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Swiss Federal Institute of Technology Zurich

Solid-State Laser

(rev. 01. 2012 by Clara Saraceno)

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1 Introduction: general laser physics concepts

1.1 Goal of the experiment

Basic laser equations can be commonly found in literature [Siegman], and are usually enough to understand and model basic operation of a laser. However, the equations often hardly reflect the problems and challenges that appear when building a laser in the lab. You will find in this easy experiment that the main difficulty arises only from lack of expertise. It is therefore necessary to learn by doing (like in any other field of experimental physics).

The first goal of this experiment is to get acquainted with laser technology by learning the basic steps of building a laser: the pump geometry and its characterization, the gain medium and the need for a stable resonator design. For this purpose, the main elements of a basic laser will be studied and built and compared to simulated resonator designs. As a second step intracavity frequency doubling will be investigated.

1.2 Basics of Lasers

A laser consists mainly of three elements (Figure 1):

- Gain medium: optical transitions that can be excited to generate stimulated emission: the laser crystal.
- Pump source: the energy is brought to this gain medium usually as radiation from another light source that we refer to as the pump source.

- Stable resonator: usually formed by mirrors. The most important elements are the end mirrors of the cavity. In particular, one of the end mirrors has a certain amount of loss in order to extract the laser radiation from the cavity.

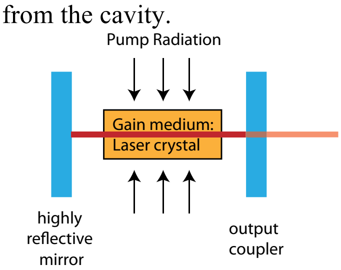


Figure 1: Simple schematic picture of a laser

In the following paragraphs we will quickly review the role of each one of these parts.

1.2.1 Gain medium: solid-state laser

The gain element's role is to compensate for the different sources of loss in the resonator. Some losses are necessary to be able to extract the generated laser light, and therefore wanted (output coupling rate), but some are undesired losses that can arise for example from dirty optics in the resonator, etc.... .
The term "solid-state laser" originates in the nature of the gain medium- in this case a solid crystal. Other laser gain media are based on gases (ie. Helium-Neon lasers, CO_2 lasers ...), or liquid (ie. Dye lasers...) media. The most common type of laser materials are, however, solid (crystal, ceramic or semiconductor). These lasers have the advantage that they are significantly easier to handle and have much longer lifetimes. We refer to these lasers as solid-state lasers. In this experiment we will build a solid-state laser based on a common crystalline laser material Nd^{3+}:YVO_4 (more commonly referred to as neodymium doped vanadate).

1.2.2 Pumping schemes

The pump element brings energy to the gain medium by means of a population inversion. In order to efficiently pump a laser medium the emission wavelength of the pump has to match an absorption line of the gain medium. The absorption spectrum of Nd:vanadate is shown in Fig.2.

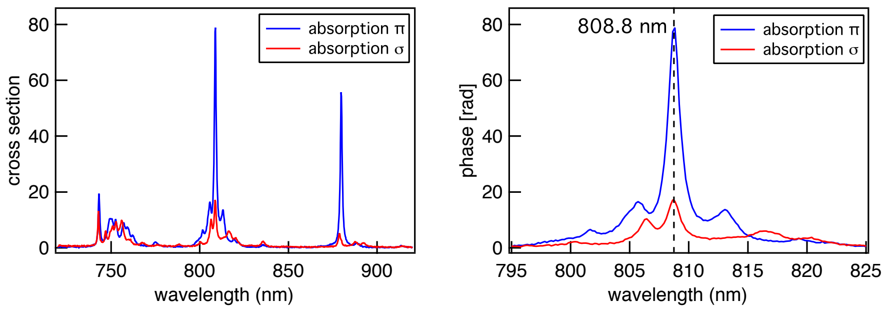


Figure 2: Absorption cross section of Nd:vanadate [6]

Vanadate is a tetragonal crystal (therefore anisotropic) with one c and two a axes, sig is for sigma, that is "senkrecht" (perpendicular) to the c axis (greek sigma for german "S"), pi is "parallel" (greek pi for german "parallel") to the c axis. In this experiment we use an unpolarized pump beam. Therefore, our effective absorption cross section will be somewhere in between σ and π spectra presented here.
As we can see in Figure 2, the absorption lines are quite narrow. Therefore, in order to efficiently pump this material diode lasers are most commonly used, which emit in a narrow linewidth and can be temperature tuned for maximum absorption. Diode lasers are inexpensive, have an excellent electrical-to-optical conversion efficiency (around 50%) and have a narrow linewidth that can be overlapped with the absorption band of most laser media. This makes the pumping process much more efficient. Some lasers use flashlamps as a pump. However, the pumping process is, in this way, very inefficient since the emission spectrum of a flashlamp is very broad. Therefore only a fraction of the available power is used to create inversion.
Furthermore, the lifetime of a laser diode is much larger than that of other pump sources. The main disadvantage of laser diodes is the poor beam quality at high power levels (asymmetric and non diffraction limited beam at power levels > a few watts). However, a proper resonator design can operate with strongly multimode pumping schemes and obtain nearly diffraction limited laser beam quality.

1.2.3 Resonators: cavity design and thermal lens

1.2.3.1 Resonator and laser operation

In order to build a laser, we need to generate a steady-state radiation field in the resonator. This means that both the amplitude and the phase of the electric field have to be reproduced after one round trip in this resonator. Whether this condition is fulfilled or not depends on the wavelength on the radiation, but also on geometrical considerations such as the spacing of the different elements used for the cavity.

The most basic understanding of a laser resonator begins with the passive Fabry Perot Interferometer (FPI). In this case, two plane mirrors with 100% reflectivity separated by a distance L_0 are used. A variation of the separation between these two mirrors results in a variation of the transmission of the device with peaks at integral multiples of half the wavelength. If losses are present, these peaks are broadened. (Figure 2) This is in close parallel with a laser cavity, where an appropriate resonator design is essential to be able to extract laser radiation.

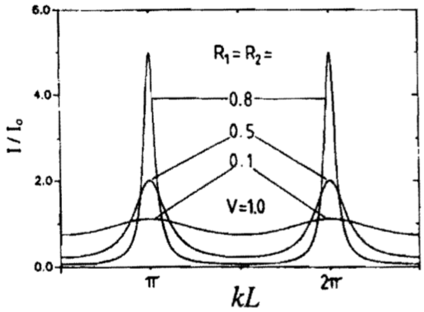


Figure 3: The Fabry-Perot interferometer (FPI): a simple example of a passive resonator and the effect of changing the loss rate of the resonator.

In the case of a laser resonator, the picture is slightly more complicated than the passive FPI since there is a gain medium in the resonator, which modifies the behavior of the FPI. However, if one thinks that gain acts as a partial compensator for the losses of the resonator, this means the resonance lines are narrowed by the presence of gain. Using a gain medium is a common technique to increase the spectral resolution of a passive resonator. If the gain is chosen in such a way that it exactly compensates for the losses of the resonator, this combination of gain medium plus resonator becomes a laser resonator.

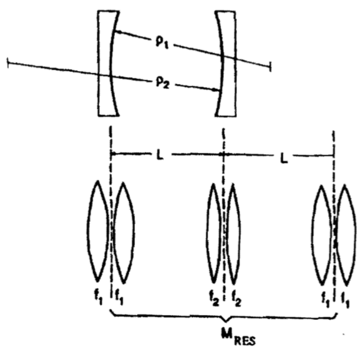
Furthermore, the gain medium has a certain gain bandwidth, which only allows laser radiation to be generated in a certain window. In the end, the number of frequency lines are approximately the product between the gain bandwidth and the spacing between the lines of the resonator.

For more details on FPIs and laser resonators, see [Koechner, Hodgson].

1.2.3.1 Resonator design

A very basic optical resonator usually consists of two mirrors with radius of curvature R_1 and R_2. If a ray launched inside of the cavity parallel to the optical axis remains inside the resonator for an infinite (a very large) number of bounces, the resonator is said to be stable. In this regime, the resonator has self-reproducing field configurations (or transverse mode structures) that can be described taking into account the shape and dimension of the optical elements in the cavity (see next paragraph)

To simulate stability of laser cavities, ray transfer matrices are commonly used to simulate ray propagation. A roundtrip in an optical resonator with two spherical mirrors ρ_1 and ρ_2 is easily described as a transit on an equivalent waveguide (Figure 3, left).



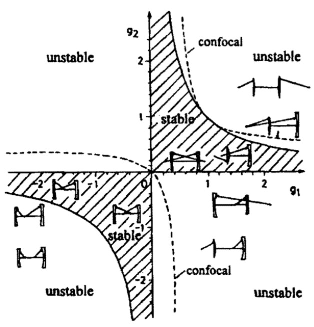


Figure 4: Propagation in a resonator consisting of two curved mirrors can easily be represented by ray transfer matrices in an equivalent waveguide consisting of standard lenses. The eigenmodes of the equivalent matrix of this system Mres can be solved to find stable solutions.

It is straightforward to determine the eigenmodes of the corresponding transfer matrix, corresponding to the self-reproducing waves of the resonator. In this way we can determine the stability regions of a resonator as a function of the g-parameters of the optical resonator ($g_i=1-L/\rho_i$) (Figure 3, right). It is easy to demonstrate for simple linear cavities described by two g-parameters (such as for example the one depicted in Figure 3) that the stability condition is given by:

$$0<g_1g_2<1$$

Q: As a simple example, determine the stability region of a simple resonator corresponding to one flat mirror, and one curved mirror of radius of curvature R>0 separated by a distance L.

For more details on ray transfer matrix methods and gaussian beam propagation see [Koechner, Hodgson].

1.2.3.2 Transverse Mode Structures

We are interested in the transverse field distributions that represent the steady-state solutions of the stable resonators. If we consider that the mirrors in our resonator are infinitely large, an infinite amount of modes could be supported. In practice, the finite sizes of the mirrors and their shape have to be taken as a boundary condition, leading to privileged distributions. In the case of circular symmetry for example (case of particular relevance, because laser mirrors are usually round), the Gauss-Laguerre polynomials $L_p^{(l)}$ describe the solutions (more details on these polynomials in [Hodgson, Koechner]).

A steady-state solution oscillating inside a laser cavity is an eigenmode of the resonator. The eigenmodes are characterized by the transverse mode structure (characterized by the two indexes p,l) and the axial mode q. Most commonly, the axial mode order is left out, and we only refer to the transverse structure. The notation for the different modes is $TEM_{p,l}$ (originally from Transverse Electro Magnetic). Some of these modes are illustrated in Fig 4. The structure of the different modes can be seen in [Koechner].

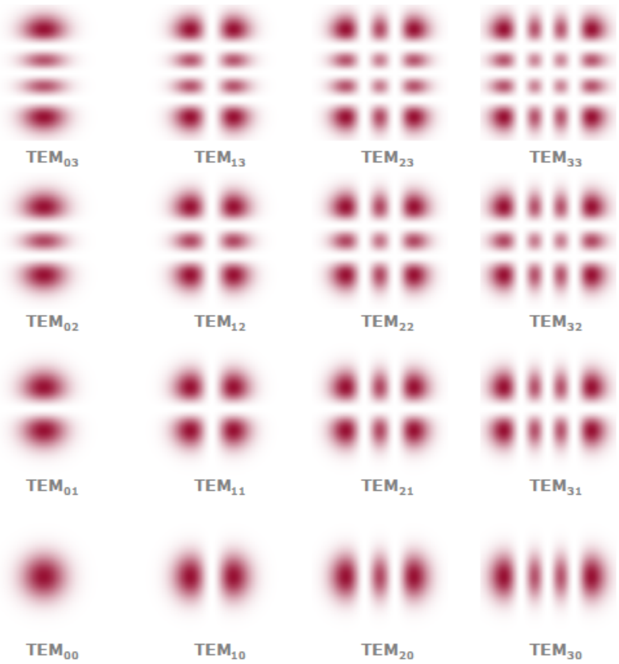


Figure 5: Transverse TEM modes

For circular or rectangular mirrors, the lowest order mode TEM_{00} is identical and has a Gaussian intensity distribution. It corresponds to the smallest mode that can circulate in a stable cavity and is generally referred to as the *fundamental mode* or the Gaussian beam. For certain applications, fundamental mode operation is necessary, for example for ultrashort pulse generation using passive modelocking.

1.2.3.3 Thermal lens

Only a fraction of the pump radiation absorbed by the laser medium in effectively transformed into laser radiation. An important fraction of the power is deposited in the form of heat into the crystal. Since the refractive index of the laser material is dependent of the temperature of the crystal through its d*n*/d*T* coefficient, the heat deposited can be treated as a lens, in this case a lens with a variable focal length as a function of the pump power. An approximate formula in the case of a radial heat flow and a uniform pump profile is given by:

$$f^{-1} = \frac{dn/dT}{2\kappa A} P_{heat}$$

where f^{1} is the thermal lens expressed in diopters (m^{-1}), d*n*/d*T* is the dependence of the refractive index to the temperature, κ the thremal conductivity of the material, and P_{heat} the amount of heat deposited on the crystal. It is important to notice that although the main contribution to the thermal lens is the d*n*/d*T* coefficient, other effects such as stress or bulging related to the material's mechanical strength can also influence the thermal lensing behavior.

This lens can be quite strong particularly for materials with weak thermal conductivity, and needs to be taken into account as an extra element in the cavity design. For more details on thermal lensing see [Koechner].

1.3 Frequency doubling

Nonlinear materials allow to transfer energy between different electromagnetic fields, given that certain conditions are fulfilled. In the case of frequency doubling, the energy of an electromagnetic field with frequency ω, will be transferred into an electromagnetic field with frequency 2ω. This means that two photons with an energy $\hbar\omega$ give rise to a photon of energy $2\hbar\omega$. In order for this to be possible, energy and momentum have to remain constant.

$$2\hbar\vec{k}_1 = \hbar\vec{k}_2$$

with $k_1 = \dfrac{\omega}{c} n(\omega)$ and $k_2 = \dfrac{2\omega}{c} n(2\omega)$.

This leads to the following condition:

$$n(\omega) = n(2\omega)$$

This condition is called phase-matching condition. In normal conditions, the indexes of refraction of the nonlinear material at the two considered wavelengths are different. Therefore one typically uses a nonlinear material that is birefringent, where the two fields have different polarizations. In this case, the condition becomes:

$$n_{pol1}(\omega) = n_{pol2}(2\omega)$$

and is fulfilled for a certain temperature and angle. This means that for a given nonlinear crystal the crystal angle and temperature need to be adjusted to achieve maximum conversion efficiency.

For a given nonlinear crystal and fulfilled phase-matching condition, the intensity obtained in the second harmonic $I^{2\omega}$ scales quadratically with the input intensity at the ground frequency I^{ω}. Therefore the conversion effciency becomes:

$$\eta = \frac{P^{2\omega}}{P^{\omega}} \propto I^{\omega} = \frac{P^{\omega}}{\pi\omega_0^2}$$

This means that in order to reach a high conversion efficiencies, high intensities are required.
For more details on frequency conversion see [Svelto]

2 Components

2.1 Gain Material

The crystal used for this experiment is a plane-plane cut 1-mm thick 1% doped Nd:YVO4 (Neodymium-Yttrium-Orthovanadate) crystal. $YVO4^{-}$ is a granate crystal which was doped with active

Nd^{3+} ions, responsible for the laser operation. Some material parameters can be found as an appendix in table 1.

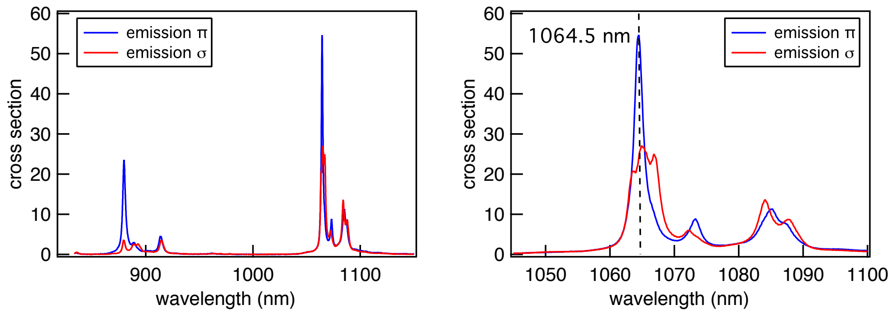


Figure 6: Emission cross sections of Nd:YVO4 [6]

An important absorption peak is observed at a wavelength of 808 nm (Figure 2), wavelength accessible to diode lasers. This laser material can therefore be pumped efficiently in this line with low-cost diode lasers.
The maximum amplification of light occurs at a wavelength of 1064 nm (Figure 6). **This means that this laser operates in the near infrared, where the eye is not sensitive – and therefore is not eye-safe.** It is of particular importance in this case to wear appropriate safety goggles.
The crystal has dielectric coatings on both sides. On one side, it has a highly reflective coating for the laser wavelength (1064 nm) and a highly transmissive coating for the pump light (808 nm). The other side has an anti-reflective coating for the laser wavelength. This allows us to use the crystal itself as a flat end mirror for our resonators.

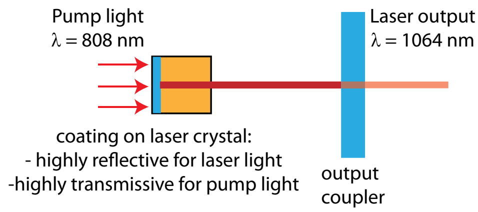


Figure 7: Schematic of the laser crystal used for this experiment

2.2 Pump source

We use as a pump source a fiber coupled diode capable of emitting up to 4 W of power at a wavelength of 808 nm (Lumics GmbH). The corresponding maximum current through the diode is 5.3 A. The U-I characteristic of the diode is given in the appendix.

Q1: Calculate the corresponding electrical to optical efficiency. Give an estimation of the amount of deposited heat in the crystal when there is no laser operation (no power extracted).

Q2. Given the emission spectra of the pump diode at different temperatures and the absorption spectrum of Nd:YVO4, what can be expected as an optimum temperature?

The pump diode is placed on a cooling block that allows to set and stabilize the temperature of the diode by a thermoelectric element. The emission wavelength of laser diodes is strongly dependent on the temperature. Therefore temperature of the diode needs to be optimized for best absorption of the pump power by the laser crystal. The user interface for this diode laser allows to control the temperature of the diode from 10degC to 35 degC

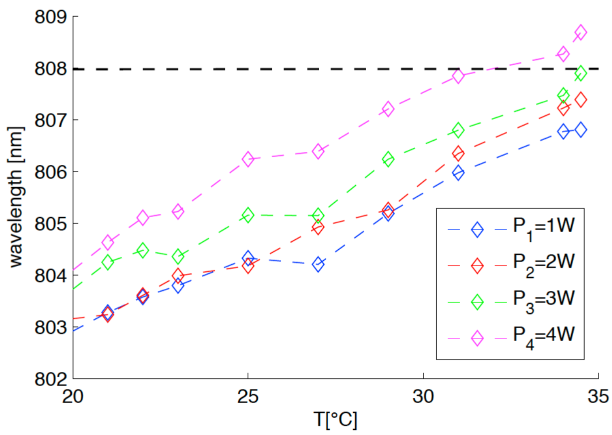


Figure 8: Peak emission wavelength as a function of temperature for different output power levels of the pump diode

For more technical details concerning this diode, a specification sheet is available on demand.

2.3 Frequency Doubling Crystal: KTiOPO4 (KTP) crystal

The crystal used for the frequency doubling experiments is a 5mm thick KTiOPO4 (KTP) crystal. This crystal is cut in such a way that at room temperature and at normal incidence phase-matching is fulfilled. This crystal has a highly reflective coating for the laser wavelength (1064 nm) and an anti-reflective coating for the second harmonic wavelength (532 nm) on one side, and an anti-reflective coating for the laser wavelength on the other side. This means that this nonlinear crystal can also be used as an end mirror that will couple the green light out from both sides. In this case, one has to consider that only half of the achieved second harmonic is available out of the laser cavity.

3 Instructions for the experiment

3.1 Pump Characterization

The pump geometry used for building the laser is shown in figure 5. The diode is strongly multimode after the delivery fiber, which has a core diameter of 125 µm and a numerical aperture of NA=0.15. A first achromatic lens is used to collimate the beam, and a second lens is used to focus the pump on the laser crystal. In this configuration, the spot radius achieved is approximately 100 µm X 100 µm at the position of the crystal.

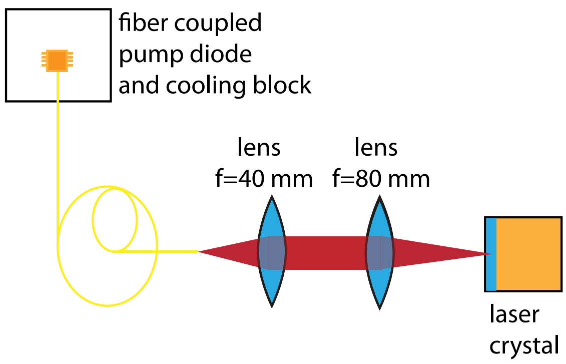


Figure 9: Pump geometry. The diode used is fiber coupled. The first 40 mm lens collimates the beam and the second focuses the pump light on the crystal.

Q3 Collimation and alignment. Remove all optical components from the rail. Collimate the pump beam using the first lens (f = 40 mm). Focus the pump beam using the second lens (f = 80 mm).

Q4 Stabilize the diode at 35 deg C. Measure the optical power of the pump diode at the point where the laser crystal will be versus the current applied to it. Evaluate the threshold and slope of the diode and compare to the values given by the manufacturer.

The emission wavelength of the pump diode is strongly dependent on the temperature. The peak emission wavelength as a function of the temperature is given in Figure 8: Peak emission wavelength as a function of temperature for different output power levels of the pump diode

Q5 What is the estimated optimal temperature of the diode considering the absorption of the laser material?

3.2 CW laser operation

3.2.1 Alignment of the different components for laser operation

A red laser pointer is available to pre-align laser elements to a given axis. The alignment is done in different steps:

- Align the laser pointer to the rail
- Align the crystal to the laser pointer beam
- Align the different reflections from the optics to the laser pointer beam reflections on the crystal.

The different elements should now be pre-aligned.

Caution! There are some optical elements that should not be moved to avoid misalignment (and therefore long re-alignment). Please do not move the pump diode lenses or the laser crystal.

3.2.2 Cavity no.1

The first cavity suggested for the experiment consists of the crystal used as an end-mirror and a curved output coupler with an outcoupling rate of 2% and a radius of curvature of 80 mm.

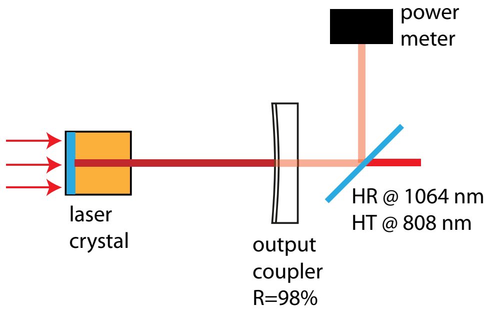


Figure 10: Cavity with curved output coupler

Q6 Stabilize the diode at 30 deg C. Start the laser operation at a distance of approximately 65 mm (take care of aligning the output coupler for maximum power). Measure the output power for different pump power levels. Plot output power versus input pump power, the corresponding optical-to-optical efficiency and slope efficiency.

Q7 Place yourself at the maximum output power, and change the temperature of the diode. Does this correspond to the estimated optimal temperature?

Q8 Place yourself at a safe operation point, and vary the length of the resonator. Plot output power versus length of the resonator (don't forget to realign the mirror at every step)

3.2.3 Cavity no.2

The second cavity uses a plane output coupler with the same outcoupling rate and a lens inside the cavity.

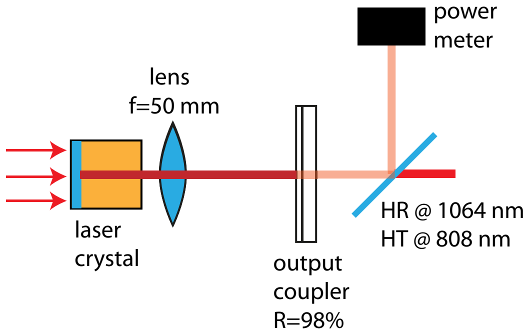


Figure 11: Cavity with plane outcoupling mirror

Q9 All measurements should be done at the optimal temperature. Measure the output power for different pump power levels. Plot output power versus input pump power, the corresponding optical-to-optical efficiency and slope efficiency. Optimize the position of the end mirror for maximum output power.

3.3 Frequency doubling

3.3.1 Intracavity frequency doubling

The KTP crystal used for frequency doubling has a highly reflective coating for the laser wavelength (1064 nm) and an anti-reflective coating for the second harmonic wavelength (532 nm) on one side, and an anti-reflective coating for the laser wavelength on the other side. This means that this nonlinear crystal can also be used as an end mirror that will couple the green light out from both sides. We will use it at the position of the outcoupling mirror. In this case, one has to consider that only half of the achieved second harmonic is available out of the laser cavity.

Q10: We will use cavity number 2, and place the nonlinear crystal at the position of the output coupler. Justify the presence of a lens in the cavity. Does the cavity work without the lens?

Build this cavity with the nonlinear crystal. In the output of the laser, we use a dichroic mirror to separate the remaining infrared light from the generated green light that we want to measure and observe.

Q10: Measure the power obtained in the green as a function of the pump power, and try to observe different transverse structures of the green radiation.

4 Things to take into account when working with lasers

4.1 Laser Safety: infrared light

As we mentioned in the first part, the pump laser and the laser itself operate in the near infrared (808 nm and 1064 nm), wavelength region where the eye is not sensitive. Therefore it is of great importance to always wear the safety goggles provided with the experiment equipment when operating the laser. In order to visualize the laser light, fluorescent cards are provided.

4.2 Optical Components: handle with care!

The optical components used in this experiment are expensive and have to be handled with care. The optics should never be touched directly with bare hands, and cleaning them requires special attention. It is very easy to scratch and damage these parts. If you think the optics are not clean enough, ask your supervisor to tell you how to clean optical components.

5 Appendix: Literature

5.1 References

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5.2 Extra data

Property	Value
chemical formula	$Nd^{3+:}YVO4$
crystal structure	tetragonal
mass density	4.22 g/cm3
Moh hardness	5–6
Young's modulus	133 GPa
tensile strength	53 MPa
melting point	1810 °C
thermal conductivity	≈ 5 W / (m K) (values around 9–12 are also found in the literature)
thermal expansion coefficient	11 × 10−6 K−1 (*c* direction), 4.4 × 10−6 K−1 (*a* direction)
transparency range	0.3–2.5 µm
birefringence	positive uniaxial
refractive index at 1064 nm	2.17 for *c* polarization (extraordinary), 1.96 ordinary index
temperature dependence of refractive index	3 × 10−6 K−1 in *c* direction, 8.5 × 10−6 K−1 in the *a* direction
Nd density for 1% at. doping	1.24 × 1020 cm−3
fluorescence lifetime	90 µs
absorption cross section at 808 nm	60 × 10−20 cm2 (*c* polarization)
emission cross section at 1064 nm	114 × 10−20 cm2 (*c* polarization)
gain bandwidth	1 nm

Table 1: Some properties of neodymium-doped yttrium vanadate

5.3 Cavity Simulations

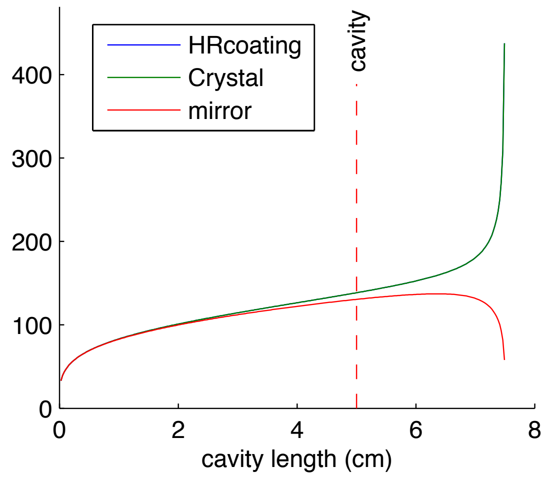
The following simulations were using Matlab programs written in the ULP (ultrafast laser physics) group at ETH Zurich. They are used to simulate the stability regions of the two resonators built in this experiment in order to interpret the results. The programs are available on demand.

The **input parameters** are:
- The operation wavelength of the laser
- The thermal lens of the pumped medium
- The different optical components used in the cavity (for example curved mirrors, flat mirrors, output coupler, etc...)
- The distances between different optical components

For each optical component, a transfer matrix is computed, and a gaussian beam is propagated. In the case of a laser cavity the resulting standing wave pattern is calculated.

The **output** shows the size of the beam on the different components of the laser. Of particular importance is the size of the beam at the position of the laser crystal. In fact, we want to match the laser beam as close as possible to the pump beam.
The results from these simulations are shown in the following figures for cavity 1 and cavity 2.

<u>Cavity no.1:</u>
a)



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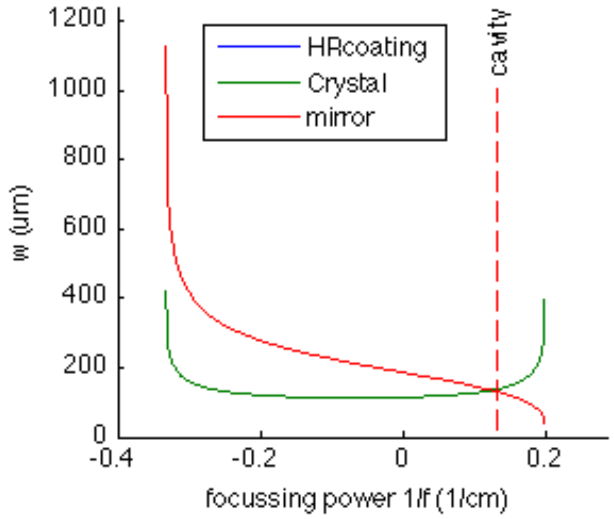

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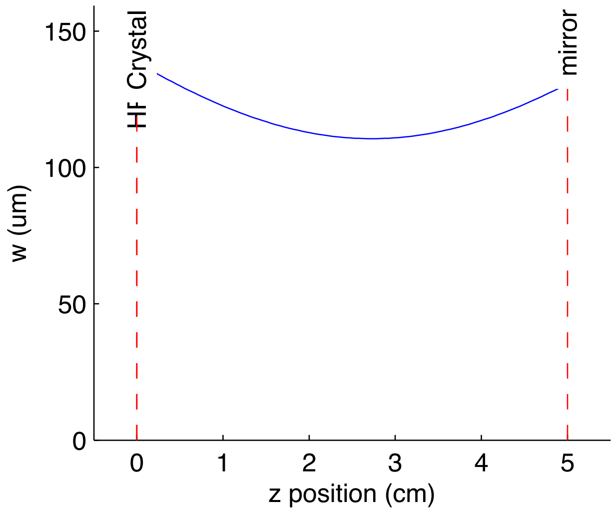
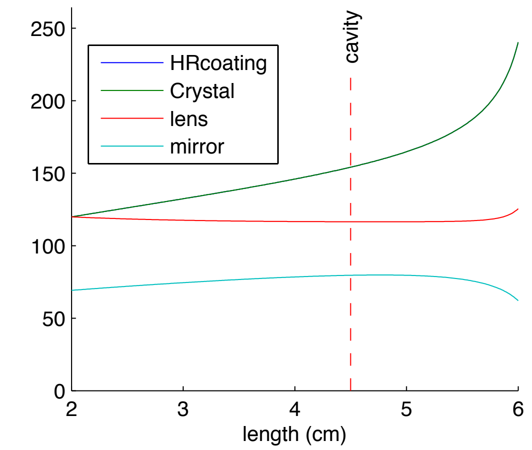
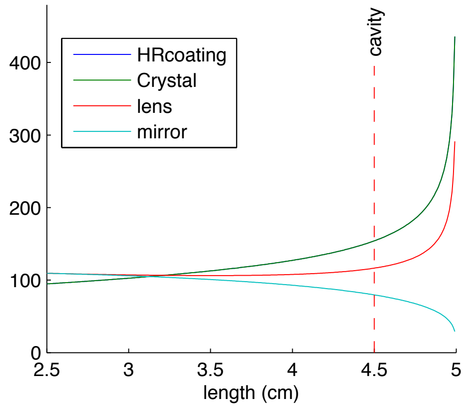


Cavity no.2:

a)





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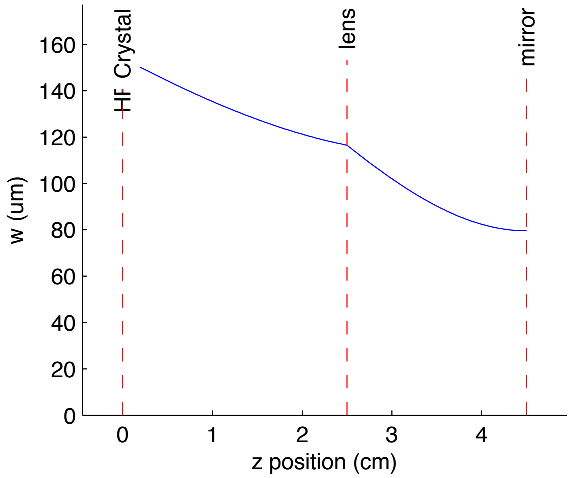

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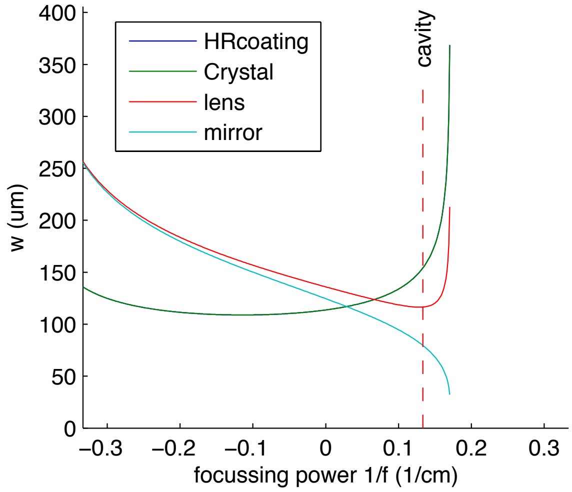

Cavity 2 with no lens