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Self-Contained Dye Laser Cavity for UV Testing

Project Idea

Our senior design project idea is to create a dye laser with a self-contained laser cavity that can be swapped out. Laser cavities are generally made with a gain medium placed between two carefully positioned surfaces reflective to the lasing wavelength. This is very simple with a solid-state laser. But, with a dye laser, one must contain the dye separately. On top of that, for high-power dye lasers, the medium must be constantly swapped out as the chemical can get bleached (unlike most solid-state lasers). With this idea, the current high powers of dye lasers would not be as easily achieved, but a single laser device would have the capacity to be used for multiple different lasing wavelengths.

"Self-contained laser cavity" can be described in more detail as two meniscus lenses or curved dichroic mirrors placed together and attaching them with a liquid-proof glass sealant so that the liquid gain medium may be placed between the lenses. This would allow for the laser cavity to be easily placed into a laser setup and swapped out with other such self-contained cavities. Due to the fact that laser cavities can be very finicky, it may also be necessary to use an adhesive that is rubbery and to create a more mechanically sophisticated slot for it in the laser setup so that the relative position of the surfaces may be adjusted ever so slightly in the device.

A user will be able to receive information and control the device via a display, push buttons, and kinematic mounts. An embedded computer will control all information functions and the push buttons. Liquid Crystal Displays (LCDs) will provide users with information such as the frequency/power of the emitted electromagnetic radiation, power being supplied, and battery life available. The embedded computer will require other components to measure the data to know what to display. The information about the electromagnetic radiation will be monitored using a spectrometer. The spectrometer will receive electromagnetic radiation after it has gone through a beam splitter. A battery monitoring system will have to be developed to determine the battery life and total power. The push buttons will power the device on and off, or just the display. The kinematic mounts will be mechanical. It will be used to control the position of the laser cavity which can affect lasing and the direction of the output radiation.

Goals

A primary goal in the design of this project is to decide on a pump-source and a primary dye to use in this project. Multiple dyes can be efficiently pumped by a single source. A pump source must be chosen based on the amount of power it needs to function and if that power should be delivered using Direct Current (DC). The dye selected will need to be well-pumped by the chosen source and will be affected by dye prices. It will also have an effect on the design of other laser cavity components such as the lens separation and curvature since the dye's refractive index affects optical path length (OPL) within the cavity.

Some goals in the optical compartment involve designing a functioning laser cavity, splitting off beam segments for real-time analysis, and focusing the output beam. Proper laser cavity design will involve running both transfer matrix equations and complex beam parameters and finding lens sets that show stability under the ABCD law. Splitting off a small beam segment should be done with beam samplers with high transmittance to reflectance (T/R) ratios and careful placement of said samplers so that no stray beams escape the device from unexpected locations or angles. Finally would be to focus the output beam. The potential beam vectors and dispersions should be determined first, after which lens powers and separations may be selected. Much of these predictions and calculations may be done with Zemax, which I (Ryan) have yet to gain access to to see exactly what it is capable of. These goals and objectives can be seen tabulated in table 1.

Table 1 - Optics Compartment Goals & Objectives

Goals	Objectives
Get lenses to allow for lasing, focusing, and directing	Lens waveguide calculations
	Complex beam parameter and ABCD law testing
	Analysis of beam exit locations and angles once lenses are chosen
	Figure adapter necessities for cavity-mount connection once pieces have been selected
Split small beam segments off for real-time analysis	Selection of small-size, high transmission/reflection ratio beam samplers
	Mounting beam samplers to redirect segments of laser beam to a spectrometer and power meter
	Experimentally determining proper layout of optical mounts in custom housing before creating an optical housing
Beam collimation at output of device	Determine potential beam vectors and dispersions by the end of the device
	Few-lens (preferably 2 at max) setup to focus the output beam to a desirable spot-size

An additional segment that may come into the design for the optical compartment is the spectrometer and power meter that actually read the beam samples. These components have shown to be quite expensive even on the lower end. As a result, we are considering designing rudimentary versions of these ourselves and buying the components to make them for the sake of budgeting. The general design steps in the creation of such components are outlined in table 2 below, and a visual of a general spectrometer setup is shown in figure 1 below. There are, however, many ways to build a spectrometer, and so the provided design steps may vary based on ease of construction and cost.

Table 2 - General Spectrometer and Power Meter Design

Spectrometer Design	Direct light to collimating mirror/lens
	Collimate light towards a diffraction grating
	Pass light through a diffraction grating to separate frequencies by exit angle
	Read relative intensities of different frequencies after significant spreading has occurred
Power Meter Design	Pass light through a lens for spot size control
	Place a photodiode (or other photo-sensitive electronic component) in the beam's path
	Control the spot size so the spot is no larger than the photodiode's active region, and not so small to damage or oversaturate it

Figure 1 - Example Spectrometer Design

https://www.laserlabsource.com/Spectrometers/spectrometer-basics

Larger scale project goals for the final project involve being lightweight, hand-held, and low power. We want to make this device so that it can be used easily in the hands of the operator, unlike some medical laser devices that are mounted to the ground due to their size. Additionally, because we want this device to be handheld, it should be light-weight so that extended use does not become cumbersome. Another way that we wish to make this device easier to use is to make it battery-operated, with low enough power consumption so that plugging it into a wall outlet is not necessary.

Many LCDs use a communication protocol to control the display. The signal from the computer will be sent to a module which can be found connected to the back of the display or on a separate part of the PCB. Communication protocols have varying transfer speeds within a type of communication protocol but our display will not require very fast transfer speeds. We will also have to learn the communication protocol. There are also considerations that must be taken for specific devices. We will determine the brightness needed to see the display in laser testing environments and select accordingly. The brightness should be adjustable but does not need to have a large range of possible brightness levels.

The microcontroller will be coded using C. This will require us to learn the intrinsic functions of the microcontroller, the drivers for the peripherals, and communication protocols. We will need to use a manufacturer provided integrated development environment (IDE). We will also need a timer to schedule periodic updates to the LCD by using the digital signals it received. When it is not updating the LCD, it should be in a low power mode. Another important feature is the number of input ports and we need at least 8 for our different sensors. The user may want precise information about the radiation. An external analog-to-digital can be used to provide a digital signal with many bits and low noise. This will also require the microcontroller to be able to store and perform operations using a large binary number.

For the physical inputs, we must figure which type of features we want it to control and how many of each. We currently want to use physical inputs to control the brightness, control the position of the laser cavity, switch the power modes, and change the blocker position. We will need dials for analog inputs and buttons for digital inputs. The type of input depends on the type of feature we want to control. We will also determine the precision required for specific features. For example, positioning the laser cavity will require more precision than the brightness of the display even though both of their inputs will be analog. The purely mechanical physical inputs include the blocker for the laser and the kinematic mounts. A material that blocks the radiation will need to be procured. We will have to find out how to sculpt it, mount it, and adjust it. It can be moved on hinges but it will require a locking mechanism. A small permanent magnet can be placed on the housing and the blocker could have a ferromagnetic tip. The permanent magnet will apply a force on the tip (enough to keep it closed when near).

Our team has decided that the best battery chemistry for the laser is Nickel Metal Hydride (NiMH). NiMH batteries have an extensive operational temperature range. We have set a goal to keep the temperature of the battery/housing below 42 °C and that is within range. Determining the sufficient number of batteries will require us to find the current/power requirements for each device. The number of batteries affects the total cost and recharge time of the power supply. We want to provide the user with at least 500 charge cycles before needing to replace the batteries. Designing the power supply circuit will require us to procure a step-down controller, resistor, capacitors, and inductor. The other components should operate using the same voltage to avoid having to create multiple power circuits which will reduce the area of the printed circuit board (PCB) and the cost. We would like the battery to use the least amount of space on the PCB. We may have to stack batteries on top of each other. We need to find a battery holder that allows for this type of positioning or design it ourselves. The battery holder should also allow the user to easily swap out the battery.

Requirements and Specifications

Most of our laser design sprouts off the stem of ease of use. Using a self-containing dye laser cavity works to ease laser cavity usage. Implementing an in-design spectrometer and power meter provides the user with information on the laser without having to measure it externally. On top of these design aspects of the laser, we wanted to keep going in the direction of prioritizing ease of use. This has included striving to make our design lightweight (definitely less than 7.5 kg) and centered in the user's hand(s).

Many laser safety requirements are given out by the American National Standards Institute (ANSI), the International Organization for Standardization (ISO), and the International Electrotechnical Commission (IEC). However, viewing these standards require payment. UCF's Environmental Health and Safety (EHS) department might be able to provide us with access to these standards so that actual values can be given for things such as safe laser powers for given frequency emissions, safe beam divergences for a laser, acceptable housing material dispersion/reflectance/absorption, etc. Thankfully, some safety requirements for lasers are met by the manufacturers of the optics that we will purchase. A large degree of safety with lasers is making sure that the used optics affect the light in predictable ways reliably. There is still the factor of designing a safe layout of such optics, but at least the makeup of the pieces is already met by the manufacturers.

On top of general laser safety and UV laser safety, our design will need to pay attention to legal specifications on safety of carcinogen use in products. Most lasing dyes are carcinogenic, and should thus be sure to follow set standards for safe use of carcinogens in commercially available products. Many everyday products contain toxic chemicals already, so we doubt meeting these standards should be all too difficult.

For the power requirements we want to make sure to abide by them. Not following the requirements might result in personal injury or shock might. Also fire or damage to the device might occur.

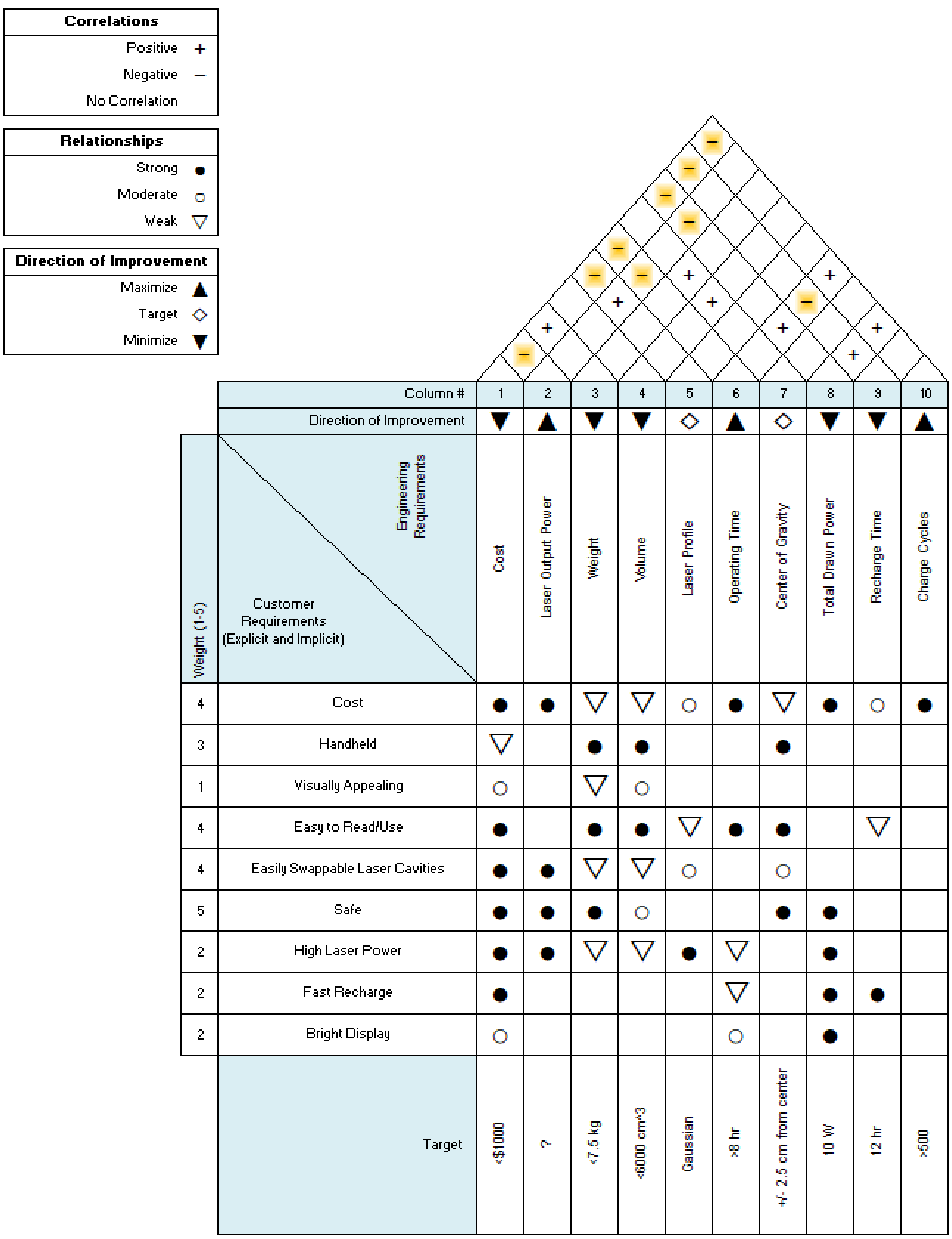
A more detailed listing of requirements and specifications (both those set by us for our project, and those set by industry standards and regulatory organizations) that pertain to our project can be seen in table 3. This also includes a listing of some of the specific specs that one could search for online to find more detailed information.

Table 3 - Design Specs

Requirements and Specs	Details
Laser Power Specification	Multiple organizations have specifications for the classification of lasers into 4 broad types based mostly on power output. This class must be displayed on the outside of the laser. IEC 60825-1:2014 ANSI Z136.1
Laser Safety	The output should be well guided. Have not seen who officially gives details on such a condition. There should be no alternative path for the beam to exit the device or materials for the beam to disperse off of (such as metal). IEC 60825-1:2014
Battery Power Output Limit	The laser will require a varying amount of power. We must ensure that it does not draw more current from the battery than it can safely provide.
Microcontroller Power Requirements	This reference is for the MSP430 family of microcontroller devices. The MSP430 device requires only a single 3.3V input. The operating input voltage for this reference design is 3.6V to 15V.
Display Power Requirements	The typical operating voltage of a 20x4 LCD module is 5V
Dye Safety	Multiple organizations (including the EPA) have standards for the safe handling and storage of hazardous organic dyes. U.S. EPA, 1986a
Thermal limits	Many components have a thermal range in which they can normally operate. If the components get too hot they can be permanently damaged. The housing of all of the components could melt if we are not careful about the placing of the components and selecting parts that do produce too much heat.
Laser Guidance	ISO has many specs on the materials that should be used to guide laser light. The actual material composition and production is met by the optics suppliers being used. Each component should have a limit to the power concentration that can be applied to it as well. ISO 12123:2018 ISO 1:2016
Weight	It should weigh less than 7.5 kg.
Optical Output Power	Typically 5 to 500 mW is considered class 3R for visible lasers, and above that is class 4. For application, differing levels of UV could be desired, but higher limits allow for stronger and stronger use.
Operating Time	A user should be able to use the laser for more than 8 hours before needing to recharge.
Center of Gravity	The center of gravity should be in the palm of the user's hand if we make the device single-handed, and between the users' hands if we make the device two-handed (within 2.5 cm of the center along its length) .
Total Power	The device should not draw more than 10 W.
Cost	The total cost of the components should be less than $1000.
Temperature	No components touching the housing or near the battery should be greater than 45°C.
Volume	The total volume of the device should be less than 6000 cm^3.
Recharge time	The battery should not take longer than 12 hours to recharge.
Charge Cycles	The number of charge cycles it can go through should be more than 500.
Housing Thermal/Electrical Conductivity	If a component overheats or a potential difference is placed between two points on the housing the thermal/electrical conductivity needs to be low. The thermal conductivity needs to be less than 0.05 W/(m•K). The electrical conductivity needs to be less than 0.1 S/m.

Our project is our own idea, not funded or sponsored by a company, professor, or anyone. As such, we do not have an actual client that is giving us requirements to meet for our design. We have, however, set some goals four ourselves that are comparable to things a non-engineering client might ask for. Such goals include lower costs, making the device handheld and visually appealing, easy to use, and safe, and having a bright display, fast recharge rate, high output laser power, and easily swappable laser cavities. An interaction of these self-set "customer requirements" with the engineering requirements we established in the *Requirements and Specifications* section can be visualized in figure 2 below.

Figure 2 - House of Quality



System Breakdown, Inputs, and Outputs

The optical system will consist of an optical pumping source, laser cavity, beam sampling setup, spectrometer, power meter, frequency doubling setup, and collimating setup. The optical pumping source is likely to be a Nd:YAG laser due to such pumping systems being high intensity and relatively cheap. This means we can get more pumping power efficiency for the laser cavity while still maintaining a relatively low cost and being able to lase multiple different dyes. It has an input of electrical power from the power supply system and an output of a pumping laser directed at the laser cavity.

The laser cavity itself is proposed to be designed as a pair of curved dichroic mirrors or meniscus lenses with coatings reflective to the visible spectrum (wavelength specific to the dye used) and transparent to the 1064 nm light emitted from our pump source. These two surfaces will be connected preferably by a water-tight glass sealant that is resistant to the solution used for any specific dye. On the perimeter of this seal there should also be a sealable access port through which the dye can be inserted and removed, which will also allow the inside of the cavity to be cleaned if need be. The laser cavity will receive the optical pumping input from the pump source, will be aimed by a kinematic mount, and will have an output of a visible spectrum laser beam to the beam sampling setup.

The beam sampling setup will be primarily composed of a beam sampler and a beam splitter. The former is designed to reflect <1% of a visible spectrum beam for sampling so as not to remove the majority of the beam, and the latter will be a more equal T/R ratio beam splitter to send significant data to both the spectrometer and power meter from the sampling beam. The input to the beam sampler setup will be the laser emitted by the laser cavity, and it will output both the main laser beam to the frequency doubling setup and the sample beam to the spectrometer and power meter. At both the input and sampled outputs, it is possible that a focusing or defocusing lens may be necessary. This will be determined by measuring the actual power we are able to obtain out of our laser cavity and comparing that to the spatial power density safety levels for the sampling components purchased.

As mentioned in *Goals*, we may end up designing the spectrometer and power meter from scratch due to commercial costs of these parts relative to their components. The spectrometer's job is to separate and sense the frequencies of the radiation to convert it to an electrical signal for the computer to read. Similarly, the power meter's job is to measure the power and send an electrical signal to the computer. The inputs of both of these are the sample beam and electrical power from the power supply, and their outputs are data regarding the sample beam that will be sent to the computer.

The computer (microcontroller) will send signals to several components. We are using the MSP430 microcontroller for our device. The microcontroller will turn on and off the sensors for the spectrometer and power meter. It will intake the analog data from both the spectrometer and power meter, and send the digital data to an LCD display. The microcontroller will have a push button to turn on and off the power which will turn on the LCD display. Another button will turn on and off the pump source in order to begin using the laser.

The LCD display component will intake the data from the microcontroller to show the frequency, battery life, laser beam output power, and/or any other information we deem to be necessary in the future for our applications. We consider a 20x4 LCD display sufficient to show all information necessary.

The power supply will use a rechargeable NiMH battery that will deliver power to the pump source, spectrometer, power meter, microcontroller and the display. The power supply components are: the battery holder case, the NiMH rechargeable batteries, a battery monitor circuit, and the buck controller. The battery holder case will be designed to accommodate the right amount of NiMH batteries to supply power to all the components which require an input. The NiMH batteries will be acquired and as mentioned will be determined by our power need which still has to be calculated and researched. The battery monitor circuit will be utilized to check the battery discharge percentage. The buck controller will be employed to optimize the power supply to meet our requirements like step-down voltage or to reach a level of output power.

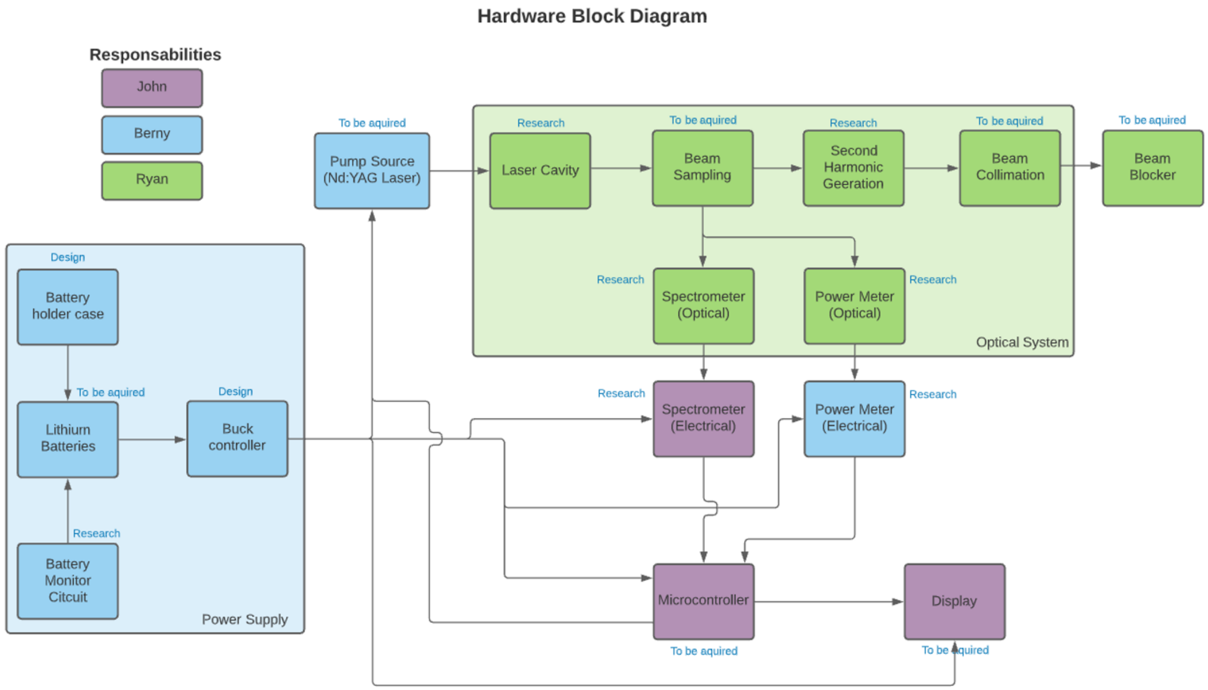
The frequency doubling setup will be composed almost exclusively of a non-linear optics crystal designed to perform second harmonic generation (SHG) on visible frequency light. This will convert the visible laser light to ultraviolet (UV) laser light. As mentioned with the beam sampling setup, a focusing or defocusing lens may be required before the crystal based on the laser beam's power and the maximum safe spatial power density for the crystal. It's input will be the visible laser beam, and its output will be an UV laser beam.

Near the end of the device is the collimating setup. This will be designed to collimate the output UV beam at a desired spot size. Currently, the spot size will be restricted to a maximum of the device's internal optical cavity, which is currently set to be slightly over 1 inch in diameter due to limited optical component size choices and costs of optical components and laser dyes associated with increasing the size.

The final component of the optical system is the beam blocker. Most visible spectrum lasers would not require a beam blocker. This is because visible wavelengths do not have the ability to harm us (with the exception of retina damage). Instead, a visible laser can be harmful if it's intensity is very large. UV light, however, whether it is a laser or not, has a small enough wavelength to disrupt our cellular makeup. UV is a well-known carcinogen, and can lead to general cell death in the short term. A beam blocker is a requirement that serves to add an additional level of safety to a laser by allowing the user to leave the laser closed at any given point whether it is turned on or off.

All of these systems described above culminate into our self-contained, self-sampling, dye laser. A block diagram making the aforementioned connections visual can be seen below as figure 3.

Figure 3 - Project Systems Block Diagram



Parts

We are still currently in the early stages of project design, and we are not set on specific part numbers or suppliers (and in some instances, even the type of part) that should be used across the span of this project. A very early parts breakdown with costs can be seen in table 4 below.

Table 4 - Early Cost Estimation

1	Total Estimated Cost	$436		
2				
3				
4				
5	Item	Quantity	Price	Total
6	Lasing Dye	1	$63	$63
7	Lenses	4	$35	$140
8	Beam Sampler	1	$40.35	$40.35
9	Beam Splitter	1	$34.91	$34.91
10	Power Meter	1	$27.99	$27.99
11	Spectrometer	1	$99	$99
12	Embedded Computer	1	$25	$25
13	Display		$10.90	$0.00
14	Switch	1	$0.50	$0.50
15	Battery	2	$2	$4
16	Voltage Regulator	5	$0.15	$0.75

Early estimations of the optical system components included laser dye, lenses, beam sampler, beam splitter, power meter, and spectrometer. Further work on the design of this laser has expanded this list and given more detail to certain parts, as can be seen in table 5. Volumes of dye solution and glass sealant that will be used are currently unknown. A calculation was run for the volume of dye solution needed, but I (Ryan) misplaced said calculation and will need to rerun it. It should also be noted that this parts list assumes we design our own spectrometer and power meter and would thus need the parts to build them.

In table 5, a custom 3D printed housing is referenced. The actual housing for the device will be designed on optics components' necessary spacing and orientations and 3D printed. From there, the optics components will be attached to mounting surfaces in the housing in positions and orientations determined both from prior geometric-optics light-guiding calculations and in-lab setup testing. What type of adhesive to use has not been discussed yet, which is the reason for it's vague listing in the table. The rest of the optical components listed in table 5 have been discussed in sections prior.

Table 5 - Parts List

Part	Quantity
Laser dye	Est. 4 g
Dye solution	N/A
Dichroic mirrors / Meniscus lenses with visible reflectance and 1064 nm transparency	2
Focusing/Defocusing lens	1-5
Collimating lens/mirror	2
Beam sampler	1
Beam splitter	1
Diffraction grating	1
Photodiode	1
1-dimensional sensor array	1
20x4 LCD Display	1
Microcontroller MSP430	1
Rechargeable NiMH battery	Undetermined
Wattmeter	2
Push Buttons/Dials	8
Buck control	1
Battery Monitoring Circuit	1
Battery holder case	1
Permanent Magnet	1
Adhesive	N/A
SHG crystal	1
Nd:YAG laser	1
Custom 3D printed housing	1
Glass sealant	N/A
Sealable port	1
Kinematic mount	1
Beam blocker	1
Small piece of iron	1

Project Milestone

This group's formation happened at the start of Senior Design 1. Not being a group that knew each other or had ideas or planned ahead of time, the majority of the first two weeks went into trying to get to know each other a little better while also figuring out where we wanted to go with our project. Most of the month of September involved our research into the systems that are required to make a self-contained, self-sampling dye laser. This was more so oriented on researching the general design that goes into lasers and beam sampling devices. We settled on implementing a spectrometer and power meter into our beam sampling setup. Further research into exactly how to design these systems has been done at the end of September and will continue to be done through October.

This process will slowly transition from the research of how to design these systems to the actual design process of them. The first systems that must be fully designed before anything more can be done will be the power system, followed by the laser cavity. The power system is required to power the pump source for the laser cavity to work and the microcontroller to communicate with the display, spectrometer, and power meter. We hope to be trying to wrap up the design process as November approaches, and proceed to begin gathering parts for project demos. Working on project demo construction will take place through most of November. Of course, there will likely be changes to the project design as we run into problems or concerns during demo construction. This is a natural process in design: no matter how much planning is done, it is inevitable that something will come up that was not expected during construction and testing. Such concerns and changes will likely also come up over the course of senior design 2, during which we will continue with the purchasing of parts, construction, and testing. Additionally, over the course of senior design 2, we will try to pay attention to where we notice something could have been designed or implemented more effectively so as to boost the efficiency and functionality of our device.

A more detailed breakdown of dates and tasks involved in the research, design, construction, and testing processes can be seen in table 6.

Table 6 - Project Milestone

Senior Design 1 Task	Time
Producing project ideas	8/23/21 - 8/31/21
Deciding what the project will be	9/3/21-9/14/21
Researching the dye	9/1/21 - 10/8/21
Designing the laser cavity	9/15/21 - 10/30/21
Researching displays	9/1/21 - 9/30/21
Researching pump sources	9/25/21 - 10/8/21
Researching spectrometer	9/25/21 - 10/10/21
Researching communication protocols and what operation settings (from the computer) are needed for our circuit	9/23/21 - 10/12/21
Designing the Printed Circuit Board in computer software	9/22/21 - 10/15/21
Researching the orientation of the beam splitter	10/9/21 - 10/18/21
Researching the power meter	10/17/21 - 10/30/21
Determining the power requirements and purchasing batteries.	10/25/21 - 11/5/21
Finalizing the parts list	11/3/21 - 11/7/21
Purchasing and purchasing demo parts	11/8/21 - 11/19/21
Assemble and test demo	11/20/21 - 12/2/21
Project Demo and Final Documentation	12/7/21
Senior Design 2 Task	**Time**
Purchasing the other components	1/10/22 - 1/24/22
Configuring the parts and testing	1/25/22 - 2/19/22
Discover issues and making the appropriate changes	2/20/22 - 3/1/22
Reconfigure and test again to confirm it operates.	3/2/22 - 3/24/22
Final Presentation preparation	3/25/22 - 5/9/22
Final Presentation	5/10/22