Lab work in photonics

Laser

Salles	**L1**	**L2**	**L3**	**L4**
	S1.25	S1.17	S1.20	S1.21

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Engineer - 2nd year - S7 -Palaiseau
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Preamble

Objectives

At the end of this labwork block, you will have implemented lasers in the three most common forms:

- semiconductor lasers (laser diodes)
- solid state lasers (laser crystals and nonlinear crystals)
- fiber lasers

You will be able to:

- manipulate a laser beam
- use the components of a laser system: laser diode, laser crystals and non-linear crystals, fibers, mirrors, fibered Bragg grating
- Set up and optimize laser sources in general (including lasers and nonlinear frequency conversion, oscillator, amplifier, continuous-wave and pulsed lasers)
- Use laser source characterization instruments (power meter, optical spectrum analyzer, fast photodiode, scanning Fabry Perot)
- characterize a laser system (efficiency curves, time course, spectral properties)
- master the orders of magnitude associated with laser sources
- interpret the effects observed in practice considereing the theoretical notions of 3-level and 4-level laser systems, semiconductor laser, laser amplification, laser oscillator in continuous-wave or pulsed mode

How to

For each subject, the body of the text presents the spirit of the labworks and the proposed activities. It gives protocols for the adjustments, in support of the explanations which will be given by the supervisor. It is also accompanied by appendices serving as theoretical and practical support for the experimental work.

In each subject, the first appendix serves as a preparation for the practical work and should be read before the session. Some of them include preparation questions that the supervisor will correct at the beginning of the session.

The actions to be done during the session and requiring the supervisor's control are noted **C**. They punctuate the learning of "experiment" skills (experimental know-how: alignments, setting up and use of measuring devices).

The activities to be done for the report are noted **Q**. They punctuate the learning of "measurement" skills (ability to make quality measurements: right range of uncertainty, right resolutions and dynamics to see the phenomena, quality graphs) and "physics" skills (understanding of physical phenomena, mastery of orders of magnitude).

Lab 1

Nd:YAG Laser

Contents

Skills to be acquired with this labwork

The skills to be acquired in this labwork, classified in 3 categories, are the following:

"Experimental" skills:

- Collimation of a laser beam
- Alignment of an optical pumping system and a laser cavity
- Achieving the laser effect in the infrared using the tools adapted (infrared card, infrared, photodiode viewer or CCD camera)
- Optimization of laser performance

"Measurement" skills:

- Measuring the efficiency curve of a laser
- Using a fast oscilloscope (ns)
- Characterization of a pulsed laser

"Physics" skills:

- Understanding the parameters that affect the output power of a continuous laser: focusing of the pump beam, orientation of the mirrors, transmission of the output mirror
- Understanding the pulse regime by gain modulation (gain-switch) and the parameters that influence it.
- Understanding the Q-switch regime and the parameters that influence it.

Prerequisite

- General notions on laser physics from the first year: 4-level system, lifetime of the top level, threshold of a laser oscillator, expression of the output power of a laser oscillator in continuous mode, laser in gain-switch mode, laser in Q-switch mode
- Review of TD n°4 of the first year Nd:YAG laser course
- Reading of Appendix 1
- Laser safety

Laser safety specific to this labwork

In this labwork, the pumping laser diode emits up to 1 W, i.e. 1000 times the burn threshold of the eye. Wearing protective glasses is mandatory as soon as the laser diode is working. The optics must never be moved off the bench when the laser diode is working at maximum. For any change on the optical bench, lower the power of the laser diode to the minimum.

1 Labwork at a glance

The "Nd:YAG" laser is composed of a crystalline solid laser medium (an yttrium-aluminum garnet $Nd^{3+}:Y_3Al_5O_12$) doped with neodymium ions whose energy levels are used to achieve the laser effect. It is a laser that is widely used in industry for its emission properties in the near infrared, at 1064 nm. Nd:YAG can be optically pumped by flash lamps or laser diodes.

In this work, we are studying the optical pumping by a laser diode. Here, the pumping is longitudinal: the propagation axis of the pumping optics is collinear to the axis of the laser cavity. The goal of the labwork is to build a diode-pumped Nd:YAG laser, to know how to adjust it and to characterize it. Several time regimes will be studied: the continuous regime, the gain-switch regime and the Q-switch regime

Figure 1.1 gives a general view of the laser to be mounted. The laser diode emits up to 1 W of power at 808 nm, corresponding to an absorption band of Nd:YAG. La longueur d'onde de la diode de pompage varie avec la température et le courant de pompage (voir TP diode laser). On se placera dans l'ensemble du TP à une température fixe notée sur le boitier de la diode. The wavelength of the pumping diode varies with temperature and pumping current (see the labwork related to the laser diode). During all this labwork, we seet the laser diode at a fixed temperature noted on the diode housing. The radiation of the laser diode is collimated and then modified by an anamorphic prism to make the beam less elliptical at the focus point (see appendix 2). A lens is used to focus the pump beam in the Nd:YAG. YAG crystal. On this crystal is directly deposited the first mirror of the cavity. This mirror is totally reflective at the laser wavelength (1064 nm) and transparent at the pump wavelength (808 nm). It is a flat mirror. The second cavity mirror is concave, with a radius of curvature of 100 mm. It is also the output mirror. Several transmissions will be studied in the labwork (T = 3% and T = 20%). Two characterization tools are at your disposal: a photodiode mounted on the laser bench, and a power meter (not shown in figure 1.1). For visualization, you have at your disposal an infrared sensor card, an infrared viewer and a CCD camera.

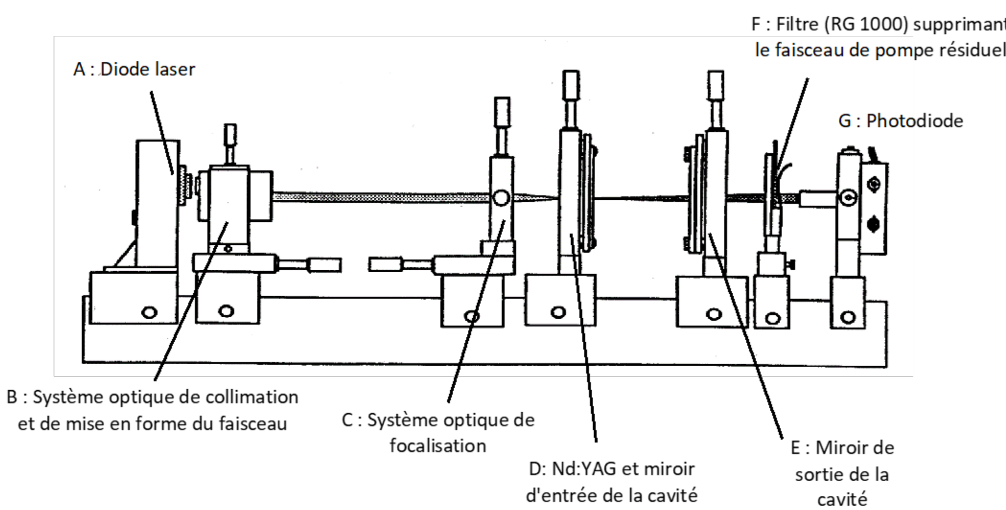

Figure 1.1 – global view of the Nd:YAG labwork steup

2 Experimental activities

2.1 Laser tuning

As the pumping of the laser is longitudinal, the laser adjustment consists in aligning the mirrors of the cavity perpendicularly to the optical axis of the pump beam. This requires this axis to be well defined and aligned to be used as a reference for all the other compoements. The laser is therefore adjusted by :

- building the reference collimated beam
- aligning the flat mirror of the cavity with this reference (without the focusing lens)
- focusing the laser beam in the crystal
- aligning the output mirror on the reference axis and finely tuning it to find the laser effect

The following describes the adjustment step by step.

Setting up the pump beam as the reference beam

⇝ Start by checking that the pump beam after the anamorphic prism is properly collimated. To do so, make sure that the size and shape of the beam is maintained throughout the bench. If it is not the case, adjust the collimation using the translation of the anamorphic prism along the optical axis.

⇝ The pump beam must also be perfectly parallel to the bench. Use the Nd:YAG crystal mount and check that the beam is well centered on the crystal whatever its position on the bench axis, from end to end. If not, readjust the direction of the beam using the two transverse translations of the anamorphic prism.

C1 Have the pump beam adjustment checked.

Autocollimation of the flat mirror on the reference axis

The flat mirror deposited on the entrance face of the Nd:YAG crystal must be well perpendicular to the optical axis. As this one does not transmit perfectly all the pump power, we use the parasitic reflection to autocollimate the mirror on the reference axis. We thus use the infrared viewer or the CCD camera to observe the reflection from the flat mirror returning to the anamorphic prism.

⇝ PPlace the Nd:YAG crystal mount at the end of the bench and proceed to autocollimate the flat mirror. The adjustment screws of the Nd:YAG allow to tilt the reflected beam until the autocollimation is well done.

Positioning the concave mirror

To align the concave mirror on the optical axis by autocollimation, it is necessary to couple it with the focusing lens to ensure that the reflected beam is well collimated towards the anamorphic prism.

⇝ Determine the necessary condition on the distance between the objective and the concave mirror such that autocollimation can be achieved (the collimated beam must return on itself).

⇝ Place the concave mirror and objective alone on the bench, with the correct separation distance, and observe the reflected beam back to the anamophic prism. Adjust the autocollimation with the rotation screws of the concave mirror mount.

Focusing of the pump beam in the laser medium

⇝ Place the Nd:YAG crystal back on the bench at the focal spot of the objective. To do so, observe the size of the pencil beam in the crystal (emitted fluorescence following the pump absorption) with the infrared viewer or the CCD camera and adjust the position of the crystal to make it as thin as possible.

Getting the laser effect

The concave mirror alignment procedure placed the cavity at the limit of stability.

⇝ Start by bringing the concave mirror closer to the crystal so that the distance between the two mirrors (concave and flat) is well below the radius of curvature of the concave mirror (R_C = 100 mm).

You can observe the laser output with the CCD camera or with the infrared card. A bright point (or line) should appear: this is the laser effect at 1064 nm. If there is no signal, try to adjust the orientation of the concave mirror.

⇝ Optimize the orientation of the mirror to have a round beam at the output.

C2 Have the laser effect checked.

2.2 Characterization of the laser in continuous-wave regime

We perform here the measurement of the output power P_{out} as a function of the pump power P_{P}. For simplicity, the pump power can be measured between the anamorphic prism and the focusing lens, where the beam is collimated. The variation of the pump power is provided by the variation of the laser diode current.

We have two concave mirrors of radius of curvature R_C = 100 mm and different transmissions: T = 3% and T = 20% (if there is enough time left).

$\leadsto$ Before starting the measurements, optimize the output power for the maximum pump power with all the elements (conacve mirror, crystal mount, focusing lens...). Then place the power-meter as far as possible on the bench to avoid measuring the residual pump power.

Q1 For each output coupler, draw the characteristic curves $P_mathrmout = f(P_mathrmP)$ and do a linear fit after the threshold to derive accurately the laser efficiency (in %) and threshold power (in mW). Comment on the differences between the curves (thresholds and slopes) compared to the theory.

2.3 Laser in gain-switched regime

Gain-switching consists in making the laser diode work in pulsed regime, in the form of rectangular crenels. This signal is produced by a low frequency generator and sent to the laser diode power supply.

$\leadsto$ Set the low frequency generator to generate a rectangular signal between 0 V and 4 V with a frequency of 5 kHz.

$\leadsto$ Replace (if necessary) the output coupler with transmission T = 3% and make the cavity as small as possible by bringing the concave mirror as close as possible to the crystal.

In these conditions, we want to observe the laser signal in the temporal domain and study its variations according to various parameters: pump power, pumping time, laser settings (orientation, focusing of the pump beam). We use the photodiode at the end of the bench, aligned in the laser beam path. As a reminder, the detection set (photodiode + cables + oscilloscope) is equivalent to a low pass filter. Here the load resistance of the photodiode can be adjusted according to the needs. It should also be noted that the total capacitance to be taken into account (photodiode + cable + oscilloscope) is about 250 pF.

C3 Have the assembly allowing to observe a pulsed laser signal checked.

Q2 Take a picture of the transient regime of the laser and explain its physical origin.

We define the creation time of the laser pulse as the difference between the onset of lasing and the onset of pumping.

Q3 OObserve and report (photos or graphs) the variations of the creation time with the settings: explain the origins of the evolution of the creation time.

C4 Adjust the duration of the pumping time to have only one laser peak in a single pumping time and have it checked.

Q4 Measure the duration, energy and peak power of a laser peak, paying attention to the response time of the detection chain.

2.4 Laser in Q-switched regime

Q-switching is provided by a saturable absorber (Cr:YAG) placed in the cavity. In this part, the pumping is continuous. The output mirror remains at a transmission of T = 3%.

⇝ First optimize the cavity without the saturable absorber.

C5 Insert the saturable absorber in the laser cavity and observe the laser signal obtained with the photodiode.

Q5 Observe the effect of the variation of the pump power on the frequency of the emitted pulses and explain its physical origin.

Q6 Measure the duration, the energy and the peak power of a laser peak for the maximum pump power, taking care of the response time of the detection chain.

Q7 Measure the pulses durations for two different cavity lengths: for the smallest possible cavity and for a 5 cm long cavity. Explain the physical origin of the different durations observed.

Q8 Compare the pulses in gain-switched and Q-switched regimes.

Appendix 1 : préparation

Etude de cas: Laser Nd : YAG pompé par diode

II

L'objectif de cette étude de cas est de regarder concrètement comment construire un laser Nd:YAG pompé par diode émettant à 1064 nm. Cette étude de cas permet de préciser et d'approfondir certaines notions dans une perspective concrète de mise en application. Nous allons voir quels sont les ordres de grandeurs et quels sont les points clefs technologiques.

A. Spectroscopie de l'ion néodyme

1. Présentation des niveaux d'énergie

L'ion néodyme (Nd^{3+})dans la matrice de YAG ($Y_3Al_5O_{12}$, grenat d'yttrium et d'aluminium) possède une multitude de niveaux qui peuvent donner différentes transitions laser. La figure E1 repère les niveaux d'énergie en nombre d'onde σ exprimés par convention en cm^{-1}. Pour obtenir la longueur d'onde λ (en m) correspondant à une transition entre deux niveaux 1 et 2, il faut écrire : $\lambda = 10^{-2}/(\sigma_2 - \sigma_1)$.

Les niveaux d'énergie de l'ion Nd^{3+} sont repérés par un ensemble de lettres et de chiffres qui donnent les nombres quantiques associés aux différentes composantes : la lettre correspond au nombre quantique orbital, le chiffre en exposant donne le nombre quantique de spin et la fraction en indice le nombre quantique angulaire. A cause du champ cristallin (effet Stark), les niveaux d'énergie sont éclatés en sous niveaux qui sont repérés par des lettres indicées (Z_1...R_2).

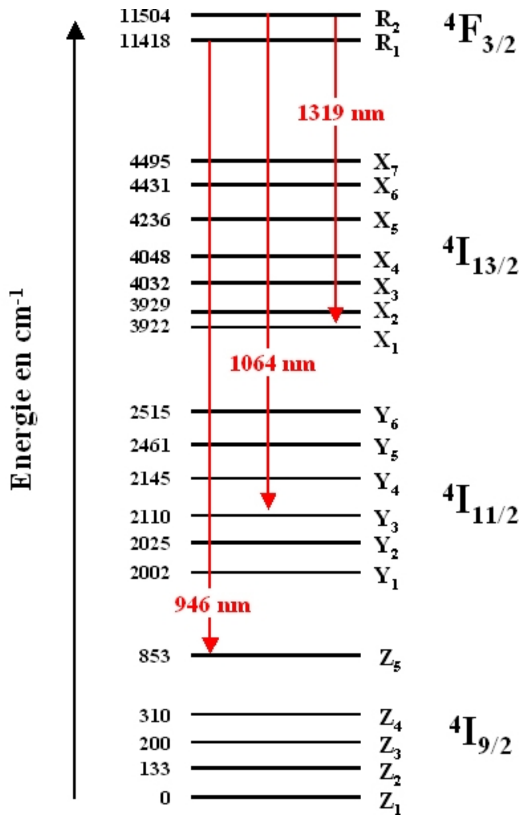

Figure E1 : Différents niveaux de l'ion néodyme. (il existe également des niveaux d'énergie plus élevées non représentés qui ne participent pas à l'émission laser)

Le niveau $^4F_{3/2}$ est le seul dans lequel les ions néodyme restent longtemps. Le temps de vie de ce niveau est de l'ordre de 230 µs alors qu'il est inférieur à la nanoseconde sur les autres niveaux. Les ions vont donc s'accumuler dans ce niveau et peuvent en descendre par émission stimulée intense.

Définition

le temps de vie d'un atome dans un niveau donne le temps moyen de présence dans ce niveau avant désexcitation. On peut montrer que si la population du niveau est N_0 à t=0s, elle vaut $N(t)=N_0 \exp - t/\tau$, à l'instant t, avec τ le temps de vie.

La figure E1 montre une multitude de niveaux d'énergie et donc une multitude de possibilités d'émission et de transitions laser à partir du niveau $^4F_{3/2}$. Les flèches en rouge donnent les longueurs d'onde sur les transitions lasers les plus utilisées : 1064 nm correspond à la transition qui a la probabilité d'émission stimulée la plus grande. Il existe également une raie dans l'infrarouge plus lointain vers 1320 nm. Enfin, le Nd:YAG possède aussi une transition assez efficace dans l'infrarouge proche, à 946 nm.

2. Peuplement des "niveaux du bas" à température ambiante

Afin de connaître l'efficacité d'une transition laser, il est important de savoir si le niveau du bas est peuplé ou non à l'équilibre thermodynamique. Pour cela, on applique la loi de Boltzmann : $N_1 = N_0 \times \exp\left(-\frac{E_1}{kT}\right)$,

N_0 étant la population du niveau fondamental dont l'énergie est prise à 0, N_1 étant la population du niveau d'énergie E_1 que l'on considère.

Afin d'en avoir une utilisation facile, on peut convertir l'énergie "thermique" kT en cm^{-1} grâce à la formule donnée en remarque ci-dessous. Pour une température de 300 K, on trouve kT=208 cm^{-1}.

Remarque

A partir de la relation entre une fréquence et un niveau d'énergie : $E = h\nu$, on peut en déduire la relation entre les énergies exprimées en nombre d'onde et les énergies exprimées en joule : E(J) = 100 h c E(cm^{-1})

En appliquant la loi de Boltzmann, on peut donc montrer que les niveaux du bas pour les transitions à 1064 nm et à 1320 nm ne sont pas peuplés car ils sont situés à plusieurs milliers de cm^{-1} du niveau fondamental : le rapport E_1/kT est alors très faible.

En revanche, le niveau du bas (Z_5) pour la transition à 946 nm a une énergie qui est du même ordre de grandeur que kT. 1,6 % de la population du niveau fondamental se trouve dans le niveau du bas. Pour réaliser une inversion de population, il faudra donc mettre au moins la même quantité d'ions dans le niveau du haut et cette quantité ne sera pas utilisable pour l'amplification par émission stimulée, d'où une perte d'efficacité par rapport aux transitions précédentes.

3. Le système fonctionnant à 1064 nm pompé par diode à 808 nm

L'ion néodyme a également d'autres niveaux situés à une énergie plus élevée que le niveau $^4F_{3/2}$. (que nous n'avons pas représenté sur la figure E1 par souci de simplicité). Par exemple, le niveau $^4F_{5/2}$ permet l'absorption de lumière à 808 nm. A partir du niveau $^4F_{5/2}$, les ions redescendent de façon non radiative sur le niveau $^4F_{3/2}$. Ainsi, la transition de pompage ($^4I_{9/2}$ vers $^4F_{5/2}$) est effectué sur deux niveaux différents de ceux de la transition laser ($^4F_{3/2}$ vers $^4I_{11/2}$). Le système est donc à quatre niveaux (figure E2).

Il faut également noter que les ions ne s'accumulent pas sur le niveau du bas une fois qu'ils ont cédé leur énergie sous forme lumineuse : le passage entre le niveau $^4I_{11/2}$ et le niveau fondamental est très rapide.

Le cycle d'un ion néodyme est résumé sur la figure E2. Il s'agit en fait du schéma spectroscopique idéal car tous les ions excités s'accumulent sur le niveau du haut et le niveau du bas n'est jamais peuplé, ni à l'équilibre thermodynamique, ni en fonctionnement laser.

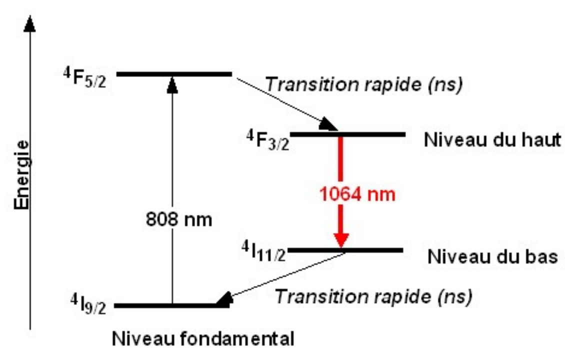

Figure E2 : Schéma simplifiée pour la transition à 1064 nm.

B. Le milieu amplificateur pompé par diode

1. Description expérimentale

Le pompage à 808 nm est assuré par une diode laser. Celle-ci émet une puissance de 500 mW sur une surface émettrice rectangulaire (1 μm par 100 μm). Le rayonnement de pompe est collecté par un objectif qui renvoie l'image de la surface émettrice à l'infini (collimation). Il est ensuite focalisé dans le cristal de Nd:YAG. Le grandissement de l'ensemble des optiques (collimation + focalisation) est de 1. Le rayonnement issu de la diode laser est très divergent (50°), il est donc nécessaire d'utiliser des optiques qui sont très ouvertes pour collecter l'ensemble du flux issu de la surface émettrice. C'est pourquoi nous utilisons ici un objectif de collimation avec une ouverture numérique de 0,5.

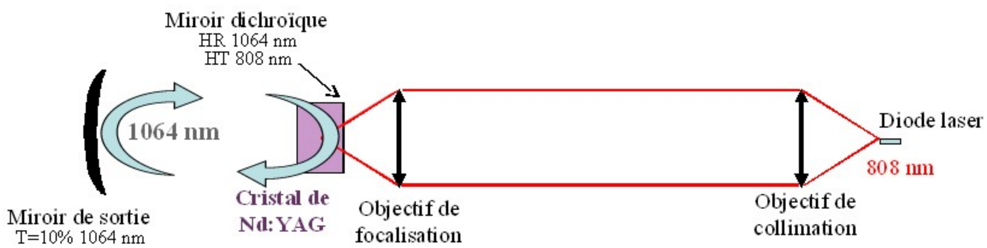

Figure E3 : Schéma de l'optique de pompage.

Le cristal laser a une longueur de 10 mm. L'axe optique de la cavité est dans le prolongement de l'axe optique de pompage : on parle de pompage longitudinal. Le cristal possède un traitement diélectrique sur sa face d'entrée. Il s'agit d'un traitement miroir à la longueur d'onde 1064 nm et anti reflet à 808 nm. Ainsi, le faisceau de pompe traverse le cristal pendant que le signal laser est réfléchi.

Le point de focalisation dans le cristal laser est de l'ordre de 20 μm par 100 μm (les aberrations des optiques font que la section rectangulaire la plus fine de la diode (1 μm) n'est pas imagée correctement). Ce point peut sembler très petit mais il est essentiel que le faisceau de pompe soit focalisé dans le cristal pour que le pompage soit efficace et que le gain effectif atteigne une valeur importante, suffisante pour dépasser le seuil d'oscillation. En effet, on peut montrer que lorsque le faisceau laser a une intensité très petite, le gain effectif G_0 est lié à l'éclairement de la pompe E_p sur le cristal par la formule suivante (dans l'hypothèse où le faisceau de pompe et le faisceau laser ont la même section).

$G_0 = \exp(\mathrm{Cste} \,.\, E_P)$ où Cste est une constante qui dépend des paramètres spectroscopiques du cristal et de la taille des faisceaux.

Expérimentalement, on peut facilement mesurer le gain dans le montage de la figure E3. Pour une pompe de 500 mW focalisé sur une surface d'une centaine de microns de côté, G_0 est de l'ordre de 1,5 à 1064 nm pour le Nd:YAG.

C. La mise en cavité du cristal de Nd :YAG

Afin de parvenir à construire un oscillateur laser, nous mettons en place un miroir de sortie faisant face au miroir qui est déposé sur le Nd:YAG. Le choix de ce miroir est important au niveau de sa transmission à 1064 nm, de sa réflectivité aux autres longueurs d'onde et de son rayon de courbure.

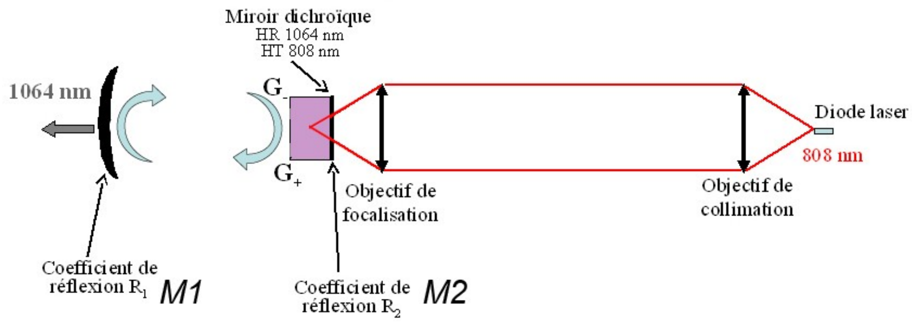

Figure E4 : Schéma du montage complet avec le miroir de sortie.

1. Puissance de pompe au seuil

a) Transmission du miroir de sortie

La transmission du miroir de sortie doit être choisie en fonction du gain disponible dans le milieu amplificateur. On sait, d'après le cours, que le produit des gains dans un sens et dans l'autre, G_+G_- doit être supérieur à $1/R_1R_2$. (voir figure E4 pour les grandeurs) pour avoir une oscillation laser. Ici, on suppose que le miroir déposé sur le cristal de Nd:YAG est très réfléchissant, de telle sorte que $R_2=1$. Cependant, la cavité peut avoir quelques pertes aux passages de l'interface cristal-air dans la cavité ou par diffusion sur des poussières collées sur les miroirs. Pour en tenir compte, nous les regroupons par convention sur le miroir M2 en donnant un coefficient de réflexion légèrement inférieur à 100 %. Ces pertes, dites passives, sont généralement de l'ordre de 1 % à 2 % dans ce type de cavité laser. Nous prenons ici 2 %, donc R_2 = 98%. La transmission du miroir de sortie M1 restant petite (T_1=10%), l'intensité dans le laser ne va pas varier fortement avant et après le cristal. On peut donc supposer que dans tous les cas, $G_+=G_-$.

Sachant que $R_1=1-T_1$, la condition d'oscillation s'écrit : $G^2>1/R_1R_2$.

A pleine puissance de pompe, et pour un signal à 1064 nm petit, G_0^2 vaut 2,25 d'après l'ordre de grandeur donné dans la partie « le milieu amplificateur pompé par diode ». La fraction $1/ R_1R_2$ vaut 1,13. On est donc largement au dessus du seuil d'oscillation.

b) Puissance de pompe au seuil d'oscillation

On peut calculer la puissance de pompe P_P nécessaire pour atteindre le seuil d'oscillation (de telle sorte que $G_0^2=1/R_1R_2$. Pour cela, on peut donner l'expression du gain G_0 en fonction de la puissance de pompe en utilisant la formule de la partie « le milieu amplificateur pompé par diode » :

$$G_0 = \exp\left(\frac{P_P \ln G_{0\max}}{P_{Pmax}}\right)$$

avec G_{0max}=1,5 et P_{pmax}=500 mW. D'où :

$$P_{Pseuil} = \frac{1}{2}\frac{P_{Pmax}}{\ln(G_{0\max})}\ln\left(\frac{1}{(R_1 R_2)}\right)$$

Ce qui donne une valeur pour la puissance de pompe au seuil de 77 mW.

c) Pourquoi faire des faisceaux si petits ?

Les faisceaux à 808nm et à 1064nm ont une dimension de l'ordre de 70µm en rayon à l'intérieur du cristal. Cette taille peut sembler très petite mais elle est nécessaire pour que le nombre d'ions par unité de volume soit suffisante et également pour que le nombre de photons à 1064nm soit suffisant pour déclencher une émission stimulée efficace. En utilisant la formule du gain en fonction de l'éclairement, on peut également introduire la puissance de pompe et le rayon du faisceau de pompe, r : $E_P = P_P/(\pi r^2)$. En supposant que les faisceaux à 808nm et à 1064nm gardent le même rayon, on peut calculer le rayon limite tel que le laser soit au seuil d'oscillation avec un miroir de sortie transmettant 10% et la puissance de pompe maximale :

Pour faire ce calcul, on reprend la formule $G_0 = \exp(\text{Cste} . E_P)$ avec les conditions suivantes données dans la partie « le milieu amplificateur pompé par diode » : G_{0max}=1,5 pour une puissance de pompe de P_{Pmax}=500mW focalisé dans le cristal sur un rayon de r_{max}=70µm. La constante peut donc se trouver facilement : $\text{Cste} = \ln(G_{0\max})\pi r_{max}^2 / P_{Pmax}$.

Pour être au seuil avec la puissance de pompe maximale, il faut que G_0^2=1/(1-T) avec

$$G_0 = \exp\left(\frac{\ln(G_{0\max}) r^2{}_{max}}{r^2}\right)$$

On en déduit que le rayon r vaut

$$r = r_{max} \sqrt{2 \frac{\ln(G_{0\max})}{\ln\left(\frac{1}{R_1 R_2}\right)}}$$

On trouve que r=178µm. Ce qui veut dire que si les faisceaux ont un diamètre supérieur à cette valeur, la puissance de pompe est insuffisante pour atteindre le seuil d'oscillation. On voit qu'il faut garder des tailles largement inférieures au millimètre pour les rayons des faisceaux.

2. Sélection de la transition laser à 1064 nm, choix des miroirs diélectriques

On a vu dans la partie « Spectroscopie de l'ion néodyme » que le Nd:YAG pouvait fonctionner sur de nombreuses transitions laser, en particulier sur trois "massifs" de raies : vers 1064nm, vers 946 nm et vers 1320nm. Il se trouve que la transition correspondant à 1064nm est, de loin, celle qui donne le plus grand gain effectif. Le laser va donc naturellement avoir tendance à fonctionner à 1064nm.

Cependant, pour éviter toute oscillation parasite, il vaut quand même mieux contrôler le coefficient de réflexion des miroirs aux longueurs d'onde indésirables. Ainsi, on va s'arranger pour que le produit 1/ $R_1(\lambda)R_2(\lambda)$ soit plus grand que le gain disponible G_0^2 à la longueur d'onde λ définie comme indésirable. Le seuil ne pourra donc pas être atteint.

Les traitements diélectriques utilisés pour réaliser les miroirs utilisent en fait le principe des interférences : il s'agit d'un dépôt de couches minces (par exemple une alternance de couches SiO_2 et TiO_2) telle que certaines longueurs d'onde se trouvent en interférences constructives à la réflexion sur l'ensemble des couches. Les interférences sont constructives pour certaines longueurs d'onde mais pas pour d'autres. Les miroirs diélectriques ont une bande de réflectivité donnée qui s'étend généralement sur quelques dizaines de nanomètres en longueur d'onde. De part et d'autre de la bande de réflectivité, le miroir est généralement bien transparent. La figure E5 présente une courbe de réflectivité classique pour un miroir réfléchissant à 1064nm ainsi qu'une photo d'un tel miroir posé sur une feuille blanche. On voit clairement la feuille blanche à travers le miroir, preuve que ce dernier est transparent dans le visible alors qu'il est complètement réfléchissant dans l'infrarouge proche.

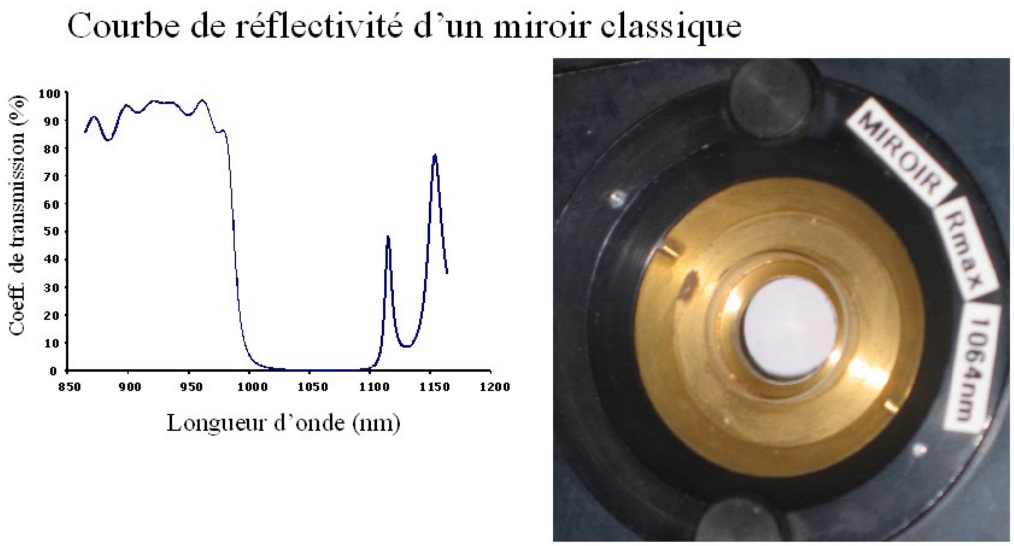

Figure E5 : Photo d'un miroir hautement réfléchissant à 1064 nm et courbe de réflectivité associée.

Remarque

Les miroirs utilisés dans les lasers ne sont jamais des miroirs métalliques. En effet, ces derniers ont un coefficient de réflexion moins bon, de l'ordre de 97%. Le reste étant absorbé par la surface métallique. Ces miroirs créent non seulement des pertes indésirables mais sont également sujet à un échauffement lorsqu'ils sont mis dans un laser. Il peuvent même avoir tendance à se déformer localement sous l'influence du faisceau laser.

3. Choix du rayon de courbure du miroir, mode laser dans la cavité

La cavité décrite sur la figure E4 est une cavité dite "plan-concave" : composée d'un miroir plan déposé sur le cristal de Nd:YAG et d'un miroir concave de sortie. Le rayon de courbure du miroir ainsi que la distance entre les deux miroirs ne sont pas quelconques. Ils sont choisis pour qu'il puisse exister une onde gaussienne capable de se propager indéfiniment dans la cavité en gardant la même forme en tout point de la cavité.

La figure E6 donne l'allure du front de cette onde en quelques points de la cavité. Son rayon de courbure épouse la forme des miroirs d'extrémité : concave d'un côté et plan de l'autre. Pour qu'une telle onde gaussienne existe dans une cavité plan concave, on peut montrer que la longueur de la cavité doit être inférieure au rayon de courbure du miroir concave. On dit alors que la cavité est stable.

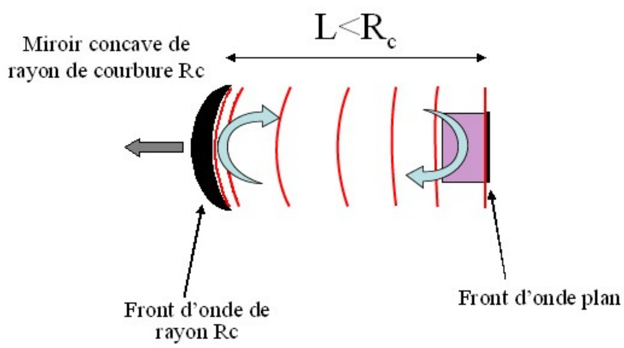

Figure E6 : Allure du front de l'onde gaussienne se propageant indéfiniment dans la cavité.

D. Mise en oeuvre du laser

1. La diode laser pour le pompage

Cette partie décrit concrètement avec quels composants réels est construit le laser.

Le boîtier de la diode laser est visible sur la figure E7. Un zoom permet de voir la diode laser elle-même avec sa surface émettrice rectangulaire de 1 µm par 100 µm. Elle est posé sur un socle vertical à l'intérieur du boîtier. Celui-ci contient également un élément Peltier qui permet de réguler la diode en température. Le boîtier est monté sur un radiateur métallique afin d'évacuer la chaleur dégagée lors du fonctionnement de la diode. Pour que la diode laser émette 500 mW à 808 nm, il faut lui injecter un courant de 1 A sous 2V environ.

Sur la figure E7, on voit également l'ensemble des fils électriques qui vont vers l'alimentation permettant de contrôler le courant injecté dans la diode ainsi que sa température.

Le contrôle de la température est important car la longueur d'onde d'émission de la diode laser varie environ de 0,3 nm par °C. Selon le courant injecté, l'échauffement de la jonction de la diode n'est pas le même et le spectre varie facilement de plus de 1 nm. Ceci est à prendre en compte car le spectre d'absorption du Nd:YAG est centré à 808 nm avec une largeur de l'ordre du nm. Un glissement de la longueur d'onde de la diode laser va donc entraîner une baisse d'absorption (les photons de pompe ne seront plus accordés avec la transition de pompe) et par conséquent une baisse du gain effectif.

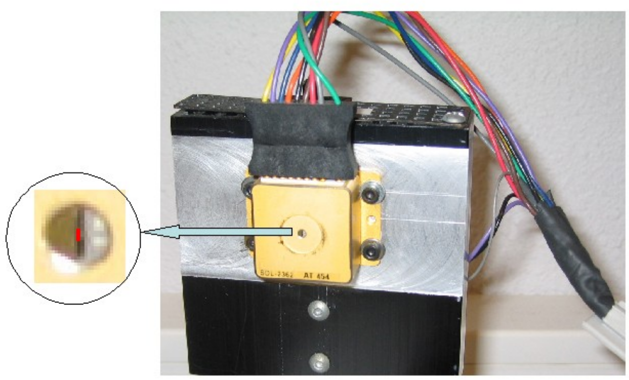

Figure E7 : Photo du boîtier de la diode laser.

2. Le laser Nd :YAG

L'ensemble du laser est visible sur la figure E8. On y reconnaît les différents composants du laser, son optique de pompage et la cavité. Cette photo permet de constater que les différents composants sont positionnés dans des montures réglables : les objectifs de collimation et de focalisation sont montés dans des translations "xyz" dans les trois directions.

Il est important de comprendre que ces translations doivent être très précises. En effet, la taille des faisceaux dans le cristal de Nd:YAG n'est que de 70 µm en rayon. Pour que le faisceaux laser et le faisceau de pompe soient au même endroit, il faut donc être capable de déplacer le faisceau de pompe avec une précision d'une dizaine de microns dans le plan perpendiculaire à l'axe optique.

Les miroirs de la cavité (Nd:YAG d'un côté et miroir de sortie de l'autre) sont montés dans des supports réglables en angle. En effet, il faut que les miroirs soient en regard l'un de l'autre avec une très grande précision pour que l'onde gaussienne puisse faire indéfiniment des allers et retours dans la cavité. Pour avoir un ordre de grandeur de la précision angulaire du réglage sur le miroir de sortie, il faut pouvoir régler son axe optique afin qu'il traverse la zone pompée dans le cristal. Cette zone ne faisant qu'une centaine de microns, il faut un réglage à 10 µm près alors que le miroir de sortie se trouve à 7 cm environ du Nd:YAG. Ceci donne un angle de 0,1 mrad.

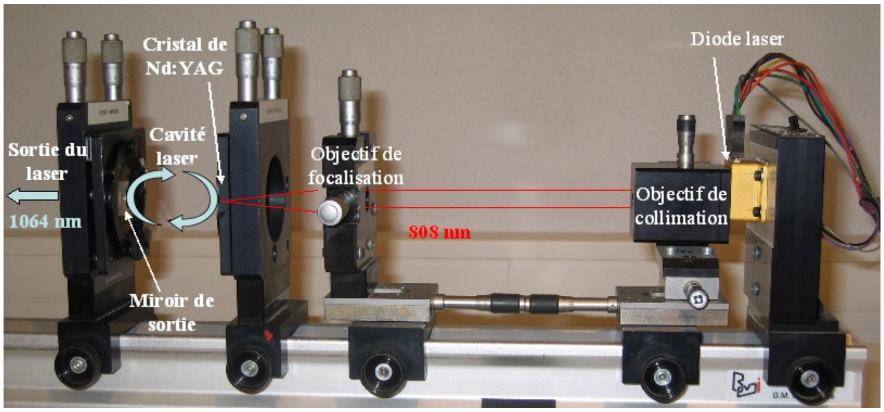

Figure E8 : Photo de l'ensemble des composants du laser (construit par BM Industries).

Pratiquement, on commence par collimater le faisceau de pompe puis par l'aligner parallèle au banc. Le faisceau de pompe défini alors un axe de référence (l'axe optique) qui va nous être utile pour régler les miroirs de la cavité. En effet, nous sommes ici dans le cas d'un pompage "colinéaire" pour lequel l'axe de pompe est confondu avec l'axe optique de la cavité.

On profite donc de ce faisceau pour régler le miroir "Nd:YAG" par autocollimation. On fait de même avec le miroir de sortie. On focalise ensuite le faisceau de pompe dans le cristal de Nd:YAG. En plaçant le miroir de sortie à une distance inférieure à la distance critique (qui est ici de 100 mm = Rc), on obtient assez facilement l'effet laser.

Celui-ci se caractérise par un point lumineux intense, bien sûr invisible à l'oeil (nous sommes à 1064 nm) mais visible avec une caméra CCD ou un simple appareil photo, comme le montre la figure E9. Cette photo est prise hors de l'axe optique. Les photons laser qui arrivent sur le détecteur sont des photons diffusés par le miroir. Proportionnellement aux photons qui sont dans l'axe de la cavité, ils sont très peu nombreux. Ils sont cependant en nombre largement suffisant pour créer un signal sur le détecteur du même ordre de grandeur que celui des montures et de la pièce environnante. Il faut bien comprendre que si nous avions mis l'appareil photo directement dans le faisceau de sortie, celui-ci aurait été fortement ébloui, voir même endommagé. On peut noter également sur la photo E9 que le faisceau laser a une faible extension spatiale par rapport à la taille du miroir. Sur le miroir de sortie, il a un rayon de l'ordre de 1 mm.

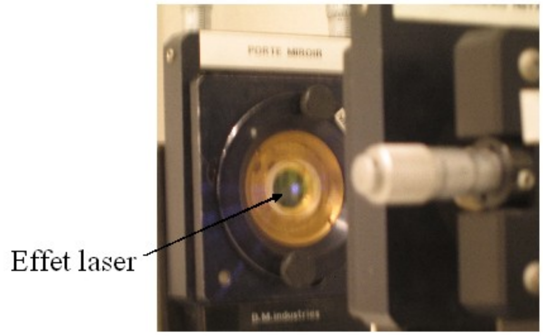

Figure E9 : Photo du miroir de sortie en présence d'effet laser. Le point est invisible à l'oeil mais visible par le détecteur de l'appareil photo numérique.

E. Puissance de sortie

1. Allure du grain

Avant de calculer la puissance de sortie, il est intéressant de regarder le comportement du gain effectif dans le laser en fonction de la puissance de pompe. En dessous du seuil d'oscillation, le gain effectif varie exponentiellement en fonction de P_P.

$$G = \exp\left(\frac{Cste\ P_P}{\pi r^2}\right)$$

A partir du seuil d'oscillation et au delà lorsque le laser oscille, le gain effectif vérifie : $G^2=1/(R_1R_2)$. Il est donc bloqué à une valeur fixée par les coefficients de transmission des miroirs et les pertes passives de la cavité. La figure E10 donne l'allure de cette évolution en fonction de la puissance de pompe. Lorsque la puissance de pompe est nulle, le gain effectif vaut 1. Ceci est du au fait que le niveau du bas de la transition laser est vide. Il ne peut donc pas y avoir d'absorption. La figure E10 montre également l'évolution du gain effectif si la cavité n'existait pas : le gain continu alors sa croissance exponentielle.

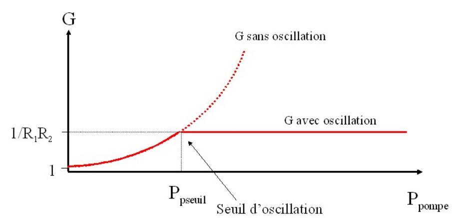

Figure E10 : Allure du gain effectif G dans le cristal de Nd:YAG en fonction de la puissance de pompe.

2. Expression de la puissance de sortie

A partir du seuil d'oscillation, la puissance à 1064nm devient non négligeable dans le laser. Pour simplifier, on va supposer que chaque photon de pompe au delà du seuil d'oscillation se transforme en un photon laser qui sort de la cavité. Pour cela, les photons ont deux solutions, soit traverser le miroir de sortie, soit subir les pertes passives de la cavité. La figure E11 permet de comprendre où se trouvent les différentes sorties du laser. Comme vu sur la photo de la figure E9, il y a des pertes par diffusion sur les miroirs et globalement sur toutes les interfaces. Ces pertes, ainsi que le résidu de transmission sur le miroir M_2, ne peuvent pas être utilisables : ce sont les pertes dites passives. La seule partie du faisceau utile est celle qui sort par le miroir M_1. La puissance qui sort par ce miroir est appelée la puissance de sortie P_{sortie}.

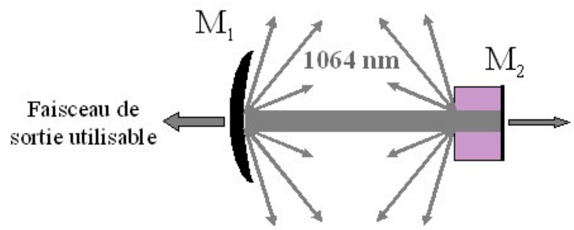

Figure E11 : Sorties de la cavité laser.

Comme expliqué dans la partie « Puissance de pompe en seuil », nous choisissons par convention de regrouper toutes les pertes passives en une seule grandeur : la transmission du miroir M_2. En utilisant la transmission T_1 du miroir de sortie : $T_1=1-R_1$ et T_2 définie par $T_2=1-R_2$, et en définissant la puissance P_{intra} circulant à l'intérieur de la cavité, $P_{émise}$ la puissance totale émise à 1064 nm s'écrit :

$P_{émise}= T_1P_{intra} + T_2P_{intra}$.

La puissance de sortie vaut : $P_{sortie} = T_1 P_{intra}$.

Par rapport à la puissance totale émise, elle vaut donc : $P_{sortie} = P_{émise} T_1/(T_1+T_2)$.

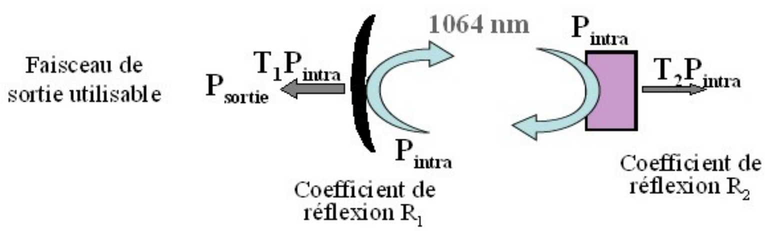

Figure E12 : Grandeurs utilisées pour le calcul de la puissance de sortie.

Au dessus du seuil, on suppose que tous les photons de pompe sont absorbés par le cristal de Nd :YAG et se transforment par émission stimulée en photons laser. Le nombre de photons de pompe convertis par seconde vaut : $(P_P-P_{Pseuil})/h\nu_P$. Le nombre de photons laser émis s'écrit $P_{émise}/h\nu$. D'où l'égalité : $(P_P-P_{Pseuil})/h\nu_P=P_{émise}/h\nu$

Finalement la puissance de sortie du laser peut s'écrire sous la forme :

$$P_{sortie}=\frac{T_1}{T_1+T_2}\frac{\lambda_P}{\lambda}(P_p-P_{pseuil})$$

3. Application numérique

La figure E13 présente ce que l'on appelle la courbe d'efficacité du laser : la puissance de sortie en fonction de la puissance de pompe. On constate d'après la formule précédente qu'il s'agit d'une droite dont la pente dépend de deux paramètres :

- la part relative de la transmission du miroir de sortie par rapport à l'ensemble des pertes de la cavité : pour maximiser la puissance de sortie, il faut donc minimiser ces pertes.
- le rapport de la longueur d'onde de pompe sur la longueur d'onde laser. Ce rapport est fixé par rapport au système laser que l'on considère. Dans notre cas, il vaut 0,76.

La pente de la droite est souvent appelée l'efficacité du laser. Dans notre cas, elle vaut 63%. En utilisant la puissance de pompe au seuil calculée dans la partie «Puissance de pompe au seuil», on en déduit par le calcul une puissance de sortie égale à P_{sortie}=266mW pour la puissance de pompe maximale (500mW). Cette valeur est assez proche de ce que l'on trouve expérimentalement.

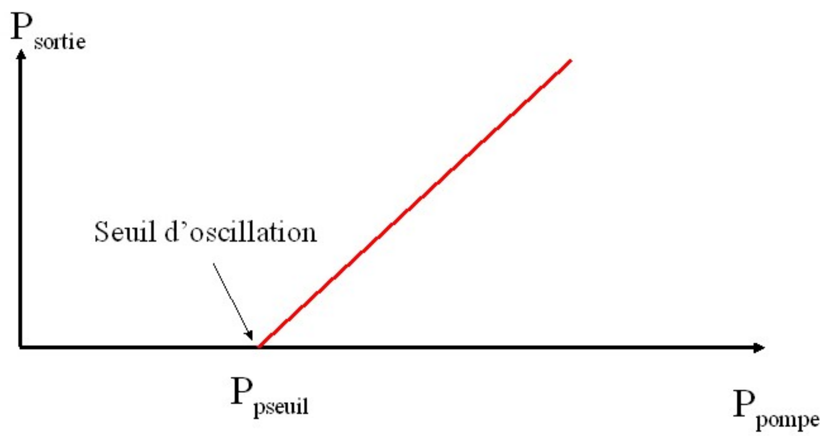

Figure E13 : Courbe d'efficacité du laser : puissance de sortie en fonction de la puissance de pompe.

Appendix 2 : pump system specifications

Description of the emission diagram of the laser diode

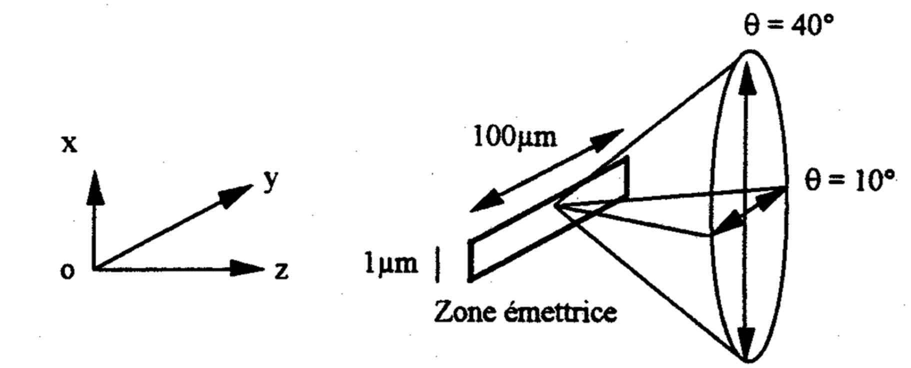

Figure 1.2 – description of the emission diagram of the laser diode

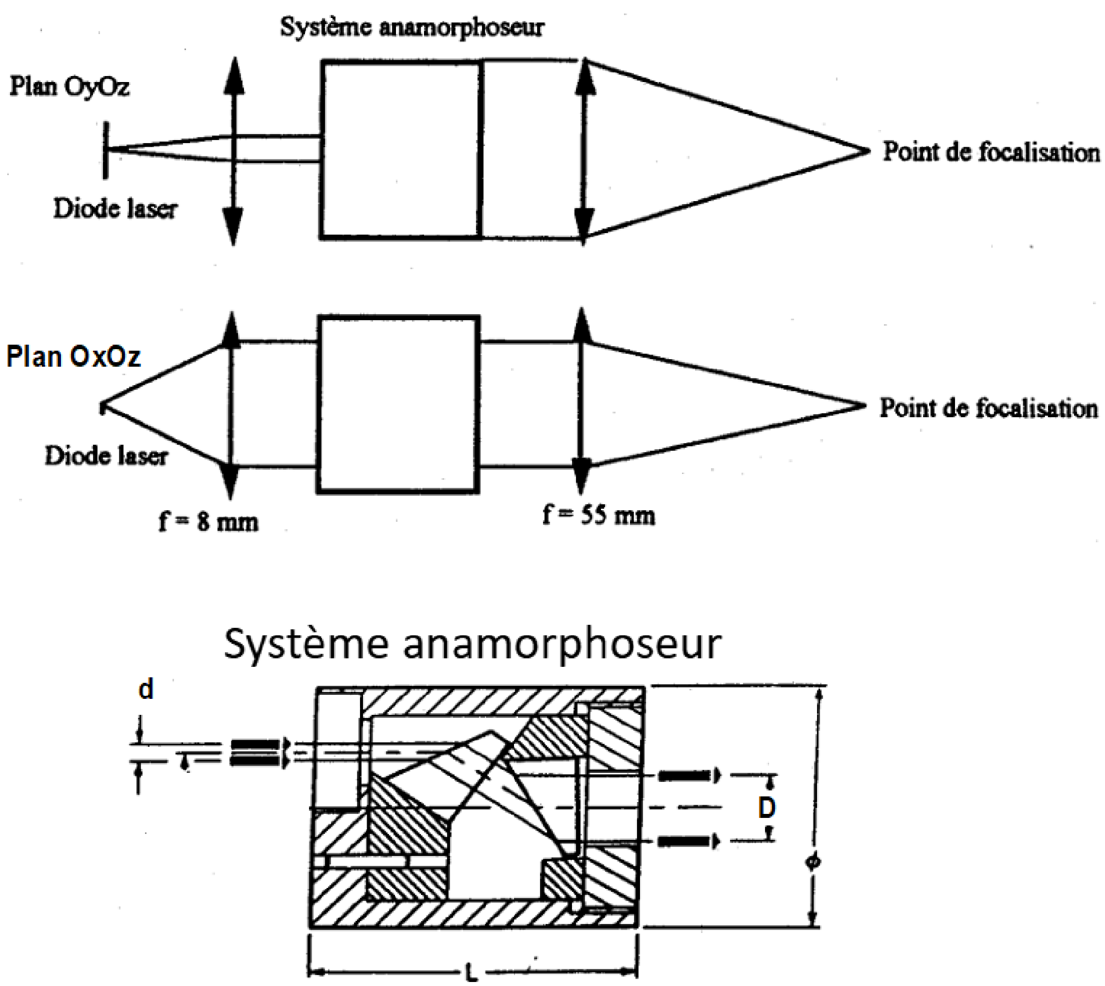

Figure 1.3 – description of the anamorphic pumping system

Lab 2

Laser diode

Contents

Skills to be acquired with this TP

The skills to be acquired in this labwork, classified in 3 categories, are the following:

"Experimental" Skills:

- Coupling of a laser beam into an optical fiber

"Measurement" Skills:

- Use of an optical spectrum analyzer
- Use of a Fabry Perot Scanner
- Measurement of the laser diode performance (spectrum and output power) as a function of temperature and current

"Physics" skills:

- Analyze power and spectrum measurements and correlate them to semiconductor and laser physics
- Understand the effect of amplitude modulation on a laser spectrum

Pre-requisite

- General notions on laser physics from the first year course : cavity, mode, gain, amplifying medium, losses, laser threshold
- Principles of a Fabry-Perot analyzer
- Principles of a grating spectrometer
- Reading of the appendix on the description of laser diodes
- Laser safety

Laser safety specific to the TP

The laser diode emits a maximum power of about 30 mW in the near infrared (795 nm), thus at the limit of the visible spectrum. This power corresponds to 30 times the burn threshold of the eye. The diode is thus dangerous in direct vision and in "specular" reflection (for example on a watch glass or on an optic).

Wear protective glasses when you move elements of the setup.

1 The labwork at a glance

Laser diodes are the most widespread lasers. They represent 40% of the world market of laser sources. They have the advantage of using an electrical pumping and having an excellent electrical-optical efficiency (up to 50%). They are very compact and can provide powers of several tens of watt with dimensions of few cm. The most used wavelengths are in the blue, red and near infrared (800 nm-980 nm and 1400-1550 nm) regions.

The goal of this labwork is to characterize a laser diode in power and spectrum and to understand its behavior as a function of current and temperature. The laser diode used here is a low power (30 mW max) transverse single mode diode whose datasheet is available in appendix 3.

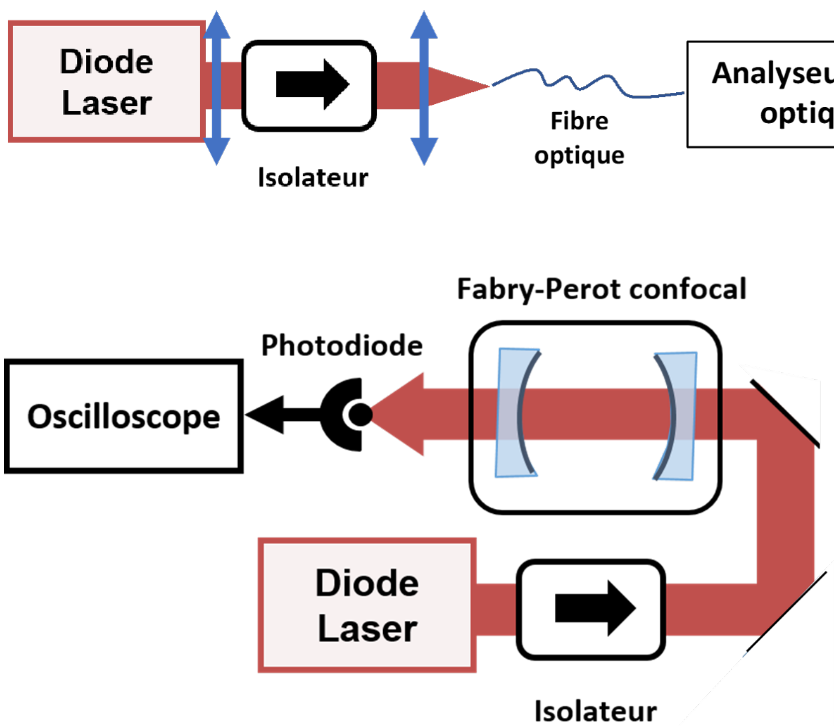

Figure 2.1 – global view of the laser diode with OSA analysis (top) and confocal Fabry-Perot analysis (bottom)

The global setup is described in figure 2.1. As the radiation from the laser diode is very divergent, it is necessary to collimate it by a lens to be able to propagate it all throughout the experiment.

The output mirror of the laser diode is weakly reflective (of the order of a few %), the laser diode is therefore very sensitive to light feedbacks. They can change its performance in temrs of power and spectrum. To avoid this, a Faraday isolator is placed after the collimation lens. It is composed of a Faraday rotator and two polarizers oriented at 45 degrees one from another.

The power measurement is performed by a power meter using a silicon cell.

The measurement of the spectrum is carried out by two different devices:

- a grating spectrometer, also called optical spectrum analyzer (or OSA for Optical Spectrum Analyser, cf. appendix 5)
- a scanning Fabry Perot interferometer

These two devices have very different spectral bandwidths: the OSA allows a measurement on a broad spectral range of several hundred nanometers. It has a maximum resolution of about 0.05 nm. The Fabry Perot has a much smaller resolution, related to its Lorentzian finesse but has an analysis range limited by its free spectral range.

The input of the OSA is fibered. It is thus necessary to inject the beam of the laser diode into the optical fiber of the OSA. This injection is done by means of a focusing lens close to the input face of the optical fiber. The observation of the beam (which is at the extreme limit of the visible spectrum) is done by means of an infrared viewing card.

2 Experimental activities

2.1 Output power versus current

We are interested in this part in the output power of the laser diode as a function of the supply current. The output power is measured with the power meter, placed at the output of the laser diode, before the Faraday isolator.

Q1 Draw the efficiency curve $P_{\mathrm{out}} = f(I)$ (I in mA) for temperature values of 5 kΩ and 20 kΩ and draw linear fits after the threshold to derive accurately the laser efficiency (in mW/mA) end threshold current (in mA) and comment the differences between these two cases.

2.2 Setup for a measurement with the optical spectrum analyzer

$\rightsquigarrow$ Put the laser diode at maximum current (about 100 mA) and with a temperature close to room temperature (corresponding to a thermistor of 10 kΩ). Check the power of the diode at the output of the Faraday isolator (about 5 mW).

The optical fiber of the OSA is a multimode fiber whose core has a diameter of 50 µm. The coupling of the laser diode beam into this fiber requires an accurate adjustment related to the position of the focusing lens which is mounted on x/y translations perpendicular to the optical axis and a z translation along the optical axis. To achieve efficient injection, we first look at the power transmitted through the fiber, before it is connected to the OSA.

$\rightsquigarrow$ Disconnect the fiber from the OSA and plug it on its specific support equipped with a fiber connector on the optical table (vertical plate fixed on a rail). Place the power meter just behind, next to the plate.

$\rightsquigarrow$ Place the rail containing the focusing lens and the fiber holder on the bench, after the Faraday isolator, making sure that it is roughly aligned with the laser beam propagation axis. Then adjust the position of the focusing lens along the three axes to optimize the power coupled into the fiber.

Note : The adjustments must be made step by step. Indeed, the translation along the mechanical axis z, is not necessarily parallel to the optical axis of the lens nor to the optical axis of the optical fiber. For each focusing test, it is therefore necessary to check that the beam is well centered with respect to the center of the fiber in x/y.

C1 Have checked the setting and the coupled power in the fiber and give the coupling efficiency in the fiber.

2.3 Dependance of the spectrum on temperature and current

⇝ Set the laser diode to a fixed temperature (e.g. 10 kΩ) and observe the evolution of the diode spectrum as the current is varied (above the laser oscillation threshold). It should be noted that the oscillation wavelength evolves in a continuous piecemeal fashion: first, a linear evolution is observed over a certain current range, until a fairly clear mode-hopping is observed. If none of these hops is visible over the whole current range, change the temperature by a few kΩ.

⇝ Start by taking measurements over a wide current range and determine the overall evolution of the diode's oscillation wavelength in nm/mA, including mode hops.

⇝ Do the same measurements over a much smaller interval, taking care to maintain a continuous evolution of the diode spectrum, and determine the slope of the curve in nm/mA.

⇝ Repeat the same protocol at fixed current (approx. 100 mA), this time varying the temperature from 5 kΩ to 20 kΩ, first over a wide span (including hops) and then over a more restricted range (continuous evolution).

Caution: Check that the temperature has stabilized before taking any measurements. Temperature stabilization can often take a while, especially for large variations.

⇝ From these measurements, deduce the two coefficients of variation in wavelength with respect to the temperature, in nm/°C.

Q2 Summarize in a table the evolution of the diode spectrum as a function of current and temperature, in the two operating regimes (continuous or stepwise).

Note: The following sections (2.4 and 2.5) will help you understand the mechanisms behind the evolution of the diode's spectrum, both in terms of linear evolution and the origin of mode hopping.

2.4 Observation of the fluorescence spectrum of the laser diode

As indicated on the optical power versus current characteristic (see appendix 3), the laser diode has a current oscillation threshold. Below this threshold, the emitted power is very low, mainly due to spontaneous emission. It is however measurable. Its spectral analysis gives a lot of information on the behavior of the laser diode. The goal of this part is to observe experimentally the spectral behavior which is given on the figure 2.3 of the appendix 1 and to understand the evolution by jumps observed in the previous part.

The observation below the emission threshold allows to follow the evolution of the modes without being disturbed by the laser effect which strongly changes locally the shape of the spectrum (longitudinal mode which oscillates).

⇝ Choose a current below the threshold current of the laser diode. Observe on the OSA the fluorescence spectrum of the laser diode. This spectrum is located around 790 nm and has a spectral width of several tens of nanometers.

C2 Superimpose on the OSA the curves at 5 kΩ and at 20 kΩ and have them checked.

Q3 Measure the shift of the top of the fluorescence spectrum as a function of temperature in nm/°C and compare it to the value found in Q**??**.

Q4 While remaining under the oscillation threshold, measure the shift of the top of the fluorescence spectrum as a function of the current in nm/mA and compare it to the value found in Q**??**.

2.5 Laser diode longitudinal mode evolution

The fluorescence spectrum of the laser diode is filtered by the Fabry-Perot cavity because it is observed in the output axis of the laser cavity. The OSA is sufficiently resolving to observe these longitudinal modes. We can therefore observe the transmission peaks of the Fabry-Perot cavity which are also the longitudinal modes of the laser cavity. In the following, we "zoom" strongly around the maximum of emission of the laser diode to observe these modes. Thanks to the dynamics of the OSA, we can observe as much the longitudinal modes which oscillate as the modes which don't.

Q5 Measure the free spectral range of the Fabry-Perot cavity of the laser diode with the OSA and compare it to the theoretical order of magnitude (a laser cavity of 0.5 mm length and a refractive index of 3.7).

⇝ Above the oscillation threshold, follow the spectral evolution of a longitudinal mode which does not oscillate as a function of the current (typically over 10 - 20 mA)

Q6 Measure the value of the shift of a mode as a function of the current in nm/mA.

Q7 Repeat this study by changing the temperature over a range of a few ˚C .

Q8 Measure the value of the shift of a mode as a function of the temperature in nm/°C.

Q9 Make a summary table of the different measurements. This table should give you orders of magnitude concerning the evolution of the gain curve and the evolution of the longitudinal modes as a function of the temperature and the current.

2.6 Effect of a fast modulation on the emitted spectrum

By modulating the current injected in the diode, it is possible to modulate its output power. The dynamics of the carriers being very fast (the typical life time of the carriers is of the order of the nanosecond) the modulation bandwidths attainable are of a few GHz. These very large bandwidths along with the simplicity of implementation were at the origin of the interest of laser diodes in the field of optical telecommunications. Up to 2.5 Gbits/s, the transmitted information is obtained by direct modulation of the laser diode.

The high frequency modulation of the laser diode current is realized by a generator delivering a sinusoidal signal of variable frequency in the range 1 Hz - 1.2 GHz, and of electric power ranging between -127 dBm and + 13 dBm (i.e. 2.10^{-13} mW and 20 mW). The modulation of the laser diode is carried out through a "bias T", which superimposes the modulated signal on the DC supply current.

The amplitude modulation of the signal emitted by the laser diode, which is an optical wave, will have an effect on the spectrum emitted by the diode (see appendix). The purpose of this part is to observe this effect.

To do so, we use a spectrum analyzer much more resolving than the OSA: it is a Fabry-Perot scanner. The distance between its mirrors is modulated through a piezoelectric device. The system involves a silicon photodiode at the back of the output mirror, as well as a focusing lens at the input (see labwork He-Ne of first year). The global assembly is described in figure 2.1.

⇝ Remove the injection assembly in the OSA fiber and check that the beam is well injected in the Fabry-Perot.

C3 Have the assembly checked with the oscilloscope ready to make a measurement of the evolution of the spectrum by the Fabry-Perot.

⇝ Connect the cable allowing to apply a current modulation of the laser diode. Gradually increase the power of the modulation from a value of -40 dBm, until you see sidebands around the Fabry-Perot peaks.

Q10 Take a picture of the effect of the current modulation on the spectrum of the laser diode and comment your observations.

⇝ Modify the modulation frequency between 100 and 250 MHz to see the effect on the Fabry-Perot signal.

Q11 Using the fact that the frequency gap between two transmission peaks is equal to the free spectral range of the Fabry-Perot (1.5 GHz), measure the frequency gap between the central peak of the signal and a sideband. Compare this gap to the applied modulation frequency.

Appendix 1 : preparation

Short review on semiconductor physics

Laser diodes are laser sources based on semiconductor materials. More precisely, the amplifying medium of laser diodes is a direct biased PN junction, i.e. fed by a direct current from the anode to the cathode (see figure 2.2). Laser diodes are made by doping a thin layer deposited on a crystalline substrate. The cleaved faces of the semiconductor crystal on either side of the junction constitute the mirrors of the laser cavity.

Under the effect of an electric current, a process of light emission occurs at the interface between the doped layers respectively P and N, by recombination of the conduction electrons, majority carriers in the N layer, with the valence holes, majority carriers in the P zone. The emitted photons have then an energy close to the gap energy of the semiconductor material of the junction. Above the threshold, the light power emitted by the laser is proportional to the supply current.

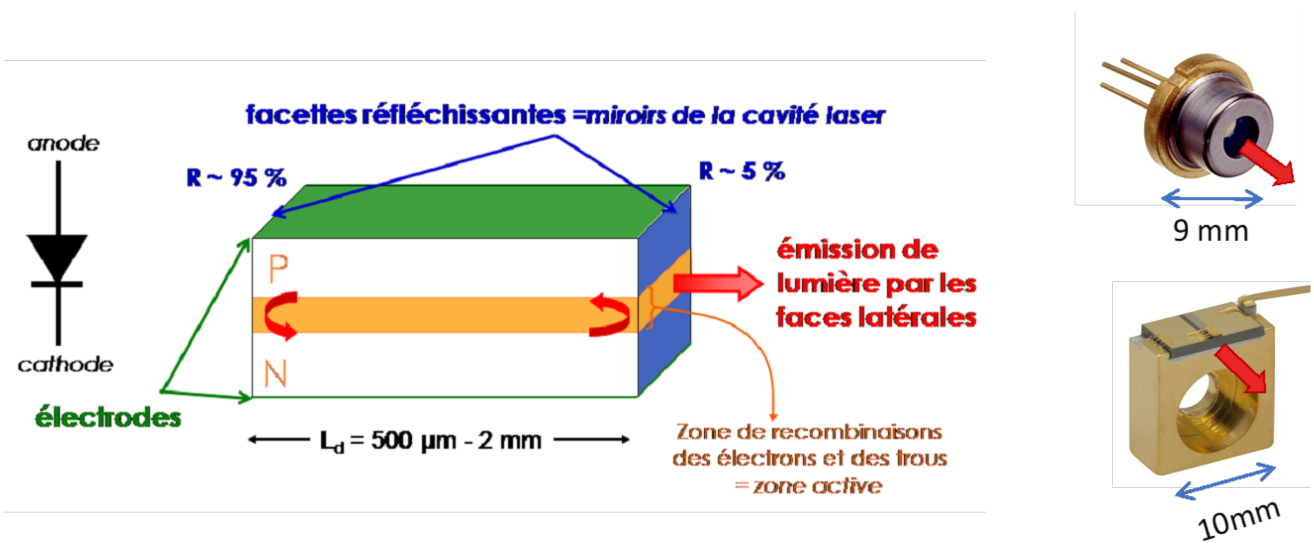

Figure 2.2 – Structure of a laser diode (left) and examples of laser diode packages (right)

A specificity of laser diodes is the spectral range on which the emission of light can occur, of the order of ten nanometers. This results in a tunability of the emission wavelength, as we will see during this labwork.

Several properties of semiconductor physics explain this tunability of laser diodes:

- The width of the gain curve as a function of the wavelength, due to the existence of bands and not to discrete energy levels. This gain curve is deduced from the carrier distribution statistics in the valence and conduction bands, dictated by the Fermi-Dirac statistics. In this case, the gain broadening is of homogeneous type.

- The gap energy E_G of the semiconductor material depends on the temperature; more precisely, E_G decreases when the temperature increases. In other words, an increase in temperature shifts the gain curve towards longer wavelengths (see figure 2.3).

- The electric power which is not converted into optical power (efficiency of electric/optical conversion of the order of 50%) is converted into heat. Thus, the circulation of an electric current induces a heating of the diode, and thus a modification of the wavelength of emission.

- Moreover, the temperature directly influences the length of the cavity and the effective refractive index of the amplifying medium. Thus, an increase in temperature, leading to an expansion of the optical length of the cavity, results in shifting the emission wavelength.

- The temperature has a spreading effect on the distribution of carriers in the bands. Thus, the density of carriers decreases with temperature. This is the main effect that explains the decrease of the linear gain.

We can therefore modify the emission wavelength by changing either directly the temperature or the supply current.

Figure 2.3 presents curves of gain corresponding to various currents and temperatures, where one can observe the shift in wavelength. As in any laser, the lasing effect occurs provided that the gain exceeds the losses. Figure 2.3 also shows that the threshold of laser oscillation increases with temperature.

Implementation of a laser diode

Figure 2.2 right shows boxes on which laser diodes are mounted. These boxes are supplied with current and regulated in temperature because since the temperature plays an important role in the nature of the emission of a laser diode.

Temperature control

In general, the laser diode is mounted on a copper block regulated in temperature by means of a Peltier element : it is a thermoelectric device based on a semiconductor which imposes a temperature difference $DeltaT$ between its two faces according to the current supplied. In particular, this device is able to heat or cool the laser diode support, depending on the sign of the current that drives it. The maximum current supported by the Peltier element is 2 A.

A thermistor measures the temperature of the case: it is a resistance whose value depends on the temperature. In general, the resistance decreases when the temperature increases. The one used in the labwork has a value close to 10 kΩ at room temperature. The calibration curve of the thermistor is given in the following. In the text of the labwork, we assimilate the temperature to the value of the thermistor, by language abuse.

The temperature controller drives the temperature of the diode by controlling the supply current of the Peltier to compensate for thermal fluctuations measured by the thermistor, and thus to impose a constant temperature .

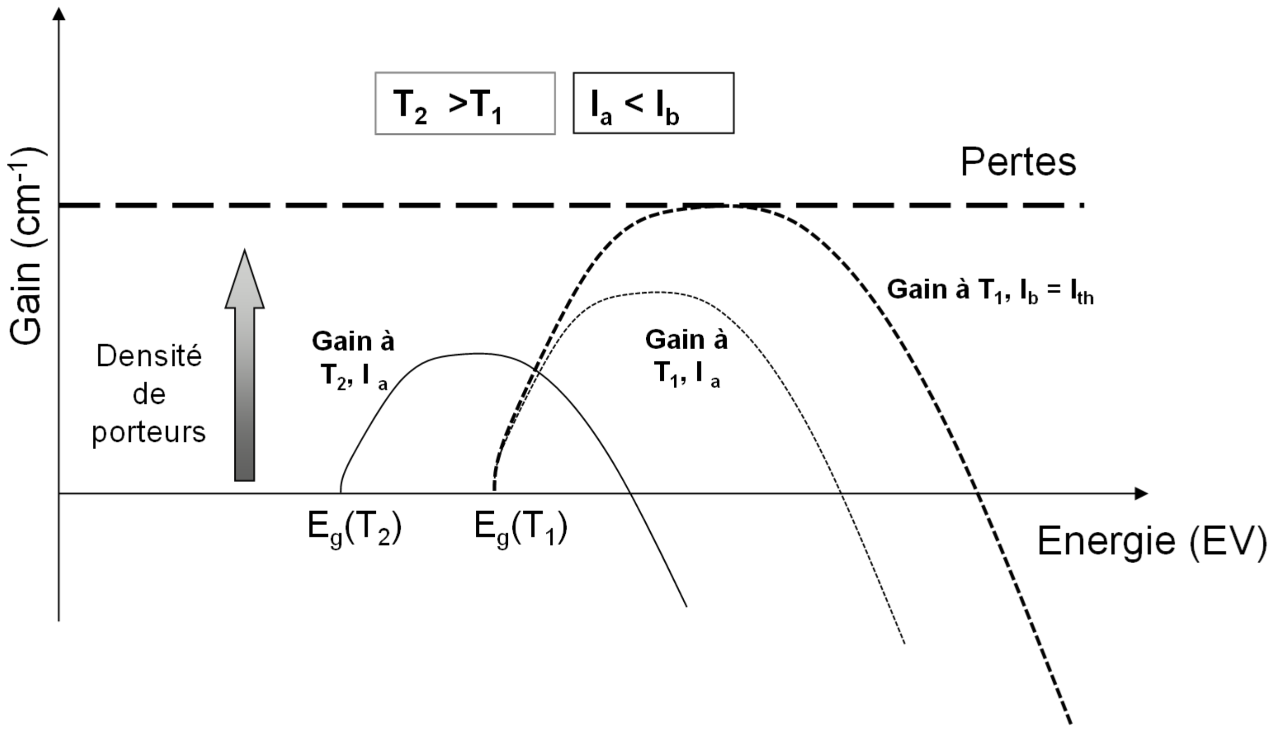

Figure 2.3 – evolution of the gain curve of a laser diode as a function of the photon energy according to the values of the pumping current and the temperature

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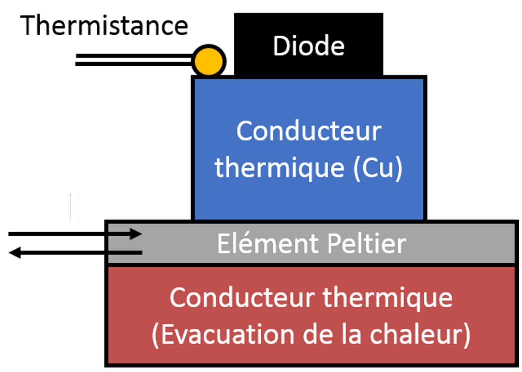

Figure 2.4 – schematic diagram of the laser diode temperature control system

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Current control

Laser diodes are simple components to use, but very fragile from an electrical point of view. They are very sensitive to electrostatic discharges. Handling laser diodes therefore requires special precautions: never touch them when they are powered and never disconnect them from their power supply, which is designed to protect them from electrostatic discharges.

Laser diodes are very sensitive to sudden changes in supply current and to exceeding the maximum allowed current, even for a very short time. Therefore, laser diodes are driven by specific current supplies, stabilized and protected from interferences. The maximum supply current is limited to 150 mA.

For safe operation of the laser diode, the current generator must always be set to zero before being switched off or on. The laser diode must not be switched off abruptly using the power switch or the electrical panel.

Appendix 2 : current modulation on a laser diode

In the absence of current modulation, the light emitted by the laser diode used in the lab has a monochromatic spectrum and a constant optical power. The modulation of the electric current of the diode leads to a modulation of power and frequency of the emitted light.

For frequencies below GHz, the optical/electrical efficiency (in mW/mA) and the frequency variation coefficient (in nm/mA) are expected to be about the same as in continuous operation (see the results of the 2.6 part). In the following, we are only interested in the power modulation.

Let a power modulation of the type $P(t) = P_0 \left[1 + M \cos(2\pi F_{\mathrm{m}} t)\right]$, where P_0 is the unmodulated power, $P(t)$ the modulated power and M is called the power modulation index. The signal received by a photodiode will thus be modulated at the frequency F_{m}.

For a low modulation index M, the electric field of the light can be written :

$$E_{\mathrm{L}}(t) = A \left[1 + \frac{M}{2}\cos(2\pi F_{\mathrm{m}} t)\right] \cos(2\pi \nu_{\mathrm{L}} t + \phi_{\mathrm{L}})$$

or:

$$\begin{aligned} E_{\mathrm{L}}(t) &= A \cos(2\pi \nu_{\mathrm{L}} t + \phi_{\mathrm{L}}) \\ &+ M\frac{A}{4} \cos\left(2\pi \left(\nu_{\mathrm{L}} - F_{\mathrm{m}}\right) t + \phi_{\mathrm{L}}\right) \\ &+ M\frac{A}{4} \cos\left(2\pi \left(\nu_{\mathrm{L}} + F_{\mathrm{m}}\right) t + \phi_{\mathrm{L}}\right) \end{aligned}$$

The above expression highlights the fact that the power-modulated laser wave decomposes, at first order, into three optical frequencies: the carrier at ν_{L} and two sidebands of same amplitude at $\nu_{\mathrm{L}} - F_{\mathrm{m}}$ and $\nu_{\mathrm{L}} + F_{\mathrm{m}}$. The powers associated to each peak of the spectrum are proportional to $A^2/2$ for the central peak, and $M^2A^2/2$ for the sidebands. We notice in particular that the intensity of the central peak does not depend on the modulation index M.

Appendix 3 : laser diode datasheet

MITSUBISHI LASER DIODES

ML6XX10 SERIES

FOR OPTICAL INFORMATION SYSTEMS

ABSOLUTE MAXIMUM RATINGS

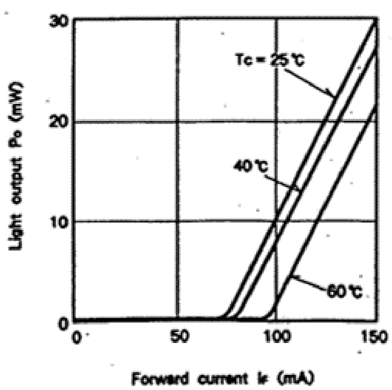
Symbol	Parameter	Conditions	Ratings	Unit
Po	Light output power	CW	35	mW
		Pulse (Note 1)	45	
V_{RL}	Reverse voltage (laser diode)	–	2	V
V_{RD}	Reverse voltage (Photodiode)	–	30	V
I_{FD}	Forward current (Photodiode)	–	10	mA
Tc	Case temperature	–	−40～+60	℃
T_{stg}	Storage temperature	–	−55～+100	℃

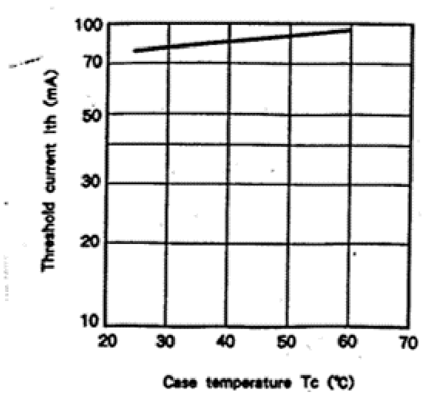
Note 1 : Duty less than 50 %, pulse width less than 1 μs.

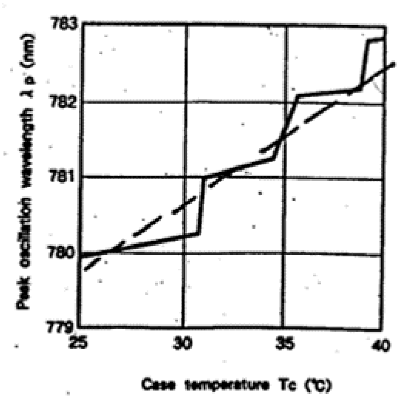
ELECTRICAL/OPTICAL CHARACTERISTICS (Tc = 25℃)

Symbol	Parameter	Test conditions	Limits Min.	Typ.	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	μA
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.







Appendix 4 : thermistor datasheet

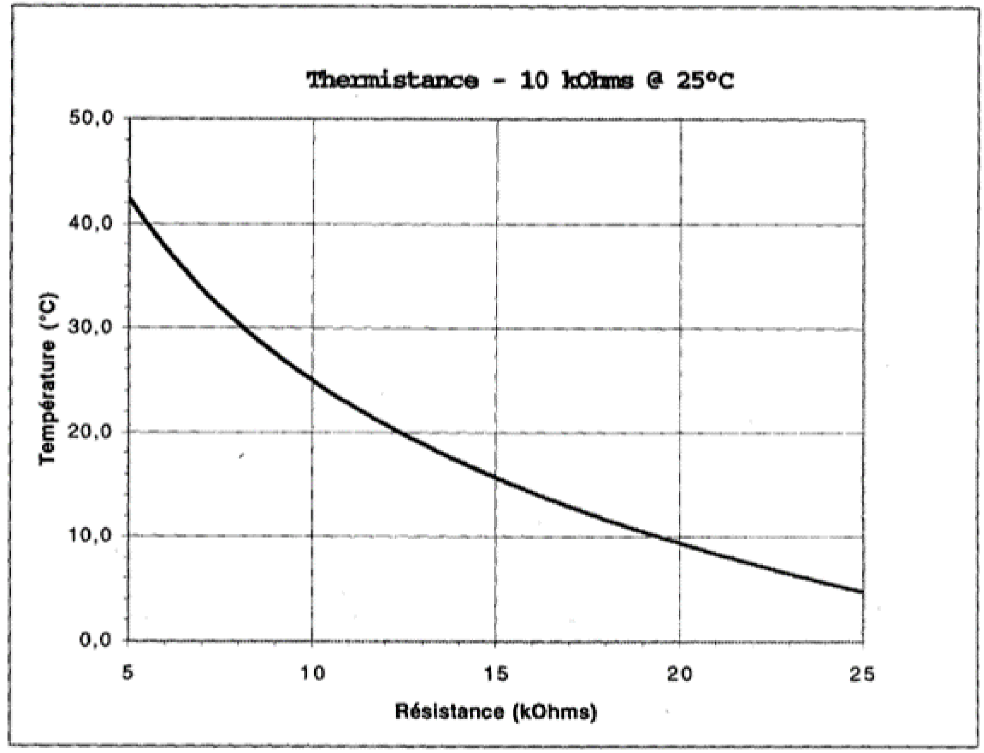
Appendix 5 : optical spectrum analyzer

The schematic diagram of the OSA is presented in figure 2.5. Its input is optical: it is connected through an optical fiber carrying the signal to be studied. It is followed by a tunable optical filter of width RBW (for "Resolution BandWidth") which sweeps a defined spectral range (the excursion or "SPAN") periodically. The filter is followed by a photodetector of high sensitivity followed by an electrical amplifier of high dynamics. The dotted optical attenuator is only used when the input optical power exceeds the maximum allowed power (10 dBm, i.e. 10 mW).

The curve displayed on the screen of the OSA represents the power in the RBW band as a function of λ, that we can note $P_{\mathrm{RBW}}(\lambda)$. The RBW is thus the width at half maximum of the peak displayed by the OSA when seeded by a quasi-monochromatic optical signal. The default display is in logarithmic units (powers in dBm).

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



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

avec $B = 3750K$

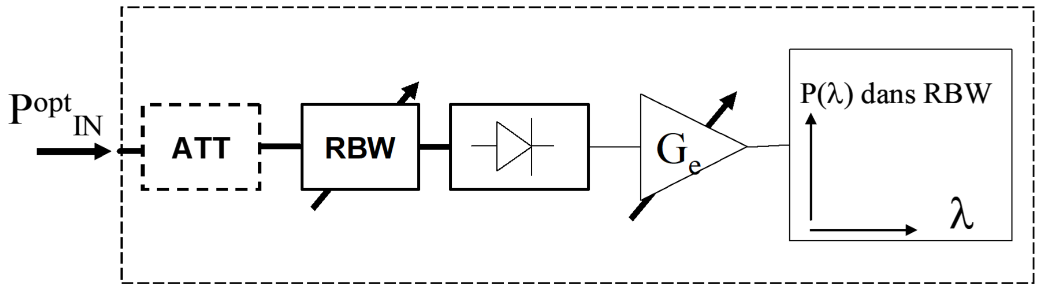


Figure 2.5 – schematic diagram of the optical spectrum analyzer

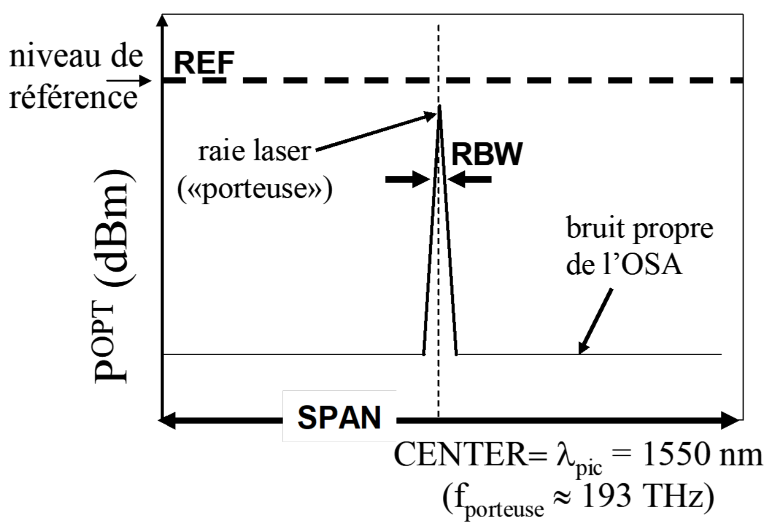


Figure 2.6 – representation of the settings and measurements of the OSA

Lab 3

Fiber laser and amplifier

Contents

Skills to be acquired with this labwork

The skills to be acquired in this labwork, classified in 3 categories, are the following:

"Experimental" skills :

- Use of fibered components (assembly by block using fiber patchcords and various types of connectors).
- Realization of a fiber amplifier and a fiber laser.

"Measurement" skills:

- Use of an optical spectrum analyzer
- Measure the performance of a fiber amplifier (gain, efficiency, noise level).
- Measure the performance of laser cavities (power, efficiency).

"Physics" skills:

- Analyze the spectroscopic properties of a broadband optical amplifier.
- Analyze the efficiency and gain curves of erbium-doped fiber amplifiers.
- Understand the amplified spontaneous emission and its influence on the output signals of a fiber amplifier.

Prerequisite

- General notions on the laser physics from the first year course : amplifying medium, gain, gain saturation, amplified spontaneous emission, effective cross section, linear cavities
- Review of the TD n°2 of the first year course on the erbium-doped fiber amplifier
- Reading of the appendix 1 on fiber amplifiers and answering the preparation questions (correction at the beginning of the session)
- Laser safety

Laser safety specific to this labwork

The pump laser diode emits a power of the order of 50 mW in the near infrared (980 nm), which is 50 times the damage threshold for the eyes. However, this pump beam remains confined in optical fibers when the experiment is in place. It is however essential to systematically switch off all sources (pump and signal) before disconnecting and reconnecting fibers. Only turn on the sources when the assembly is all-fibered.

The laser signal to be amplified (or generated in a cavity) has a spectrum around 1550 nm, with powers of the order of a few mW, without danger for the eyes in this spectral band known as eye-safe.

Special precautions for optical fibers

Fiber inputs/outputs at connector level are particularly fragile and sensitive to dust. The power density can be very high, and even simple contamination can lead to burning of the fiber output faces, causing irreversible damage. It's essential never to touch the fiber output facets directly, and to **always switch off pump and signal power** when handling the assembly (disconnections, reconnections).

1 The labwork at a glance

The Erbium-Doped Fiber Amplifier (EDFA) is probably the most widely used optical amplifier, especially in fiber optic telecommunications networks. Indeed, the gain of the erbium ion extends over a wide band of several tens of nm around 1550 nm, allowing the transmission of information at very high speed by spectral multiplexing. This average wavelength also corresponds to the minimum internal losses of optical fibers. The signal propagation can thus be done on very long distances (kilometers), with however the need to re-amplify the signal regularly in order to compensate for the losses and preserve all the information. These amplification steps must be done with maximum efficiency and minimum noise. A more detailed description of erbium-doped fiber amplifiers is given in the appendix 1.

The principle of this labwork is to realize and characterize an amplification system and a laser cavity using fiber technology. We have a pump diode at 980 nm, whose output is fibered, and a signal diode to amplify emitting at wavelengths ranging from 1500 to 1600 nm, also fibered. The pump power is adjustable by the injection current of the diode, and an optical attenuator inserted after the signal source allows to modify its power accurately. The two laser sources are grouped within the same fiber by means of a multiplexer ("Y" coupler), whose output is connected to a doped fiber. The output beam is characterized in power and spectrum by means of an optical spectrum analyzer (OSA). All the components, their operation and their precautions of use are presented in appendix: read it carefully before starting the manipulations.

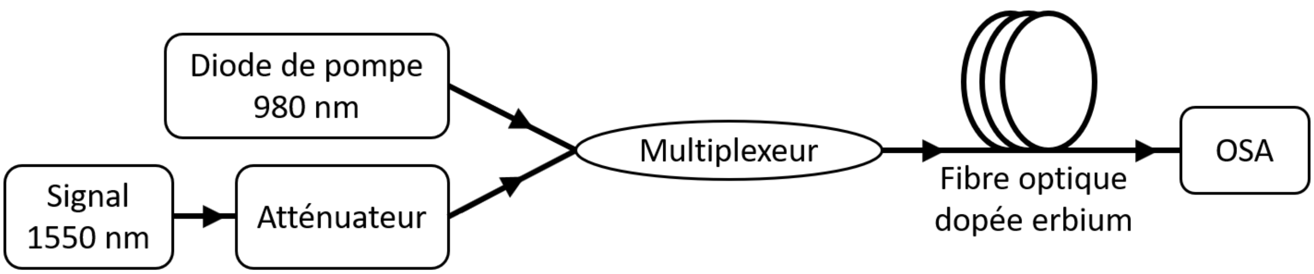


Figure 3.1 – schematic diagram of the system.

The first part focuses on the spectroscopic properties of the Er^{3+} ion inserted in an optical fiber (glass) by studying the spontaneous emission of the system and observing the available radiative transitions. In a second part, we also study the amplified spontaneous emission in a very long doped fiber (20m) to observe the behavior of the gain over broad spectral bands.

In the second part, we study the performance of the erbium doped fiber as an amplifier. We characterize the behavior of the amplifier as a function of the pump power and the injected signal power.

Finally, we place this amplifier in a laser cavity and characterize the oscillator performances.

2 Experimental activities

2.1 Study of pump and signal sources

The pump power is controllable with a potentiometer allowing to adjust the supply current of the pump diode, displayed in mA. The figure 3.2 shows the characteristic curve of the diode and its equation.

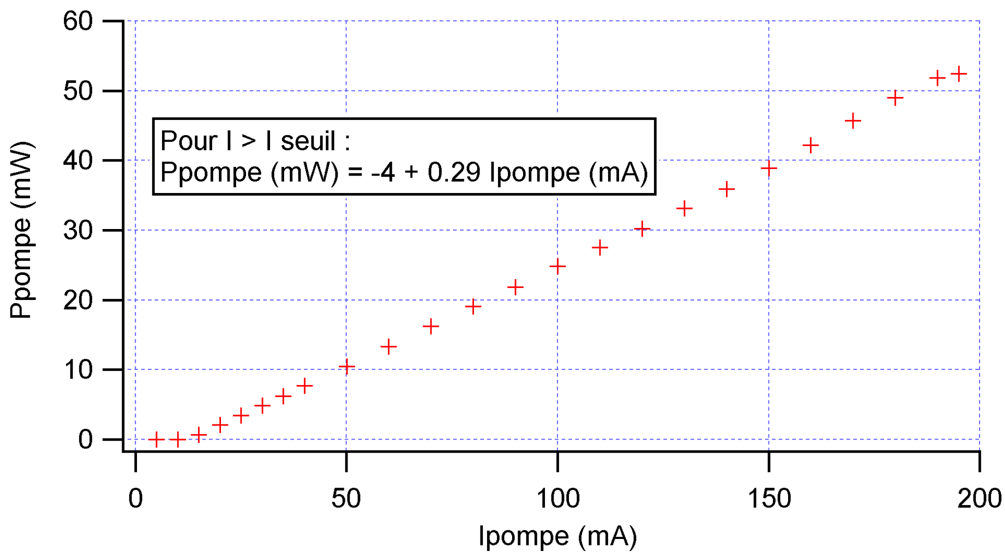


Figure 3.2 – Characteristic curve and equation of the pump diode at 980 nm

⇝ We start the manipulations with all the laser sources turned off and the potentiometer of the pump diode at 0 mA. Connect the output of the signal diode to the input of the attenuator with losses set to the minimum. Then connect the output of the attenuator and the pump diode to the multiplexer to their respective input ports. Finally, connect the output of the multiplexer directly to the OSA.

Caution: the OSA cannot handle powers higher than 10 mW (10 dBm). The pump diode, up to 50 mW, is likely to damage the OSA irreversibly. Always remember to set the pump potentiometer to 0 mA before switching it off: otherwise, turning it on suddenly without knowing the supply current can lead to bad surprises.

⇝ Switch on the pump diode at 0 mA and gradually increase its current to 30 mA (power < 10 mW). Also turn on the signal source (at maximum power, no risk for the OSA from the laser signal).

⇝ Observe first the signal spectrum on a sufficient spectral width (window of 100 nm around 1550 nm). Check that its wavelength is indeed at 1550 nm, otherwise adjust it using the potentiometer.

Q1 Measure the power in dBm of the signal source using the OSA for two different resolutions, one intermediate (1 nm) and the other as low as possible. Explain why these two measurements are different.

Q2 Study the spectrum of the pump diode around 980 nm : what is its spectral width ?

Q3 Measure the total power of the pump diode in dBm using the OSA and justifying your method. Compare it with the characteristic curve of the diode.

2.2 Spectroscopic properties of the Er^{3+}-doped fiber

This part is dedicated to study of the spectroscopy of the erbium ion inserted in glass (Er^{3+}:SiO_2 system) by comparing the experimental observations with the data provided in appendix. To do so, we measure the spontaneous emission spectrum (fluorescence spectrum) of a doped fiber as well as the amplified spontaneous emission spectrum (ASE spectrum, see appendix). The signal diode will remain turned off in all this part.

Fluorescence spectrum

⇝ After turning off all the laser sources, insert the 1 m doped fiber (green patchcord) between the multiplexer and the OSA, using the necessary components and adapters to connect them together.

Caution: The 1 m doped fiber is too short to absorb all the pump power at full power, so there is still enough residual pump power at the fiber output to risk damaging the OSA. Once again, be very careful about the level of pump power used.

C1 Turn on the pump diode at 0 mA then gradually increase its current to 50 mA (residual power < 10 mW). Observe the spectrum at the output of the OSA doped fiber between 1500 and 1600 nm in linear scale (be careful, the OSA displays the spectra in logarithmic scale by default).

Q4 Rigorously speaking, which spectrum is observed under these conditions? Is it comparable to the spectroscopic data provided in the appendix?

Q5 Explain why it is necessary to use a short fiber in this experiment. Suggest another more rigorous method for measuring the fluorescence spectrum (if not using an even shorter fiber...).

Amplified spontaneous emission (ASE) spectrum

In this sectino, we study the ASE spectrum at different pump power levels using the 20 m long doped fiber. The system is designed such that, at full pump power, the population inversion is maximal along the entire fiber with little residual pump power at the output. It is therefore possible to use the full power excursion of the pump diode for the following experiments, without risks of damaging the OSA.

⇝ Replace the 1 m doped fiber with the 20 m one (in on of the racks of the IDIL box) and switch the OSA to logarithmic scale.

C2 Measure the spectra between 1500 and 1600 nm for various pump powers (4 or 5 values, by exploiting at best all the power excursion of the diode). Store each of them in the OSA to observe them simultaneously.

Q6 Comment on the evolution of the shape of the ASE spectrum and give an interpretation using the gain curves of the erbium doped fiber provided in appendix.

2.3 Performances of the Er^{3+}-doped fiber amplifier

The objective of this section is to characterize the performance of an erbium-doped fiber amplifier at the signal wavelength of 1550 nm. We will be particularly interested in the efficiency curve of the amplifier (output signal power vs. pump power) and the behavior of the gain as a function of the pump and signal powers. The OSA allows to measure the power at the signal peak at 1550 nm, thus allowing to eliminate the power of the ASE at the neighbouring wavelengths without biasing the measurement (something that we cannot do with a simple power meter).

In this part, it is necessary to modify the injection power of the signal accurately. To do so, we use the optical attenuator (already inserted in the setup), whose losses are expressed in dB. From the measurement of the signal power at the multiplexer output in the first part (with minimal attenuation), it is easy to deduce the injection power in the amplifier for any attenuation value. This avoids systematically disconnecting/reconnecting the input signal to measure its power.

Measurement of the characteristic curve

⇝ Adjust the attenuator so as to obtain an input signal power of -20 dBm.

Q7 Measure and plot the evolution of the output signal power as a function of the pump power (in Watts for each). Deduce the amplification efficiency and compare it to the quantum efficiency of the laser system.

Measurement of the gain versus the injection signal power

The focus of this section is on the evolution of the performances of the amplifier as a function of the input signal power, at full pump power. To do so, we start from the maximum signal power, then progressively increase the attenuation and stop when the signal observed at the OSA at the fiber output is "drowned" in the ASE (insufficient signal, around the -40 dBm of injection power).

For the following measurements, the spectral bandwidth (RBW) of the OSA shall be set at **the minimum** to properly discriminate the signal and the ASE, and avoid misleading measurements.

Q8 Set the pump power to its maximum (current at 200 mA) and measure the output power of the signal as well as the power of the ASE, read just next to the signal (at the edge of the peak at 1550 nm) as a function of the injection power of the signal

Q9 Plot the evolution of the gain of the amplifier (in dB) as a function of the input signal power (in dBm).

Q10 Plot the ASE signal power (in dBm) measured at the edge of the signal spectrum as a function of the input signal power (in dBm).

C3 Highlight the gain saturation phenomenon from the results obtained in questions Q9 and Q10. Determin and explain its impact on the ASE signal.

2.4 Er^{3+}-doped fiber laser

This part is dedicated to designing and imlementing a linear laser cavity. The signal at 1550 nm will thus not be useful in the following. The output coupler used for the laser cavity is a Bragg mirror, which is reflective only on a narrow spectral band, the rest of the spectrum being totally transmitted. It is thus on this spectral band that we can expect a laser effect.

Characterization of the Bragg mirror

To study the Bragg mirror, we measure its transmission using the OSA to highlight its spectral selectivity. We also need a very broad spectrum to study the spectral transmission: the amplified spontaneous emission of the doped fiber will do the trick.

⇝ Starting from the setup of the previous part, turn off the signal at 1550 nm and disconnect its patchcords from the multiplexer.

⇝ Increase the pump power to the maximum (200 mA). If a spurious laser effect appears at the OSA, decrease the pump power until it disappears.

Q11 Insert the Bragg mirror after the doped fiber and measure the ASE spectrum at the output. Determine the operating wavelength of the mirror and estimate its reflectivity (to do so, extrapolate from the curve the ASE power at this wavelength in the absence of mirror).

Realization of a linear cavity

C4 Design (make a block diagram) and realize a linear laser cavity starting from the previous setup using the two available mirrors (Bragg and metallic). Do not forget that the multiplexer allows to mix or divide the laser and pump signals according to its way of use.

Q12 Give the minimum value of the gain to ensure the oscillation condition with this cavity: is the available gain sufficient (cf. Q9)?

⇝ At full pump power, check that the laser cavity is functional and compare the oscillation wavelength with that of the Bragg mirror.

Q13 Measure the output power of the laser as well as the power at the edge of the oscillation peak for different pump powers.

Q14 Draw the efficiency curve of the laser oscillator and deduce the oscillation threshold and the optical/optical efficiency. Also draw the ASE curve and interpret its evolution.

Appendix 1 : preparation

Overview on optical fibers

Optical fibers allow to confine and guide light over long distances, even on a non-rectilinear path (one can bend a fiber on itself with a radius of curvature of a few centimeters, while keeping the light confined inside). Standard fibers are composed of fused silica (glass), structured in two layers. The first layer in the center, of index n_1, constitutes the core and is surrounded by a second layer, the cladding, of lower index n_2. The light coupled into the fiber core can therefore undergo total internal reflection at the core-cladding interface. This is only valid if the numerical aperture of the beam does not exceed the numerical aperture of the fiber, defined as the critical aperture angle beyond which the total internal reflection is no longer verified (which can be derived from Descartes' laws).

We use in this labwork so-called single mode fibers, which offer an excellent spatial beam quality, very close to a TEM_{00} Gaussian mode. The typical dimensions of single mode fibers are about 5 µm core diameter, and 125 µm outer diameter for the cladding. They are therefore particularly thin, barely thicker than a hair. They are protected by a third plastic sheath, much larger and thicker, avoiding damage and easing its manipulation.

Principle of fiber amplifiers

A fiber optic amplifier is nothing but an optical fiber whose core has been doped with ions that can generate a laser effect. The most common doping ions are rare earth ions (lanthanides in the periodic table) such as erbium, ytterbium, thulium, holmium, etc.. These ions have the specificity to generate a laser effect in the near infrared (between 1 and 2 µm) with the help of an infrared optical pumping closer to the visible (< 1 µm), easily accessible by the laser diodes on the market.

The pump laser is coupled into the fiber core as well as the signal. For pumping, single transverse mode laser diodes must therefore be used for optimal coupling. Thus, fiber amplifiers simultaneously guide the pump and the signal to be amplified over large distances and in the same transverse mode. They allow a very efficient amplification due to a near perfect pump/signal spatial overlap over a long porpagation length, leading to a very high total gain in a single pass. These properties are considerable advantages compared to free-space amplifier geometries (e.g., rod-based). On the other hand, at high power, the strong confinement of the beam implies high intensities and the appearance of non-linear effects. These effects, exacerbated by the large propagation distance, drastically reduce the performance of the laser system at high powers.

The orders of magnitude of the gain are such that we express the optical powers and the gain in logarithmic units, in dBm and dB respectively. For the optical power (noted P_{W} in watts and noted P_{dBm} in dBm), we express $P_{\mathrm{dBm}} = 10\log\left(\frac{P_{\mathrm{W}}}{1\ \mathrm{mW}}\right)$ and for the gain, we simply have $G_{\mathrm{dB}} = 10\log(G)$. It is important to note that P_{dBm} is an absolute quantity (related to a power value) whereas G_{dB} is a relative quantity (related to a power ratio).

Broadband optical amplifiers

The fiber used in this TP is erbium doped. It is pumped at 980 nm and emits around 1550 nm. It is assimilated to a 3 levels laser system, which is absorbent at the laser transition at thermodynamic equilibrium (without pumping). Its spectroscopy is presented in figure 3.3.

The erbium doped fiber has the specificity to emit laser photons over a wide range of wavelengths around 1550 nm. This property comes from the amorphous character of the glass composing the fiber (unlike a well-structured crystalline matrix) which induces a "disorder" in the arrangement of the dopant ions. This leads to a splitting of the energy levels of the erbium ion into manifold sub-levels, thus offering a large number of possible transitions and thus very broad emission spectra.

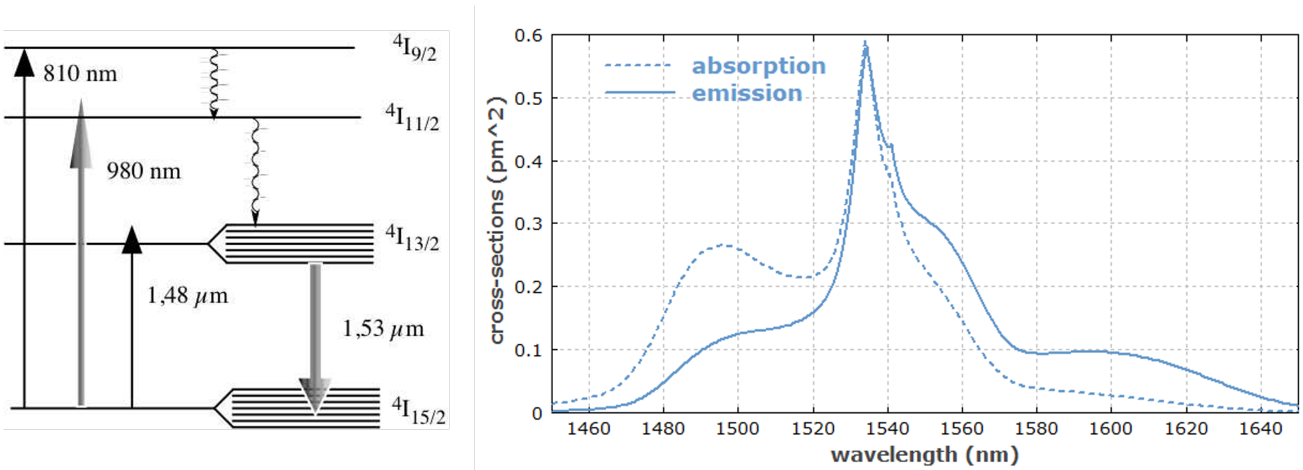


Figure 3.3 – spectroscopie du système Er^{3+}:SiO_2 (gauche) et sections efficaces effectives d'absorption et d'émission pour la transition laser autour de 1.53 µm (droite).

To easily express the gain with spectroscopic systems comprising manifold sub-levels, we prefer to use the effective cross-sections rather than the simple effective cross-sections for each transition. In this case, the linear gain is written as: $g(\nu) = \sigma_\mathrm{e}(\nu)n_1 - \sigma_\mathrm{a}(\nu)n_0$ with n_1 the population density of the upper band $({}^4\mathrm{I}_1^{3/2})$ and n_0 the population density of the fundamental state $({}^4\mathrm{I}_1^{5/2})$.

P1 Using conservation of ion density ($n_0 + n_1 + n_2 = n_\mathrm{t}$) and considering that the n_2 pump level is rapidly depopulated to the n_1 level (very fast non-radiative transition, $n_2 \simeq 0$), give the expression of the gain $g(\nu)$ as a function of the effective cross sections σ_e and σ_a with respect to n_t and n_1. Under which condition on n_1 is the gain positive?

P2 We assume that the upper and lowers levels of the laser transition are identically populated ($n_1 = n_0 = n_\mathrm{t}/2$). Under what condition on the effective cross sections is the gain positive?

P3 Under these same conditions and using the figure 3.3 (right), estimate the wavelength corresponding to the transparency of the medium and determine if the regions of the spectrum on both sides of this wavelength are amplifying or are absorbent. Compare these observations with the curves in Figure 3.4.

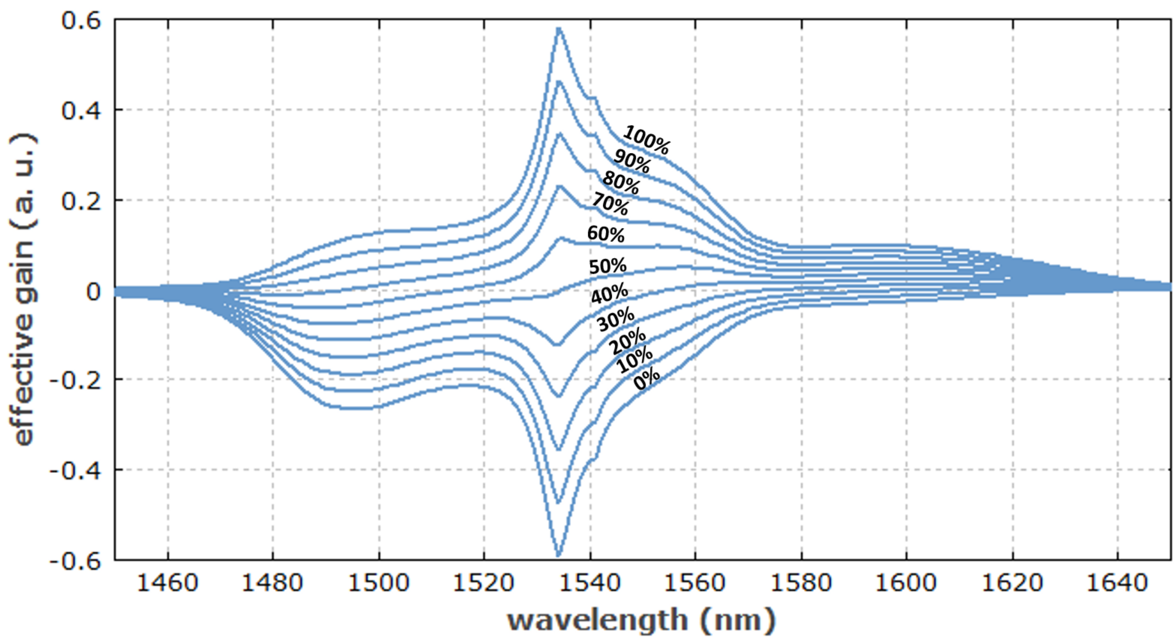


Figure 3.4 – Effective gain per unit length deduced from effective cross sections as a function of wavelength. The curves from bottom to top are for an excitation degree n_1/n_t from 0% to 100% by steps of 10%.

Amplified spontaneous emission (ASE)

The amplification of a signal by stimulated emission is always accompanied by spontaneous emission, which by definition does not share any of the properties of the signal to be amplified (wavelength, phase, polarization...). This one being emitted in all directions ($4pi$ steradians), only a part of the photons is coupled into the fiber, in the solid angle calculated with the numerical aperture of the fiber. This fraction of incoherent photons is therefore guided in the fiber and propagates alongside the signal. It can also be amplified by stimulated emission and take part of the gain useful to the signal: it is the amplified spontaneous emission (or ASE).

The total optical power of the ASE accumulated along the fiber is added to the useful signal and is generally considered as a noise source. Because of the guiding and high gains properties of the fibers, the ASE can become very high to the point that fiber amplifiers add much more noise than free space (rod-based) laser systems. It is therefore necessary to find the best amplification conditions (pump and injection powers, fiber length...) in order to extract as much signal power as possible while limiting the ASE power. It is also necessary to have the necessary methods and tools to measure the useful power and the incoherent noise at the amplifier output.

Appendix 2 : Components description

In this labwork, we have elementary fibered components (laser sources, gain media, measuring instruments, etc.) that must be wisely connected to each other by means of fibered patchcords. The basic elements and measuring instruments available are :

- A diode laser source to be amplified (from Photonetics "TUNICS"), tunable in wavelength between 1500 and 1600 nm whose output is directly fibered. It has two potentiometers, one allowing to increase its power (it must always remain at the maximum) and the other one to tune the wavelength between 1500 and 1600 nm.

$bullet$ An optical attenuator, introducing programmable losses. It can be used to modify the power of the laser source at 1550 nm accurately.

- An EDFA kit rack, manufactured by the company IDIL, composed of various elementary drawers entirely fibered.

  The elements available for the design of an amplification system are :

  ▷ A laser diode emitting at 980 nm, used as a pump source for the optical amplifiers, whose output is fibered (never disconnect the patchcord that comes out of it). Its optical power is adjustable from 0 to 50 mW thanks to the diode supply current (from 0 to 200 mA).

  ▷ A multiplexer with two inputs and one output, allowing to mix two signals of different wavelengths in a single fiber (here the pump at 980 nm and the signal at 1550 nm). Conversely, it can be used in the other direction (demultiplexer) to separate these two signals into two different channels. The (de)multiplexer is equivalent to a dichroic mirror.

  ▷ An erbium doped fiber of 20 m length, used as a gain medium.

  Two mirrors are also available to design a linear laser cavity:

  ▷ A Bragg grating mirror, equivalent to a narrow band plane mirror (reflects only a narrow spectral line, the rest of the spectrum being completely transmitted).

  ▷ A metallic mirror, highly reflective over a very broad spectral band, including 1550 nm.

- An erbium-doped fiber of 1 m length. This fiber is not part of the EDFA kit (green patchcord, stored with the other yellow undoped patchcords) and will only be used once at the beginning of the labwork for a specific study.

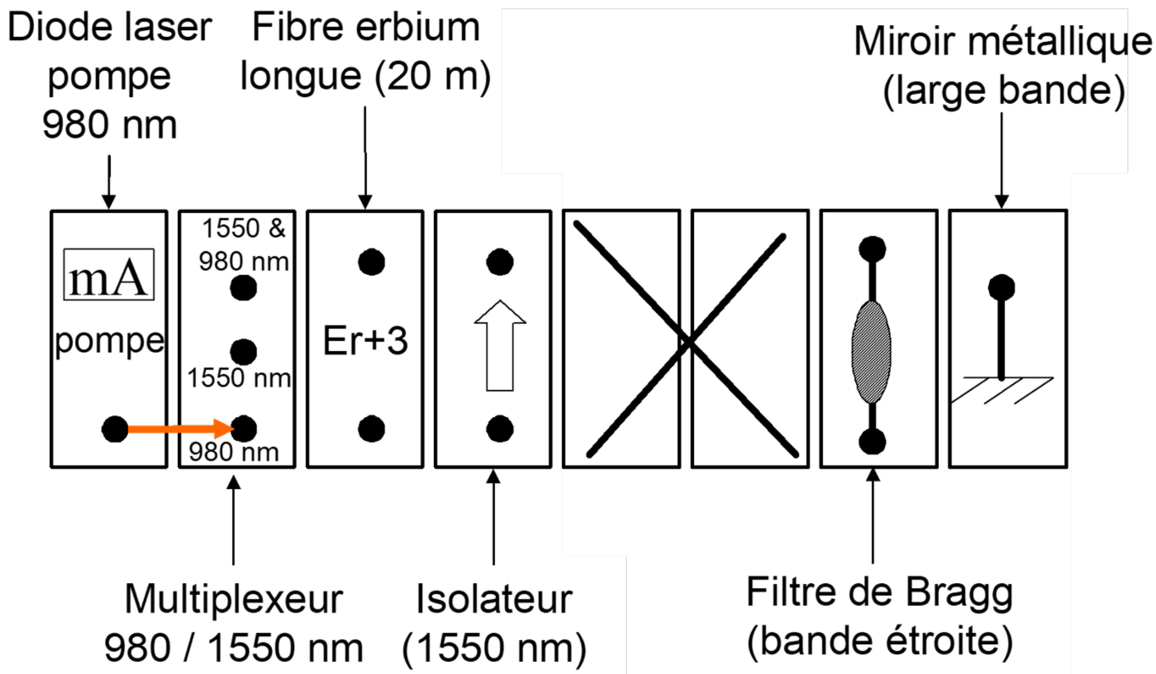


Figure 3.5 – EDFA kit rack

- An optical spectrum analyzer (or OSA), allowing to study laser spectra on large wavelength ranges (several hundreds of nm) at high resolution (a few tens of pm). It also measures the optical power of signals (in dBm) with a high dynamic range (about 80 dB). We can thus see the optical spectrum analyzer as a power meter with high sensitivity and wavelength resolution. A specific appendix (appendix 3) is dedicated to it.

All these elements (except the 1 m doped fiber) have fiber inputs/outputs, equipped with female connectors. To connect them together, patchcords are used, having male connectors at each end. There are two connector conventions involved in this labwork:

- The E2000 standard, the most practical and the most widespread in telecommunications, which is clipped when the connector is correctly plugged (it is necessary to push the male connector until the end of the plug, at the risk of having a weak, or even no coupling). A black protective cap automatically seals the fiber exit face when the connector is unclipped.

- The FC-PC standard (or FC-APC) whose male connector is to be screwed on the female part. There is a notch on this connector that must be aligned on both male and female parts in order to obtain an optimal coupling. It is absolutely necessary to always check this notch when connecting the FC connectors, otherwise there is a risk of almost no coupling. The FC connectors are not self-sealed, so it is important to put a cap on them as soon as they are exposed to the air in order to protect the output face of the optical fiber, which is very fragile.

Figure 3.6 – connector norms involved in this labwork

Not all components and measuring instruments have the same connector standards. On the other hand, some patchcords are exclusively E2000 or FC-APC at both ends, others are mixed. It is therefore necessary to choose the right patchcords according to the components to be connected. Although the fibers are bendable and protected by a plastic cladding, they are still fragile. It is important to avoid knotting them, pinching them, crushing them or putting objects on them.

Appendix 3 : optical spectrum analyzer

The schematic diagram of the OSA is presented in figure 2.5. Its input is optical: it is connected through an optical fiber carrying the signal to be studied. It is followed by a tunable optical filter of width RBW (for "Resolution BandWidth") which sweeps a defined spectral range (the excursion or "SPAN") periodically. The filter is followed by a photodetector of high sensitivity followed by an electrical amplifier of high dynamics. The dotted optical attenuator is only used when the input optical power exceeds the maximum allowed power (10 dBm, i.e. 10 mW).

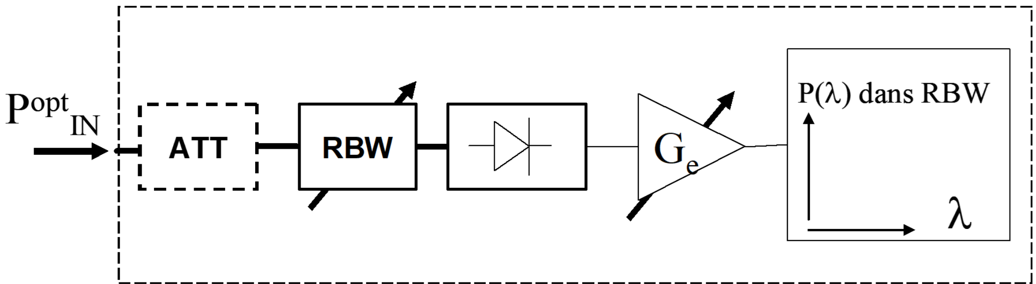


Figure 3.7 – schéma de principe de l'analyseur de spectre optique

The curve displayed on the screen of the OSA represents the power in the RBW band as a function of λ, that we can note $P_{\text{RBW}}(\lambda)$. The RBW is thus the width at half maximum of the peak displayed by the OSA when seeded by a quasi-monochromatic optical signal. The default display is in logarithmic units (powers in dBm).

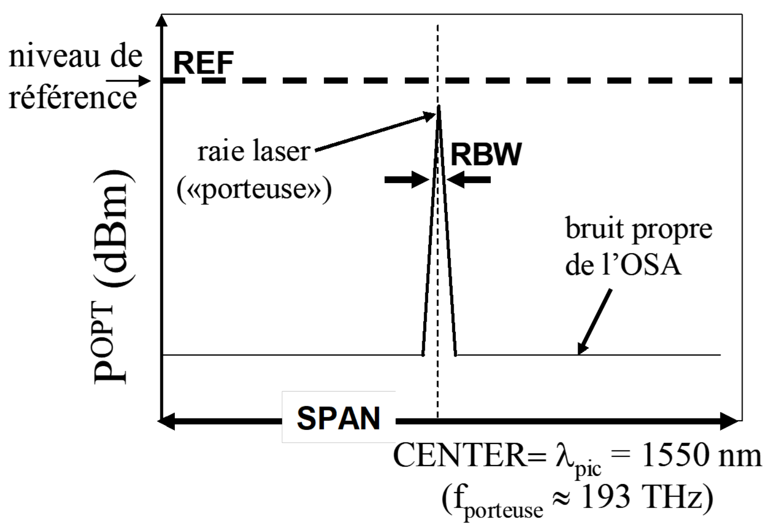


Figure 3.8 – représentation des réglages et des mesures de l'OSA

Lab 4

Nonlinear optics

Contents

Skills to be acquired with this labwork

The skills to be acquired in this labwork, classified in 3 categories, are the following:

"Experimental" skills :

- Characterization of the performances of a pulsed laser
- Alignment and optimization of a frequency doubling setup
- Coupling of a laser beam into an optical fiber

"Measurement" skills :

- Mesure of the repetition rate, duration and peak power of a pulsed laser
- Mesure of the average power of a pulsed laser

"Physics" skills:

- Analysis of the properties of a Q-switched laser
- Analysis the frequency doubling performances (power and spatial quality) according to the characteristics of the birefringent crystals (nature, interaction length)

prerequisite

- basics on laser physics from the first year course : cavity, mode, gain, amplifying medium, losses, oscillation threshold
- Anisotropic dielectric media: birefringence, ordinary and extraordinary waves
- Reading of the appendix 1 on the description of the frequency doubling.
- Laser safety

Laser safety specific to the TP

The fundamental laser emits an average power of about 50 mW in the near infrared (1064 nm), thus at the limit of the visible. This average power corresponds to 50 times the damage threshold of the eye. The protective glasses are thus essential.

The frequency-doubled beam (at 532 nm) emits a power of a few hundreds of μW and up to 10 mW (depending on the crystal involved) that is 10 times the damage threshold of the eye. The radiations can thus be dangerous in direct vision or in specular reflection. At this power level, scattered reflections are not dangerous, which will allow the use of diffusing cards to see the green beam.

As the objective is to characterize the frequency doubling in the green, the choice was made to wear glasses that protect from infrared radiation but not from the green radiation, in order to allow you to see the green beams. This choice imposes a great rigor at the experimental level:

- Remove any reflective object (watch, bracelet) which could cross the beam path.
- When moving optical components on the beam, make sure that the laser is closed (mechanical shutter on the laser).
- The propagation of the green beam must always be controlled.

In order to limit the risks of being dazzled, the green beam propagates in an enclosure, which is protected by absorbent plastics.

1 The lab at a glance

The objective of this labwork is to study two specific nonlinear effects: frequency doubling (second order nonlinear effect) and the Raman effect (third order nonlinear effect).

Frequency doubling is a nonlinear phenomenon widely used with laser sources to shift the wavelength range. For example, from infrared lasers, we can generate laser beams in the visible range. In this labwork, a simple setup allows to convert an infrared source of wavelength $lambda$ = 1064 nm (fundamental source), into a source of double optical frequency at $lambda$ = 532 nm in the visible range (frequency-doubled beam).

The nonlinear conversion requires high optical intensities for the fundamental beam. The fundamental laser used is pulsed, offering much higher peak powers than a continuous-wave laser. The first part of the labwork consists in characterizing this source (rate, pulse duration, peak power) in order to become familiar with the orders of magnitude required for frequency doubling.

The second part of the labwork consists in studying the frequency doubling in different nonlinear birefringent crystals (cf appendix 1) : we will study crystals of different lengths and chemical compositions. We will be particularly interested in the total power of the converted beam at 532 nm as well as in its spatial quality (see the first setup in figure 4.1 above).

Finally, the third part of the labwork allows us to highlight another non-linear effect found in optical fibers: the Raman effect. This one is due to the coupling between an optical wave and a vibration mode of a given molecule, corresponding to a frequency ν_{mol}. A light beam of frequency ν and of sufficiently high power will create two new optical signals of frequency $\nu - \nu_{\mathrm{mol}}$ (called Stokes signal) and of frequency $\nu + \nu_{\mathrm{mol}}$ (called anti-Stokes signal).

Raman conversion is used in many applications: spontaneous Raman scattering allows the identification of molecules, each type of chemical bond corresponding to a specific vibration frequency (Raman spectroscopy). Stimulated Raman scattering is used to create light amplifiers or Raman laser oscillators. The Raman conversion can also be an undesirable effect as in the case where one transports optical signals of high peak power in an optical fiber. The assembly used is summarized on the figure 4.1 (bottom), it uses the green beam created in the previous parts of the TP, coupled into an optical fiber.

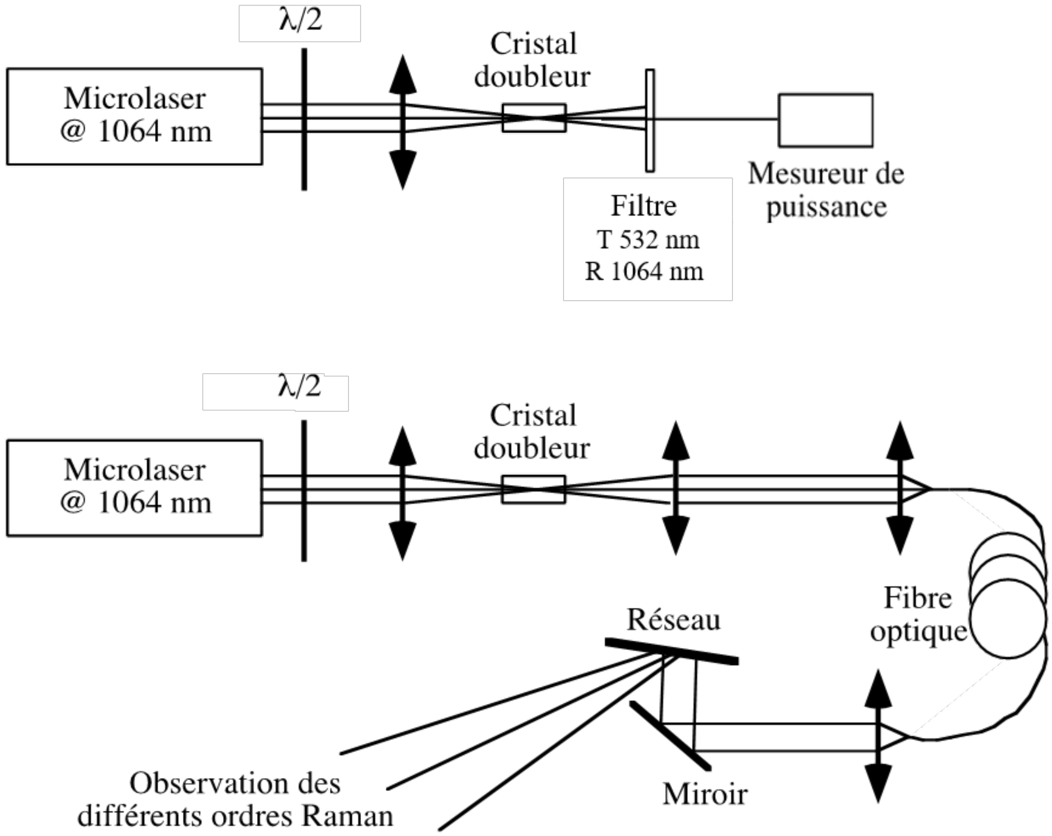


Figure 4.1 – (top) setup used for frequency doubling, (bottom) setup used for Raman effect

2 Experimental activities

2.1 Study of the fundamental laser source

The fundamental source is a laser passively Q-switched by a saturable absorber placed inside the cavity. It emits pulses of nanosecond duration at 1064 nm. The architecture of the laser is described in figure 4.2. The saturable absorber used to realize the passive Q-switching is a Cr^{4+}:YAG crystal glued on a Nd^{3+}:YAG laser crystal. The length of the cavity is about 1 mm. The infrared beam emitted by this laser is linearly polarized.

To characterize the source, we have a fast photodiode, a variable load impedance to choose the response time of the measurement line, and an oscilloscope. We estimate that the parasitic capacitance of the measurement line is 250pF.

In addition, a power meter can characterize the power of laser beams, both the fundamental source and the doubled beam. Be careful, this power meter uses a silicon detector whose response varies according to the wavelength: it will thus be imperative to check that it is set on the right wavelength calibration depending on beam to measure (fundamental or doubled).

Q1 Calculate the lowest response time of the measurement line according to the available impedances and the performances of the oscilloscope. Is it possible to correctly measure the

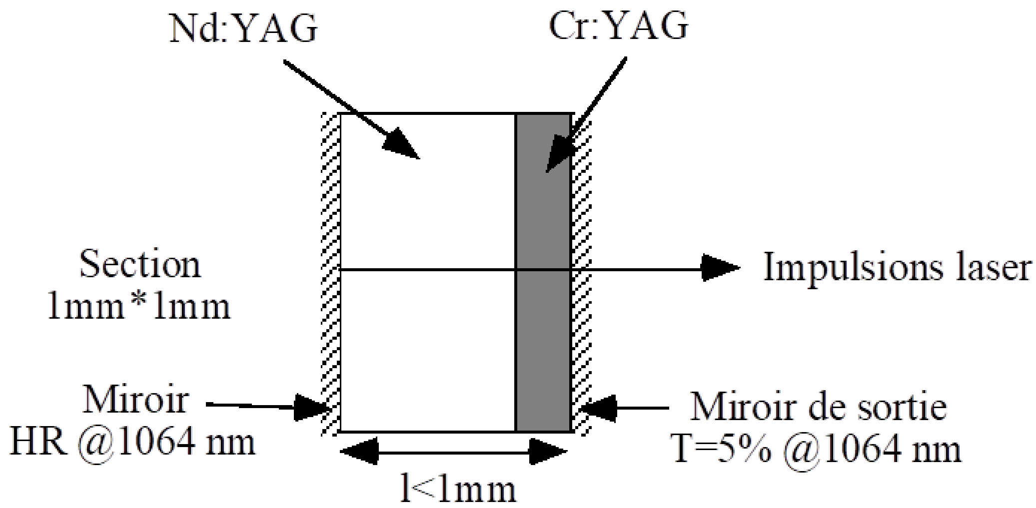


Figure 4.2 – schematic of the fundamental laser

duration of the microlaser pulses?

⇝ Place the photodiode in beam path of the microlaser. Adjust the input impedance of the oscilloscope so that a pulse train is clearly visible.

Q2 Measure accurately the pulse repetition rate.

Q3 Measure the average output power using the power meter. Deduce the energy of the pulses as well as their peak power (assuming that the pulse shape is rectangular with a duration of 1 ns).

2.2 Efficiency and quality of frequency doubling

Figure 4.3 recalls the setup scheme for frequency doubling. The fundamental source at 1064 nm, linearly polarized, is focused in a nonlinear crystal in order to obtain the intensity levels required for frequency doubling. The polarization of the incident wave is a critical parameter: a half-wave plate is used upstream of the doubling crystal in order to modify the orientation of the incident polarization at will. The 1064 nm $\rightarrow$ 532 nm conversion is not complete, it is necessary to use a filter to only transmit the doubled beam to be characterized.

The non-linear crystals available for the study of frequency doubling are :

- 3 crystals of BBO (for barium beta-borate, β-BaB_2O_4) of respective lengths 0.5, 4 and 7 mm
- 1 crystal of KTP (for potassium titanyl phosphate, $KTiOPO_4$) of length 7 mm

All these crystals are cut such that the phase-matching condition performed by birefringence is realized for a fundamental beam arriving in normal incidence on the entrance facet

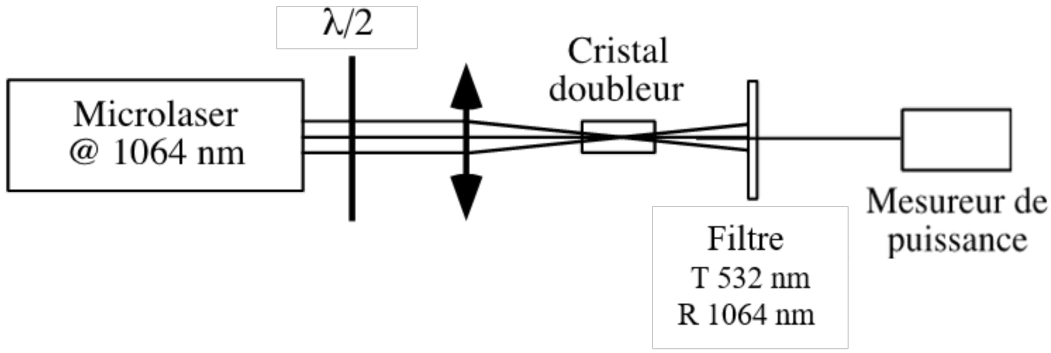


Figure 4.3 – schematics of frequency doubling

of the crystal. To find the phase tuning, a good starting point is to start with an autocollimation alignement on the crystal to study using the infrared beam.

⇝ Start the experiment with the 0.5 mm long BBO crystal, placing it as close as possible to the focus of the objective. Under these conditions, a green beam should already appear at the output.

⇝ Make a rough optimization by observing the intensity of the green beam after the dichroic filter (either by diffusion on a cardboard or with the power meter), by playing with the translation of the focusing lens and by adjusting the orientation of the polarization of the infrared beam.

C1 Observe the spatial profile of the beam (let it diverge on 20 cm) by adjusting the orientation of the crystal. Note that there is an optimal position for which a symmetrical fringe pattern is observed, with an intense fringe in the center and weaker bands on each side.

Q4 Recalling that the phase-matching condition is only fulfilled or normal incidence, and that the fundamental beam diverges in the crystal, explain the origin of this fringe pattern.

Q5 Measure the converted power at 532 nm by taking care of measuring the whole beam and by optimizing all the parameters, especially the crystal tilts (pay attention to the wavelength calibration of the power meter !).

Q6 Repeat the same procedure with the two other BBO crystals of 4 mm and 7 mm thickness (study of the spatial profile and measurement of the converted power).

Q7 For each crystal, calculate the conversion efficiency (defined by the ratio between the power at 532 nm and the incident power at 1064 nm). What is the theoretical evolution of the conversion efficiency with the length of the crystal ? How to explain such a huge difference ?

Q8 Repeat this study with the KTP crystal: measure its conversion efficiency and describe the spatial profile of the converted beam.

Q9 Compare the performances of the KTP with those of the BBO crystals and justify them with regard to the properties of the crystals given in the table 4.1.

	BBO	KTP
χ_{eff} **(pm/V)**	2,0	3,6
Angular acceptance (mrad.cm)	0.8	14

Table 4.1 – some properties of BBO and KTP crystals

2.3 Effect of fundamental wave polarization on frequency doubling

Q10 What are the law describing the variation of the frequency doubled power as a function of the orientation of the incident polarization of the fundamental wave for type I phase-matching ? and for type II phase-matching?

⇝ With the 7 mm BBO crystal, plot the evolution of the output power in the green as a function of the angle of the half-wave plate and deduce the evolution of the converted power as a function of the polarization of the fundamental wave.

⇝ Repeat the same protocol with the KTP crystal.

C2 Group the results of the KTP and the BBO on the same curve (normalize them from 0 to 1) and deduce their respective phase-matching types.

2.4 Raman conversion in a silica fiber

In this part of the labwork, we want to demonstrate the Raman effect in an optical fiber using a laser source at 532 nm. For a fused silica fiber, made of SiO_2 molecules, the vibration mode corresponds to a frequency ν_{mol} =13,2 THz (440 cm^{-1}).

At thermodynamic equilibrium, silica molecules are mostly in their ground state so that the main interaction phenomenon is the excitation of the molecules, leading to a ν_{mol} Stockes shift. The opposite phenomenon, corresponding to the de-excitation of the molecules and an anti-Stockes $\nu + \nu_{\text{mol}}$ shift, is thus very unlikely in the conditions of the labwork and will not be visible to the eye.

Unlike gases for which the Raman shift (ν_{mol}) is perfectly defined, fused silica has a wide range of frequencies ν_{mol} centered around 13.2 THz (figure 4.4).

The fiber used here has a length of 50 m and a core radius of 3.3 µm. The general setup for this study is shown in figure 4.5. The first part corresponds to the setup of the previous parts, with the KTP as frequency-doubling crystal. A second objective is placed behind the non-linear crystal in order to collimate the doubled beam. A last objective focuses the beam at 532 nm into the optical fiber core. At the exit of the fiber, an objective recollimates the beam and a diffraction grating disperses the rays to observe the different Raman orders.

The protocol for coupling the 532 nm beam into the fiber is as follows:

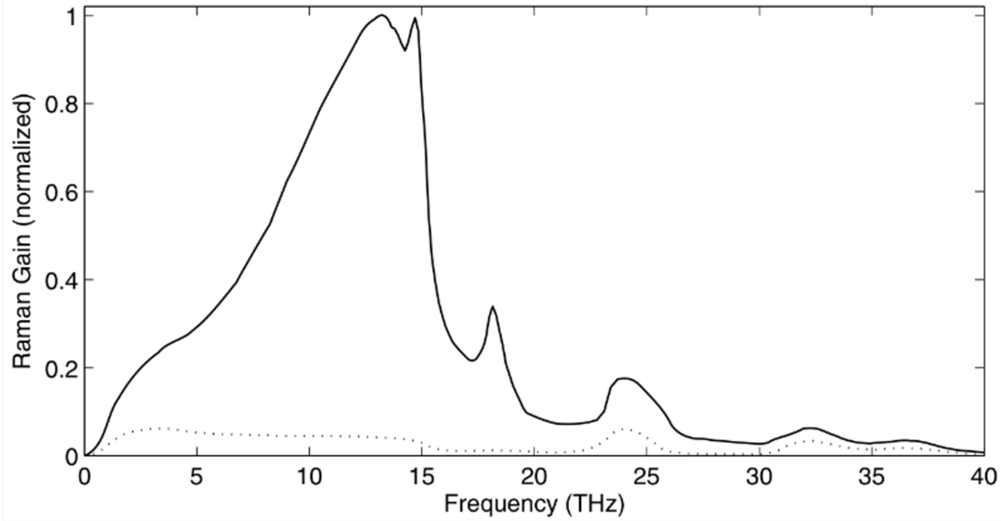


Figure 4.4 – normalized Raman gain spectrum for fused silica

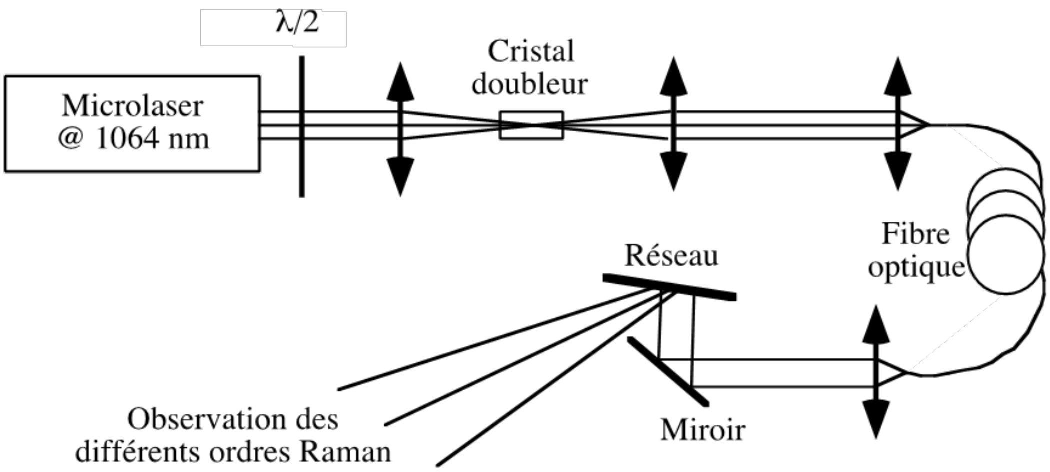


Figure 4.5 – experimental setup for the observation of Raman conversion in an optical fiber

- Optimize the efficiency of the frequency doubling setup as much as possible to obtain at least 10 mW of average power at 532 nm.
- Fine tune the beam collimation after the KTP crystal using the second objective. To do this, look at the beam size as far as possible on the bench.
- Before injecting into the fiber, reduce the power to half (or even less) using the half-wave plate to avoid burning the fiber cladding during the alignement.
- The focal point of the beam must be located exactly on the entrance facet of the fiber at the core. Using the focusing lens, start by injecting the beam roughly into the fiber so that some green light is visible at the fiber exit.
- Choose a direction of translation of the focusing lens parallel to the optical axis. Once

the objective is moved, readjust the injection into the fiber with the lateral knobs. If there is more light coming out, you are moving the focus point closer to the input side of the fiber (this is the right direction!). If not, you are moving this point away from the input face.

- When the optimum seems to be reached, raise the average power of the beam at 532 nm to its maximum using the waveplate.
- If necessary, repeat the optimization **very carefully** with very small steps. At high power, coarse adjustments may damage the fiber input face.
- **If there is any doubt, call the supervisor**.

When the adjustments are done, one should be able to observe different colors, from green to red, corresponding to the cascade conversion of the Stokes signals. We can easily observe this effect of cascade conversion by changing the power at 532 nm injected into the fiber with the waveplate.

Q11 Calculate the theoretical wavelengths of the Stokes signals for the first 6 orders. Do your experimental observations seem consistent with your theoretical predictions?

Q12 How can you explain the spectral broadening of the different Raman orders as the wavelength increases?

Appendix 1 : préparation

Nonlinear response of a dielectric medium

A dielectric medium responds to the excitation of an electromagnetic field $\mathbf{E}$ by a polarization field $\mathbf{P}$. This polarization is a source term which will itself emit an electromagnetic wave added to the initial field. In the general case, the response of the medium is expressed as a function of the n-th powers of the $\mathbf{E}$ field and the $\chi^{(n)}$ susceptibilities of order n :

$$\mathbf{P} = \epsilon_0 \left(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{E}^2 + \chi^{(3)}\mathbf{E}^3 + \chi^{(4)}\mathbf{E}^4 + \cdots \right) \tag{4.1}$$

The first term describes the linear response (proportional to the excitation field) while the following terms correspond to the nonlinear responses of orders 2, 3, 4, etc. For a monochromatic field $\mathbf{E}$ oscillating at the pulsation ω, the linear term corresponds to a radiation at the frequency ω which adds to the exciting field and highlights the refractive index of the medium ($n = \sqrt{1+\chi^1}$). The nonlinear terms $\mathbf{E}^n$ result in a response of the medium at harmonic frequencies 2ω, 3ω, etc. We stop here at the second order, which is called second harmonic generation, or more simply frequency doubling.

Phase tuning condition

For an efficient frequency doubling, there is a critical condition called the phase-matching condition. In the nonlinear medium, the fundamental wave vector $k(\omega)$ defines the wave vector of the linear polarization $k_P^{(1)} = \frac{\omega}{c} n(\omega) = k(\omega)$ and that of the nonlinear polarization of order 2, $k_P^{(2)} = \frac{2\omega}{c} n(\omega)$. We notice a factor 2 between the two terms, representative of the frequency doubling, but we also notice the same refractive index, expressed at the frequency ω for both terms.

On the other hand, a wave generated at the frequency 2ω by the nonlinear polarization propagates in the crystal with a wave vector $k_{2\omega} = \frac{2\omega}{c} n(2\omega)$. We note that this wave vector differs from that of the second order polarization by the refractive index term. In the general case, nonlinear media are also dispersive, such that $n(2\omega) \neq n(\omega)$, and thus $k_P^{(2)} \neq k_{2\omega}$. Thus, the doubled field generated at the beginning of the crystal does not remain in phase with the nonlinear polarization induced by the exciting field (see figure 4.6). We have therefore, at any point of the crystal, a 2$omega$ radiation coming from the nonlinear polarization which is a priori not in phase with the pre-existing 2$omega$ radiation.

All the contributions from the different points of the crystal add up and interfere, sometimes even destructively to the point of completely extinguishing the generation at 2ω. The frequency doubling cannot be generated efficiently. To avoid this phenomenon, we define the phase-matching condition such that $\Delta k = k_P^{(2)} - k_{2\omega} = 0$, which is equivalent to obtaining $n(2\omega) = n(\omega)$ (cf. next part). In this case, all the contributions generated at any point of the crystal interfere constructively.

When there is phase mismatch, we notice a particular interaction length for which the phase shift $\delta\varphi = \delta k \times z$ between the nonlinear polarization and the doubled field generated at $z = 0$ is exactly π. It is defined as the coherence length of the frequency doubling: $L_{\mathrm{C}} = \frac{\pi}{\Delta k}$ (cf figures

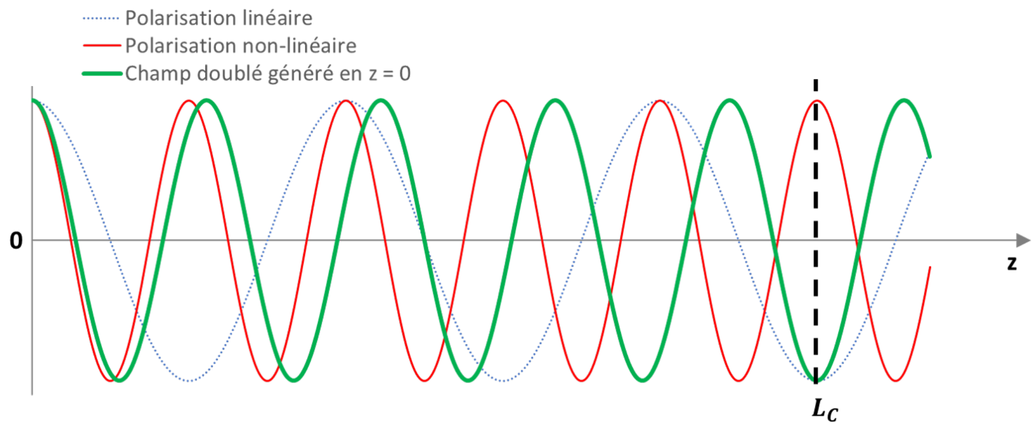


Figure 4.6 – Representation of the linear and nonlinear polarizations of order 2 generated by an intense electric field, as well as the doubled electric field generated by the nonlinear polarization in $z = 0$.

4.6). If we are interested in the evolution of the intensity of the doubled field $I_{2\omega}$ along the crystal, we notice a first maximum at $z = L_{\mathrm{C}}$, (cf figure 4.7). Indeed, beyond L_{C}, all the waves of double frequency generated between L_{C} and $2L_{\mathrm{C}}$ will have exactly the opposite phase to those which were generated between 0 and L_{C}. There is thus a progressive decay until a perfect extinction of the doubled field at $2L_{\mathrm{C}}$. This phenomenon repeats periodically every $2L_{\mathrm{C}}$.

In general, the evolution of the doubled field intensity $I_{2\omega}$ as a function of the fundamental intensity I_{omega}, the crystal length z and the phase detuning Δk in the regime of low conversion efficiency (i.e. considering that the fundamental strength I_{omega} remains constant all throughout the crystal) is expressed by :

$$I_{2\omega} \propto |\chi^{(2)}_{\mathrm{eff}}|^2 I_\omega^2 z^2 \mathrm{sinc}^2\left(\frac{\Delta k \times z}{2}\right) \begin{cases} \xrightarrow{\Delta k \to 0} & |\chi^{(2)}_{\mathrm{eff}}|^2 I_\omega^2 z^2 \\ \xrightarrow{\Delta k \neq 0} & |\chi^{(2)}_{\mathrm{eff}}|^2 I_\omega^2 \left(\frac{2}{\Delta k}\right)^2 \sin^2\left(\frac{\Delta k \times z}{2}\right) \end{cases}$$

$\chi^{(2)}_{\mathrm{eff}}$ is the effective nonlinear susceptibility. It depends on the properties of the crystal and on its orientation with respect to the propagation direction.

For a given phase mismatch, we find an evolution according to z in sine square of the intensity with a period of $2L_C$. On the other hand, for a zero phase detuning, the factor in sinc becomes equal to 1 and the evolution of the intensity $I_{2\omega}$ is then quadratic along z.

Phase matching by birefringence

The phase-matching condition can be obtained only in the case where the optical indices at ω and 2ω in the nonlinear medium are equal, which is never verified in isotropic media due to dispersion. On the other hand, in anisotropic media such as birefringent crystals, it is possible to propagate two waves, ordinary and extraordinary, with a different refractive indices. This property can be used wisely if the birefringent medium is also nonlinear in order to verify the

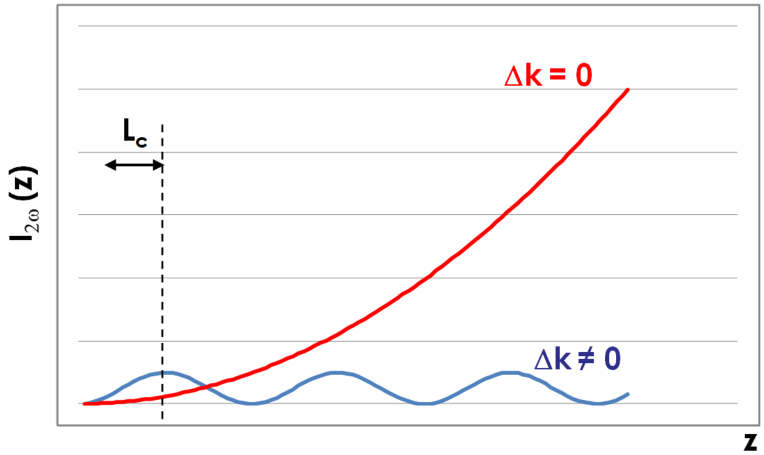


Figure 4.7 – evolution of the intensity at 2ω along the propagation direction z in case of a phase mismatch ($\Delta k \neq 0$) and phase-matching ($\Delta k = 0$)

phase-mathcing condition in the context of frequency doubling. In this case, the dispersion is compensated by the birefringence.

In a uniaxial crystal, with ordinary index n_0 and principal extraordinary index n_e, the ordinary wave sees index n_0 while the extraordinary wave sees an index denoted $n_e(\theta)$ ranging from n_0 to n_e, depending on the angle θ between the optical axis of the crystal (axis of index n_e) and the direction of propagation of the beam (axis defined by the wave vector $\overrightarrow{k}$. The value of the index $n_e(\theta)$ is obtained by:

$$\frac{1}{n_e^2(\theta)} = \frac{cos^2\theta}{n_0^2} + \frac{sin^2\theta}{n_e^2}. \tag{4.2}$$

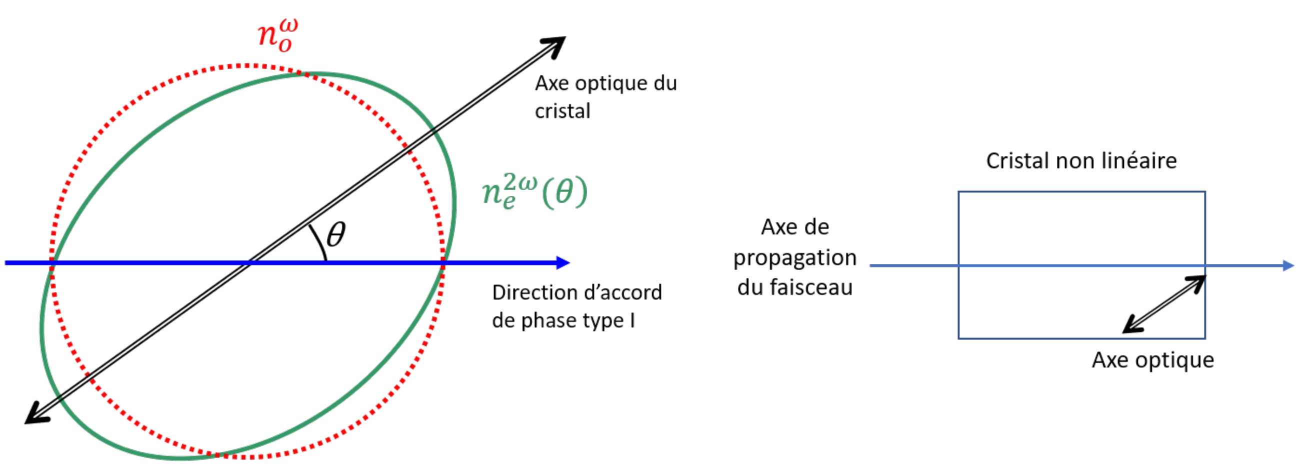


Figure 4.8 – index surfaces cross-sections at ω and 2ω for a negative uniaxial crystal (left) and orientation of the crystal with respect to its optical axis (right)

For some well chosen birefringent (and nonlinear) crystals, it is possible to find an angle of incidence θ fulfilling the phase-matching condition(see figure 4.8 left). In practice, the crystal is cut so as to obtain the phase matching when the fundamental laser beam is perpendicular to the entrance facet of the crystal. It is thus the optical axis of the crystal which has an angle θ compared to the normal of the faces of entry/exit of the crystal (cf figure 4.8 right).

Tolerance on phase tuning: angular acceptance

The doubled intensity $I_{2\omega}$ is dependent on the phase-matching condition through the term $\mathrm{sinc}^2\left(\frac{\Delta k \times z}{2}\right)$. If we find ourselves in a situation where the phase matching is not perfect, we can ask ourselves under which conditions the conversion efficiency remains acceptable. We then define a limit $\mathrm{sinc}^2\left(\frac{\Delta k \times z}{2}\right) = \frac{1}{2}$, at half of the maximum accessible with a perfect phase-matching. This translates into a condition on the product $\Delta k \times z \simeq 2.78$, unitless value. It is important to note the z dependence in this product. From a given phase mismatch Δk , we obtain the maximum crystal length for which we arrive at the tolerance limit. A phase detuning twice as important would thus restrict to a crystal half as long. Conversely, from a given crystal length, one can deduce the maximum tolerable phase mismatch.

For a phase-matching performed by birefringence, Δk depends on the angle θ between the optical axis of the crystal and the direction of propagation of the beam. We can define the maximum angle deviation $\Delta\theta$ around the phase-matching position such that the conversion efficiency is divided by two (or $\Delta k \times z \simeq 2.78$). We thus obtain the criterion of angular acceptance by the product $\Delta\theta \times z$, which we express in rad.m (more generally in mrad.cm). The angular acceptance is a quantity fixed by the nature of the crystal (each one has its own relation in $\Delta\theta$ and Δk) and by the angle θ of phase-matching. Its theoretical calculation is related to the relative slope of the index surfaces at the phase-matching position and its value is generally found in the literature for a variety of birefringent nonlinear crystals.

The angular acceptance is critical in a frequency doubling experiment because the incident fundamental beam always has a certain numerical aperture α (or divergence from the point of view of a laser beam). Figure 4.9 allows to compare the set of directions contained in the fundamental beam with the possible phase-matching directions. It allows us to understand why frequency-doubled beams appear as fringes in a given direction (which would be vertical here).

Type I or II doubling - application to the crystals used in the TP

The 2nd order nonlinear polarization vector can be generated from a fundamental wave with a certain polarization direction $\mathbf{P}^2 = \epsilon_0 \chi^2 \mathbf{E}^2$. This is called type I phase-matching. It can also be generated from a combination of fundamental waves on two different polarization directions: $\mathbf{P}^2 = \epsilon_0 \chi^2 \mathbf{E_1} \mathbf{E_2}$. In this case, we talk about a type II phase-matching.

The phase-matching conditions are different according to the orientations and the possibilities offered by the crystals: dispersion, nature of the birefringence (positive or negative uniaxial). The table 4.2 summarizes all possible configurations.

One should note that crystals are not always either type I or type II: it all depends on the shape of their dispersion curves but also on the wavelength of the fundamental beam. Some crystals can even be used in both types of phase-matching, such as the BBO at 1064 nm.

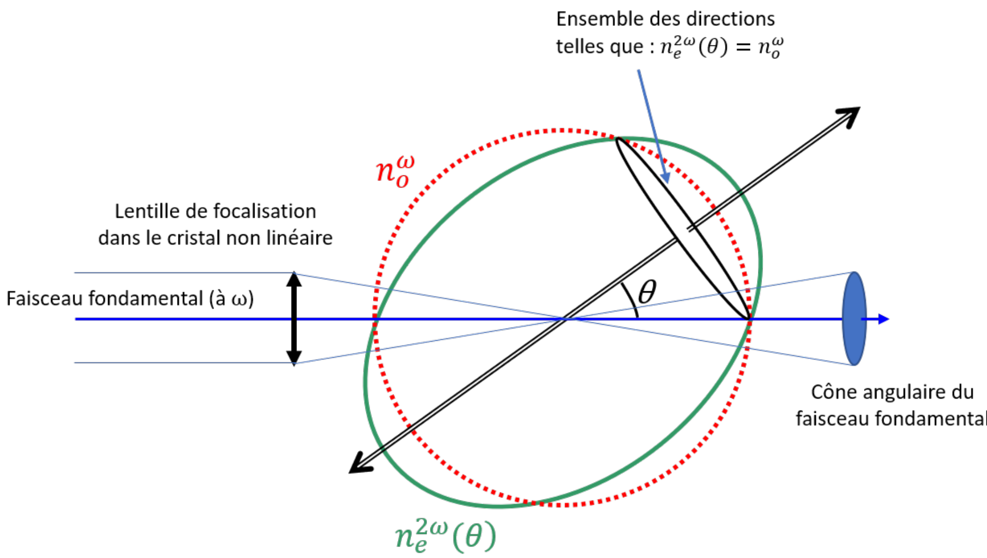


Figure 4.9 – 3D comparison of the phase matching directions and angles included in the fundamental beam focused in the frequency doubling crystal

	Type I	Type II
polarization orientation	$o+o \rightarrow e$ $e+e \rightarrow o$	$o+e \rightarrow e$ $o+e \rightarrow o$
Angle between polarizations fondamental and frequency-doubled	90°	45°
indices relationships pour $\mathbf{n(2\omega) = n(\omega)}$	$n_\theta(2\omega) = n_o(\omega)$ $n_o(2\omega) = n_\theta(\omega)$	$n_\theta(2\omega) = n_o(\omega) + n_\theta(\omega)/2$ $n_o(2\omega) = n_o(\omega) + n_\theta(\omega)/2$
$\mathbf{I_{2\omega}}$ proportional to	I_o^2 I_θ^2	$I_o I_\theta$

Table 4.2 – Properties of phase-matching conditions of types I and II

We use in the first part of the labwork a BBO crystal (presented in its dedicated part of the text body). Its principal extraordinary index is lower than the ordinary index in the considered wavelength range, which makes it a negative uniaxial crystal (see figure 4.10). The crystal used in this labwork is cut for type I phase-matched doubling at the fundamental wavelength of 1064 nm.

P1 What are the polarization directions (ordinary or extraordinary) of the waves at 1064 nm and 532 nm when phase-matching is performed in the BBO for a type I doubling ?

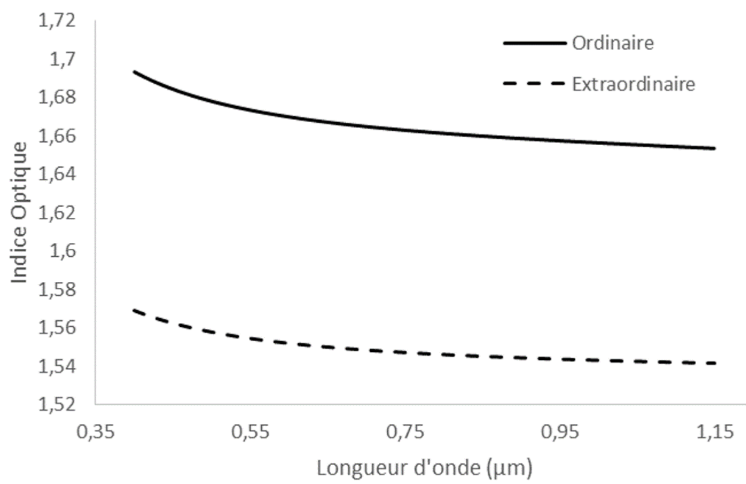


Figure 4.10 – ordinary and extraordinary index profiles of BBO versus wavelength