Laser Physics
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A DIODE-PUMPED Nd:YAG LASER

Laboratory exercise instructions
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Stockholm 2014

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1 Introduction

1.1 Background

This laboratory exercise deals with the construction of a solid-state laser. It is a diode-pumped Nd:YAG laser and we will investigate the various components like the pump diode, discuss the pumping optics, the solid-state host, the rare-earth ion energy levels, the cavity configuration and the stability, input-output characteristics, spectral properties, modes and up-conversion. We will first build a continuous wave laser, then a Q-switched and finally a frequency doubled version.

1.2 Exercise preparation

To prepare read in *Principles of Lasers* (Svelto) on solid-state lasers (chap. 9.1-9.2.2.), resonator modes (5), laser diode pumping (6.1- 6.3), Q-switching and saturable absorption (8-8.4), diode lasers (9.4) and nonlinear optics and frequency doubling (12.4).

1.3 Equipment

The following equipment is included in the laboratory kit:

- LPS1-2T Laser diode driver and double temperature controller.
- Pump laser diode: Max. output power 2 W@808 nm, current limit 2.7 A, emitter dimensions 200 µm × 1 µm. Normally we run it max at 1.9 A.
- Pump optics: 1 aspheric lens, f = 6.0 mm, AR/AR@808 nm, images the pump spot as approximately 200 µm × 200 µm. Built into a brass unit at the front of the diode.
- Laser crystal, Nd:YAG: 2.4 mm thick, Nd:doping 1 at.%, HR@1064 nm/HT@808 nm (side A) and AR@1064 nm (side B), 808 nm absorption is 7 cm^{-1}.
- Concave mirror, R = 98%, ROC = -80 mm or -400 mm.
- SHG crystal, KTP. AR@1064 (side A) and HR@1064 nm/AR@532 nm (side B)
- Passive Q-switch crystal, Cr^{4+}:YAG
- UPD-300-SP ultrafast photodiode
- IR-visualizer

Additional equipment needed:

- Power meter(s)
- Filter(s)
- Oscilloscope (with impedance matching)
- Holders for cover glass and filters
- Spectrum analyzer
- Better IR-visualizer (optional)

1.4 Safety and proper handling

1.4.1 Safety

The following wavelengths are used during the lab exercise: 1064 nm (Nd:YAG, up to around 500 mW), 808 nm (pump LD, up to 2 W) and 532 nm (frequency doubled Nd:YAG, up to 50 mW). The 1064 nm beam is invisible to the human eye and considerable retinal thermal damage may occur before the damage is apparent.

- Keep your eyes out of the height of the laser beam.
- Do not look directly into the beam, even if you are wearing protection goggles.
- Remove any reflective items from your wrists, hands or fingers before using the Nd:YAG kit.
- Do not send beams around in an uncontrolled fashion. You might hit other persons in the eyes!
- Inspect the beam propagation paths in order to maintain control and avoid mishaps.
- Do not insert or remove equipment in sections that are exposed to a laser beam. This can be achieved by always turning the laser OFF before adding or removing any equipment.
- Use protective eyewear that blocks all wavelengths that are produced by the laser.

1.4.2 Proper handling

- Be careful with the optics and only touch the holders, never the crystals or mirrors directly.
- All components (crystals and mirrors) must be oriented with their labels toward the pump laser diode.
- Do not remove the laser crystal or other equipment from their holders. The crystal orientation is optimized with respect to pump absorption and the absorption attenuates the pump radiation.

2 Characterization of the diode laser

2.1 Diode power vs. current

Equipment:

- Pump laser diode.
- Power meter, up to 2 W @ 808 nm.

When you switch on the diode the radiation can be seen using an IR viewer or a card with upconversion powder which transfers the IR radiation into visible light. Measure and plot the diode output power in, for example, 100 mA decrements from the maximum 2A drive current down to the threshold. Make a plot in the report. This is input data for your next tasks.

3 Aligning and optimizing a plano-concave resonator

3.1 Positioning the laser medium and the output coupler

Equipment:

- Pump laser diode.
- Laser crystal.
- Concave mirror output coupler.
- Alignment laser diode.
- Power meter, up to 500 mW @ 1064 nm.
- Spectrum analyzer with detector fiber.

3.1.1 Crystal position

Align the crystal position by finding most visible emission (which is believed to be upconversion from a minimal amount of Er-ions in the crystal!). Do this in the following steps:

- Drive the diode just above the threshold.
- Find the focus with an IR indicator.
- Place the crystal approximately in the focus.
- Increase the laser diode current to 2A. A weak visible whitish spot can now be observed in the crystal based on upconversion. It is at maximum when the laser crystal is optimally placed in the focus.
- Find the crystal position where the up-conversion is the most intense by carefully moving the crystal holder.
- Secure the crystal holder.

3.1.2 Output coupler position

A plano-concave resonator is at its most stable point for

$$L_{Res} = R/2 = Z_R$$

where L_{Res} is the cavity length, R is the radius of curvature (ROC) and Z_R is the focus Rayleigh length;

$$Z_R = \pi\omega_0^2/\lambda.$$

ω_0 is the beam waist radius, λ is the wavelength.

The pump volume in the crystal must be optimally overlapped with the lasing mode volume in order to maximize the output power. The pump spot size is around 200 μm × 200 μm. Optimum overlap occurs here for $\omega_{0,\ \mathrm{laser}} \approx 1.2\ \omega_{0,\ \mathrm{pump}}$.

Combining these conditions shows that the ROC of -80 mm is a good choice. It also shows that the optimal cavity length is 40 mm. However, because of thermal lensing induced by the heat in the crystal, the optimal length is a bit longer; it has been experimentally found to be in excess of 60 mm. *Update: If you use a mirror with 400 mm ROC you should have a slightly longer cavity; 60-80 mm.*

3.2 Starting the laser with curved output and adjusting the output coupler

Place the output coupler at 60 mm from the input surface of the laser crystal. On a lucky day the laser can be seen as a beam on the IR card or with the viewer, most likely as a straight trace. Otherwise, follow the instructions below.

- Take away the output coupler!
- Mount and start the adjustment diode laser.
- Identify the reflections from the laser crystal on the laser shoot target and try to remember the position.
- Place the output coupler (OC) in position. Now you will get the red reflection on the paper from the output coupler. Try to place the reflection from the output coupler on the same spot where the reflection from the laser was.
  (In other words: Adjust the cavity by making the two reflections overlap on the white screen (or right next to it) surrounding the adjustment laser.)
- Remove the adjustment laser or at least properly block the output of the Nd:YAG laser. Otherwise, the output from the Nd:YAG can destroy the adjustment laser.
- Put an IR converter on the expected beam path and find a lasing mode by fine tuning the output coupler angle.
  If this does not work, please, take help of the lab assistant.

3.3 Fundamental mode lasing

If the laser happens to start in a higher order mode, this will appear as two (or more) dots interconnected by a thin line (in fact several spots which are the mode maxima). Adjust the output mirror angle so that the laser operates in the fundamental transversal mode (a single dot).

3.3.1 Output power vs. diode drive current

Measure the output power versus diode drive current.
Plot the output power vs. input pump power. Mark the threshold power and calculate the slope efficiency (dPout/dPin).

3.3.2 Spectrum

Use a spectrum analyzer for acquiring a spectrum in a suitable interval around 1064 nm.
Is the laser oscillating on one or several transitions simultaneously? What wavelengths did you measure? Can you resolve longitudinal modes? In that case, what is the mode separation?
Probably the mode separation is not as distinct as you expect as the spectrum analyzer has a limited resolution.

4. Q-Switching the laser

Equipment:

- Pump laser diode.
- Laser crystal.
- Passive Q-switch crystal.
- Power meter.
- Fast photodiode.
- Oscilloscope.
- 50 Ohm impedance match to oscilloscope

Insert the saturable absorber, a Cr^{4+}:YAG crystal, into the cavity. Use the UPD-300-SP ultrafast photodiode with an oscilloscope to measure the pulses from the laser. If the diode saturates, either use lens tissues to attenuate the beam or divert a weak reflection from the beam with a piece of glass, and measure on that.
To be able to resolve the short pulse you need to impedance match with 50 Ohm to the oscilloscope.

4.1 Measurements

4.1.1 Pulse energy and peak power

Adjust the laser so the pulse train is stable. Measure average power, pulse width and repetition frequency.
Calculate/estimate the pulse energy and pulse peak power from the pulse width, pulse separation and the beam power.

5 Frequency doubling of a Nd:YAG laser with a KTP crystal

Equipment:

- Pump laser diode.
- Laser crystal.
- Passive Q-switch crystal.
- SHG crystal.
- Power meter.
- IR-Filter

The laser cavity should this time just consist of the Nd:YAG and a KTP crystal with the back side coated for second harmonic generation (SHG). It is advantageous to put the KTP crystal inside the laser cavity, as frequency doubling is a nonlinear process where the second harmonic signal power is growing with the square of the fundamental power. When the cavity is plane-plane it will be very sensitive with respect to cavity stability. However, when pumped the thermal lens in the Nd-crystal will stabilize the cavity to some extent. Why is there a thermal lens?
Assume that the KTP crystal is reflecting 99% of the IR and x mW is measured outside the cavity. How much higher is the circulating power inside the cavity?

5.1 Positioning the crystal

It is easiest to get the lasing with a short cavity. The crystal should be placed in the cavity oriented as a diamond in a deck of cards. This has to do with the phasematching condition for KTP which is Type II (you will learn more about it in the Quantum Electronics course)). Most likely you would need to use the red diode laser to get the crystals aligned. Follow the same adjustment procedure as previously, when the correct alignment is (very) close, you will be able to see green "sparks", i.e. the SHG turns on and off. Fine tune!

5.2 Measurement

5.2.1 Output powers vs. diode drive current

The green light looks strong, but is it really, or is it an effect of the eye's sensitivity?
Plot the green power vs. IR power. You can use the green glass filter to eliminate the IR signal.
Explain magnitudes and behavior, compare to previous results.

Appendix A: How to write a laboratory report

The following catalogue of questions is intended to help you to write your laboratory report in a formally correct way. Only hand in your report if you can answer all questions with yes. No handwritten reports are accepted (pdf files preferred)!

1. General remarks:

- Is the report written in whole sentences and in proper scientific English?

2. Title page:

- Are all names and email addresses of the participants listed?

3. Introduction:

- Is everything essential for the lab formulated on maximum one page (background and an overview of the experiment)?

4. Experiments:

- Did I make a sketch of all experimental setups (when necessary)?
- Did I write down all materials and instruments that I used during the experiments and state their corresponding physical/technical properties if necessary? (Not a copy paste from the instructions.)
- Did I explain the experiments and measurements in a way that another student who didn't do the laboratory would understand it?

5. Results:

- Are the results properly summarized and comprehensible for the reader?
- Are the presented results correct?
- Did I refer to the corresponding figures and tables?
- Are numerical results stated with the correct number of decimal places and units?

6. Figures and tables:

- Does the figure or table clearly show what it is intended to show?
- Are all figures, tables and sketched numbered?
- Do all figures have a caption with a full sentence and do they end with a point (.)?
- Are all the axis of the figures completely labeled (number of tick labels, unit, scale,...)?
- Do all columns have the correct units and the numbers the correct number of decimal places?
- Are all data points in the figure and have a single symbol?
- Do all figures have a legend which describes what you see in the figure?
- Are all figures explained in the text? (What can you see from the figure?)

7. Discussion and results:

- Did I state all important results qualitative in words and whole sentences?
- Did I comment all results and compared them with other sources?

8. Conclusion/ Summary:

- Does the report end with a short summary including the most important results and findings?