Lab 5 Diode-Pumped YAG Laser

EECS 4614 Electro-Optics

Fall 2022

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1 Safety

Laser radiation from the 808-nm diode laser can be up to 3W. This is a **class IV laser.** This laser together with the generated 1064 nm laser can cause serious eye or skin damage if exposed. Prior to the start of the experiment, ensure the light on the sign at the exterior of the lab is turned on to warn others.

<u>Keep away from the focusing location of the 808 nm pump laser where the energy is highly concentrated. Never look into any laser beams even wearing laser safety goggles.</u>

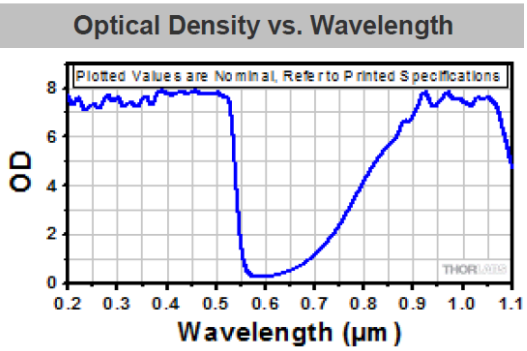
The laser beam should be terminated on a material that diffuses or absorbs light.

Warning: **special care must be taken to avoid eye or skin exposure to direct laser light or undesired laser reflections from mirrors or other reflecting surfaces.**

1. Never wear watches, rings, or anything that can reflect laser light during experiment.
2. Do not use any mobile devices such as cell phones and iPads near the experimental setup.
3. Never place anything other than the components provided in the laser path.
4. Minimize laser current before putting or removing components in or out of the laser path.
5. Wearing appropriate laser safety goggles is required for operating this setup.
6. Keep laser safety googles from scratching, cracking, or any other physical damage.
7. Check laser googles before experiment and replace damaged laser googles if necessary.
8. This setup should be operated in a supervised laser area with restricted access.

The laser safety goggles in this kit should provide OD +4 or above protection against 532 nm, 808 nm, and 1064 nm laser radiation, **<u>but one should never look into any laser beams directly even wearing the laser safety goggles</u>.**

OD Specs (ANSI Z136)
190 to 534 nm, OD = 7+
800 to 925 nm, OD = 4+
925 to 1070 nm, OD = 6+
960 to 1064 nm, OD = 7+



2 Introduction

In this lab you will build a diode-pumped solid-state (DPSS) laser. You will set up the semiconductor diode pump laser that provides the optical energy to the gain medium, which is a Nd:YAG crystal. By putting the crystal into a resonant cavity and optimizing all parameters, you will establish the conditions that turn it into a laser.

Acknowledgement: This lab handout is based on the equipment instruction manual provided by Lambda Scientific.

3 Theory

3.1 Introduction of solid-state lasers

A solid-state laser employs a doped crystal or glass such as a ruby crystal, a Neodymium glass, or a Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) crystal as the gain medium to generate laser light. Compared to other types of lasers, solid-state lasers possess attractive features such as high output optical energy, high output peak power, compact structure, and robustness. Among solid-state lasers, diode-pumped solid-state (DPSS) lasers are well known for their following characteristics: (1) high energy conversion efficiency: the pumping diode laser has a narrow spectral line that can be tuned precisely to match the absorptive peak of a gain medium. Moreover, a good spatial match can be achieved between a pumping diode and a gain medium using an end surface pumping mechanism. Ultimately, these matches yield higher energy conversion efficiency for DPSS lasers than flash lamp pumped solid-state lasers; (2) high thermal stability: high energy conversion efficiency makes the laser system generate less heat for its gain medium leading to much improved thermal stability of the laser system. A benefit from this is the improved coherence of the laser (narrow line-width of the laser spectral line); (3) long lifetime: the above characteristics of a DPSS laser yield a long lifetime of the laser for robust and easy operation.

3.2 Theory of lasers

The emission of a common light source such as lamp, flame, or sun is due to the interaction of the medium of the light source with external energy (optical, electric, or thermal). Electrons in the atoms are excited from a lower energy state to an upper energy state by absorbing the external energy, a process called the excitation of atoms or **stimulated absorption**. Due to the short lifetime (10^{-8} to 10^{-9}s) of electrons at an upper energy state, electrons at an upper state are spontaneously released to a lower energy state, giving off photons. The process is called **spontaneous emission** with the frequency of the photon radiated as

$$h\nu = E_2 - E_1$$

where h is the Planck constant, E_2 and E_1 are the energies of the upper and the lower states, respectively. The spontaneous emission of atoms is random, as these atoms are independent of

each other without correlation. So the phase or polarization of these radiative photons bears no fixed relationship and the photons are radiated randomly in all directions.

Under thermal equilibrium, the population of atoms at an upper state is much lower than that at a lower state, as described by the **Boltzmann distribution law**

$$N \propto e^{-\frac{E}{kT}}$$

where N is the population of atoms at energy level E, k is the Boltzmann constant, and T is absolute temperature in Kelvin. Thus, the population ratio of atoms at two states is

$$\frac{N_2}{N_1} \propto e^{-\frac{E_2-E_1}{kT}}$$

Since $E_2>E_1$, $N_2<N_1$. For example, the energy of Hydrogen atoms at the ground state is known as E_1=-13.6 eV, while the energy of Hydrogen atoms at the first excited state is E_2= -3.4 eV. At 20°C, $kT\approx0.025$ eV, so$N_2/N_1\propto e^{-400}\approx0$. This means that almost all the Hydrogen atoms stay at the ground state at 20°C. For light emission, external pumping energy must be provided to excite these atoms from the ground state to an upper state. Generally, common light emission is caused by stimulated absorption and spontaneous emission, so the intensity of spontaneous emission is not strong and the optical energy is divergent in all directions.

By contrast, laser is generated by a process called **stimulated emission** described below. When an atom at upper state E_2 is stimulated by an external photon with energy $h\nu$ ($h\nu=E_2-E_1$), it is released from upper state E_2 to lower state E_1 giving off a new photon that bears the same energy, phase, polarization, and directivity as the stimulated photon. Two identical photons are released with one photon incidence, and light amplification is achieved. Such stimulated emission and light amplification is **laser**.

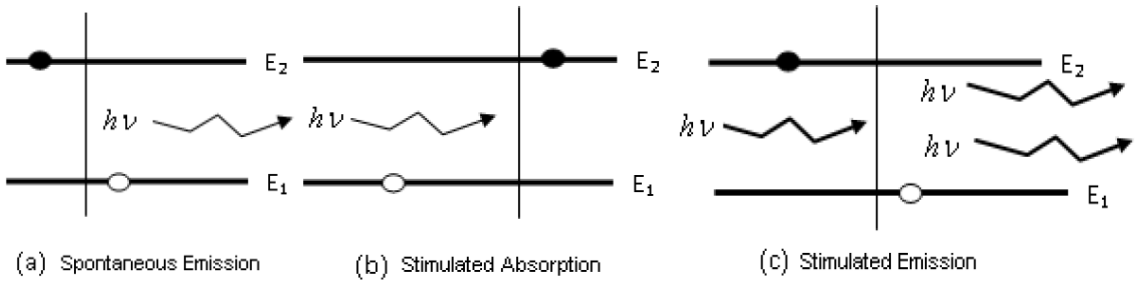


Figure 1 Schematic of three transitions of atoms in a two-energy system

On one hand, a stimulated photon can trigger stimulated emission; on the other hand, it is also subject to stimulated absorption. Normally in thermal equilibrium, stimulated emission cannot exceed stimulated absorption unless the population of atoms at an upper state exceeds that at a lower state, called population inversion, which is a necessary condition for the creation of laser

light. In general, a laser is composed of three components, a gain medium, an excitation source or pumping source, and a resonator.

3.3 Nd:YAG as gain medium

The physical and spectral characteristics (absorption spectra, fluorescence spectra, and thermal conductivity) of a gain medium affect the overall performance of the laser. Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) is crystallized by melting Al_2O_3, Y_2O_3, and Nd_2O_3 with a certain percentage in a furnace. The active ion in a Nd:YAG crystal is the Neodymium ion (Nd^{3+}) whose absorptive spectrum is shown in Figure 2. As seen in Figure 2, there is a strong absorption peak around 808 nm that can be used to pump the Nd:YAG crystal. As the output wavelength of a diode laser is affected by its temperature, a temperature stabilized diode laser is normally needed as the pumping source to achieve optimal **spectral matching**.

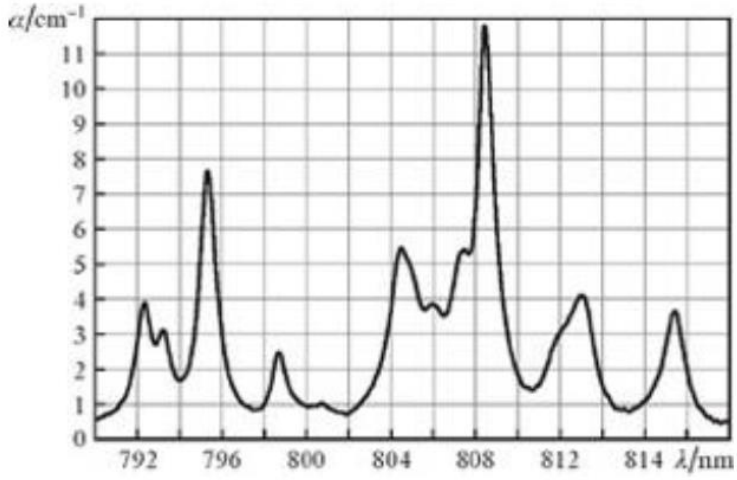


Figure 2 Absorption spectrum of Nd^{3+}: YAG crystal

A simplified schematic diagram of the energy levels of Nd^{3+}: YAG crystal is shown in Figure 3. It is basically a four-level energy system with Nd^{3+} ions pumped by a 808-nm diode laser from the ground state ($^4I_{9/2}$) to the excited state ($^4F_{5/2}$) from which the excited Nd^{3+}ions are transferred into the upper level ($^4F_{3/2}$) by a non-radiative transition. Stimulated emission is from the upper level ($^4F_{3/2}$)to the lower level ($^4I_{11/2}$), giving off a photon at a wavelength around 1064 nm.

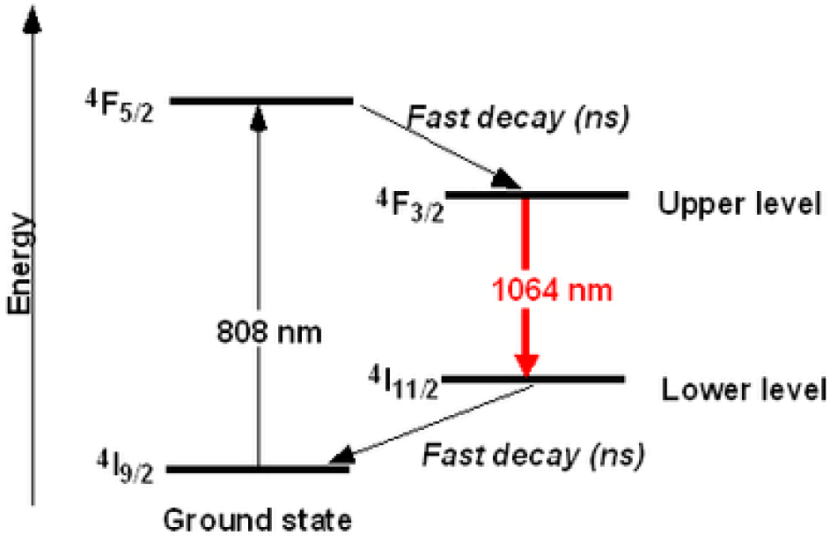


Figure 3 Schematic diagram of Nd^{3+}: YAG energy levels

3.4 Optical resonators

The DPSS laser in this lab employs an end surface pumping mechanism as shown in Figure 4. The high reflectance (HR) coating at 1064 nm on the left surface of a Nd^{3+}: YAG crystal and the partial reflectance (~95%) coating at 1064 nm on a concave mirror with a radius of curvature of 250 mm form the resonator. Apart from the spectral matching between the pumping diode and the gain medium, mode matching between pumping light and 1064-nm laser light in the resonator should be achieved for efficient pumping outcome. The resonator shown in Figure 4 is a hemispherical type with the beam waist located on the plane coating surface of the crystal.

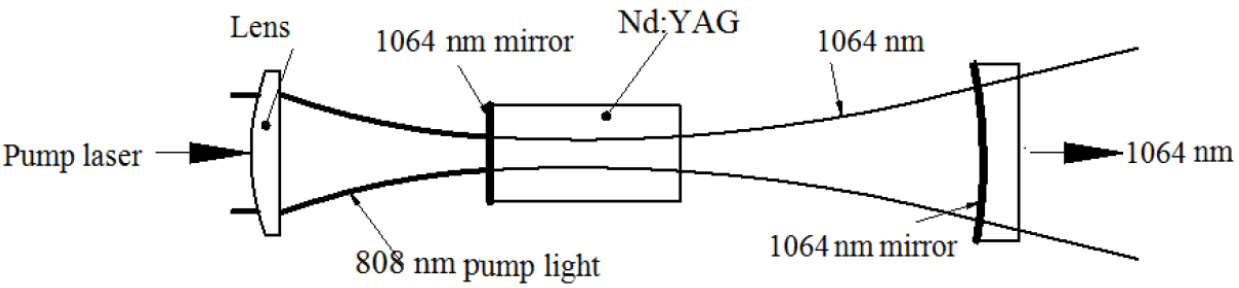


Figure 4 Schematic of Nd:YAG laser resonator

Normally, the optical resonators employed by lasers are considered as ideal resonators without side optical boundary, namely open resonators as in most gas lasers. For solid-state lasers, if the diameter of the gain medium is much greater than the laser wavelength, whereas the length of the gain medium is much smaller than the length of the laser resonator, such resonator can be treated as an open resonator.

Optical resonators are further classified into stable resonators, unstable resonators, and critical resonators in terms of escape loss of optical rays from the resonators. An off-axis optical ray in a stable resonator bounces for multiple times within the resonator without escaping from the resonator (low geometric loss); while an off-axis optical ray in an unstable resonator bounces only a few times before escaping from the resonator (high geometric loss). A critical resonator is between the above resonators with limited optical rays kept bouncing within the resonator. Figure 5 illustrates the geometric configurations of some typical resonators.

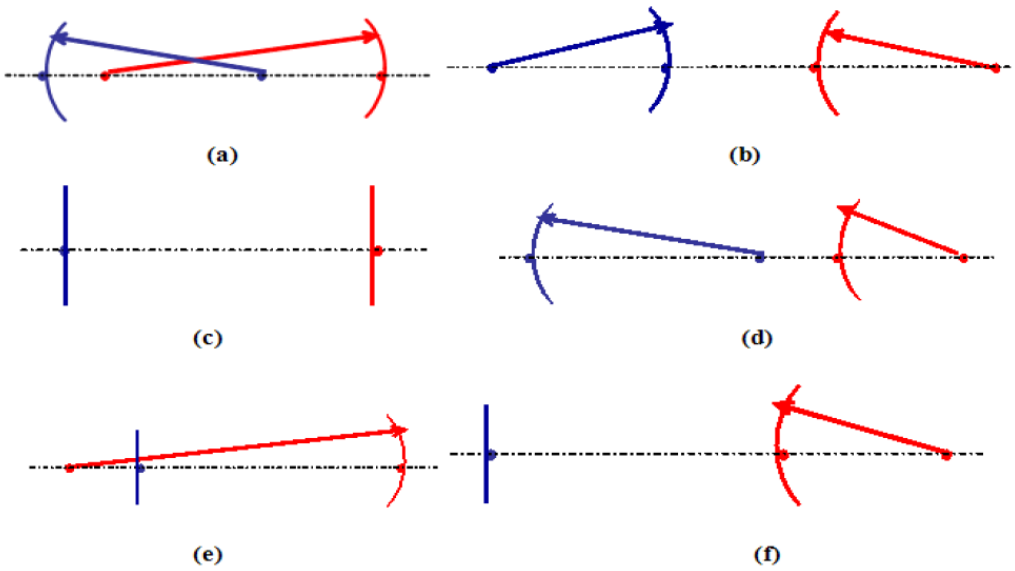
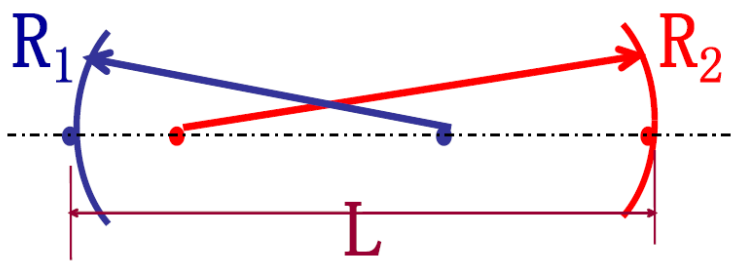


Figure 5concave-concave (a) convex-convex (b) plano-plano (c) concave-convex (d) plano-concave (e) and plano-convex (f)

For a typical two-mirror resonator, there are two important parameters (geometric parameters) that can be used to determine the stability criterion of the resonator.



R_1, and R_2 are the radii of curvature of the resonator mirrors, respectively.

L is the length of the resonator.

$$g_1 = 1 - \frac{L}{R_1}, \quad g_2 = 1 - \frac{L}{R_2}$$

The stability criterion of a resonator is determined as follows,

(1) stable resonator: $0<g_1g_2<1$

(2) unstable resonator: $g_1g_2<0$ or $g_1g_2>1$

(3) critical resonator: $g_1=0$ or $g_2=0$ or $g_1g_2=1$

This criterion can be better illustrated in Figure 6 in which the blue filled areas as bounded by line $g1g2=1$ and the axes are stable resonators whereas resonators on the line or the axes are critical resonators. The laser beam from a stable resonator is a Gaussian beam that follows the Gaussian distribution profile in propagation.

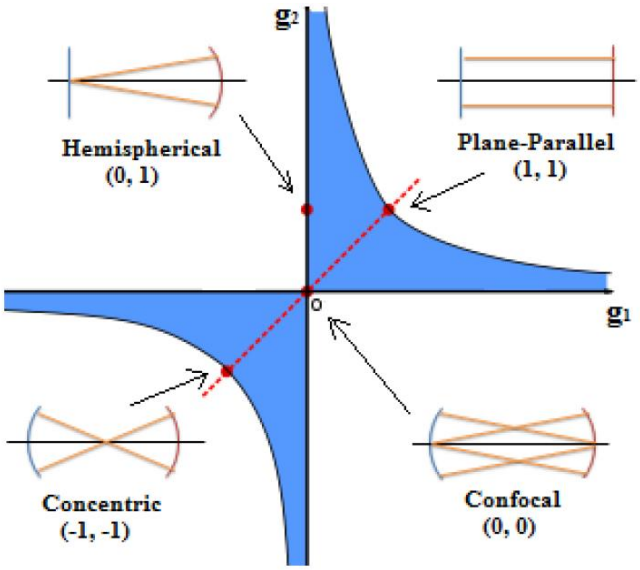


Figure 6 stability criteria for two-mirror resonators

3.5 Diode laser as pumping source

Since the gain medium in a solid-state laser is an insulated crystal, it is usually pumped by an optical source that meets two basic conditions: (1) high luminous efficiency, and (2) spectral coverage of the absorption spectrum of the gain medium.

When a traditional lamp is used as the pumping source, the energy conversion efficiency is so low that only a small portion of the luminous energy is absorbed by Nd^{3+} ions whereas the rest of the luminous energy is absorbed by the host material and transformed into heat. This inevitably produces an uneven temperature distribution in the gain medium degrading the overall performance of the solid-state laser or even causing a serious “temperature quenching” failure. For this reason, a traditional solid-state laser often needs a bulky water or air cooling system. By contrast, the cooling system in a DPSS laser is more compact and robust due to the high energy

conversion efficiency as a result of the wavelength matching between the diode and the gain medium.

In this apparatus, a multimode InGaAlAs/GaAs quantum-well diode laser at 808nm is used as the pumping source whose output power is more than 2 W but can be adjusted by changing the driving current. Unlike other lasers, the stimulated emission in a diode laser occurs between energy bands rather than discrete energy levels, resulting in a broader spectral line-width as compared to other lasers. Moreover, the spectral profile of a diode laser can be shifted slightly by varying the temperature or driving current of the laser. For this reason, the diode laser in this apparatus is temperature stabilized using thermoelectric (TE) cooling for stable operation. TE cooling of a high-power diode laser also helps extend the lifetime of the laser.

Another characteristic of a diode laser is its high beam divergence as the emitting laser is from a tiny rectangular edge (PN junction) of approximately 150×1 μm in cross section resulting in severe beam diffraction. Typically, the beam divergence angles of an edge-emitting diode laser can be 38°×10° in lateral and vertical directions, leading to an elliptical beam spot in the far field region. The beam divergence angles of the diode laser in this apparatus are suppressed with built-in optics so that a near-rectangular beam spot is achieved for use with common lenses.

3.6 Passive Q-switching

The Q factor is a figure of merit for an optical resonator, defined as the ratio of the stored energy to the rate of the energy loss in the resonator. In general, the Q factor of a resonator is determined by two factors, the intra-cavity loss and the mirror reflectivity of the resonator. A higher-Q resonator needs lower pumping threshold to start stimulated oscillation. For a pulsed solid-state laser without Q-switching, the duration of the pulsed stimulated oscillation would last for the same amount of the population inversion can be maintained, on the order of milliseconds. For such lasers, the output pulsed power is quite limited. Q-swithcing is the adjust the rate of the energy loss to control the stimulated oscillation in the resonator, since the stimulated oscillation occurs only when the optical gain exceeds the energy loss for the gain medium, otherwise the stimulated oscillation would cease. If a special device like a fast optical switch is placed in the resonator to deliberately reduce the Q factor of the resonator by increasing the intra-cavity loss during optical pumping, stimulated oscillation cannot occur so that the degree of population inversion would continue to increase by optical pumping until the Q factor of the resonator is suddenly boosted (Q-switching) to start stimulated oscillation. As a result, the accumulated high degree of population inversion at the upper energy level is momentarily released to the lower energy level, giving rise to high pulsed power output from the laser.

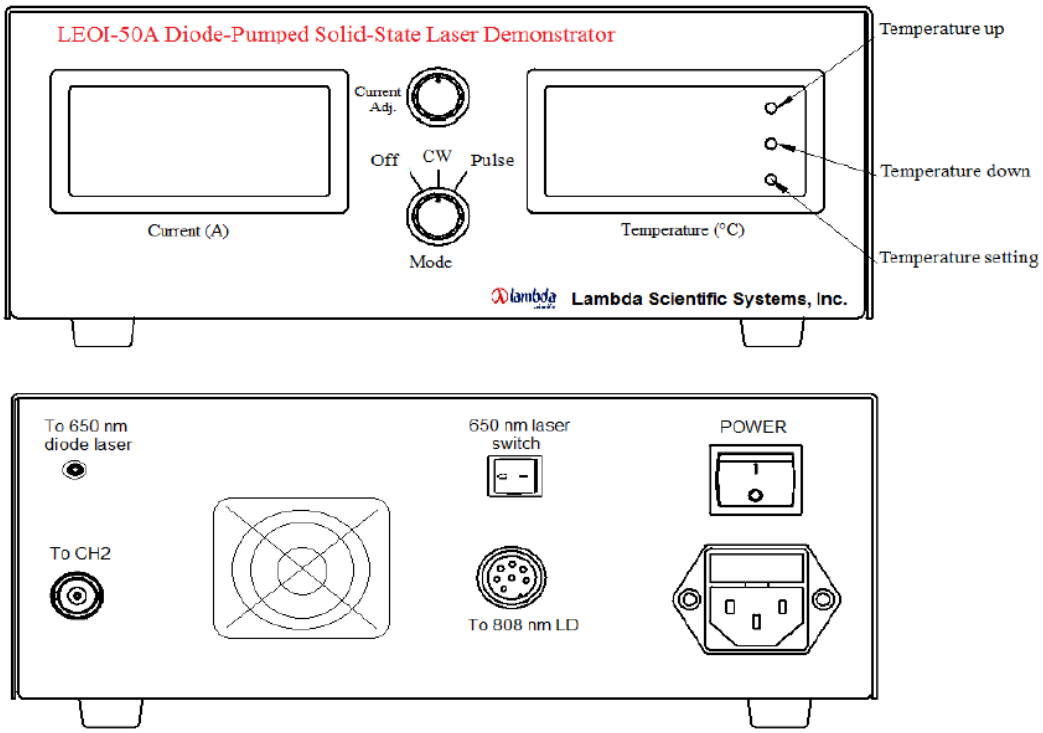
Technically, Q-switching can be achieved using electro-optic or acousto-optic effects (active Q-switching) or with a saturable absorber (passive Q-switching). In this apparatus, a passive saturable absorber (Cr^{4+}:YAG) is used as the Q-switching device whose transmission increases when the intensity of the light exceeds some threshold. Initially, the transmission of the absorber placed in the resonator remains low even when photons continue to build up in the resonator as the degree

of population inversion increases in the gain medium due to optical pumping, until the absorber is saturated resulting in a sudden increase in transmission. At this moment, the laser output reaches a peak level. Hereafter the absorber recovers to its low-transmission state before the gain recovers, so that the next pulse is delayed until the energy in the gain medium is full replenished.

4 Equipment

Description	Specifications	Qty
Optical bench	Length: 0.8 m	1
Laser diode (LD)	2 W at 808 nm with TE cooling	1
Laser diode driver	0 ~ 3 A with temperature controller	1
Alignment diode laser	4 mW at 650 nm with 2-D tilt adjustable holder	1
Lens (collimating & focusing)	Incl 2-D adjustable holder, ± 2.5 mm	1 each
YAG crystal	Incl 4-D adjustable holder	1
KTP crystal	Incl 5-D adjustable holder	1
Laser power meter	2 mW/20 mW/200 mW/2 W	1
Probe of laser power meter		1
Photo-detector (PD)		1
Partial reflecting mirror	Radius of curvature: 250 mm; reflectance: 95%	1
Interference filter I	HT $\leq$ 532 nm, while blocking 808 nm & above	1
Interference filter II	HT $\geq$ 1064 nm, while blocking 808 nm & below	1
Collimation aperture	Incl 2-D translation holder	1
Laser safety goggles	190 to 534 nm, OD = 7+ 800 to 925 nm, OD = 4+ 925 to 1070 nm, OD = 6+	1
Passive Q-switching device		1
IR viewing card		1
Allen wrench		1
BNC cable		1
Power cord		2

The controller unit mainly consists of two parts: 1) current driver; 2) temperature controller.



A. Current driver

There are three modes for the driving current of the 808 nm pump laser: Off, Continuous (CW) and Pulse. Current is adjustable within a range of 0~2.5 A by using the adjustable knob.

Note Do not operate or maintain the 808-nm diode laser at current larger than 2 A for a long period of time, doing so would significantly reduce the lifetime of the 808 nm laser.

B. Temperature controller

There are three push buttons on the temperature controller: “Temperature up”, “Temperature down”, and “Temperature setting”. Press the “Temperature setting” button once, the actual temperature of the 808 nm laser is shown on the display and the last digit of the temperature reading flashes. Press the “Temperature up” or “Temperature down” button continuously to change the temperature. Finally, press the “Temperature setting” button again to complete the temperature setting. If the set temperature is lower than the actual temperature of the laser, the indicator on the upper-left corner of the display is on, and the TE cooler starts cooling the laser; if the set temperature is higher than the actual temperature of the laser, the indicator is off and TE cooler does not work.

Note

1. Always set the temperature below the room temperature as there is no heater in the 808-nm laser module to heat the laser above the room temperature.

2. An overheating protection circuit is built in the 808-nm laser module to automatically shut off the driving current if the temperature of the laser exceeds 45°C.

WARNING

To avoid damaging the 808 nm laser, never exceed a drive current of 2.5 A. Turn the current control to minimum before turning on the current driver, and dial in the current slowly, so that you don't exceed a current of 2.5 A.

5 Experiments

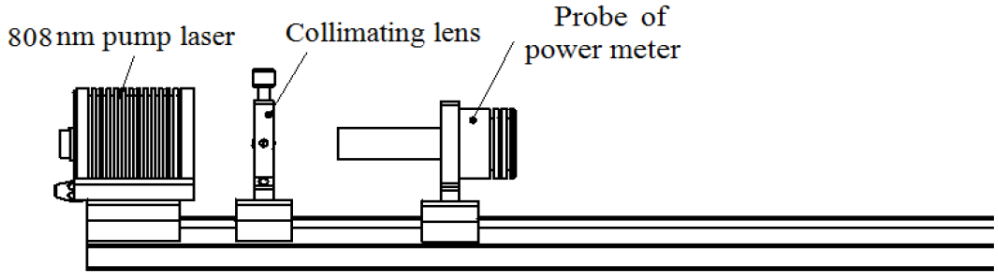
5.1 Electro-optic characteristics of diode lasers

Notes:

1. Always set the control temperature at or below room temperature as there is no heater but cooler incorporated in the 808-nm laser module.

2. Do not operate or maintain the 808-nm diode laser at current larger than 2.0A or a high temperature extensively, doing so would significantly reduce the lifetime of the laser.

3. An overheating protection circuit is built in the 808-nm laser module to automatically shut off the driving current if the temperature of the laser exceeds 45°C.



Procedure:

1. Mount 808-nm diode laser, collimating lens, and probe of laser power meter on optical rail.

2. Set the switch on the main controller to “Off” position and turn the current adjustment knob counter-clockwise to minimum.

3. Turn on the main controller and the power meter.

4. Set temperature to 22 °C and power meter to 20mW scale, and zero the power meter reading.

5. Set the switch to “CW” and driving current between 0.6~1 A. Now, the diode laser emits 808 nm near infrared light with a rectangle-shaped green spot as viewed on the IR viewer card.

6. Adjust the collimating lens forward/backward until the 808-nm laser light is collimated (collimated distance at about 1.5 cm separation between holders measured on the rail), and then adjust the lens up/down and left/right until the collimated beam propagates along the rail with the aid of the alignment aperture. When the beam is collimated, its size won’t change as function of distance from the lens. Next, remove the alignment aperture, 808 nm laser should illuminate on the active area of the power meter.

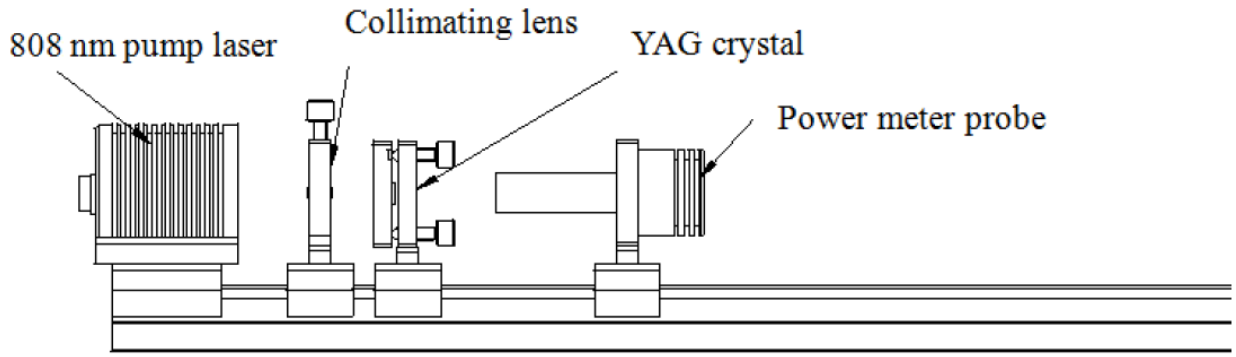
7. Set the current to minimum and ensure the temperature is stabilized at the desired value. Increase the current slowly in 0.1 A steps while recording the corresponding output laser power from the power meter. Reduce the current to minimum after measurement.

8. Plot the power-current (*P-I*) curve of the laser to get the threshold current of the laser, which is the current at which the laser starts to lase.

Report the results to the TA.

5.2 Absorption of Nd:YAG material

808-nm absorption by a Nd:YAG crystal can be verified by measuring the laser power of the 808-nm laser light passing through the crystal. The emission wavelength of the 808-nm diode laser can be tuned by changing its temperature to the wavelength of the absorption peak of the crystal. Under such condition, a significant decrease in power reading is observed indicating peak absorption by the crystal.



1. Insert the YAG device between the collimating lens and the power meter (note: if there is a cover cap on the crystal, remove the cap before placing the crystal into the optical path).

2. Set the current at 1.2A.

3. Decrease the temperature with a step size of 1°C while recording the corresponding power meter reading (take data only when temperature stabilizes). Take 10~15 data points.

4. Plot *P*-*T* curve to observe the absorption effect of the crystal.

Report the results to the TA.

Notes

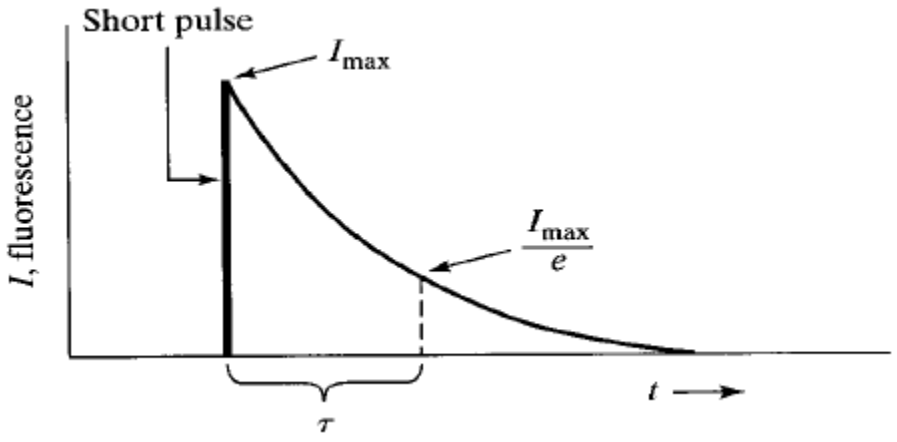
1. The temperature tuning coefficient of the 808-nm laser is approximately 0.3 nm/°C.

2. Correct any drift of driving current during experiment.

3. Keep the power meter probe away from the YAG crystal to eliminate the impact of the fluorescent light from the crystal on power reading.

5.3 Fluorescence lifetime of the Nd:YAG crystal

Fluorescence is the emission of light by a substance called fluorophore that has absorbed the energy from an excitation source such as a laser. The fluorescence lifetime is a measure of the time a fluorophore takes in the excited state before returning to the ground state by emitting a photon. This process is governed by an exponential function with time and the fluorescence lifetime τ is the time when the fluorescence intensity drops to $1/e$ of the initial intensity, as shown below.



1. Put the interference filter II (1064 nm) to the back of the YAG crystal and replace the power meter with a photodiode (PD).

2. Connect the output of the photodiode to CH1 of an oscilloscope.

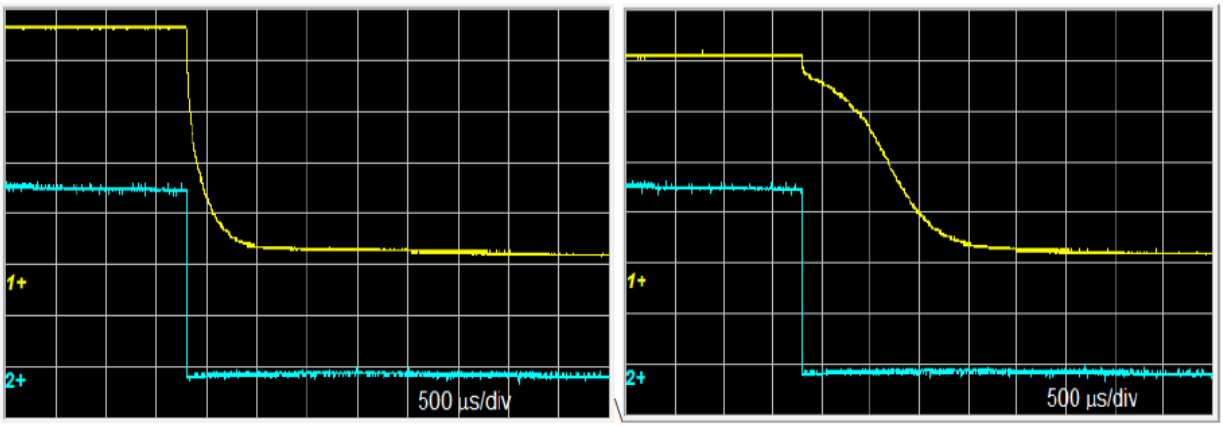
3. Connect the “pulse output” terminal on the rear panel of the controller unit to CH2 of the oscilloscope with a BNC cable, and set both channels to DC coupling.

4. Set the switch on the main controller to “Pulse” and current to 1A.

5. Record the time scale reading of the point whose voltage reading drops to 1/*e* of the peak on CH1 of the oscilloscope. Reduce the current to minimum.

6. Remove the YAG crystal and increase the current to 1A and record the time scale reading of the falling edge on CH1 of the oscilloscope. The difference between the two time scale readings is the fluorescence lifetime of the YAG crystal.

Report the results to the TA.



5.4 Characteristics of DPSS laser

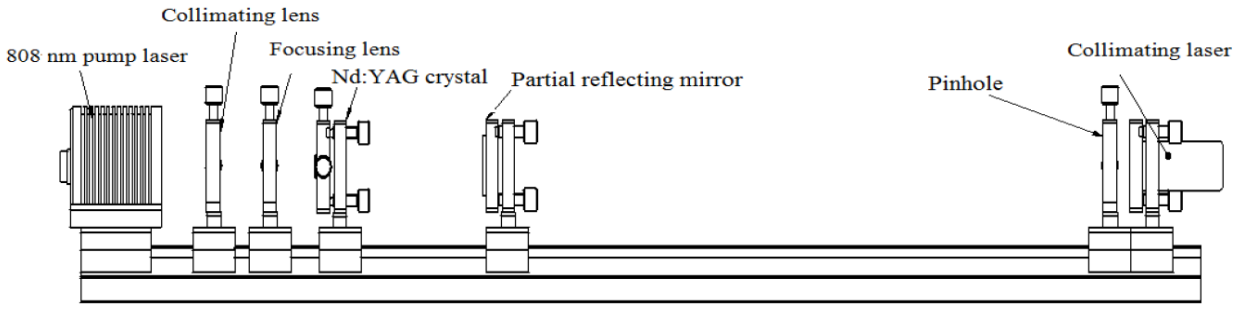
Warning

1. The intensity of the 808 nm pumping laser is extremely high at the focusing point that it can ignite paper and other flammable items.

2. Keep the HR coating surface of the YAG crystal free of contaminants such as dust, dirt or finger print.

3. Before experiment, if necessary, clean the HR coating surface of the YAG crystal by dragging a lens tissue soaked with Ethanol over the HR coating surface.

4. The 808 nm laser can cause serious eye or skin damage if exposed directly or indirectly. Read and follow the LASER SAFETY instructions before doing any experiment with the 808 nm laser.



Procedure

1. Arrange the components on the optical rail per the above configuration, but do not place the partial reflecting mirror on the rail now.

2. Set the switch to "CW" and current between 0.6~1A, find the focal point of the 808 nm light behind the focusing lens with the IR viewing card, and place the HR coating surface of the YAG crystal at the approximate location of the focal point.

3. Increase the current to ~2-2.5A, while observing the focusing position of the 808 nm light on the front surface of the YAG crystal. A thin white line along the optical path should be observed in the crystal, which is the fluorescence emitted by the crystal excited by the 808 nm laser. Move the YAG crystal back and forth until the brightest white line is observed. Then reduce the current to 0.6A. **Warning:** observe the white line in YAG crystal from the side of the focusing lens on top of the laser path (**DO NOT** look into the YAG crystal from the side of the collimating 650 nm laser). As the white line is weak, it may be visible only under dim environment.

4. Turn on the collimating 650 nm laser. Adjust the collimating laser beam and the pinhole at the other end of the rail until the 650 nm red alignment beam passes through the pinhole and shines at the focusing point of the 808 nm pumping light on the YAG crystal. To determine that the 650 nm laser light and the 808 nm pump light overlap on the YAG crystal, you can use the IR viewing card on the focusing lens side of the YAG crystal. This will show a green halo where the 808 nm light passes through, and a red halo where the 650 nm light goes. Adjust the 650 nm light until it overlaps with the 808 nm light.

5. Find the red alignment beam spot that is reflected by the HR coating surface of the YAG crystal back onto the pinhole surface; adjust the tilt controls of the YAG crystal to let the spot pass through the pinhole. This will ensure that the alignment beam is perpendicular to the HR coating surface of the YAG crystal.

6. Place the partial reflecting mirror "reflector" between the pinhole and the YAG crystal, about 100mm away from the YAG crystal. Now, an additional reflected spot of the 650 nm light should be observed on the pinhole surface, the previous one was from the HR coating surface of the YAG crystal (spot #1), and a new one from the partial reflecting mirror (spot #2).

7. Adjust the partial reflecting mirror tilt controls so that the 650 nm light refelcted from its surface goes through the pinhole. Now, the HR coating surface of the YAG crystal and the partial reflecting mirror are parallel, forming an optical resonator. Turn off the 650 nm collimating laser.

8. Increase the current to 2.5A, and 1064nm laser should be emitted as observed with an infrared viewing card. If not, or the beam is distorted (a line instead of a dot) finely adjust the partial reflecting mirror while observing the infrared viewing card until a well-defined and circular light spot is observed on the infrared card.

9. Insert the power meter probe between the partial reflecting mirror and the pinhole to measure the output power of the 1064 nm laser. Adjust the partial reflecting mirror until a maximum power reading is observed from the power meter.

10. Change the length of the resonator by moving the partial reflecting mirror back and forth, while observing the change in output power and spot shape (impact of resonator parameter on output power). Note: the partial reflecting mirror and the YAG crystal may need fine tilting alignments to observe output power changes

11. Finely move the focusing lens back and forth to observe the change in output power (impact of mode matching on output power). Note: the focusing lens and the YAG crystal may need fine tilting alignments to observe output power changes.

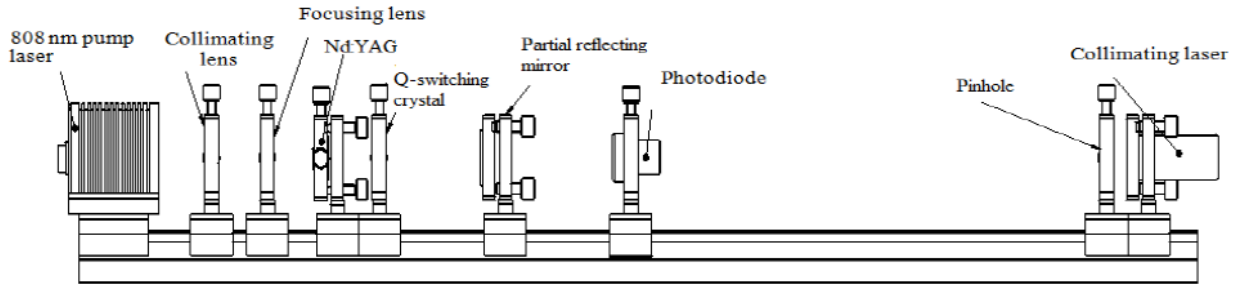
12. Optimize steps 10) and 11) so that a maximum power output is achieved at a given current under a desired temperature value, and then reduce the current to minimum.

13. Increase the current from minimum at a step size of 0.1A while recording the output power of the 1064 nm laser from the power meter. **Reduce the current to 0.1A after measurements.**

14. Based on the P_{808}-I curve of the 808 nm pumping laser in section 4.1, plot the P_{1064}-P_{808} curve to determine the threshold and power conversion efficiency of the 1064 nm laser.

Report the results to the TA.

5.5 Q-switching



1. Per the above configuration, set the current to minimum before placing the Q-switching device in front of the partial mirror and replace the power meter with the photodiode.

2. Connect the output of the photodiode to an oscilloscope on DC coupling.

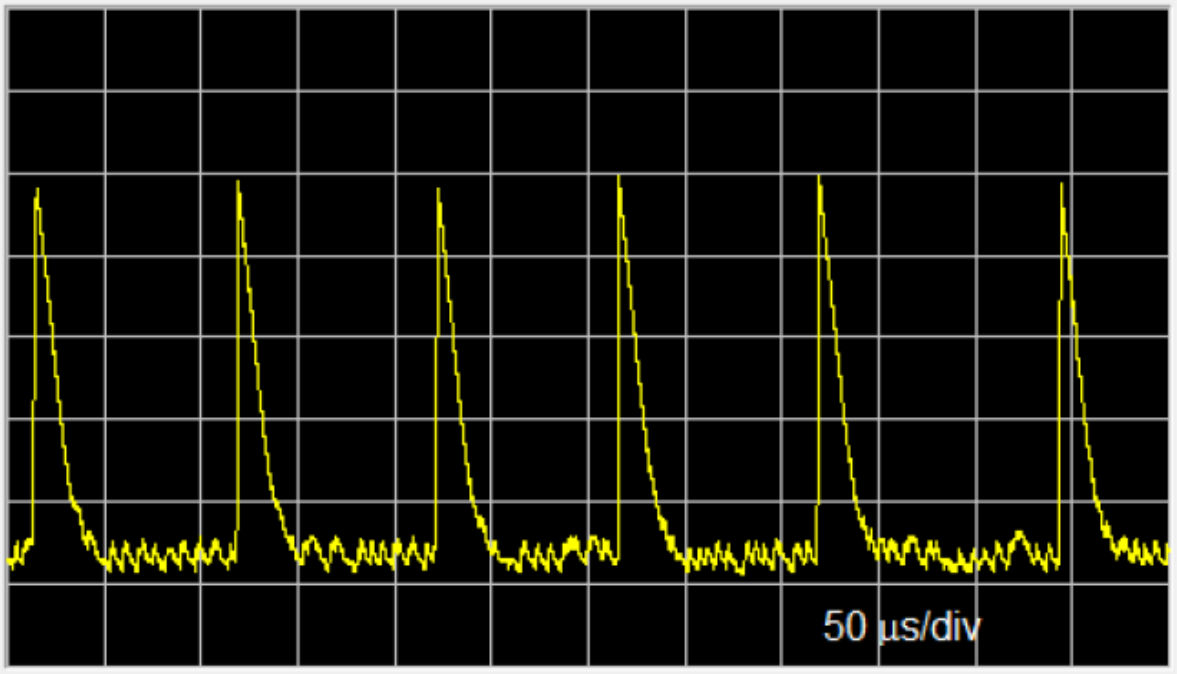
3. Set the switch on the main controller to “CW” and current to 2.5 A to observe the output pulsed waveform on the oscilloscope. You may have to optimize the partially-reflecting mirror for best laser performance after inserting or taking off the Q-switching device.

4. Reduce the current to observe the change in output pulsed waveform on the oscilloscope.

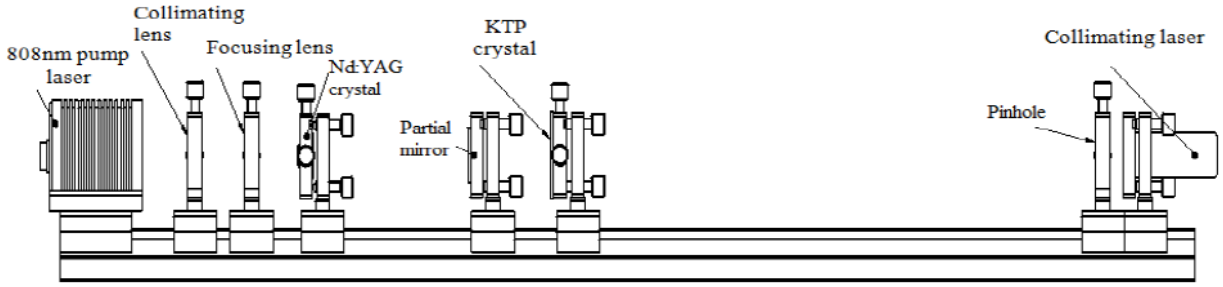
5. Reduce the current to minimum and then remove the Q-switching device out of the resonator.

Report the results to the TA.

NOTE: If the photodiode is saturated, move it off the maximum power location via its 2D mount to avoid saturation.

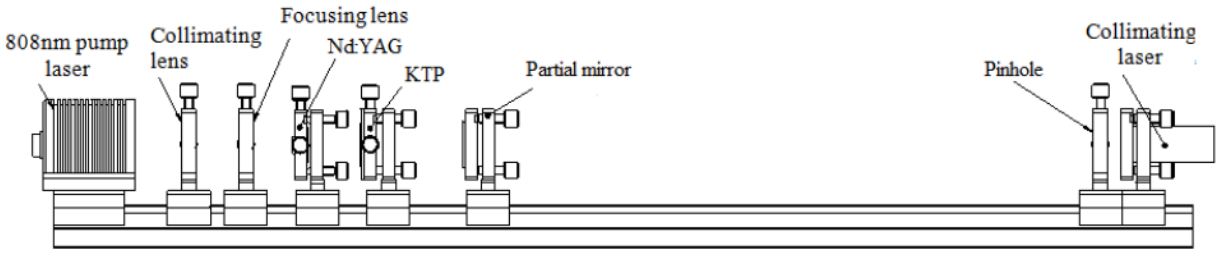


5.6 Frequency doubling



1. Set the current to minimum, and place the KTP crystal behind the partial reflecting mirror (now the KTP is out of the resonator).

2. Set the switch to “CW” and the current to 2.5 A, and adjust the the KTP crystal by turning the scale disk and tilt controls to observe intensity change of the 532 nm green laser (angle matching and phase matching).



3. Set the current to minimum and place the KTP crystal in front of the partial reflecting mirror (now the KTP in within the resonator).

4. Set the current to 2.5 A and compare the intensity of the 532 nm green laser with the previous experiment to understand the quadratic relationship of the intensities between the second harmonic light and the fundamental light. You may have to re-optimize the partially-reflecting mirror when taking the KTP crystal in or out of the resonator.

5. Reduce the current to minimum after the experiments.

Report the results to the TA.