# Lab work in photonics

## Lasers




lense.institutoptique.fr | Deuxième année | Photonique S7

Engineer - 2$^{nd}$ year - S7 - Palaiseau
Version : July 6, 2019
Year 2019-2020

# Diode pumped Nd:YAG LASER

## 2019-2020

### Report

After the labwork, you will write a report of maximum 2 pages. The subject will be indicated at the end of the labwork

### Remarks

***-Questions are given in order to help students in their research work. The report is not supposed to be a list of question answers. A work of synthesis is consequently asked.***
***-Each experimental results is interesting and thus need to be commented (comparison with theory, derivations of order of magnitudes or important characteristics).***

# Preparation and theory

You should take some time to revise the following points before the start of the lab experiment:

- ➔ 4-Level laser system
- ➔ Pump absorption in a 4-Level laser
- ➔ Temporal and spatial properties of fluorescence emission
- ➔ Stability of Gaussian beams in a two mirrors cavity
- ➔ Q-switched lasers

You should understand and be able to explain the basic principles of the points given below during the experiment. The preparation is taken into account for the evaluation.

# Introduction

Owing to laser diodes properties, diode-pumped solid-state lasers can be very compact, have lifetimes greater than 10.000 hours and consume little electric energy but still provide high output powers and excellent beam quality.

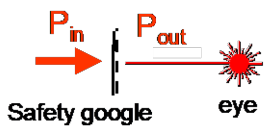
During this labwork, we are going to study a laser using a YAG (yttrium aluminium garnet) crystal doped with neodymium ions as active medium. Historically, the Nd:YAG laser is one of the first diode-pumped solid-state laser that have been demonstrated. Nowadays, it is the basis of numerous commercial products.

## Warning:

### 1. Laser Safety

**Nd:YAG LASER**
**USER EYE SAFETY**

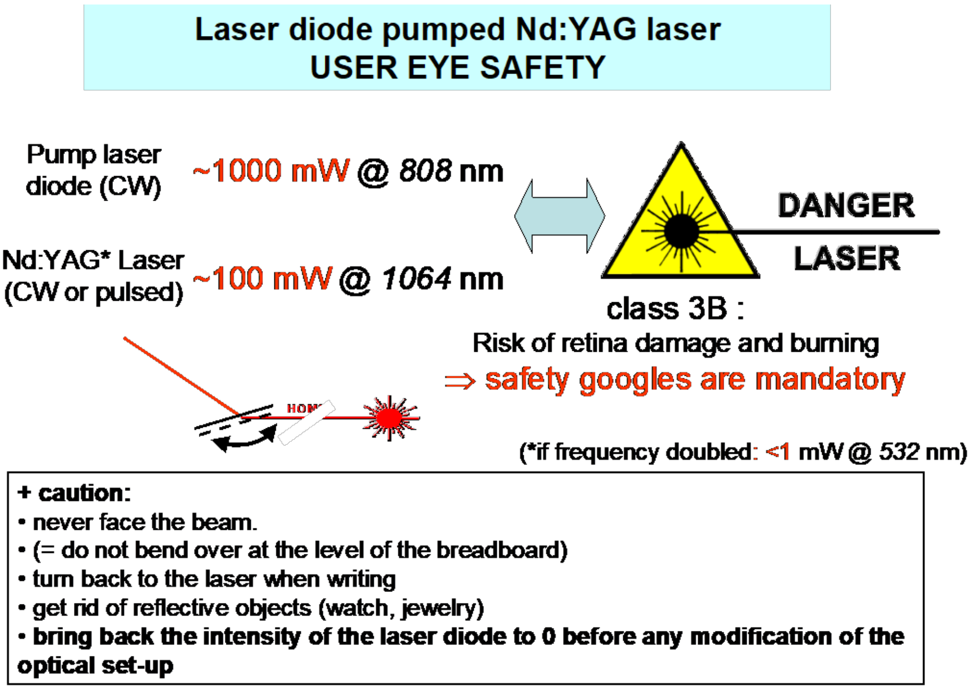

Classe ≥ 3B :
Risk of retina damage and burning
⇒ safety googles are mandatory
choose relevant googles!
(read both $\lambda$ *cut-off* and *OD*)




transmission = $10^{-OD}$
where OD : Optical Density

e.g.: type B safety googles
See data on side of the googles:
[750 nm ; 850 nm] : OD>5
⇒ @ 808 nm , transmission < $10^{-5}$

| type | A | B | C |
|---|---|---|---|
| $\lambda$ cut-off (nm) | 1064 | 1064 | 1064 |
| | | 980 | 980 |
| | | 808 | 808 |
| | 532 | | 532 |
| | | 355 | 355 |




The pump diode output power is about 500 mW. You may note that such a power at ~810 nm would be visible on a cardboard screen!

**Turn the pump current at minimum during any modification of the setup.**

### 1. Using the laser diode

The cable between the power supply and the laser diode <u>must not be unplugged.</u>

The diode temperature is controlled and you can display either the command or the real value of the temperature (which should be the same is the feedback loop works correctly). You can now switch to the mode ON and slowly increase the pump current while checking its value on the screen.

The pump current of the laser diode can also be modulated. The voltage of the modulation command must be set between 0 and 4 V, before being plugged to the power supply (coaxial input at the back of the laser diode power supply)

### 2. Handling the different parts of the laser

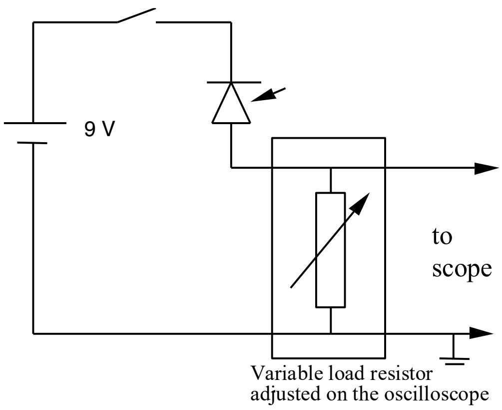
All the elements of the laser are fragile, especially the mirrors: handle them very carefully. After the labwork, make sure you carefully put each element back into its box.

### 3. Using the fast photodiode and the power meter

The fast photodiode Motorola MRD510 used during this labwork is inversely polarised as described in the figure below. The load resistor, which closes the circuit, is tunable from 50Ω to

1MΩ. This allows you to change the photodiode sensitivity and bandwidth (or time constant) as a function of the time characteristic of the observed phenomenon.

Warning: The photodiode power supply is a 9V battery, **do not forget to turn it off before leaving**!




Circuit layout of the photodiode

The THORLABS power meter allows you to measure powers from the μW to the W, from visible wavelength to the near infrared. As the detector is a silicium photodiode, its response strongly depends on the wavelength. **Do not forget to adjust the wavelength to correct value.**

There is **no tunable optical filter in such a device**: when measuring a polychromatic laser beam, it is then necessary to use external filters to be sure to measure the power of only one wavelength (hence the use of the filter RG1000 in the following).

You will have the possibility to draw the signals observed on the scope on a sheet of paper like you do in electronics labwork, or take a picture with your smartphone.

For each curve appearing in your report, a title describing what signal you present and the axis scales must appear.

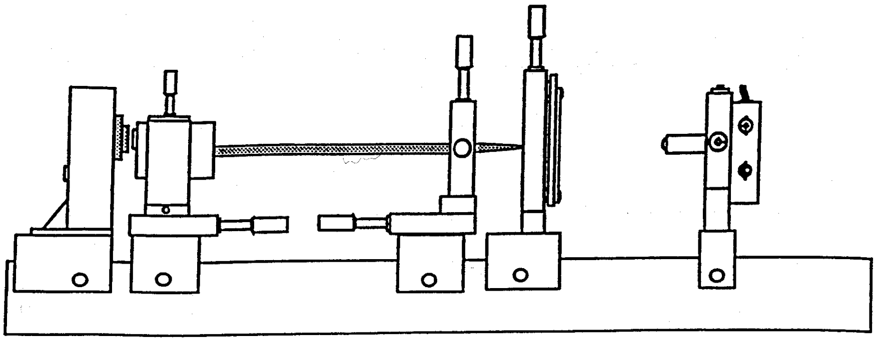
## I. Characteristics of the pump

This pumping scheme is called longitudinal pumping since the pump diode beam and the laser beam are collinear. This configuration allows better efficiency than transverse pumping (better pump and signal waists superposition) but also require more optical components and adjustments. However, longitudinal pumping configuration is limited in input power due to thermal problems which could damage the laser crystal.

## I.1. Collimation of the pump laser diode and prepositioning of the laser cavity

**Objective:** Correct alignment is necessary to achieve good performances in diode pumped solid state lasers. This first part of the experiment is to verify a good collimation of the pump laser diode and a good absorption of the light in the crystal.

**Setup:** The experimental setup is shown in Fig 1. Fig 2 describes the emission geometry of the Spectra Diode Labs (SDL) laser diode used to pump the Nd:YAG crystal as well as the collimation and focalisation optics and the anamorphic system. The anamorphous ratio is 6.



A = pump laser diode; B = anamorphic collimator;
C = focusing lens; D = Nd:YAG crystal; G = Photodiode

Figure 1: Absorption measurement setup.

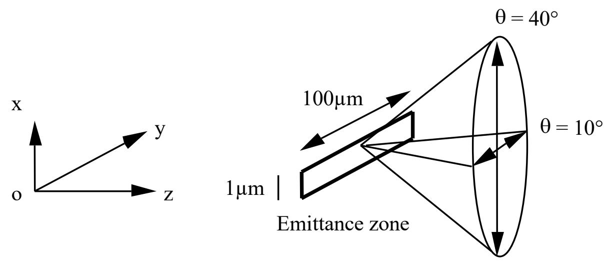



Fig 2a: Emission diagram of the pump diode

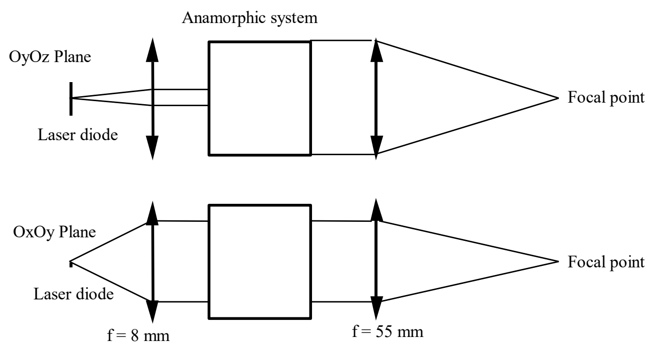



Fig 2b: Layout of the optical pump system.

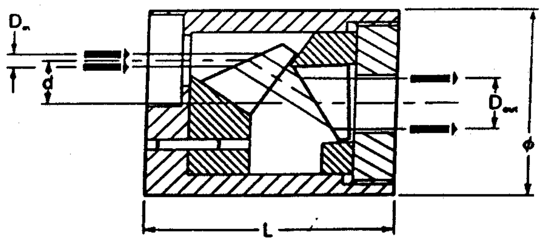



Fig 2c: Schematic of the anamorphic system ($D_{out}/D_{in} = 6$).

- Turn on the laser diode power supply. Set its maximum current to 1.0 A if it is not already set. Switch to the ON mode and progressively increase the current to its maximum value. If the power supply LED flickers, slightly decrease the current.

- First adjust the collimation and anamorphic systems while observing the radiation on a target, in order to obtain a pump beam well collimated and parallel to the laser bench. This alignment must be done very carefully to make further alignment easier. You should make sure that the collimated beam hits the surface of the photo-detector over the entire length of the bench.

Preliminary alignment of the optics

During the measurements you will use two mirrors and a Nd:YAG rod. In order to pre-align these optics so that their surface is perpendicular to the collimated beam you should proceed as follows with each of these optics, one after the other. Position the optic to align on the bench and align the reflection of the collimated beam onto it so that this back reflection is collinear to the forward pump beam (the back reflection should be aligned with the output hole of the collimator of the pump beam).

Remove the optic from the bench before proceeding.

Insert the focalisation lens on the bench. The diode wavelength is a function of the temperature and the pump current. (see the Laser Diode labwork). During this session, the laser diode temperature will be set to the temperature indicated on the laser diode case. The temperature determines the SDL diode wavelength as the laser diode wavelength shifts of 0.3 nm per degree. At this temperature, the laser diode emits around 808nm, the highest Nd:YAG absorption peak.

**Investigation and Measurements:** Document your measurements and answers to the following questions.

1. **Calculate the pump beam sizes and divergences in the crystal, in the planes OyOz and OxOy.**
2. **« Quickly [1]» plot the power characteristic of the pump diode right after the focalisation[2] lens (make sure the whole spot is detected), as a function of the pump current i.e. the characteristic "$P_{useful\ pump}$ (I)".**

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[1] Measure the power for pump current from 0.3 to 1A by 0.1A increments.

[2] **NEVER place the detector at the focal point**. It could saturate de photodiode (or damage it).

This curve will help you during the whole session to know what optical pump power is injected in the Nd:YAG rod.

3 **Position the Nd:YAG crystal at the focal point the lens. Optimise the rod position: when the rod is correctly aligned, the red spot on the crystal turns white (due to nonlinear effects caused by high intensity).**

4 **Measure the pump power transmitted by the Nd:YAG rod for a pump current of 1 A, and deduce the pump absorption. Estimate the $Nd^{3+}$ doping concentration inside the crystal from your measurement and the data below.**

| | |
|---|---|
| **Crystal length** | 5 mm |
| **Absorption cross-section at 808 nm** | $7\ 10^{-20}$ cm$^2$ |
| **$Nd^{3+}$ density for a 1% doped crystal** | 1,36 $10^{20}$ atomes/cm$^3$ |

Specifications of the laser crystal

## II. Characteristics of the amplifying medium: measurement of the fluorescence

**Objective:** By modulating the diode supply current with a square signal, it is possible to observe the fluorescence of the neodymium ions (spontaneous emission).

**Setup:** First, set the pump current to minimum (0 A). Then, adjust the low-frequency generator: it should deliver a positive square signal of 0-4V (max) of frequency below 500Hz. Please verify that the modulation signal corresponds to a modulation from 0 to 4 V (and not between 1 and 5 V for example) before connecting the modulator to the laser diode.
Plug this signal to the "Analog input" of the diode power supply box. Insert the RG1000 filter (characteristic given in appendix) between the photodiode and the Nd:YAG rod. Chose an adequate distance to the Photodiode.

**Investigation and Measurements:** Optimize the signal on the Oscilloscope. Change the load resistance and observe the different signal. Then document your answers to the following points:

5 **Why and how do the sensitivity and bandwidth of the detector vary according to the load resistor? What is the constant time of this detection system? Describe how, in practice, you choose the load resistance to measure the fluorescence lifetime of the neodymium ions**
Note: The total capacitance of the system (photodiode+cable+scope) is about 250pF

6 **Using the obtained signal, measure the characteristic time with one of the classical methods (slope at the origin, $t_{10-90} = 2{,}3\tau$, etc.). This time is the excited level ($^4F_{3/2}$)**

**lifetime. Compare the value you measure to the one given in the table below ("laser properties of Nd :YVO4 vs Nd :YAG"). Evaluate the error on your measurement.**

7 **How does the lifetime for Nd:YAG compare to other laser materials. What is the benefit of a high lifetime?**

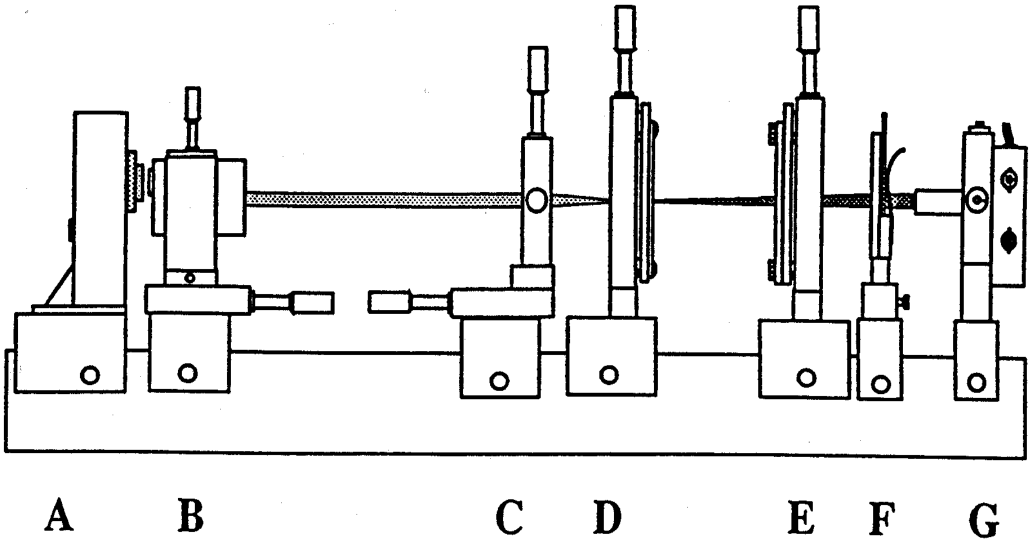
8 **Remove the RG1000 filter. Interpret the observed signal. What is the purpose of the RG1000 filter?**

## III. Laser effect at 1.06µm

**Objective:** realisation and characterisation of a simple linear cavity in CW

**Setup:** Lower the diode supply current, then insert into the setup, the cavity output mirror with a reflectivity Rmax = 97% at 1064 nm, the emission wavelength of the laser. This spherical mirror has a curvature radius R = 100 mm. The entry face of the Nd:YAG crystal is recovered by a highly reflective coating (Rmax) at 1064 nm (make sure the Nd:YAG crystal is inserted correctly);

The experimental setup is shown in Fig 4.




A = pump laser diode ; B = anamorphic collimator ; C = focusing lens ; D : Nd:YAG rod ; E = output mirror ; F = RG1000 filter ; G = powermeter

Figure 4: Laser setup.

Position correctly the elements of the laser cavity (choose a stable cavity length) and increase the diode supply current back to 1 A. The laser radiation is invisible (1064 nm). A small piece of Thorlabs cardboard (infrared converter) allows you to visualise the laser by a small orange spot when placed in the beam path.

**Investigation and measurements:** Align the cavity to obtain a $TEM_{00}$ mode. Then, optimise it to increase the laser output power. Then document your answers to the following points:

9 **Measure the laser output power for pump currents from 0.3 to 1 A by 0.1 A steps. By using the curve obtained earlier. Plot the laser output power vs the pump power (do not forget the transmission of the RG1000 filter). Determine the pump power at threshold.**

10 **Calculate the following efficiencies**

- **the pump differential efficiency (slope over threshold of the output laser power vs the emitted pump power)**
- **the pumping efficiency (Maximum laser output power/launched pump power),**
- **the global efficiency (laser output power/electric power used)**
- **the quantum efficiency (quantity of photons emitted at 1064 nm/photons launched at 808 nm)**
- **the quantum defect (1 - energy of a photon at 1064 nm/energy at 808 nm).**

**Why is it interesting to define these different efficiencies?**

| laser crystal | Nd doped (atm%) | emission cross section σ ($10^{-19}cm^{2}$) | lifetime τ ($10^{-6}$s) |
|---|---|---|---|
| $Nd:YVO_4$ (a-cut) | 1.1 | 25 | 90 |
| $Nd:YVO_4$ (c-cut) | 1.1 | 7 | 90 |
| Nd:YAG | 0.85 | 6 | 230 |

**Table 1 :** Laser properties of Nd :$YVO_4$ vs Nd :YAG [Koechner : Solid-state laser engineering, Springer, 2013.]

## IV. Q-Switch mode laser operation

**Objective:** realisation and characterisation of a simple linear Q-switched cavity using a saturable absorber

**Setup:** The $LiF^2$ crystal is a saturable absorber at 1064 nm: when the optical power density is high enough, its absorption saturates and its transmission become close to 1. This allows you to make the laser operate in a passive Q-Switch regime. This crystal deteriorates when exposed to UV radiation, it is stored in a black box. Replace it quickly in its box after use.

Lower the pump current and then insert the $LiF^2$ crystal in the cavity. To prevent interferences between its faces, the crystal is horizontally wedged. This is why you lost the laser operation when inserting the $LiF^2$ crystal in the cavity. Increase the pump power and realign the cavity to recover laser operation.

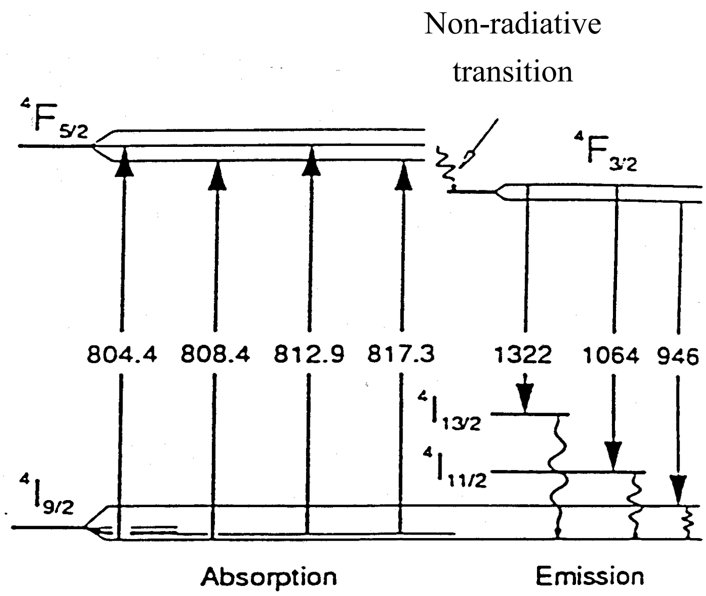
**Investigation and measurements:** Optimise the detected output power (some µW) with the screws on the $LiF^2$ mount (essentially the rotation) and the cavity output mirror until re-obtaining the laser effect. Then document your answers to the following points

11 **Recall briefly the working principle of a Q-switch laser. How does the saturable absorber work? How does it allow the emission of laser pulses?**

12 **Observe and plot the signal on the oscilloscope. Which load resistance should you use? Optimise the alignment of the cavity (average power, repetition rate) and justify your choices.**

13 **Determine the pulse energy and the peak power. Give the advantage of pulsed lasers compare to continuous lasers in terms of power.**

**APPENDIX:**




Energy levels of Nd:YAG when optically pumped by laser diode

(figures in nm)

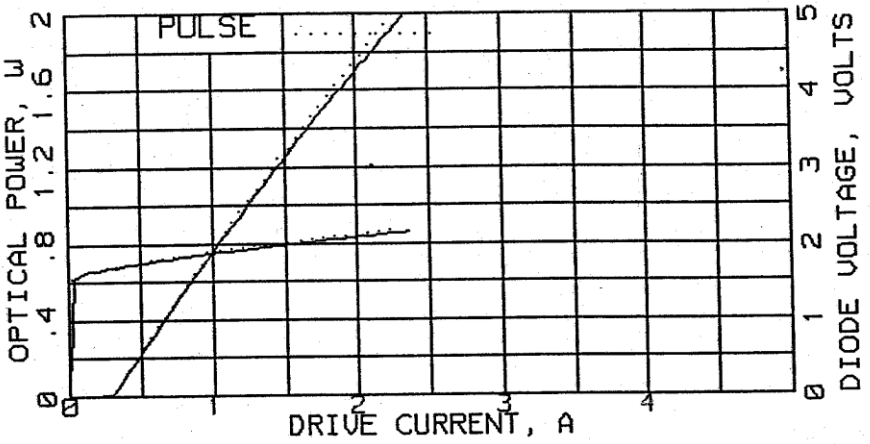
| **Wavelength (nm)** | 532 | 808 | 1064 |
|---|---|---|---|
| **RG1000 transmission** | $10^{-5}$ | $10^{-4}$ | 0,65 |

Filter optical properties

DEVICE TYPE: SDL-2362-P1 SERIAL NUMBER: AT454
DATE: 16 JUNE 1998 TIME: 10:27

| PARAMETER | PULSED | CW | UNITS |
|---|---|---|---|
| THRESHOLD | .24 | .22 | A |
| DIFF. Q. E. | 66 | 63 | % |
| SLOPE EFF. | 1.00 | .96 | W/A |
| V AT 1.5 A | 2.0 | 2.0 | VOLTS |
| RESISTANCE | .209 | .209 | OHMS |
| I AT 2.00 W | 2.255 | 2.346 | A |
| V AT 2.00 W | 2.18 | 2.15 | V |
| T'MISTOR RES | 9.8 KOHMS | | |
| WAVELENGTH | | 811 | nm |

MONITOR GAIN: 1.9 mA/W
TEST TEMP = 25 C PULSE: WIDTH = 15 usec, RATE = 133 Hz



INSTITUT D'OPTIQUE GRADUATE SCHOOL

# LASER DIODE

**2019-2020**

## Report

After the labwork, you will write a report of maximum 2 pages. The subject will be indicated at the end of the labwork

## Remarks

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***-Each experimental results is interesting and thus need to be commented (comparison with theory, derivations of order of magnitudes or important characteristics).***

## Goal of the labwork

The goal of this labwork is to highlight some properties that are specific to semiconductor lasers. First, the the labwork will focus on the investigation of the evolution of the characteristics of the laser diode with operating current and temperature. More precisely, the laser diode spectrum depends on the two parameters referred above, which explains its wide tenability with respect to other laser types, and their use in spectroscopy area.

Another property quite interesting about laser diodes relies on the possibility to modulate at very high flux the emitted light by directly modulating the operating current. The passband is typically few GHz wide, which is at the origin of their use in high flux optical telecommunications. This will be investigated in the second part of the labwork.

The studied laser diode emits a CW beam at $\lambda$ = 794 nm. It is connected to a power supply and temperature controller.

## Prerequisites

- General knowledge on laser physics (cavity, modes, saturated/unsaturated gain, amplifying medium, losses, laser threshold).
- Principle of Fabry-Pérot analyzers. Differences with grating spectrum analyzers.
- Spectrum characteristics of a laser source single mode longitudinally modulated in frequency or amplitude. You can use appendix 2.

## A. <u>Description of the setup</u>

### 1. *<u>Equipment</u>*

On the optical table, you can find:

- The laser du diode fixed on the table
- A collimating lens to use in order to increase the injection efficiency of the beam into the optical fiber.
- The input of the fiber used to send the beam into the spectrum analyzer.
- An half-reflecting mirror used in order to send half of the beam into the Fabry-Perot cavity, the other part being available to realize other measurements.
- A silicon powermeter.
- A Fabry-Perot analyzer pre-aligned
- An infrared card allowing the display of the diode laser beam

## 2. Using the laser diode

The laser diode driver is used to control the laser diode. It contains a temperature controller system and a current generator. A procedure is available below the driver.

- **Temperature controller :**

The laser diode is mounted on a copper block above a Peltier element: it is a thermoelectric device made of a semiconductor material which imposes a temperature difference $\Delta T$ between its facets as a function of the current fed to the device. In particular, this device can either heat or cool the laser diode support, depending on the sign of the applied current. The maximum current supported by the Peltier element is 2A.

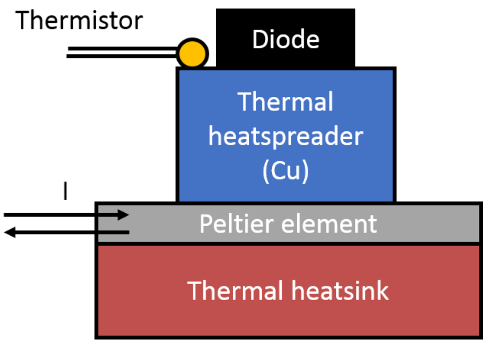



Figure 4: Schematic diagram of the temperature control for diode laser.

A thermistor is used to measure the temperature of the laser mount: this is a resistor which resistance is temperature-dependent (negative temperature coefficient). The thermistor we are using in this setup has a resistance of about 10 kΩ at room temperature; its resistance decreases as temperature increases. The calibration curve of the thermistor is given as an appendix.

The temperature regulator controls the temperature of the diode by adjusting the current supplied to the Peltier to compensate for thermal fluctuations and to maintain a constant temperature.

- Set the target temperature ($T_{set}$) with the potentiometer ADJUST on the temperature regulator, by defining the target resistance read on the LCD display screen on the controller. Always remain in the operating temperature range of the laser diode, 10°-50°C.Verify that the actual temperature of the diode ($T_{act}$) is stabilized before increasing the current.

- **Current generator :**

Laser diodes are simple to use, but are very fragile from the electronics standpoint. In particular, they can be destroyed by large or abrupt current changes, as well as by a current exceeding the specified current limit even for a very short time. The diode is fed by a stabilized current generator, protected from static discharges and abrupt transients. The maximum current is 150 mA. The anode being connected to ground, the current is negative, corresponding to a forward bias.

THE CURRENT GENERATOR MUST ALWAYS BE SET ON ZERO BEFORE BEING TURNED ON OR OFF. DO NOT TURN THE DIODE OFF ABRUPTLY BY JUST HITTING THE "OFF" BUTTON OR BY CUTTING THE POWER ON THE TABLE.

- Gradually increase the operating current ($I_{LD}$) of the laser diode with the potentiometer ADJUST.
- Verify that it emits red light.

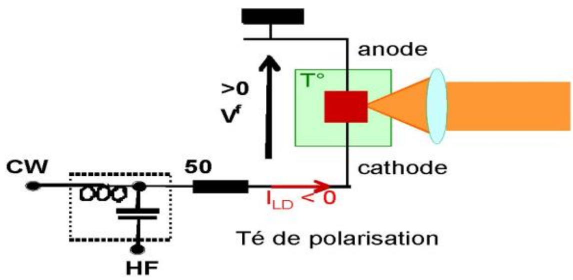



Figure 5: Electronic configuration of the laser diode; continuous supply current + RF modulation

- **Function generator**

The high frequency modulation of the laser diode current is done with a “synthetizer” (sine wave function generator delivering a sinusoidal signal of variable frequency within the 1 Hz - 2 GHz range and RF power between –127 dBm and + 13 dBm (or $2.10^{-13}$ mW and 20 mW). The modulation is applied through a bias Tee, which superimposes the modulating signal over the static bias current. The circuit layout is represented in Fig. 4. **The modulation will only be applied in the last part of this labwork**.

## 3. *Optical setup*

The characterization will be performed using several instruments:

- A power meter
- A broadband Optical Spectrum Analyzer (OSA) – moderate resolution (grating-based monochromator equipped with a CCD detector on the output slit)
- A narrow band [optical] spectrum analyzer– high resolution (tunable filter made of a scanning confocal Fabry-Perot interferometer with a single photodiode on the output port).
- A fast photodiode.

The different parts are described in detail in the specific paragraphs corresponding to their use, as well as precautions and/or adjustments directions.

## B.Characterization of the laser diode in CW operation

WARNING! LASER DIODES ARE FRAGILE DEVICES, PARTICULARLY SENSITIVE TO ELECTROSTATIC DISCHARGES. DO NOT TOUCH THE DIODE WHILE IT IS TURNED ON, DO NOT DISCONNECT IT FROM ITS POWER SUPPLY, AND DO NOT LOOK DIRECTLY AT THE BEAM.

In this section of the lab, we will measure the optical power emitted by the diode as a function of applied current for several values of temperature, and observe how the emitted spectrum evolves.

- Increase gradually the injected current in the diode ($I_{LD}$) using the ADJUST knob.
- Verify the laser diode emits a collimated beam with an IR detector card.

### 1. $P_{opt} = f(I)$

The optical power emitted by the diode is measured with a photovoltaic detector calibrated at the wavelength of the diode (Si photodiode - Thorlabs cell). The optical power is read in Watts.

The optical isolator place after the diode is a polarizing elements which prevents any optical feedback, coming from following optical elements, to return in the laser diode. Such optical feedbacks can disturb laser stable operation or burn the active region in the worst case. The arrow indicates the beam direction which is transmitted.

Place the detector at the output of the {diode+isolator}, in the collimated beam, taking care to intercept the whole beam.

**1. Plot (quickly) the curves of emitted power $P_{opt}$ as a function of current applied to the diode, for several temperatures (for example T = 25° and 40 °C).**

**2. Deduce from your graphs the value of the threshold current $I_s$ at each temperature. Explain how you define the threshold. Considering the gain curves given in figure 1, explain the variation of the threshold with temperature.**

**3. Evaluate the slope of the curves above threshold at the various selected temperatures. This slope is the optical/electrical efficiency (in mW/mA).**

## 2. *Emission spectrum*

The emission spectrum of the laser diode is first analyzed with an Optical Spectrum Analyzer (OSA).

- **Evolution of the optical spectrum as a function of current and temperature:**

Set the OSA central wavelength to ~795 nm. Set the current of the laser driver at approximately $I$ = 75 mA and $T_0$ = 25°C. Focus the collimated beam onto the core of the optical fiber that is connected to the OSA using a lens.

**4. Considering a 0.5 mm long laser cavity and a refractive index of 3.7, calculate its free spectral range (in nm). Compare that value to typical gain width of laser diode (~10 nm). Comment.**

**5. Observe the emission spectrum of the laser diode. Make sure you have a good signal to noise ratio in order to see parasitic emission peaks next to the laser peak.**

**Give the laser wavelength**

**How many longitudinal modes oscillate? Why?**

**6. Interpret the change of the spectrum below and above the laser threshold, and give the origin of the parasitic peaks. Deduce the experimental free spectral range in nm and the cavity length. Compare the result with question 4.**

**7. Explain the (linear) variations of the laser wavelength with injected current $I_{LD}$ and diode temperature T.**

**8 Study the evolution of the curve λ(I) above the laser threshold. Is the emitted wavelength evolving in a regular manner? Can you observe mode hopping? At what pump current? Can you explain why this phenomenon occurs?**

**9. Measure the coefficient $\left(\frac{d\lambda}{dI}\right)_{T_0}$ (on a linear range!) around I=75 mA (in pm/mA),**

Setup the diode current to $I_0$ = 75 mA, and vary the diode temperature in the range 10°C-40°C with increasing value only.

**10. Observe eventual mode hops. How many hops? What is the wavelength range covered with a temperature change from 10°C to 40°C? (No need to plot the curve λ(T)).**

**11. Measure the coefficient $\left(\frac{d\lambda}{dT}\right)_{I_0}$ (on a linear range) around T =25 °C (in nm/°C), ± 2 °C is enough with a 1°C step.**

## C. RF modulation of the laser diode current

By modulating the diode injected current, the excited carriers density inside the semiconductors is modified. The modulation is thus transmitted to the emitted laser power. Since the carriers dynamic is very fast (carrier lifetime is of the order of the nanosecond), the modulation bandwidth can be very high, up to several GHz. The large bandwidth of direct laser diode current modulation and its simplicity explains why it is widely used in optical telecommunication systems. This solution is used for systems with bit-rate below 2.5 Gbit/s. For higher bit-rates, an external modulator is used to transmit the information.

The high frequency laser diode current modulation is done with the help of a sine function generator delivering a sine signal of adjustable frequency from 1Hz to 1.2GHz and electrical power ranging from -127dBm to +13dBm. This modulation is done through a polarization T, that superimpose the modulated current to the CW current.

The RF signal is fed to the diode through the bias tee. A fast PIN silicon photodiode (bandwidth 1.5 GHz on a 50 Ω load) allows the display of the emitted power on the oscilloscope (set the input impedance to 50 Ω).

### 1. *Current modulation*

As the modulation is applied directly to the cathode of the laser diode, it is essential to make sure that the total supply current (continuous + modulated) remains negative in order to avoid damaging the diode with too large a positive current (inverse bias).

- **Frequency generator**

The frequency generator delivers a sinusoidal modulation of very precise frequency. The different settings of the modulation signal (here, frequency and power only) are controlled with the button on the right of the screen, after you have selected FREQUENCE or AMPLITUDE, respectively. The power delivered by the generator is measured in dBm:

$$P_{dBm} = 10\log P_{mW}$$

The output impedance of the generator is 50 Ω; in order to match the impedances, the laser diode is mounted in series with a 50 Ω resistor[1]. The amplitude $\Delta i$ of the current modulation applied to the diode is therefore related to the power delivered by the generator by:

$$\Delta i = \sqrt{2} \times \sqrt{\frac{P_{(W)}}{50\ \Omega}}$$

Thus, a 13dBm (20 mW) sinusoidal power modulation corresponds to a current modulation of ±28 mA (peak amplitude) across 50 Ω. <u>WARNING:</u> DO NOT APPLY THE

[1] The cable we are using has an impedance of 50 Ω, and all connections are adapted to RF modulation.

MODULATION EXCEPT WHEN THE DIODE IS RUNNING CONTINUOUSLY; VERIFY AHEAD OF TIME THAT THE SUM OF THE CONTINUOUS AND MODULATED CURRENT CONTRIBUTIONS WILL REMAIN LARGER THAN THE LASER EMISSION THRESHOLD.

### Measurement with the fast photodiode:

Apply a large current modulation (around +10 dBm) on the diode (previously biased with a constant current) with frequency $F_m$ = 250 MHz. Observe the detected signal on the oscilloscope. Decrease the modulation current and observe the evolution of the corresponding optical power modulation.

**12 Do you observe an intensity modulation? From the signal seen on the oscilloscope, estimate the contrast of the modulation. Given the modulation power and the CW current, deduce the maximum and minimum values of the modulated current used. Using the results obtained in CW (previous part), estimate the optical power range expected in CW corresponding to these current values. Calculate the associated contrast and compare it to the measured value.**

We have seen in the previous part that the laser wavelength depends on the injected current through the measured coefficient $d\lambda/dI$.

**13 What is the result of amplitude modulation on the spectrum (see appendix)? Can this effect be observed using the OSA? Comment.**

## 2. Spectrum analysis of the modulated diode with a Fabry-Perot spectrum analyzer

To study the laser spectrum, we will use a Melles-Griot confocal Fabry-Perot type spectrometer. This Fabry-Perot's free spectral range is *FSR* = 2GHz, and its finesse is *F* = 256. The distance between the mirrors is modulated by a piezoelectric actuator. The Fabry-Perot includes a silicon photodiode behind the exit mirror, as well as a focusing lens at the input (see the He-Ne labwork, study in 1st year).

The experimental setup is as follows:

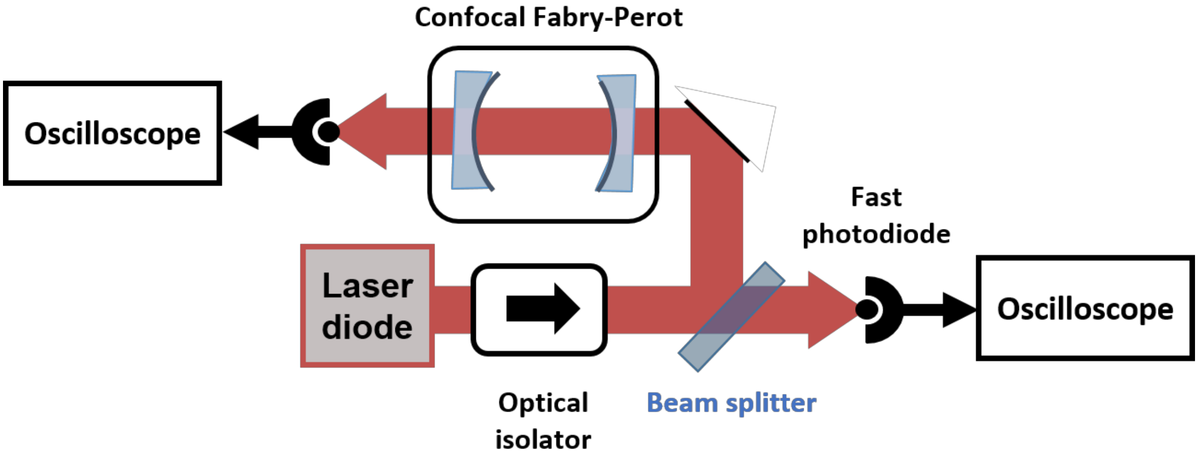



Figure 6: Experimental set-up to study the effects of the current modulation.

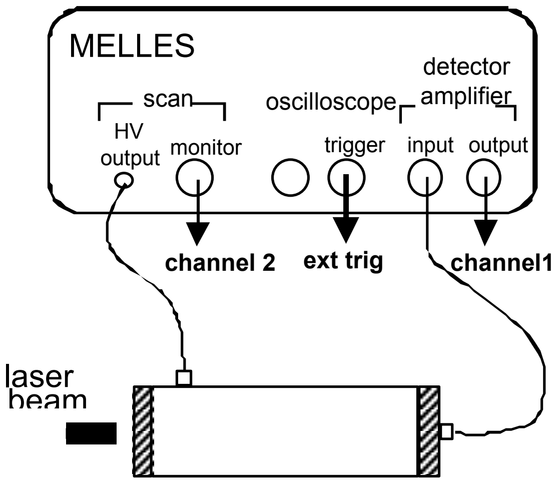



Fig. 7: Fabry-Perot connections

The high-voltage power supply of the Fabry-Perot includes an amplifier for the signal coming out of the detection photodiode, the gain of which we will adjust. We will eventually also add an offset voltage.

**14. Justify the use of the Fabry-Perot analyzer to see the modulation sidebands in laser spectrum with respect to the gratings spectrum analyzer used in the previous section. Calculate $\Delta\lambda_{FP}$ corresponding to $\Delta\nu_{FP}$. Calculate the theoretical resolution $\delta\nu_{theo}$. Convert it in terms of $\delta\lambda_{theo}$ (in nm). Compare this value to the best resolution of the OSA.**

**15. Conclude as to the advantages and drawbacks of these two types of spectrum analyzers.**

- Connect the Fabry-Perot following the layout of Fig. 5; observe the triangular modulation signal applied to the piezoelectric actuator (scan/monitor) on the oscilloscope ($I = 75$ mA and $T = 25°C$).
- Choose a stable operating point for the laser diode, for which the emission is monomode.
- Adjust the laser beam input in the Fabry-Perot by tilting the input mirrors in order to observe a unique, narrow peak for each free spectral range.

<u>Measurement with the scanning Fabry-Perot</u>:

Observe the laser optical spectrum measured by the Fabry-Perot for several modulation current and for a frequency modulation of 250 MHz.

**16. Measure the frequency splitting between the main central peaks and the sidebands when the diode current is modulated.**

**17. Given the observed spectrum (number, size and spacing of the peaks), is the dominant mechanism intensity or frequency modulation? Compare to what you observed in continuous wave and comment.**

**18. (If you have time left) What is the value of the AC current modulation corresponding to an extinction of the central peak? What is then the value of the optical frequency modulation index " m", and what is the peak-to-peak deviation of the optical frequency modulation, $\Delta\nu$ (in MHz)? Calculate the coefficient $\Delta\nu/\Delta I$ then $\Delta\lambda/\Delta I$ in pm/mA. Compare with the result of question 8. Comment.**

# Appendix 1: Laser diodes

Laser diodes are semiconductor sources consisting of a forward-biased PN junction and powered by injecting electric current from the anode to the cathode.

A laser diode is formed by doping a very thin layer on the surface of a crystal wafer. The cleaved facets of the semiconductor crystal serve as mirrors for the laser cavity. A recombination between the electrons of the n-junction and the holes of the p-junction is obtained by an electric current. Photons emitted into a mode of the waveguide will travel along the waveguide and be reflected several times by the mirrors (see Figure 1). When the gain is higher than the losses of the cavity the laser starts to oscillate. The energy of the emitted photons is therefore approximately equal to the bandgap energy of the semiconductor. The optical power emitted by the laser is proportional to the current supplied to the diode.

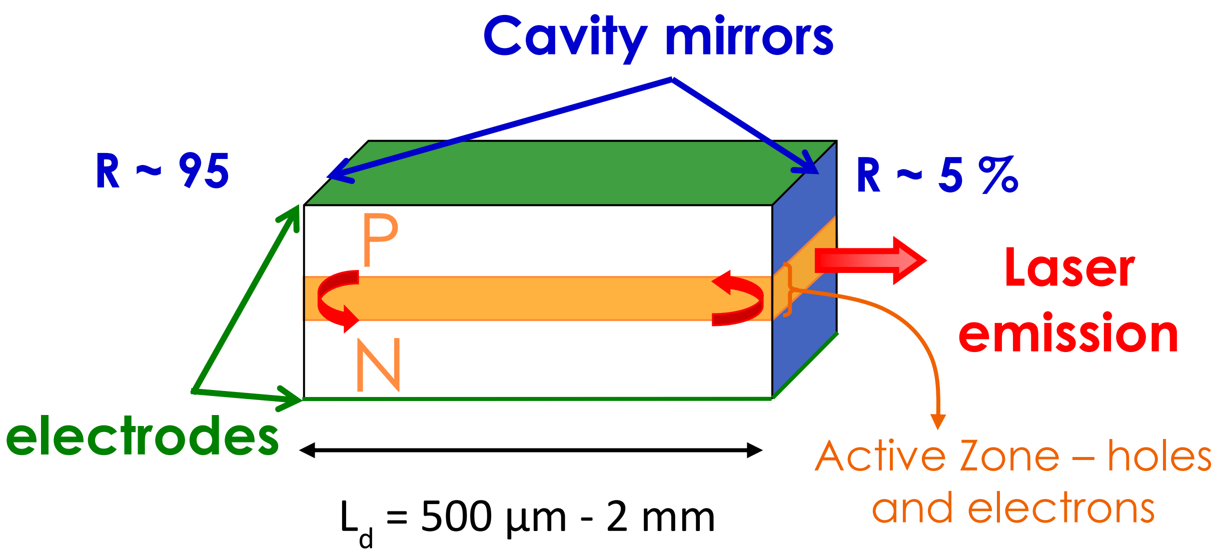



Figure 1: Diode laser structure.

The relatively large spectral bandwidth of the diodes, several tens of nanometers in the infrared range, allows a wide tunability of the laser emission, as will be shown in this labwork.

This large tunability of the laser emission is due to different characteristics of the semiconductor:

1 - The large gain curve of the laser diode is due to the existence of bands and not discrete levels of energy as in doped crystals. This gain curve is given by the statistics of the carrier density in the conduction and valence bands, described by the Fermi-Dirac distribution. In this case the gain broadening is homogeneous.

2 - The energy gap $E_g$ depends on the temperature, $E_g$ decreases when the semiconductor temperature increases. The increase in semiconductor temperature shifts the gain curve towards longer wavelength, see Figure 2.

3 - The temperature changes the laser cavity length and the effective refraction index. An increase in the semiconductor temperature produces a dilatation of the laser cavity shifting the emission wavelength.

4 – The electrical power which is not converted in optical power (electrical to optical efficiency around 50%) generates heat inside the laser diode. For this reason when an electrical current passes through the laser diode its temperature increases and the wavelength changes. It is therefore possible to change the emission wavelength of a laser diode by changing its current.

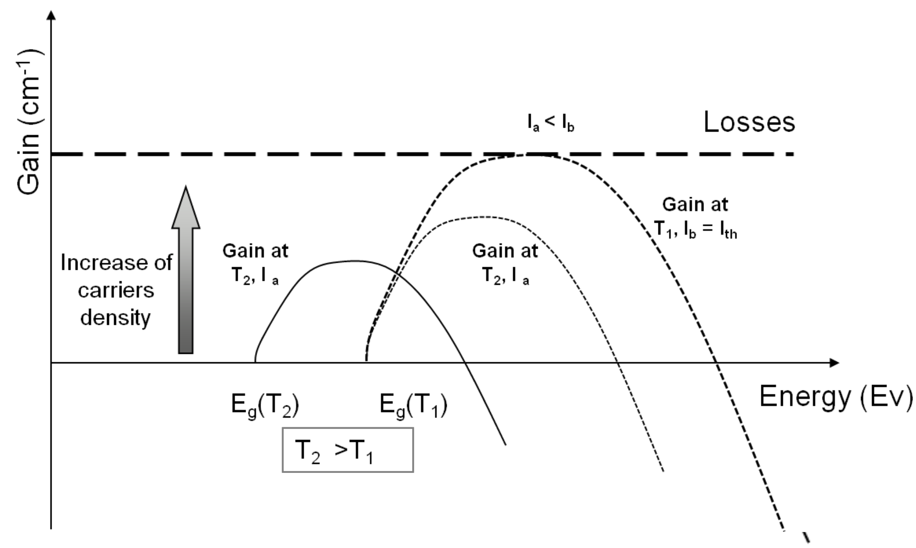



Figure 2: Gain evolution in a laser diode with respect to the pump current I and temperature T.

Finally, contrary to other types of lasers, the gain in the laser diode is not fixed only by the spectroscopic properties of the gain medium at a given temperature and pressure. Indeed, the gain depends on the population inversion inside the diode and thus on the pump current. The gain curves obtained for different pump currents and temperatures are shown in Figure 2. For a given laser diode cavity, laser emission is possible only when the unsaturated gain is higher than the cavity losses. In addition, Figure 2 shows that for increasing temperatures the current threshold increases and the wavelength becomes larger.

In the first part of this labwork we will study the influence of temperature on the wavelength of the emitted laser light.

# Appendix 2: Current modulation of a laser diode

In the absence of current modulation, the diode emits a constant-power monochromatic light. The current modulation induces a variation of the power and frequency of the beam. For frequencies below 1 GHz, we expect the optical / electrical efficiency (mW/mA) and the frequency variation coefficient (nm/mA) to remain constant.

**Optical power modulation**

We consider a power modulation given by $P(t) = P_0[1 + M \cdot \cos(2\pi F_m t)]$, where *$P_0$* is the unmodulated power and *P(t)* is the modulated power. The parameter M is called the power modulation index.

The signal on the photodiode is modulated at a frequency *$F_m$*. At the output of the Fabry-Perot, we observe the optical spectrum. For weak M, the electric field can be written as follows: : $E_L(t) = A \cdot [1 + \frac{M}{2} \cdot \cos(2\pi F_m t)] \cdot \cos(2\pi \nu_L t + \phi_L)$

Hence:

$$\begin{aligned} E_L(t) &= A\cos(2\pi\nu_L t + \phi_L) \\ &+ M\frac{A}{4}\cos(2\pi(\nu_L - F_m)t + \phi_L) \\ &+ M\frac{A}{4}\cos(2\pi(\nu_L + F_m)t + \phi_L) \end{aligned}$$

This expression shows that the field can be decomposed, to first order, in three contributions at different optical frequencies: The optical carrier at $\nu_L$, and two sidebands with the same amplitude at $\nu_L - F_m$ and $\nu_L + F_m$. The power associated with each peak are equal to *$A^2/2$ for the carrier and $M^2A^2/32$* for each sideband. In particular, the intensity of the central peak does not depend on the modulation index.

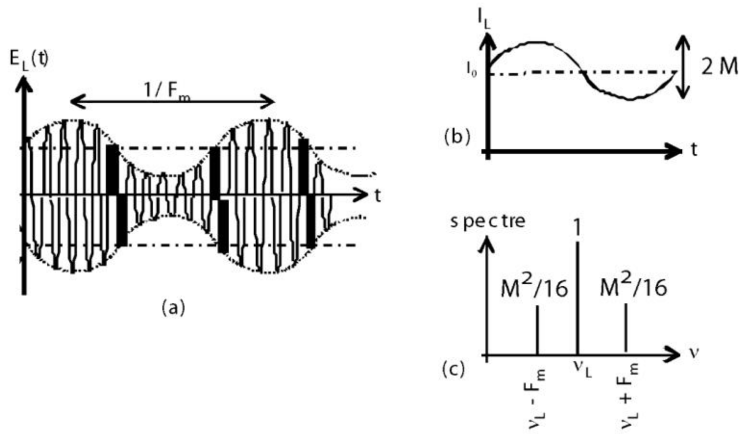



Figure 6: (a) Electric field of the power-modulated laser (b) Photodiode signal (c) Spectrum of the optical field

**Frequency modulation**

Let us now consider a pure sinusoidal frequency modulation at frequency $F_m$: $\nu(t) = \nu_L + \Delta\nu \cdot \cos(2\pi F_m t)$.

The phase of the electric field dis given by: $\int_0^t dt' \; \nu(t') = \nu_L t + \frac{\Delta\nu}{2\pi F_m} \sin(2\pi F_m t)$

The electric field can therefore be expressed as follows:

$$E_L(t) = A \cdot \cos\left[2\pi\nu_L t + \frac{\Delta\nu}{F_m} \cdot \sin(2\pi F_m t) + \phi_L\right]$$

*We define $m = \Delta\nu/F_m$ as the frequency modulation index.*

This field can be expanded in a sum of sinusoidal terms using Fourier techniques as follows:

$$\begin{aligned}
E_L(t) = {} & A \cdot J_0(m) \cdot \cos(2\pi\nu_L t + \phi_L) \\
& - A \cdot J_1(m) \cdot \cos(2\pi(\nu_L - F_m)t + \phi_L) \; + A \cdot J_1(m) \cdot \cos(2\pi(\nu_L + F_m)t + \phi_L) \\
& + A \cdot J_2(m) \cdot \cos(2\pi(\nu_L - 2F_m)t + \phi_L) + A \cdot J_1(m) \cdot \cos(2\pi(\nu_L + 2F_m)t + \phi_L) \\
& - A \cdot J_3(m) \cdot \cos(2\pi(\nu_L - 3F_m)t + \phi_L) + A \cdot J_1(m) \cdot \cos(2\pi(\nu_L + 3F_m)t + \phi_L) \\
& \ldots
\end{aligned}$$

Frequency modulation is therefore characterized by the presence of sidebands at harmonics of the modulation frequency. Bessel function can evaluate to zero for specific values of the modulation index. For example, $J_0(2.4) = 0$: the optical carrier at $\nu_L$ is suppressed for the modulation index equal to m=2.4. The sidebands can also be extinguished for specific values of m.

The photodiode is not sensitive to the slight optical frequency modulation of the laser diode. Therefore, in the case of a pure frequency modulation, the photodiode signal would be constant. However, the scanning Fabry Perot is able to measure the sidebands and shows more sidebands as the frequency modulation gets stronger.

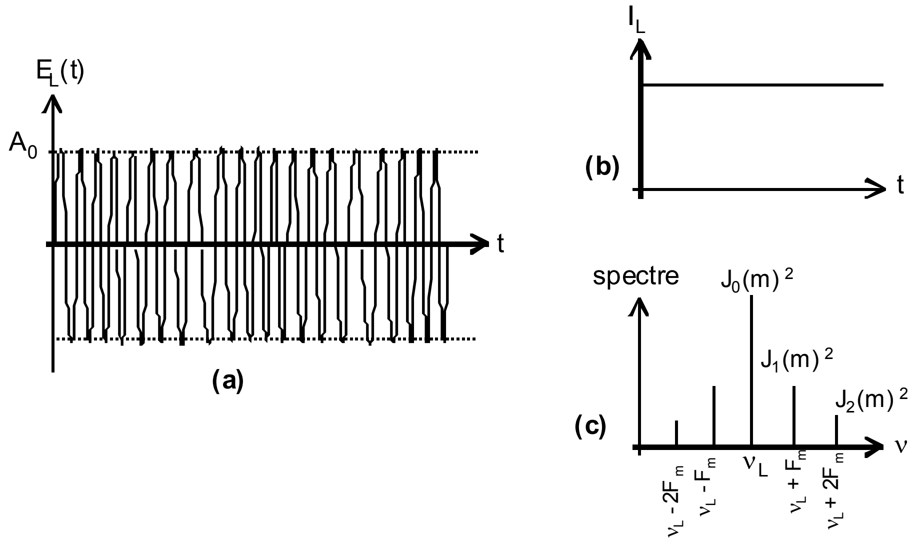
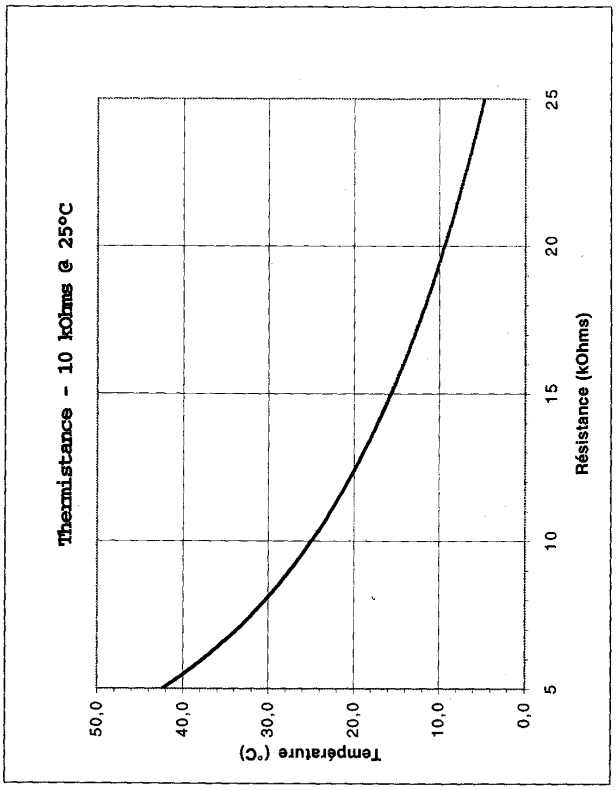



Figure 7: (a) Frequency-modulated electric field (b) Photodiode signal
(c) Spectrum of the field, as measured by a scanning Fabry-Perot

Finally, note that the sidebands at ± $F_m$ are out of phase in the case of frequency modulation, as opposed to in-phase sidebands in the case of mower modulation. The scanning Fabry Perot measures the intensity of the spectral components, and does not allow this distinction. However, when power and frequency modulation are mixed, this induces an asymmetry of the spectrum intensity.

## Appendix 3: Thermistor




$$T_{(°C)} = \frac{1}{\frac{1}{B}\ln\frac{R_{th}}{R_{th}(25C)} + \frac{1}{298{,}15}} - 273{,}15$$

avec $B = 3750\,K$

| R (kOhms) | T (°C) |
|---|---|
| 5 | 42,4 |
| 5,2 | 41,4 |
| 5,4 | 40,4 |
| 5,6 | 39,4 |
| 5,8 | 38,5 |
| 6 | 37,6 |
| 6,2 | 36,8 |
| 6,4 | 36,0 |
| 6,6 | 35,2 |
| 6,8 | 34,4 |
| 7 | 33,7 |
| 7,2 | 33,0 |
| 7,4 | 32,3 |
| 7,6 | 31,7 |
| 7,8 | 31,0 |
| 8 | 30,4 |
| 8,2 | 29,8 |
| 8,4 | 29,2 |
| 8,6 | 28,6 |
| 8,8 | 28,1 |
| 9 | 27,5 |
| 9,2 | 27,0 |
| 9,4 | 26,5 |
| 9,6 | 26,0 |
| 9,8 | 25,5 |
| 10 | 25,0 |
| 10,2 | 24,5 |
| 10,4 | 24,1 |
| 10,6 | 23,6 |
| 10,8 | 23,2 |
| 11 | 22,8 |
| 11,2 | 22,3 |
| 11,4 | 21,9 |
| 11,6 | 21,5 |
| 11,8 | 21,1 |
| 12 | 20,7 |
| 12,2 | 20,4 |
| 12,4 | 20,0 |
| 12,6 | 19,6 |
| 12,8 | 19,3 |
| 13 | 18,9 |
| 13,2 | 18,6 |
| 13,4 | 18,2 |
| 13,6 | 17,9 |
| 13,8 | 17,6 |
| 14 | 17,2 |
| 14,2 | 16,9 |
| 14,4 | 16,6 |
| 14,6 | 16,3 |
| 14,8 | 16,0 |

| R (kOhms) | T (°C) |
|---|---|
| 15 | 15,7 |
| 15,2 | 15,4 |
| 15,4 | 15,1 |
| 15,6 | 14,8 |
| 15,8 | 14,5 |
| 16 | 14,3 |
| 16,2 | 14,0 |
| 16,4 | 13,7 |
| 16,6 | 13,5 |
| 16,8 | 13,2 |
| 17 | 12,9 |
| 17,2 | 12,7 |
| 17,4 | 12,4 |
| 17,6 | 12,2 |
| 17,8 | 11,9 |
| 18 | 11,7 |
| 18,2 | 11,4 |
| 18,4 | 11,2 |
| 18,6 | 11,0 |
| 18,8 | 10,8 |
| 19 | 10,5 |
| 19,2 | 10,3 |
| 19,4 | 10,1 |
| 19,6 | 9,9 |
| 19,8 | 9,6 |
| 20 | 9,4 |
| 20,2 | 9,2 |
| 20,4 | 9,0 |
| 20,6 | 8,8 |
| 20,8 | 8,6 |
| 21 | 8,4 |
| 21,2 | 8,2 |
| 21,4 | 8,0 |
| 21,6 | 7,8 |
| 21,8 | 7,6 |
| 22 | 7,4 |
| 22,2 | 7,2 |
| 22,4 | 7,0 |
| 22,6 | 6,8 |
| 22,8 | 6,7 |
| 23 | 6,5 |
| 23,2 | 6,3 |
| 23,4 | 6,1 |
| 23,6 | 5,9 |
| 23,8 | 5,8 |
| 24 | 5,6 |
| 24,2 | 5,4 |
| 24,4 | 5,3 |
| 24,6 | 5,1 |
| 24,8 | 4,9 |
| 25 | 4,8 |

# Appendix 4: Laser diode specifications

ER DIODES

# ML6XX10 SERIES

## FOR OPTICAL INFORMATION SYSTEMS

### ABSOLUTE MAXIMUM RATINGS

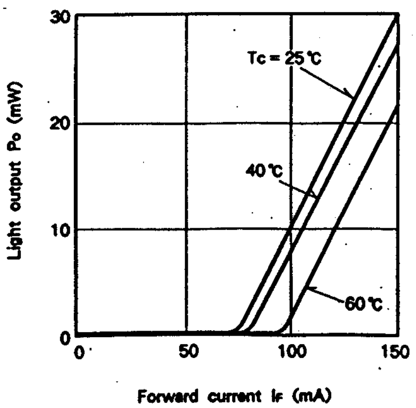
| Symbol | Parameter | Conditions | Ratings | Unit |
|---|---|---|---|---|
| $P_o$ | Light output power | CW | 35 | mW |
| | | Pulse (Note 1) | 45 | |
| $V_{RL}$ | Reverse voltage (laser diode) | – | 2 | V |
| $V_{RD}$ | Reverse voltage (Photodiode) | – | 30 | V |
| $I_{FD}$ | Forward current (Photodiode) | – | 10 | mA |
| $T_c$ | Case temperature | – | $-40 \sim +60$ | ℃ |
| $T_{stg}$ | Storage temperature | – | $-55 \sim +100$ | ℃ |

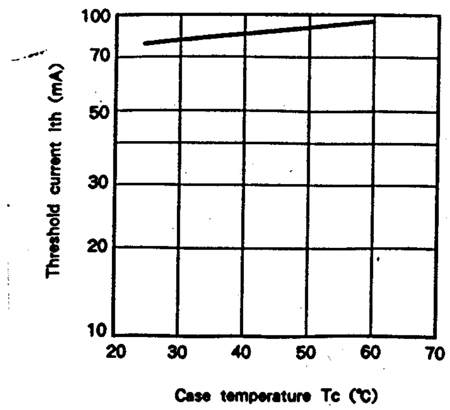
Note 1 : Duty less than 50 %, pulse width less than 1 $\mu$s.

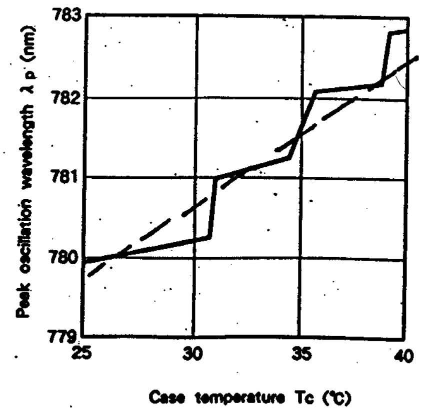
### ELECTRICAL/OPTICAL CHARACTERISTICS ($T_c$ = 25℃)

| Symbol | Parameter | Test conditions | Limits | | | Unit |
|---|---|---|---|---|---|---|
| | | | Min. | Typ. | Max. | |
| $I_{th}$ | Threshold current | CW | – | 70 | 85 | mA |
| $I_{OP}$ | Operating current | CW, $P_o$ = 30mW | – | 140 | 160 | mA |
| $\eta$ | Slope efficiency | CW, $P_o$ = 30mW | – | 0.4 | – | mW/mA |
| $V_{OP}$ | Operating voltage | CW, $P_o$ = 30mW | – | 2.0 | 2.5 | V |
| $\lambda_P$ | Peak wavelength | CW, $P_o$ = 30mW | 770 | 785 | 800 | nm |
| $\theta_{//}$ | Beam divergence angle (parallel) | CW, $P_o$ = 30mW | 9 | 10.5 | 13 | deg. |
| $\theta_{\perp}$ | Beam divergence angle (perpendicular) | CW, $P_o$ = 30mW | 24 | 26.5 | 28 | deg. |
| $I_m$ | Monitoring output current (Photodiode) | CW, $P_o$ = 30mW, $V_{RD}$ = 1V, $R_L$ = 10 Ω (Note 3) | 1.0 | 3.0 | 6.0 | mA |
| $I_m$ (Note 2) | | | 0.6 | 2.7 | 4.0 | mA |
| $I_D$ | Dark current (Photodiode) | $V_{RD}$ = 10V | – | – | 0.5 | $\mu$A |
| $C_t$ | Total capacitance (Photodiode) | $V_{RD}$ = 0V, f = 1MHz | – | 7 | – | pF |

Note 2 : Applicable to ML64110R.
3 : $R_L$ = the load resistance of photodiode.



# Second-harmonic generation in nonlinear crystals and Raman scattering in silica optical fiber

## 2019-2020

**Report**

After the labwork, you will write a report of maximum 2 pages. The subject will be indicated at the end of the labwork

**Remarks**

***-Questions are given in order to help students in their research work. The report is not supposed to be a list of question answer. A work of synthesis is consequently asked.***
***-Each experimental results is interesting and thus need to be commented (comparison with theory, derivations of order of magnitudes or important characteristics).***

The goal of this manipulation is to the study two nonlinear effects. This lab illustrates the principle of the second harmonic generation (SHG) effect in 2nd order nonlinear crystals. The doubling frequency beam will then be injected inside an optical fiber made of silica to generate Raman scattering effect, a 3rd order nonlinearity. Among the various applications of Raman scattering in optical fibers, one can cite the Raman amplifier for optical telecommunication systems, or the Raman fiber laser.

***In order to prepare this labwork, we recommend that you read the appendix 1, the lecture notes on nonlinear optics, especially the chapter relative to the 2nd order nonlinear effects and the exercise devoted to SHG optimization in a uniaxial crystal.***

# I Second Harmonic Generation

The second harmonic generation (SHG) in a nonlinear crystal is based on the experimental set-up depicted in Fig. 1.

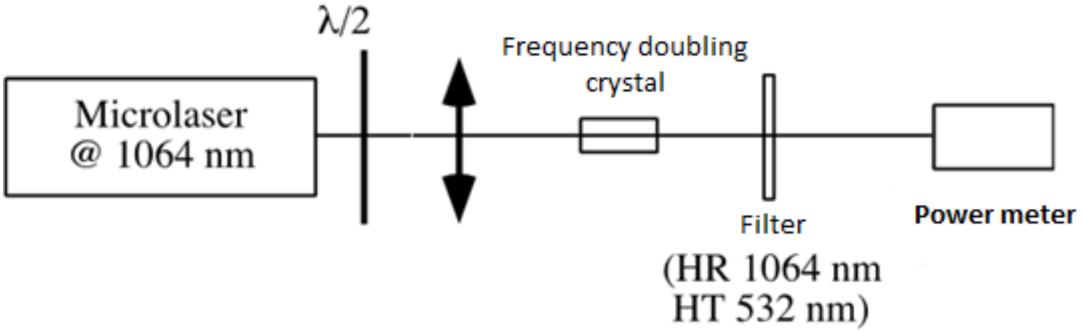



*Figure 1: Second Harmonic Generation experimental set-up.*

It consists in using a high peak power laser in order to achieve measurable conversion efficiency. The 1064 nm infrared beam from a pulsed laser is focused into the nonlinear crystal using a lens. The half-wave plate enables to set the direction of polarization of the infrared beam. The power of the doubled frequency beam is measured using a power meter. A selective filter with high-reflective coating at 1064 nm and high-transmission at 532 nm, is inserted between the nonlinear crystal and the power meter.

## I.1 Characterization of the laser source

The laser at 1064 nm is a passively Q-Switched microchip laser. The laser cavity, see Fig. 2, contains a $Cr^{4+}$:YAG saturable absorber crystal that has been directly epitaxied on a $Nd^{3+}$ : YAG laser crystal. The length of the cavity is less than 1 mm (typically about 800 μm). The laser delivers 620 ps pulse width at 1064nm.
The output beam of the laser is linearly polarized. Note that the direction of polarization can vary in time due to the heating of the crystal.

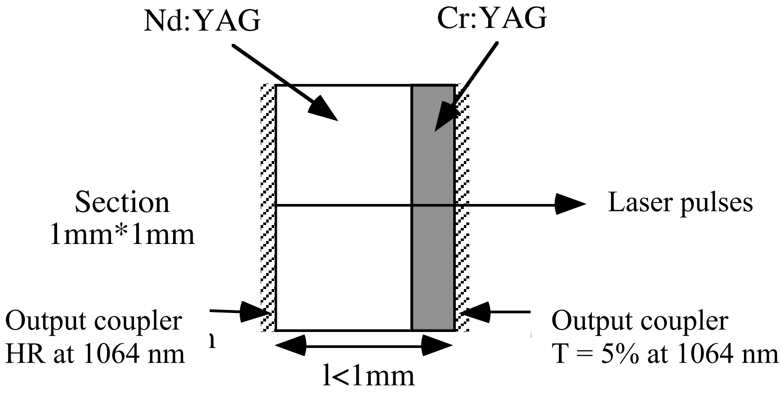



*Figure 2: Sketch of the microchip laser*

**Question 1:** Using a fast photodiode, measure the pulse repetition rate and the pulse duration. The last measure agrees with mentioned value above? Using the power meter, measure the average power of the laser. Assuming a rectangular pulse shape, deduce the value of the laser peak power.

**Do not forget to set the wavelength on the power-meter.** Do not use the power-meter with a focused beam in order to prevent damages.

**Question 2**: Explain the interest of a pulsed laser for non-linear conversion. Why do we focus the infrared beam inside the crystal?

## I.2 Dependence of the SHG efficiency with the crystal length

In this part, we test different crystals of BBO ($\beta$-$BaB_2O_4$) with a crystallographic cut optimised for a phase-matching of type I between the fundamental wave at 1064 nm and the doubled one at 532. Phase-matching is achieved for the direction of propagation that is perpendicular to the parallel faces of the crystal. For BBO, the extraordinary optical index is smaller than the ordinary optical index at a given wavelength.

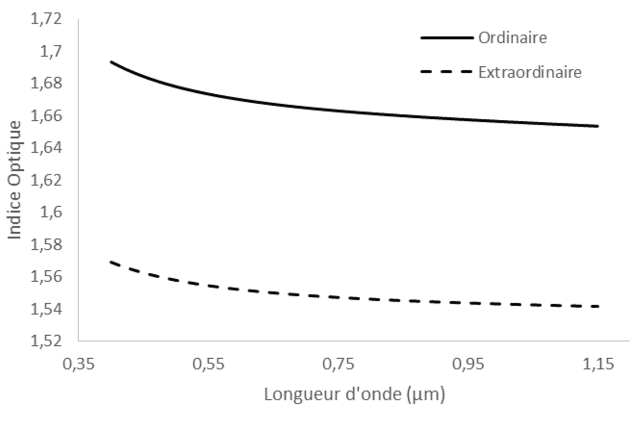



*Figure 3: BBO refractive index as a function of the wavelength.*

**Question 3:** What are the polarization states of the waves at 1064 nm and 532 nm when phase matching is achieved? Draw the optical index surfaces in order to show the direction for which phase matching is observed.

Adjust the first half wave plate in order to maximise the incident power at 1064 nm.

The focal length of the lens is about 55 mm. By focusing the laser beam into the BBO crystal, one might easily see at the crystal output a green beam. Optimize the quantity of green light by adjusting the different optical components (focalization, adjustment of the polarization at 1064 nm, adjustment of the direction). Do the optimization by looking at the green beam, without any collimation, on the white cardboard (20 cm after the crystal and after the filter).

**Question 4**: Changing the orientation of the non-linear crystal, you should observe several fringes in the green beam. What is their origin?

For each BBO crystals (0.5 mm; 4 mm; 7 mm), and using the power meter, optimize the power of the green beam. Observe the shape of the green beam in each case. This measurement is rather delicate since the green and infrared beams are nearly collinear at the output of the crystal. In spite of the optical filter (Fig. 1), a small fraction of the infrared beam can be transmitted. This parasitic infrared power adds an offset to the measurement. It corresponds to the power level measured when the half wavelength plate is rotated to suppress the green.

**Question 5:** For each crystal, give the conversion efficiency (defined as the ratio between the power at 532 nm and the incident power at 1064 nm). Observe the spatial shape of the output green beam.

**Question 6:** Estimate the theoretical conversion efficiency expected with a laser source with the same average power in continuous regime. Comment

| | BBO | KTP |
|---|---|---|
| $d_{eff}$ (pm/V) | 2,0 | 3,6 |
| Angular acceptance (mrad.cm) | 0,6 | 10 |
| Walk-off (mrad) | 56 | 4 |

Some properties of the non-linear crystals

**Question 7:** Comment about your measurements: is the variation of the conversion efficiency with the crystal length is in agreement with the theoretical expectation? Give explanations.

**Question 8:** Calculate the divergence of the 1064 nm laser beam in the non-linear crystal, assuming a beam with 500 µm laser waist and a beam quality factor $M^2 = 5$.

**Question 9:** Comment about the spatial shape of the output green beam for each crystal. Which effect is responsible for these variations on the spatial shape?

### I.3 Influence of the direction of polarization of the fundamental wave

**Question 10:** Assuming a linearly polarized infrared beam, remind the dependence of the SHG beam power with the direction of the linear polarized infrared beam (respect to the eigen polarized states) for a type I and type II phase matching.

**Question 11:** Using the 7 mm thick BBO crystal, measure the SHG beam power variation with the angular position of the half wave plate N°2. Then plot the SHG beam power as a function of the polarization angle of the fundamental wave (choose your own 0° origin). Use the result from the previous question to plot on the same graph the theoretical curve.

**Question 12:** Do the same for the KTP (KtiPO4) crystal. After optimization, you should obtain more than 2 mW of green power.

**Question 13:** Deduce from these two curves the type of phase matching in used for BBO and for KTP.

**Question 14:** Compare the doubling efficiencies and the beam shapes obtained with the KTP and BBO 7 mm. Comment by relying on the properties of crystals data shown above.

# II Raman scattering in a silica fiber

The Raman effect is caused by the interaction between an optical wave at $\omega$ and a vibrational mode of a molecule (or a crystal lattice) at the frequency $\omega_{mol}$. The spectrum of the scattered light, which is emitted isotropically, contains new frequency components respectively towards $\omega$-$\omega_{mol}$ (the Stokes wave) and $\omega$+$\omega_{mol}$ (the Anti-Stokes wave).
The frequency shift between the incoming wave, hereafter referred to the pump beam, and the Stokes and Anti-Stokes wave is independent of the frequency of the pump. It depends on the chemical composition of the material and is related to the spectrum of the rotational-vibrational eigenstates of the molecules or the crystal lattice structures. Raman scattering finds numerous applications in spectroscopy. It allows, for example, to identifying chemical bounds and constituents of a material. Sending into the material a pump and a signal beam at the Stokes frequency can stimulate the Raman scattering effect. It can be shown that the interaction of these two waves inside the material leads to an optical amplification of the Stokes signal.

The aim of the experiment is to observe the Raman scattering effect in an optical fiber made of silica. The spectrum related to the vibrational modes of the molecule SiO2 is centred at 13,2 THz (440 $cm^{-1}$), with a linewidth of about 10 THz (see the spectrum in Fig. 3).

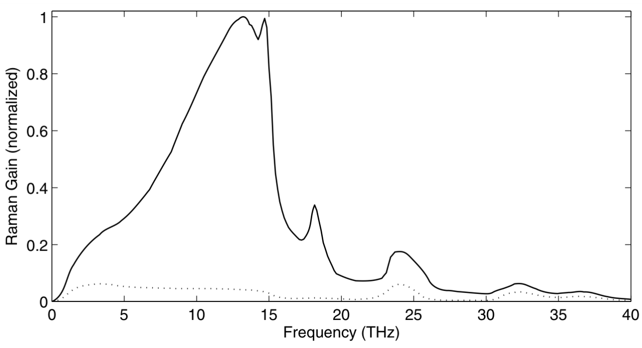


Figure 4: Normalized Raman gain spectrum for fused silica (G.P Agrawal, *Nonlinear Fiber optics*, Academic Press, San Diego, CA, 2001)

The experimental set-up that is used to study the Raman scattering effect is depicted in Fig. 4. The SHG beam generated into the KTP nonlinear crystal is collimated and then injected into a 50 m long optical fiber, with a 4.3 µm core radius. At the output of the fiber, the beam is collimated and sent to a diffraction grating.

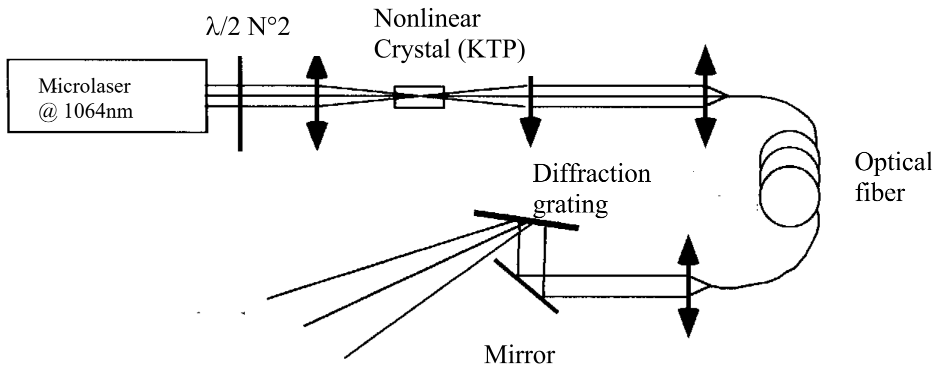



Figure 5: Experimental set up for the observation of the Raman scattering effect in an optical fiber.

**Question 15**: Calculate the theoretical wavelength of the 6 first Stokes orders. Are your experimental observations in agreement with your theoretical estimations?

## Appendix: Key notions to understand the labwork

This document summarizes the key notions to understand the frequency doubling labwork.

**Non-linear response:**
The total polarization radiated by a media in the presence of an electric field E can be written as a polynomial:

$$\boldsymbol{P} = \varepsilon_0[\chi^{(1)}\boldsymbol{E} + \chi^{(2)}\boldsymbol{E^2} + \chi^{(3)}\boldsymbol{E^3} + \chi^{(4)}\boldsymbol{E^4} + \cdots]$$

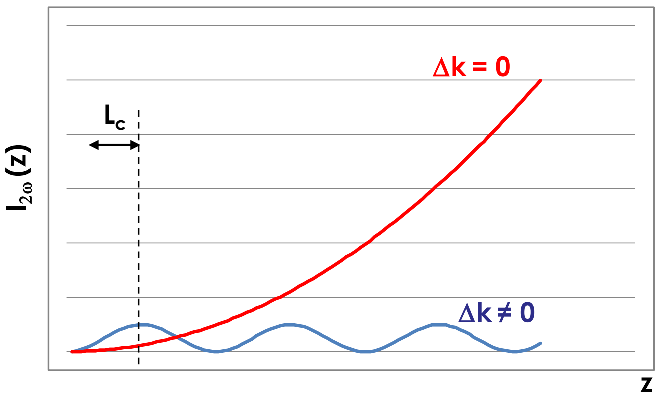
$\chi^{(n)}$ is the $n^{th}$ order non-linear susceptibility. The first term corresponds to a linear response and the next ones to non-linear responses of $2^{nd}$, $3^{rd}$, $4^{th}$… order. In practice, non-linear responses are usually very weak and can only be observed for very large field amplitudes.

**Phase matching: a requirement to be able to observe frequency doubling**
A beam at a given fundamental frequency will induce local non-linear responses at each point along its propagation axis. These microscopic non-linear responses will add up to form a macroscopic response. Phase matching correspond to a situation in which all contributions will add up coherently (in phase). Away from the phase matching condition, microscopic contributions will mostly interfere destructively and the resulting macroscopic field is generally extremely weak.
The phase matching condition can be written: $\Delta k = 2k_\omega - k_{2\omega} = 0$

Intensity at 2ω $I_{2\omega}$ depending on the intensity at ω $I_\omega$, the crystal length L and the phase mismatch Δk in low efficiency regime (or pump non-depletion hypothesis aka weak interaction regime) :

$$I_{2\omega} \propto \left|\chi^{(2)}_{eff}\right|^2 I_\omega^2 L^2 \left(\frac{\sin(\Delta k L/2)}{\Delta k L/2}\right)^2$$

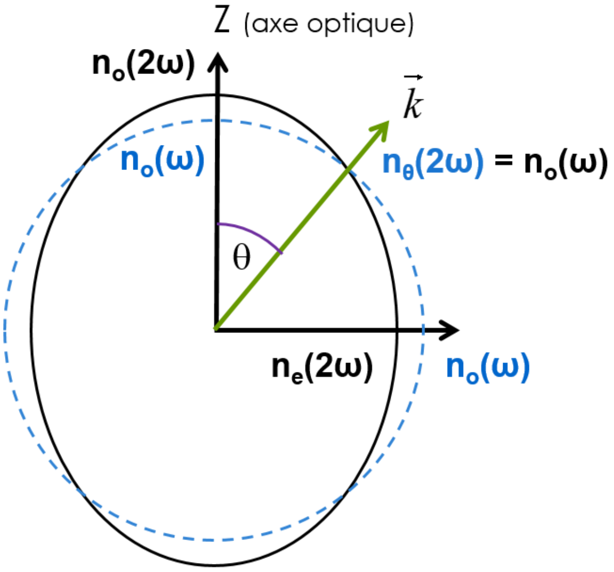
$\chi_{eff}$ is the effective non-linear susceptibility which depends on the non-linear media and experimental conditions. It is one of the parameter which can be tuned to optimize the conversion efficiency but its calculation is not done during this labwork.




*Intensity at 2ω along the propagation direction z in case of phase matching (Δk = 0) and in case of phase mismatch (Δk≠0). $L_c$=π/Δk is the coherence length.*

Phase matching conditions can be met when optical indexes at ω and 2ω are equals. This situation can be obtained using birefringent crystals offering more flexibility than isotropic materials.

For a uniaxial crystal, the optical index for an ordinary wave is $n_o$ whereas for the extraordinary wave the optical index $n_\theta$ is between $n_o$ and $n_e$ depending on the angle between the crystal optical axis and the propagation axis. $n_e$ is called main extraordinary index and does not depend of θ.




$$\frac{1}{n_\theta^2} = \frac{\cos^2\theta}{n_o^2} + \frac{\sin^2\theta}{n_e^2}$$

*Left: Optical indexes surfaces at ω and 2ω for a uniaxial crystal. Right: Extraordinary index as a function of the direction of propagation.*

In practice, we choose θ by changing the crystal cut orientation in order to observe phase matching at normal incidence.

## Doublage de type I ou II

| | **Type I** | **Type II** |
|---|---|---|
| Polarization direction | Notation : o + o -> e **or** e + e -> o<br>In practice: Fundamental and frequency doubled fields are polarized perpendicularly | Notation : e + o -> o ou o + e -> o **or** e + o -> e **or** e + o -> e<br>In practice: Fundamental and frequency doubled fields are polarized at 45° |
| Relation between optical indexes | $n_o(2\omega) = n_\theta(\omega)$<br>***ou***<br>$n_\theta(2\omega) = n_o(\omega)$ | $n_o(2\omega) = (n_o(\omega) + n_\theta(\omega))/2$<br>***ou***<br>$n_\theta(2\omega) = (n_o(\omega) + n_\theta(\omega))/2$ |
| The intensity at 2ω is proportional to: | $A_o^2$ *ou* $A_\theta^2$ | $A_oA_\theta$ |

# Optical fiber amplifier and oscillator

## 2019-2020

### Report

After the labwork, you will write a report of maximum 2 pages. The subject will be indicated at the end of the labwork

### <u>Remarks</u>

***-Questions are given in order to help students in their research work. The report is not supposed to be a list of question answers. A work of synthesis is consequently asked.***
***-Each experimental results is interesting and thus need to be commented (comparison with theory, derivations of order of magnitudes or important characteristics).***

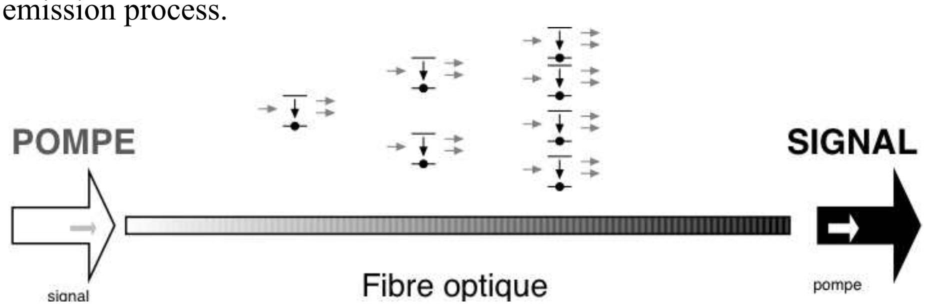
**PRELIMINARY WORK**

Make sure you understand the following notions:

- Laser amplification in a 3 levels media
- Homogeneous and inhomogeneous spectral broadening
- Absorption and gain saturation

# 1. Introduction

The general principle of optical amplifiers relies on the phenomenon of stimulated emission. The optical signal propagates in a gain medium. For **EDFAs (Erbium-Doped Fiber Amplifier)**, gain is obtained by population inversion of the active ions (erbium) that have been included in the fiber core. These ions have to feature a radiative transition in the wavelength range of the injected signal, which is at 1550 nm in this first part. The population inversion is obtained through optical pumping by an external laser source. The increase of the signal intensity is the result of an energy transfer from the pump to the signal through a stimulated emission process.




Let us recall that the emitted photons possess the same phase, polarization and wavevector as the incident photons. This is different from spontaneously emitted photons that have no relationship with the signal. They will therefore form an optical noise at the output of the amplifier. This noise intensity increases with the fiber length: the noise photons can also be amplified through stimulated emission. This phenomenon is called Amplified Spontaneous Emission (ASE) noise. This ASE noise is the limiting factor in many optical transmission systems.

The EDFA is the most common optical amplifier because of its use in optical fiber telecommunications networks. The gain of the erbium ion is several tens of nm wide and centered around 1550 nm, a wavelength at which the losses of optical fibers are the lowest.

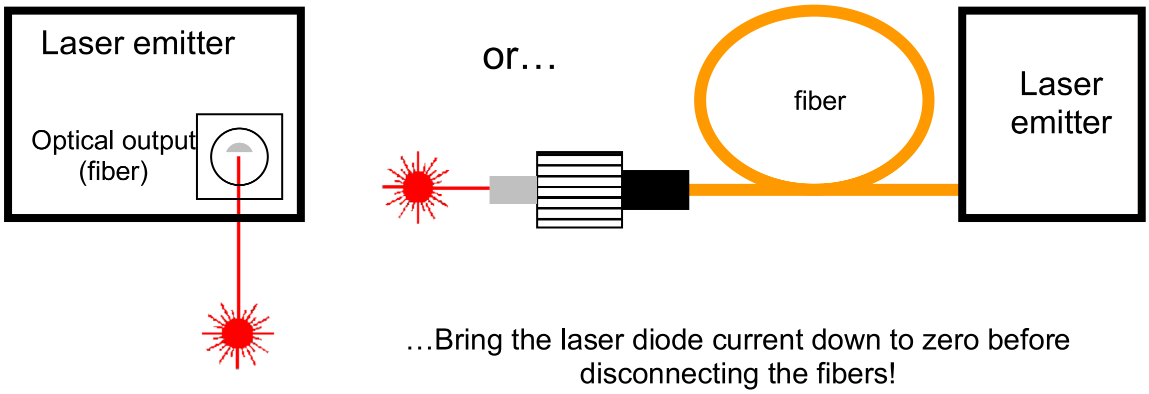
This labwork is divided in two parts:
- First, the study of the principle and characteristics of an EDFA at 1550 nm.
- Second, the study of two different Erbium doped fiber lasers.

## EYE SAFETY

2 types of CW fiber lasers

60 mW @ *980* nm

10 mW @ *1550* nm

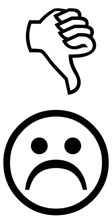



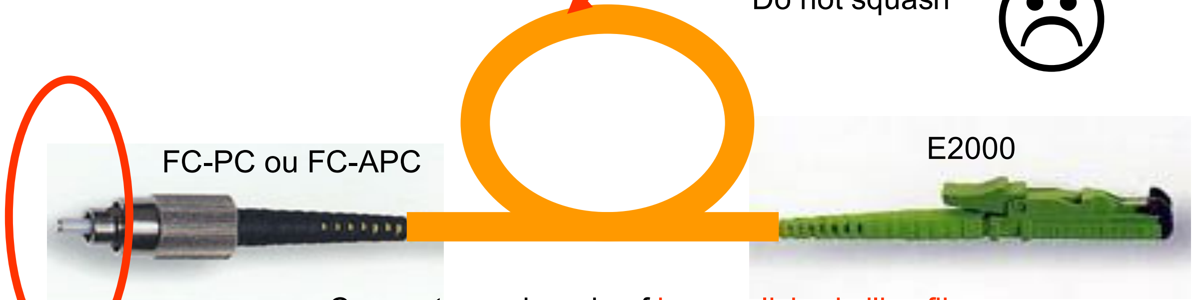

…Bring the laser diode current down to zero before disconnecting the fibers!

## FIBER MANIPULATION

Reinforced protection sleeve **but…**

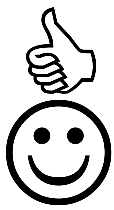
- Do not tie in a knot
- Do not squash






Connector end made of bare polished silica fiber:

- Handle with care during (dis)connections
- Protect with a cap when not connected



# 2. Study of the EDFA

We will first assemble and characterize an EDFA after preliminary measurements of:

– Spontaneous emission spectra and amplified spontaneous emission spectra,
– Amplifier gain as a function of pump power and input signal power (study of the saturation phenomena)

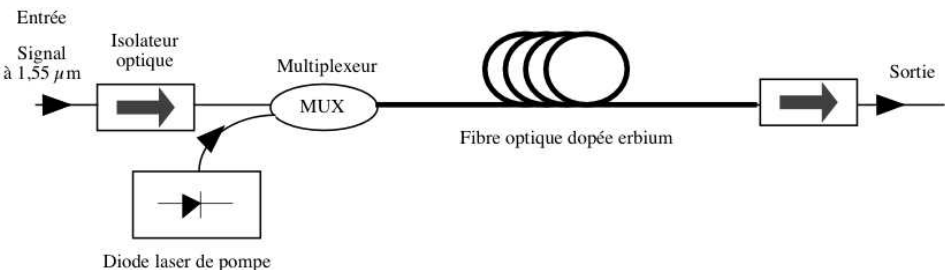
### *Description of the optical components and equipment*

The available equipment, described below, will allow you to make the required measurements:

– The EDFA kit is made of separate modules that can be interconnected using fiber-optic patchcords;
– A powermeter calibrated at 980 nm and 1.55 µm;
– An optical spectrum analyzer: This equipment is a monochromator with a rotating grating, and a user-friendly interface. It allows the measurement of spectra in the wavelength range 600 nm – 1750 nm, with a resolution of 0.07 nm, and a good detection dynamic range (80 dB). You can save the recorded spectra, as ASCII text arrays ($\lambda_i$, $P(\lambda_i)$) or as screen image files (bmp).
– A variable optical attenuator.
– A wavelength-tunable laser source (1500 nm to 1600 nm, brand Photonetics « TUNICS »).

### *Setup and characterization of the EDFA kit*

The typical structure of an EDFA is as follows: the gain medium is an erbium-doped fiber. The pump wave (delivered by the 980 nm laser diode module included in the kit) and the signal wave are propagating together in the active fiber. The pump wave creates a population inversion, thereby allowing the amplification of the signal. The figure below is a sketch of a co-propagating EDFA configuration.




**Erbium-doped fiber**

The main characteristics of the doped fiber are:

- Core diameter 2a = 2,9 µm,
- Cutoff wavelength $\lambda_c$ = 900 nm,
- Erbium ion concentration: around 400 ppm,
- Length = 20 m.

You will find in the appendix a brief description of spectroscopic properties of the erbium ion.

**Pump module**

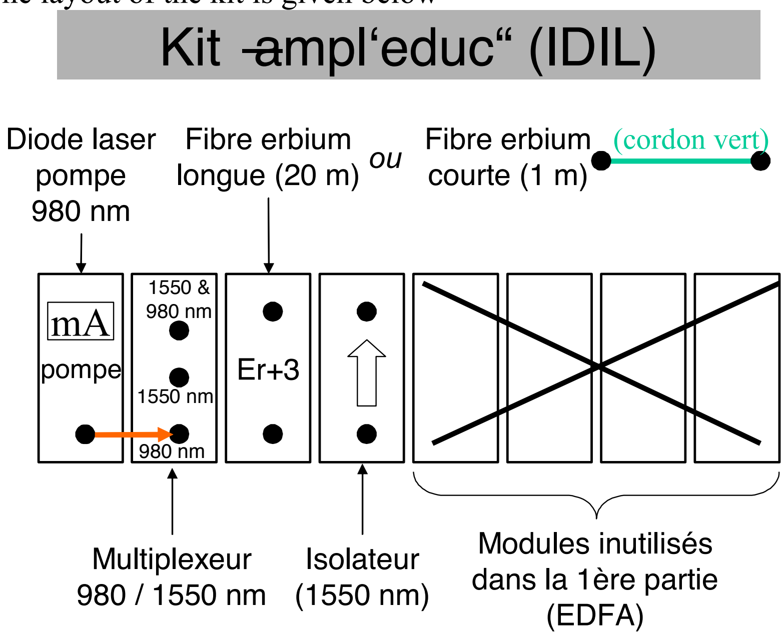
The second advantage of the erbium ion, besides the existence of transitions around 1550 nm, is the presence of absorption bands around 980 nm and 1480 nm, which permits the use of laser diode pumps. This results in compact and power-efficient systems, at a rather low cost.

The issues of pump laser diode are the available power, and the spatial quality of the beam to allow a good coupling in the monomode fiber. Diodes are fiber-pigtailed. Their temperature is regulated through a Peltier element that is integrated in the module, to stabilize the optical spectrum. The technical specifications of the pump diode are as follows:

- Maximum power $P_{pump} \approx 60$ mW,
- Wavelength $\lambda_p = 980$ nm.

**Multiplexer** (« MUX » in the amplifier setup)
The multiplexer (or pump combiner) is a passive fiber element that allows the coupling of two signal at different wavelengths coming from distinct fibers in the same fiber. You will use it to combine the signal and pump in the doped fiber. When reversed (demultiplexer, « DEMUX »), this component can separate the two wavelengths in the two output fibers

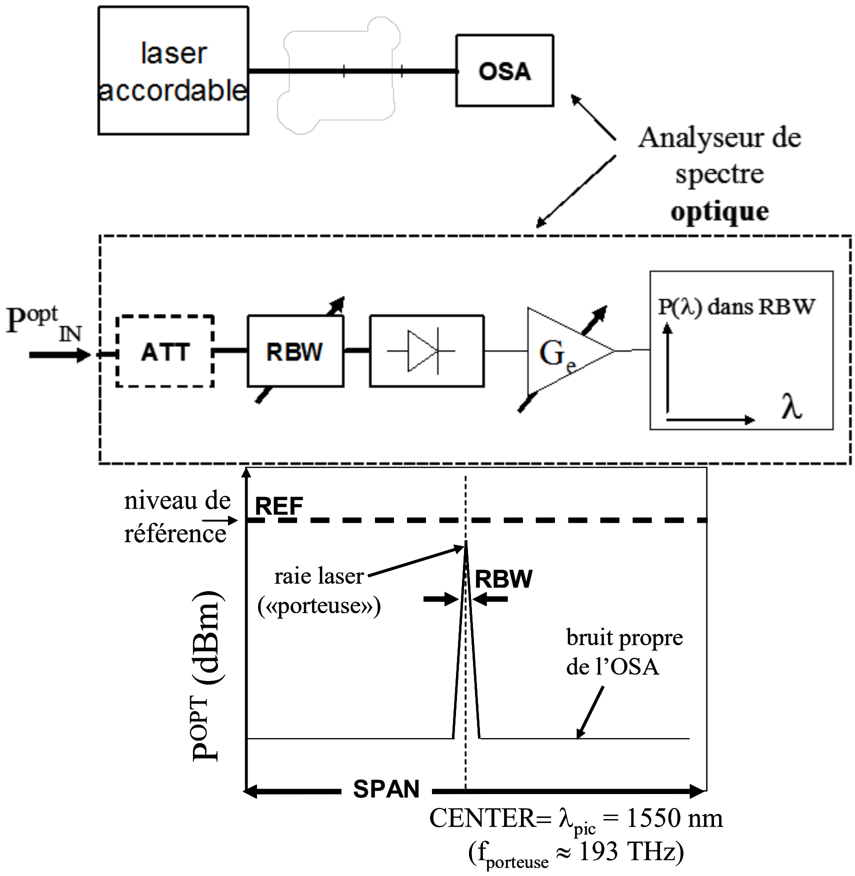
**Source: signal laser diode**
Instead of the DFB (Distributed FeedBack) laser diode included in the kit, we will use the tunable (from 1500 nm to 1600 nm) source « TUNICS », which specifications are given in the appendix. Its output power and side-mode suppression ratio are comparable with the DFB. The main interest resides in the fact that it will allow us to measure the gain as a function of wavelength. The layout of the kit is given below




*Les éléments fibrés sont dans les modules du kit*
*Seuls sont représentés les connecteurs d'entrée ou de sortie*
*La pompe doit IMPERATIVEMENT rester reliée à l'entrée [980 nm] du MUX*
*(ne pas déconnecter le cordon orange)*

### *Preliminary experiment: measurement of optical spectra*

The preliminary experiment will make you familiar with the optical spectrum analyzer (OSA). The tunable laser (TUNICS) is set at 1550 nm, and fed to the OSA through the optical attenuator (ATT1), as shown below.




The principle is also recalled above. A tunable bandpass optical filter with a width given by RBW (Resolution BandWidth) is scanning periodically a wavelength range given by SPAN. The filter is followed by a high sensitivity photodetector and high dynamic range electrical amplifier. The optical attenuator is used when the input optical power exceeds the maximum optical power (10 dBm, i.e. 10 mW).

The display of the OSA shows the power in the bandwidth RBW as a function of λ, denoted $P(\lambda)_{RBW}$. The RBW is therefore the Full Width at Half Maximum of the peak displayed by the OSA when a monochromatic signal is analyzed (The external-cavity laser diodes used here have a linewidth of ≈100 kHz, corresponding to 1 fm at 1550 nm).

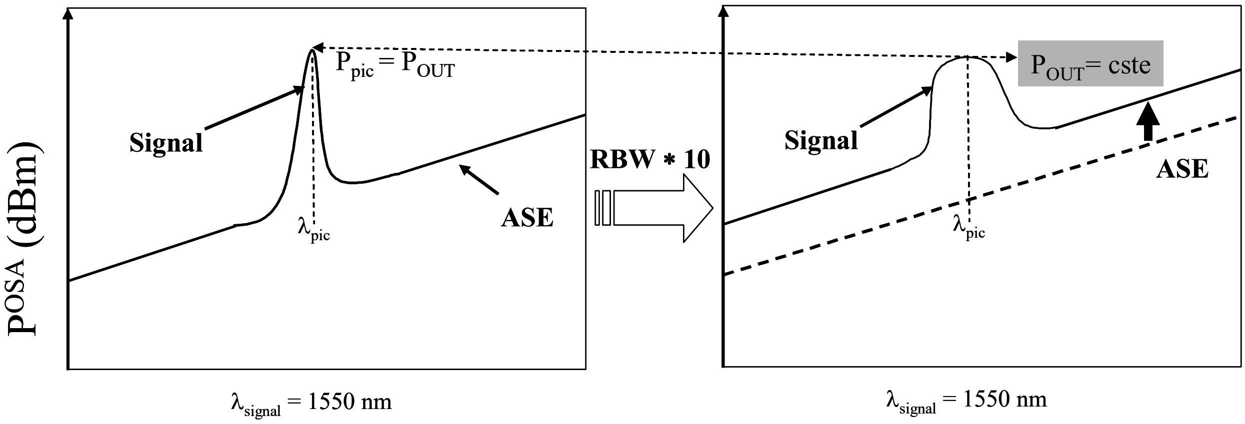
The choice of the reference level (REF or Ref Level) is also important to display correctly the measurement. It defines the power level 2 divisions below the upper side of the display. By adjusting it, the spectra can be shifted vertically to fully display it. Finally, another parameter is important to display properly the measured spectra: the video bandwidth (VBW). Its value can be set automatically, but you can adjust it at an inferior value to lower the noise. This will also make the measurement slower.

Connect the output of the tunable laser directly to the OSA to observe both the laser peak and the noise floor due to the amplified spontaneous emission. The sensitivity of the spectrum analyzer can be modified in the "Sensitivity" menu. It is particularly important when it comes to measure low power.
Then, measure the spectrum of this signal with the following parameters:
- center wavelength (CENTER) 1550 nm
- SPAN : 50 nm, center the spectrum and reduce the span to 5 nm
- RBW : 0.1 nm
- REF : 0 dBm.

These 4 current values are displayed in the bottom left part of the screen. Then, use the PEAK SEARCH function and MARKER TO CENTER to pinpoint and follow the peak at the center of the display.

On the optical spectrum of this emitter, check, observe, explain the influence of the various settings of the OSA (REF, SPAN and above all RBW) and also the calibration of the optical attenuator ATT1.

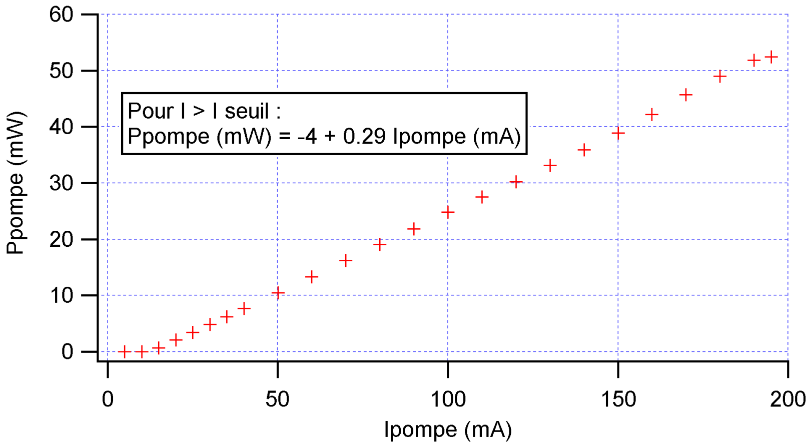
**Q1. In particular, change BW from 0.1 nm to 1 nm. Measure the peak and the background levels in both configurations using the cursors ('Marker' menu). Explain the influence of the resolution on the peak width. Explain how the peak level $P_{OUT}$ (peak) and the background level P (background) of the spectrum change with the Resolution BandWidth? <u>Explain very clearly this important point</u>.**




### *Pump laser characteristics*

| |
|---|
| **Never disconnect the orange patchcord** connecting the diode to the multiplexer. |

Below is the curve representing the optical power versus applied current for the pump diode P(I) (along with a typical emission spectrum): **you only have to adjust the current by rotating the control of the pump diode to know the power injected in the doped fiber.**




Observe the pump diode spectrum directly at the output of the multiplexer (MUX) for a pump current of 30 mA (**in order not to go beyond the maximum input power of the OSA which is 10 mW**).

**Q2. Compare qualitatively the spectrum emitted by the pump laser diode at 980 nm to the spectrum of the signal laser diode at 1550 nm.**

### *Fluorescence curve of the Er3+-doped fiber*

It is easy to observe the presence of radiative transitions of the erbium ion around 1550 nm. To do so, we will measure a fluorescence spectrum of the short doped fiber (one meter long green fiber, as opposed to the 20 m fiber included in the kit), in the presence of a pump beam. Connect the output of the MUX to one end of the short doped fiber, and connect the other end to the spectrum analyzer (you will need to use a fiber connectorized with E2000 and FC/APC connectors)
Display the spectrum in linear scale ('Level scale'->'Linear level') and adjust the reference level using the Peak->Ref level button.

**Q3. Measure the fluorescence spectrum between 1500 nm and 1600 nm, for a 50 mA pump current (verify that, for this current, the pump power is below 10 mW). Comment. Explain why, in this experiment, a short fiber must be used. Suggest a more rigorous fluorescence spectrum measurement.**

### *Amplified spontaneous emission spectrum (ASE)*

**Q4. Repeat the same measurement using the long fiber in the EDFA kit. Keeping the pump power constant, compare the obtained spectrum with the short and long fibers.
In order to display two spectrum at the same time, use the TRACE mode (measure the first ASE spectrum in Trace A, then switch to Trace B ON).**

This fiber is around 20 m long: the attenuation of the pump beam is sufficient to use it at full power (200 mA).

**Q5. Acquire the spectra between 1500 nm and 1600 nm for various pump powers. You can operate the pump diode at full power due to the high attenuation of the long fiber. Comment and interpret the results. Use the energy levels of the erbium ion, and small-signal gain as a function of population inversion given in the appendix.**

### *Gain measurements*

In this section, the goal is to study the influence of pump and signal power on the amplification of the signal in the Erbium doped amplifier. The different measurements of the gain will be performed **using the Optical Spectrum Analyzer (OSA)** using 'Peak search' or the cursors ('Marker' menu)**.**

If the output signal power is denoted $P_{OUT}$ and $P_{IN}$ the "signal" power at the input of the amplifier, the gain is defined by:

$$G = \frac{P_{OUT} - P_{ASE}}{P_{IN}} \approx \frac{P_{OUT}}{P_{IN}} \quad soit\ G_{[dB]} \approx P_{OUT[dBm]} - P_{IN[dBm]} \text{ si } P_{OUT} >> P_{ASE} \,.$$

1st IMPORTANT remark: You can save a lot of (dis)connections by measuring once for all the input signal power $P_{IN}$ for a given attenuation value (e.g. 0 dB). Then you can modify the attenuation level to change the injected signal power $P_{IN} = P_{IN}(0dB)$ - $\text{attenuation}_{dB}$.

2nd remark: One can measure the signal power $P_{IN}$ to the EDFA either at the input or output of the multiplexer. It is more appropriate to measure it at the input of the MUX, since the multiplexer is part of the EDFA. The measured gain will therefore take into account the insertion loss of the multiplexer.

#### 2.7.1 *Adjust the input signal power to $P_{IN}$=-20 dBm. Measurement of the gain as a function of $P_{pump}$*

**Q6. For input signal power $P_{IN}$=-20 dBm, plot the evolution of the amplifier gain (in dB) as a function of injected pump power (in W). Interpret the observed saturation phenomenon.**

#### 2.7.2 *Measurement of the gain as a function of $P_{IN}$*

**Q7. At maximum pump power, plot the evolution of amplifier gain (in dB) as a function of input signal power $P_{IN}$ (in dBm) for an input power ranging between -45 dBm and 0 dBm. Comment. Explain why this phenomenon is different from the one observed in the previous question?**

**Q8. Observe the ASE level versus $P_{IN}$. Comment. Explain clearly the evolution of the ASE level. What does it imply in terms of gain broadening in the fiber?**

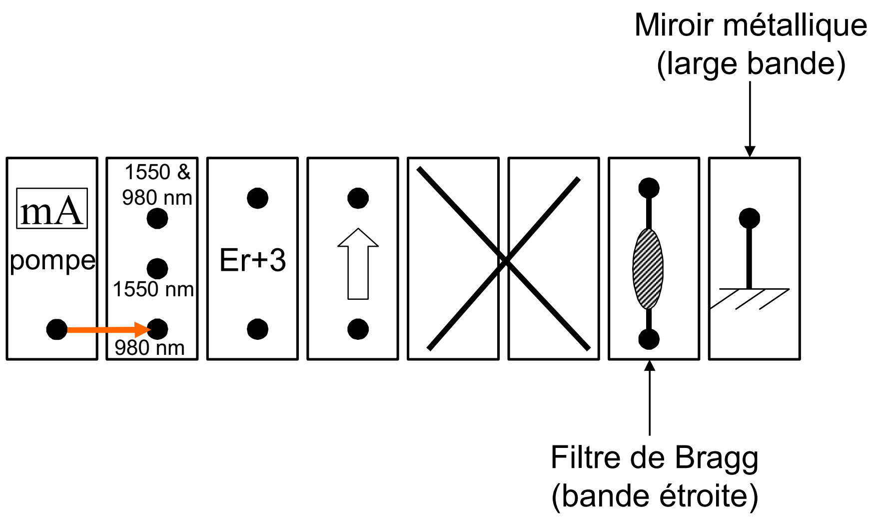
#### 2.7.3 *Study of the parasitic cavity effect*

**Q9. Assuming a parasitic reflexion air/silica (R ~= 4%) at each facet of the erbium-doped fiber, calculate the minimum gain necessary to ensure a laser effect inside the cavity formed by the two end-facet of the fiber. Comment about the result.**

**Q10. What could be the drawback(s) of such a parasitic laser effect on the amplifier gain? Suggest one (or more) solution to counteract this effect (help: look for the characteristics of connectors FC/PC or FC/APC).**

# 3. Fiber laser

## *3.1. Preliminary experiment: transmission curve of the Bragg filter*



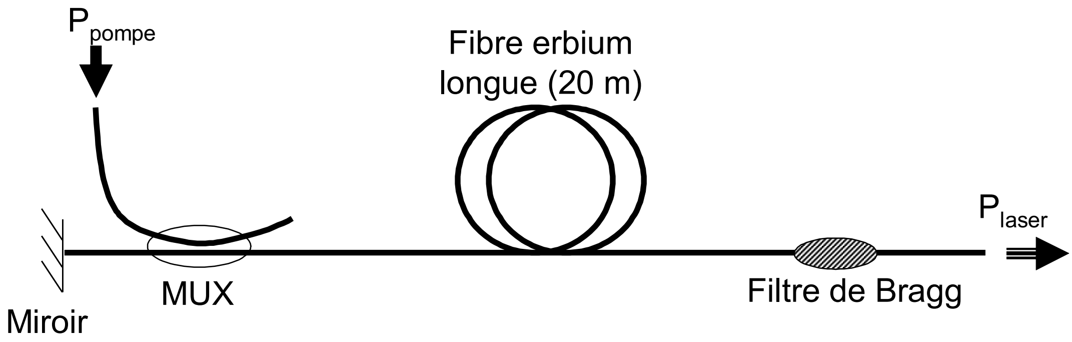
To characterize the transmission of the Bragg filter (which is equivalent to a narrow bandwidth mirror), use the broadband ASE light (without signal!):

- Memorize the ASE spectrum at the input of the filter in Trace A.
- Switch to Trace B. Measure the output of the filter using the OSA

**Determine the central wavelength and bandwidth of the filter.**

### *3.2. Linear cavity laser*

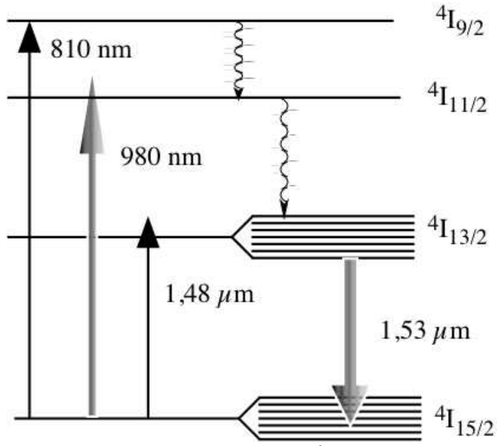
Make the following setup



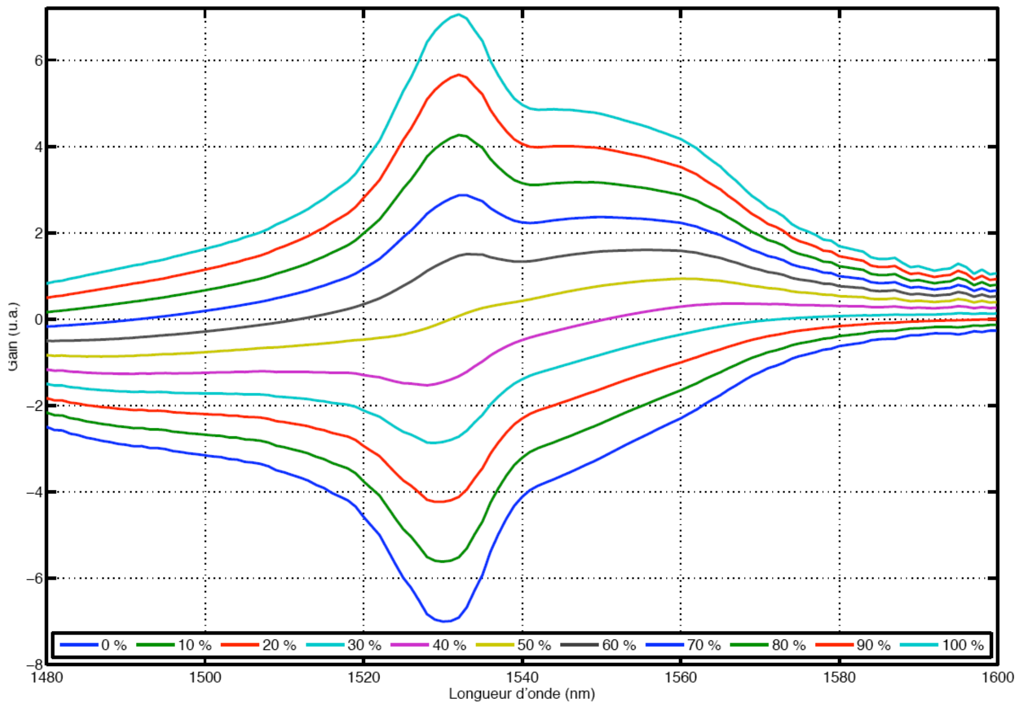

**For a given operating point, record a spectrum with a large and small wavelength range (e.g. SPAN =50 nm and RBW=1 nm, then SPAN =5 nm et RBW=0.1 nm).**

**Appendix:** Spectroscopic properties of the erbium ion

The erbium element belongs to the rare-earth family (Lanthanides) which are very often used to dope solid-state materials and used as gain media in lasers. Other rare-earths include: neodymium, praseodymium, thulium, holmium. Rare-earth ions possess numerous radiative transitions in the visible and near infrared [4]. The major interest of erbium is the presence of such transitions in the 1550 nm range, as shown by the energy levels sketched below




*Energy diagram of the $Er^{3+}$ ion in glass*




*Small-signal gain versus wavelength for different population inversions*

The main absorption band are around 810 nm ($^4I_{15/2} \rightarrow {}^4I_{9/2}$), 980 nm ($^4I_{15/2} \rightarrow {}^4I_{11/2}$ ) and 1,48 µm ($^4I_{15/2} \rightarrow {}^4I_{13/2}$ ). The transition around 1.55 µm takes place between the levels $^4I_{13/2}$ and $^4I_{15/2}$. The $^4I_{13/2}$ level is split into multiple sublevels [6]. Optical pumping at 1.48 µm is possible because the absorption cross-section is greater than the emission cross-section. The lifetime of the metastable level $^4I_{13/2}$, in silica, is on the order of 10 ms. The emission cross-section at 1,53 µm (central wavelength of the emission spectrum) is $8.1.10^{-21}cm^2$. The absorption cross-section at 980 nm is $2.4.10^{-21}cm^2$. The transitions $^4I_{9/2} \rightarrow {}^4I_{11/2}$ and $^4I_{11/2} \rightarrow {}^4I_{13/2}$ are non-radiative, and will be considered to be much faster than the lifetime of the level $^4I_{13/2}$.