Diode-pumped Nd:YVO_4 Laser and Nonlinear Optics

Wear laser goggles at all times during this experiment!

1 Introduction

The goal of this lab is to set up, align, Q-switch, and study the output of a diode-pumped Nd:YVO_4 laser. The pulsed output of this laser is used to generate second-harmonic radiation. Students are advised to consult textbooks on Lasers (e.g., [1]) and Nonlinear Optics (e.g., [2]) to prepare for this experiment. In particular, familiarize yourself with solid-state lasers, semiconductor lasers, Q-switching, and second-harmonic generation (SHG).

2 Background

2.1 The Nd:YVO_4 Laser

The laser medium Nd:YVO_4 stands for the host crystal Vanadate doped with Neodymium atoms. The Nd atoms act as active material. Another widely used host crystal for Nd atoms is Yttrium Aluminum Garnet (YAG). Nd:YAG and Nd:YVO_4 are very similar in their laser characteristics. An energy level schema of the transitions most important for lasing and the optical pumping with diode lasers of Nd:YVO_4 is shown in Fig. 1.

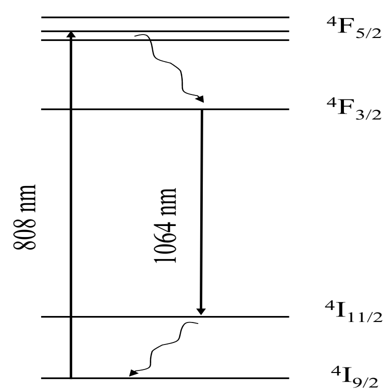

Figure 1: Energy level scheme of Nd ions embedded in Vanadate host crystal.

The YVO_4 crystal ($d_L = 1$ mm) is doped with Nd (1%) resulting in an absorption coefficient at the pump wavelength ($\approx$ 808 nm) of $\alpha \approx 31$ cm^{-1}. The crystal plane facing the pump is anti-reflection (AR) coated for the pump wavelength and has a high-reflection (HR) coating for the fundamental laser wavelength, 1064 nm. The opposite crystal face is AR-coated for the fundamental laser wavelength, cf. Fig. 2.
Do not move, remove or touch the laser crystal.

2.2 The Diode Laser Pump Source

Diode lasers allow for an efficient pumping of the Nd:YVO_4 laser. Compared to discharge lamps the diode laser spectrum is much narrower and can be tailored to the absorption lines of the Nd atoms. Subsequently the overall laser efficiency increases from a few percent in lamp pumped systems to $> 50\%$ in diode pumped systems.

The active medium of a diode laser consists of a pn-junction. Upon application of a forward bias voltage a current flows producing a population inversion of electrons in the conduction band and holes in the valence band in the region of the junction. Recombination of electrons and holes results in the emission of photons. The end faces of the semiconductor crystal can act as end mirror and outcoupler, respectively. The laser wavelength λ depends on the temperature T and the current I. Why?

In a small wavelength region around a mean temperature T_0 and mean current I_0 a linear relationship holds:

$$\lambda(I,T) = \lambda(T_0, I_0) + a(T - T_0) + b(I - I_0), \tag{1}$$

where a and b are material constants.

2.3 Q-switching

Q-switching is a technique used to generate high energy laser pulses with a duration in the nanosecond regime. The technique is based on a device which can alter the quality (Q) factor of the optical resonator. The Q-factor of the device is switched from a low to a high value, when a maximum stored energy is reached in the laser medium as a result of pumping. The rapid buildup of radiation leads to a giant pulse. The repetitive operation of the device leads to a pulse train with a repetition rate in the kHz-MHz regime. The switching mechanism in the device can be active or passive. In this experiment we will use a passive device, which is based on the phenomenon of saturable absorption.

2.4 Second-Harmonic Generation

Second-harmonic generation (SHG) is a nonlinear optical effect of second-order that doubles the frequency of the incident light. The electric field amplitude of the SH

$$E_{SH} = \epsilon_0 \chi^{(2)} E_F^2 \mathrm{sinc}(\frac{\Delta k d}{2}) \tag{2}$$

where $\chi^{(2)}$ is the nonlinear susceptibility of second order and E_F is the electric field amplitude of the fundamental wave, d is the thickness of the crystal and Δk is the phase mismatch of fundamental and second-harmonic waves.

2.5 Optical Components and Technical Information

- **Pump laser diode:**
  Output power: 2W at 808 nm. Laser diode (LD) current: max. 2500 mA. Optimum temperature: 31^{o}C. Emitter dimensions: 200μm $\times$1μm.

- **Laser crystal:**
  Thickness: 1 mm. Nd:doping 1%. Absorption coefficient at the pump wavelengths 31 cm^{-1}. Pumped area (cross section): 200 μm $\times$ 200 μm. Coatings according to Fig. 2.

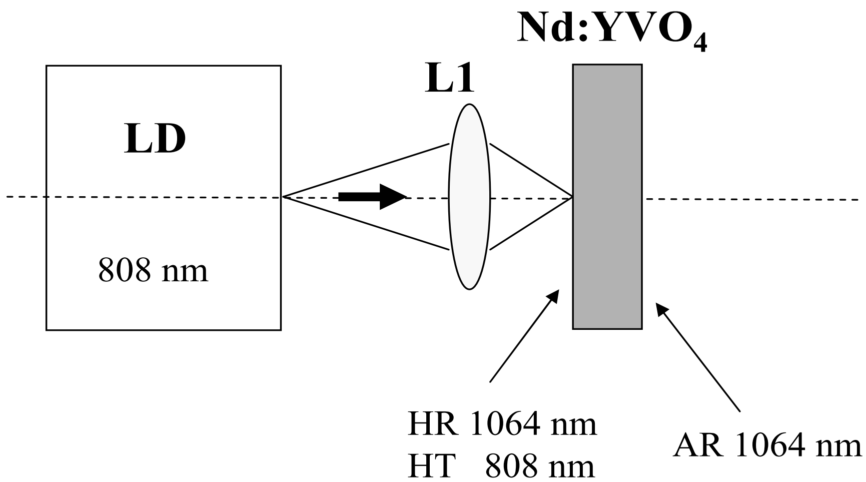

Figure 2: Scheme showing laser diode (LD) pumping the laser active medium ($Nd:YVO_4$) through an aspheric lens (L1) of focal distance $f = 6$ mm. The laser crystal is coated by high-reflection (HR), anti-reflection (AR), and high-transmission (HT) coatings at various wavelengths in the orientation shown in the figure.

- **Q-switch:**
  The Q-switch used in this experiment is a YAG crystal doped with Cr^{4+} ions. The initial small signal absorption at the laser wavelength is about 95%. The faces of the crystal are AR coated at 1064 nm. The recovery time and the saturation fluence is 8.5 μs and 0.5 J/cm^2, respectively.[1]

- **KTP crystal:**
  Crystal class: mm2 (positive biaxial). Dimensions: $5 \times 3 \times 3$mm (length $\times$ width $\times$ height). Phase matching type: Type II (1064 (e) + 1064 (o) = 532 (e)). Principal plane: XY. Phase matching angles: $\theta = 90^o$, $\phi = 23.5^o$ with $d_{\text{eff}} = 3.59$ pm/V. Coatings according to Fig. 3.

All components (mirrors and KTP) must be oriented with the labels towards the pump laser diode.

3 Experiments

3.1 Continuous Wave (CW) Laser at 1064 nm

Set up a laser according to Fig. 4. Determine the range of cavity lengths L for which the resonator is stable, that is you obtain laser output. Align the laser with the help of the red laser diode (670 nm). Observe the beams reflected from various cavity components on the white screen attached to the laser diode. The reflection from the output coupler should almost coincide with the beam reflected at the laser crystal. Both reflected beams should be incident on the screen close to the diode's aperture, but without passing through it. This is to avoid laser damage of the alignment diode laser. You can observe lasing by inserting an IR-sensor in the

[1]For more details, see http://www.alphalas.com/PDF/cr-yag.pdf.

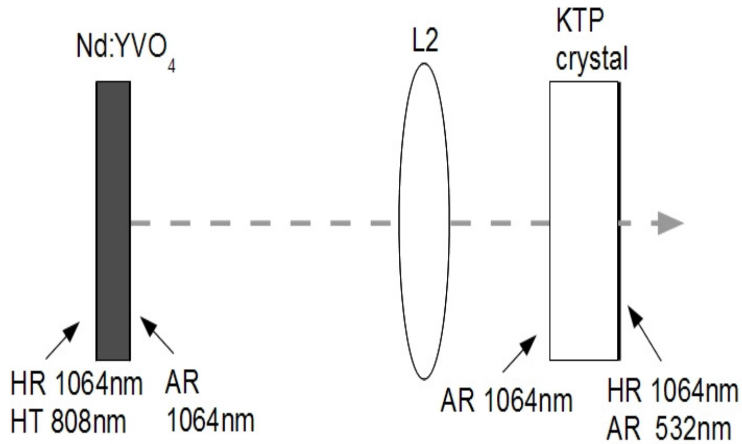

Figure 3: Scheme showing experimental arrangement for intracavity second-harmonic generation and the proper orientation of coatings of the frequency-doubling crystal, where the crystal is also used as the output coupler.

beam. Perform this experiment with a focusing outcoupler (f= -80 mm) and a plane outcoupling mirror.

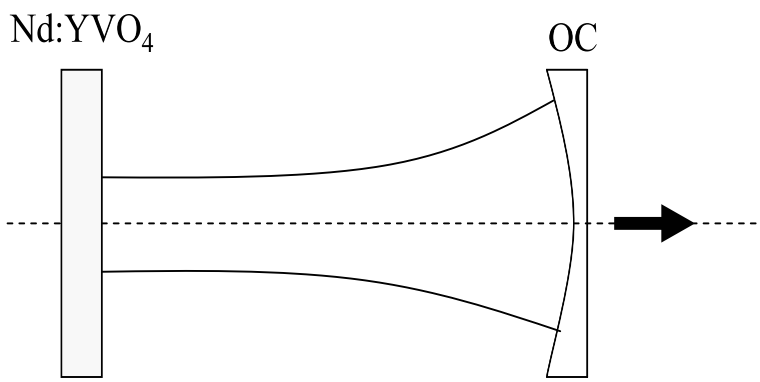

Figure 4: Scheme showing experimental arrangement for continuous wave laser operating at the fundamental wavelength, 1064 nm.

- Which output coupler (OC) facilitates TEM_{00} modes? Using the plane OC, observe what happens to the spatial mode profile, when L is very small.
- Calculate the stability range of the two resonators and compare the results with your measurements. The pumped laser crystal forms a thermal lens. Use your experimental data to estimate the focal length of this lens. Record the corresponding pump current. Does the thermal lens have an effect on the stability region, when the curved OC is used? Explain.
- Measure and plot the laser output power as a function of the cavity length. Always maximize the power by re-aligning the outcoupler after you move it. Make sure that the

power meter head is far enough from the pump laser diode, otherwise a significant part of the 808 nm radiation reaches it.

- Explain your output power versus cavity length plots. Is there a difference between the cavity with the focusing OC and the cavity with the plane OC in this respect? Consider the beam size at the laser crystal. The pumped region has a cross section of about $200 \times 200\ \mu\text{m}^2$. An optimum overlap between the pump and cavity laser modes is realized, if $2w \approx 1.2 \times D$, where w and D are the cavity beam radius at the Nd:YVO_4 crystal and the pump spot diameter, respectively.

3.2 Q-switched Laser at 1064 nm

Insert the Q-switch in the laser resonator between the laser crystal and the output coupler at a location, where the aperture of the Q-switch does not clip the laser beam. The Q-switch does not need angular alignment and is fixed in the holder. Use either the plane or the focusing output coupler. Use the fast photodiode[2] and an oscilloscope to observe the temporal output of the laser. Measure the pulse length τ_p and pulse separation τ_{rep} at two different values for the cavity length. Explain the dependence of τ_p and τ_{rep} on cavity length using the concept of cavity lifetime and the recovery time of the saturable absorber. Also measure the average output powers.

3.3 Continuous Wave Laser at 532 nm

Equation 12.2 shows that higher fundamental power is needed to get higher conversion efficiency. Comparing with extracavity SH generation, the intracavtiy SH generation way would supply much higher fundamental power. So, intracavity setup which is shown in Figure 12.3 is adopt here. Please make sure that the AR-coated side of the KTP crystal at 1064 nm (on the side of the label) is towards the laser.[3] Otherwise the other side, which is HR-coated at 1064 nm will cause damage of the optical components inside the cavity.

- Optimize the SH power by rotating the KTP crystal in its holder and aligning the mount and by changing the distance between the lens and the KTP crystal.
- Maximize the SH output power under three different cavity lengths. Use the provided neutral density filters while measuring the SH output power. Even though the KTP crystal has fundamental HR coating at the output side. There is still some portion of the fundamental that is transmitted through the frequency doubling crystal. Therefore, the use of a green color filter in front of detector is necessary, when measuring second-harmonic beam parameters!
- In order to find out the conversion efficiency, the fundamental power inside the cavity still needs to be measured. Think about how to get it? Hint: First, try to measure the transmission coefficient of the KTP crystal for 1064nm. Then, measure the output power of the fundamental with intracavity SH generation setup.Another filter should be used here to filt out the 532nm. Now, the fundamental power inside the cavity used for SH generation could be obtained from calculation.

[2]The UPD-300-SP is a Si diode with a risetime of 300 picoseconds. Use 50Ω load.

[3]One face of the SH crystal is HR for 1064 nm, the other is AR coated for 1064 nm. Therefore the crystal can also act as flat end mirror of the laser. One side is AR coated at 532 nm.

3.4 Q-switched Laser at 532 nm

Put Q-switch in the cavity between the laser crystal and focus lens. Optimize the SH power following the procedure in the previous section. Measure τ_p and τ_{rep} at the two different cavity length used for the measurement in Section 3.2. Compare these values to the corresponding values obtained with the Q-switched laser at 1064 nm. Is the dependence of τ_p and τ_{rep} on cavity length consistent with your observations in Section 3.2? What is the relationship between τ_p(1064nm) and τ_p(532nm)? Also measure the average output powers.

3.5 Spectral measurement

Measure the fluorescence spectrum using the HR2000CG-UV-NIR spectrometer. For this measurement, remove the output coupler. Compare the so-obtained spectrum with the spectrum of the fundamental and the frequency-doubled laser beams. The fiber tip of the spectrometer can pick up enough scattered laser light even from a piece of paper inserted into the beam path. Therefore, using a lens to focus the laser light into the fiber is not necessary. Ensure that the entire signal is on scale. If the signal you collect is saturating the spectrometer (intensity greater than 4000 counts), you can decrease the light level on scale in scope mode by: decreasing the integration time (between 3 ms and 65 s) or attenuating the light going into the spectrometer with neutral density filters.

4 Summary

Now you should have aquired the following data:

- Stability range for the curved and the flat OC.
- Output power over cavity lenghth plot for both OCs.
- Repetition rate and pulse duration for the Q-switched laser both for the fundamental and the SH
- Average output power for the Q-switched laser for the cavity lengths in question
- SH output power
- Spectral measurements

With this data you should be able to calculate/ explain the following

- Focal length of the thermal lens in the laser crystal
- Explain the output power vs cavity length plots
- Try to explain the values for the repetition rate and pulse duration for the Q-switched laser
- Conversion ratio for the SH-generation
- Pulse energy for Q-switched laser

5 Appendix - The HR2000CG-UV-NIR spectrometer

The HR2000CG-UV-NIR (Ocean Optics Inc.) is a high-resolution fiber optic spectrometer with a silicon CCD array detector (with detection wavelength range of 200-1100 nm). The HR2000 spectrometer connects to a notebook via USB port and draws power from the host PC eliminating the need of an external power supply. OOIBase32 is the operating software for the spectrometer. Place OOIBase32 in scope mode by clicking the scope mode icon on the toolbar or selecting Spectrum/Scope Mode from the menu bar.

Use the Configure Cursor, Set Scale, and Autoscale icons on the toolbar as needed to measure the wavelength of the spectral peaks, and to change the horizontal and vertical scales. OOIBase32 can copy spectral data directly to the Windows clipboard. This data can be pasted into a variety of applications, include Microsoft Excel, for further data analysis. This data is arranged in columns, with the wavelengths and spectral intensities for each selected spectrometer channel arranged in adjacent columns. An optional header identifies each tab-delimited column. The measured spectrum can also be saved in ASCII format by selecting File/Save/Processed in the menu bar.

References

[1] Joseph T. Verdeyen. *Laser Electronics*. Prentice Hall, 1994.

[2] W. Boyd. *Nonlinear Optics*. Academic Press, New York, 1991.