Lab work in photonics.
Advanced Laser Technologies.

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Engineer - 3rd year - Palaiseau
Master 2 QLMN

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Construction and characterization of a diode-pumped picosecond laser

The first objective of the labwork is to mount a diode-pumped laser emitting short pulses (of the order of a few picoseconds). The pulses are obtained by passive mode-locking. In a second step, the labwork propose to characterise the pulses temporally.

For the report, answer the questions asked only: the description of the experiment and its alignments are not useful.

Important note concerning laser safety. The lasers used is are in class 3R meaning that they are dangerous even with small hazardous reflections.

- Wear the protective sunglasses,
- NEVER look at the beam from the front,
- When taking notes, TURN THE BACK to the LASER,
- Remove any reflective objects.

I Description of the source

The setup of the laser is shown in Figure 1. The laser uses a wide-stripe laser diode (1 μm by 100 μm) emitting 800 mW at 808 nm at a current of 1 A as a pump source.

The first lens, L_1 (4 mm focal length and 0.5 numerical aperture), collimates the pumping beam. The second lens, L_2 (8 mm focal length and 0.5 aperture), focuses it into the laser crystal.

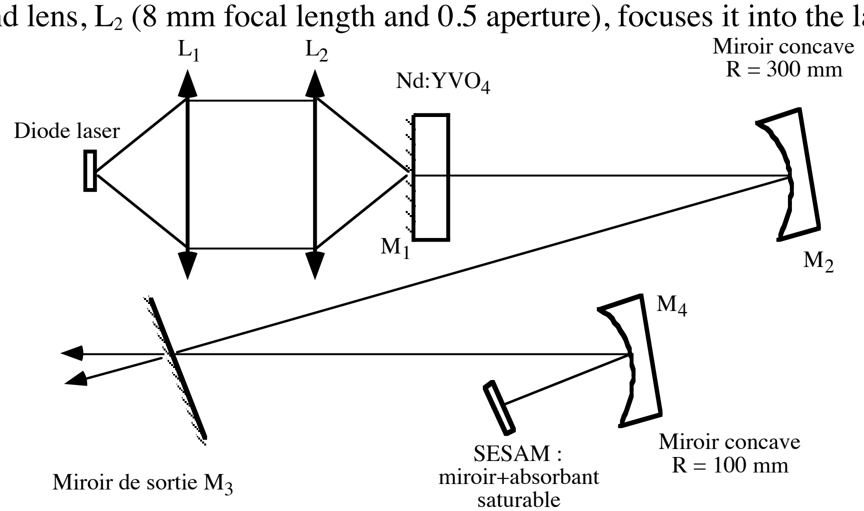

Fig.1: Cavity diagram.

The gain medium is a $Nd^{3+}:YVO_4$ (yttrium vanadate doped with neodymium ion) crystal. Some physical properties are given in table 1. One of the advantages of this crystal is the value of the product "effective cross-section * fluorescence lifetime" (which characterizes the efficiency of a continuous laser). This product is twice as high as that of Nd:YAG. In addition, $Nd^{3+}:YVO_4$ has a higher absorption coefficient than Nd:YAG (at equal doping), useful for diode pumping with divergent pump beams.

Percentage of Nd ions: 1.1%.
Melting point: 1810°C
Density: 4.24 g/cm3
Linewidth at 1064 nm: 1.3 nm
Refractive index at 1064 nm: 1.958 (o) and 2.168 (e)
Fluorescence lifetime: 115 μs

Table 1: Some characteristics of the Nd:YVO₄.

The Nd:YVO_4 is a four-level laser described in Figure 2.

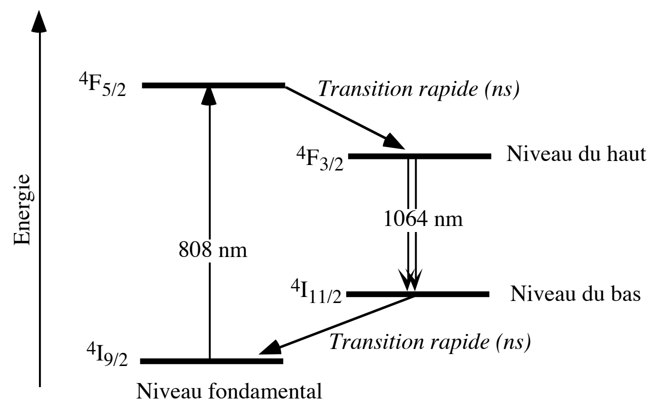

Fig.2: Energy levels of Nd3+.

The crystal used has a length of 2 mm. Its first side has a reflective coating at 1064 nm. It is also anti-reflectively coated at the pump wavelength (808 nm). Its second face is anti-reflective coated at 1064 nm to minimise losses in the cavity. The crystal is prismatic in order to avoid parasitic Fabry-Perot effects between its two faces.

The cavity consists of five mirrors. The first one (M_1), is constituted by the first face of the crystal. The second (M_2), which is highly reflective at 1.06 μm, is a concave mirror with a radius of curvature of 300 mm, which allows a small waist to be obtained in the crystal. The third (M_3) is the output mirror. Its transmission is 2% at 1064 nm. As it is not placed at the end of the cavity, there are two beams at the output of the laser. The fourth mirror (M_4) is a concave mirror (R=100 mm) which focuses the beam into the saturable absorber. The fifth mirror, called SESAM (for SEmiconductor Saturable Absorber Mirror) is a Bragg mirror (stack of AlAs-GaAs layers) on which a layer of InGaAs saturable absorber is located.

The latter ensures an absorption of 1% when it is not saturated. It becomes totally transparent when saturated, thus ensuring greater reflectivity for the entire structure. Attention, here, the saturable absorber gives a very low modulation of the losses in the cavity. It cannot therefore be used to favour the Q-switched regime. However, the small loss modulation will favour the mode-locked regime, to the detriment of the continuous regime.

Question to be prepared before arriving in TP: The spectral width of the emission at 1064 nm is given in Table 1 for Nd:YVO_4. Assuming that the cavity modes completely fill this spectral band, what is the order of magnitude of the theoretical pulse duration?

Question 1: Explain why and how a saturable absorber with a low modulation amplitude induces mode-locked operation.

Question 2: The distances between the mirrors are as follows (these are orders of magnitude):
- distance between M1 and M2: 170 mm
- distance between M2 and M3: around 50 cm
- distance between M3 and M4: around 50 cm
- distance between M4 and SESAM: 55 mm

Draw the beam pattern in the cavity (calculation not necessary), specifying where the waists planes are.

II Mounting the laser

Mounting the laser source involves two main steps: mounting the Nd:YVO_4 laser in continuous operation and then switching to pulse operation by inserting the SESAM into the cavity.

II.1 Continuous laser

This part of the labwork is used to adjust the pumping of the amplifying medium and the alignment of the cavity. The aim is to obtain the highest possible output power with a TEM_{00} mode of the laser beam. For the adjustments, you have at your disposal an infrared sensitive card, a CCD camera and an infrared viewer.

II.1.1 Adjusting the pump optics and the crystal

Place the emitting area of the laser diode at the focus of the first lens and adjust the distance to properly collimate the pump beam in the diffraction-limited direction (vertically).

Before inserting the focusing lens, orient the crystal so that it is autocollimated with respect to the incident beam.

Insert the focusing lens. When the beam from the diode is correctly focused, a whitish dot appears in the crystal. This corresponds to different wavelengths emitted by a process called frequency conversion by energy transfer. In fact, two ions in the upper level (Figure 3) have the ability to interact and exchange their energy in such a way that one of them rises to a higher energy level ($^4G_{7/2}$) while the other falls to a lower energy level ($^4I_{13/2}$). The ion that has reached the excited state $^4G_{7/2}$ is radiatively de-excited by emitting red, yellow or green radiation depending on the arrival level. This effect is all the more important as the density of atoms in the upper level is high (the more numerous the ions are in the upper level, the more likely they are to interact). Since this density is a function of the size of the pump beam in the crystal, the more focused the pump beam is, the greater the radiation emitted in the visible.

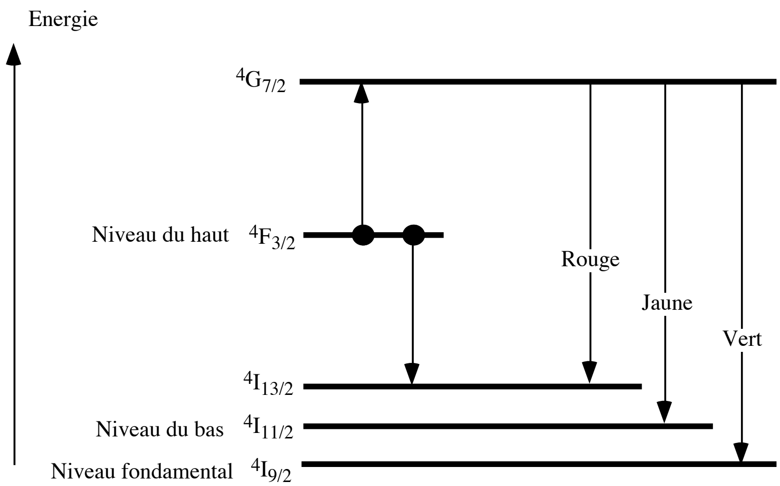

Fig.3: Partial energy diagram of the Nd3+ ion.

II.1.2 Installation of a first cavity with three mirrors

The first cavity to aligne is described in figure 4. M'3 is an plane output mirror with a transmission equal to 10 %.

The part of the pump beam transmitted by the crystal will be used to align the cavity. Using a infrared card, place the M'3 mirror in autocollimation. The laser effect is normally obtained by rotating M'3 around this position.

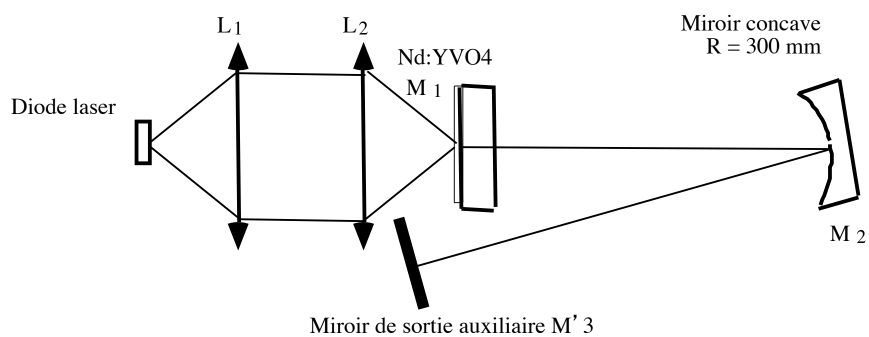

Fig. 4: Diagram of the three-mirror cavity.

Optimising the cavity, mainly by playing with the settings of L_1 and L_2 lenses and the settings of M'_3, to obtain maximum output power.

Question 3: How much power do you get?

II.1.3 Installation of the final cavity

Adjust the rest of the cavity by autocollimation using the camera and multiple returns. Remove the auxiliary mirror M'3 . The laser effect must be achieved.

II.2 Pulsed laser

One of the two output beams is sent to a fast photodiode (rise time of the order of 1 ns). This photodiode has a very small surface area, so care must be taken to position it correctly.

Question 4: Explain why a fast photodiode must have a small sensitive surface.

Observe the signal on the oscilloscope. The laser should normally produce pulses corresponding to a phase-synchronised regime of the cavity modes (mode-locking).

Question 5: What is the repetition rate of the pulses? Deduce the length of the cavity. Is this consistent with the length of the cavity that you can measure with a ruler?

Question 6: Observe the signal on the spectrum analyser. What do the different peaks correspond to?

Question 7: Estimate the rise time of the whole detection chain (photodiode + oscilloscope).

Question 8: Is it possible to correctly observe the temporal shape of the light pulses with the oscilloscope?

III Temporal characterisation of the pulses

Question 9: Imagining that you take a picture of the pulses coming from the laser (temporal width predicted by the theory), give the spatial extension of the pulses along their propagation axis.

III.1 Principle

Since the pulses from the laser are too short to be measured with a fast photodiode, indirect time measurement using an optical autocorrelator is required.

The idea is to use frequency doubling in a birefringent KTP crystal. It cut and oriented for phase-matching in type II at 1064 nm : to create a photon at 532 nm, one needs a photon at 1064 nm with ordinary polarization and one at 1064 nm with extraordinary polarization.

The role of the optical autocorrelator is to create two beams of equal intensity I_1 and I_2 at 1064 nm with orthogonal polarisations (ordinary and extraordinary) with an adjustable delay (Fig.5).

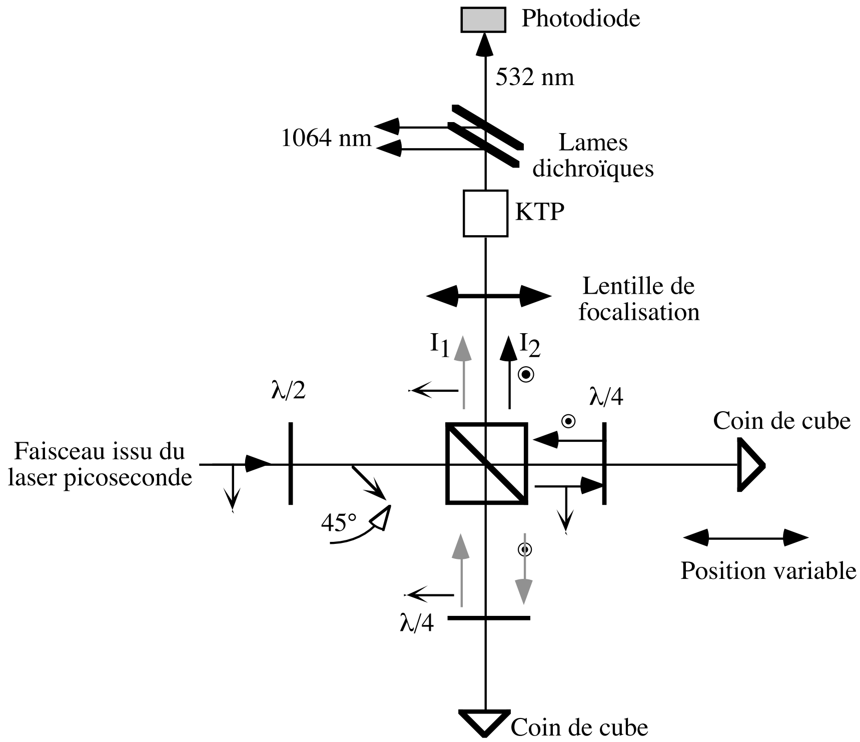

Fig.5: Diagram of the autocorrector.

The two beams are then recombined in the frequency doubling crystal (KTP). The KTP thus sees the intensities $I_1(t)$ and $I_2(t\text{-}/c)$ where c is the speed of light in air. At instant t, the doubled intensity $I_{vert}(t)$ is proportional to the product of the intensities on the fundamental beams :

$$I_{vert}(t)\ I_1(t) * I_2(t\text{-}/c).$$

$I_{vert}(t)$ varies like the pulses emitted by the laser. However, fast fluctuations cannot be resolved temporally because the detector used here has too slow a response time (typically in the microsecond range). Assuming that the detector has a rectangular pulse response of width τ_r, the signal is proportional to the mean value of $I_{vert}(t)$:

$$I_{vert}(\tau_r) = \int_0^{\tau_r} I(t) I(t - \delta / c) dt$$

τ_r being sufficiently long in relation to the characteristic variation times of the intensities, the signal detected in the green corresponds to the autocorrelation function. To access the different values of this function, simply change the delay between the two beams.

The autocorrelator of this labwork looks a bit like a Michelson interferometer, but here it is not an interference phenomenon (the two waves at 1064 nm are perpendicularly polarised).

A first half-wave plate allows the polarisation of the laser to be rotated at 45° to the figure plane. The polarisation beam splitter transmits the polarisation parallel to the figure plane and reflects the perpendicular polarisation. Thus, the half-wave plate and cube are used to create two beams of orthogonal polarization and equal power. Each of the two beams then undergoes a 90° polarisation rotation thanks to a double passage in a quarter-wave plate and a reflection on a corner cube. Thanks to this rotation, the beam that was transmitted during the first passage through the cube is now reflected during the second passage. Conversely, the other beam is transmitted.

The delay between the two beams can be adjusted by moving one of the two cube corners parallel to the optical axis. The two beams, spatially merged together, are then focused in a KTP crystal.

III.2 Settings and measurement

Use the second output beam of the laser.

Approximately equalize the distances of the two channels of the auto-corrector.

Turn the half-wave plate so that the beams are of equal power on both sides of the cube (eye observation with the IR card).

Adjust the quarter-wave plates so that the beams are correctly reflected or transmitted as appropriate.

Adjust the orientation of the corner cubes (WITHOUT FORCING when you reach the translation stop) so that the beams are correctly superimposed after the polarization beam splitter.

Adjust the lens distance-KTP to obtain the most intense green beam possible. CAUTION, the green beam should only be produced when both waves are present simultaneously, check that frequency doubling does not occur when only one of the two beams is present.

Question 10: Knowing that the KTP operates in type II phase matching, explain in which case frequency doubling do occur when only one of the two beams is present? In practice, how can this effect be avoided?

Place the filter that only transmits the beam at 532 nm and a photodiode behind the KTP. The photodiode used here has a response time too long to see the pulsed signal in the green. It therefore delivers a continuous signal whose value is proportional to the average intensity in the green, according to the formula given above.

Measure and plot the intensity in the green according to the delay (which you will vary point by point).

Assuming that the pulses have a Gaussian time profile, the full width at half maximum of the autocorrelation function is related to the pulse duration by the formula :

$$\Delta t_{impulsion} = \frac{\Delta t_{autocorrélation}}{\sqrt{2}}$$

Question 11: Evaluate the pulse duration produced by the laser. Comment.

Optical Parametric Oscillator and Titanium-doped Sapphire Laser

For the report, only the questions are asked to be answered. Support your answers with diagrams, impulse traces taken with the oscilloscope... Any remark, any further explanation is welcome but there is no need to copy the text of the labwork!

The aim of this labwork is to study two tunable sources from the same pumping laser (Nd :YAG frequency doubled at 532 nm and tripled at 355 nm). The two sources are fundamentally different: the first is based on a non-linear crystal (it is an Optical Parametric Oscillator, OPO). The second is based on a laser crystal, titanium-doped sapphire.

Very important note on laser safety :

The pump laser you are going to use is dangerous even by diffusion on non-reflective surfaces (class 4). There is also a risk of burning the skin.

- Wearing glasses is absolutely mandatory when the laser is in operation. There are two types of glasses available depending on the wavelengths emitted by the laser.

The green coloured glasses are to be used for the OPO. They protect the eyes from ultraviolet rays. Caution, they do not protect the eyes from the visible beams emitted by the OPO.

The orange-coloured glasses are for use with the titanium-doped sapphire laser. They protect the eyes from the green beam (532 nm) and the beam at 800 nm.

- Remove any reflective object (bracelet, watch, etc.).

- When taking notes, turn your back to the laser,

- The beams are a priori located in a horizontal plane. **Never bend down while the laser is in operation.**

- Do not put your hands in the beams.

I. Study of a tunable OPO in the visible range

An optical parametric oscillator (OPO) consists of a non-linear crystal placed between two mirrors forming a resonant cavity. The OPO converts a pump beam of wavelength λ_p into two beams called respectively "signal beam", of wavelength λ_s, and "idler beam", of wavelength λ_i. In the OPO we are going to study, only the signal beam oscillates in the cavity.

The general set-up for this study is described in Figure 1 and consists of a flash-pumped, triggered Nd:YAG laser emitting nanosecond pulses of the order of 350 mJ at a frequency of 20 Hz in the near infrared (1064 nm). The radiation is then converted into frequency in two successive non-linear crystals to reach a wavelength of λ_p=355 nm. The first crystal is a frequency doubler converting the infrared beam (1064 nm) into a green beam (at 532 nm, vertically polarised). The second is a crystal called a frequency tripler (3) which performs the frequency sum between the green beam and the infrared beam which has not been converted to green. The energy per pulse is of the order of 50 mJ at 355 nm. The polarisation of the UV beam is horizontal.

This ultraviolet beam is used to pump the OPO, which consists of a non-linear BBO crystal (β-BaB_2O_4) and two mirrors reflecting in the visible. The frequency conversion is efficient thanks to type I phase matching: the pump beam is polarised along the extraordinary axis of the crystal while the signal beam and the complementary beam are ordinarily polarised.

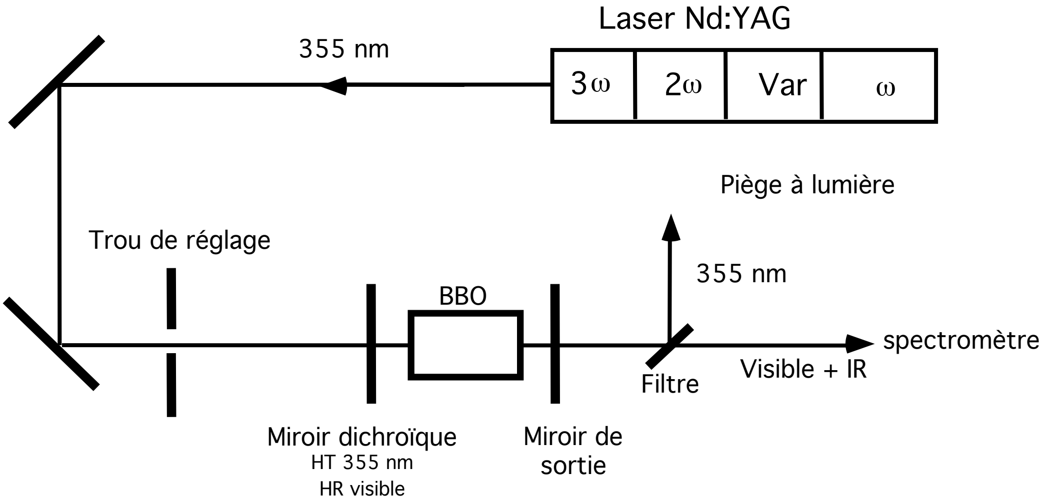

Fig. 1: Experimental setup of the visible OPO

The Nd:YAG source has a power variator (Var) consisting of a half-wave plate and a polarizer before of the frequency converter stages. Two deflecting mirrors allow a good alignment of the UV beam in relation to the rail axis where the OPO is located. A 4 mm diameter hole is used for alignment. The first mirror of the OPO is dichroic, i.e. it transmits the UV beam and completely reflects the visible beams. The second is an output mirror whose transmission curve is given in figure 2.

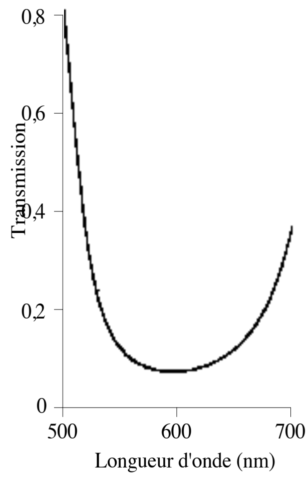

Fig. 2: Transmission of the visible OPO output mirror as a function of wavelength.

At the output of the OPO, a dichroic filter separates the pump wavelength from the emitted wavelengths. It reflects the pump beam that has not been converted in the OPO to a light trap, while it transmits the visible and infrared wavelengths.

Question 1.1: Explain why each set of wavelengths (signal + idler) corresponds to a specific phase matching angle of the BBO crystal.

Question 1.2: Explain why the rotation of the non-linear crystal will allow the OPO to be tuned.

Adjust the orientations of the phase matching angle of the non linear crystals of the Nd:YAG laser to obtain maximum power in the UV (0.9 - 1 W).

Adjust the alignment of the pump beam with respect to the bench axis at reduced power. Align the pump beam to the bench axis. Then place the crystal in its mount so that its largest dimension is horizontal: the horizontal polarisation of the UV beam is then along the extraordinary axis of the crystal. Place the crystal mount so that the UV beam is centred on the crystal.

Then adjust the mirrors of the OPO and the crystal by autocollimation on the UV beam by superimposing the reflections of the different elements on the alignment hole. The tunability of the OPO is achieved by turning the BBO crystal around a vertical axis. Look for a visible signal by turning the BBO around this axis.

Question 1.3: Qualitatively observe the decrease in efficiency of the OPO as the length of its cavity increases. Explain this phenomenon.

Question 1.4: Can you tune the OPO by turning the crystal around a horizontal axis? Explain why.

Question 1.5: Using the spectrometer, visualise the signal and idler wavelengths. Plot on a graph the wavelengths emitted by the OPO as a function of the angle of rotation of the BBO crystal.
Note 1: As the TP is relatively long, do not take more than ten points.
Note 2: As the crystal mount is not angle-graduated, it is necessary to make a (rough) calibration of the angle of rotation in relation to the adjusting screw on the side of the mount.

Question 1.6: What is the wavelength of the beams emitted by the OPO at the degeneracy?
Observe the spectrum of the signal and idler beams in the vicinity of the degeneray.
How can the observed phenomenon be explained?

Question 1.7: Observe the signals from the OPO using the photodiode. What comments can you make?

II. Study of a titanium-doped sapphire laser

Titanium-doped sapphire crystal has an absorption band in the blue-green and an emission band in the near-infrared, centred at 800 nm. Both absorption and emission are polarisation-dependent. The objective is to study the titanium-doped sapphire laser described in Figure 3.

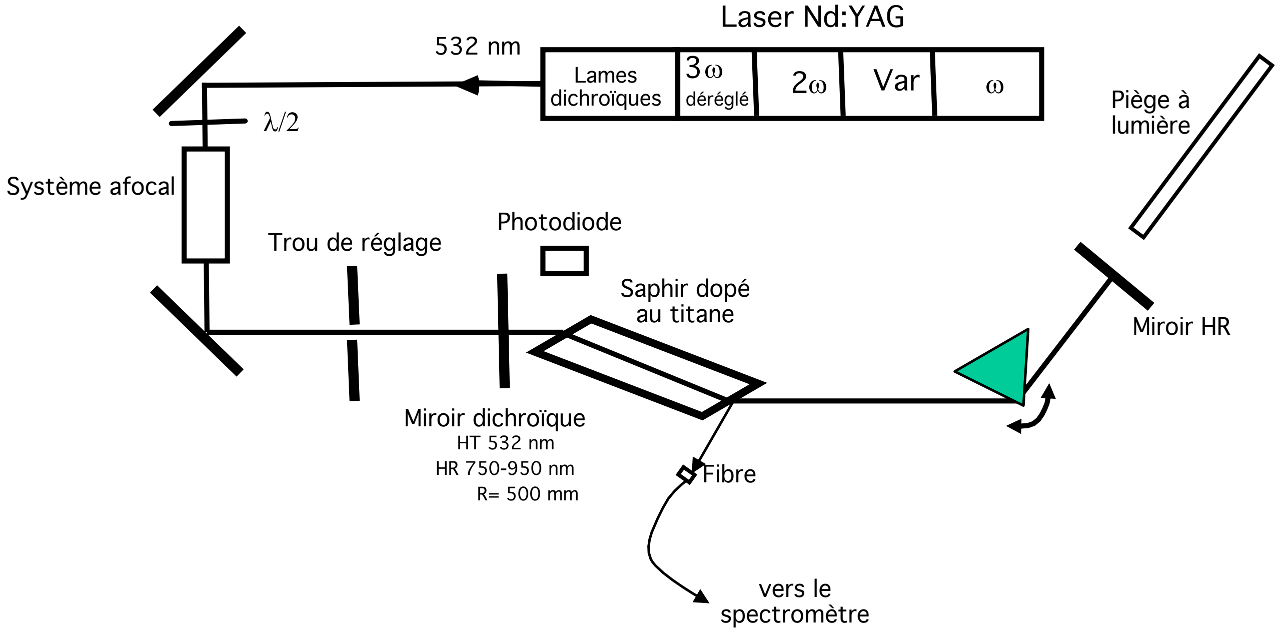

Fig. 3: Experimental set-up for the titanium-doped sapphire laser.

Pumping is performed at 532 nm by the previous Nd:YAG laser, but this time in a frequency doubling configuration (it is necessary to misalign the frequency tripler stage and change the laser output: call the supervisor for this operation).

The pump laser beam at 532 nm is carried to the study bench by means of 2 mirrors reflecting at 532 nm. A half-wave plate is used to control the direction of polarisation of the pump beam. When this is horizontal, the absorption in the titanium-doped sapphire crystal is maximum.

In order to facilitate laser operation, the pump beam size is reduced by means of an afocal system.

The laser cavity consists of two mirrors and a prism. To facilitate the adjustment of the cavity, both mirrors are highly reflective in the infrared. The prism is used to tune the cavity.

The titanium-doped sapphire crystal is cut at Brewster's incidence to limit losses at the interfaces and to avoid additionnal anti-reflective coatings on the faces.

For laser analysis, a photodiode is placed near the laser. This is covered with an orange filter to prevent glare from the pump beam. It will allow the fluorescence of the laser to be observed, as well as the laser effect itself, by diffusion on the optical surfaces.

The spectral analysis will be performed by placing the spectrometer's fibre input close to the crystal, in the path of a laser leakage when the laser is operating.

The green beam that is not absorbed in the titanium-doped sapphire is stopped by means of the light trap.

Question 2.1: Give a method for adjusting the half-wave plate.

Align the pump beam to the titanium-doped sapphire crystal using the same method as for the OPO setting.

Question 2.2: Using the photodiode (with its orange filter), placed on the side of the crystal, observe the fluorescence of the titanium-doped sapphire.
Give a method to measure the lifetime of Ti^{3+} ions in the upper level with this experiment. Give the value of the measured lifetime.

Note: By shifting the orange filter slightly, it is possible to bring pump photons to the sensitive surface of the photodiode (the pump diffuses strongly throughout the room). It is interesting to observe both signals at the same time.

Question 2.3: The prism index is about 1.7 for laser wavelengths.
- Calculate the angle at the top of the prism so that the laser beam is at Brewster's incidence on the entrance and exit faces of the prism.
- What is the angle of incidence so that the prism is at the minimum deviation?

Question 2.4: Explain with a figure how the prism can achieve laser wavelength tunability.

Align the prism and the HR mirror. To do this, proceed in two steps: first align these elements with the green beam (adjust the prism around the minimum deviation). Then turn the HR mirror along a vertical axis of rotation to look for the laser effect, which is visible at the signal given by the photodiode.

Question 2.5: Observe the laser emission spectrum with the spectrometer. Give the tuning range of the laser.

Question 2.6: Observe the laser pulse in relation to the pump pulse.
The laser pulse builldup time is defined as the time between the pump pulse and the maximum of the laser pulse. Observe <u>and</u> analyze the evolution of the buildup time as a function of :

- the pump power (variable thanks to the control box),
- cavity losses (by adjusting the HR mirror, the diffraction losses on the laser mode in the cavity can be increased)

Question 2.7: Observe the fluorescence of the laser with both the photodiode and the spectrometer. Comment on the evolution of the fluorescence of titanium-doped sapphire with and without laser effect.

Question 2.8: Summary of the labwork
Make a comparison between the two tunable oscillators you have studied in this labwork.

Flashlamp-pumped Nd:YAG laser

The purpose of this lab is to explore the performance of a flash-pumped Nd:YAG laser derived from a commercial version. This laser is class 4: the slightest scattering can be dangerous for the eyes.
It is absolutely mandatory to wear glasses as soon as the pumping flashes are started.
For the report, answer the questions asked, the description of your manipulations is not useful. Take pictures of your results that you can insert in the report.

I. Presentation of the laser

1. The amplifying medium

The amplifying medium is a YAG crystal (Yttrium Aluminum Garnet $Y_3Al_5O_{12}$) doped with neodymium ions Nd^{3+}. The YAG matrix, synthesized for the first time in 1961 in the USA (AT&T Bell Laboratories), is known for its solidity and its good thermal conductivity. Nd:YAG is therefore well suited for the realization of powerful lasers requiring intense pumping. It is used in many commercial lasers. Its main emission wavelength is 1064 nm.
The energy levels involved are described in figure 1-left. The Nd:YAG is a four-level laser. The lifetime of the top level of the laser transition is 230 µs.
Nd:YAG can be pumped by xenon flash lamps emitting an intense white light (see spectrum in figure 1-right).

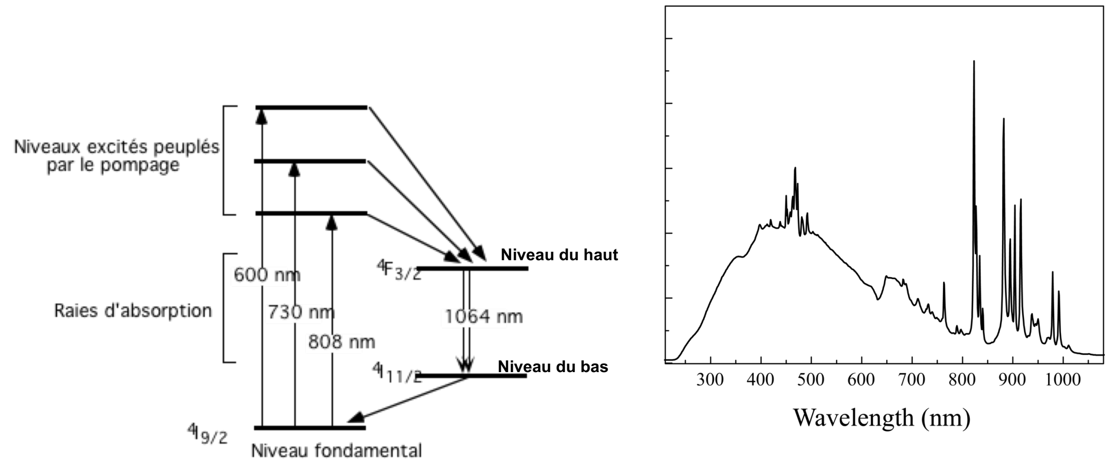

Fig.1 Left: Energy levels of Nd^{3+}. Right: emission spectrum of a xenon flash.

2. Pumping

The Nd:YAG amplifying medium is in the form of an elongated rod (length ≈ 80 mm) with a circular cross section (diameter 4 mm). It is pumped by a xenon flash, placed close to the rod (Fig. 2). The assembly is placed in a reflective elliptical cavity, with the flash and the laser rod on the foci of the ellipse. The assembly is cooled by water.
The pump device and the amplifying medium form a "laser head": an assembly capable of amplifying light. This head can be placed in a cavity, or simply crossed by a laser beam making one or more passages in the Nd:YAG crystal.

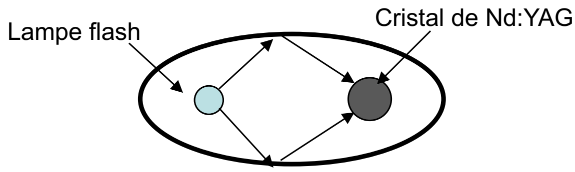

Fig.2 : Diagram of the flash pumping.

3. The global scheme of the laser

The laser is derived from a commercial Nd:YAG system that has been simplified for teaching purposes. The global schematic is given in figure 3. The setup consists of two parts: a laser oscillator emitting at 1064 nm and a double pass laser amplifier. At the output of the laser, a non-linear KDP crystal can be placed to convert the radiation to 532 nm by frequency doubling.
A helium neon laser is placed on the assembly to facilitate the alignments. It materializes the optical axis of reference, on which the laser optics will be aligned by autocollimation.
The polarizer at the input of the amplifier transmits the horizontal polarization and reflects the vertical polarization.

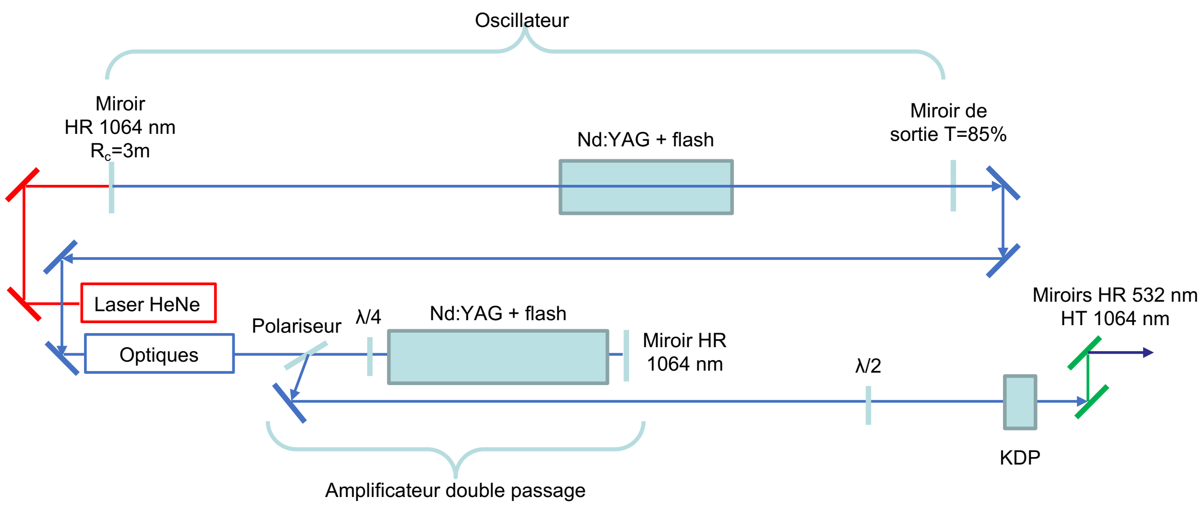

Fig.3 : Experimental setup of the laser.

The cavity consists of a spherical mirror with a radius of curvature Rc=3 m, totally reflecting at 1064 nm, and a partially reflecting plane output mirror (T=85%, R = 15%).

Question 1: Calculate the single-pass gain G0 in the Nd:YAG head of the oscillator required to reach the oscillation threshold (it is assumed that there are no other losses than the output mirror).

The polarizer at the input of the amplifier transmits the horizontal polarization and reflects the vertical polarization.
Question 2: Explain how the two passages are realized in the amplifier.

Question 3: Explain the purpose of the half-wave plate placed just before the KDP crystal.

II. Laser study

The study of the laser is done in 3 parts: first a characterization of the oscillator in two operating regimes, then a characterization of the amplifier and finally an exploration of the performances in frequency doubling. The characterizations are made by photodiodes and by an energy meter (pyroelectric detector).

1. Characterization of the oscillator

1.1 Alignment of the oscillator cavity

Using the He-Ne laser, check that the two mirrors of the cavity are in autocollimation. Switch on the power supply. Check that the flash potentiometers are at minimum. Start the flashes and progressively increase the flash of the oscillator to its maximum.
To verify that the laser effect is achieved, simply place an old black Polaroid photo at the outlet of the laser. The laser pulses burn the Polaroid locally.

1.2 Pulse measurement in free-running

The free-running regime corresponds to the operation of the laser when the pumping is pulsed and there is nothing in the cavity to control the pulses emitted.
The goal of this part is to analyze temporally this temporal regime of the laser and to evaluate the peak power emitted by the laser at each flash.

In order to study the pumping flash and laser pulses, a fast avalanche photodiode is placed just above the pumping head of the oscillator. This position allows to detect light leakage from the flash and the laser. The photodiode is reverse biased at a voltage of 200 V. To ensure a fast response time of the detection chain, the photodiode must be connected to the input impedance 50 ohms of the oscilloscope.

Question 4: Observe the signal given by the photodiode
- give the duration of the flash (at half height)

- give an estimate of the duration of the laser emission on a flash (we do not take into account the fast modulations of the laser emission: to measure its duration, it is enough to locate the start of the laser emission and the end of the emission)

Question 5: Explain why the laser starts with a delay compared to the beginning of the flash.

Question 6: The delay between the start of the flash and the start of the laser is called the buildup time of the laser pulse.
Observe the evolution of the buildup time with the pump power (variation of the power with the potentiometer on the flashes supply). How to explain this?

Question 7: Observe the evolution of the buildup time with the adjustment of the orientation of the mirrors of the cavity. How to explain this?

1.3 Energy measurement in free running operation

The energy of the emitted pulses is measured by a pyroelectric detector. This one gives an electric impulse signal when it receives a light impulse. The maximum of this signal is proportional to the energy received. The calibration of the detector is given on its mount (9.83 V/J). It works with the 1 MΩ load resistor of the oscilloscope, unlike the photodiode. Attention, the impulse response of the detector is of the order of a millisecond, much longer than the duration of a flash.

Caution: Never place the detector directly on the output laser beam (risk of damage).

To avoid damage to the pyroelectric detector, a leakage of the beam is measured by a reflection on a glass slide. Send the reflection to the pyroelectric detector. By keeping a small angle of incidence on the glass plate, we will consider that 8% of the total energy is measured (corresponding to the two reflections of 4% on each face of the plate assumed index n=1.5).

Question 8: Give the value of the energy emitted by the laser on a flash (potentiometer controlling the intensity of the flashes at maximum), deduce the peak power of the pulse.

1.4 Operation in Q-switched regime

The Q-switched regime allows to obtain intense and relatively regular peaks: its principle is to impose a high level of losses at the start of the pumping, so that the population inversion becomes very important, then to abruptly lower the level of losses to give an intense pulse. In the laser studied here, this operation is obtained by using a saturable absorber inserted in the cavity. It is a passive Q-switching. The saturable absorber is placed in the oscillator, between the laser head and the output mirror.

Question 9: Explain the meaning of the term saturable absorber. Explain how the saturable absorber allows to realize the Q-switched regime. Explain the different phases of construction of the laser pulse in this regime.

Question 10: Observe the signal given by the photodiode. Why are there several peaks during the duration of a flash.

Question 11: Give the peak power corresponding to one pulse (give the method to make this measurement).

Question 12: Add a second saturable absorber to the cavity. Comment on the differences in the pulse regime.

The laser consists of several longitudinal modes whose frequencies are equal to kc/2L, L being the optical length of the cavity, k an integer and c the speed of light in vacuum. These different modes are spatially superimposed and therefore give interferences. As the frequencies are different, we observe frequency beatings, or mode beatings resulting in a periodic signal.

Question 13: Give an order of magnitude of the period of the beatings for two consecutive modes. Observe the beatsings with the photodiode by zooming in on a laser peak of the Q-switched regime. Compare the value measured on the oscilloscope with the estimated value.

2. Characterization of the amplifier

The performance of the amplifier is measured for an oscillator operating at maximum power in the free-running regime. This regime of the oscillator gives a more stable energy per pulse than in the Q-switched regime. The laser oscillator therefore operates without a saturable absorber that must be removed from the cavity for this study.

2.1 Gain measurement

The amplifier works even when the potentiometer of its flash is at minimum. The goal here is to make a first measurement of the gain in this configuration. The gain of the amplifier G is defined as the ratio between the energy at the output of the amplifier (after 2 passes) and the incident energy just at the input of the amplifier.

The incident energy is difficult to measure directly due to the size of the optics. It is estimated to be half of the output energy of the oscillator, taking into account that the laser is not polarized and that the polarizer transmits only the horizontal polarization.

Question 14: Give the value of the gain of the amplifier , G_{ampli}

In order to characterize the performance of the amplifier, we measure the G_{ampli} gain as a function of the pumping power. This last one is measured in a relative way by a photodiode placed near the flash of the amplifier.

Question 15: Plot the gain of the amplifier as a function of the pump power.

Question 16: By looking at the curve of gain versus pump power, indicate if the amplifier operates in the "small signal" regime or in the saturation regime.

2.2 Frequency doubling

Place the KDP crystal at the output of the amplifier, according to the diagram in Figure 3. The two mirrors placed at the output of the KDP crystal are used to filter the green signal at 532 nm from the fundamental beam at 1064 nm, collinear. Despite this filtering, there will remain a residual infrared on the detector that must be taken into account in the measurement.

Question 17: Set the KDP crystal to be in phase matching. Measure the energy in the green when the laser oscillator is in free running and the pumping powers of the flashes are maximum (for the oscillator and for the amplifier). What method should be used to make this measurement correctly?

Question 18: Repeat the same experiment by inserting a saturable absorber in the cavity of the oscillator. Give the value of the energy in the green. Explain the difference between the two measurements.

Femtosecond Laser

1. Preliminary study: operation of a femtosecond laser

A femtosecond laser is a laser whose modes are phase-locked to produce very short pulses, of about ten to a hundred 10^{-15} second duration.

The laser studied in thislabwork uses as amplifying medium a titanium-doped sapphire crystal whose emission band extends from 750 nm to more than 900 nm, with a maximum around 800 nm.

Short pulses are synonymous with wide spectral bands. Indeed, for a so-called Fourier transform limited pulse, there is a relationship between the temporal width Δt (at half height) and the spectral width $\Delta \nu$ (at half height) of the pulses :

$\Delta t \Delta \nu \geq K$ *where K is a constant depending on the shape of the pulses.*
K = 0,44 for a Gaussian time-form pulse and K = 0,315 for an pulse of temporal form in hyperbolic square secant.

There are several techniques for locking modes in phase : active (use of acousto or electro-optical modulators) or passive (use of non-linear effects such as absorption saturation or the Kerr effect). In this labwork, the laser uses a lens created by the Kerr effect in the titanium-doped sapphire crystal. The method is called "Kerr lens mode locking". It provides the shortest pulses.

1.1 Principle of the Kerr lens mode lock

The Kerr effect is a non-linear effect which results in the modification of the index of the medium seen by a wave propagating in it according to its intensity I. It is an effect linked to the third order dielectric susceptibility coefficient of χ^3 the medium. Thus, by noting n_0 the linear index of the medium and n_2 its non-linear index, a beam of intensity I propagate in the medium with the refractive index :

$$n(I) = n_0 + n_2 I$$

In a cavity, the spatial distribution of beam intensity is Gaussian in a plane transverse to the propagation axis. Consequently, when a Gaussian beam of power P_0 passes through a medium with a Kerr effect $n_2 > 0$, it is focused (called self-focussing) because the medium acts as a converging Gaussian lens. It is shown that the resulting Kerr lens has a vergence of :

$$D_{Kerr} = \frac{1}{f_{Kerr}} = \frac{n_2 L_{mat}}{\pi w_0^4} P_0$$

where w_0 is the radius of the waist, L_{mat} is the length of the material passed through and the P_0 peak power of the beam.
For sapphire, the coefficient n_2 is of the order of 3.10^{-16} cm^2/W.

The existence of the Kerr lens will allow us to favour the pulsed regime by introducing more losses on the continuous regime. Indeed, the intensity in the continuous regime is 4 orders of magnitude lower than the intensity in the pulsed regime. Thus, the Kerr lens only exists in the pulsed mode. By inserting a slit in the cavity at a point where the "pulsed" beam is smaller than in the continuous regim, it is then possible to introduce more losses on the continuous beam (see Figure 1).

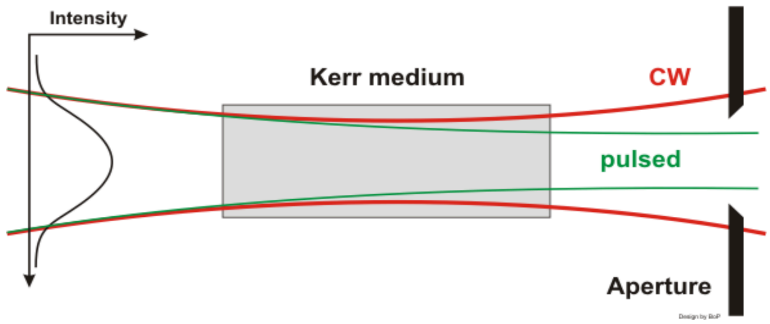

Figure 1: Selection of the pulsed mode by Kerr effect.

1.2 Phase dispersion and self-modulation

This part helps to understand how the pulsed regime favoured by the Kerr lens can be stabilised over time.

In the cavity, two phenomena tend to modify the pulse (on the temporal and spectral level). For more details, see Appendix 1.

- The first is the spectral dispersion of the components (in the classic case of a higher index in blue than in red, this is called positive dispersion). Since the spectrum of the pulses from 100 fs to 800 nm is wide (of the order of several nm), the spectral components will propagate at different speeds, each accumulating a different phase. The pulse will tend to widen temporally as it passes through the cavity optics. With each round trip through the cavity, the pulse will accumulate group velocity dispersion (GVD). The "red" part of the pulse will be ahead of the "blue" part of the pulse. This is called frequency drift (or chirp).

- The second is self-phase-modulation. The instantaneous intensity of the pulse varies very strongly over time. This will lead to an instantaneous change in index by the Kerr effect, and therefore to a variation in phase. This Kerr effect observed in the time domain (and not in the spatial domain as in the previous section) is called self-phase-modulation (or SPM). It results in the generation of new frequencies (because frequency is the derivative of temporal phase, see Appendix 1). The new frequencies are time-dependent, resulting in frequency drift. This is of the same type as the frequency drift imposed by dispersion: the "red" part of the pulse will be ahead of the "blue" part of the pulse.

To achieve a stable state of the laser, an optical system must be introduced into the cavity to compensate for this positive dispersion. In this labwork, the system used is a pair of prisms, shown below :

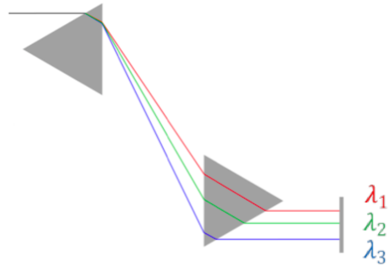

Figure 2: Two-prism system allowing the introduction of negative dispersion for dispersion compensation.

In this configuration, the "red" wavelength λ_1 travels a smaller optical path than that of the "blue" wavelength λ_3. An adjustable negative dispersion can therefore be introduced by changing the distance between the prisms or the thickness of glass passed through.

When the prisms are correctly adjusted, it is possible to fully compensate for the positive dispersion created by the cavity components and self-phase-modulation. The laser generally reaches a stable regime called soliton regime (described in Appendix 2) where the pulse retrieved its temporal shape after a round trip in the cavity.

1.3 Description of the laser cavity

The crystal is pumped using a frequency-doubled $Nd:YAG$ laser that emits at a wavelength of 532 nm with a maximum output power of 10 W in continuous operation.

The femtosecond laser cavity is given in Figure 3 (a picture of the laser is given in Appendix 4).

The Lyot filter (birefringent filter, BRF in figure 3) allows the laser to be tuned in wavelength.

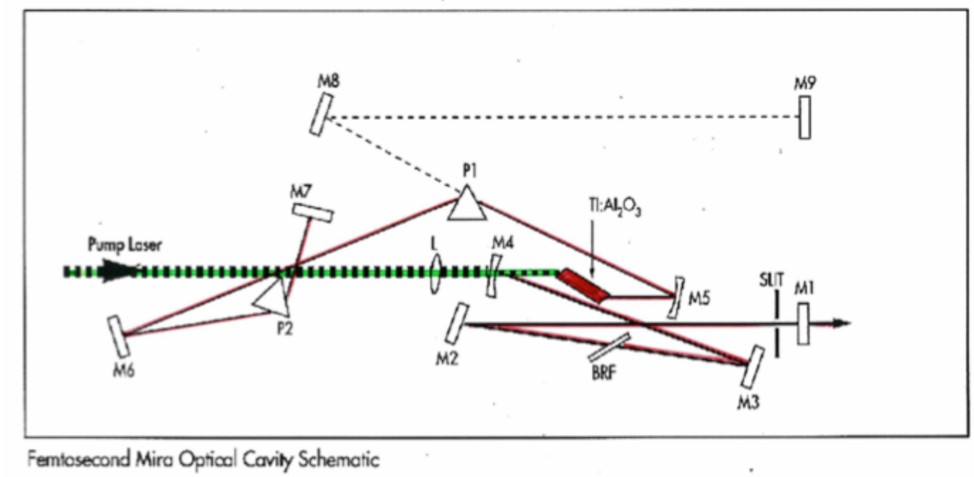

Figure 3: Diagram of the femtosecond laser cavity.

Preliminary questions

P1: The length of the laser cavity is about 2 m (linear cavity). Give the pulse rate.

P2: The pulse duration will be around 100 fs. Give an order of magnitude of the width of the spectrum emitted by the laser (in nanometres).

P3: The average power of the laser will be around 100 mW. Give an order of magnitude of the peak power of each pulse.

P4: Calculate an order of magnitude of the focal length $\mathbf{f_{Kerr}}$ of the Kerr lens in the titanium-doped sapphire crystal (inside the cavity) where: w_0= 30 µm, L_{mat} = 20 mm, output mirror transmission: 1%, average laser power: 100 mW, cavity length: 2 m.

P5 Summarise in a table the optical elements and physical phenomena required to generate femtosecond pulses via Kerr lens mode-locking (some elements may have multiple roles).

Cavity component	**Physical effect**	**Role**
Crystal Ti :sapphire	Laser gain	Optical amplifier
Crystal Ti :sapphire	Spatial Kerr effect	…
Slot	...	...
Prisms	...	...

2. Obtaining the femtosecond regime and first characterizations

LASER SAFETY: the laser is dangerous. Its power makes it necessary to wear type B glasses as soon as the shutter of the pump laser is open.

Procedure for obtaining the femtosecond regim

1. Open the shutter of the pump laser ("shutter" button).
2. Open the slit as wide as possible.
3. Adjust the Lyot filter (using the spectrometer) to set the center wavelength of the laser emission towards the center wavelength of the laser. 800 nm $\pm$ 5 nm.
4. If necessary, adjust the back-cavity mirror (M7 in Figure 3) to maximize the output power, the value of which is given in tree units on the laser control box.
5. Close the slit to divide the laser power by 2, making sure that the slit is well centred on the beam (the power should be maximized by centering).
7. Switch to ML (mode-locking) on the control box. This mode allows the laser to be started in femtosecond mode. Indeed, a vibrating optical component (starter mechanism on the photo in appendix 4) will create disturbances in the cavity to obtain noise peaks which will constitute the seed of the pulses.
8. The femtosecond regime is obtained when the pulse train is stable and the spectrum is smooth (corresponding to the Fourier transform of a pulse). If the pulse regime is not stable, finely move the Lyot filter over the range [780 nm ; 810 nm].

To characterise the femtosecond laser beam, the set-up includes a fast photodiode and oscilloscope as well as a spectrometer.

Q1: Measuring the pulse rate. Deduce the length of the cavity.
Q2: Measure the width of a pulse at half height with the oscilloscope. What do we deduce from this?
Q3: Using the spectrometer, measure the width of the resulting spectral band. From this, deduce the theoretical value of the pulse duration, in the case of a pulse limited by the Fourier transform whose temporal form is a hybrid secant squared.
Q4: Measure the average power of the pulses. Deduce the energy and peak power of the pulses.

3 Pulse duration measurement by autocorrelation

3.1 Principle of autocorrelation

Since the pulses from the laser are too short to be measured with a photodiode, an indirect measurement of the duration must be made using an optical autocorrelator (Fig.4).

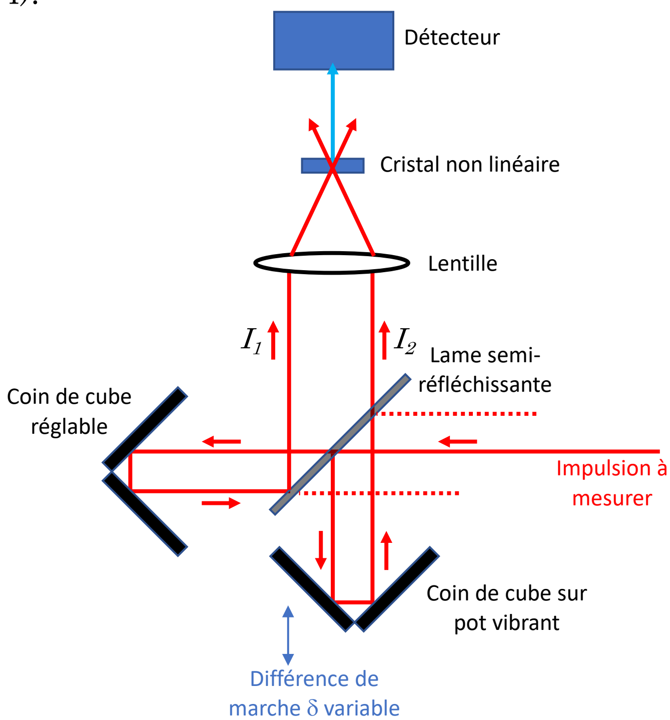

Figure 4: Schematic diagram of an autocorrector.

The idea is to use frequency doubling in a non-linear crystal ($\chi^{2)}$, here a barium beta-borate crystal: BBO). A phase tuning is carried out in order to obtain an efficient frequency doubling: to create one photon at 400 nm, two photons are needed at 800 nm.

The role of the optical autocorrelator is to create two beams of equivalent (ideally equal) intensities I_1 and I_2 (here thanks to a semi-reflecting plate) from the pulse beam to be measured. A movable cube corner allows an adjustable δ delay between the two beams.

The two beams are then recombined in the frequency doubling crystal (BBO), located at the focus of a lens. The BBO therefore sees the intensities $I_1(t)$ and $I_2(t-\delta/c)$ where c is the speed of light in air. At instant t, the doubled intensity $I_{blue}(t)$ is proportional to the product of the intensities on the fundamental beams :

$$I_{blue}(t) \propto I_1(t) * I_2(t - \frac{\delta}{c})$$

$I_{blue}(t)$ varies with the pulse rate of the laser, but this intensity cannot be resolved temporally because the detector used here has a too slow response time (typically in the microsecond range). Assuming that the detector has a rectangular pulse response of width τ_r, the signal is therefore proportional to the average value of $I_{blue}(t)$:

$$1/\tau_r \int_0^{\tau_r} I_1(t) * I_2(t-\frac{\delta}{c})dt$$

τ_r being sufficiently long in relation to the time variations of the intensities, the signal detected in the blue corresponds to the autocorrelation function because I_1 and I_2 come from the same temporal signal. To access the different values of this function, simply modify the delay δ between the two beams.

Q4: In fig.4, the frequency-doubled beam is the bisector between the two infrared beams: explain why.

3.2 Description of the autocorrector

The autocorrelator is described in Figure 5. The first cube corner is mounted on a vibrating pot. The second is mounted on a micrometric translation plate.

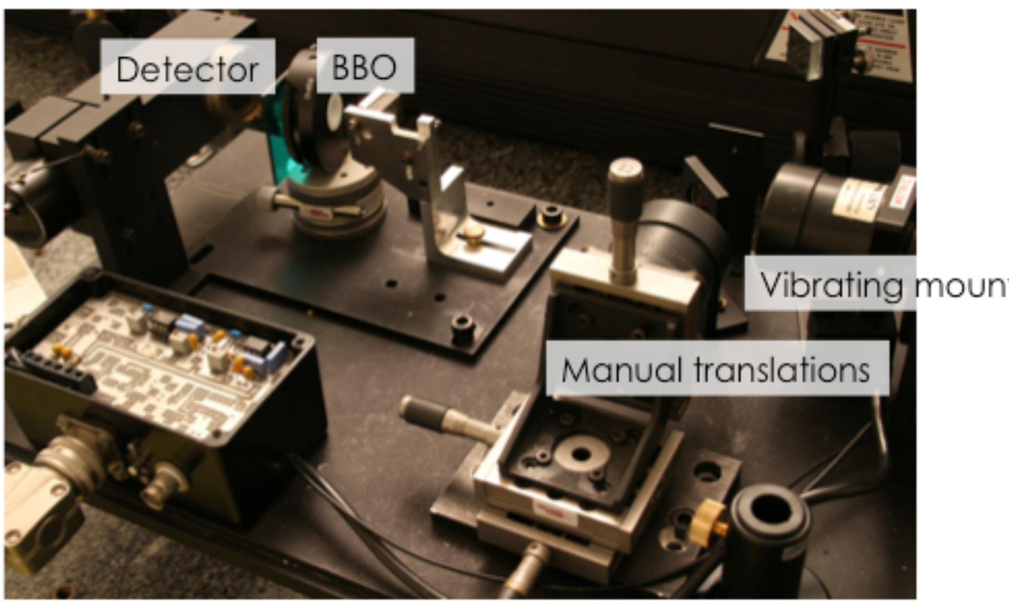

Figure 5: Photo of the autocorrelator.

The signal is detected by a photomultiplier (PM) in front of which a blue filter is placed.

Two external devices are required to use the auto-correlation unit: the vibrating pot power supply, which enables the amplitude and frequency of its movement to be managed, and the PM interface box. These two units will then be connected to the oscilloscope in order to display the autocorrelation signal and the control voltage of the vibrating pot as a function of time.

Q6: The BBO crystal is 200 µm thick. Why is it so thin?

Q7: The pot vibrates with an amplitude of about 1 mm. Is it suitable for viewing the entire autocorrelation function of a 100 fs pulse?

3.3 Adjusting the autocorrector (if necessary)

In order to facilitate the adjustment of the auto-correlation unit, first work with collinear and merged I_1 *and* I_2 beams on the BBO crystal as shown in figure 6. This setting simplifies the obtaining of the frequency-doubled signal.
The adjustment of the autocorrelation starts with an alignment of the beam to be measured in the centre of the inlet diaphragm and the BBO. To do this, perform a "laser alignment" using the two mirrors at the input of the autocorrelator and remove the focusing length in front of the BBO crystal.
Check that the PM is well centred on the beam (it can easily translate into its mechanical support).
Add the lens on the beam axis, without misaligning the beam.
Switch on the vibratory pot and trigger the oscilloscope on the control signal of the vibratory pot (sinusoidal signal). The vibratory frequency will be set to 20 Hz (at higher frequencies the signal will be attenuated by the response time of the PM and its electronics, which react like a low-pass filter).

Observe a signal doubled in frequency with the PM by playing on the orientation of the BBO.
Adjust the orientation of the BBO and the focus of the lens to have a maximum frequency doubled signal.

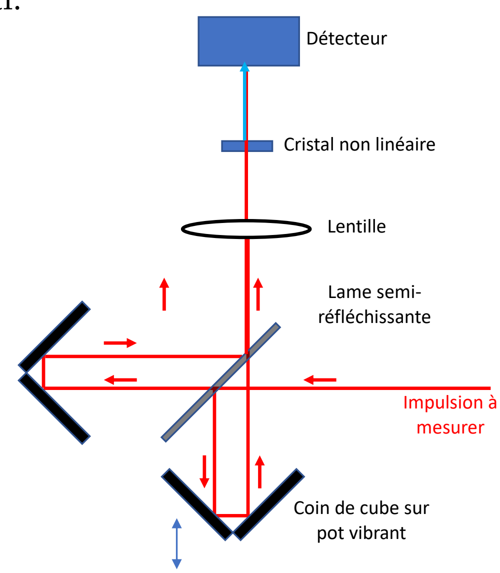

Figure 6: Autocorrelation set with collinear beams.

Shift the lens and the adjustable cube corner to find the configuration shown in Figure 4. Find the autocorrelation function on the oscilloscope.

3.4 Measuring pulse duration

The duration of the autocorrelation function is measured by calibration. The adjustable cube wedge is used for this purpose, the translation of which along the beam axis is marked by a micrometer. This micrometer will be used to calibrate the displacement of the vibrating cube corner in order to know the delay it imposes on beam 2. From this, the calibration on the oscilloscope can be deduced.

Q8: Translate the cube wedge by noting its displacement (cube wedge vernier reading) for two positions of the autocorrelation function observed on the oscilloscope. The translation of the cube wedge corresponds to an optical delay (by dividing by the speed of light - beware of the factor of 2 related to the return of the beam in the cube wedge). Deduce the calibration of the oscilloscope with respect to the optical delay measured.

Q9: It is assumed that the pulse has the form of a hyperbolic secant squared. In this case, the mid-height widths of the pulse Δt and its autocorrelation function Δt_{autoco} are related by $\Delta t = \Delta t_{autoco}/1.54$ (for information, in the case of a Gaussian form $\Delta t = \Delta t_{autoco}/\sqrt{2}$). Measure the pulse duration and determine the measurement uncertainty.

4 Temporal manipulation of femtosecond pulses

Now that you have mastered the femtosecond pulse duration measurement tool, the aim of this part is to make duration measurements under different conditions.

4.1 Effect of dispersion in the laser cavity

Dispersion and role of prisms in the cavity

In the case of the Ti:Sapphire laser oscillator, self-phase-modulation (SPM) is located in the Ti:Sapphire crystal; group velocity dispersion (GVD) is related to the optical components of the cavity (positive dispersion) and the two-prism negative dispersion system. It is possible to establish a relationship between the duration Δt, dispersion β_2, self-phase-modulation and the electric field envelope $|a|$ (known as the soliton area formula, see Appendix 2) :

$$\Delta t = \frac{-\beta_2}{\gamma |a|^2} = \frac{-\phi_{2,cavité}}{\gamma L_{cristal} |a|^2}$$

It can be shown that by changing the dispersion, the regime can remain solitonic. The pulses adapt their duration to find a new balance between dispersion and self-phase-modulation and their spectral phase remains flat. To test this phenomenon, one of the prisms is translated perpendicularly to the optical axis, which has the effect of modifying the thickness of the glass through which it passes, e and thus the second-order spectral phase of the cavity (see Appendix 2).

Vary the amount of material passed through one of the prisms (typically between the 5 and 10 graduations of the vernier).

Q10: Plot the duration of the measured pulse as a function of the prism movement. Display the error bars. Do the results validate the soliton air formula?

4.2 Effect of an optical dispersive element on a femtosecond pulse

In a dispersive element, the different spectral components will not travel at the same speed, resulting in a temporal spread of the pulse. This time spread depends on the duration of the input pulse (see Appendix 3).

Place the two crystals of YVO_4 in the beam path.

Q11: Measure the pulse duration Δt_{out} using the autocorrelator by varying the duration of the Δt_{in} input pulse (as in 4.1). Make a curve $\Delta t_{out}=f(\Delta t_{in})$.

Q12: Derive an estimate of the dispersion β_2 in $fs^2.mm^{-1}$ for the YVO_4.

5 Annexes

5.1 Appendix 1 - Phase dispersion and self-phase-modulation

The emitted pulses can be described either in the time domain or in the spectral domain.

We define E(t) the complex amplitude of the associated electric field and E(ω) the complex amplitude in the spectral domain, I(t) and I(ω) the intensities in the temporal and spectral domains, ($\omega = 2\pi\nu$, ν being the frequency considered).

E(t) and E(ω) can be written :

$$E(t) = \sqrt{I(t)}.e^{j\varphi(t)} \quad et \quad E(\omega) = \sqrt{I(\omega)}.e^{j\varphi(\omega)}$$

with $\varphi(t)$, the temporal phase of the pulse and $\varphi(\omega)$, the spectral phase of the pulse.

In general (it is the case in this labwork), the two complex amplitudes are linked by the Fourier transform.

Group velocity dispersion changes the spectral phase

Usual optical media such as those forming the cavity have a so-called normal or positive dispersion. This has the effect of temporally spreading polychromatic pulses because "red" wavelengths have a higher group velocity than "blue" wavelengths.

To understand the effect of group velocity dispersion, a time-frequency representation called a spectrogram is used. Figure A1.1 (left) shows the typical spectrogram of a femtosecond pulse. In red, the spectral and temporal phases are represented: in the ideal case, they are constant. On the right, the spectrogram of an pulse which has passed through a positive dispersive medium is shown. It can be seen that the pulse is temporally broadened. Its spectrum is identical but its spectral phase is modified.

Red propagates faster than blue: a frequency drift (or chirp) is observed.

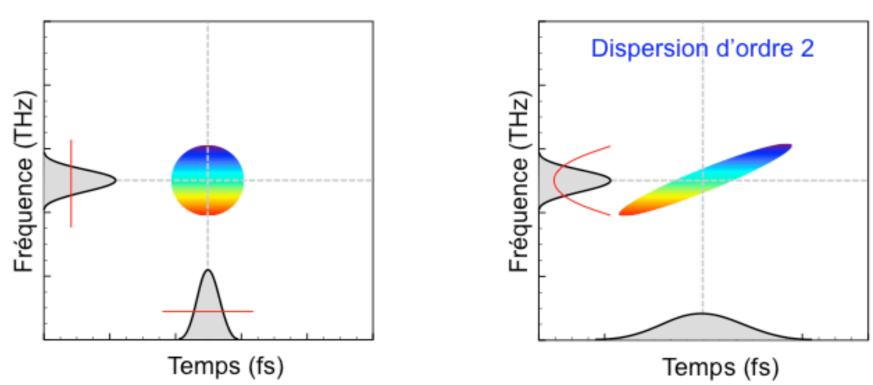

Figure A1.1: Spectrographs of an ideal pulse (left) and a pulse that has passed through a medium with normal dispersion [courtesy of Franck Morin, class of 2007].

Self-phase-modulation changes the time phase

Suppose a Gaussian pulse with the following expression :

$$I(t) = I_0 e^{-\frac{t^2}{2(\Delta\tau)^2}}$$

Therefore, when the pulse propagates in a medium with the Kerr effect, the intensity at one point in the medium will vary over time. This will cause a temporal variation in the index seen by the wave. The instantaneous phase acquired by the pulse as it passes through the medium of thickness L then depends on the time according to :

$$\phi(t) = \omega_0 t - \frac{2\pi}{\lambda_0}\left(n_0 + n_2 I(t)\right)L$$

The pulsation ω =2πν of the pulses, defined as the time derivative of the instantaneous phase, is therefore of the form :

$$\omega(t) = \omega_0 + \frac{2\pi n_2 L I_0}{\lambda_0 \Delta\tau^2} t e^{-\frac{t^2}{2(\Delta\tau)^2}}$$

So we can see that there is a temporal dependence of the pulsation. New frequencies are therefore created. There is a red shift in the leading edge of the pulse and a blue shift in the trailing edge (see Figure A1.2). In the case of self-phase-modulation, the frequency drift is positive. In addition, the temporal phase is modified. However, self-phase-modulation does not change the pulse duration.

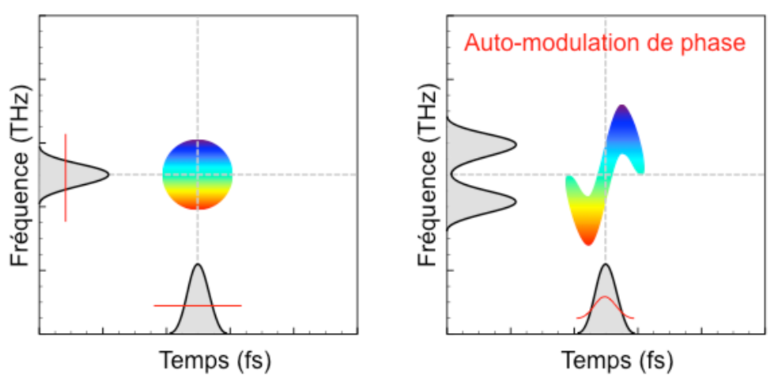

Figure A1.2: Spectrograms of an ideal pulse (left) and a pulse modified by self-phase-modulation (right) [courtesy of Franck Morin, class of 2007].

5.2 Appendix 2 - Solitonic Regime

The solitonic regime is the solution to Schrödinger's non-linear equation of writing the electric field envelope $|a|$ of a pulse propagating in a dispersive, non-linear medium :

$$i\frac{\partial a}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 a}{\partial t^2} + \gamma|a|^2 a = 0$$

where β_2 is the second order dispersion coefficient, corresponding to the group velocity dispersion. By doing Taylor development of the spectral phase around the central wavelength, we find :

$$\beta_2 = \frac{\lambda^3}{2\pi c^2}\frac{d^2 n}{d\lambda^2}$$

and the non-linear coefficient γ corresponding to self-phase-modulation. It is related to the non-linear Kerr index by :

$$\gamma = \frac{2n_2}{\lambda_0 w_0^2}.$$

It can be shown that it is necessary to have γ and β_2 opposite signs for there to be a soliton type solution. This solution is written in the form of a hyperbolic square secant function.

$$P(t) = P_0 sech^2\left(\frac{t}{1.76\Delta t}\right)$$

where Δt is the temporal width of the pulse at half height and P_0 is the peak intracavity power.

In the case of the femtosecond laser oscillator in this labwork, self-phase-modulation and dispersion occur in different media and not simultaneously. However, since the variations due to these two phenomena at each round trip are small, the laser's pulse regime can be assimilated to the soliton regime. It is shown that there is then a relationship between the pulse duration at mid-height *Δt*, γ and β_2 (called the soliton area formula) :

$$\Delta t = \frac{-\beta_2}{\gamma|a|^2} = \frac{-\phi_{2,cavité}}{\gamma L_{cristal}|a|^2}$$

With : $$\phi_{2,cavité} = \phi_{2,prismes} + \phi_{2,matériau} + \phi_{2,miroir}$$

It is shown that for one pass in the Ti:sapphire crystal :

$$\phi_{2,matériau} = \frac{\lambda_0^3}{2\pi c^2}\frac{d^2 n}{d\lambda^2}L_{cristal}$$

$$\phi_{2,mirror} \simeq 0 \text{ (this quantity is neglected here)}$$

$$\phi_{2,prismes} \simeq -\frac{2\lambda_0^3}{\pi c^2}\left(\frac{dn}{d\lambda}\right)^2 D + \frac{2\lambda_0^3}{2\pi c^2}\frac{d^2 n}{d\lambda^2}e$$

where D is the distance (apex) between the two prism tips and e is the thickness of the crossed prism.

The first term of the equation on $\phi_{2,prismes}$ is negative and allows to (over)compensate the dispersion of the sapphire crystal. The second term is positive and allows to finely adjust the total dispersion of the cavity: one of the prisms is positioned on a vernier in order to control e.

5.3 Appendix 3 - Calculation of extra-cavity dispersion

Let's define a pulse of width at 1/e in intensity t_{in}
(note that $2\sqrt{\ln 2}\,t_{in} = \Delta T_{FWHM}$).
We have :

$$E_{in}(t,0) = e^{-\frac{t^2}{2{t_{in}}^2}}$$

By doing the Fourier transform, we obtain :

$$E_{in}(\omega,0) = \sqrt{2\pi {t_{in}}^2}e^{-\frac{\omega^2 {t_{in}}^2}{2}}$$

After propagation over a length z in a material with a coefficient of dispersion β_2 The pulse accumulates a spectral phase, allowing us to deduce :

$$E(\omega,z) = \sqrt{2\pi {t_{in}}^2}e^{-\omega^2\left(\frac{{t_{in}}^2}{2}-\frac{i\beta_2 z}{2}\right)}$$

An inverse Fourier transform is used to determine the equation of field evolution as a function of time. After propagation over a distance z, the field is written as :

$$E_{out}(t,z) = E_0 e^{-\frac{4ln2.t^2}{2\Delta t^2+8i.ln2.\beta_2 z}}$$

Thus Δt_{in} and the total mid-height Δt_{out} widths (FWHM) of the input and output pulses are related by the relation :

$$\Delta t_{out} = \Delta t_{in}\sqrt{1+\left(\frac{4ln2.\beta_2 z}{\Delta t_{in}{}^2}\right)^2}$$

5.4 Appendix 4 - Photo of the laser cavity

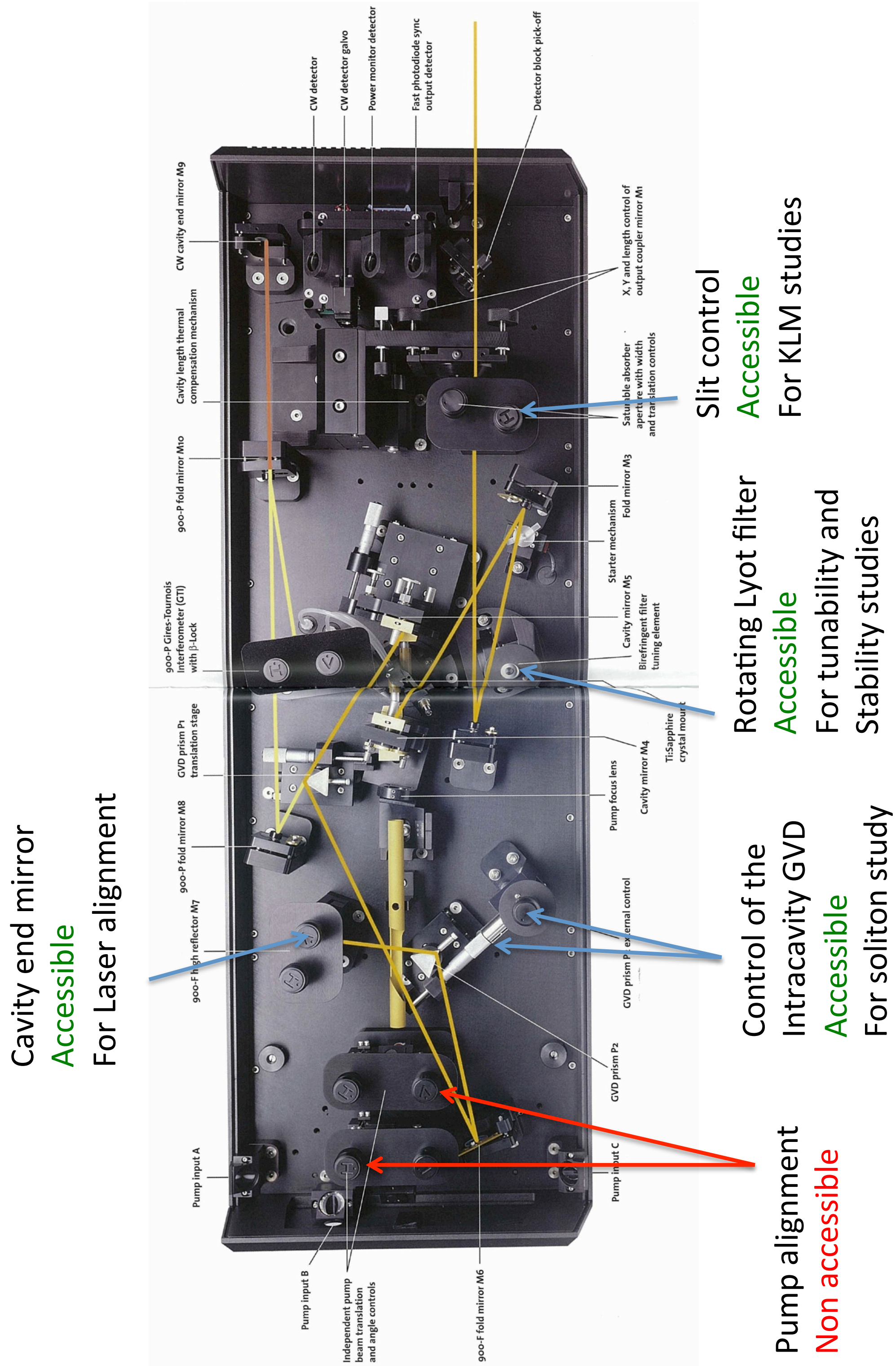

Figure A4.1: Coherent Mira 900 cavity