Labwork in photonics

Lasers

Engineer - 2nd year - S7 - Palaiseau
Version : July 14, 2017
Year 2017-2018

Règles de fonctionnement du LEnsE

Absences

La présence des étudiant·e·s à toutes les séances de travaux pratiques prévues à l'emploi du temps est obligatoire et impérative. En cas de difficulté majeure, **si un membre d'un binôme est toutefois absent, l'autre doit venir à la séance et faire le TP**. Et, en Optique, chacun des membres du binôme rendra un compte-rendu individuel.

Absence excusée. Justificatif Le justificatif d'absence doit être déposé au secrétariat, les élèves concerné·e·s doivent aussi prévenir directement les responsables du LEnsE du motif de l'absence (à l'avance, si l'absence est prévisible).

Absence excusée. Rattrapage L'élève doit impérativement prendre contact avec les enseignant·e·s de TP pour étudier la possibilité de rattrapage (suivant la disponibilité des enseignant·e·s, du matériel et des salles). L'élève rattrape alors le TP et :

- **En optique,** l'élève rédige un CR qui sera noté. S'il n'est pas possible de trouver une date de rattrapage suite à une impossibilité du service des TP, le TP ne sera ni rattrapé ni noté (la moyenne sera faite sur les notes restantes). Ce TP restera néanmoins au programme de l'examen et l'étudiant·e pourra être interrogé·e sur ce TP lors de l'examen de TP.
- **En ETI et ProTIS,** la synthèse du thème concerné, rédigée par le binôme, devra contenir des résultats des deux séances individuelles (la séance normale et celle de rattrapage).

Si l'élève refuse la date de rattrapage proposée, il ou elle sera considéré·e comme absent·e non excusé·e.

Absence non excusée Toute absence non justifiée entraîne :

En optique, un zéro pour la séance et l'impossibilité de travailler sur ce TP avant la période de révision. En cas d'absences répétées, le responsable d'année interdira à l'étudiant·e de passer l'examen en fin d'année.

En ETI et ProTIS, un zéro pour la note de synthèse concernée.

Retards

Aucun retard n'est acceptable et en cas de retard important (ou de retards fréquents) d'un·e étudiant·e, celui-ci ou celle-ci se verra refuser l'accès au laboratoire. Les conséquences en seront identiques à celles d'une absence non excusée (voir plus haut).

Plagiats

Le plagiat est le fait de s'approprier un texte ou partie de texte, image, photo, données... réalisé par quelqu'un d'autre sans préciser qu'il ne s'agit pas de son travail personnel. On plagie quand on ne cite pas l'auteur des sources que l'on utilise. Exemples de plagiat :

- Copier textuellement un passage d'un livre ou d'une page Web sans le mettre entre guillemets et/ou sans en mentionner la source.
- Insérer dans un travail des images, des graphiques provenant de sources externes (hors énoncé du TP) sans en indiquer la provenance.
- Utiliser le travail d'un·e autre élève et le présenter comme le sien (et ce, même si cette personne a donné son accord !).
- Résumer l'idée originale d'un auteur en l'exprimant dans ses propres mots, mais en omettant d'en indiquer la source.
- Traduire partiellement ou totalement un texte sans en mentionner la provenance.

Tout binôme convaincu de plagiat dans un compte-rendu ou une synthèse de TP se verra attribuer la note de 0/20 à ce TP ou cette synthèse et encourt les sanctions disciplinaires prévues au règlement intérieur.

Respect du matériel et des locaux

Le LEnsE met à votre disposition une très grande quantité de matériel scientifique.

Ces matériels sont très fragiles, sensibles à la poussière, aux traces de doigts, aux rayures, etc. Merci d'en prendre le plus grand soin.
Il est donc formellement interdit d'apporter de la nourriture ou des boissons dans l'ensemble du service (couloirs compris). Merci de veiller aussi à laisser les locaux particulièrement propres (si vos chaussures sont sales, retirez-les et laissez-les à l'entrée !)

Pour toute demande d'accès en dehors des séances de TP, vous devez impérativement (et à l'avance) vous adresser au responsable technique du LEnsE, Thierry AVIGNON ou à Cédric LEJEUNE (bureau S1.18).

INSTITUT D'OPTIQUE GRADUATE SCHOOL

Diode pumped Nd:YAG LASER

2017-2018

Oral presentation

During the session, you will prepare an oral presentation (5 min) about your results and observations on questions 4 to 8.

Preliminary questions (answer them before the session)

P1 Explain what the term "spontaneous emission". Define the lifetime of the upper level in a laser transition.

P2 Recall the concept of geometric stability of a laser cavity. For a cavity composed of a plane mirror and a concave mirror with radius of curvature R, what is the stability condition?

P3 Describe how the passive losses of the cavity can be evaluated from the laser threshold and the slope efficiency measured for two different output couplers.

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.

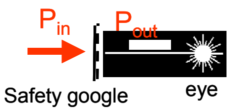
During this labwork, we are going to study a laser using a YAG (yttrium aluminium garnet) crystal doped with neodymium ions as active medium. Historically, the Nd:YAG laser is one of the first diode-pumped solid-state laser that have been demonstrated. Nowadays, it is the basis of numerous commercial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

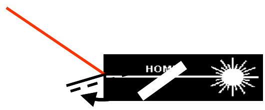
type	A	B	C
λ cut-off (nm)	1064	1064	1064
		980	980
		808	808
	532		532
		355	355

Laser diode pumped Nd:YAG laser
USER EYE SAFETY

Pump laser diode (CW) ~1000 mW @ *808* nm

Nd:YAG* Laser (CW or pulsed) ~100 mW @ *1064* nm

class 3B :
Risk of retina damage and burning
⇒ safety googles are mandatory



(*if frequency doubled: <1 mW @ *532* nm)

+ caution:
- never face the beam.
- (= do not bend over at the level of the breadboard)
- turn back to the laser when writing
- get rid of reflective objects (watch, jewelry)
- **bring back the intensity of the laser diode to 0 before any modification of the optical set-up**

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 must not be unplugged.

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

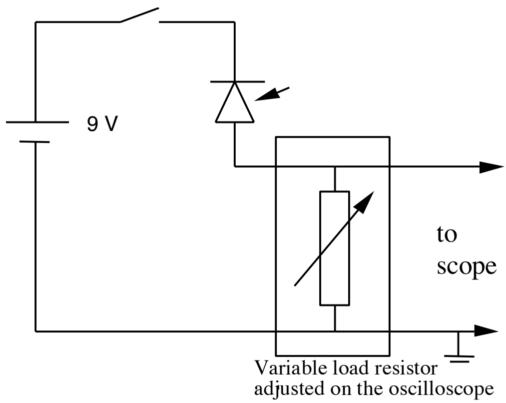
All the elements of the laser are fragile, especially the mirrors: handle them very carefully.

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.

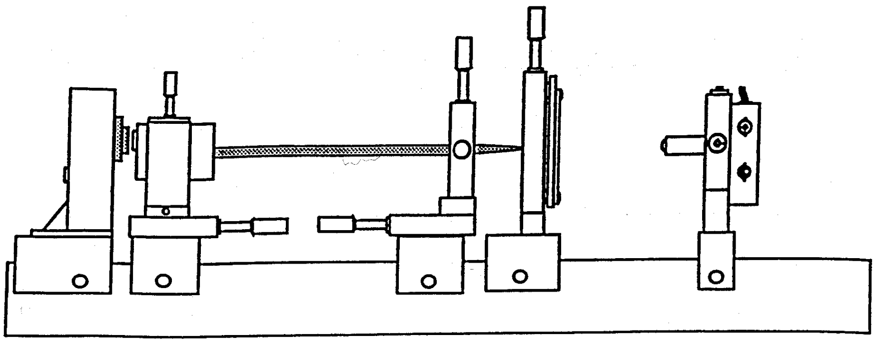
I. Characteristics of the pump

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

The experimental setup is shown in Fig 1.

The 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.

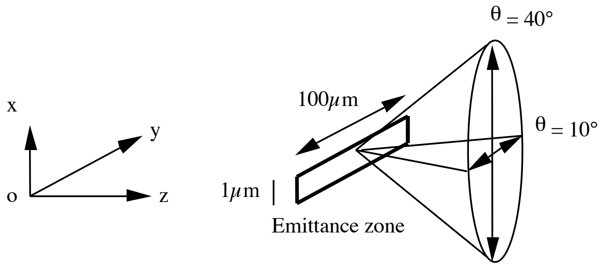


Fig 2a: Emission diagram of the pump diode

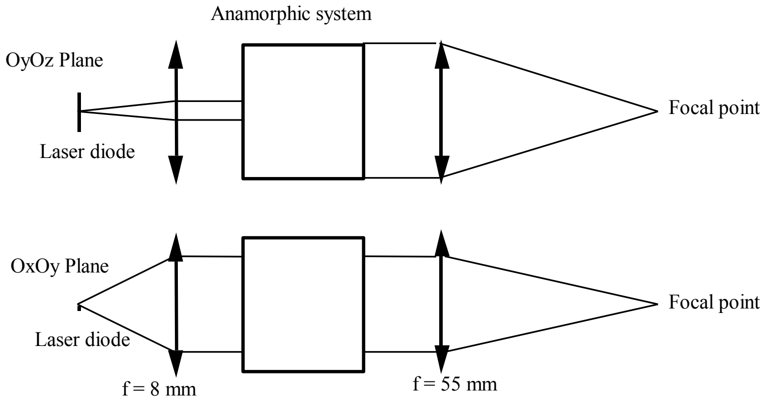


Fig 2b: Layout of the optical pump system.

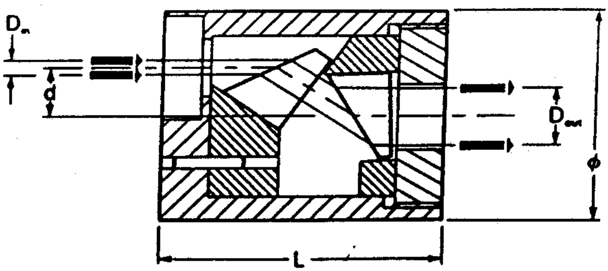


Fig 2c: Schematic of the anamorphic system ($D_{out}/D_{in} = 6$).

Q1. Calculate the pump beam sizes and divergences in the crystal, in the planes OyOz and OxOy.

- 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.

I.2. Absorption optimisation

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 casing.

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.

Q2. « 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)".

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

Q3. Measure the pump power transmitted by the Nd:YAG rod for a pump current of 1A, and deduce the pump absorption. Estimate the Nd3+ doping concentration inside the cristal from your measurement and the data below.

Crystal length	5 mm
Absorption cross-section at 808 nm	$7\ 10^{-20}$ cm^2
Nd3+ volumic density for a 1% doped crystal	$1{,}36\ 10^{20}$ atomes/cm^3

Data on the laser crystal

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

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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).

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

Lower the pump current to minimum.

First, adjust the low-frequency generator: it should deliver a positive square signal of 0-4V (max) of frequency below 500Hz. 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.

Oral

Prepare a short (5min) oral presentation summarizing your answers of the questions 4-8 concerning the measurement of the fluorescence lifetime:

Q4. What is the purpose of the RG1000 filter?
Observe and copy the signal obtained across the load resistor with the scope. Adjust its value to "optimize" the signal.

Q5. 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.
Note: The total capacitance of the system (photodiode+cable+scope) is about 250pF

Q6. 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.

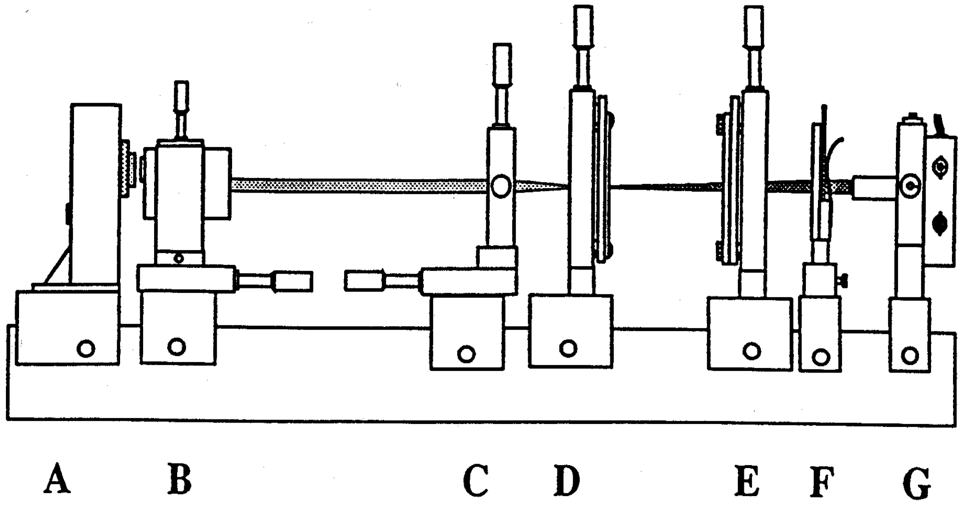
Q7. Why is the Nd:YAG an excellent candidate to build a laser?

Q8. Remove the RG1000 filter. Interpret the observed signal.

III. Laser effect at 1.06μm

Lower the diode supply current, then insert into the setup, the cavity output mirror with a reflectivity Rmax = 99.95% 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 on 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.

Align the cavity to obtain a TEM_{00} mode. Then, optimise it to increase the laser output power.

Q9. Measure the laser output power for pump currents from 0.3 to 1 A by 0.1 A steps. By using the curve obtained in Q2, plot the laser output power vs the pump power (do not forget the transmission of the RG1000 filter).

Q10. Reproduce the same type of measurement with mirror R = 97%. Deduct passive cavity losses from these two measurements by comparing the thresholds or the slopes of laser efficiency and assuming passive losses are identical.

Q11. Calculate and compare the following efficiencies for the laser with the mirror R = 97% reflectivity:

- **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 :YVO4 vs Nd :YAG

[Koechner : Solid-state laser engineering, Springer, 2013.]

IV. Q-Switch mode laser operation

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.

As 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. Increase the pump power and realign the cavity to recover laser operation (which should be visible with the Kodak cardboard). 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.

Alignment procedure: optimisation of the 1064 nm fluorescence.

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.

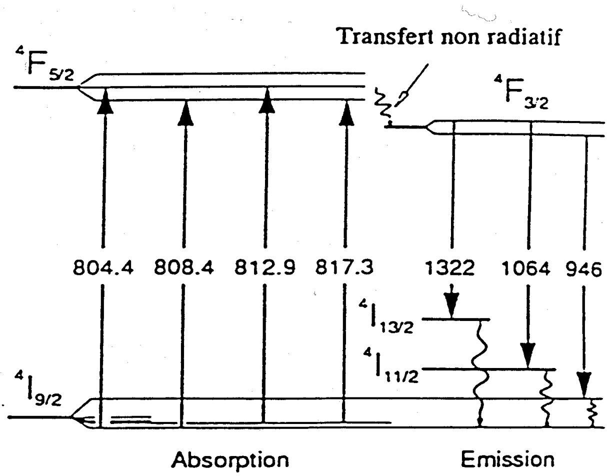
Q12. Recall briefly the working principle of a Q-switch laser. How does the saturable absorber work? How does it allow the emission of laser pulses?

Q13. Observe and plot the signal on the oscilloscope. Mention the load resistance used. Optimise the alignment of the cavity (average power, repetition rate) and justify your choices.

Q14. Determine the pulse energy and the peak power. Give the advantage of pulsed lasers compare to continuous lasers in terms of power.

APPENDIX:

Non-radiative transition



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

(figures in nm)

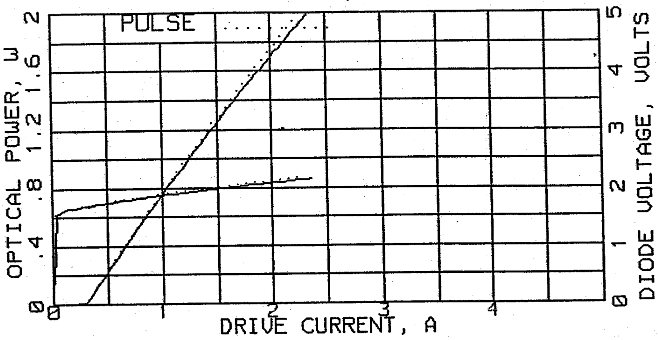
Wavelength (nm)	532	808	1064
RG1000 transmission	10^{-5}	10^{-4}	0,65

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



Laser Diode

2017-2018

Oral presentation

During the session, you will prepare an oral presentation (5 min) about your results and observations on questions 13 and 14.

PRELIMINARY QUESTIONS (answer them before the session)

P1 Explain, in one sentence, what the laser threshold is.

P2 In a laser cavity, compare the unsaturated gain, the saturated gain, and the cavity losses in three different situations: below threshold, precisely at threshold, above threshold.

P3 Give the characteristics of the spectrum of a single longitudinal mode laser source whose power or frequency (i.e. wavelength) is modulated. You can find help in the appendix 1.

P4 Recall the working principle of a spectrum analyzer Fabry-Perot (see TP HeNe 1A).

Goal of the labwork

The goal of this labwork is to highlight some properties that are specific to semiconductor lasers. The core of the experiment is to study various properties, such as emitted power and wavelength, as a function of temperature and operating current. In a second step, the analysis will be based on spectral properties of the semiconductor laser, and on high-frequency modulation characteristics. The studied laser diode emits a CW beam at $\lambda = 794$ nm. It is connected to a power supply and temperature controller.

A. Principles

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.

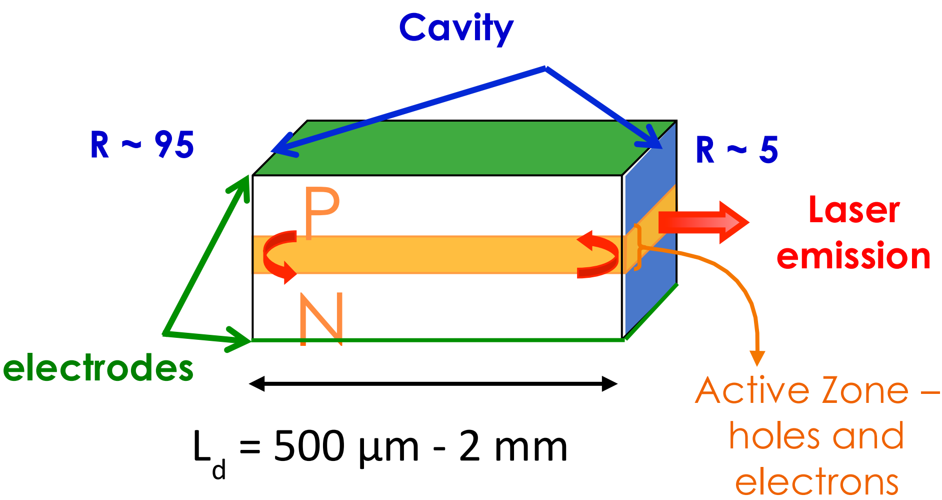


Figure 1: Diode laser structure.

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.

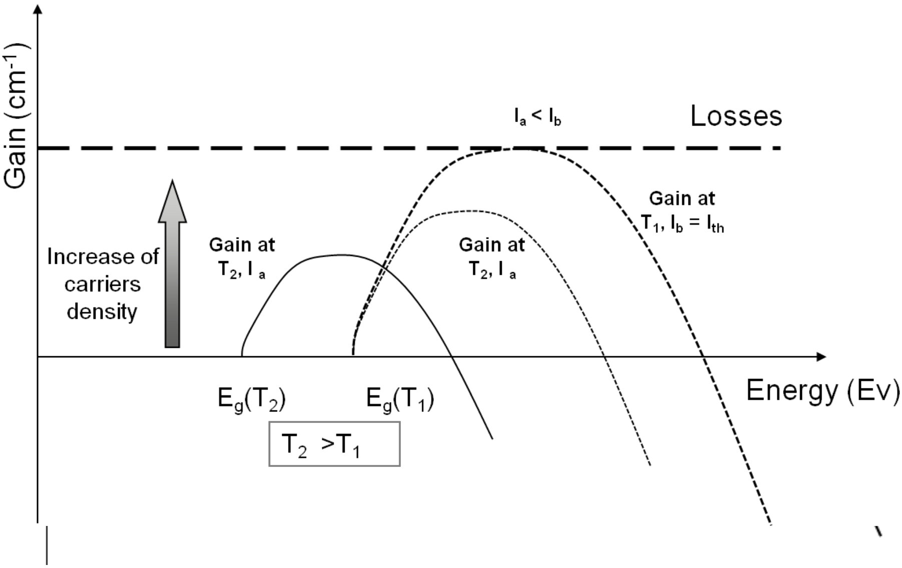


Figure 2: Gain evolution in a laser diode with respect
to the pump current I and temperature T.

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.

Another important characteristic of laser diodes is their capability to be modulated at high frequencies, which can be few GHz. This is exploited mainly in optical data transmission, but also in spectroscopy, for stabilization to external cavities, etc.

In the second part of this labwork, the current fed to the diode will be modulated to study the influence of this modulation on laser emission.

Figure 3: Examples of packages laser diodes: (left) TO-moubt ; (right) C-mount.

B. Description of the setup

1. 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 ΔT 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.

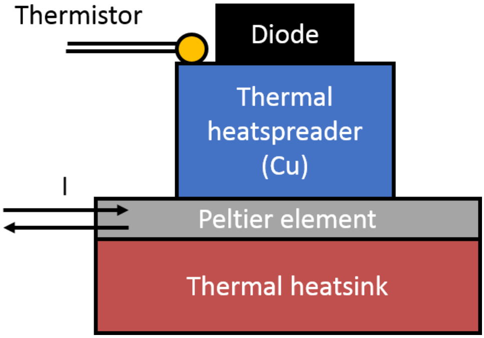


Figure 4: Schematic diagram of the temperature control for diode laser.

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.

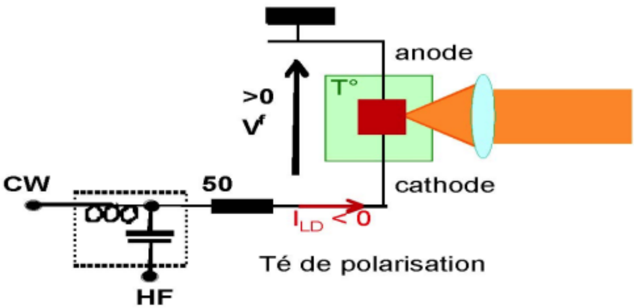


Figure 5: Electronic configuration of the laser diode; continuous supply current + RF modulation

- **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**.

2. *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.

C. 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.

Q1. 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).

Q2. 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.

Q3. 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.

Q4. 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.

Q5. 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?

Q6. 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.

Q7. Explain the (linear) variations of the laser wavelength with injected current I_{LD} and diode temperature T.

Q8 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?

Q9. 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.

Q10. 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)).

Q11. 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.

Q12. Conclude as to how to precisely adjust the laser diode emitted wavelength on a wide range.

C. <u>RF modulation of the laser diode current</u>

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 bandwith 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 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 Δi 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.

---

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

WARNING: DO NOT APPLY THE 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.

Q13 Do you observe an intensity modulation? Compare the modulation depth with what you could expect for a similar current modulation at low frequencies using your previous measurement.

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

Q14 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:

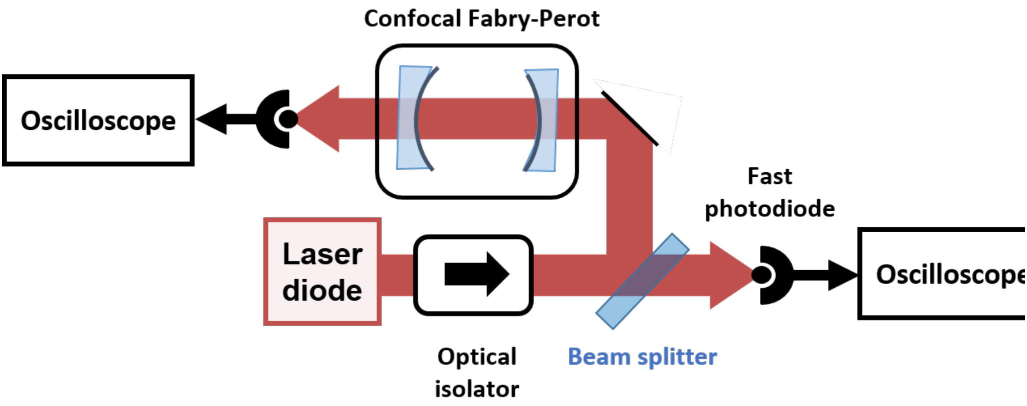


Figure 6: Experimental set-up to study the effects of the current modulation.

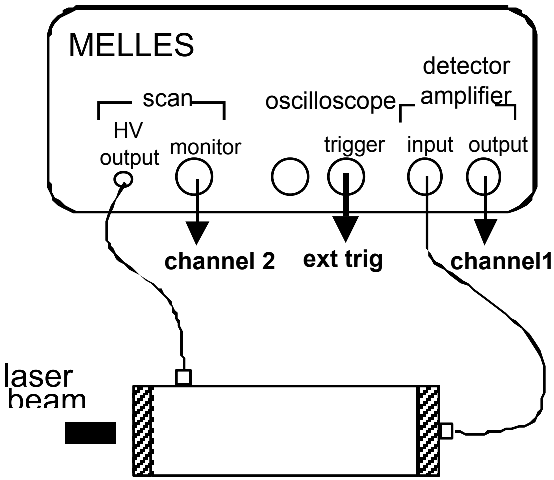


Fig. 7: Fabry-Perot connections

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.

Q15. 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.

Q16. 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.

Measurement with the scanning Fabry-Perot:

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

Q17. Measure the frequency splitting beatween the main central peaks and the sidebands when the diode current is modulated.

Q18. Given the observed spectrum (number, size and spacing of the peaks), is the dominant mechanism intensity or frequency modulation?

Q19. Conclude as to the global nature of the optical modulation induced by the current modulation. Comment on the physical origin of the optical modulation in comparison to what you observed in continuous wave. Is this an advantage or a drawback for optical telecommunications applications?

Q20. (bonus) 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, Δν (in MHz)? Calculate the coefficient Δν/ΔI then Δλ/ΔI in pm/mA. Compare with the result of question 8. Comment.

Appendix 1: 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 $P(t) = P_0\left[1 + M \cdot \cos(2\pi F_m t)\right]$, 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: : $E_L(t) = A \cdot \left[1 + \frac{M}{2} \cdot \cos(2\pi F_m t)\right] \cdot \cos(2\pi \nu_L t + \varphi_L)$

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 ν_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.

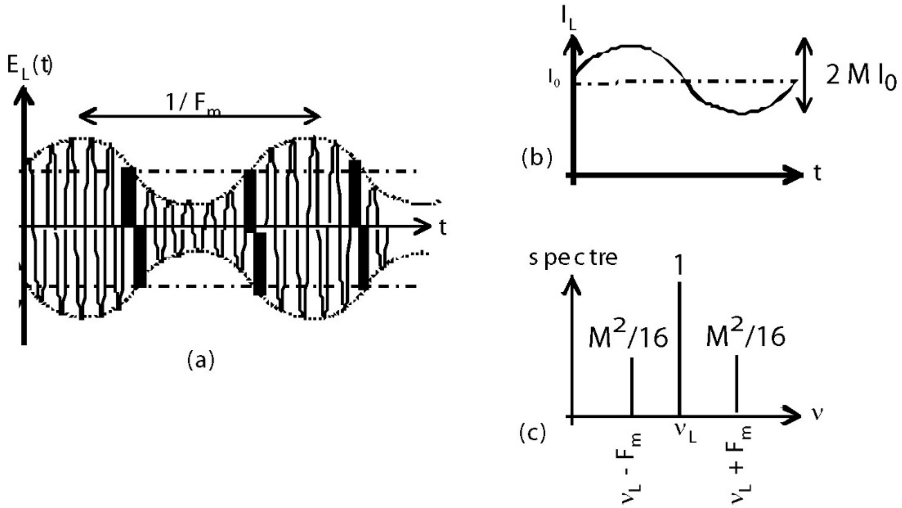


Figure 6: (a) Electric field of the power-modulated laser
(b) Photodiode signal
(c) Spectrum of the optical field

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:

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

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:

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

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 ν_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.

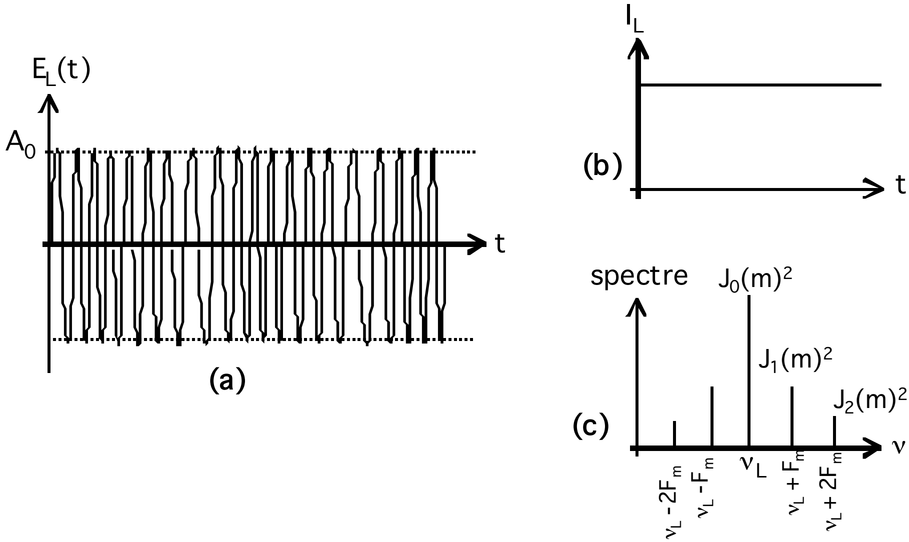
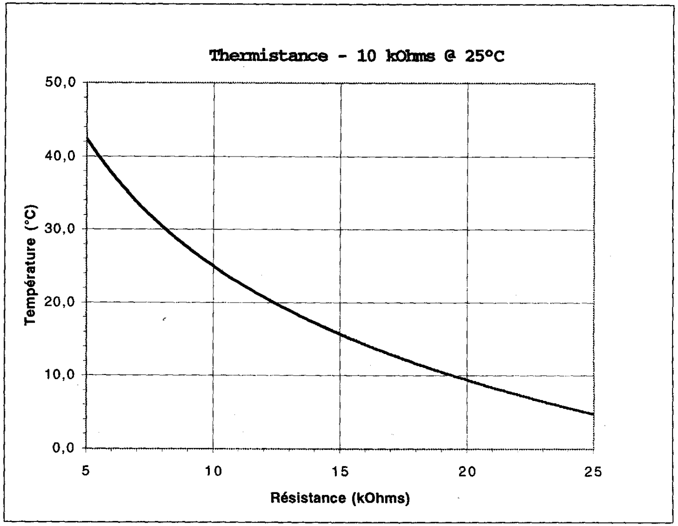


Figure 7: (a) Frequency-modulated electric field
(b) Photodiode signal
(c) Spectrum of the field, as measured by a scanning
Fabry-Perot

Finally, note that the sidebands at $\pm F_m$ 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 2: Thermistor

R (kOhms)	T (°C)	R (kOhms)	T (°C)
5	42,4	15	15,7
5,2	41,4	15,2	15,4
5,4	40,4	15,4	15,1
5,6	39,4	15,6	14,8
5,8	38,5	15,8	14,5
6	37,6	16	14,3
6,2	36,8	16,2	14,0
6,4	36,0	16,4	13,7
6,6	35,2	16,6	13,5
6,8	34,4	16,8	13,2
7	33,7	17	12,9
7,2	33,0	17,2	12,7
7,4	32,3	17,4	12,4
7,6	31,7	17,6	12,2
7,8	31,0	17,8	11,9
8	30,4	18	11,7
8,2	29,8	18,2	11,4
8,4	29,2	18,4	11,2
8,6	28,6	18,6	11,0
8,8	28,1	18,8	10,8
9	27,5	19	10,5
9,2	27,0	19,2	10,3
9,4	26,5	19,4	10,1
9,6	26,0	19,6	9,9
9,8	25,5	19,8	9,6
10	**25,0**	20	9,4
10,2	24,5	20,2	9,2
10,4	24,1	20,4	9,0
10,6	23,6	20,6	8,8
10,8	23,2	20,8	8,6
11	22,8	21	8,4
11,2	22,3	21,2	8,2
11,4	21,9	21,4	8,0
11,6	21,5	21,6	7,8
11,8	21,1	21,8	7,6
12	20,7	22	7,4
12,2	20,4	22,2	7,2
12,4	20,0	22,4	7,0
12,6	19,6	22,6	6,8
12,8	19,3	22,8	6,7
13	18,9	23	6,5
13,2	18,6	23,2	6,3
13,4	18,2	23,4	6,1
13,6	17,9	23,6	5,9
13,8	17,6	23,8	5,8
14	17,2	24	5,6
14,2	16,9	24,2	5,4
14,4	16,6	24,4	5,3
14,6	16,3	24,6	5,1
14,8	16,0	24,8	4,9
		25	4,8



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

avec $B = 3750\,K$

Appendix 3: Laser diode specifications

MITSUBISHI LASER DIODES

ML6XX10 SERIES

FOR OPTICAL INFORMATION SYSTEMS

ABSOLUTE MAXIMUM RATINGS

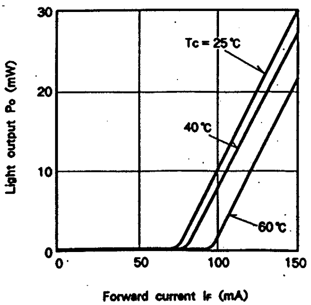
Symbol	Parameter	Conditions	Ratings	Unit
Po	Light output power	CW	35	mW
		Pulse (Note 1)	45	
V_{RL}	Reverse voltage (laser diode)	–	2	V
V_{RD}	Reverse voltage (Photodiode)	–	30	V
I_{FD}	Forward current (Photodiode)	–	10	mA
Tc	Case temperature	–	−40～+60	℃
T_{stg}	Storage temperature	–	−55～+100	℃

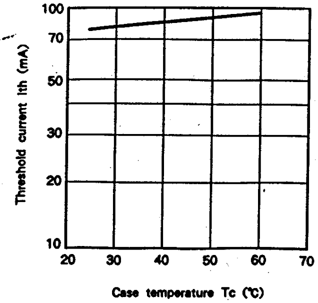
Note 1 : Duty less than 50 %, pulse width less than 1 μ s.

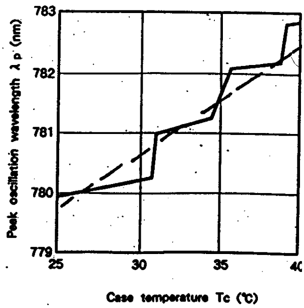
ELECTRICAL/OPTICAL CHARACTERISTICS (Tc = 25℃)

Symbol	Parameter	Test conditions	Limits Min.	Limits Typ.	Limits Max.	Unit
I_{th}	Threshold current	CW	–	70	85	mA
I_{OP}	Operating current	CW, Po = 30mW	–	140	160	mA
η	Slope efficiency	CW, Po = 30mW	–	0.4	–	mW/mA
V_{OP}	Operating voltage	CW, Po = 30mW	–	2.0	2.5	V
λ_P	Peak wavelength	CW, Po = 30mW	770	785	800	nm
$\theta_{//}$	Beam divergence angle (parallel)	CW, Po = 30mW	9	10.5	13	deg.
$\theta_{\perp}$	Beam divergence angle (perpendicular)	CW, Po = 30mW	24	26.5	28	deg.
I_m	Monitoring output current (Photodiode)	CW, Po = 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	μ 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

2017-2018

Oral presentation

During the session, you will prepare an oral presentation (5 min) about your results and observations on questions 1 and 2.

PRELIMINARY QUESTIONS

(ANSWER THEM BEFORE THE SESSION)

P1. By using experimental details, find n°1 half-waveplate and polarizing beamsplitter cube roles. What is the goal by using these two optical elements? Why do we need a second half-waveplate?

P2. To obtain optical pulses with a q-switch laser like in this experiment, what is the impact of cavity size on optical pulse duration?

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 2^{nd} order nonlinear crystals. The doubling frequency beam will then be injected inside an optical fiber made of silica to generate Raman scattering effect, a 3^{rd} 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 lecture notes on nonlinear optics, especially the chapter relative to the 2^{nd} 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.

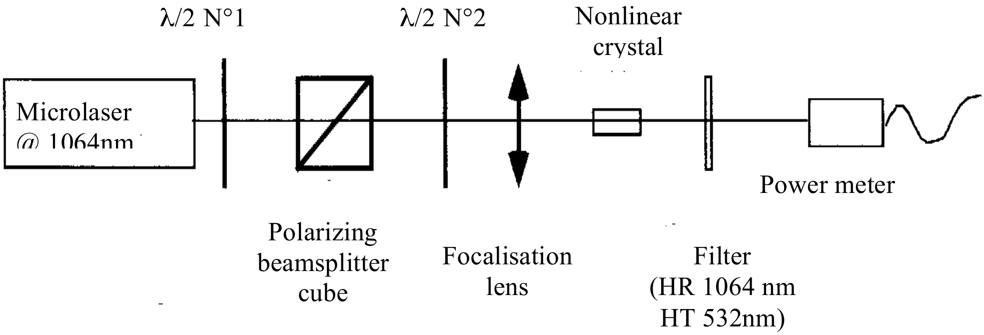


Figure 1: Second Harmonic Generation experimental set-up.

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 incident power is adjusted by means of the half-wave plate n°1 and the polarizing beamsplitter cube. The second half-wave plate (n°2) 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.

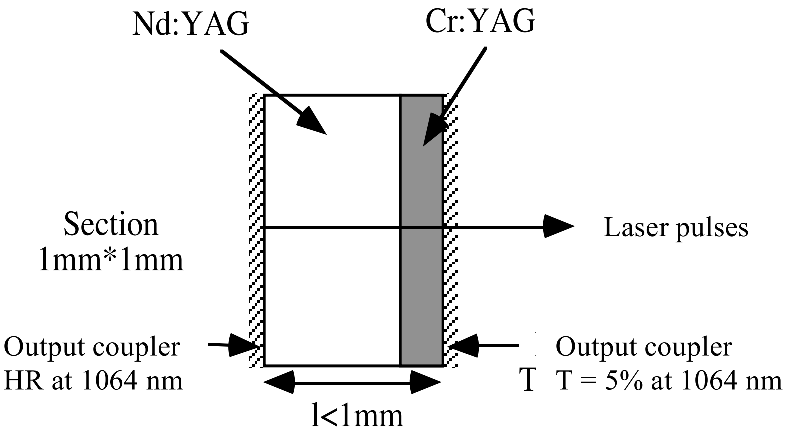


Figure 2: Sketch of the microchip laser

Oral

Summarize your results for questions 1 and 2 about the laser characterization, and advantages of use it to obtain nonlinear effects, in a short oral (5min).

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 (β-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.

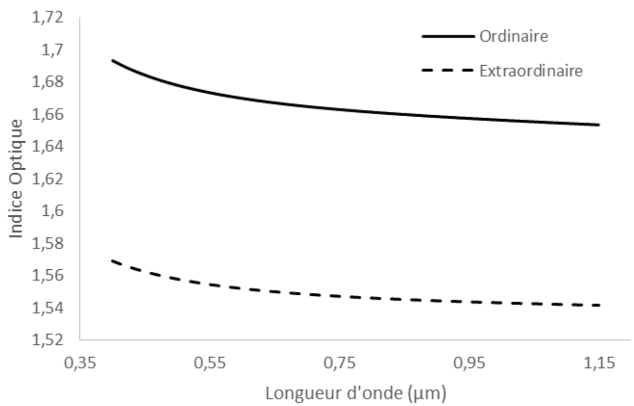


Figure 3: BBO refractive index as a function of the wavelength.

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.

I.4 Dependence of the SHG beam power with the power of the fundamental beam

For this part, we use the KTP crystal.

Question 14: Optimize the output power of the green beam and plot the dependence of the SHG beam power with the input infrared beam at 1064 nm (by rotating the first half wave plate). Make sure to take enough measurements at low power. Comment the shape of the curve at low and high power. Plot a fitting curve for your experimental data points in the low power regime.

Question 15: 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 ω and a vibrational mode of a molecule (or a crystal lattice) at the frequency ω_{mol}. The spectrum of the scattered light, which is emitted isotropically, contains new frequency components respectively towards ω-ω_{mol} (the Stokes wave) and ω+ω_{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).

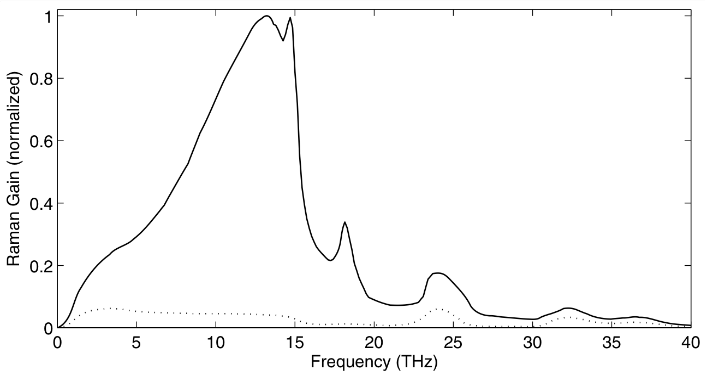


Figure 4: Normalized Raman gain spectrum for fused silica (G.P Agrawal, *Nonlinear Fiber optics*, Academic Press, San Diego, CA, 2001)

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.

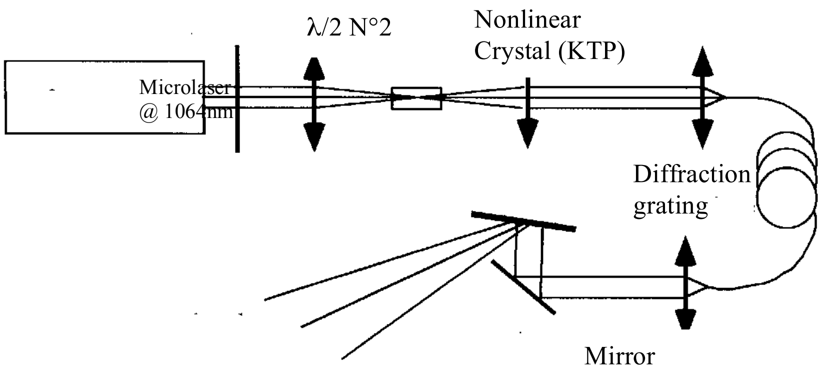


Figure 5: Experimental set up for the observation of the Raman scattering effect in an optical fiber.

Question 16: Calculate the theoretical wavelength of the 6 first Stokes order. Are your experimental observations in agreement with your theoretical estimations?

Optical fiber amplifier and oscillator

2017-2018

Oral presentation

During the session, you will prepare an oral presentation (5 min) about your results and observations on questions 12 and 13. You will present a summary of the results obtained in the part "Fiber Laser", more particularly concerning the emission spectrum observed in the case of the ring cavity and the linear one.

PRELIMINARY QUESTIONS (answer them before the session)

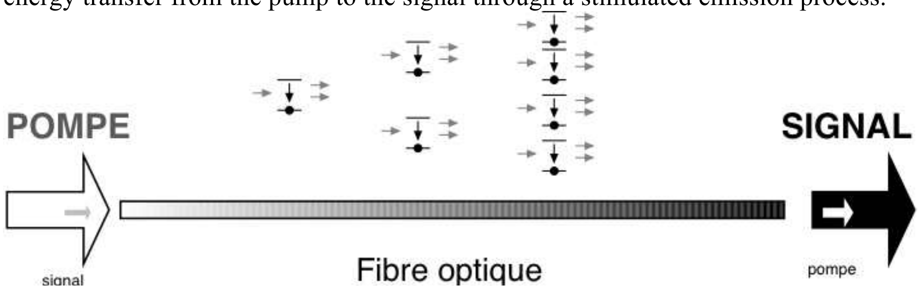
P1 Describe, using a few sentences, spontaneous and stimulated emission processes.

P2 Give the expression for the optical gain in a medium as a function of population inversion density, emission cross-section, and length.

P3 Describe briefly what does inhomogeneous or homogeneous spectral broadening means and comment on the physical origins.

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.



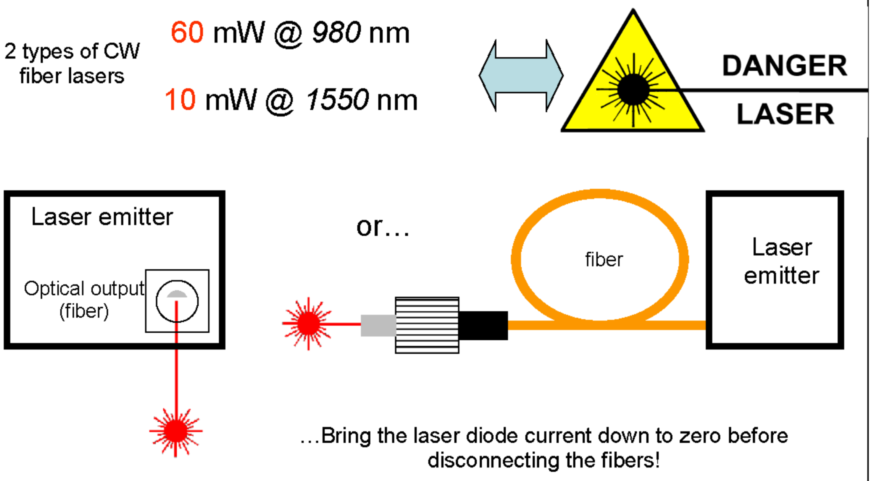
Let us recall that the emitted photons possess the same phase, polarization and wavevector as the incident photons. This is different from spontaneously emitted photons that have no relationship with the signal. They will therefore form an optical noise at the output of the amplifier. This noise intensity 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.

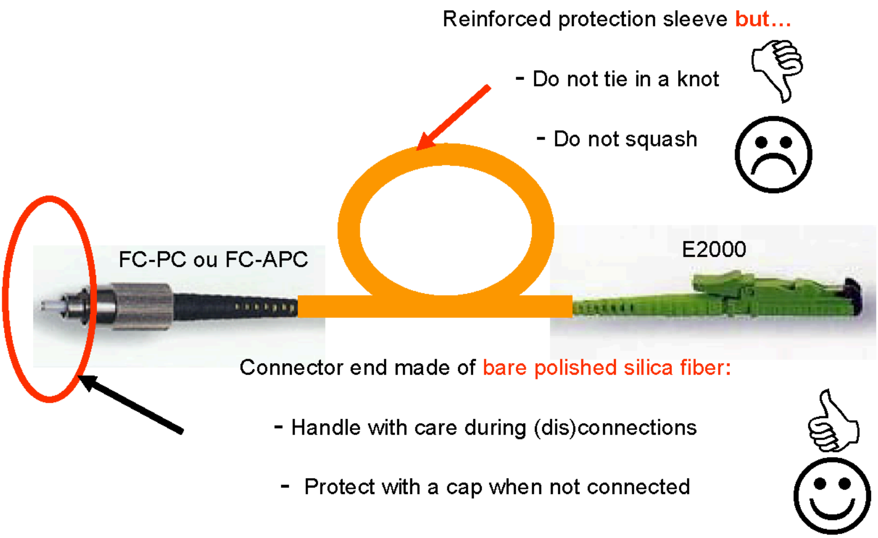
This labwork is divided in two parts:

- 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



FIBER MANIPULATION



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)

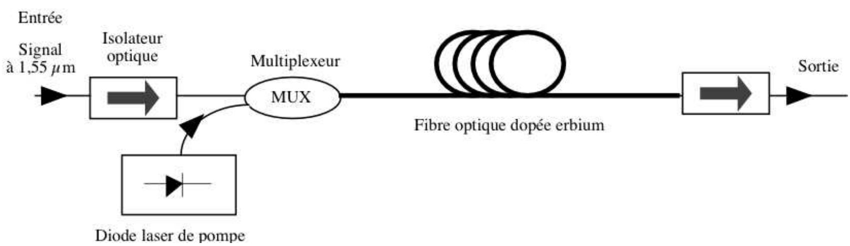
Description of the optical components and equipment

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 (λ_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 λ_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 λ_p = 980 nm.

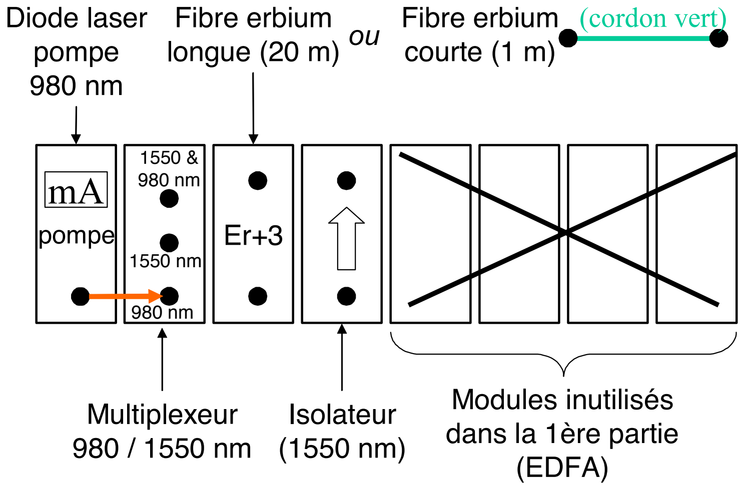
Multiplexer (« MUX » in the amplifier setup)

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

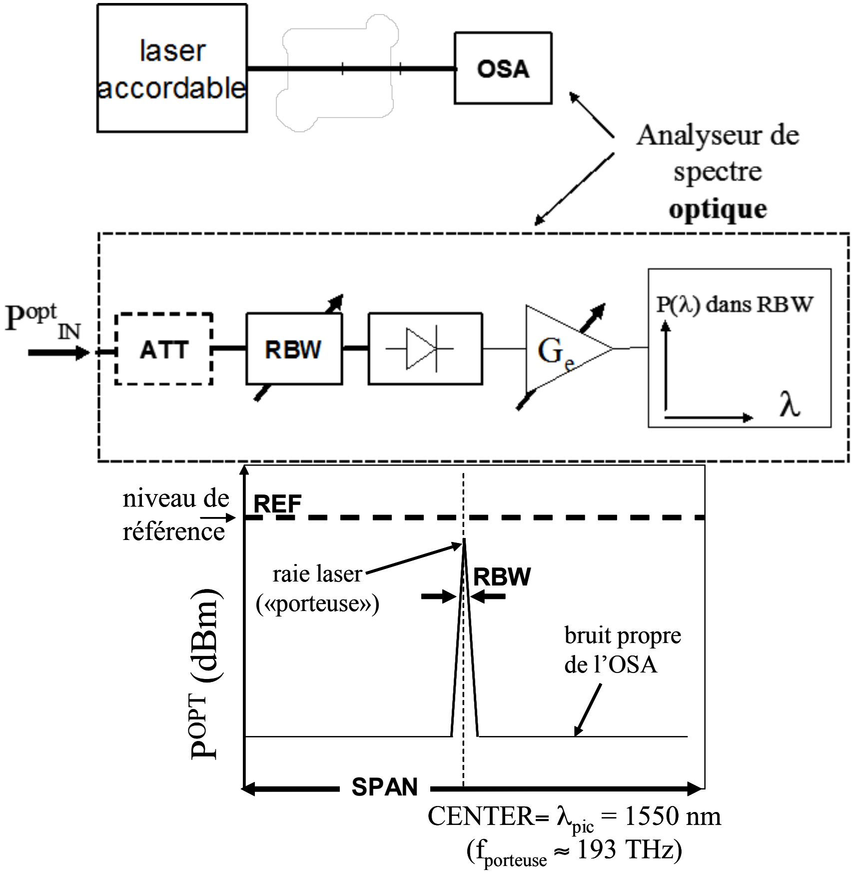
Kit “ampl‘educ“ (IDIL)



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).

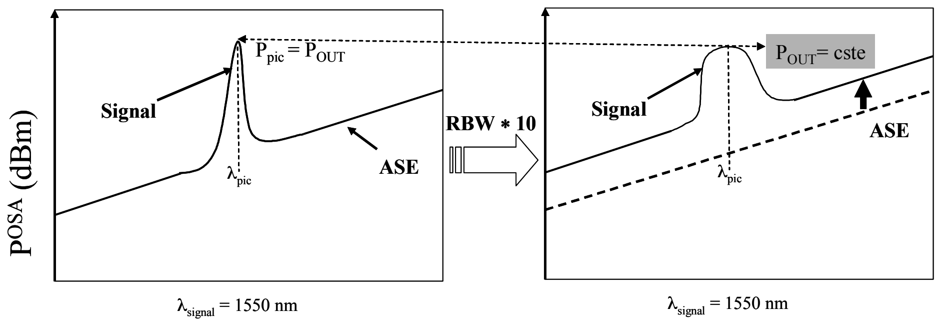
The choice of the reference level (REF or Ref Level) is also important to display correctly the measurement. It defines the power level 2 divisions below the upper side of the display. By adjusting it, the spectra can be shifted vertically to fully display it. Finally, another parameter is important 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.

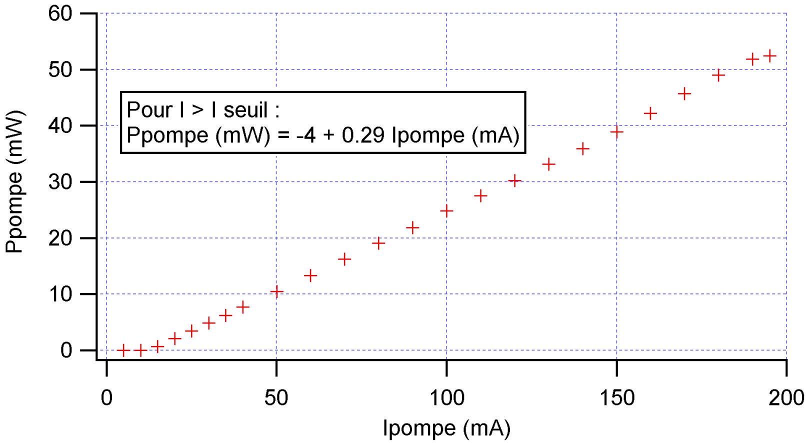
Q1. In particular, change BW from 0.1 nm to 1 nm. Measure the peak and the background levels in both configurations using the cursors ('Marker' menu). Explain the influence of the resolution on the peak width. Explain how the peak level P_{OUT} (peak) and the background level P (background) of the spectrum 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 Analyser (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?

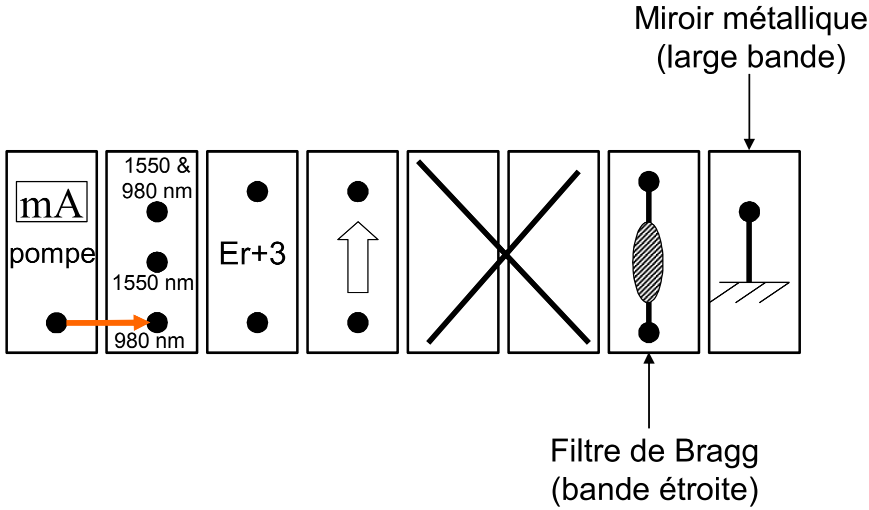
2.7.3 Study of the parasitic cavity effect

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

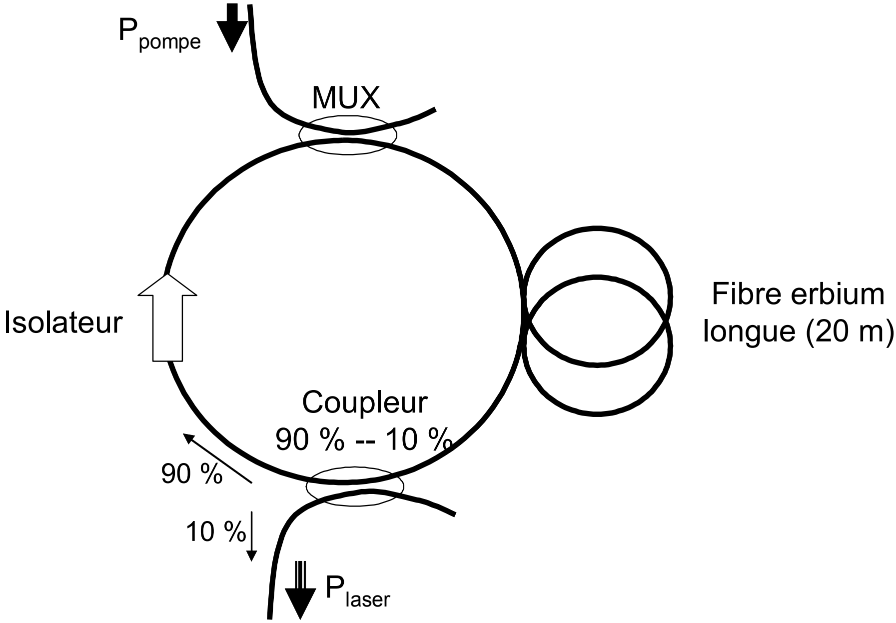


To characterize the transmission of the Bragg filter (which is equivalent to a narrow bandwidth mirror), use the broadband ASE light (without signal!):

- 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

Q11 Determine the central wavelength and bandwidth of the filter.

3.2. Laser ring cavity

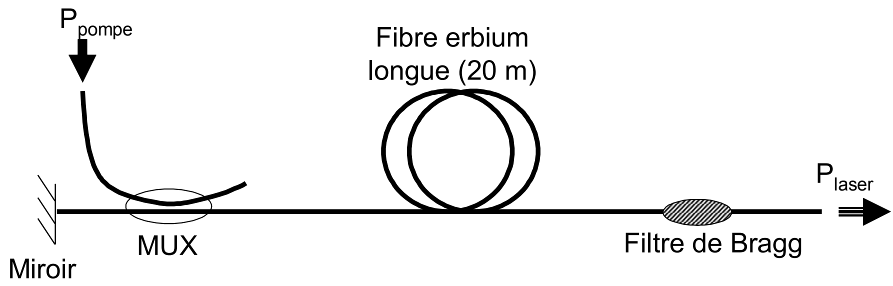


The presence of the optical isolator inside the cavity is optional.

Q12 Observe the output spectrum and its evolution with the pump power. What determine the laser emission here?

3.3. Linear cavity laser

Make the following setup

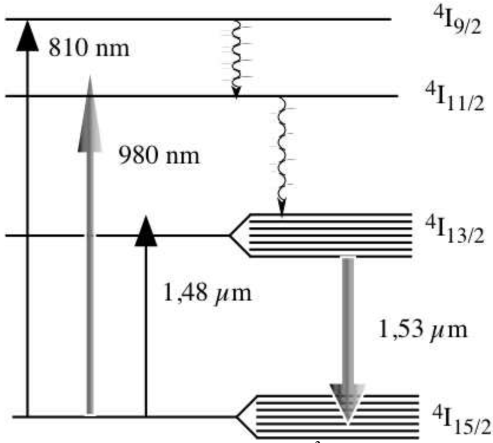


Q13 For a given operating point, record a spectrum with a large and small wavelength range (e.g. SPAN =50 nm and RBW=1 nm, then SPAN =5 nm et RBW=0.1 nm). Comment the obtained laser wavelength Explain the difference with the wavelength obtain with the ring cavity.

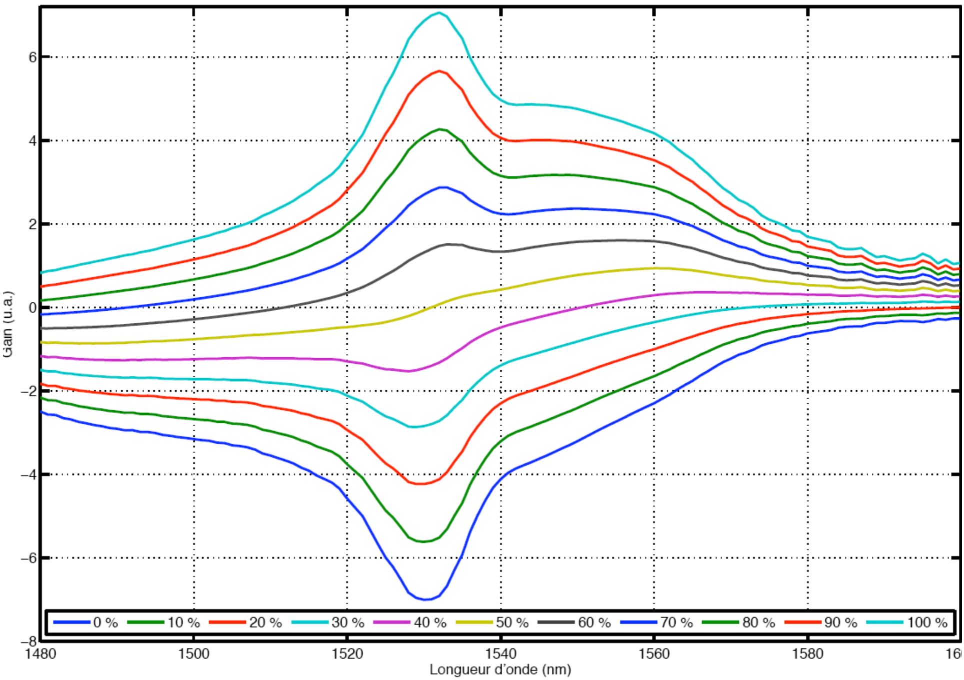
Q14 From observations on the 2 set-ups, suggest a laser cavity scheme in order to obtain a tunable laser wavelength.

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 $^4I_{13/2}$.