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Simple Diode Pumped Solid State (DPSS) Laser Demonstration

Undergrad /Grad Experimental Physics Lab

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Goals and Objectives

The main goal is to understand some basic laser theory and the method of creating a 532 nm (green) laser emission from an 808 nm (IR) laser. In the process you will learn the basics about laser diodes, pumping a gain medium, the purpose of special optical coatings, second harmonic generation, and the electronics / measurement tools for optical characterization.

Basic Theory

Two, Three and Four State Lasers

When a photon is incident upon a molecule, many interactions can occur; the chief ones being;

- Excitation from a lower to a higher level (excitation, pumping, or stimulated absorption)
- Excitation from a higher to a lower level spontaneously
- Excitation from a higher to a lower level in phase (stimulated emission)

The energy state of a molecule depends on the state it was in to begin with. Atoms, molecules and crystal lattice structures have many energy levels associated with them. These energy levels are related to vibration, rotation, electronic states, spin, etc. and have many possible combinations, due to these degrees of freedom (DOF) and quantum mechanical configurations. We will focus on the electronic states of some lasing material. In reality this could be a gas, liquid or crystal lattice. This lab deals with a crystal of Nd: YVO_4 in particular. If the molecule was at rest in the ground state and a traveling photon interacts with it, provided the single photon has the sufficient energy to make the transition to the excited electronic state, it will make a transition from the ground to the excited level.

Just as a side note, if two or more photons of sufficient combined energy arrive within 10^{-16} to 10^{-18} seconds of each other, the same process will occur. This process is called multi-photon absorption. This would only occur if lots of photons arrive at the same time which typically implies a very intense pulse, ideal for a titanium sapphire laser also known as an ultrafast laser due to the very short, intense pulses it puts out.

If one starts with a simple system with two-energy levels, one can see why this isn't a good idea for a laser. Materials normally have a thermal energy population with most of the atoms in a ground state. The desired state in a laser is to have a "population inversion" where as many of the atoms as possible are in the excited state. This is an essential concept needed for lasing. Once the population inversion is established a gain can be established within the lasing material, in which an avalanche effect occurs where the excited states depopulate in such a manner to have the photons emitted in phase and growing across the lasing medium, resulting in a strong laser output. The two-level

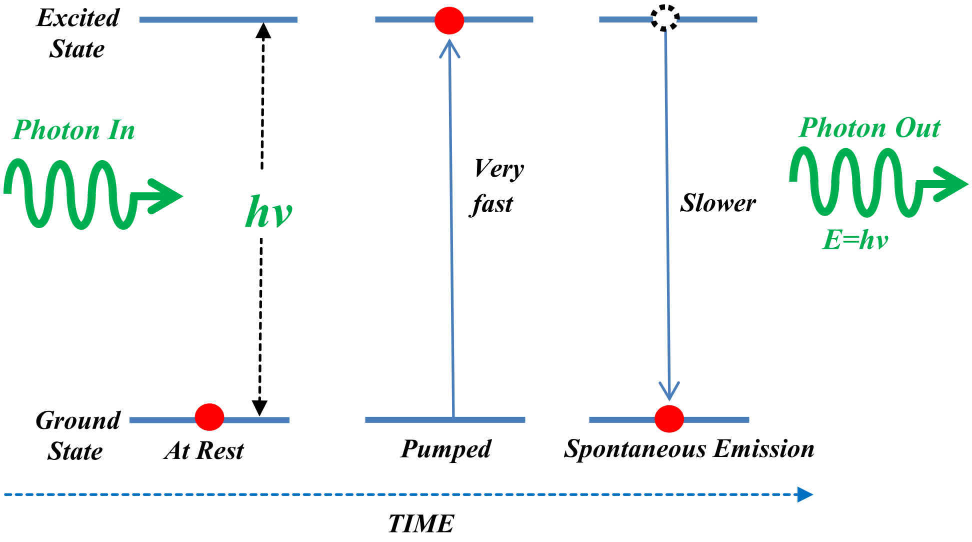


Figure 1, Energy diagram for a two-level system undergoing spontaneous emission. This process of emission occurs statistically sometime after the photon pumped it to the excited state and cannot be predicted exactly in time and is out of phase with the pump photons.

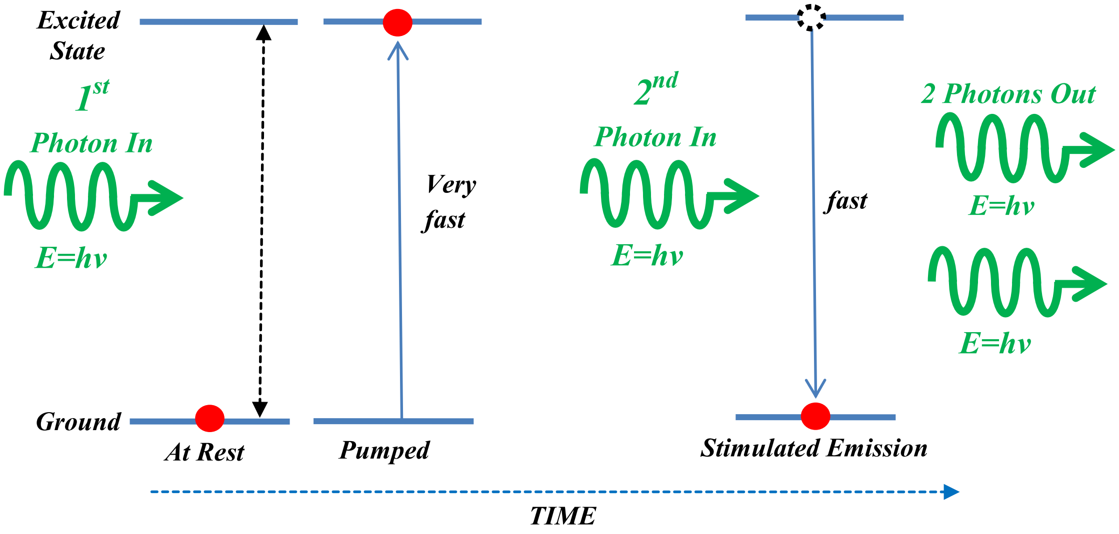


Figure 2, Energy diagram for a two-level system undergoing stimulated emission. This process of emission occurs right after the second photon interacts and is in phase with the 2nd photon.

system unfortunately cannot achieve this process and suffers from having as many atoms in the ground as in the excited state, thus cannot achieve a population inversion. This process of excitation and emission can be illustrated by energy diagrams. If a photon matching this energy ($E = h\upsilon$) is incident upon the system, the energy of the system jumps from ground to the excited state. It then spontaneously (at some random time or statistically determined time later) jumps back down in energy to the ground state. Figure 1 shows a two-level system undergoing spontaneous emission with an energy difference between the ground and the excited states of $h\upsilon$. If we had a row of many of these two-level systems and pumped them all to the excited state, then let us say the first one on the left makes a transition down it will emit a photon (see figure 2).

If we use this model and try to make a laser with a two-level system with a ground and excited state, it would not have much output due to a lack of gain. The fact that the ground state is a loss mechanism for emission in one stop leads to a problem. The two-level laser has the same pump and emitted photon energies, thus each stimulated absorption process removes one photon from the process of emission. A better laser model would have the lasing output levels separated from the pump energy values where the stimulated upper laser level and lower laser level are somehow protected from competing mechanisms and thus achieve a population inversion and a very high gain. This can be seen in a three-level and better even, a four level-laser.

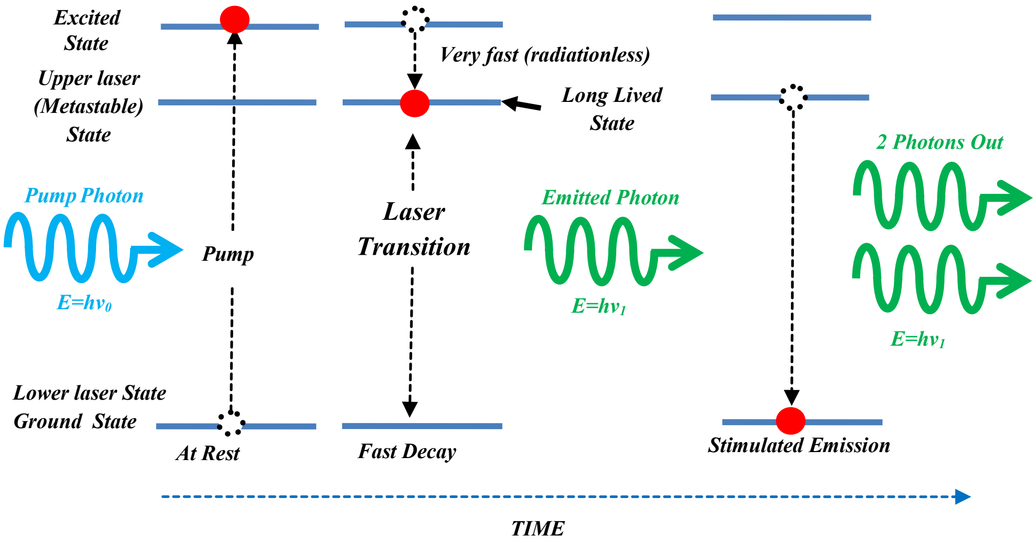


Figure 3, Energy diagram showing the first process in a three-level laser. The pump photon (blue) gets the atom into a higher energy state which decays to the upper laser transition (metastable) very quickly without emitting a photon. The upper laser state is long lived and eventually goes back to the ground state and emits a photon spontaneously (green). This photon can then stimulate the emission for another atom which is still in the upper lasing level. This process therefore produces two photons in phase, which then go on to repeat this process and eventually creates a large photon flux within the lasing medium.

In a three-level laser, an additional level is added so that a different energy is needed for pump and laser emission. Figure 3 shows the energy diagram showing the first process in a three-level laser. The pump photon (blue) gets the atom into a higher energy state which decays to the upper laser transition (or metastable state) very quickly without emitting a photon. The upper laser state is long lived and eventually goes back to the ground state and emits a photon spontaneously (green). This photon can then stimulate the emission for another atom which is still in the metastable state. This process therefore produces two photons in phase, which then go on to repeat this process and eventually creates a large photon flux within the lasing medium.

One problem with the three-level system is that it has a serious loss mechanism, which, luckily, can be circumvented. When the atom is in the ground state (or lower laser state) another photon of energy equal to hv_1 can cause stimulated absorption back up to the upper lasing state, instead of the photon adding to the avalanche effect, it is a loss for the stimulated emission process. One needs a lot of pump power to overcome these losses. The way to get around this is a four-level laser.

In a four-level laser everything is the same except for the transition from the upper lasing state goes down to a different state than the ground state. Figure 4 shows the energy diagram for a four-level system. The advantage of this system lies in the lower laser state going straight to the ground state for the pump laser. This fast relaxation minimizes the chances of the atom going through a stimulated absorption, another loss mechanism. Once the atom relaxes back to the pump ground state, the atom can only be excited by the pump laser. This type of four-level system is what is typically used in high power systems today. A three-level laser might still be used for a

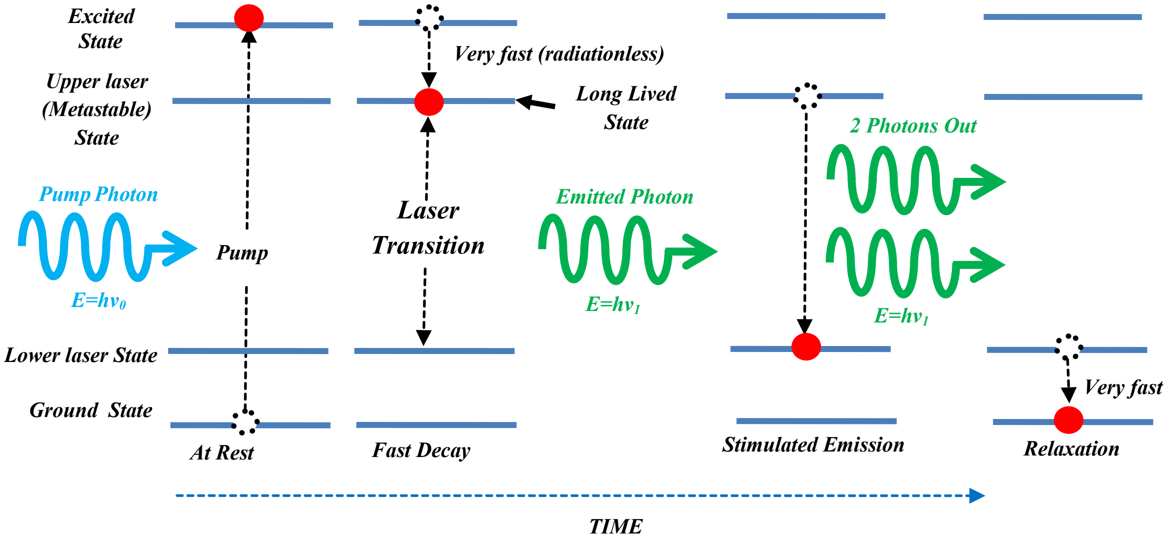


Figure 4, Energy diagram for a four-level system. This system has the advantage of minimizing the stimulated absorption from the lower lasing state in order to get most of the atoms into the upper lasing state.

unique property of wavelength or pulse-width capability even though it will require a lot of pump power to achieve decent gain, ie. the ruby laser (Cr^{3+}:Al_2O_3).

Experimental Introduction

The overall setup consists of many components:

- (A.) 808 nm diode laser assembly with TEC cooler/fan
- (B.) Homemade diode laser power supply
- (C.) Large optical breadboard (metric/steel)
- (D.) Small optical rail (English/black anodized aluminum)
- (E.) Two optical holders with matched short focal length lenses
- (F.) Optical holder with laser cavity assembly crystal (glue assembly - MCA)
- (G.) Optical holder with visible pass filter (BG39)
- (H.) Optical holder with visible/NIR block filter (BG1000)
- (I.) Optical holder with adjustable white plate and fiber coupler
- (J.) Computer with Ocean optics fiber coupled spectrometer
- (K.) Mobile white screen for checking focusing

The optical components all fit onto the rail at the proper spacing. Figure 5a & b show the setup with proper alignment for the main diode laser (A) and the laser assembly (F).

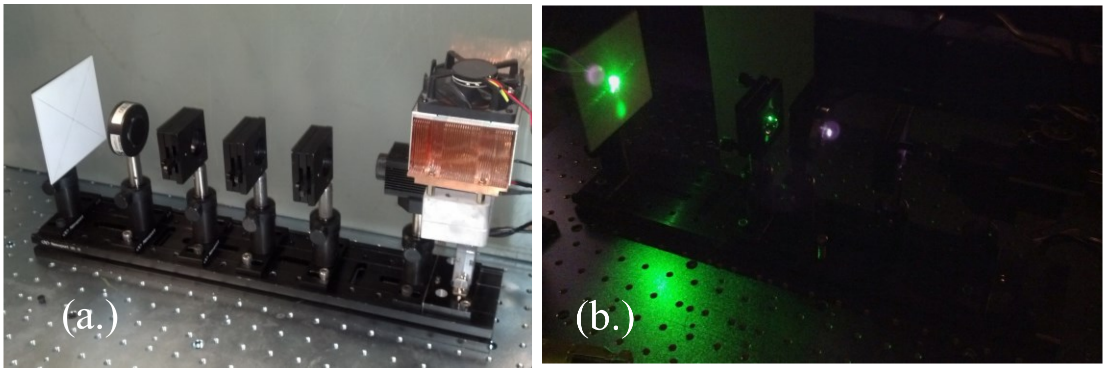


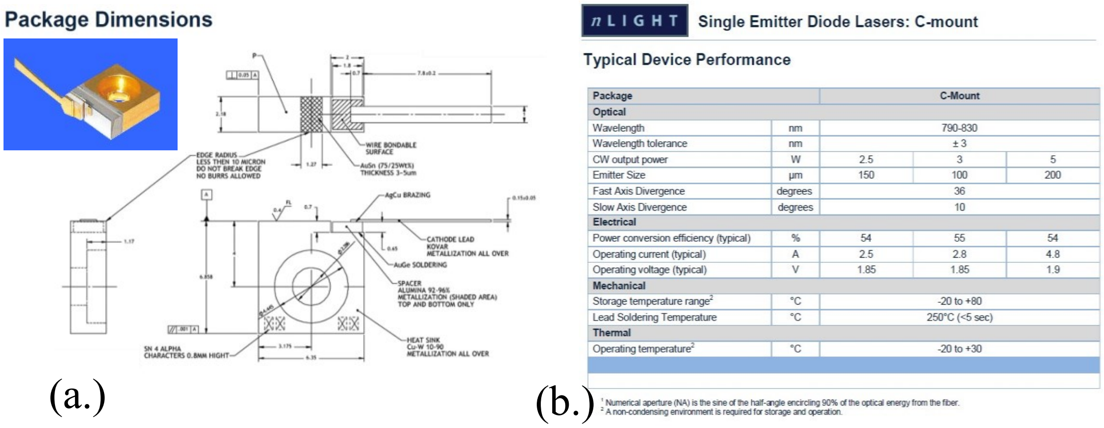
Figure 5, (a.) Collimated IR diode laser on the optical rail, **(b.)** properly aligned laser cavity (F.) on the optical rail, green light is seen at the screen/fiber unit (I.).

In this lab you will:

- Measure a Current /Power curve of the NIR diode laser.
- Align the diode laser to collimate the beam with the use of two lenses (E.)
- Align the optical components in order to achieve an efficient doubling of the laser cavity assembly (F.)
- Measure the temperature/spectral output characteristics (optional).
- Measure the excited lifetime of the Nd:YVO_4 and determine dopant concentration of the Nd:YVO_4 crystal.

Diode Laser (808 nm – from nLight™)

The starting point of the lab is the IR diode laser assembly. The laser diode is from nLight™ is a single emitter c-mount style laser (figure 6a, b). It is capable of putting out up to 5 watts, however for this lab, it will be limited to around 200 mW. The diode is placed within a housing with a collimating lens, thermoelectric cooler/heater, thermistor (for measuring temperature) and fan/heatsink combination. Due to the high power levels, many safety features have been installed in order to make this lab safe. The first interlock is that the laser will not turn on if it is removed from the base, in addition the laser is mounted such that it will only emit parallel to the rail (see figure 5a). The power is limited by the commercial driver (wavelength electronics, PLD-5000) inside the controller. Do not place objects (paper, clothing, etc.) within the beam path at maximum power, they will ignite and create a fire hazard as well as coat the expensive optics with soot. If there are any problems, ask the TA or the instructor.



nLIGHT Single Emitter Diode Lasers: C-mount

Typical Device Performance

Package		C-Mount		
Optical				
Wavelength	nm	790-830		
Wavelength tolerance	nm	± 3		
CW output power	W	2.5	3	5
Emitter Size	µm	150	100	200
Fast Axis Divergence	degrees	36		
Slow Axis Divergence	degrees	10		
Electrical				
Power conversion efficiency (typical)	%	54	55	54
Operating current (typical)	A	2.5	2.8	4.8
Operating voltage (typical)	V	1.85	1.85	1.9
Mechanical				
Storage temperature range[2]	°C	-20 to +80		
Lead Soldering Temperature	°C	250°C (<5 sec)		
Thermal				
Operating temperature[2]	°C	-20 to +30		

[1] Numerical aperture (NA) is the sine of the half-angle encircling 90% of the optical energy from the fiber.
[2] A non-condensing environment is required for storage and operation.

Figure 6, (a.) Dimensions of the c-mount diode laser, **(b.)** specifications of laser diode.

Like any diode, the laser conducts very little current until a particular voltage threshold is applied. Once this threshold is reached, the power on the diode goes up very quickly. The laser has been current limited, thus power limited by the driver. Try to keep the laser power under 500 mW unless otherwise told by the instructor. In particular, never let high laser powers into the fiber optic cable, it will damage the CCD in the ocean optics computer spectrophotometer card. You will know if you have too much power by the saturation of the spectra and railing at the maximum count rate of 4096 points. You should have nice peaks which are sharp and easy to tell the center maximum wavelength, so adjust the laser current/white screen accordingly to maintain this proper power level into the fiber.

The laser diode controller (B.) (figure 7b) consists of many subcomponents in one box. To turn on the power, turn on the **MAIN** switch to position **1**. Then if the beam pathway looks safe, set the switch to **ANALOG**, turn the **LASER LEVEL** knob all the way down (full CCW), turn on **LASER ON** and **LASER ENABLE**. **LASER ENABLE** is used as a resettable switch in case you over-current the laser diode (based on the LIMIT I ADJUST position set by your instructor).To adjust the power level of the laser diode, turn the **LASER LEVEL** knob CW until the desired current is found.

The laser diode controller has a second mode which is **PULSE**. This mode is used to turn the laser on and off very fast. Once you switch to **PULSE**, the analog switch will not control the laser diode output. The input can only be 0 - 5 volts input range. Be aware that this pulse unit starts out with a bipolar output and needs an offset voltage such that the output is unipolar. The power level being used for this lab will not exceed 0- 2.5 volts. More will be discussed later on the Fluorescence Lifetime Measurement section.

EXPERIMENT: Determination of the I/P Curve for the diode laser.

With the optical power meter in the beam path, measure the power of the laser diode as a function of the current. Please be aware that the Thorlabs PM206 power meter with the **SC310C** is rated from 10 mW to 10 W of optical power. The **S130C** power meter head is rated from 500 pW - 5 mW without the Neutral density (ND) filter in place and up to 500 mW with a filter in place. The voltage supplied to the diode laser can be measured on the front panel and is not adjusted by the student, it will change according to the PLD-5000 unit and can be somewhat misleading, essentially 5 volts is supplied to the laser diode, one can only adjust the current by the **LASER LEVEL** knob. Starting at zero amps, ramp the current up to the laser's maximum allowed value and measure the power levels. You can set the intended range of photon energy for the power meter in nanometers (it is usually good for many nms around that range selected).

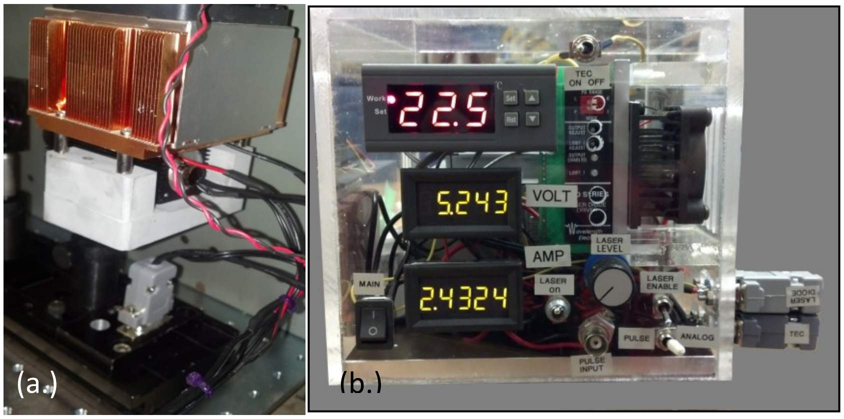


Figure 7, (a.) Laser assembly diode with homemade mounting bracket and thermoelectric unit, **(b.)** laser diode controller with thermoelectric controller.

Experiment: Setup Laser Cavity

Once the laser diode controller is set properly, the first lens (**E.**) is placed on the rail only a couple of inches away from the diode laser to create a very small focus at a focal length a short distance away. Use the white mobile screen (**K.**) to check for alignment of the focus. Measure the focal length of the lenses and place them roughly at twice that distance from each other as seen in figure 8b. Make sure they are aligned to place the resulting collimated laser diode emission into the central part of the fiber couple white screen (**I.**) (figure 8a).

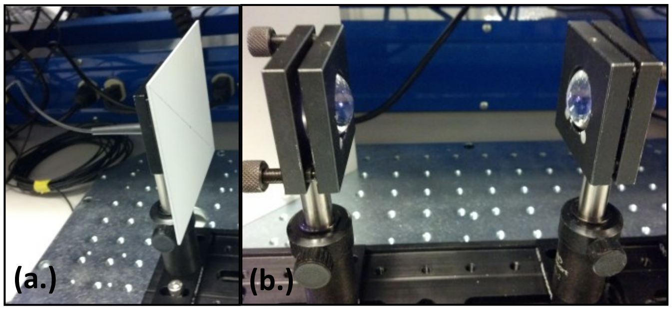


Figure 8, (a.) Optical white screen (**I.**) with fiber coupling on back, (b.) optical lenses (**E.**) placed at twice the focal length from each other, place the laser cavity (**F.**) at the center where the focal point lies.

The focal spot between the lenses contain many photons per cross-sectional area per time which is also known as fluence of the laser beam. **Question:** How many photons of this wavelength are going through this focus spot per second? Answer this in your lab notebook. Hint: What is the energy of the photon?

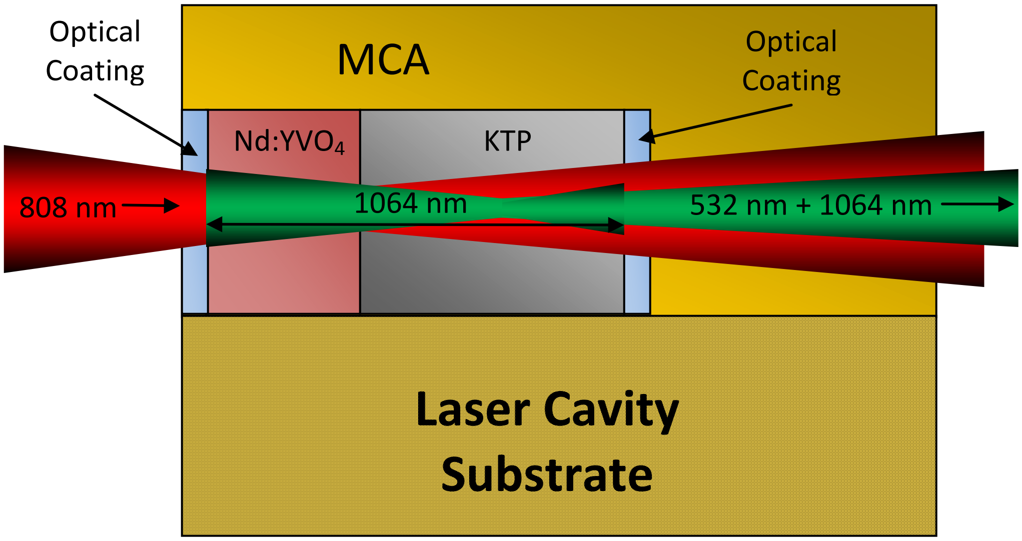


Figure 9, Laser assembly (**F.**) Nd:YVO$_4$ gain medium and KTP doubling crystal.

The next step is to place the Laser cavity unit (**F.**) into the focus. The holder has the ability to make minor lateral/vertical adjustments with the side levers. Figure 9 shows the cavity (**F.**), which is defined as an optical coating on a Nd:YVO$_4$ (Neodymium-doped Yttrium Orthovanadate) crystal glued to a KTP (Potassium titanyl phosphate (KTiOPO$_4$)) crystal, which has another coating on the other side. This assembly is known as a Glue unit, since it is glued together or simply MCA (Multiple Crystal Assembly) (figure 10a, b). The word cavity is used due to the effect of the coatings on the light

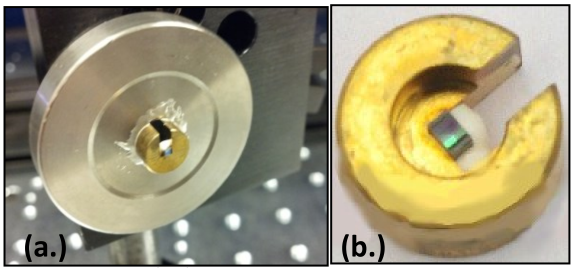


Figure 10, (a.) holder for the laser cavity (**F.**),(b.) and a zoom in image of the cavity mounted MCA unit.

being generated by the Nd:YVO_4, which bounces back and forth between the specialized coatings.

Optical Coatings (QWOT)

The optical coatings are achieved through a technique of thin film deposition, normally using sputtering or electron beam evaporation. The films require a spectroscopic capability of passing some colors really well, and blocking other colors. A simple metal coating would be too broadband in blocking colors so another technique is employed; it involves use of quarter wave optical thick (QWOT) layers of dielectric/metal oxide materials alternating with high and low index of refraction such as TiO_2 (n=2.4) and SiO_2 (n=1.49). With the proper construction a mirror can be made with reflections up to 99.99% and rejections up to 5-6 OD. A metal film can reflect at best 90-98% of visible light, depending on the material and is unable to tailor a reflectance region other than its broadband characteristic across the visible spectrum which is given by its fixed reflectance curve. Some alternating films can be up to 30 layers, to achieve specific spectroscopic curves. Fresnel equations are generally used to design such filters and many excellent books have been written on the subject.

The first coatings on the Nd:YVO_4 crystal of the MCA unit have the spectroscopic characteristics shown in figure 11a, also known as the high reflective (HR) coating. This coating must pass 808 nm laser light into the cavity in order to excite a specific transition of the Nd:YVO_4 crystal, also known as the gain medium. We will find out later that the gain medium will output 1064 nm light and the KTP crystal will double the frequency to 532 nm. The diode laser is given the designation as the pump laser for the Nd:YVO_4 gain medium. The figure shows the ability of the coating to pass <1% of the 808 nm light into the cavity and effectively reflect >99% of 532 nm /1064 nm photons being generated within the cavity.

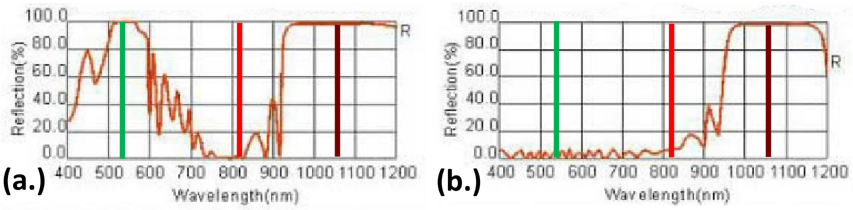


Figure 11, (a.) High reflection (HR) optical coating on the Nd:YVO_4 crystal input face, (b.) the 1064 nm HR coating on the KTP crystal face, with a high pass <1% for 532 nm photons. (Ref. 1)

Once the pump laser is in the cavity the Nd:YVO_4 crystal generates coherent 1064 nm photons which go into the KTP doubling crystal generating a 2ω signal, or 532 nm photons. The coating on the end of the cavity (other side of KTP) has to reflect as much of the 1064 nm light as it can in order to have many passes for the Nd:YVO_4 as well as for the KTP crystal. On the other hand, the 532 nm photons are passed through this coating with a very small <1% reflectance as seen in figure 11b.

Nd:YVO_4 (Neodymium-doped Yttrium Orthovanadate)

The word laser is an acronym meaning, Light Amplification by Stimulated Emission Radiation; although it is often not capitalized since it has become such a common household word. Ironically the first laser (Ruby host medium), conceived in 1957 by Charles Hard Townes and Arthur Leonard Schawlow at Bell Labs, then later constructed by Theodore H. Maiman in 1960 at Hughes Research Laboratories was particularly difficult to make work in terms of the type of energy levels involved. It was considered a three-level laser, which not very effective in terms of pumping efficiency. In order to get the atoms to the proper energy state to create the lasing effect, you have to pump a lot of energy into the gain medium. Later a four-level was created, which was more efficient with regard to pumping. Eventually after a few decades, a very efficient gain medium was found in the use of a YVO_4 crystal with inclusion of Nd^{3+} ions. Nd:YVO_4 is one of the most efficient crystals currently being made for diode laser-pumped solid-state (DPSS) lasers. Hence it is now used for most green laser pointers. As a laser medium, Nd:YVO_4 has excellent properties in the following parameters:

- high laser induced damage threshold,
- large stimulated emission cross-section,
- high absorption coefficient,
- wide absorption bandwidth,
- good mechanical properties.

Other commonly used crystals with diode pumping are Nd:YAG (Yttrium Aluminum Garnet) and the Nd:YLF (Yttrium Lithium Fluoride). The Nd:YVO_4 crystal possess the advantages of relaxation of pump wavelength on lasing efficiency as a function of temperature, the wide absorption band, the higher efficiency, a lower lasing threshold, as well other characteristics. Figure 12a shows a boule of Nd:YVO_4 created through the Czochralski crystal growth method and a corresponding cut section from the boule in the form of a laser cavity element (figure 12b). Figure 13a, b shows the energy levels of the Nd:YVO_4 crystal. Starting with the $\mathbf{Z_1}$ substrate of the $^4\mathbf{I}_{9/2}$ ground level, the 808 nm pump laser excites the atom to the excited $^4\mathbf{F}_{5/2}$ level very quickly. This transition corresponds to an energy level difference of 12,362 cm^{-1}. The atom then quickly relaxes

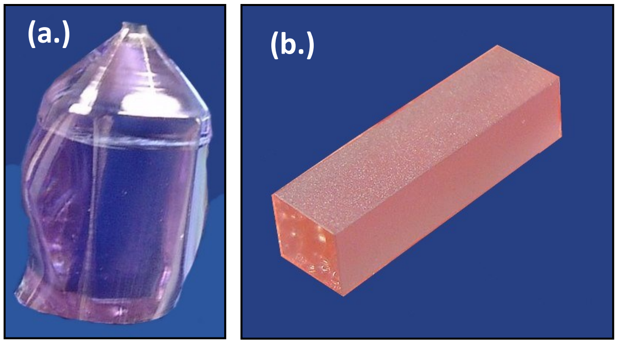
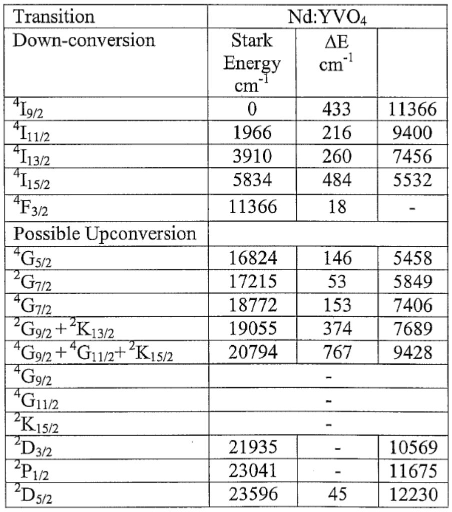


Figure 12, (a.) Nd:YVO$_4$ crystal boule pulled from a Czochralski process, (b.) laser crystal cut at the proper angle from within the boule with the ends polished and antireflection (AR) coated. (Ref. 2)

to the $^4\mathbf{F}_{3/2}$ level (upper lasing level) without radiating visible light. It waits at this level for a short time, then spontaneous decays by emitting a 1064 nm photon and dropping down to the $^4\mathbf{I}_{11/2}$ level. This photon then encounters another atom in the $^4\mathbf{F}_{3/2}$ excited level and stimulates it to drop to the $^4\mathbf{I}_{11/2}$ level by coherently emitting a photon with the incoming one, thus adding to the emitted field. In turn, these photons further encounter another atom in the same excited state and so forth. Ignoring the KTP crystal for a moment, eventually the coherent emission hits the output mirror and bounces back and repeats the process. Depending on the efficiency of this process, the laser can generate a very strong field which has a very high intensity. If the output mirror was coated with a 85% - 95% reflectance then the output of the cavity would be a high power 1064 nm laser beam. Now we shall examine the role of the KTP crystal in the process.

(a.)



Transition	Nd:YVO$_4$		
Down-conversion	Stark Energy cm^{-1}	ΔE cm^{-1}	
$^4I_{9/2}$	0	433	11366
$^4I_{11/2}$	1966	216	9400
$^4I_{13/2}$	3910	260	7456
$^4I_{15/2}$	5834	484	5532
$^4F_{3/2}$	11366	18	-
Possible Upconversion			
$^4G_{5/2}$	16824	146	5458
$^2G_{7/2}$	17215	53	5849
$^4G_{7/2}$	18772	153	7406
$^2G_{9/2}+{}^2K_{13/2}$	19055	374	7689
$^4G_{9/2}+{}^4G_{11/2}+{}^2K_{15/2}$	20794	767	9428
$^4G_{9/2}$		-	
$^4G_{11/2}$		-	
$^2K_{15/2}$		-	
$^2D_{3/2}$	21935	-	10569
$^2P_{1/2}$	23041	-	11675
$^2D_{5/2}$	23596	45	12230

(b.)

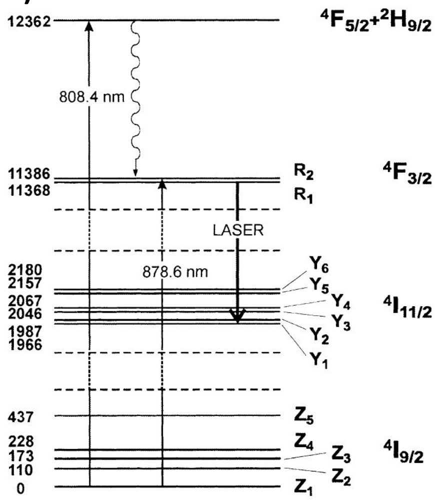


Figure 12, (a.) Table of the Energy levels for Nd:YVO$_4$, (.) Energy level diagram for the pump and lasing transitions. (Ref. 3)

KTP (Second Harmonic Crystal)

Typically the KTP (Potassium titanyl phosphate (KTiOPO$_4$)) crystal is grown by the top seeded growth (TSSG) and flux methods and results in the shapes as shown in figure 14a & 14b. Similar to the boules for Nd:YVO_4, the final product is carefully cut from the grown large crystal with the proper angle to make the emission desired at normal incidences to the front face of the crystal (figure 14c). These crystals were cut to maximize the 1064 nm second harmonic generation process used in making green light at 532 nm. The theory of second harmonic generation (2ω) is beyond the scope of this lab, however you are encouraged to go to the web and library for many excellent books on the topic.

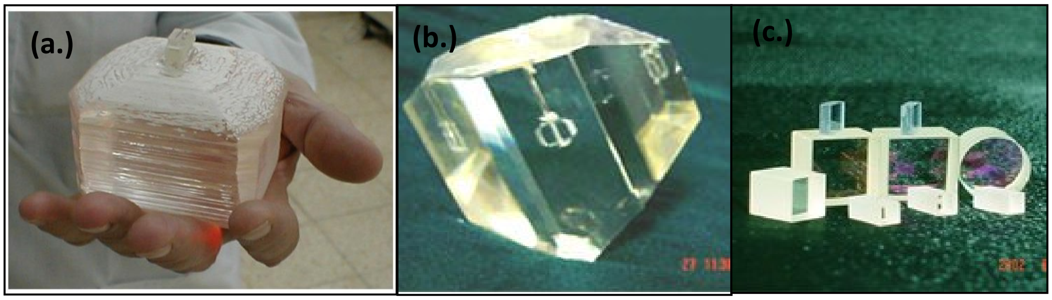


Figure 14. (a.) KTP crystal growth via the TSSG process, (b.) growth through another method, (c.) laser cavity crystals cut from the similar growth products in (a.) and (b.). (Ref. 4)

The coating on the KTP crystal can be seen figure 11b and shows a very low reflectance on the output; the multiple passes of the 1064 nm lead to efficient generation of the 2ω emission without multiple 532 nm photons traversing multiple passes through the cavity. Refer to Appendix A for details on the KTP crystal. Figure 15 shows the overall power output of the 532 nm generation with respect to the initial 808 nm power input.

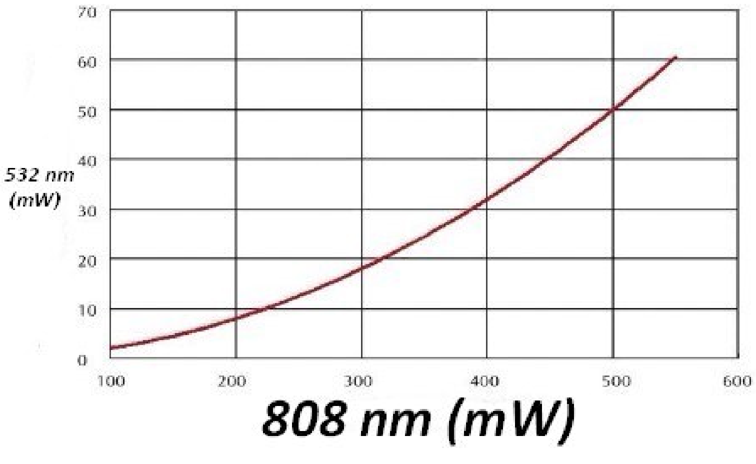


Figure 15, A graph of the second harmonic generation of the 532 nm laser output level as a function of 808 nm diode laser input to the cavity.

Experiment: Measure 532 nm power with input 808 nm power level.

Base the 532 nm power measurement on the power meter and the 808 nm power on your previous data for the current output to the laser diode. Make a graph like figure 15. Block the 808 nm and 1064 nm laser lines from getting to the power detector with the BG39 filter. (see Appendix B for filter information)

Experiment (Optional): Measure Temp/Wavelength Characteristics.

The laser diode wavelength has a limited range of adjustability which can be altered with a changing temperature. Nd:YVO_4 has a known temperature/wavelength relationship as shown in figure 16. The graph shows the trend for a similar material, Nd:YAG, which undergoes a more detailed change across the given temperature range.

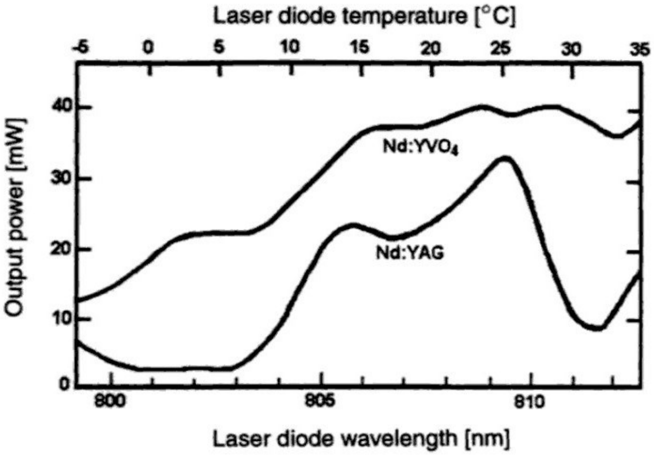


Figure 16, Laser temperature/wavelength curve for Nd:YVO_4 and ND:YAG.(Ref. 5)

Using the manual for the thermoelectric controller as seen in figure 7b.(red LEDs), control the temperature range for the laser as it is directed into the fiber and plot the curve in figure 16. Be aware that the shape of the curve should still be seen even if the spectrometer is slightly off in calibration. The temperature unit has a PID loop control and many other input characteristics, see the data sheet for it near the experiment.

Measurement of excited state lifetime and Dopant level

Using a pulse generator (Rigol™ DG1022G) and a digital storage oscilloscope (Rigol™ DS1102D), measure the fluorescent lifetime of the emission at 1064 nm which corresponds to from the excited $^4\mathbf{F}_{3/2}$ state level to the $^4\mathbf{I}_{11/2}$ ground state level (see figure 13). Once the initial pump of the Nd:YVO_4 crystal by an 808 nm laser from one of the $^4\mathbf{I}_{9/2}$ ground substates to the excited $^4\mathbf{F}_{5/2}$ state occurs (absorption), the energy level is held for a very short amount of time. It comes down to the $^4\mathbf{F}_{3/2}$ state through a radiationless transition. This is where the interesting stuff occurs in terms of lasing (emission) through an induced interaction down to the $^4\mathbf{I}_{11/2}$ ground state level. The energy level of the system is then free to thermally relax back to the $^4\mathbf{I}_{9/2}$ ground state.

This laser is considered a four-level system; Absorption, Radiationless Transfer, Emission and Relaxation as seen in figure 17.

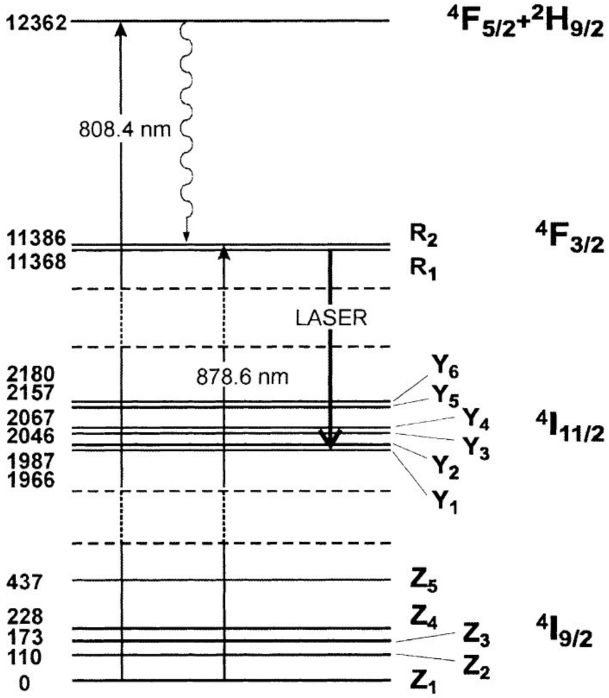


Figure 17, Energy level diagram for Nd:YVO$_4$ (vertical scale in terms of cm^{-1}) being pumped by an 808.4nm diode laser. (Ref. 3)

If the laser medium is placed in an excited state and the pumping abruptly stops, the electrons will spontaneously drop down to the ^{4}**I**$_{11/2}$ ground state level, this will cause the emission to occur in a non-coherent manual and drop off the population of ^{4}**F**$_{3/2}$

Figure 18, Fluorescence lifetime decay for Nd: YAG, similar but longer than Nd:YVO$_4$.(Ref. 6) through an exponential temporal profile similar to what is seen in figure 18. Figure 18 demonstrates an oscilloscope trace for a fluorescence lifetime curve measured for Nd:YAG. not Nd:YVO$_4$, so the values will be different. Also, the voltage levels do not correspond to those of your setup, since the detector is different (use a 50 Ω terminator or low impedance input for scope). You want to measure the 1/*e* level of the decay curve; this is your fluorescence decay lifetime. Once you have the lifetime information, use the graph in figure 19 to determine the dopant level of ND^{3+} in the Nd:YVO$_4$ crystal.

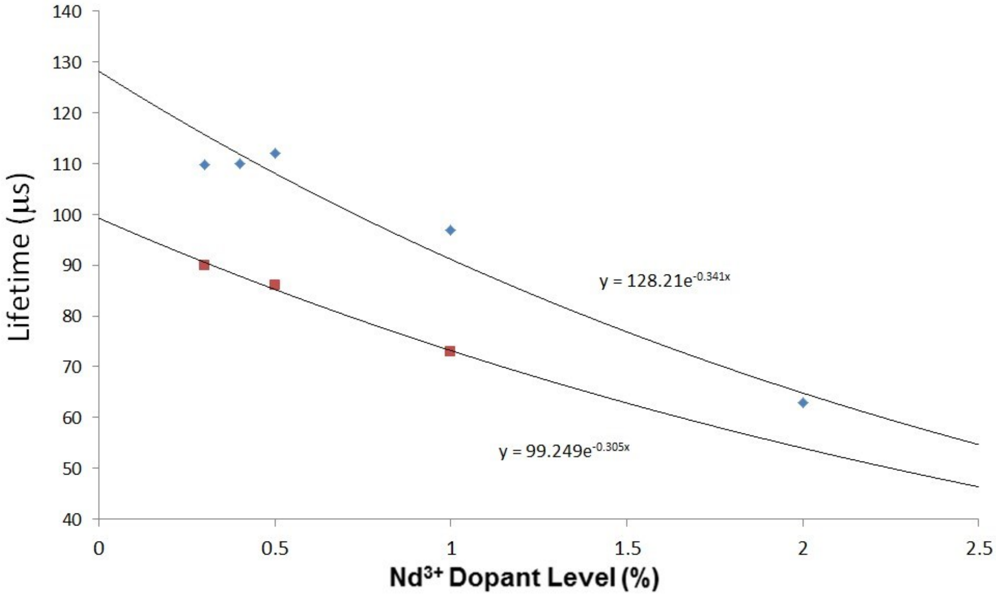


Figure 19, Fluorescence lifetime decays for Nd:YVO$_4$ as a function of dopant concentration of Nd^{3+}. The diamonds (◆) represent use of a low power (>1 Watt) diode laser for excitation, and the squares (▪) represent high power. (based on ref. 7)

Use the RG1000 optical filter (see appendix B) in order to filter out the 532 nm and 808 nm laser lines. The detector cannot see large power levels (model ET-1000-see Appendix C), so be careful about flooding the front lens of the little detector opening with lots of light, the detector will saturate easily; just maintain the voltage level right below saturation as seen on the oscilloscope. The settings on the diode laser controller can be tricky and you must be familiar with how to use the DSO, if you have tried and can't get it to work, let the TA or instructor know.

Acknowledgments

Inspiration for this lab was derived from the Leybold Didactic DPSS lab (document# 4747106en) (Dr. Walter Luhs 2003). Which was originally found in a document on the web by Dr. Ing. Dickmann from Fachhochschule Münster/Fachbereich Physikal. Technik).

References

1. Graph from Ebay™ purchase item # 120921436407.

2. web search and Meredith instruments (Ebay sale).

3. Ian Oliver Musgrave, “Study of the Physics of the Power scaling of End-Pumped Solid–State Laser Sources Based on Nd:YVO_4”Thesis University of South Hampton, Optoelectronics Research Centre- September 2003.)

4. (a.) from M. Roth, M. Tseitlin, “Growth of large size high optical quality KTP-type crystals” *Journal of Crystal Growth* Volume 312, Issue 8, 1 April Pages 1059–1064 (2010). (b.) and (c.) from web search.

5. R.A Fields, M Birnbaum, and C.L. Fincher: Appl. Phys. Lett. 51, 1885 (1987).

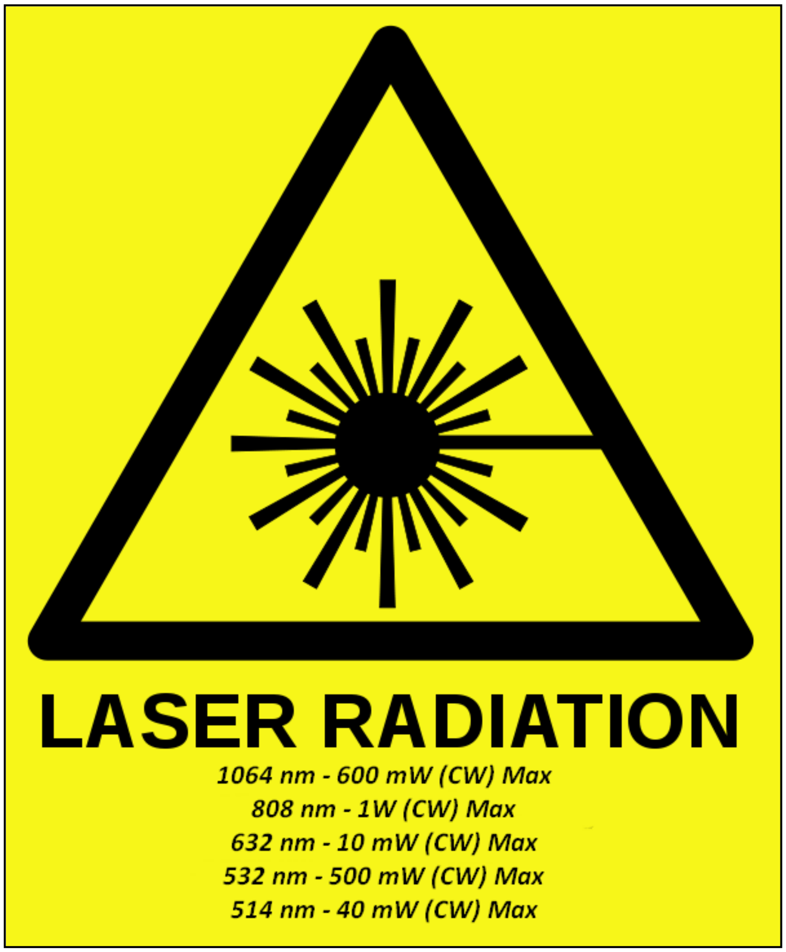
6. Dr.-Ing. Dickmann - Fachhochschule Münster/Fachbereich Physikal. Technik/Leybold Didactic).

7. V. Lupei, N. Pavel, T. Taira, “Highly efficient laser emission in concentrated Nd:YVO_4 components under direct pumping into the emitting level” *Optics Communications* 201 pp.431–435 (2002).

Laser Safety

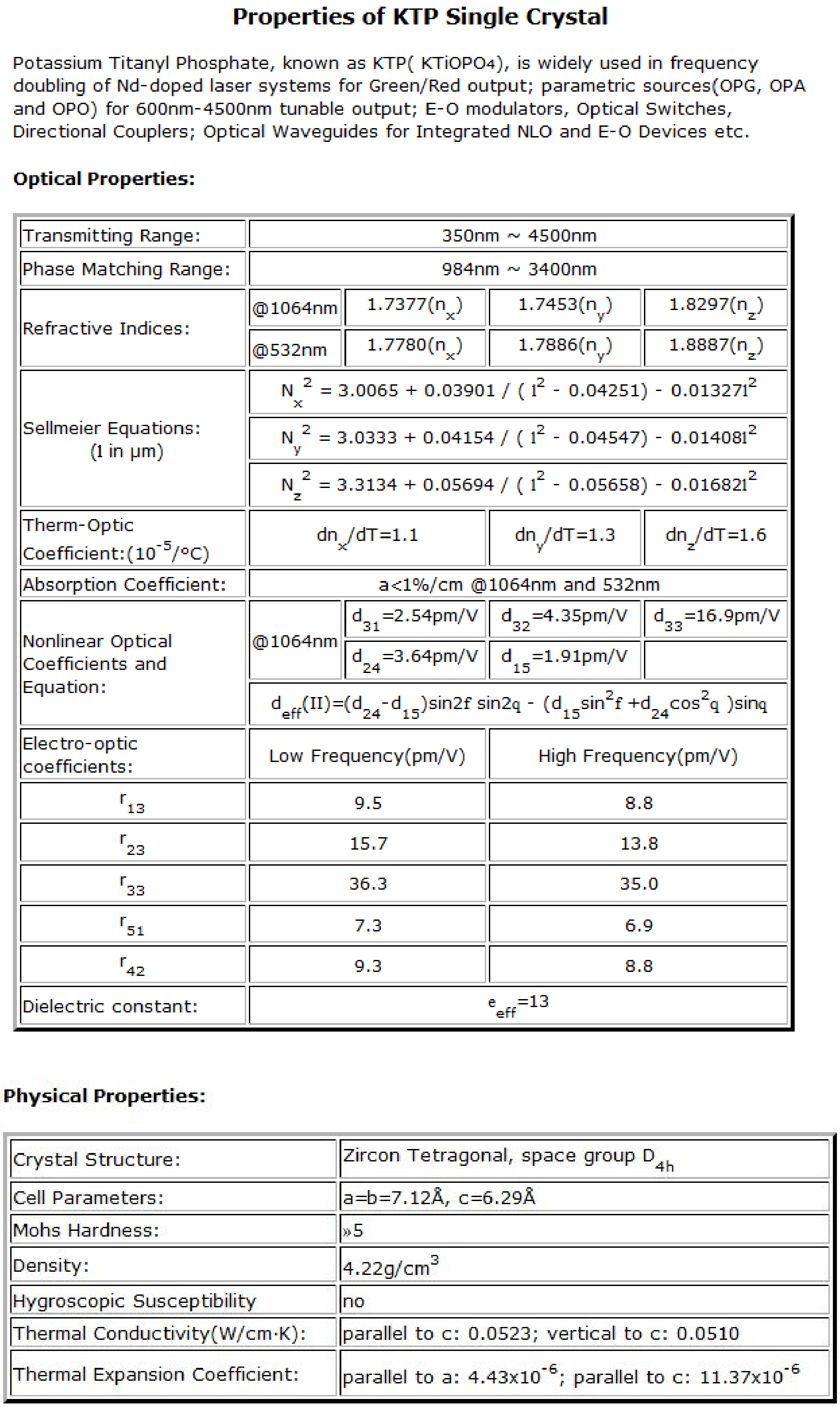
Laser safety practices must be followed via ANSI Z136 in the US and IEC 60825 internationally which can be found in a summarized format on http://en.wikipedia.org/wiki/Laser_safety .

If there are any questions concerning laser use in the lab, please let the instructor or PSU's radiation safety officer know.



This sign reflects the users used in this lab as well as other ones in the room.

Appendix A.



Properties of KTP Single Crystal

Potassium Titanyl Phosphate, known as KTP(KTiOPO4), is widely used in frequency doubling of Nd-doped laser systems for Green/Red output; parametric sources(OPG, OPA and OPO) for 600nm-4500nm tunable output; E-O modulators, Optical Switches, Directional Couplers; Optical Waveguides for Integrated NLO and E-O Devices etc.

Optical Properties:

Transmitting Range:	350nm ~ 4500nm			
Phase Matching Range:	984nm ~ 3400nm			
Refractive Indices:	@1064nm	1.7377(n_x)	1.7453(n_y)	1.8297(n_z)
	@532nm	1.7780(n_x)	1.7886(n_y)	1.8887(n_z)
Sellmeier Equations: (l in μm)	$N_x^2 = 3.0065 + 0.03901 / (l^2 - 0.04251) - 0.01327 l^2$			
	$N_y^2 = 3.0333 + 0.04154 / (l^2 - 0.04547) - 0.01408 l^2$			
	$N_z^2 = 3.3134 + 0.05694 / (l^2 - 0.05658) - 0.01682 l^2$			
Therm-Optic Coefficient:(10^{-5}/°C)	$dn_x/dT=1.1$		$dn_y/dT=1.3$	$dn_z/dT=1.6$
Absorption Coefficient:	a<1%/cm @1064nm and 532nm			
Nonlinear Optical Coefficients and Equation:	@1064nm	d_{31}=2.54pm/V	d_{32}=4.35pm/V	d_{33}=16.9pm/V
		d_{24}=3.64pm/V	d_{15}=1.91pm/V	
	$d_{eff}(II)=(d_{24}-d_{15})\sin 2f \sin 2q - (d_{15}\sin^2 f + d_{24}\cos^2 q)\sin q$			
Electro-optic coefficients:	Low Frequency(pm/V)		High Frequency(pm/V)	
r_{13}	9.5		8.8	
r_{23}	15.7		13.8	
r_{33}	36.3		35.0	
r_{51}	7.3		6.9	
r_{42}	9.3		8.8	
Dielectric constant:	$e_{eff}=13$			

Physical Properties:

Crystal Structure:	Zircon Tetragonal, space group D_{4h}
Cell Parameters:	a=b=7.12Å, c=6.29Å
Mohs Hardness:	»5
Density:	4.22g/cm^3
Hygroscopic Susceptibility	no
Thermal Conductivity(W/cm·K):	parallel to c: 0.0523; vertical to c: 0.0510
Thermal Expansion Coefficient:	parallel to a: 4.43x10^{-6}; parallel to c: 11.37x10^{-6}

Appendix B.

Optical Filters (BG39 and RG1000)

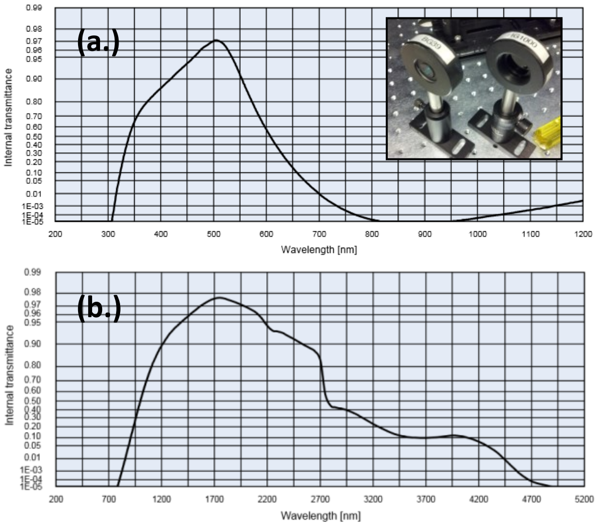
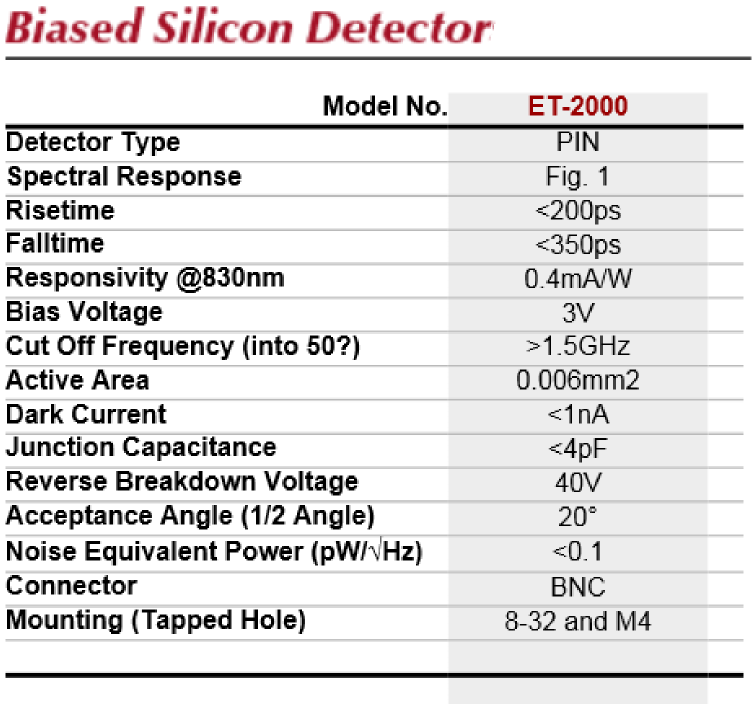


Figure 20, (a.) Optical transmittance curve for a BG39 optical filter, which is a commonly used filter for cutting off IR in digital cameras and camcorders, (b.)an RG1000 optical filter, used to pass IR. The inlay shows the actual filters that will be used for the experiment.

http://www.us.schott.com/advanced_optics/english/products/filter overviewdetail-longpass.html

Appendix C.



Biased Silicon Detector

Model No.	ET-2000
Detector Type	PIN
Spectral Response	Fig. 1
Risetime	<200ps
Falltime	<350ps
Responsivity @830nm	0.4mA/W
Bias Voltage	3V
Cut Off Frequency (into 50?)	>1.5GHz
Active Area	0.006mm2
Dark Current	<1nA
Junction Capacitance	<4pF
Reverse Breakdown Voltage	40V
Acceptance Angle (1/2 Angle)	20°
Noise Equivalent Power (pW/√Hz)	<0.1
Connector	BNC
Mounting (Tapped Hole)	8-32 and M4

Instructor Information

This section is for the fabrication of the setup and things to consider. Basically the setup can be made for under $1,000 (2013 dollars) if you use things laying around and do some machining. It is assumed you have the basic support equipment such as a scope, pulse generator, power meter, etc…

One major concern is the high laser power, hence the optic/laser mounting system should not be able to be rotated in order to protect the students from inadvertent reflections, and your local laser safety officer should be consulted for the basic setup you construct. A smaller power laser can be used than what is specified here in this manual, but try not to go below 100 mW, as misalignment can cause very low 532 nm output. In addition a laser interlock was implemented such that if the student becomes curious as to the destructive power of the pump laser, once the 808 nm laser unit is removed from the rail, the interlock shuts the power off. This mechanism can be seen in figure 19. It consists of a piece of anodized aluminum with a DB-9 connector mounted and electrically connected to a limit switch in such a way that as long as the limit switch is pushed, the circuit applies current to the laser.

Figure 21, Image of interlock unit for safety. The red circle indicates the limit switch which is connected to the DB-9 connector. If the laser unit is not pressed up against this unit, the laser shuts off.

Because of the students desire to see the laser burn things, you might want to do a controlled burning of paper (in a safe manner) to get it out of their system, but explain that the smoke from the burning paper will coat the optics and cause damage. My experience is that students take this seriously. Emphasize to them the importance of laser safety. The end screen (painted aluminum sheet with crosshairs drawn and a hole in the middle) should not be removed from the system as another precaution. It doesn't need to be removed, as I have placed a hole in it and the fiber coupler can be unscrewed from the fiber mount behind it. Thus the photo-detector can be aligned behind the hole for the lifetime measurement. Also make sure high power is never put into the fiber unit, it can damage the computer CCD spectrometers.

Another issue to be aware about in the fabrication process is the electronics, although the wiring is pretty straight forward, the LED meters I purchased needed separate power sources from the measuring supplies, thus a couple supplies are needed, I have also encountered a problem with the TEC taking more current than I would like and thus altering the output for the laser current reading, a third small supply might suffice in the project box for the control system. I would leave the TEC off until it is needed for the optional experiment. I have found that although it is fine to measure the laser voltage, the meter for this purpose is not essential and can be omitted.

Another thing to be aware of is having decent XY control of the lens and MCA units. One can normally achieve doubling to 532 nm within seconds after turning on the 808 nm pump laser if the rails are aligned, but I have seen students spend over an hour trying to figure out alignment with a prototype version I had that didn't have XY motion control of the items, this might be apparent in the some of the images. Be aware of lifetime measurement being affected by a photodiode which is may be slow or if the reverse bias is reduced due to low batteries.

Materials (in 2013 dollars)

Components

1 ea. 100 mw 1 Watt - 808 nm diode laser, C-mount, Ebay	\$15-\$35.00
1 ea. 5 digit LED voltage meter, Ebay	\$10.00
1 ea. 5 digit LED Current meter, Ebay	\$10.00
1 ea. C-mount –housing (Mdl# 3380-BL) w/lens Ebay	\$20.00
1 ea. 5A laser diode driver – PLD-5000 Ebay	\$80.00
1 ea. 532 nm Green Laser Module - GLM Nd:YVO$_4$+KTP, Ebay	\$20.00
1 ea. EOTECH – 350 ps Photodiode Mdl# ET-2000	\$300.00
1 ea. Thorlabs RG1000 color filter Mdl# FGL1000	\$35.00
1 ea. Thorlabs BG39 color filter Mdl# FGB39	\$25.00
2 ea. Thorlabs filter holder Mdl# LMR1	\$16.00
1 ea. Thorlabs Alum. Breadboard Mdl# MB824	\$240.00
4 ea. Thorlabs Translating Lens mount Mdl# LM1XY	\$135.00
2 ea. Thorlabs – 1" diam. 50 mm fl Lens uncoated –LBF254-050	\$40.00
1 ea. Newport – URL-18 (18") rail (or equiv. rail system w/ holders)	\$75.00
6 ea. Thorlabs – 2" post holder Mdl# PH2 (or equivalent)	\$8.00
1 ea. Thorlabs – 2"x 3" Mounting Base Mdl# BA2 (or equivalent)	\$8.00
6 ea. Thorlabs – 1"x 3" Mounting Base Mdl# BA1 (or equivalent)	\$6.00
7 ea. Thorlabs – 3" posts (1/5" diam.) Mdl# TR3	\$6.00
TEC Controller – BWH7016R (or equivalent), Ebay	\$35.00
TEC – Mdl# CP1-12710 -168 W, Ebay (4 cm X 4 cm x 3mm)	\$25.00

1 ea. Fan/Heatsink (Intel Xenon style Cu Heatsink – Med. Sized) Ebay	$35.00
20 - 30 ea. ¼-20 screws	$10.00
3/16 Hex. Ball driver tool.	$5.00
Total:	**~$1,820.00**

Test Equipment

Rigol 1022A – Arb. Waveform Gen. 25 MHz (or lesser equivalent)	$499.00
Rigol DS1000E – Two Ch. DSO - 50 - 100 MHz - (or equivalent)	$329.00
USB Spectrometer ASEQ (or Ocean Optics) - 200 - 1200 nm	$750.00
Laser power meter (.001 to 1 watt range)	$ misc.
3 ea. Misc BNC cables	$10.00
50 ohm termination	$5.00

Fabricated Items

2 ea. White Plate w/ Hole for Fiber and photodetector opening
Laser interlock unit (misc. metal/connectors)
Power supply box, with misc. volt/current meter/ATX supply/misc small supply for laser power unit (separate from current meter).
GLM Crystal holder for lens/mirror mount.
Note: Modify the Laser holder for Thermister and TEC/Heatsink/Fan