achievable (while actually amplifying the signal)? What is the spontaneous emission factor n_{sp} necessary to reach the best noise figure possible? You should find out that, in the high gain limit $G \to \infty$ the noise figure cannot drop below $NF_{\min} = 2 \approx 3\,\text{dB}$. This is is known as the *quantum limit of an amplifier*, and is intrinsically connected to Heisenberg's principle [5].

6. Sketch the evolution of:

   - the pump power
   - the signal power
   - the power of ASE propagating with the signal

   that you expect as a function of the propagation distance in the doped fiber for each pumping configuration. What could be the advantages and drawbacks of each pumping configuration?

5 Experiments

The experimental setup of the erbium doped fiber amplifier (EDFA) experiments is shown in Figure 8. It is a typical setup of telecom optical communication based on optical fiber.

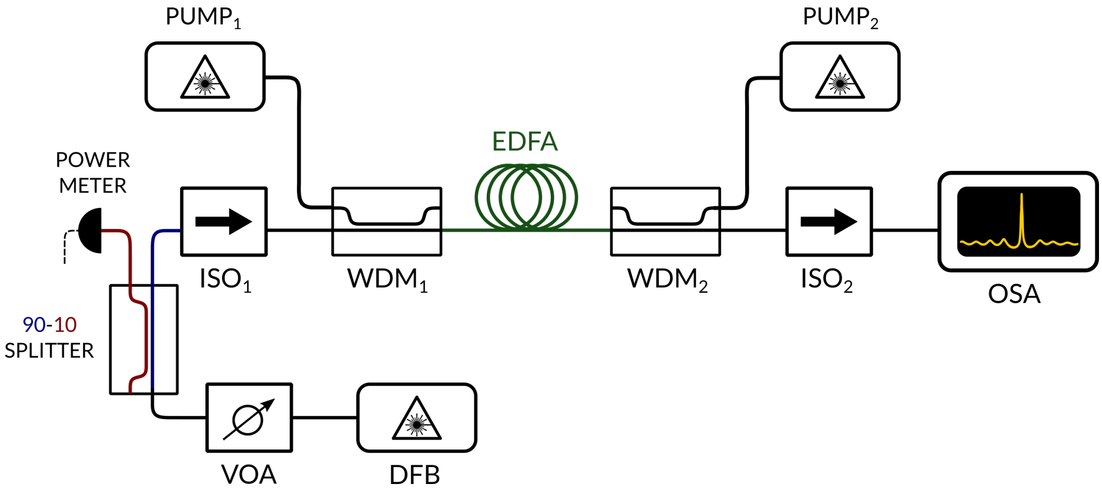

Figure 8: Schematic layout of the EDFA experiment.

The signal laser is a distributed feedback (DFB) single mode laser operating at 1550. The laser output is directly coupled to an optical fiber (known as fiber pigtail). For the purpose of the experiment, in order to vary the signal power, the signal light goes through a mechanical *variable optical attenuator* (VOA)[1]. The power at the input of the EDFA is monitored with a coupler, which takes 10% of the light to a power meter.

The EDFA itself consists of a given length of erbium doped fiber, sandwiched between two *wavelength division multiplexers* (WDMs). The WDM is a wavelength-selective component, which in one direction can combine two signals in different wavelength ranges and in the other can separate them. They are used here to combine the pump light at 980 nm with the signal at 1550 nm.

Optical isolators (ISO) are inserted before and after the EDF. These are *non-reciprocal* devices exhibiting a high directionality: they allow the propagation of light in the forward direction but strongly attenuate light that propagates backwards. For this reason they are sometimes called “optical diodes”. They are useful to damp back-reflections introduced by fiber connectors and various components, that can perturb greatly the dynamics of a laser, when coupled back to the laser cavity, or the performance of an EDFA, for example by partially depleting its population inversion.

Most commonly, optical isolators are realized using a *Faraday rotator*, a slab of magneto-optical material that causes a rotation of the polarization of a linearly-polarized beam dependant on the direction and intensity of an externally-applied magnetic field. Since the sign of polarization rotation is dictated by the direction of the magnetic field, the Faraday rotator introduces an opposite polarization rotation for beams impinging in the forward or backward direction. Combined with a

[1]The fiber-coupled VOA that is employed in our setup is a simple device in which fiber propagation is interrupted for a certain length and light is coupled to free space. The free-space beam is collimated by a lens, and the field can be partially blocked by the insertion of an opaque beam block, whose position can be manually regulated. After the beam block, the remaining fraction of the beam is coupled to the output fiber with a second lens. The operator can thus regulate the introduced by the device.

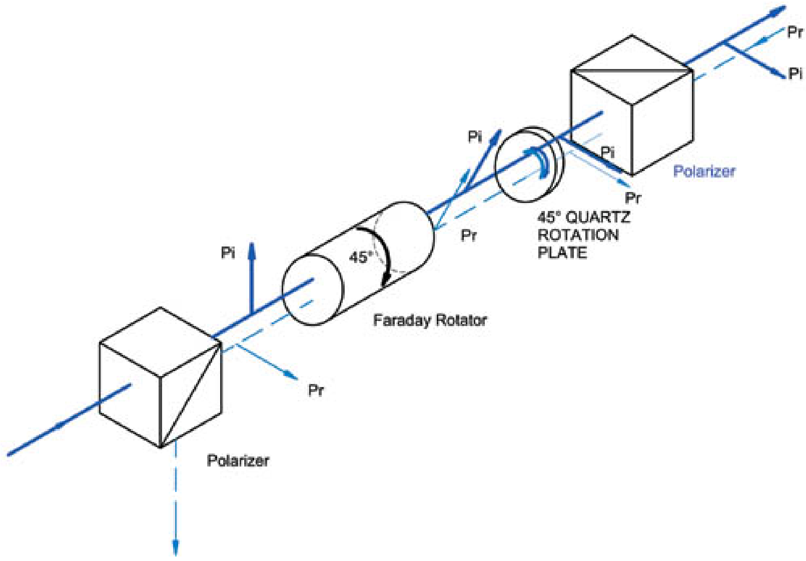

Figure 9: Scheme of an optical isolator, employing a Faraday rotator, two polarizers and a $\lambda/2$ waveplate. The forward- (backwards-) propagating beam and its polarization axis are indicated with the index i (r) and full (dashed) lines.

$\lambda/2$ waveplate (a reciprocal element) and two orthogonally-oriented polarizers, the Faraday rotator realizes the simplest incarnation of an optical isolator, as illustrated in Figure 9. More complex designs allow isolation also for beams with arbitrary polarization states, as encountered in fiber optics [6].

We will analyze the light at the output of the EDFA in the frequency domain, with an *Optical Spectrum Analyzer* (OSA). In this device, a grating disperses the light, an aperture selects a narrow spectral window in the dispersed light, and the power going through it is measured. Rotating the grating sweeps the spectral window to reconstruct the optical spectrum. A simplified scheme is shown in Figure 10.

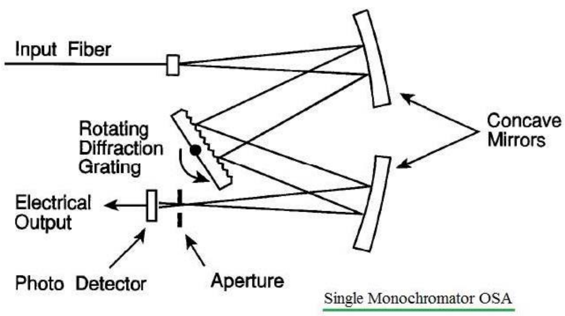

Figure 10: Schematic illustration of a diffraction grating-based OSA.

The OSA can be used also to measure the overall power of a narrowband signal (for example, a laser tone): if the bandwidth of the OSA (corresponding, in the spatial domain, to the slit aperture) is set to be much larger than the signal spectral distribution, the OSA will integrate the whole spectral content. Correspondingly, we will observe a flat-top trace on the OSA trace, proportional to the convolution of the signal with the OSA spectral response. The value of the plateau will be equal to the signal power, with a small error due to the noise floor at the signal wavelength.

5.1 Task 1: Laser diodes characterization

The diode lasers used here have a different purpose: the pump lasers are designed for the efficient pumping of Erbium. The signal laser will carry the information; thus we require a good stability and spectral purity. We will observe the practical consequences on the laser design and properties.

1. Turn off all the lasers. Connect pump 1 laser's fiber output directly to the powermeter head. On the powermeter, change the wavelength setting to 980 nm (otherwise the power reading will be wrong).

2. Set the current of pump 1 laser to 0 mA. Turn on pump 1 laser and vary the current slowly from 0 mA to 500 mA by steps of 5 mA (101 points in total). At each step, measure the output power of pump 1 laser. (you cannot go higher, a limit is set on the current driver).

3. Plot the evolution of the power as a function of the current. What phenomenon do you observe? What quantities can you extract for describing the operation of the laser?

4. Turn off all lasers before disconnecting the fiber connection. Repeat the current-power measurement on pump 2 laser (from 0 mA to 500 mA by steps of 5 mA), and signal laser (from 0 mA to 25 mA by steps of 0.5 mA) What phenomenon do you observe?

5. If you want to have the same output power on pump 1 and pump 2, what's the current you need to apply? What's the relation between the currents of pump 1 and pump 2?

6. Connect pump 1 laser's fiber output directly to the OSA. Set the current so that the output is around 50 mW and turn on the laser. Set the OSA in the following configuration:

   - Center: 980 nm
   - Span: 20 nm
   - Resolution: 0.02 nm

   Record and save the optical spectrum (insert a flash drive and save a trace through the "File" menu). Turn off pump 1 laser. Repeat the same measurement for pump 2 laser.

7. Disconnect both pump lasers and connect the fibers back to the WDM input ports. Now connect signal laser output fiber directly to the OSA. Set the current of this laser to maximum (25 mA; this is the limit is enforced on the current driver) and turn on the laser. Set the OSA in the following configuration:

   - Center: 1550 nm[2]
   - Span: 20 nm
   - Resolution: 0.02 nm

   Record and save the optical spectrum. Measure the maximum laser power by using the peak detection of the OSA. Turn off signal laser.

8. Compare the width of the spectral peaks of each laser. Which laser has the best coherence? Zoom in the spectrum view and estimate the optical signal-to-noise ratio of the signal laser, $OSNR_{\text{LD}}$.

[2] You can adjust the OSA range after acquiring a spectrum with the Peak → Center function

5.2 Task 2: Measurement of the ASE

You will be able to determine a great deal about the system's amplification abilities without actually amplifying a signal. Amplified Spontaneous Emission (ASE) arises from a tiny fraction of the natural fluorescence of Er^{3+} around 1550 nm coupling to the fiber core and extracting gain from the pumped amplifier as it propagates. Since the spectral profile of ASE is greatly influenced by the wavelength-dependent gain, it will provide a good indication of the frequency-dependent behaviour of the EDFA as an amplifier.

1. Place the system in the following configuration: Signal laser turned off; Pump 1 off; Pump 2 on (Backward pumping, but no input signal).
2. Make sure the EDFA output fiber (ISO's output) is connected to the optical spectrum analyzer. Set the OSA in the following configuration:
   - Start wavelength: 1400 nm
   - End wavelength: 1700 nm
   - Resolution: 0.10 nm
3. Record the optical spectrum for a current in Pump 2 of 0, 50, 100, 150, 200, 250, 300, 350, 400, 450 and 500 mA.
4. Switch off Pump 2 and change the configuration to forward pumping with pump 2. Repeat the measurement and compare the ASE between forward pumping and backward pumping. What is the configuration that yields a higher ASE level?

5.3 Task 3: Gain and noise characteristics

You will now investigate the behavior and limitations of the system in amplifying signals, and in particular measure the physical properties described in the introduction section.

1. Connect the output of the EDFA to the OSA. Use the following settings:
   - Center: 1550 nm
   - Span: 20 nm
   - Resolution: 0.02 nm
2. Place the system in the following configuration: Forward pumping with pump 2. Turn on the signal laser and set the signal current to the maximum allowed (25 mA).
3. Turn the screw of the VOA such that the input of the EDFA (the 90 end of the splitter) is $P_{\text{in}} = -15$ dBm. Theoretically, what power (in both mW and dBm unit) should you measure on the powermeter head (the 10 end of the splitter) to ensure you have -15 dBm at the EDFA input (asssuming no loss in the beam splitter)? In reality, what power did you measure? Don't forget to verify the wavelength setting of the powermeter.
4. Vary the pump current from 0 mA to 500 mA by step of 25 mA (21 points in total). Measure the $OSNR$ of the amplified laser tone from its prominence over the noise background (as in Figure 6). Also look at how the ASE evolves as you raise the pump power.

5. Record and plot the gain, $G|_{dB} = P_{\text{out}}|_{dB} - P_{\text{in}}|_{dB}$ as a function of the pump power. To infer P_{out} you will need to set the resolution bandwidth to be much larger than the linewidth of the amplified signal, and measure the height of the spectrum peak.

   Comment on the behavior of the system, especially the sign of the gain and the evolution of the curve.

6. The power conversion efficiency is defined as the ratio of the signal power added by the amplifier over the pump power:

$$\eta = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{pump}}} \tag{7}$$

   The theoretical maximum conversion efficiency is obtained when all the pump photons are converted to signal photons:

$$\eta_{\text{max}} = \frac{h\nu_{\text{signal}}}{h\nu_{\text{pump}}} = \frac{\lambda_{\text{pump}}}{\lambda_{\text{signal}}} \approx 63\% \tag{8}$$

   Plot the evolution of the conversion efficiency as a function of the pump power. Why the actual conversion efficiency is smaller than the theoretical value?

7. Measure the optical power directly at the output of the VOA. Infer the attenuation $L|_{dB} = P'_{\text{in}}|_{dB} - P'_{\text{out}}|_{dB}$ of the signal laser by the VOA. An attenuator introduces an SNR degradation corresponding to the noise figure $NF_{\text{VOA}} = L$.

   You can then estimate the optical noise figure of the EDFA in the following way:

$$NF = (OSNR_{\text{laser}} - L) - OSNR_{\text{out}}, \tag{9}$$

   if all the quantities are expressed in dBs.

   Plot NF as a function of pump power.

8. Repeat the above measurement and analysis but place the system in the following configuration: backward pumping with pump 2. Compare G, η and NF for the two cases and explain the results qualitatively.

5.4 Task 4: Gain saturation

In this part of the experiment, we will keep the pump power constant and vary the input signal power, to observe how the small-signal gain drops as the signal becomes strong enough to perturb the population inversion in the EDF, as discussed in section 3.3.

1. Place the system in the following configuration: Forward pumping with pump 2 at 250 mA. Turn on the signal laser and set the signal current to the maximum allowed (25 mA).

2. Turn the screw of the attenuator VOA such that the input power in the EDFA (the 90 end of the splitter) is maximized. What's the maximized power P_{in} (use dBm unit)?

3. Plan 21 measurement points spanning on interval from −40 dBm to the maximum P_{in} available. Take uniform steps in logarithmic scale, i.e. use a constant increment in dBs. Calculate the corresponding power to measure at the powermeter head for each value [3].

4. At each step, measure the signal level with the peak detection on the OSA. Use the following configuration:

   - Center: 1550 nm
   - Span: 20 nm
   - Resolution: 0.02 nm

5. Plot the gain as a function of the input power. From your graph, estimate the saturation power P_S, defined conventionally as the value of the input power for which the gain has dropped of 3 dB from its small-signal value.

5.5 Task 5: Fiber laser (Optional)

A gain medium is one of the key ingredient to make a laser, the second one being a cavity (i.e. a positive feedback looping the amplifier on itself).

1. Based on the elements at your disposal, propose a scheme to build a fiber laser.

2. Connect the fibers in the desired configuration and observe the resulting laser output on the OSA.

3. Repeat the measurement for some representative pump powers and try to estimate the threshold pump power. For each chosen power, measure the laser linewidth. Display the spectra on the same plot.

4. What determines the lasing wavelength and linewidth? List and discuss the most relevant factors.

6 Evaluation criteria

You have **two weeks after the last lab session** to hand in the lab report. Alongside, you should include a copy of your annotations, that you should keep during each lab session, including comments and observations on the experimental methods, unexpected results, interpretation of data or schematic drawings. Lab notes should be synthetic but include useful insight, especially for interpretation of the data at home. New input or information from the teaching assistant can also be included in the notes.

The criteria that will establish your final grade are:

- Preparation prior to the first lab session and understanding of the principles of the experiment
- Quality and organization of the work during the lab sessions
- Quality of the report: thoroughness, correctness of the mathematical results, quality of data presentation, soundness of physical insight and its expression

[3] It is helpful to plot the gain versus the input power while you are collecting the data. Around the value of P_{in} where the gain starts to drop, you can refine the measurement by collecting a few more points.

- Relevance and usefulness of the lab notebook.

Different weights are applied to these aspects for the purpose of calculating the final grade.

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