Self-Contained Dye Laser Cavity for UV Sunscreen Absorbance Testing

UNIVERSITY OF CENTRAL FLORIDA
1963

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Table of Contents

Total Pages: 108

1. Executive Summary

Our senior design project started as a technology-push project stemming from some of the issues that come with dye laser usage. These problems include fluorescent dye bleaching, containment of the dye, safety hazards that come with dyes, and the bulk of pump systems to circulate dye. These issues all tend towards making dye lasers very large and unseemly for anything other than tabletop usage for space that has been dedicated to the laser in the long term. Our initial goal was to make the use of dye lasers easier. This has, however, also resulted in the design of a laser that is less powerful and resourceful than a traditional dye laser.

There must, however, always be an explicit problem to solve that is testable and quantifiable, for senior design. Dye lasers most commonly emit in the visible electromagnetic spectrum, though they can also emit in the near infrared (NIR) and high ultraviolet (UV) regimes. These visible wavelengths generated are most commonly used by the layperson as basic laser pointers. However, that isn't a scientifically testable application. Additionally, other applications of dye laser outputs tend towards atomic and molecular spectroscopy. This, however, is far beyond our abilities. What we tended our design towards is the capacity to generate second optical harmonics in nonlinear optical crystals (NLOs). Such crystals allow for the wavelength of the incident radiation to be halved, and thirded, and so on. This means we can turn our visible wavelength laser into a UV wavelength laser. UV light is highly usable in killing cells and cleaning surfaces. Thus, we decided to work towards designing this laser to be used for testing SPF values for sunscreen via absorbance testing.

On top of this, we still sought to make this an easy to use laser. This factor had a major impact on the parts we considered, the physical layout of the device, the user interface, the longevity of the electrical components, and generally to any part of the design that a laser user might want to be done a certain way to make using the laser easier.

Because we are without a real client or specific problem, as one would see in an application-pull project, there aren't many design specs that we are called upon to meet. Some that we wished to pay attention to for this project, however, were laser beam profile, power, and divergence, electrical power consumption, battery life, and beam sampling resolutions. The parameters here that were to most likely affect testing our application were the primary laser beam output characteristics, but all of these are important in making an easy to use, friendly laser.

We wanted to keep the end result under $1000, though the final project cost stretched slightly beyond this. A large part of this is due to the cost of optical equipment, especially NLO crystals, and the vast number of $20-$40 lenses required for focusing or collimating light at every optic. Thankfully, however, due to the prevalence of electrical equipment and how good we as humans have gotten at making them, the electrical components for the project did not surmise to too much.

2. Project Description

Our senior design project idea was 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 organic dyes become bleached over time (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 without the mechanical complexity of tunable lasers.

“Self-contained laser cavity” can be described in more detail as two concave mirrored surfaces placed together and attaching them at a fixed distance apart with a liquid-proof sealant to contain the liquid gain medium. This would allow for the laser cavity to be easily placed into a laser setup and swapped out with other such self-contained cavities. Additionally, since this approach restricts adjustment of the two mirrored surfaces, it was very important to design the cavity to be both stable and very resistant to longitudinal, lateral, and rotational misalignments.

A user would be able to receive information via a display and an embedded computer controls all information functions (buttons were deleted from design since the power being supplied and battery life available were omitted from the design) Liquid Crystal Displays (LCDs) would provide the user with information such as the wavelength and power of the emitted electromagnetic radiation. The embedded computer would require other components to measure the data to know what to display. The information about the electromagnetic radiation is monitored using a spectrometer. The spectrometer receives electromagnetic radiation after it has gone through a beam sampler. A switch is used to turn on and off the device. The rotation mount is mechanical. It is used to angle-tune the NLO crystal from outside of the device. Additionally, in the original design, it would have been pertinent to have a kinematic mount for the laser cavity so that the output could be directed down the rest of the optical system properly.

2.1 Purpose

The end goal of this project was to create a UV-emitting laser device that is easy to operate and can be used effectively for UV absorption testing of sunscreen. The sun bombards us with all kinds of radiation all the time. Some of the most harmful radiation that reaches us in sizable quantities is UVA and UVB sunlight. These wavelengths are damaging to our skin, can kill bacteria, and act as carcinogens. This is largely because the wavelength of this UV light is typically between 200nm and 400nm. Much smaller than our cells, these wavelengths are able to penetrate our cells and disrupt the chemical makeup inside of them, reaching even to our DNA.

Because of the damage that UV radiation causes, it is a valuable thing to be able to test how protective barriers to UV perform before selling them to the masses to be used as cancer protection. There are currently devices on the market sold as solar simulators, whose purpose it is to simulate the spectral output from the sun and expose a test area to this light. Using a solar simulator, one can test how sunscreen for example will perform in sunlight without the issue of irregular radiation from the sun, clouds, testing at night, and testing outside. In a lab, you can control these things along with temperature, external lighting, microbe exposure, particle exposure, and chemical interaction.

These solar simulators typically function off of an arc lamp or a filament bulb. These sources have a very broadband emission typically, and for cases where the emission is not spectrally similar to the sun, filters can be used to make the output of the device more comparable to actual sunlight (or at least the UV part of it).

We sought to create a UV-emitting laser that could be used for comparable purposes to these solar simulators. A notable advantage to this approach is the ease with which you can focus on a substance's reaction to a specific wavelength as opposed to broadband stimulation. Not only is the linewidth of a laser much narrower than the bandwidth of an arc lamp, but the optical power per unit wavelength is greater due to a laser's use of gain. A device like this would not only serve to mimic solar simulators, but could easily be adapted to alternate UV laser applications such as UV laser spectroscopy or fluorescence microscopy.

The fact that we wanted our device to be easy to use also served another purpose. Comparable to how one can buy 20 screwdrivers, or one screwdriver with 20 heads, this laser device would be capable of lasing at multiple different wavelengths for a singular device. There are tunable lasers on the market, but part of the issue with them is that they are extremely expensive, in part due to the extreme mechanical sophistication that is required to fine-tune the wavelength of a single laser cavity. Our design, however, would simply require swapping out the laser cavity and tweaking its alignment with the pump source and the alignment of the NLO crystal for VIS to UV conversion. This is a sufficiently cheaper option than standard wavelength-tunable lasers.

2.2 Goals and Objectives

A primary goal early on in the design of this project was to decide on an optical pump source. Most laser dyes can be effectively pumped by multiple sources, but are most effectively pumped by a specific one. Since we desire for this device to be able to use many different laser cavities, the selection of laser dyes was limited to those that can be effectively pumped by the chosen optical pump source. Electrically, it is important to know whether the optical pump source is operated using direct current (DC) or alternating current (AC).

Once a pump source had been selected, we would have the information we needed to start on the design of many other systems. These systems include the power supply, the dye selection, laser cavity mirror selection, and cavity layout. The pump wavelength must be able to enter the cavity, and the wavelength emitted by the laser dye must be mostly reflected by the mirrors, but slightly transmitted (this transmitted light is the actual laser light we get out of the cavity).

Some goals in the optical compartment involve designing a functioning laser cavity, splitting off beam segments for real-time analysis, and collimating the output beam. Proper laser cavity design involved running both transfer matrix equations and complex beam parameters and finding lens sets that show stability under the ABCD law and strong resistance to misalignments that may happen during the fixing of the laser cavity. Splitting off a small beam segment was done with a beam sampler with a high transmittance to reflectance (T/R) ratio and careful placement of said samplers so that no stray beams escape the device from unexpected locations or angles. Finally was to collimate the output beam. It was important that the potential beam vectors and dispersions were determined first so that proper lens powers and separations could be selected that would prevent stray beams from losing confinement in the laser system. Much of these predictions and calculations can be done with geometric optics. I would also have liked to become accustomed to Zemax to more accurately test the setup later on, though computers breaking and limited access to the software prevented this for a large portion of senior design 1 and 2. Using an advanced ray tracing software would have been more useful in fine-tuning any imperfections that result from the fact that most geometric optics equations are based on paraxial approximations and gaussian beams. 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
	Use Solidworks to create custom adapter for lenses and fill port
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
	Use provided equations for the effects of on beam path through lenses and diffraction gratings to map out proper meter layouts

Frequency conversion from VIS to UV	Research on frequency doubling nonlinear optics (NLO) crystals for converting VIS to UV
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 two sections had been added to the light of optical design systems early on. These were the spectrometer and optical power meter. These two systems work together to sample the laser beam for the user to provide them with the laser's operating wavelength and output power. It was originally thought that we could buy these components and simply integrate them into our design. However, the cheapest quality optical power meters only went down to a few hundred dollars, and the single cheapest spectrometer that we were able to locate was $99. For these purposes, we designed our own spectrometer and optical power meter. In table 2 below, you can see an outline of the steps involved in a spectrometer and power meter system.

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
	Focus wavelengths to pixels on an image sensor
	Read relative intensity of different wavelengths at different pixels
Power Meter Design	Pass light through a lens for spot size control
	Place a photodiode 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

Larger scale project goals for the final project involve being lightweight, hand-held, and low power. We wanted 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 wanted this device to be handheld, it should be light-weight so that extended use does not become cumbersome. Another way that we wished 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 is 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 does not require very fast transfer speeds. There are also considerations that must be taken for specific devices. We planned to 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 was coded using C. This required us to learn the intrinsic functions of the microcontroller, the drivers for the peripherals, and communication protocols. We planned to use a manufacturer provided integrated development environment (IDE). We needed 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 could have been used to provide a digital signal with many bits and low noise. This requires 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 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 also planned to determine the precision required for specific features. For example, positioning the laser cavity requires more precision than the brightness of the display even though both of their inputs are analog. The purely mechanical physical inputs include the blocker for the laser and the kinematic mounts. A material that blocks the radiation needed to be procured. We planned to sculpt it, mount it, and adjust it. It can be moved on hinges but it requires a locking mechanism. A small permanent magnet can be placed on the housing and the blocker could have a ferromagnetic tip. The permanent magnet applies a force on the tip (enough to keep it closed when near).

Our team has to decide on the best battery chemistry for the laser. We have two options: Nickel Metal Hydride (NiMH) and Lithium-ion rechargeable batteries. We have set a goal to keep the temperature of the battery/housing below 42°C and both batteries are within range. Determining the sufficient number of batteries requires 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 requires us to procure a step-down and step-up regulators, resistors, capacitors, diodes and inductors. Components with the same voltage input should use the same voltage regulators to avoid having to create multiple power circuits, and this reduced 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. The goals met were choosing the type of batteries (Li-ion rechargeable) and we determined the number of batteries We procure the necessary voltage regulators and parts along with it. Other goals were not met due to changes in design including not having the battery holder case on the PCB and our charge cycles cycles were equal to or greater than 300.

2.3 Industry Requirements 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 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 requires payment. UCF’s Environmental Health and Safety (EHS) department was unable to provide us with access to these standards, meaning that the actual values could not 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 purchased. A large degree of safety with lasers is making sure that the used optics affect the light in predictable ways reliably. There was 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 would 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 meeting these standards did not pose as much difficulty as one might think and largely end up defaulting to storage requirements.

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 - Optical Design Specs

Requirements and Specs	Details
Laser Optical 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 1.8V to 3.6V.
Display Power Requirements	The typical operating voltage of a 16x2 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
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
UV blocking	Not just any material can be placed at the front of the laser to block UV light. Specific materials made to absorb UV should be used.

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.

Table 4 - Non-Optical Design Specs

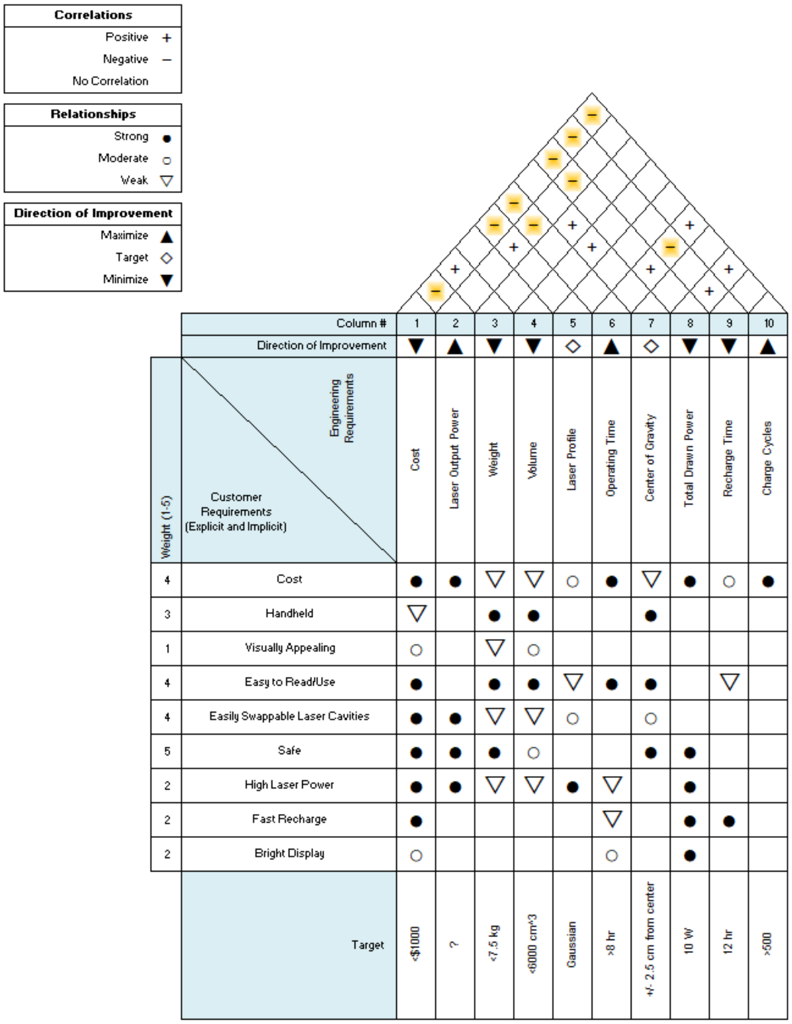
	Desired	Outcome
Operating Time	A user should be able to use the laser for more than 8 hours before needing to recharge.	20.5 hr
Total Power	The device should not draw more than 10 W.	>.3105 A*
Recharge time	The battery should not take longer than 12 hours to recharge.	Unknown
Housing Thermal/Electrical 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.	Unknown
Charge Cycles	The number of charge cycles it can go through should be more than 500.	>300
Volume	The total volume of the device should be less than 6000 cm^3.	15.905 cm^3**
Cost	The total cost of the components should be less than $1000.	~$1,009.43
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).	Unknown
Weight	It should weigh less than 7.5 kg.	<1 lb
Temperature	No components touching the housing or near the battery should be greater than 45°C.	Unknown
Thermal limits	None of the components should produce enough heat to melt its surrounding	Unknown

	components.	

2.4 Quality of House Analysis

Our project is our own idea, not funded or sponsored by a company, professor, etc. As such, we do not have an actual client that is giving us requirements to meet for our design. We had, however, set some goals four ourselves that are comparable to things a non-engineering client might ask for. Such goals included 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 1 below.

Figure 1 - House of Quality



	Column #	1	2	3	4	5	6	7	8	9	10
	Direction of Improvement	▼	▲	▼	▼	◇	▲	◇	▼	▼	▲
Weight (1-5)	Engineering Requirements / Customer Requirements (Explicit and Implicit)	Cost	Laser Output Power	Weight	Volume	Laser Profile	Operating Time	Center of Gravity	Total Drawn Power	Recharge Time	Charge Cycles
4	Cost	●	●	▽	▽	○	●	▽	●	○	●
3	Handheld	▽		●	●			●			
1	Visually Appealing	○		▽	○						
4	Easy to Read/Use	●		●	●	▽	●	●		▽	
4	Easily Swappable Laser Cavities	●	●	▽	▽	○		○			
5	Safe	●	●	●	○			●	●		
2	High Laser Power	●	●	▽	▽	●	▽		●		
2	Fast Recharge	●					▽		●	●	
2	Bright Display	○					○		●		
	Target	<$1000	?	<7.5 kg	<6000 cm^3	Gaussian	>8 hr	+/- 2.5 cm from center	10 W	12 hr	>500

3. Research

3.1 Similar Technology

Because we are applying the technology of lasers to solar simulation testing in the UV, a technique that has not really a practice that has spread out to anywhere, we have two major types of technologies to compare our project to on the optical side: technologies with similar applications and technologies with similar functioning principles.

3.1.1 Solar Simulators

As discussed briefly earlier, solar simulators are devices made with the intent of simulating the spectrum of light emitted by the sun. Some of the main solar simulators observed online are those produced by Oriel®. They currently sell 3 main solar simulators: Xenon, Deuterium, and Quartz Tungsten Halogen (QTH). The first two of these use arc lamps as optical sources whereas the latter uses a QTH filament bulb. Solar simulators can have their emitted light aimed down or forward. Those aimed down are usually larger setups purposed only for UV testing. They are designed to have very small non-uniformity across their spatial profile. That way, every place under its illumination area will receive as equal an exposure as possible. The best non-uniformity provided for these specific devices is <5%. This is an aspect of solar simulators that would be hard to imitate with a laser. A lamp source tends to emit fairly uniformly in a spherical pattern moving outward from the arc location or filament. A Gaussian laser beam, however, emits a Gaussian pattern in one direction with a typically small beam divergence. To map a spherical intensity distribution to a flat one, lenses are used that will slow down the center of the spot, while allowing the lagging wavefronts on the edges of the mapped square to catch up. This could be theoretically done with a Gaussian laser beam, but the aberrations purposefully caused during this flattening process are closer to spherical than they are to Gaussian. Thus, only a small portion of the beam that can be approximated as spherical could be mapped to a low spatial non-uniformity like with solar simulators. An alternate solution would be to expand the beam and then cut off spatial regions that exist beyond a certain tolerance of spatial non-uniformity. The expansion of the beam is crucial here because the relatively flat surface of the intensity profile is small enough that blocking it off directly could result in another Gaussian beam being emitted, this time from diffraction.

On top of potentially emitted optical power, our approach has the added benefit of having a decently large theoretical wavelength range. The Xenon, Deuterium, and QTH sources emit in ranges of 340-2500nm, 160-400nm, and 240-2700nm respectively. Going by the dyes listed as efficiently pumped by Nd:YAG and its harmonics on Luxottica Exciton, and frequency doubling them as our project includes, we would have a spectral range of 166.5-520nm. This range is only slightly better than the Deuterium source. But still, the fact that our system can compare to commercial systems is desirable.

Another detail that is difficult to truly match is the lifetime of typical solar simulators. Xenon and Deuterium solar simulators last anywhere from 1000 to 2500 hours before the lamp itself needs to be replaced. The rest of the device is okay though. With a dye laser, the dye becomes bleached and requires replacing much more often. Even with dye-cycling dye lasers, which elongate the lifetime of the dye, doctors who used to use dye lasers report that dyes had to be replaced every month or so. Even if the device runs nonstop for a month, that only sums up to 744 hours; only a fraction of 1000 or 2500 hours. As such, regardless of how long we can get our battery to last, or how many recharges it can go through, the laser dye will most likely always be the limiting factor on long-term running time.

Finally is the output power, which for solar simulators is expressed in irradiance. The irradiances from the three simulators mentioned above are .6, 1.1, and 300 mW/(mm^2*nm). Power readings have not yet been calculated for the emission from our laser cavity due to considerations of changing the cavity layout for stronger output powers. However, the pump source we were initially looking at (which sets a maximum for output optical power) will emit 100mW at 1064nm covering a spot size of 1.5mm diameter. This equates to an illuminance of .0133, which means that out laser output will not emit as much luminance as the solar simulators in the market unless we greatly increase the output power of our pump source. The issue is that we would need to at least bring it to near 6W of optical power, which is quite a bit and begins to approach the damage threshold for some of the components that are going to be used in the device. Another major issue with this is that for our end device, we had to practically chuck the entire dye cavity system and turn the rest of our design into a module that one could attach to the front of a VIS laser system. Because of this, the four components that really determine the output power of our system are the power of the input source provided by the user, the two samplers in the module, and the NLO crystal in the module. The samplers each sample off 1 to 10% of the beam based on polarization. Assuming unpolarized laser light or circularly polarized laser light is input into the system (for which a 5.5% sampling rate may be used), then the samplers alone will reduce the output power to 89.3% of that which you input. Additionally, the conversion efficiency through the NLO would also be crucial. Issues were run into when trying to get the efficiencies for the crystal obtained due to limited access to the more powerful source used to get UV during testing, saturation of the spectrometer used to observe VIS vs UV in the output, and the lack of a VIS filter that would transmit UV.

3.1.2 Dye Lasers

The other technology to take into account is that of the dye laser. Dye lasers have not been in major use for a few decades now. This is due in part to their bleaching out over time and needing replacement dye, partially because the material is carcinogenic and messy, and partially because a solid-state laser came around that did better at the main thing dye lasers were used for: ultrashort pulses. That laser was the Ti:Sapphire laser.

Because dyes become bleached over their use, methods were devised to get as much efficiency out of the dye as possible. One of the most popular and widespread solutions was the dye jet. A medium-sized (around the size of a shoebox) dye pump was placed on the table with the rest of the laser setup, and a stream of dye was sent between two closely-placed interfaces that would hold the dye at a certain location and with a consistent curvature (based primarily on the adhesive and cohesive properties of the solved in use at the time. These setups, however, were not viable to incorporate into a portable device without making it very bulky or reengineering a liquid pump system into the laser device. Such a system could be made more compact to work with our design, though we would have wanted to get a mechanical engineer on the team if we wanted to go down this route.

Another common setup that was used in dye lasers (along with many tabletop laser setups) is a ring laser cavity. A ring laser cavity is set up so that the light only travels in one direction at any given location. Such a setup allows you to send the beam off on a longer path and interact with any number of other optical elements that you want to work with: polarizers, isolators, NLO crystals, amplifiers, resonators, and so on. It allows for a much more customizable laser system. The problem with a ring cavity is that it is harder to contain in a handheld device, and it does not solve one of the starting problems that our project sought to solve, which was that we want to contain the dye solution simply and easily in the cavity without external storage devices.

Dye lasers were commonly used for ultrashort pulses. Standard CW lasers are possible with dye lasers, but because of laser dyes' high gain coefficients, they were used to get large energy pulses. In our project, a CW beam was thought to be a more valid approach for the application we were trying to tend our project to. The sun's rays are technically not a continuous beam, but they are closer to that than they are to a pulsed laser beam. It should also be noted here, that even though we thought a CW beam would work better since we wanted to tailor our project towards a more CW application, we learned over the course of this project that CW pump sources can work well with dye jet systems, but not so much with standing cuvettes of laser dye. As a result, for the proof of concept that we were able to get for a dye laser cavity, a pulsed laser was needed.

3.1.3 Silicon Carbide

Instead of using aluminum as the thermal conductor we could have submerged the batteries in silicon carbide grains. This would have a greater surface area of contact on the batteries and would not have required the cathode/anode covers. It may have also led to a reduction in electromagnetic noise from reduced current noise. This would be due to the silicon's carbide low electrical conductivity. A major drawback of doing this is needing to contain the grains in the battery holder. We would have had to create a battery holder that would be nearly air tight to prevent these grains from escaping (caused by movements of the device). This would have very poor airflow and may lead the batteries to overheat.

3.1.4 Liquid Cooled Batteries

We also could have liquid cooled the batteries. Liquid cooling would have enabled us to achieve lower temperatures, an overall quieter system, and safer operation. Liquid cooling would have been more expensive due to the need for a pump, radiator, custom contacts, and tubing. The contact would have to be custom made due to the custom design of the battery pack. The contact would also have to be waterproof and not prone to damage by the water flowing within it. These customized components would have different standards, increasing the amount of material to research in the designing of the paper. Leaks could be catastrophic for the electrical components in the system and permanently damage them. This makes potential leaks the most expensive part of watercooling.

3.1.5 Magnetic Beam Blocker Holder

Using magnetic potential energy to hold the beam blocker in place would not have required a special hinge. Rubber bands are also susceptible to the stress that comes with deforming over an object continuously for a long period of time. Rubber bands are advantageous in our device because the magnetic holder requires us to mold a permanent magnet out into our desired shape. It would have required us to buy a ferromagnetic material, melt it, cool it down to reform it to the desired shape, and then magnetize. This requires a lot of energy and expensive equipment. This is necessary because we could not find a magnet with the desired shape.

3.1.6 Rubber Band Beam Blocker Holder

Using rubber bands to hold the beam blocker has a number of issues. Rubber bands' lose their elasticity after many stretches and lead to permanent deformation. It also weakens the bonds in the rubber which leads to it breaking. Parts of the housing would need to be modular so the rubber bands could be swapped. Determining the type of rubber band to use and its performance in our application would have been difficult to to determine due to the lack of information. Manufacturers typically do not include the stress-strain curve for their rubber bands. We would essentially have to try different rubber bands and choose one. This would work but would have required additional testing and may not provide users with all of the options available. Rubber bands can potentially be unsafe. A user could attempt to lock the holder in place and accidentally jam their finger between two parts of the housing.

3.1.7 Strictly Displaying User Information

We could have forgone supplying the user with current or temperature information. This would have reduced the cost of the laser and saved memory on the microcontroller (or reduced instructions in the program). This information is valuable for benchmarking and verifying the safe operation of the device. We expect typical users to not benefit from this and be exclusively interested in the laser beam, which is unrelated to the current and temperature. However, users with a background in testing and research may benefit from this information. Knowing the heat in the battery holder allows them to know if the battery life of their batteries is being maximized. Also, if the batteries' temperature rises rapidly and enters the danger zone the user can turn off the device or request a fix to save the device or their batteries. If they observe currents they can easily compare the efficiencies at certain frequencies and powers in the laser beam with those of the other devices.

3.1.8 ADC Variable Size

$$\frac{Vref}{\left(2^{N}-1\right)\cdot Gain\ of\ Sensor} = Smallest\ discernable\ \delta\ of\ measurment$$

Using a variable with a lower number of bits saves time and energy. Table 5 includes the amount of the units that must be changed before a digital output of one is read (from the value that creates Vin equal to 0). It can also be stated as the maximum change in the measurement for a guaranteed change in the digital output. The values were calculated assuming there is no noise present in the sensor circuits. Vref is assumed to be 1.2 V in all cases. All of the values for the 12-bit variable size were suitable for the experiment.

Table 5 - The smallest distinguishable change for each variable

	10-bit variable	11-bit variable	12-bit variable
Thermometer	-198 m°C	-98.8 m°C	-49 m°C
Photodiode	0.9 μW	0.45 μW	0.225 μW
Ammeter	2.9 mA	1.46 mA	732.425 μA

3.2 Parts

3.2.1 Design Outlook

The original optical system was to consist of an optical pumping source, laser cavity, beam sampling setup, spectrometer, power meter, frequency doubling setup, and collimating setup. The optical pumping source was going to be a Nd:YAG laser due to such pumping systems being higher intensity than broadband emitters and being relatively cheap compared to other lasers that can be used to pump laser dyes. This means we could have gotten more pumping power efficiency for the laser cavity while still maintaining a relatively low cost and being able to lase multiple different dyes. It had an input of electrical power from the power supply system and an output of a 1064 nm pumping laser directed at the laser cavity. Through prototyping, this design was changed a few times, which will be reviewed in a latter section covering prototyping and final outcomes.

The laser cavity itself was initially 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 would have been 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 would also have been a sealable access port through which the dye could be inserted and removed, which would also allow the inside of the cavity to be cleaned if need be. The laser cavity would receive the optical pumping input from the pump source, would be aimed by a kinematic mount, and would have an output of a visible spectrum laser beam to the beam sampling setup.

The beam sampling setup was originally designed to be primarily composed of a beam sampler and a beam splitter. The former is designed to reflect 1-10% 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 would have been the laser emitted by the laser cavity, and it would 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. This power concern was dropped in the end, however. Because our system ended up being a modular piece that one would place in front of a VIS laser of their own, the system instead would need a maximum power density rating to be included in the design specs so that the user would not overload the system or burn the optics.

As mentioned in *Goals*, we may (and did) 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 optical power of a portion of the beam 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) sends signals to several components. We are using the MSP430FR6989 microcontroller for our device. The microcontroller turns on and off the sensors for the spectrometer and power meter. It reads the analog data from both the spectrometer and power meter, and sends the digital data to an LCD display. The microcontroller was meant to have a push button to change between parameters that the user desires to check for in the LCD display, but later changed due to the only parameters being displayed were the wavelength and power of the emitted electromagnetic radiation.

The LCD display component reads the data from the microcontroller to show the wavelength and power of the emitted electromagnetic radiation. We consider a 16x2 LCD display sufficient to show all information necessary.

The power supply will use lithium rechargeable batteries that was meant to deliver power to the battery monitoring system, cooling system, pump source, spectrometer, power meter, microcontroller, ammeter, thermometer and the display (pump source, ammeter, and BMS removed from design). The power supply components are: the battery holder case, the li-ion rechargeable batteries, a battery monitor circuit, cooling system and voltage regulators. The battery holder case was bought to accommodate the two lithium-ion batteries and connected in parallel to increase capacity. The rechargeable batteries were acquired determined by our power needs which is explained in the power supply section 5.3.3 and contains all calculations. The battery monitoring system was meant to check certain aspects of the battery in maintenance and safety. The voltage regulators will be employed to optimize the power supply to meet our voltage requirements for all components, and will step-down or step-down the voltage..

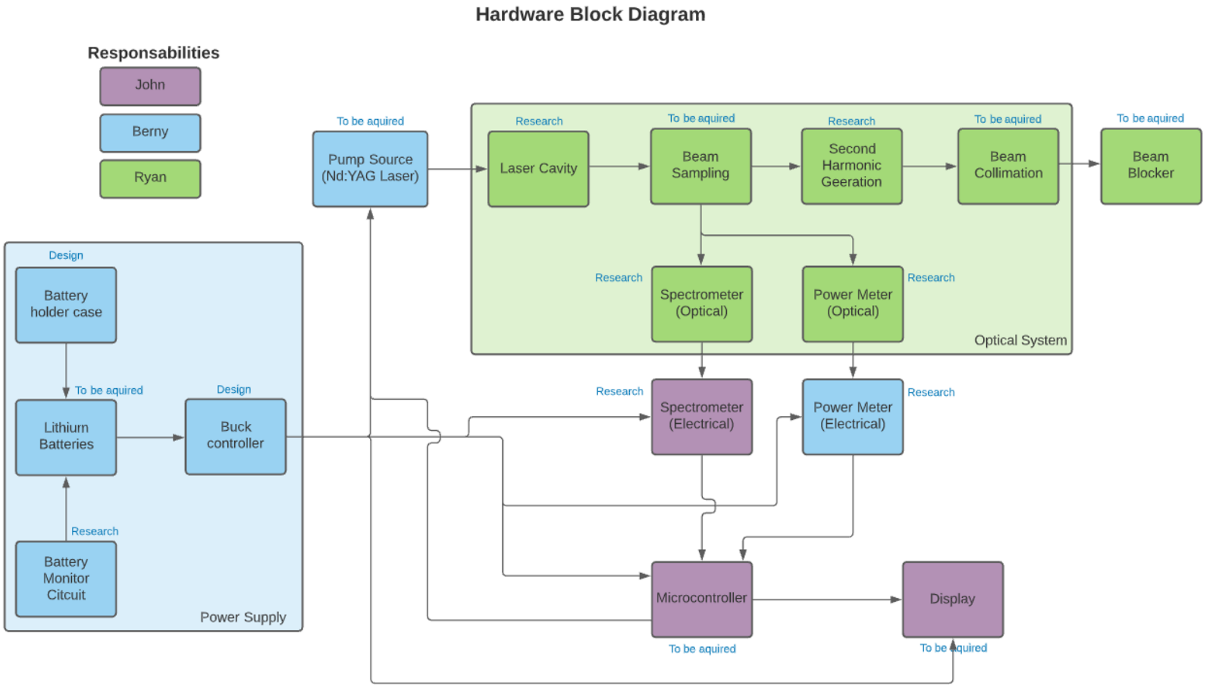
The frequency doubling setup is composed exclusively of a non-linear optics crystal designed to perform second harmonic generation (SHG) on visible (VIS) frequency light. This will convert the VIS laser light to ultraviolet (UV) laser light. As mentioned with the beam sampling setup, a focusing or defocusing lens may be required before the crystal based on the laser beam's power and the maximum safe spatial power density for the crystal. Its input will be the VIS laser beam, and its output will be an UV laser beam. In the end, it was determined that it would be best to include a focusing lens before the NLO crystal and a collimating lens after it. This is because of higher conversion efficiencies at higher fluxes.

Near the end of the device is the collimating setup. This would be designed to collimate the output UV beam at a desired spot size. The spot size was to be restricted to a maximum of the device's internal optical cavity, which was 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. By the end of the project, the smallest components used, were of 3 mm diameters, which had 9mm radii of curvatures. Due to this, beam sizes of less than 3 mm would be required for the beam to stay well confined in our design.

The final component of the optical system was to be 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 its 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. Due to how late in the project we got UV out of our system, we did not get around to obtaining and incorporating a UV beam blocker on the end of our module. In addition, because our project ended as a module that one would add in front of a separate laser, a beam blocker would be less of a necessity as opposed to if our project was its own laser system. Nonetheless, it would have been beneficial to have had it on the final project.

All of these systems described above were to culminate into our self-contained, self-sampling, dye laser. A block diagram making the aforementioned connections visual can be seen below as figure 2. This diagram consists of the state of our project as of the end of senior design 1. An updated block diagram may be seen later where the final project is discussed.

Figure 2 - Original Project Systems Block Diagram



3.2.2 Sources and Selections

The primary source of our optical components was ThorLabs. There are three major manufacturers of general optics equipment that we in CREOL are exposed to in our labs: ThorLabs, Edmund Optics, and Newport. The first is the source of almost all of our lenses, filters, irises, and pretty much anything we want to mount on a table or use to guide or influence light. The second makes higher-end equipment that runs more expensive. They also make more specialized optical equipment. Finally is Newport, who makes a lot of optoelectronic devices. These tend to be expensive, but they are nonetheless a good option for stocking your lab with equipment needed to make use out of the optical equipment obtained from the other two sources. Thorlabs was chosen as the main source for most of our optics primarily because of their decently large selection of optics for any given application and their cheaper prices. The section that likely suffered the most from this was our laser cavity. The most geometrically simple laser cavity is in fact heavily dependent on specialized parts. Such components exist for common lasers, such as Nd:YAG, but not for random laser dyes that are not used often any more. Edmund had some expensive optics that could have possibly worked in creating a geometrically simpler laser cavity design, but these pieces would have been so much more expensive that they were not chosen as our main source for optics.

One of the more confusing sources to look to was one for laser dyes. Laser dyes used to be used all of the time, specifically in creating high powered ultrashort pulsed lasers. Specialized dye flow systems were developed to keep them running smoothly and efficiently. However, though fluorescent dyes are still manufactured today, many such manufacturers are located outside of the country. Additionally was the potential concern that comes with purchasing them since they are classified as carcinogens. On the safety data sheets (SDSs) of most laser dyes, it is explicitly stated that the product is to be used “for laboratory research purposes” only and is “not for drug or household use”. This project is not technically a laboratory research project, and it could easily be tied to household use since we (living off campus) were storing most of our parts off campus, which included the laser dye. Some major sources of laser dyes currently include Luxottica Exciton and Tokyo Chemical Industry (TCI). However, being at CREOL, some professors still have some old laser dye stored away. This is exactly how we got some dye for our design. Dr. Kuebler was kind enough to offer us some Rhodamine B or Rhodamine 123. The former was selected due to larger amounts of experimental data on the dye available online off which we could make predictions for our laser system.

As of the start of senior design 2, a source had still not been selected for a VIS to UV NLO crystal. There are many companies that would sell a BBO crystal. ShalomEO and Edmund had both been looked at and considered as a source for this component. The main concern was trying to find the cheapest option. This is because at the start of senior design 2, we were very near our $1000 preferred upper limit for the total price of this project, and a NLO crystal was going to be one of the single most expensive objects in this laser. In the end, the crystal we went with was a $570 piece of BBO from Edmund Optics.

There were also a few optical components that we deemed worth buying from a 3rd party source in order to lower the cost of the project. Three such components were optical windows for the laser cavity, a transmission grating for the spectrometer, and a piece of KTP for the laser cavity. These were pieces that could later be purchased from well-known suppliers if the need arose, and we are glad that such did not need to happen.

3.2.3 Parts Selection Summary

Table 6 - Parts List

Part	Quantity				
Glass Optical Window (VIS)	2	16x2 LCD Display	1	Super Glue	N/A
1D sensor array	1	Microcontroller MSP430FR6989	1	BBO crystal (VIS to UV)	1
Photodiode (UV)	1	Rechargeable Li-Ion batteries	2	Transmission diffraction grating	1
Plano-Convex Lens, f=25.3mm	1	Switch	1	Custom 3D printed housing	N/A
Beam sampler (UV)	1	Fans	2	Plano-Convex Lens, f=9mm	2
Beam sampler (VIS)	1	Buck controls or boost converters	3	Bi-Convex Lens, f=50mm	1
Thermal Epoxy	1	Battery Charger	1	Operational Amplifier	1
Hand adjustable screw	1	Battery holder case	1		

We used surface mount technology (SMT) for mounting the electronic components, when available. SMT has been growing in popularity for the past couple of decades and for this reason a large number of components are using it. Surface mount parts have many advantages in comparison to their through-hole counterparts. Using SMT reduces the need for drilling that would be required for through-hole parts, which also reduces the cost of manufacturing the board. Also, surface mount components are typically smaller which can reduce electrical noise by shortening the length of traces. Through-hole technology has advantages in comparison to SMT. One is the mechanical strength of the adhesion that holds the components to the board. We are not concerned about this because the components are light and were supposed to be shielded by the housing. There are some components that can not easily be found using SMT. For those components we planned to use through-hole and make the necessary changes.

The ammeter we planned to use was an open-loop hall-effect sensor. They are preferred for their accuracy, requiring less testing and calibration. The drift in sensitivity caused by temperature is not of concern in this application. We planned to keep the temperature low (less than 42 °C) and nearly constant by using the battery monitoring/cooling system (the ammeter is close to the battery). The operational temperature region of the ammeter is well beyond what is needed for our laser. This technology uses a magnetic core and the magnetic field induced in this core is sensed by a hall effect sensor which creates a potential difference. This voltage is then input to operational amplifiers to apply a gain to it. The open-loop sensor has a significantly lower power requirement in comparison to close-loop sensors. Open-loop sensors are recommended in applications that use batteries. The gain on the ammeter should be large enough to avoid the use of additional op amps for reasons discussed in the following paragraph. We did not use the ammeter because we decided that knowing the electrical power is not important for the user and would have increased the price.

The cooling system was supposed to comprise of a thermometer and two fans. The thermometer produces an analog voltage signal to the microcontroller's ADC. It needs to have low power requirements and be accurate/linear (temperature vs output voltage relationship) near the batteries operating temperature. The size of the thermometer is limited by the housing/battery case but virtually any thermometer would be able to meet this requirement. The fans are DC brushless fans. DC brushless fans tend to cost more than AC fans but DC fans tend to be more efficient. Also, there is greater availability for cheap (less than $5) DC fans and to use AC fans would require DC to AC inverters, further increasing the cost of the laser. This contributes to the goal of extending the battery life. The fans' operating temperature was not of concern since they would have been located a considerable distance (more than 4 inches) away from the batteries. There will be two fans in the laser. One that brings the cool air in the laser and one that pushes the warm air out. We wanted the fans to move the most air possible at a given price. In other words, we want to maximize the CFM/$. A thermal conductor would have been used to transfer heat to the thermometer. Aluminum has high thermal conductivity but has a high electrical conductivity. Special care must be taken to minimize the electrical noise, or possibly a short, induced by the metal conductor. Thermal epoxy must be applied to adhere the PCB to the thermal contact. We planned to select the epoxy with the highest thermal conductivity possible to get the fastest thermal response time.

The beam blocker needs to include a highly conductive material and two permanent magnets. Aluminum is the metal we chose. Aluminum is quite cheap to purchase (less than $1 per pound) but purchasing is unnecessary because aluminum can be obtained for free by using scraps. Aluminum foil is commonly available and its elasticity allows us to freely design the blockers shape. The permanent magnets will be neodymium alloy magnets because of its wide availability (especially in various shapes) and low cost.

A transimpedance circuit is used to convert current to an output voltage for the purpose of calculating optical power. The photodiode needs to have a responsivity curve (with frequency as the independent variable) that is as close to flat as possible (in our laser's primary frequency range). This will make the calculation of power easier and more accurate. Otherwise, a complicated approximation function will have to be utilized to reduce the error from the varying responsivity. The op amp will need to have a low input offset voltage and a low input bias current. These contribute to the error in the output voltage. CMOS op amps can meet these requirements.The resistor should have a tolerance less than ±%1 and a power rating greater than 0.1 W. Having a low tolerance will increase the accuracy of the output voltage. For example, a resistor that's resistance has been rated as 2 kOhm but has an actual resistance of 2.1 kOhm (%5 higher), will have an output voltage 0.1 V lower than it's expected value (in our circuit). This becomes worse as the optical power (or current through photodiode) increases.

The calculated max power absorbed by the resistor in this case is 1.08W. This does not account for any inefficiencies found in the optical and electrical components or the changing responsivity. The actual absorbed power values are likely to be much less than this. To ensure proper functionality and safety of the resistors, it would be best to buy resistors with power ratings of at least 0.1 W.

The housing was planned to be made out of the most common plastics used for 3D printing. Acrylonitrile Butadiene Styrene (ABS) has a melting point of 145.2 °C. ABS has an electrical conductivity of approximately 1.5 *10^{-14} S/m and a thermal conductivity of 0.175 W/mK. They are both low and that is desired in our application. The high resistivity reduces the amount of leakage current in the housing. The low thermal conductivity protects the user in the case a short circuit occurs and excessive heat is released within the housing.possibility. ABS is considered to be strong with a tensile strength of over 20 MPa and since the weight of the laser is light it should be able to withstand falls. It costs approximately $3.30 per kg and the total would be less than $33.00 for us (it should weigh less than 10 kg)..This does not include the cost of using the 3D printer. Ultimately, we used PLA. It was available on campus and met the specification for our project.

For our optical pump source of our first prototype, we went with a Nd:YAG laser. Using a laser system can be easily modified to provide a nice, small, collimated beam. They can provide decent power, and get lots of gain per wavelength due to lasers being stimulated emission sources as opposed to spontaneous emission sources. Of the laser systems used to pump dyes, we went with Nd:YAG specifically due to it being a relatively common laser source. Most places that sell optics that go beyond the general white light focusing will sell optics designed to work with Nd:YAG emissions (1064 nm) or its harmonics (532 nm, 355 nm, and so on). This was supposed to provide a bit of ease to finding a decent pump source. On the contrary, however, we were only able to find two Nd:YAG laser systems that were not extremely expensive (like the ones you'd buy for serious lab usage) or temperature sensitive laser diodes were two different 1064 nm laser pointers. One by Titan, and the other by Roithner Lasertechnik. The laser pointer made by Titan had a higher maximum optical power, lifetime, and a better price. The one made by Roithner had a smaller beam diameter and divergence, and emits a TEM00 laser spot, but can only be operated continuously for 30 seconds. Between the two, we tried to go with Titan's, namely for the larger maximum power. The site turned out to either be bugged or it was a scam site. We instead tried to go with the Roithner laser pointer, which we were going to disassemble to whatever degree is necessary to properly connect it to our power and control systems and mount it to our optical system. This also fell through due to lack of hearing back from them. The pump source went through a few additional changes throughout prototyping and senior design 2, which will be explained in a latter section detailing this.

For our spectrometer, we could have used a transmission or reflection diffraction grating. We went with the former due to our lack of experience with reflection diffraction gratings. Additionally, the former can be obtained in non-professional forms that would function as well as we need them to while simultaneously lowering the cost of our self-designed spectrometer. We decided to design our own since the cheapest one we could find to buy as a module was $99. A 1000 lines/mm grating was chosen so that the first order diffraction of the range of 400 nm to 700 nm (the part of the visible spectrum that we care about here) would be diffracted far off to the side, but not so far as to be cut off at the 90° mark. This also results in a larger angular difference across the range, which would allow for a wider focused area onto the 1D sensor, resulting in a higher spectral resolution for our spectrometer. A 50 mm focal length bi-convex lens was chosen to focus this diffracted light onto a 1D sensor. A small focal length was desired to keep the spectrometer small (the image plane would be located 1f away from the lens), while not wanting to sacrifice all of our spectral resolution (shorter focus results in a smaller image covering fewer pixels). The TCD2557D CCD linear image sensor by Toshiba was acquired for the use of the required optical demo. It has a large pixel count for a 1D sensor, which helps with our spectral resolution, but is also quite large. The circuit for this sensor was not completed by the end of senior design 2, and so though the optical design for said system is complete, the resolution and actual functionality of the spectrometer could not be tested.

For our optical power meter setup, we chose a 3 mm diameter 9 mm focal length plano-convex lens to focus a UV sample beam onto a photodiode of active area 15 mm squared. This active area was on the larger end for the UV photodiodes that we were able to find without taking a step up in prices. The focusing lens was chosen, like the rest of the focusing and collimating lenses in this project, to be a plano-convex lens because this shape of lens does a very good job at neatly focusing a collimated beam. The diameter was chosen for the sake of price (the next diameter size up was 6 mm for nearly 150% of the price of this one), and the focal length was purposefully chosen to be so small because this optical power sampling system is already an isolated protrusion on the front of the device. Keeping it small helps to prevent there being large, apparently extraneous modules on the extremes of the device.

Concave mirrors were chosen for the laser cavity due to the increased stability that comes with a laser cavity composed of concave mirrors, and because it would allow for more gain medium to be stored between them, which we were hoping would boost the optical power of our laser. Specifics as to the mirrors selected can be observed later in section 5.2.1. A hot mirror of comparable size to the concave mirrors was selected for the first prototype so that it would not be too small and constrict the beam size inside the cavity, or too large and make the laser cavity cumbersome. This mirror type also yields reflectances for the lasing wavelengths that can be near the optimum reflectance. Cold mirrors, on the other hand, in a folded version of the same type of laser cavity, would result in pumping and laser emissions in orthogonal axes and less-optimum reflections for the lasing light. In later prototypes, a dichroic mirror was looked at and obtained for the same use as the hot mirror as described both above and in the cavity design sections later. The purpose for this redesign can be seen in later sections covering prototyping.

In the main optical train, the laser cavity output must first be collimated, sampled off, focused into a NLO crystal, collimated again, and sampled off again. For the first collimation and focusing, 25.3 mm focal length plano-convex lenses were chosen. They are the smallest focal length lens available by ThorLabs without going down a size in diameter and getting the first lens closer to the laser cavity. There must still be room after the cavity so that it can be swapped out when desired. As such, 20.52 mm of space had been left between the laser cavity and the first collimating lens. A .5" diameter VIS beam sampler was chosen to sample off approximately 5.5% of the beam light for spectral imaging. This was the smallest size available, mostly chosen for its lower cost. Additionally, larger sizes are not needed when the laser spot size can be kept small. Using the same 25.3 mm focal length lens after the sampler for focusing yet again allows for some space between this lens and the next component, which is the NLO crystal and its mount. It was possible that additional space would be needed for the mount. If so, then a longer focal length lens would have needed to be chosen. After this, the light will no longer be VIS. It will be UV, where N-BK7 is opaque. As such, a UV fused silica lens was chosen of diameter 3 mm and focal length 9 mm. The small size is to compensate for the increased prices of UV fused silica lenses, and the short focal length is needed because the lens must be close to the focal point to keep the expanding spot size from overtaking the lens. A UV beam sampler of the same physical specs as the previous VIS sampler is then used to sample off another 5.5% of the beam towards the optical power meter.

Optical windows were to be located on the entrance and exit facets of the laser cavity to contain the gain medium, and a UV optical window was to be used on the end of the device to prevent the internal optical elements from being damaged by anything near the end of the device. These windows could be purchased for large prices from any number of optics manufacturers. However, the purpose of the windows are not to be pristine optical elements. We only need them to serve as physical barriers between spaces. As such, some transmissive plastic and glass was to be be obtained for inconsequential prices.

4. Standards and Constraints

4.1 Standards

4.1.1 Optical Standards

IEC 60825-1:2014 & ANSI Z136.1 - Laser Optical Power Classification

Any time that a laser is produced, it must be properly classified based on its power and wavelength. This classification must also be clearly displayed on a label on a prominent surface on the outside of the device. This classification is to ensure that laser devices are handled properly and safely. Another part of this standard is that procedures for proper handling and usage have been laid out for each classification of laser. The common classification ranks are 1, 1M, 2, 2M, 3R, 3B, and 4. The power level numbers for visible wavelengths are available online, however the levels for UV classifications are not so easily available.

Standards for safe levels of UV exposure are, unlike for visible wavelengths, classified by exposure over given times. This limit between 180 and 300 nm is 3 mJ/cm^2 for exposure between 10^{-9} to 1000 seconds. For continuous exposure, this would limit such a laser to a maximum optical power of 3 μW/cm^2. Such levels should be easily obtainable by using internal, non-removable UV power filters. Filters come in different levels of power attenuation, and whatever attenuating we end up needing can be accounted for.

Additionally, the operating time of the pump source we are going to obtain might limit the on-time of our laser, which would allow for higher average powers. The Roithner LaserTechnik 1064 nm laser pointer we planned to get says that it should only be left on for 30 seconds. Engineers from different professions were going to be consulted on this to see if we could alter this pump source to allow for safe operation beyond 30 seconds. If this would not have been attainable, however, then the exposure time will decrease from a maximum of 1000 seconds to 30 seconds. This would allow for an increased maximum optical power of 100 μW/cm^2.

IEC 60825-1:2014 - Laser Safety

Optical setups in general should be designed by qualified professionals to make sure that the system is safe. With lasers, this is even more significant due to the higher focused power of laser light as opposed to standard light emissions from other devices. Even LED light, which can be many orders of magnitude smaller in power than laser light can still be harmful to one's eyes. None of us in this project are qualified yet on optical design, but that is what this course and CREOL are about. Multiple years of experience account for the professionalism needed here for proper laser guidance in our device. Additionally, professionals in the college were conferred with as the project continued to develop to help avoid mistakes being made that could result in improper laser guidance.

ISO 12123:2018 & ISO 1:2016 - Laser Guidance

In addition to laser safety regulations are regulations on the individual parts in the design. These requirements are there to make sure that optics manufacturers are making products that guide light in ways that would be safe to use with lasers. This includes testing safe power levels for products, focal levels, filtering levels in power and spectra, and so on. These standards are met primarily by the manufacturers in designing their components. The other half of meeting the standards is using these components properly. An absorbing ND filter for wavelengths between 400 nm and 700 nm at power levels below 1 mW at normal incidence should only be used exactly like that. Attempts to use such a component in other ways could result in improper guidance of the laser light and could result in a much more hazardous end-product.

4.1.2 Electrical and Software Standards

IEEE 1625-2008 - IEEE Standard for Rechargeable Batteries for Portable Computing

To choose the right rechargeable batteries for our power supply system for our laser project components, we adhere to the IEEE Standard for Rechargeable Batteries for Portable Computing which will guide us in this process. This standard contains the criteria for the design analysis for reliability, qualification, and quality of rechargeable battery systems for portable computing. The standard additionally includes methods for calculating the operational performance of the batteries and the related management and control systems.

UL 1642 Standard for Safety for Lithium Batteries

This standard is a complementary Standard to IEEE 1625. UL 1642 is a U.S. standard to ensure the safety of lithium batteries. The part that will be applicable to our project will be the rechargeable batteries side, but it also covers primary batteries as well. This standard is usually used for the certification of component cells, but in general we use it as a guide for safety.

Some of the aspects of this standard apply to the final product of the battery itself, and requirements include electrical, mechanical, and environmental tests. In regard to this aspect, we could make sure that when buying the batteries, they comply with the set requirements that will reduce the risk of fire or explosion, as well as to lower the risk of injury to any person using the device. Another factor that is included is the type of batteries which are metallic lithium, lithium alloy, or lithium ion containing one cell or more in series, parallel, or both.

UL 2054 Standard for Safety of Household and Commercial Batteries

Comparable to UL 1642, this standard is a U.S standard, but it covers a wider range of batteries for both commercial and household use. UL 2054 prioritizes performance and safety of portable primary and secondary batteries in products. The standard covers batteries producing electricity through a chemical reaction through a single cell or more connected in series, parallel or a combination of the two.

UL 2054 focuses on safety and its aim to decrease the possibility of fire or explosion while the batteries are being used in a product as well when they are removed to be transported, stored, or discarded. The application of the standard improves the protection of the device and gives comfort to the user as well. The standard will not only guide us as we develop the device, but also direct the user when removing the batteries from the laser. Similar to the previous standard it includes testing requirements that are more applicable to the manufacturer, but also include requirements that apply to our design like the battery holder case and pack evaluations, environmental assessments, and others additionally.

IPC-1601 Printed Board Handling and Storage Guidelines

The storing and handling of our printed board would be covered under this standard. We should not have to worry after we order our PCB because its storage, packaging, handling, and transportation should be covered under this standard by the company manufacturing it. The standard guides on how to protect printed boards from several factors like contamination, physical damage, moisture among others. Damage is a concern that we do not want to cope with since moisture for example can affect when soldering. Moisture expands causing other problems on the board. When we solder components if deterioration is present it causes irregularities or damage to other components.

IPC J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies

When soldering materials to the PCB we can surely reference this standard. The standard covers assembly of PCBs and electronic assemblies. The part that we can focus on is the best soldering practices since we have to attach components to our PBC. The standard encompasses many other factors like material, component, equipment, connections (terminal and wire), cleaning and residue requirements, and other factors. This standard applies to our device since it incorporates the assembly of our device and is a wonderful support when determining the right practices and processes of bringing together our electrical device. By abiding by this standard we ensure that our connections have been done properly and no damage comes to the PBC or other components

IPC-2221B: Generic Standard on Printed Board Design

This standard establishes the generic requirements for the design of PBC. In our project we would utilize a PBC as part of the power supply system. This standard will give us guidance especially in the areas of board electrical test, board housing, thermal stress among other properties. This standard is not ANSI approved, but it can guide us in regards to certain areas of the design of the printed board.

IEEE 829-2008 - IEEE Standard for Software and System Test Documentation

When developing and testing our software we were aided by this standard. The standard gives rules and regulations for software testing at all the stages, and the documentation necessary at each step. The standard will also demonstrate if the system and/or software will meet its purpose and user demands. When applied properly this standard will aid in the effectiveness and trust of the final product and will be supported by documentation. The standard will apply to the development, maintenance and future reusability of the software.

IEEE 1012-2016 - IEEE Standard for System and Software Test Verification and Validation

The final product of our project can be verified and validated by this standard. This standard involves the verification and validation of systems, software, hardware, and interfaces. The standard is used to determine if the product meets its intended use and user requirements. IEEE 1012-2016 helps us in the development of the systems, software, and hardware of our device, but the standard can also be used for the maintenance and reusability of them. In a way by following the standard it will demonstrate if the final product of our device meets the requirement specifications we set in our design. The standard also mentions in its purpose that in each life cycle process there is a need of required inputs and required outputs. The cycles show different integrity levels. The application of the standard to our final product will show integrity which will demonstrate that our device can be competitive with other comparable devices in the market.

ISO/IEC 9899:1999 Programming languages – C

This is an international standard which involves the C language specifying its form and establishing its interpretation of programs written in it. The standard was defined by the International Organization for Standardization and the International Electrotechnical Commission. The short name for this standard is C99. This standard specifies many subjects in which are included the syntax and constraints of the language, as well as the programs' interpretation semantic rules for C. Other specifications involved in C are input data, output data, restrictions, and limits.

We planned to use C99 due to its portability and because the software for our project will be written in C programming language. Previous standards like C89, C90 and C95 are outdated and lack compatibility and would not be useful for our software. C99 is supported by a wider range of devices even more than later versions like C11 or C18. These later versions have features that are too advanced and a lot of hardware have not caught up to these standards.

The use of ISO/IEC 9899:1999 standard will help us write the code to program our device. Also the standard will direct us when we come to a point where we can not progress with the code or to find a bug in it. The implementation of the standard will serve as one of the main parts of the software side of our project.

4.1.3 Chemical Standards

U.S. EPA, 1986a

In our project we tried to use Rhodamine B as a gain medium. This material is classified as a carcinogen, and as such has federal regulations on the proper handling/containment of such. The generality of this standard is that the ways in which this material is carcinogenic should be strongly protected against. This includes liquid-sealed storage, avoiding things like vaporization, and not handling the chemical with one's bare hands at any point in time. Additionally, this standard covers disposal. Because Rhodamine B is a carcinogen, it cannot simply be washed down the sink when done with it. Most carcinogens can be disposed of properly by contacting one's local disposal organizations for their individual processes in getting the chemical to them, from whence they dispose of it properly. This is the same as what one is supposed to do with multiple types of batteries, but is almost always ignored.

In addition to this is the proper storage of such chemicals. Most of this information is contained on a Safety Data Sheet (SDS) about the chemical that is required to be published with the product by any seller. Because were obtaining this chemical from a faculty member who has some spare dyes from when he used dye lasers, the SDS' from Luxottica Exciton were to be used. Below, some safety information about the dye will be given, though one should read the entire SDS for this dye before using it.

Rhodamine B is classified as harmful if swallowed, causes serious eye damage, and is harmful to aquatic life with additional long lasting effects. If one is exposed to the chemical then one should wash the exposed skin thoroughly, call a poison center and rinse mouth if swallowed, and rinse eyes cautiously with water for several minutes if exposed. However, to avoid such problems, PPE should be worn at least on the eyes, hands, and face during use of this dye, and one should not eat or drink while using it to avoid indirect oral exposure. Additionally, the dye should be stored in a tightly closed container in a dry, well-ventilated, cool place. Additional information on the dye and specifics about its hazards and advised steps if something goes wrong can be viewed on its SDS.

4.1.4 Impacts of Standards

The standards described above should directly guide our project. Unlike many user-safe products, our project should be handled by a trained individual familiar with laser and liquid-carcinogen safety. This is due to what our project will emit and what the user will be exposed to in the end. Our device will emit UV laser radiation and will involve the handling of liquid carcinogens. This will mean, ironically enough, that whoever uses our device will also have to abide by certain safety standards. We are still, however, required to abide by design standards in designing and building this product.

We did, however, also have to consider the longer-term responsibilities of using a carcinogen in our project. This not only impacted the actual design of our project, but it will also impact how we handle our components before construction, our construction process, and our disposal and storage afterwards. Before construction, the dye powder was going to be stored in a CREOL faculty lab (though it was advised for us to keep it with us due to how often we needed access to it). When the dye solution needed to be mixed, the powder and solute were measured and mixed in a proper lab with equipment such as pipettes so that no one is exposed to the carcinogen at any point and any spills could be easily controlled and taken care of. But once the solution was put into our finished dye laser cavity, storage could be in a wider range of locations.

Most of our laser systems were designed and built by us. The one part that was a pre-built module was the pump source for our laser cavity. This pump source was going to be a Roithner LaserTechnik 1064 nm laser pointer. Apart from this, however, every point of laser collimation, focusing, sampling, reading, and frequency doubling was done with raw optics purchased from manufacturers. This means that the SDS for this module will direct the proper implementation and handling of the pump source into our design. This also means that the optical design of the rest of our project will be guided by multiple years of laser safety and free-space optics experience in labs. Additional help could have been called upon at times from faculty in CREOL for double checking design systems for failures.

Another part of abiding by the optical standards that pertain to this project is testing each optical element to make sure that it is operating as the manufacturers say it is. This is something that shouldn't technically need to be tested, but would have been wise to do anyways. Parts that are obtained from known and respected manufacturers are more trustworthy and less likely to be an issue. But some parts that are obtained from other sources, most likely due to cost, should have especially been tested to make sure that they and our design will abide by safety standards. Three components that this immediately sticks out on will be the laser dye solution, the transmission grating, and the NLO crystal used for converting the visible light to UV. The dye solution should be tested because the dye powder will be obtained from a CREOL faculty as opposed to a manufacturer, and it will be mixed by us (it was actually mixed in a lab in the Physics department). It should be tested for its emission spectra under 532 nm and 1064 nm excitation since both of these wavelengths were to exist in the cavity for pumping under the first prototype design. The transmission grating used in the self-designed and self-build spectrometer should have been tested since prices of industrial gratings vs basic gratings can be multiple orders of magnitude different. The angles of their output beams should have been tested since this is the only real detail we care about for it. Finally, the NLO crystal should be tested, even though it is going to be obtained from manufacturers, because it will not be used for its specifically designed wavelength. NLO crystals are cut to work on a specific wavelength, and to use them for different wavelengths, the crystal should be slightly angled. It was very unlikely that we were going to get a NLO crystal specifically cut to an exact wavelength that our laser cavity emits at. And, even though we did get such a crystal, part of the idea of our project is to allow for cavity swapping. This would result in different visual wavelength emissions, meaning that the crystal would need to be tuned and sealed at all times and should only be opened in a proper lab. This is a possibility because dyes do become bleached eventually. This means that the dye will at some point lose it's fluorescent properties that we are using. If this happens, then the dye cavity should be emptied, washed out, and refilled with a new solution, all of which should be done in a lab.

The market is not trustworthy when it comes to batteries because it is filled with fake cells that do not represent their actual capacities and/or specifications. Our team was cautious when choosing the batteries for our device because of the existence of these fraudulent sellers and standards play a big role in the selection process. We have chosen Lithium-ion batteries, but we need to make sure that these cells meet the criteria when it comes to quality, qualification, and reliability for our design. Cells should comply with any necessary requirements of the certification process, disregarding such standards put our team at risk as well as any user of the laser. Also, after obtaining the batteries, we should follow the required standards while handling or storing them to ensure safety of people and protection of the device. When testing performance for these batteries and the battery monitoring system the impact is significant since failure to abide by standards can lead to having to repurchase batteries from a different source or even in an unwanted situation having to change the type of batteries. Other aspects like the design and evaluation of the battery holder case, PCB, and battery pack are also affected by the battery standards. We bought the batteries from Digi-Key a reputable electronics provider in the United States to make sure we meet standards and the batteries are RoHS compliant.

Preserving our PCB is a major concern, and standards have an effect on protecting and maintaining the condition of the printed board. The impact of the manufacturer and our team following the standards will affect the final product and/or prevent extra expenses of repurchasing another PBC. When handling and storing the printed circuit board the damage can come from many factors and their influence might not even appear during testing or when the final product is finally completed. Moisture or contamination could slowly degrade the PBC making the device malfunction or stop functioning completely. The housing design will also be affected by these requirements since it will protect the board from any damaging exterior factor or internal thermal stress on the board.

The software area of the design will communicate the outputs of the device to the user through the display. While writing code in C we need to keep all of the language standard to have a successful software. The standards will help with the development of the code and prevent bugs. Testing the software will be an essential part of the development of our device. Throughout the testing and development of the software we might find errors and/or inconsistencies that will reveal inaccurate or incorrect readings of output or power related data. Testing can also be applied towards the final product in the different areas of software, hardware, and interfaces. Standards in this area will help verify and validate any requirements that we as a group have set for the device. The impact of these tests will give confidence to users that the laser readings are accurate.

4.2 Constraints

4.2.1 Economic and Time Constraints

We would like to create a product that would have the best parts available and would produce the best final product. We have set our total cost of the components to be less than $1000. Since we have that economic constraint, we have to think of cost-effective components for our device. Even with this limitation we have to make sure to produce an efficient, user friendly and portable device.

The monetary limitation can affect our final product. The optical components of our laser costs over $900, and that is before factoring in parts for the electrical and housing design. We had to make sure to keep electrical components as low as possible as to not surpass the budget set for our device. Electrical components for our laser are not as expensive but we had to make sure that they provide the necessary power and safety for the laser to function properly. Another factor to take in account is that we want our device to be portable which itself increases the power supply cost since it will require batteries, battery holding case and a battery monitoring system for safety. Even with all these factors we have to make sure that we abide by our monetary limitation.

Besides our financial constraints, we also have time limitations. When our senior design 1 semester started, we ventured into a type of project that none of us has experience before and that we are restricted to complete in 2 semesters, or around 8 months total. Within the time constraint given was necessary to research, make decisions, structure, and build our device. We also had to take into account school schedules and work schedules to be able to have meetings and to make sure to work as a group. Another factor taken into consideration was selecting parts and ordering them in a timely manner to have them ready for prototypes and the final product presentation itself. Shipping times can also be severely affected by long shipping times for items trying to get into the US currently, which could result later on in a change in part selection from a preferred piece to a piece that will be shipped from a location in or nearer the US.

An additional sub-constraint to this project is the fact that we were only given the first 3 months to complete a full design of the project. Details of the design were open to change over the last 5 months, which drastically affected final project cost, appearance, and design. In addition to this is the fact that next to none of the actual construction of the project began until the last 4 months after Christmas break. This means we only had 4 months between starting construction of this device until we had to have tested our parts, solved every error we came across, tested the final device, and completed the necessary writings on our device and testing results. One of the main areas affected by the time restriction was being able to determine our total power needs because we had to wait on manufacturers answers and complications on picking parts.

This sub-constraint has resulted in multiple projects needing to ditch certain goals or greatly lower the final quality of the device during senior design 2 in the past. This is because 4 months between beginning construction to having everything done, tested, and written up is a very short time compared to standard engineering timelines. Optically, this could easily have resulted in lower output optical power levels, lower spectrometer resolution, less beam confinement, and messier output beam profile. Electrically we had to let go of adding parameters that might not be as important to the user like battery temperature and current drawn from the battery. These changes are not things that we desire for our project, but are things that happen often with senior design projects and were, regrettably, an expectation. This is especially the case for our project due to multiple professors overseeing the progress of our project expressing concerns for the amount of optical design required for this project and the standard complexity of both getting a laser cavity and frequency doubling with a NLO crystal to work.

4.2.2 Environmental, Health, and Safety Constraints

The primary thing to consider when talking about environmental constraints are what conditions a device should be operated in. Most of the time, lasers that are used for product testing are used inside. This is most generally done in a lab that is, for all practical purposes, just a room, but such devices can also be used in controlled rooms where things like temperature, humidity, air particle count, and more can be controlled. In general, laser devices are operated in a standard room at room temperature and with no real environmental control. However, this does mean that the optical devices should be operable under room temperature conditions. Most optical devices are made to work under these conditions and will not be of concern to us. However, the laser cavity could be of concern. Inside a laser cavity, laser intensities can be orders of magnitude higher than the actual laser output power itself. This means that the material and components inside the cavity could be heated beyond room temperature. These devices had to be made sure to operate properly at such higher temperatures. Additionally, the cavity housing and sealing materials should have been confirmed to work at higher temperatures without expanding, contracting, bending, breaking down, or losing their structural stability. Due to the fact that our specially designed cavity was more easily constructed via a 3D printer, the cavity material itself was made our of PLA, which cannot endure massively increased temperatures. Due to limitations of access to the more powerful sources used for our laser cavity proof of concept, however, we were not able to test if this material would be able to withstand higher powers of visible laser light.

Another environmental factor that will affect the quality of our device is the fact that we are trying to emit UV wavelengths in an air environment. Our device should emit in the UVB range with the laser dye we are getting, which can be heavily attenuated by air. This means that our device would have much higher output powers in a vacuum or molecule-controlled environment. Sadly, though, it would cost more to additionally design a vacuum environment to operate our device in and it would be harder to continually get access to a vacuum environment to test just our laser device in. This is not an advantage that would be worth it to us. As such, a possible improvement that we could make to our device later on to limit this environmental effect is to obtain a small vacuum cavity to place in our device at all locations where the UV beam will travel so as to limit the UVB filtering of the air between the NLO crystal where the UV light starts and the output face of the device.

Operating the laser at room temperature should keep our electrical components safe since it is within operating range for electrical parts to stay protected. The housing of the device should be able to accommodate the power supply system and we would like to keep the housing below 42 °C. The housing temperature constraint will contribute with the safety and maintenance of the PBC, batteries, and any electrical components that should not be operated at high temperatures.

The health and safety constraints on our project include those contributed by the UV light emission our device is supposed to output and the use of a carcinogenic dye. Not only can laser emissions be dangerous even at low levels, but our device is designed to convert the visible light that we are constantly exposed to in large quantities down to UV light, which is highly hazardous to humans. Visible wavelengths are not short enough to penetrate our skin enough to damage anything internal, and most of our bodies are resilient enough to such “large” wavelengths. However, UV wavelengths (200 nm to 400 nm being in consideration here) are small enough to have negative effects on the physical structures that make up our cells. So, even if the light doesn’t penetrate very deep, it is capable of destroying our skin cells, resulting in an artificial sunburn, and it is capable of breaking some of our DNA bonds, resulting in possible cancer. This being an output of our system, and even more so it being a direct and released output of our system, means that we must really take into account proper safety standards for building a device that emits UV radiation. Ignoring these standards could, even in proper usage of the device by a professional, result in giving someone cancer. Ironically, yet another component in our design can do exactly that. That is the inclusion of a liquid carcinogen in our device. This liquid carcinogen is Rhodamine B, a fluorescent laser dye. The dye in our system is already going to be well contained so that it can properly be integrated with the optics in the device, but the cell containing it, and the solution itself, should be removable. This means that the dye is not a simple toxic component of the device where proper containment and storage is enough to prevent anyone from getting hurt (such as is the case with highlighters). Instead, our design must make sure that the cavity is stable enough to contain the dye during operation, angle tuning, cavity swapping, dye swapping, and storage. Another factor that must be considered for dye safety is how it will operate or change if temperature increases with increased laser intensities inside the cavity. Essentially, the inside of a laser cavity isn’t just a storage container for the dye. It is an interesting optical location, which can result in issues when the device is in operation if dye changes during operation are not taken into account.

The ultimate safety constraint on our device is making sure that all non-user oriented components are contained inside the housing of the device and not exposed. The optics and electronics of any given device may be interesting to look at, but for an operator, exposed wires and laser beam paths only pose a safety risk and do not contribute to the design. If part of the purpose of the design was to promote laser and electronic education, then having the housing be transparent could be advantageous. But not only is this not a concern for our design, it would still involve making sure that the aforementioned components are inside the housing. Due to the fact that few of our parts are purchased as already-completed modules and we need to physically assemble this device ourselves, a custom housing should be made so that we can make sure to keep all of our parts safely contained and set up in a structure of our design.

Any material that is exposed and handled by the user specially for the housing of the device should not pose any allergy threats when it comes into contact with the skin. The use of lithium batteries could pose a safety concern which can turn into a health concern. Even though lithium batteries have standards for safety and are regulated there is always a safety concern if they leak. The fragility of these batteries makes them very dangerous when mishandled or misused so precautions have to be taken when testing and handling the cells.

4.2.3 Manufacturability and Sustainability Constraints

Most of the optics in our design were purchased from a major optics manufacturer: Thorlabs. They produce quality optical equipment that is simultaneously some of the cheaper quality optics from known manufacturers. For some of the optical components, however, a cheaper variety may be sought after. One such piece is the transmission grating for our built-in spectrometer. This is a piece that we may be able to still design a well-working spectrometer with even using a cheaper component. A major factor that influenced this decision was the fact that we were only aiming for a 1 nm resolution on our spectrometer, but under perfect conditions, it appeared that we were going to get a resolution over 9 times better than this. Therefore, we may then be able to sacrifice some optical component quality in this subsystem in order to lower our overall project cost. This is additionally something that can be redacted later if the lower quality option ends up causing us to miss our desired spectrometer resolution during testing. Nonetheless, most of our optical components will still be professionally manufactured. This means that pieces for our device should be easy to reproduce, leading to a device that is easily manufacturable. These components, however, are made mostly from glass, and some with metallic coatings. Such components are not the most sustainable. This is a known downfall to the design of optics. There are a few companies that produce biodegradable optical components so as to allow for more sustainable optical designs. However, there are relatively few of these companies, and we are only searching to make this one device. If this device were to be mass-produced, then these more sustainable lenses would be something that would be worth really looking into incorporating into our design.

The housing of our design is also easy to manufacture. We 3D printed our own custom laser cavity and the housing for our entire project. This added to our workload, but it also meant that our optical system would be well tendered to the specific physical layout that we needed, it meant we could make sure that no dangerous components or beams are exposed (which is a requirement in safe laser construction), and it meant we could custom tailor the overall device size and shape more easily. This latter detail is not as significant as an engineering specification, but we still wanted to make our device as small as possible and easy to handle/use. This detail, however, also decreases the sustainability of our project. The material that the 3D printers we have access to print in is plastic, which are infamously non-sustainable.

The dye itself also presents constraints to this project. That is because laser dyes eventually become bleached, and their capacity to lase goes away. When this happens, a whole new solution of dye must be made and swapped out with the old dye solution. The old dye solution is taken to a waste processing plant and the new dye solution is made from additional solute and laser dye powder. The components needed to make this solution are mass manufactured, and the cavity structure itself can be simply printed by a 3D printer (as discussed recently). But this also further takes away from the sustainability score of our design. Every so often the dye solution will need to be replaced, adding a periodic waste output to our design. This is a natural part of dye lasers, and is a major reason that semiconductor lasers and solid-state lasers are more popular. But, by making the laser cavity reusable, we have made sure to not add to the waste of a dye laser.

When undertaking the task of providing a battery monitoring system to our power supply the options were to build one or buy one from a manufacturer. When building one there is freedom to have our own design, but many factors prevented us from choosing this option. The high cost of parts to build a BMS and the high current draw from our power supply were two major reasons why we departed from this option. When building the BMS ourselves we factor in the complexity and time it would require a system that could be easily bought and at end would be more efficient for a power wall than a battery powered device. We chose the commercially manufactured alternative because of its low cost, low current draw and it having a great amount of features, but this option is limited by the features provided by the battery monitoring system that we buy. Texas instruments BMS gives us freedom when it comes to selecting a battery range, but again we are limited by what they consider important features for the system. The constraint of battery arrangement was not taken into consideration that would prevent us from actually having a BMS at the end. Our final battery arrangement did not require a BMS due to not having batteries in series which was not factor into the initial design.

The PCB for our power supply system should include the battery holder case, and this component should take a big portion of space in our printed board. We can try to reduce the space it takes up by stacking batteries on top of each other, but it will still be a considerable size compared with respect to the total area of the board. We might choose to custom make our own battery holder case to save space and money on the PBC. The power supply will require a certain number of batteries depending on our power/current supply needs and we have not determined the total power requirement because of time constraints. After considering this constraint we decided to not integrate the battery holder case into the PCB design.

5. Design Details

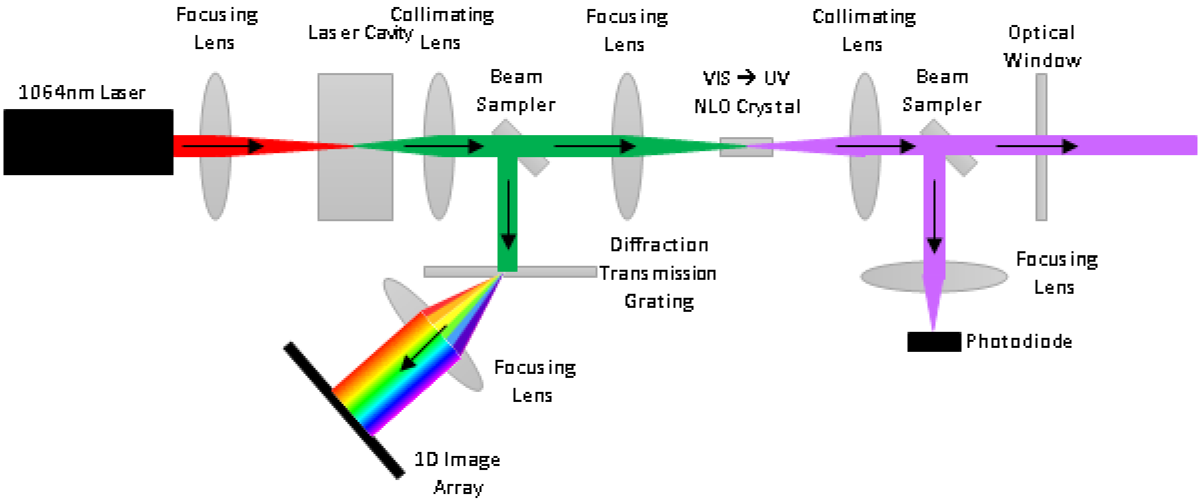
5.1 Starting Design Layouts

The primary functions of the optical design were to generate a laser beam from a dye laser cavity, self-sample the beam for wavelength and output power, and frequency double the beam from VIS to UV.

5.2 Optical Design

A summary of the entire optical layout will be described below, and a visual of this can be seen in figure 3 below. The optical system of this project involves a 1064nm-pumped self-contained dye laser cavity, a VIS spectrometry sampler, a SHG NLO crystal, and a UV optical power meter sampler. Additionally, focusing lenses must be used to focus the beam onto the laser cavity, the 1D image array, the SHG NLO crystal, and the UV photodiode. Likewise, collimated lenses must be used to collimate the beam onto the beam samplers and when exiting the device (though this should still be collimated from the lens collimating the beam into the UV beam sampler). The lenses that we use to collimate and focus the beam along the main beam path will likely all be short-focal length lenses. This is because we want our device to be small and handheld if possible. This means we need to transition between these focusings and defocusings in as little space as possible. The increased spherical aberrations that one can get from using short-focal length lenses is not so much a concern for us here as we aim to have this beam to be circularly symmetric, and small, propagating only near the centers of the lenses.

Figure 3 - Optical Layout Summary



Everything from the pump source to the collimating lens after the laser cavity are absent from the final optical design completed for senior design 2. These changes were due to a few different reasons: failures in the design process, expenses of parts, and limited access to equipment for testing prototypes. In the sections following that discuss the optical design, the original design is discussed for the entire system. Changes are noted, though not discussed in detail until the prototyping sections later on.

5.2.1 Laser Cavity

The optical cavity is the most important optical component of a laser system. A laser works by the stimulated emission of excited electrons in a gain medium. To amp up the lasing potential, you reflect the emitted light back at the medium over and over again, letting a little bit out for every pass to use. The primary issue to consider in the design of an optical cavity is to make sure that the cavity is stable. That is, to make sure that the light reflects off the mirrored surfaces in a periodic manner so that none of the light escapes the cavity except that which is purposed to transmit through the output coupler and be used as the laser output

Mirror Size/Space Constraints

Some aspects of our optical cavity are restricted by design constraints rather than by efficiency of design. The primary of these is the cavity diameter. The four constraints related to our cavity diameter are size, laser dye, costs, and commercial availability of parts. We want our device to be handheld, and although you can use a 5” diameter device in your hands, it isn’t exactly the average person’s idea of a handheld device. For this reason, we are trying to stay below 2” diameter. Then there is the laser dye. Laser dyes can be expensive; and even though we are looking at some more common dyes that are cheaper due to the frequency of their usage as laser dyes, we must take the square-cube law into consideration. The square-cube law draws attention to the fact that volume increases faster than surface area. Specifically, if the surface area is multiplied by a factor of α, then the volume is multiplied by a factor of $\alpha^{3/2}$. In our instance, a multiplication of the diameter of the cavity would result in a multiplication cubed of the volume (doubling the diameter results in an octupling of volume). Since dyes are purchased by their mass, and mass increases linearly with volume for a given dye solution concentration, this means that the cost of the dye would octuple for every double we perform on the cavity diameter. There is also the issue of costs of lenses. Using Thorlabs as a reference, taking into account their plano-concave dielectric coated mirrors and uncoated plano-convex, plano-concave, bi-convex, and bi-concave N-BK7 lenses, the .5” diameter lenses cost on average 91.31% of the 1” lenses, and the 2” lenses cost on average 159.2% of the 1” lenses. Finally is the commercial availability of lenses. Most optics suppliers sell lenses of .5”, 1”, and 2”, and a few different mm diameters. To use lenses larger than this would greatly decrease the options of focal lengths and prices that we would have to choose from. Ultimately, due to size constraints, and a large increase in the price of dye and lenses above 1”, we have settled on using lenses of a maximum of 1”, and .5” in select positions where such can be done for greater individual piece price drops without quality reduction.

The same constraints just mentioned for the volume of the laser cavity also affect the cavity length. As the cavity length doubles, the volume approximately doubles. So the shorter the cavity, the better. One concern that could then be brought up is whether a shorter laser cavity will contain enough gain to support lasing. There are 2 factors that work to negate this concern. The first is that of alternative dye laser designs. Most dye lasers (especially high powered ones) seek to optimize operation time by lasing a small stream of dye between two mirrors. This stream can be around .5mm wide and is constantly flowing with new dye. If lasing can occur with only 0.5mm of laser dye in the right conditions, then a cavity on the scale of centimeters should have plenty of gain. A second factor is one unique to dye and gas lasers: controllable concentration. Unlike a solid-state laser crystal, dye concentration can be increased or decreased based on how much dye per unit volume is used for the dye solution. This can serve to increase or decrease the gain per unit length of the cavity. There are also 2 physical constraints on the cavity length. The first is that the cavity length is measured from the center of the lenses. So if concave lenses are used, then the surfaces can only be brought so close before the edges of the lenses are in contact and would not allow the centers of the lenses to be brought any closer. Additionally, because we need to be able to get the dye solution inside the cavity, a fill port will need to be included on the custom mount that will be designed to hold the lenses together. This fill port can be of any size so long as it is large enough to pour/insert a liquid into (likely with a pipette) and pour liquid out for when the dye needs to be swapped out (since laser dyes do become bleached over time). The relatively arbitrary number that I have been giving to this thickness is 1cm between the lenses' edges.

Mirror Selection

In looking for mirrored surfaces to construct the laser cavity, a few things needed to be taken into consideration. 1) They need to be transmissive at the pump wavelength, 2) they need to be highly reflective at the lasing wavelength, 3) they need to be of a valid diameter from what was discussed earlier, 4) the substrate needs to be transmissive to the lasing wavelength, and 5) they need to be concave (the reason for this will be discussed in detail in the following sections). Two desired traits that are not absolute necessities are that they be low cost and that they have a positive transmissive power. The positive transmissive power would make the output coupler serve dually as a mirrored surface for the laser cavity and as a focusing lens for the expanding laser beam leaving the cavity assuming a basic linear cavity is used.

I was able to find a mirror that satisfied 6 of these qualities, with the only exception being the positive transmissive power. Thorlabs' CM254-E02 series are plano-concave lenses made from N-BK7 glass. They have a dielectric coating that reflects >99% of light in the range of 400nm to 750nm while transmitting approximately 76.27% of 1064nm. They come in diameters of .5", 1", 2", and 75mm. The .5" diameter version comes in ROCs of 24, 50, and 100mm, and the 1" diameter version comes in ROCs of 50, 100, 150, 200, 300, 400, 500, 1000, 1500, and 2000mm. The prices for this optic are $59.79 at .5" diameter and $85.22 at 1" diameter. Needing two of these drives the price up to a total of $119.58 or $170.44, which is quite expensive, but much cheaper than some custom cut and coated mirrors can be.

One issue that had to be addressed was the fact that this coating reflects at 532nm, which is the pump wavelength for most laser dyes. Our solution to this is to have the laser device's pump a 1064nm Nd:YAG laser, and use intracavity frequency doubling (IFD) to convert the transmitted 1064nm down to 532nm to then pump the dye. It is also worth noting here that this is why it was specified before that the mirror needed to be transmissive to 1064nm. With most laser dyes being pumped by 532nm and emitting also in the VIS spectrum, it can be hard to find cheap coatings that transmit at 532nm and reflect at other VIS wavelengths. The nonlinear optics (NLO) crystal that will be used for our cavity will be KTP (since this NLO crystal frequency doubles 1064nm quite well) and need to be in the form of a disc. The shape is important to maintain the radial symmetry of the cavity so that the gaussian-like beam does not get distorted by corners that would be present if a square cross-sectional crystal was used.

For first prototyping, however, a disc of KTP was deemed too expensive to get custom cut. As a result, a standard block of KTP will be used instead. This will greatly reduce costs of the crystal by well over an order of magnitude, but it will risk the generation of a messier beam shape.

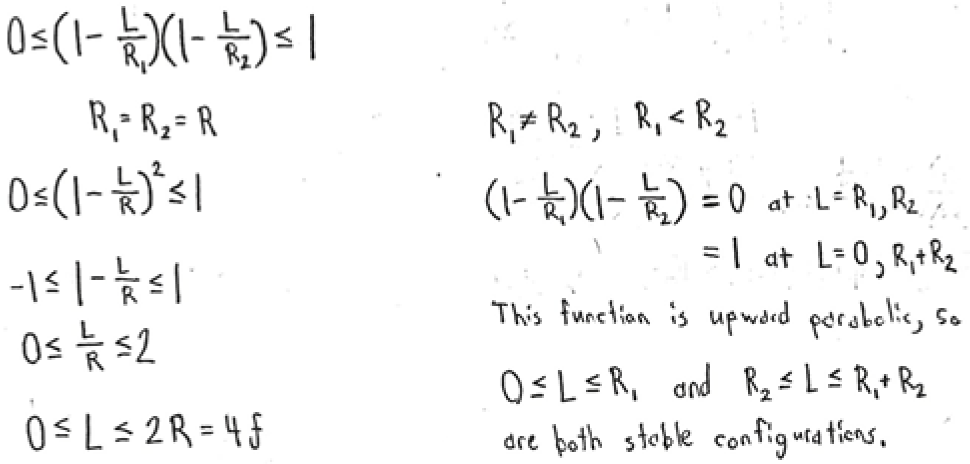
Cavity Stability

The ABCD law for laser cavities describes the conditions of a cavity transfer matrix that can result in stable lasing of a Gaussian beam. Further, solving for the transfer matrix of a two mirror linear emission laser cavity and applying the ABCD law yields the following:

$$0 \leq (1-L/R_1)\,(1-L/R_2) \leq 1$$

The most stable pair of mirrors for a laser cavity is a pair of circular concave mirrors. A circular concave-concave cavity is stable regardless of angular misalignment so far as the mirror still blocks the laser axis. Up to this point, the cavity would not stop lasing, but instead the size of the lasing beam would be limited to a fraction of the Gaussian beam. A concave-concave cavity is also quite resistant to longitudinal misalignments. When the radii of curvature (ROCs) of the two mirrors are the same, then the cavity is stable for all optical path lengths up to twice the ROC of the mirrors (the point at which the cavity is two arcs of a single circle in the case where the ROCs are the same). The effect of ROC and cavity length on cavity stability within a small range of cavity lengths being considered can be seen in figure 4. For cavities where the two ROCs of the concave mirrors are different, the cavity is stable for lengths between 0 and the smaller ROC, and between the larger ROC and the sum of the ROCs. This calculation can be seen in figure 5 below.

Figure 4 - Calculation of Stable Cavity Lengths based on ROC



$$0 \le \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \le 1$$

$R_1 = R_2 = R$

$$0 \le \left(1-\frac{L}{R}\right)^2 \le 1$$

$$-1 \le 1-\frac{L}{R} \le 1$$

$$0 \le \frac{L}{R} \le 2$$

$$0 \le L \le 2R = 4f$$

$R_1 \neq R_2$; $R_1 < R_2$

$$\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) = 0 \text{ at } L = R_1, R_2$$

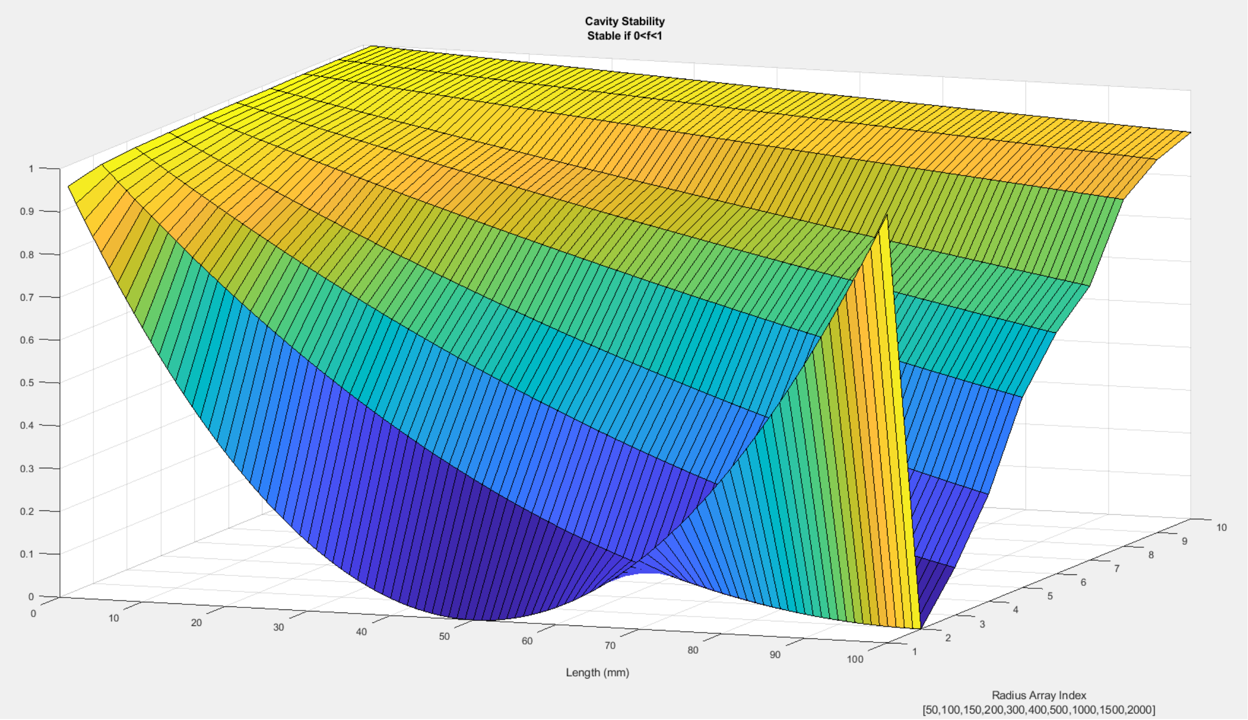
$$= 1 \text{ at } L = 0, R_1+R_2$$

This function is upward parabolic, so

$0 \le L \le R_1$ and $R_2 \le L \le R_1+R_2$

are both stable configurations.

Figure 5 - Cavity Stability Parameter as a Function of Length and Equal ROCs

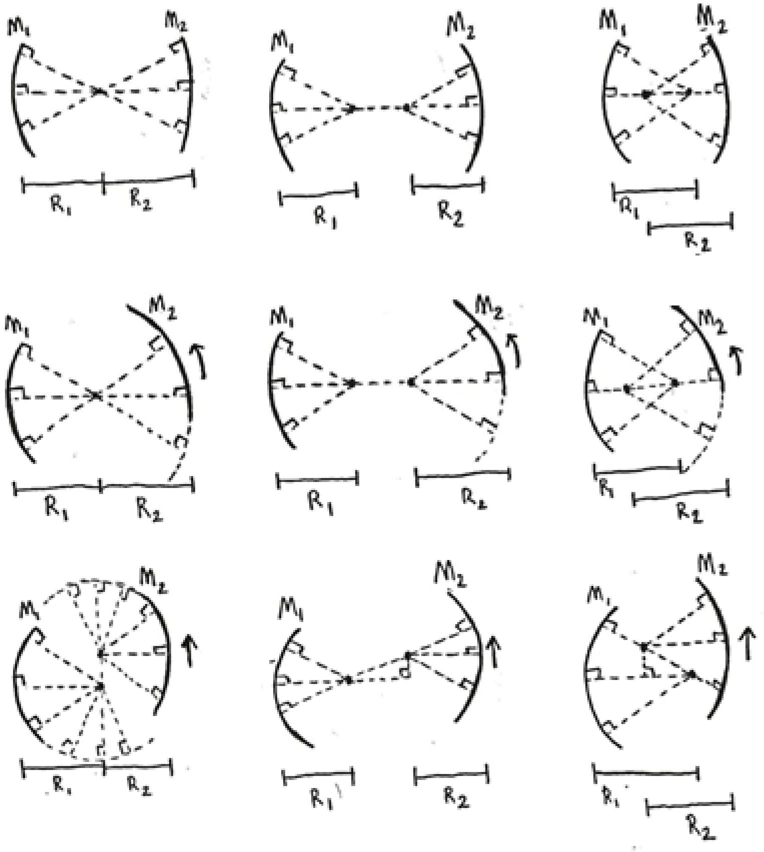


Lateral misalignments are a more complicated matter, combining rotational and longitudinal misalignments. For this third type of misalignment, I have run Matlab simulations of cavity stability based on different ROCs of the mirrors and an assumed maximum lateral misalignment of 2mm. It should be noted that a 2mm lateral misalignment when working with 1” lenses is clearly visible and controllable. This value was chosen as a severe misalignment case for testing more so than an expected tolerance of lateral alignment.

Cavity Misalignment Tolerance

I will first show here, in figure 6, sketches of the possible misalignments for a circular concave-concave cavity:

Figure 6 - Possible Misalignments of Circular Concave-Concave Cavities



The first column represents a concentric cavity setup where cavity length (L) is equal to the sum of the ROCs (R_1 and R_2), that is $L = R_1+R_2$. The second column represents cases where $L > R_1+R_2$, which I will refer to as a far cavity. Finally, the third column represents cases where $L < R_1+R_2$, which I will refer to as a near cavity. The first row represents the ideal case for the setup, with variation over longitudinal alignment, both intended and misalignment. As discussed before, the cavity is stable in length unless the length is between the sizes of the ROCs of the mirror or when it is longer than the sum of the ROCs. So if the cavity was built with two 50mm ROC mirrors at a cavity length of 25mm, there would be room for 25mm of longitudinal misalignment. This is very far outside the realm of misalignment possibilities for the human hand. Much less so is this a concern in the size of the to-be 3D printed ring that fixes the mirrors together. Any length then that is far enough away from either ROC and the sum of the ROCs will have plenty of tolerance for longitudinal misalignment.

The second row represents a rotational misalignment of a mirror around its ROC. As can be seen, the actual layout of the cavity does not change for rotational misalignments, but rather the area of the mirror around the central lasing axis decreases. If the mirror is rotated so far that the mirror surface does not actually intersect with the central lasing axis, then the cavity will lose stability.

The third row represents a lateral misalignment. Purely by glancing at the geometry of the cavity, we can see that concentric cavity setups are extremely susceptible to losing cavity stability due to lateral misalignment. Near cavity and far cavity setups, however, can withstand a degree of lateral misalignment while still having the central lasing axis reflecting back and forth between the mirrors, though the axis will then be tilted, resulting in the laser beam exiting at a different angle and location on the outside of the cavity. Figures diagramming these responses can be seen below for an assumed lateral misalignment of 2mm (which is very large compared to a 1” or .5” diameter lens, and will likely be far more than any misalignment that will actually happen).

Figure 7 - Cavity Length Change vs Cavity Length and Equal ROCs for 2mm Lateral Misalignment

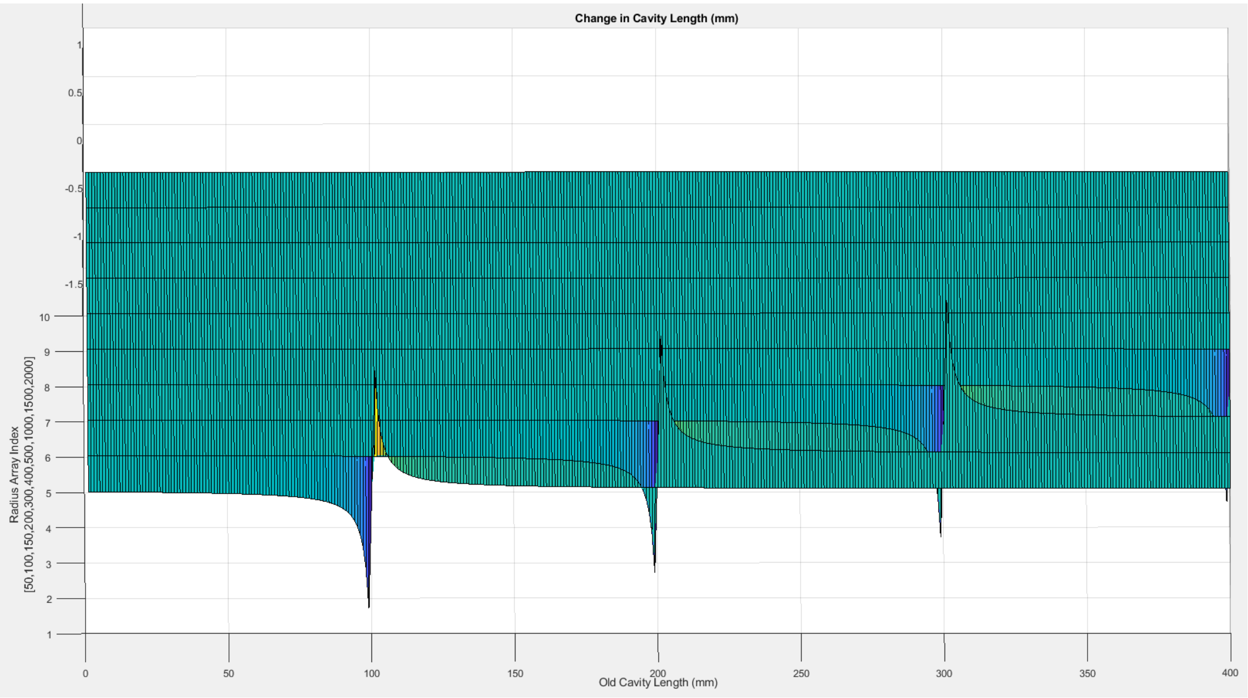
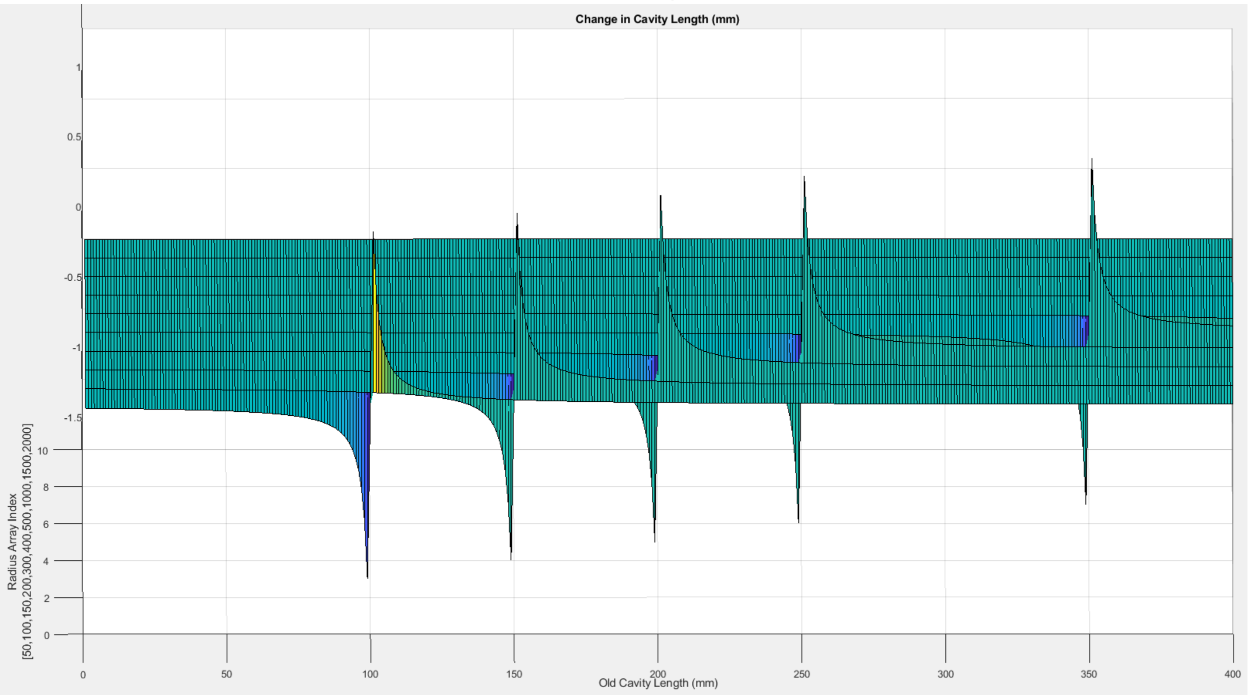


Figure 8 - Cavity Length Change vs Cavity Length and ROC$_1$=50mm for 2mm Lateral Misalignment



The diagrams above display that even a 2mm lateral misalignment will cause next to no change in the cavity length unless the starting cavity length is near the sum of the ROCs of the mirrors. Even if the smallest ROCs are selected (50mm each), then this would require having a cavity length close to 100mm to risk large changes in cavity stability. Such an option was already less than optimal since we want to design a small and easy to use cavity. Making the cavity near 100mm would cause an issue with that from the start.

Another potential problem with lateral misalignments is that they result in an angular displacement of the central lasing axis. This was also analyzed with an assumed 2mm of lateral misalignment, and the results followed the same pattern as the cavity length change in the same scenarios.

Figure 9 - Lasing Angle vs Cavity Length and Equal ROCs for 2mm Lateral Misalignment

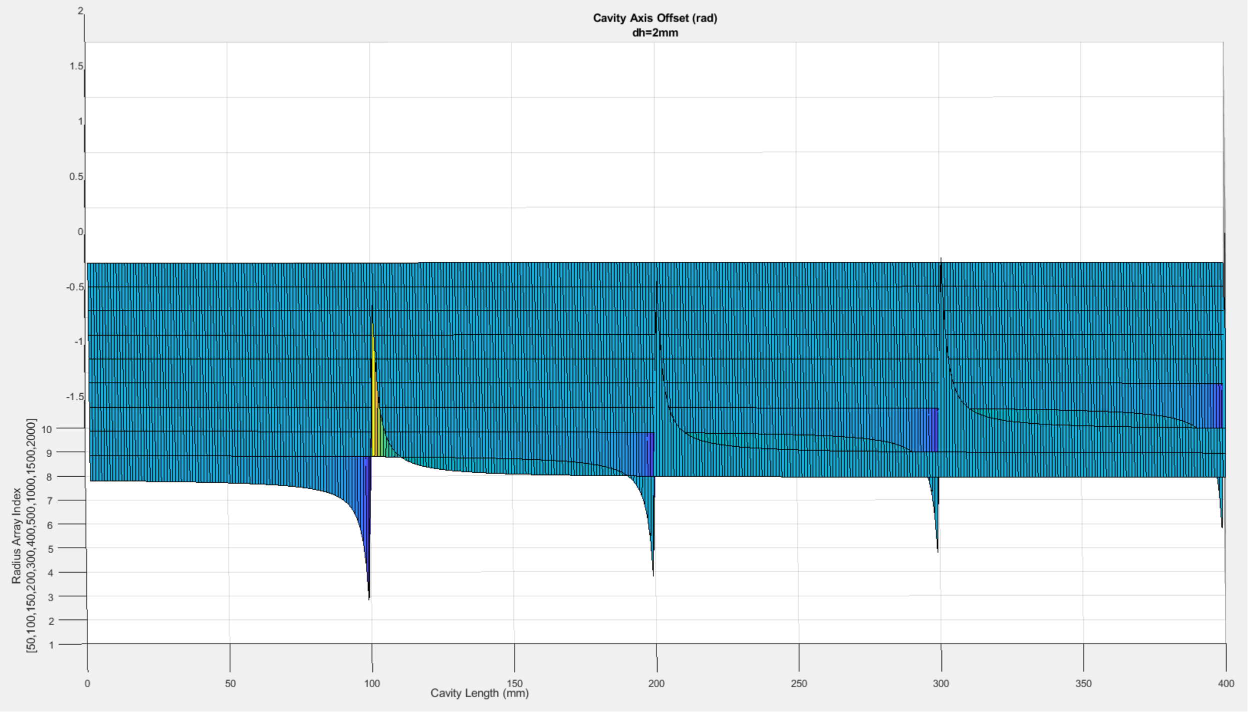
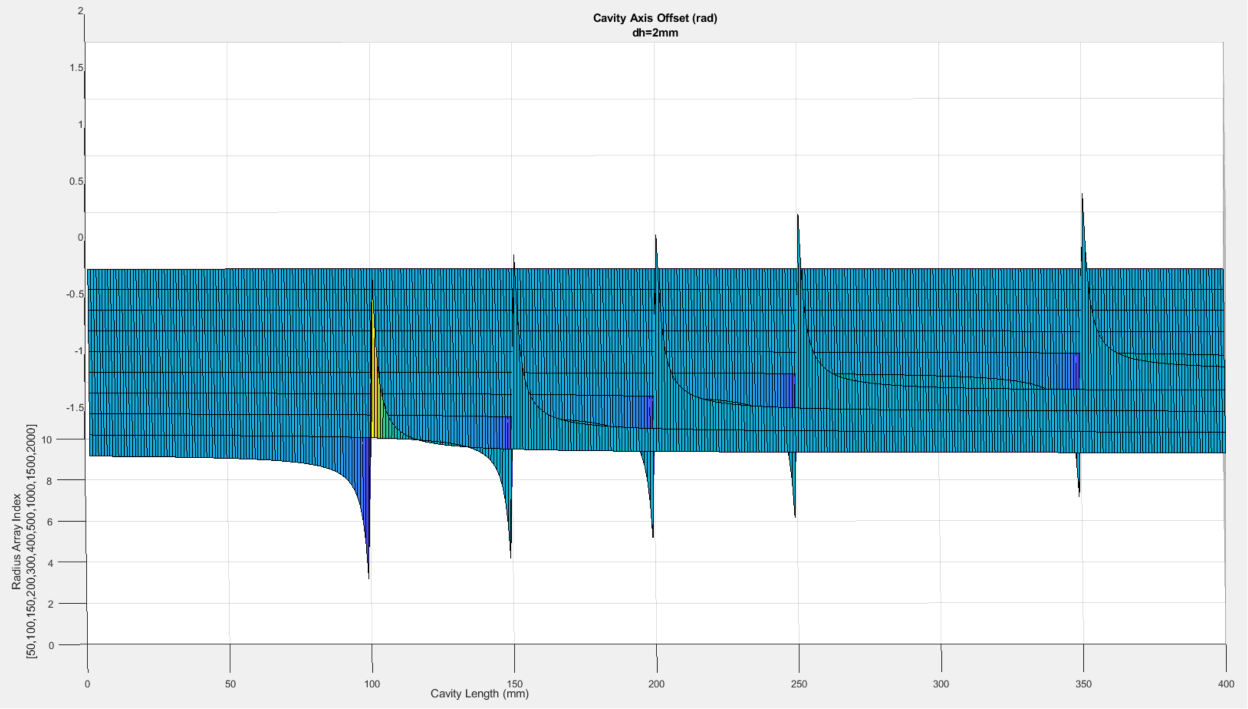


Figure 10 - Lasing Angle vs Cavity Length and ROC$_1$=50mm for 2mm Lateral Misalignment



Taking specific data from this graph would result in a <5° of axial displacement for a pair of 50mm ROC mirrors after 2mm of lateral misalignment if they were placed 77mm away from each other or closer.

In our aims to make the laser cavity relatively short, the first major limit we hit was on the overall stability parameter of the cavity. This parameter dictates that the cavity be shorter than the smaller of the two mirrors' ROC. The smallest ROC offered for the mirrors we are looking at is 50mm. Therefore, to be safe, we should aim to make our cavity less than 50mm. The stability parameter as a function of cavity length is parabolic, with the apex of the parabola half way between the ROCs of the selected mirrors. So making sure the selected cavity length is somewhere around half way between the smallest ROC and 0 would be the safest general option without knowing specific ROCs. This means a cavity length of about 25mm. Further, the length errors possible from lateral misalignments would then come nowhere near the changes that would be necessary to destabilize the cavity. And most recently, the angular displacement of the lasing axis was considered for lateral misalignments. If we wanted to aim for <5° of error in the lasing axis in the cavity, then this would mean having the cavity be less than 77mm long for a cavity of two 50mm ROC mirrors. Using larger ROC mirrors would further reduce this potential error.

The one type of misalignment not discussed here is the practical way that angular misalignments tend to manifest themselves. This is in the form of a rotation of the mirror along its center. This would result in an angular misalignment equal to that by which the mirror was tilted. But this would also result in a lateral misalignment (dh) of

$$dh = ROC*\sin(\theta)$$

For the previously assumed 2mm of maximum lateral misalignment and a 50mm ROC, we would only have to misalign the mirror by 2.29°. For larger ROCs, this value goes down. Even just the next smallest ROC offered of 100mm yields an allowed error of only 1.15°. Making sure these angles are not reached should be obtainable with the 3D printers we are able to use, but appear to be the largest issue we could come across with cavity alignment.

Beam Divergence

In looking at the divergence of the laser beam coming out of the cavity, two major factors come into consideration: minimum beam spot size and the power of the lenses that the mirrored surfaces are deposited on. The minimum beam spot size is inversely related to the angle of a Gaussian beam's divergence. These can be solved for using the complex beam parameter (q) of the Gaussian beam

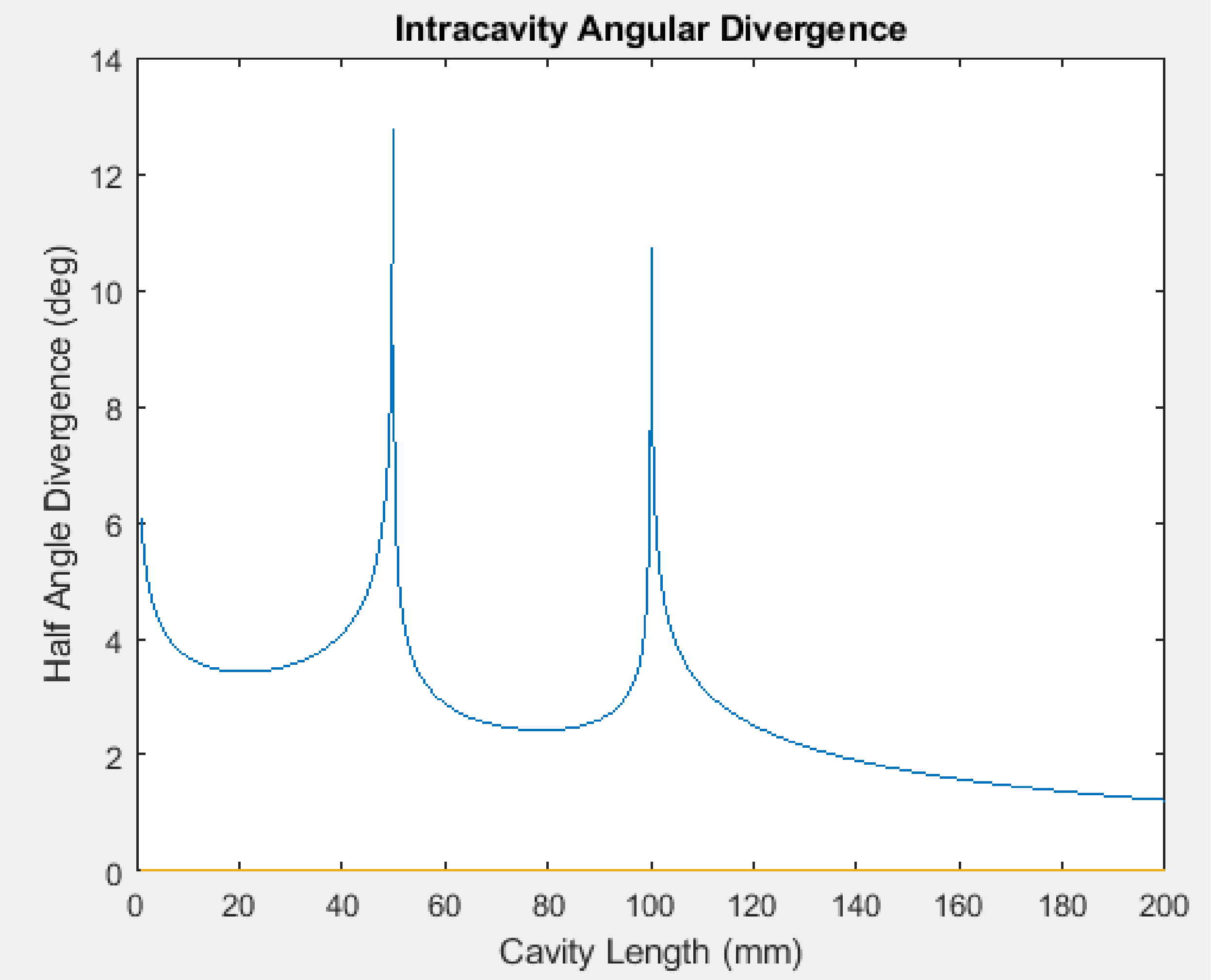
$$\frac{1}{q(z)} = \frac{1}{R(z)} - i\frac{\lambda}{\pi\omega^2(z)}$$

and the relationship between minimum spot size and half-angle beam divergence

$$\theta_{div} = \frac{\lambda_0}{\pi\omega_0}$$

Where R is the ROC of the beam's wavefront, ω is the beam spot size, λ is the beam wavelength, z is the position in the direction of propagation, and θ is the half-angle beam divergence. Between two mirrors of known ROCs, the minimum spot size ω_0 and its location can be calculated. For two mirrors of equal ROCs, the position of the minimum spot will be halfway between the two mirrors. Figure 11 shows the resulting half-angle beam divergences from a pair of 50mm ROC mirrors and 532nm light at different cavity lengths.

Figure 11 - Half-Angle Beam Divergence for 50mm ROC Mirrors at 532nm



The amount of beam divergence for a pair of mirrors with the same ROC is based on the cavity length's proximity to 0, the mirror ROC, and the sum of the mirrors' ROCs. Since realistic angular misalignment and cavity stability prompted us to look at using 50mm ROCs for our lenses and to use a cavity length about half way between them (around 25mm), we should focus on that region for the angular divergence. We can see here that the intracavity beam divergence is smallest between cavity lengths of 0 and the smallest ROC. Specifically, for a pair of 50mm ROC mirrors, the smallest beam divergence showed at ~21.1mm, yielding 3.4302°. That is a full-width beam divergence of 6.8604°. This would also correspond to a minimum beam spot size of .162064mm.

This could be brought down further by selecting mirrors of a larger ROC. Running the same calculations at 100mm ROCs yields a minimum half-angle beam divergence of 2.03961° at a cavity length of ~42.2mm. The issue with doing this, however, is that of the real angular misalignment of the mirrors as discussed before. Going up to 100mm ROCs would bring our beam divergence down by ~40%, but it would simultaneously half how much tolerance we'd have in aligning our mirrors. A half-way point for this would be if we were willing to accept that decrease in alignment for only 1 mirror, and thus use a mirror of ROC 50mm and another of ROC 100mm. This would yield a minimum beam divergence of 2.74557°. This would likely be an alteration that could be made to the cavity during senior design 2 if we are able to get incredible accuracy with the angular alignment of the mirrors during prototyping.

There is, ultimately, another factor that is going to expand the beam. That is the lens on which the mirror has been deposited. The only options offered for this mirror are plano-concave, which have a negative power. Negative powers further increase an angle of divergence, whereas positive powers would decrease the angle of divergence, and could even help serve to collimate the output beam from the cavity. However, no positive meniscus lenses are offered with this coating. The powers of the 50, 100, 150, 200, 300, 400, 500, 1000, 1500, and 2000mm ROC lenses are -10, -5, -3.33, -2.5, -1.67, -1.25, -1, -.5, -.33, and -.25D respectively. For just the 50mm ROC case looked at before with a half-angle beam divergence of 3.4302° in a cavity 21.1mm wide, the half-angle divergence of the beam as it exits the cavity will be 3.7930°. In the 100mm ROC case, it would go from 2.03961° to 2.2575°. These additions to the beam divergences caused by the exiting lens are not very large and will be easy to correct with a positive lens.

Cavity Structure Solution A

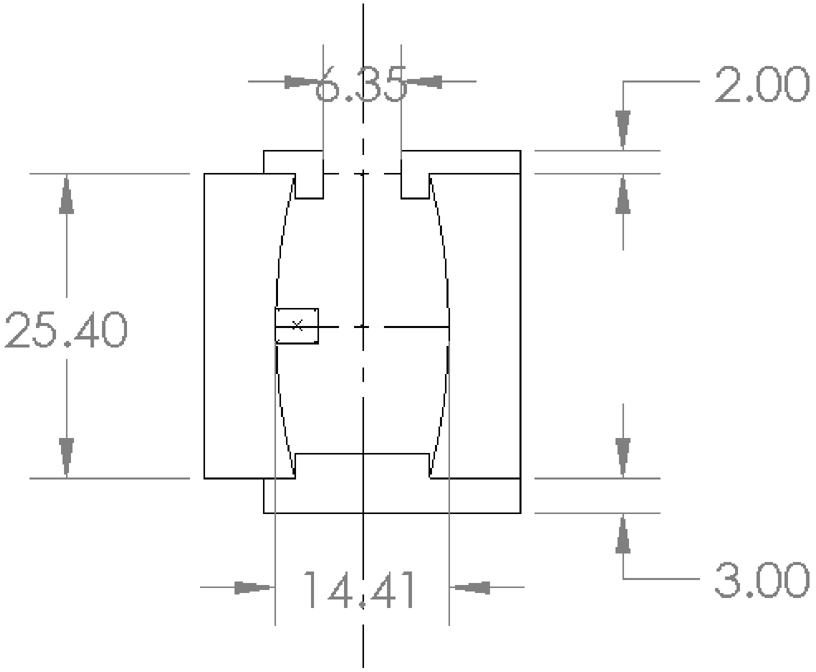
This project is not very heavy in mechanical engineering. As a result, we did not seek out a mechanical engineer to be on our team. However, because a degree of mechanical sophistication is important in the design of this self-contained optical cavity, an aerospace/mechanical engineer was consulted for advice on the construction of the cavity.

The idea was to 3D print a ring adapter with a primary inner diameter matching that of the mirror diameter on each end (so as to fit the mirror into the adapter), and a secondary inner diameter of slightly less than that, located at a to-be-determined position so as to stop the mirrors at a fixed distance away from each other, fixing the mirrors at a set separation and aligning their central axes. A flat would need to be ground down on one end of this ring so that a threaded hole could be put in the ring where a screw and o-ring could create a water-tight fill port through which dye solution could be put into or taken out of the cavity. The mirrors should be fixed in the ring with water-tight epoxy. Epoxy was chosen over alternatives like super glue due to its higher performance at fully filling the space between the attached surfaces, which is a crucial detail in water-sealing a connection. Finally, an operational constraint develops here. Because liquids are not easily compressible, the cavity could not be completely filled. If it were completely filled, and the screw on the fill port were to be fixed on, the liquid would resist compression and could pop the mirrors right out of their sockets. The solution to this is to leave a small amount of air in the top of the cavity since air is compressible. This is acceptable in terms of maintaining a stable cavity and a Gaussian-like beam since the beam should not be propagating at the far edges of the mirrors. However, because the dye solution and air are both fluids, tilting the laser would result in this air pocket moving to a different region of the laser cavity. If tilted too far, and brought into the path of the lasing beam inside the cavity, Gaussian-like profile of the beam could be badly distorted, the power of the beam should drop due to the lower dye solution length in the beam path, and the angle of the beam output could be disrupted if the dye solution to air interface were not perfectly orthogonal to the central lasing axis.

Additionally, a small bit of room around the circumference of the mirror should be left exposed on the pump source side of the cavity to allow for the kinematic mount that will hold the cavity in place to position itself around the mirror and for the set screw to be tightened down.

A sketch of this entire setup can be seen in figure 12 below.

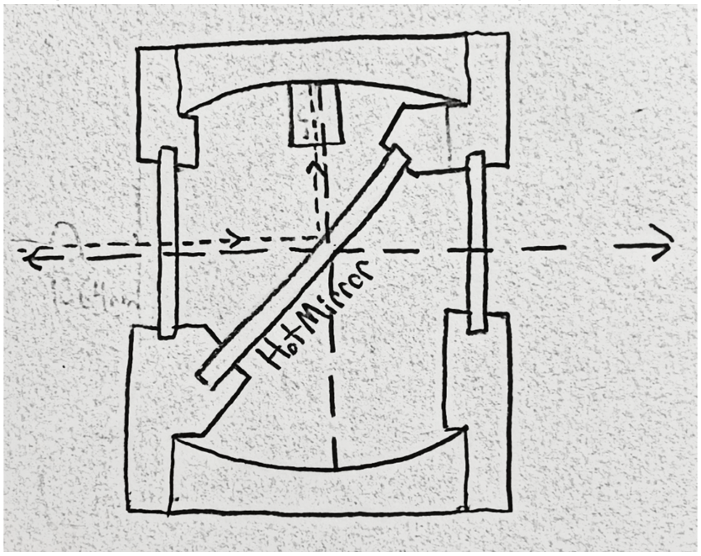
Figure 12 - Sketch of Laser Cavity Design A



Cavity Structure Solution B

There is 1 major problem with cavity structure A. That issue is that most of the non-reflected light on the mirrored surface is absorbed, not transmitted. Transmission of visible light between 532nm and 600nm (the range across which most sources claim Rhodamine B to emit at) can be as low as .000311% (this occurs specifically at 579nm). This means that next to no power generated inside the cavity will escape the cavity. What would be preferred is for a high reflectivity where the remainder is transmitted, not absorbed. One solution to this is to use a partially transmissive mirror to fold the cavity over. An example of this setup can be seen in figure 13. In the sketch, the dotted line represents the 1064 nm laser pump source, and the dashed line represents the VIS light reflecting in the laser cavity and being reflected out of the cavity.

Figure 13 - Sketch of Laser Cavity Design B



It should be noted that figure 13 is a top-down view of a cross section of the proposed laser cavity. The cavity itself will need to hold 1” diameter mirrors on either side facing inwards, a hot mirror tilted to 45° in between the mirrors, an optical window on either side for pump source entrance and laser emission exiting, and the actual dye solution, which could be contained in either of the two formed cavities or both. The cavity should still have a threaded fill port on the top (facing out of the page) through which one can fill the cavity with the dye solution and through which one could empty the cavity for solution replacement. It should also have a ring on the 1064 nm entrance side that protrudes normal from the cavity with an outer diameter of 1”. This is to replace the use of the mirror’s 1” outer diameter as a mounting surface by which the kinematic mount can be used to position the cavity. Finally, the KTP should be positioned in the cavity on the mirror by which the first 1064 nm reflection will strike, oriented facing towards the mirror so as to convert the 1064 nm to 532 nm before it strikes the convex mirror. All of these components should be fixed together with epoxy or industrial adhesive that is water-proof.

A hot mirror is a mirror designed to reflect IR light at 45 degrees and transmit VIS light at 45 degrees. The percent of VIS light reflected (that which escapes the cavity) is, however, usually within the 5-15% range. This means that a significant portion of the light inside the cavity will be reflected out in each pass. However, looking only at the reflectivity versus transmissivity of this single component in the already-existing system, the optimum transmissivity would be around 84.85%. This is just below the lower limit of the specs for a basic hot mirror from Edmund Optics. Since the emission wavelength of Rhodamine B seems to not be set in stone across experiments, it would be difficult to predict the actual transmissivity that the lasing wavelength will experience for a given cavity without testing it oneself.

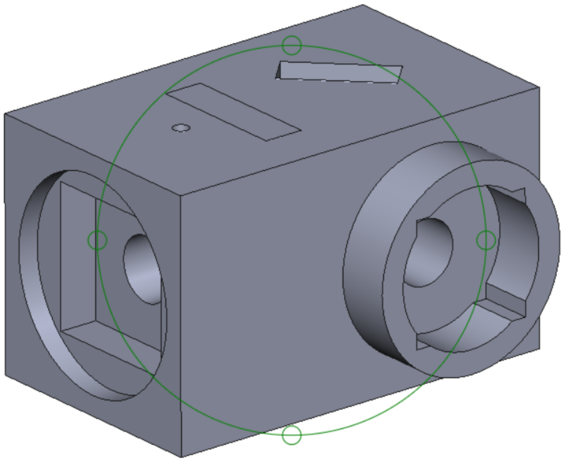
Even though this cavity solves the major problem of getting the light out of the cavity to be used, it introduces a problem of cavity length. Before, it was discussed that a nice cavity length would be about 21.1 mm in OPL. With this setup, however, the minimum possible physical length (shorter than OPL) would be 32.59 mm. This is due to having to fit the tilted hot mirror in between the two concave mirrors. With this separation of the cavity, it would be possible to fill only one side with the laser dye. This means that there would be no risk of the dye absorbing the 1064nm pump source before it could be frequency doubled.

The most significant problem that this design imposes is that it forces the cavity length to approach the ROCs of the concave mirrors. If the OPL is equal to the ROCs, then there is the risk of having an unstable laser cavity if either mirror is not perfect in its physical shape, and even if they both were, it would lead to a skyrocketing intracavity beam divergence. Keeping the cavity at around its shortest possible OPL of 32.59 mm would result in nearly 4° of half-angle divergence and a minimum beam spot size of around 1.826 µm. With the now-flat interface between the beam path and the outside air, this angular divergence would rise to 5.317° with a spot size of about .8875 mm upon exiting the cavity.

Cavity Prototype

When testing parts for the cavity solution described above, a few issues were discovered. Such issues ranged from low conversion efficiencies through KTP to high absorption of 1064 nm light through the dye solution. The redesigned solution was to move from a 1064 nm pump source to a 532 nm pump source. This would cut out the KTP and call for a change in pump source and input/output mirror. The new mirror selected was a longpass dichroic mirror (cutoff of 550 nm) from Thorlabs to reflect most of the 532 nm pump light into the cavity and reflect only about 2% of the approximately 590 nm light out of the cavity on each pass. The distances were also changed since a miscalculation on my part by the time of cavity printing led to an OPL shorter than anticipated. Finally, it was realized during prototyping that filling the curved surface of the mirrors with the dye solution would change the effective radius of curvature, and could destabilize the entire cavity. Because of this, dye containment was restricted to a small section just before the first curved mirror would be struck by 532 nm light, contained with VIS transmissive glass on both sides. A model of this may be seen in figure 14 below.

Figure 14 - Solidworks Model of Final Cavity Prototype



Additionally, the doglegging of the beam through the mirror on each pass in the cavity itself and on the output path had not previously been taken into account. On this final design, this doglegging was only about .4 mm, which is well inside the bounds to which the cavity would remain stable. Nonetheless, for optimization of the design itself, mounting locations were modified in the design to keep the cavity in its most stable designed setup. The final OPL of this design was just over 60 mm.

5.2.2 Optical Power Limits

One concern that applies to both an operation spec of our design and the ability of our design to comply with industry standards is the output optical power of the laser beam. Standards like ISO 12123:2018 and ISO 1:2016 talk about what is required of manufacturers to produce an optic and sell it as safe to use under certain conditions. The main two conditions that apply in our case are power and wavelength.

When working with ambient light or simple light sources, the optical power obtained from them tends to be very low. These sources would in normal circumstances never be able to do damage to a glass lens unless it was a very specific kind of glass that was very photosensitive. We, however, are building a laser. We are not building a very high-powered laser, so the damage thresholds of the glass used in the standard (typically N-BK7) optics are not a concern. However, any coatings applied to these optics (such as the dielectric mirror coatings) or special optics (such as the beam sampler) are more fragile than glass. In our case, the mirror coating is not fragile enough to warrant concern. However, data is readily available on damage threshold for beam samplers, standard lenses, and cube beam splitters. For the first two, the damage threshold provided by Thorlabs is 7.5 J/cm^2. Using 1” pieces, this translates to 48.387W of optical power if the full diameter is used. For .5” pieces, it would be 12.10W. The beam splitter’s data is presented differently, as 50 W/cm. This translates to 63.5W of optical power. Either way, this is far more power than we are expecting to get out of our design. Lasers that operate in the Watts range are generally high-powered lasers. Seeing as none of us have ever built a laser, and we are not using pieces specially designed and built for this laser system, the output power of this laser will likely not rank with the high-powered ones being used in industry.

The other factor to consider is the wavelength of the light that an optic is designed to properly work with. One simple factor that contributes to this is chromatic aberration. Any given material's refractive index is a function of the wavelength in consideration. Though a lens designed for VIS light can still interact efficiently with UV light, for example, the data used to properly predict how the light path is affected can be far off. Instead of collimating a beam to well control it, you could easily disperse it and start irradiating everyone near the front of the device with UV radiation. In some cases, the difference in how the intended wavelength would pass through an optic vs how the wavelength in use passes through an object can be so drastic that the light does not pass through it in an otherwise predictable way. For a lens, the light could strike the edge of the lens and disperse outward throughout the device, losing all control over the propagation of that radiation. The solution to all of this is to make sure pieces are selected for the proper wavelengths. For our design specifically, it is important that we take note of the fact that we plan to convert the VIS light emitted from the laser cavity into UV light. So, we must either select optics that work properly and predictable in both the VIS and UV ranges, or make sure of which wavelength is being controlled at each point in the system so that the proper wavelength is covered.

5.2.3 Laser Dye

Excitation & Emission

There are many important details to take into consideration when selecting a laser dye to use. The laser is pumped by a specific frequency of light, and so the cavity must be designed to transmit the pump light into it or to convert the pump light into the needed frequency to excite the dye. In our case, we are looking at Rhodamine B, which is excited by 532nm. Our laser device emits 1064nm from a Nd:YAG laser pointer. This means that we can pump dyes that are excited by 1064nm or any of its frequency harmonics. Rhodamine B is excited by its second harmonic, and so we need a piece of nonlinear optics (NLO) crystal to convert the 1064nm light into 532nm inside the cavity. If a dye excited by 1064nm itself was used, the NLO crystal would not be necessary for that cavity, and if 355 or 266nm were needed, then different NLO crystals for conversion to those frequencies would be used instead. We have selected mirrors that would work for most laser dyes. The spec identified for this is the emission wavelength of the dye and the reflectance of the mirror. Since most laser dyes emit in the VIS spectrum, and the mirrors we have selected reflect >99% in the VIS range, most dyes could be lased with these mirrors.

Another component that was significant in the dyes that would work in the final designed cavity was the dichroic mirror used to get 532 nm light into the cavity and act as an output coupler for higher wavelengths. For all visible wavelengths from about 577 nm and above, less than 3% of the light would be reflected out on each pass, allowing for a cavity with an effective output coupler of approximately 94% reflectance going by standard linear cavity designs. If one wanted to use other dyes, the folded design mentioned before that would use a cold mirror could work using other dichroic mirrors made by Thorlabs that would let a 532 nm pump source transmit into the cavity while lasing at lower wavelengths in the visible spectrum.

Refractive Index

Before now, when talking about cavity size, the true value being discussed was the optical path length (OPL) of the cavity. The OPL is simply the physical distance times the refractive index. The refractive index of the dye solution is an important factor in determining the physical length of the cavity needed to support proper lasing as per the previous design. Because dyes are usually dissolved in either ethanol or methanol in very low concentrations, the refractive index of the solute dominates. The refractive indices for these solutes are 1.3614 and 1.3284 respectively. So if a cavity length of 21.1mm was used as an example of a likely OPL that we would have used from earlier, then the actual internal length of the cavity would be 15.50 or 15.88mm respectively. The refractive index and length of the NLO crystal obtained for frequency doubling the pump wavelength would also need to be factored in here. However, data on such crystal has still not been obtained.

Later on in the construction and prototyping processes, the emission peak of our Rhodamine B in methanol solution was measured so that distances, OPLs, and doglegging could more accurately be predicted for the VIS emission of our designed cavity. This emission peak was at a maximum from 581 nm to 582 nm.

Mass/Volume/Concentration

The volume of the dye solution needed is determined by the cavity's physical length, the ROC of the mirrors, the size of the NLO crystal used, the diameter of the mirrors, and the protrusion of the custom cavity mount into the space between the mirrors. A simple calculation of the volume as a function of the diameters of the mirrors (D), the length of the cavity (L), the difference between outer and inner thickness of the mirror (t_d), and the ROC of the mirrors (assumed to be equal) yields

$$V = \pi(\frac{D}{2})^2(L - 2R + 2\sqrt{R^2 - (\frac{D}{2})^2} + \frac{2\pi t_d^3}{3}(\frac{3R}{t_d} - 1)$$

Finally, varying concentrations can be used. Out of the experiments documented by Exciton, concentrations of Rhodamine B have varied from 30.6mg/L to 10^{-3}M/L (15.65 times as concentrated). As a result, we could use a wide range of concentrations. A way to conserve solution while testing different concentrations for higher power emissions (until a limit is reached and added dye only serves to absorb power) would be to start at a lower concentration and work our way up. If more information can be acquired on Rhodamine B, then an optimum concentration may be calculable from the amount of pump power, the mirror reflectivities, and the cavity length.

Through the multiple redesigns of our laser cavity, the final volume for the dye chamber itself was around 1 mL, and the concentration we had and tried to use for testing was .6 mM. More is discussed on concentration of dye and its usability in our design as opposed to alternate dye laser cavity possibilities when the proof of concept that we were able to complete for the laser cavity is discussed in the prototyping sections below.

Solute

Multiple different solutes can be used for laser dyes. Often, water is advised against due to most laser dyes having some degree of hydrophobia. However, it can technically work. The Most commonly used solutes are ethanol and methanol due to their abundance and ease of use. These two solutes do, however, produce different results when using Rhodamine B. This has led to much of the confusion in trying to estimate the emission wavelength that our cavity will lase at. In general, however, Rhodamine B tends to lase somewhere between 560 nm and 590 nm.

Of the options available, we had narrowed down our solute selection to methanol and ethanol for exactly the reasons mentioned a moment ago: they are easy to get and use. Between the two, we decided to go with methanol. One factor in this was the slight apparent preference of methanol use as a solute for Rhodamine B usage by the experiment records of Luxottica Exciton. Another factor is that the solute of a laser dye solution tends to have the largest effect on the refractive index of the solution. This is largely due to the fact that most often dyes are dissolved in a concentration of a few centimolar at maximum, often using concentrations that are multiple orders of magnitude less. In other words, most of the actual solution is just the solute and not the dye. Methanol has a lower refractive index than Ethanol (about 1.3284 versus 1.3614). This means that our shortest possible cavity length will have a shorter OPL if we use Methanol, and here we are wishing we could have it even shorter.

5.2.4 Optical Sampling

In labs, we typically sample a beam to get measurements from it by using the entirety of the laser beam and by swapping out the system we are using the laser in. We'll place a power meter in front of the beam to capture the output optical power of the laser. Or we'll place a spectrometer in front of the beam to see the spectrum of the laser. These, however, are not the best for viewing said data about the beam over time while it is used in a system. You would have to disrupt the work being done to sample the beam. Our plan is to sample the beam actively in the device. This will be done first by using a beam sampler to take only a small portion of the beam for sampling. Because the purpose of this live sampling system is to prevent disruption of the active use of the laser, we don't want to take most of the beam away. A beam sampler is designed to do just that. Thorlabs' beam samplers split off 1% of P-polarized light and 10% of S-polarized light. If we assume the dye to emit randomly polarized light, then this would result in sampling 5.5% of the beam. If it ends up emitting at a different polarization, we should be able to see this during testing. We would then make a mark on the cavity to indicate the primary axis of polarization of the cavity. This would allow the user to place the cavity in the device in such a way to sample down to 1% of the laser light so that they can get up to 99% of the remaining power to use in their experiment/setup. After this, because we want to measure both the output optical power of the laser and its spectrum, we would need a beam splitter to split the sampled beam into two more sections, one for each sampling method. This ratio can be customized between 50/50, 70/30, and 90/10 based on if we end up needing one of the sampling systems to get more or less of the sampled beam to read properly.

5.2.4.1 Spectrometer

The frequency spectrum of light is measured with a device called a spectrometer. A spectrometer works primarily on the functioning of a diffraction grating. A diffraction grating outputs collimated light at different angles depending on the wavelength of the light. For our design, we decided to design our own spectrometer as opposed to buying one to incorporate into our design. Not only will this give us the added experience of designing a spectrometer, it will also save us some money on our project since the cheapest spectrometer we could find was $99.

Our spectrometer is purposed to give the user the peak frequency emitted by the laser device, ignoring any residual 1064nm or 532nm light that reaches it. The final output of our laser is going to be in the UV range. However, UV-sensitive image arrays are more expensive than visual image arrays. Because we only care about the peak wavelength, and that wavelength should exactly half when going from the VIS to the UV via SHG, we are able then to find the peak wavelength in the VIS side of the device and convert that to the half-as large UV wavelength that the device will emit once lined up properly with the NLO crystal.

The four parts of a spectrometer are as follows: pinhole, diffraction grating, focusing lens, 1D image array. Each of these components serves a crucial part in the resolution of a spectrometer system. One of these can actually be ignored for our design though. That component is the pinhole. In a standard spectrometer, it serves the purpose of preventing ambient light from entering the system to serve as noise on top of the signal that you wish to analyze. A larger pinhole would allow for more light to enter the system (making the spectrometer more sensitive to your signal) and more tolerance in lateral misalignment of the signal beam (larger hole means bigger target for the incoming beam), but it would also increase the acceptance angle for the spectrometer. A larger acceptance angle interferes with how cleanly the diffraction grating can separate wavelengths. However, having a pinhole that is too small might not let enough light in for your sensor to pick up without having a long exposure time and it could prevent the beam from entering the system at all if the input was not laterally accurate enough, but it would have the added benefit of decreasing the system’s acceptance angle. If you decrease the size of the pinhole to near the wavelength size, however, then you would encounter the issue of dispersing the input beam, giving you back your large angle differences in the beam that goes to the diffraction grating, while simultaneously lowering your input intensity beam even further.

The optimum scenario would be if you could have 0 noise and a perfectly collimated and centered beam. Our design solves two of these just by the nature of the project. Our spectrometer is an internal sampling system inside a laser. This section of the laser will not be exposed to outside light (thus it will not have much noise) and it will be collimated for passing through the beam sampler and for better diffraction grating performance. And, because of our design's ability to negate these first two errors, the third error becomes negligible. Thus, we do not need a pinhole for our system.

The next part in a spectrometer is a diffraction grating. These exist in transmission and reflection styles. When hit with an incident beam of light, they transmit/reflect orders of that light, and the angle is determined by the incident angle, the order, and the wavelength. This wavelength dependence is where we get the ability to break up the spectrum. For a transmission grating, this equation is:

$$a(sin\theta_m - sin\theta_i) = m\lambda$$

Where a is the diffraction period, θ_m is the transmitted angle, θ_i is the incident angle, m is the integer order of the transmitted light, and λ is the wavelength. For normal incidence, this can be simplified to:

$$\theta_m = arcsin(\frac{m\lambda}{a})$$

In figure 15 below are displayed the zeroth, first, and second order output beams from a transmission grating when hit with normal incident light across 400nm (blue) to 700nm (red) at grating frequencies of 100, 600, and 1000 lines per mm. Following, in figure 16 is displayed the same case for a grating frequency of 1000 lines per mm, but with an input collimated beam of width .25".

Figure 15 - Transmission Grating Output Beams at Normal Incidence

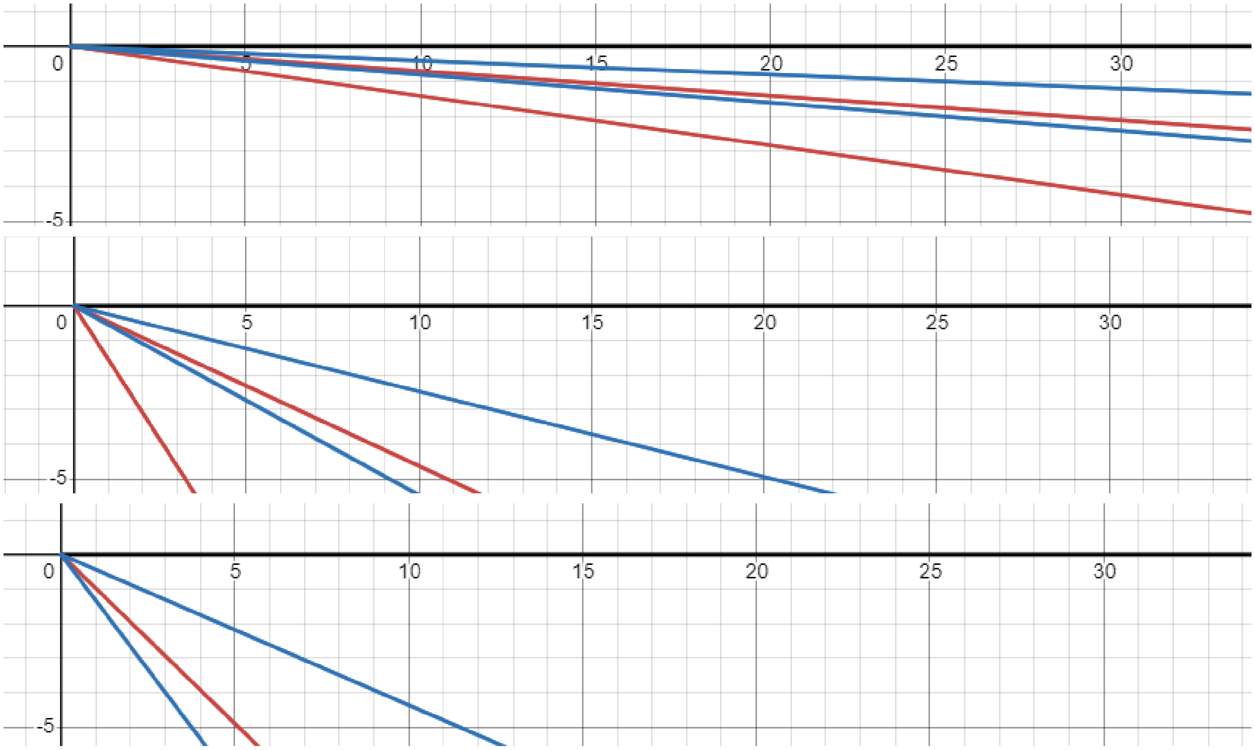
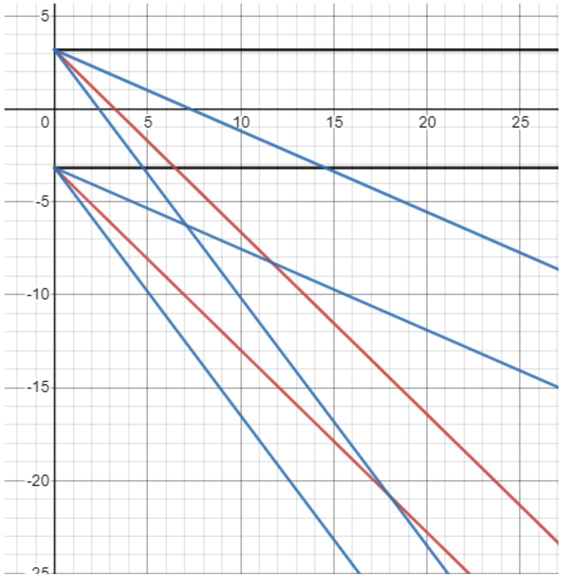


Figure 16 - Transmission Grating Output Beams at Normal Incidence



One can note from the equations for the transmitted angle that there is no dependence on where on the grating the incident beam hits. As such, all of the 700nm light that hits the diffraction grating when collimated will transmit with the same angle, thus still collimated. The same goes for every wavelength at each order. This means that we can image the light output from the grating as if it were an image coming from infinity, whereby the location in the image plane, located 1 focal length behind the lens, is determined entirely by input angle to the focusing lens, and not by where it hits the lens. The thin lens matrix for this is:

[0 , f ; -1/f , 1]

It is important to notice here that the input angle of a ray to this equation would be relative to the lens. It would be wise to have the lens centered to be normal with the middle wavelength of your system (550nm in the case of a 400nm to 700nm range). Knowing this, we can derive an equation for the focal length lens needed to form an image of a chosen width at a given grating period. This equation is as follows:

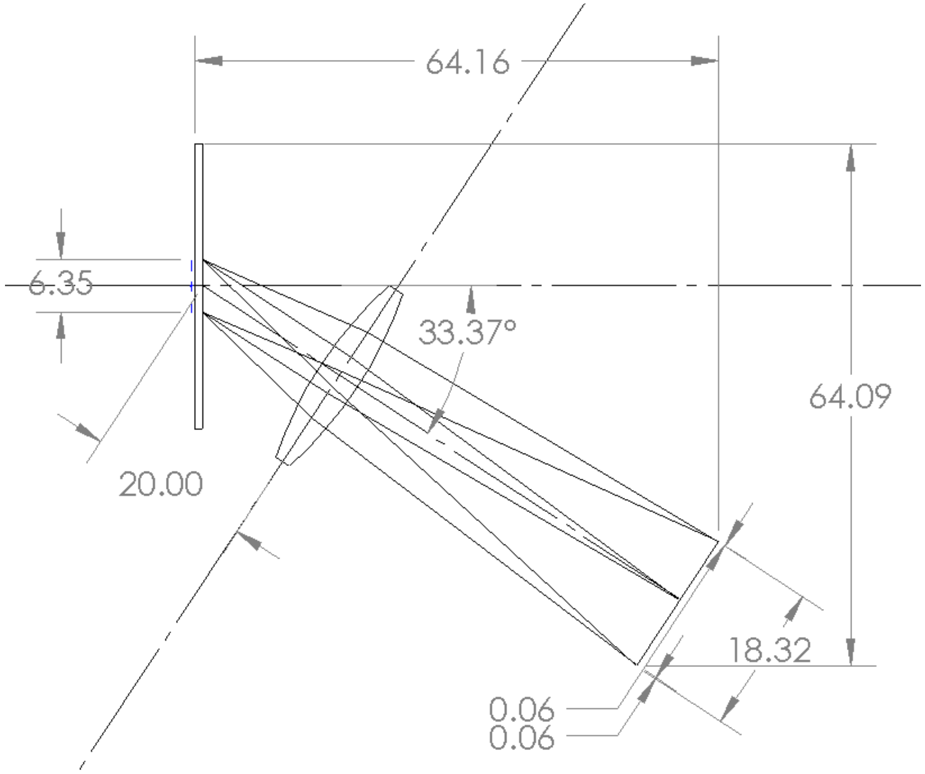
$$f = \frac{2h_0}{|arcsin(.0004/a| - arcsin(.0007/a)}$$

Where h_0 is the half width of the resulting image, and the denominator is the difference of the two most extreme angular outputs from the first order diffracted light.

A couple constraints come into play here in the decision of a transmission grating, 1D image sensor, and focusing lens. First is that we want this system to stay small. Since the image will be formed on the sensor at one focal length away, we want the focal length to stay small. This means either using a smaller sensor, or a smaller grating period. Seeing as none of us had ever designed a spectrometer before, I was thinking that a spectral resolution of 1nm per pixel would be nice. Finally is the constraint of spherical aberrations. The equations used above follow paraxial approximations, which would be quite accurate for a large grating period. But, seeing as a smaller grating period is desirable for overall image distance, some degree of spherical aberrations will start to degrade the spectrometer resolution at the edges of the analyzed spectrum.

Figure 17 below shows a sketch of a spectrometer layout using a 1000 lines/mm grating frequency, a closely placed lens of focal length 50mm. These were chosen to create a small spectrometer size while still covering at least 1024 pixels on the 1D image sensor being looked at, which was the TCD2557D at the time, with a sensor width of 37.38mm and 5340 pixels. This would give us an image size of 18.32mm, covering 2617 pixels.

Figure 17 - Approximate Spectrometer Design



In a world without aberrations, this would give us a system reading 301nm with 2617 pixels. Such an ideal system would have a resolution of .1150 nm/pixel. This is a far greater resolution that was hoped for. We can also see some of those spherical aberrations in even this thin-lens approximation. The two extremities of the spectrum are slightly out of focus on the imaging plane, each of which blurs over 60µm. The sensor has pixel widths of 7µm. This means that near the edges, each wavelength blurs over 8.57 pixels. Rounding this to 9 to be safe, if this blur existed across the whole sensor, then you'd be able to fit 290.8 of these 9 pixel widths in the image plane. That would give us a resolution of 1.035 nm/pixel. This would still not be too bad compared to our original resolution goal.

There are a few ways that these aberrations could be decreased. The easiest way would be to buy an aspheric lens built to be resistant to spherical aberrations. A more practical way would be to decrease the grating frequency. This would result in the spectra being split up over fewer angular components, which would be hard-pressed to reach as far to the edge of the lens as the rays did in this example. Another solution, one that is interesting but very expensive, is that of curved sensors. There are researchers and some manufacturers who make curved sensors to be resistant to spherical aberrations. Using such a sensor would curve the detecting surface up to where each wavelength is actually coming to a focus, thus negating its blur.

This whole system resulted in a spectrometer sizing slightly larger than 6.4cm by 6.4cm. The heights of these components range from the sensor's 9.65mm height to the 50mm height of the grating.

This system has been working optically since the senior design 1 midterm demo. Over the course of these two semesters, however, the linear image sensor circuit was not completed. Therefore, although there is a completed optical spectrometer in the final design and completed project, without the sensor, it amounts more to a spectroscope. To turn this system into a spectroscope, all that would be needed is a thin layer dispersive of VIS that one could look at to see where the illuminated region is, which would correspond to the output wavelength of your input laser system.

5.2.4.2 Optical Power Meter

Optical power is typically read by a photodiode. On larger scales, it can be done with other devices like an optical power meter or a solar cell. The photodiode will output a certain amount of current with respect to the amount of optical power that hits its active surface and the wavelength of the light that hits it. The wavelength dependence is worded as a responsivity function of the photodiode. As an example, the FDS100 photodiode from Thorlabs has a responsivity of .062 A/W at 400nm, but .389 A/W at 700nm. It is important to know just what wavelength of light is hitting it to be able to calculate just how much optical power is hitting it. Our solution to this is to use the data picked up from the spectrometer to tell the computer what wavelength is hitting the photodiode. If the laser is operating at 700nm, then the spectrometer will be able to see that and tell the computer that the responsivity of the photodiode at that moment was .389 A/W at that moment.

Another detail important to the system's ability to tell how much power is being emitted by the device is knowing how much light was split off to get to the photodiode. If, for instance, the beam sampler operated at a reflectance of R and the ratio of the photodiode area to the beam area was A, then the actual emitted laser power will be $\frac{1-R}{A}$ times the power read by the photodiode.

Our optical power meter, however, will be reading the output UV light of the system. This means that a more specialized photodiode is necessary for our purposes. Because photodiodes are typically cheap though, this is a cost well worth making for this project. A collimating plano-convex lens will collimate the UV light coming out of the NLO crystal, and a UV beam sampler will sample off a small fraction of that beam towards the photodiode, and another lens will be used to focus the collimated beam onto the photodiode. The photodiode we are looking at has an active area of 10 cm^2. Before we had come across this component, the photodiodes we were seeing had active areas on the single-digit mm scale. Because each cavity could have some degree of angular misalignment, there is a chance that the laser beam will not be precise to the mm. As such, we had 3 potential solutions for how to get the photodiode to pick up some power from the laser beam. The first was to focus it down as small as possible onto the photodiode. In the ideal case, this would mean focusing to the diffraction-limited spot size. The diffraction-limited spot size is given by:

$$d = \frac{4f\lambda}{\pi D}$$

Where d is the diffraction-limited spot size, f is the focal length of the focusing lens, λ is the light wavelength, and D is the lens diameter. Additionally, since we wish to try to design our system to work from 400nm to 700nm in the VIS spectrum, this would translate to 200nm to 350nm in the UV spectrum.

The diffraction-limited spot size for 1” lenses, like those we have been using would then be:

$$d = 1.003 * 10^{-5} * f; \lambda = 200\text{nm}$$
$$d = 1.754 * 10^{-5} * f; \lambda = 350\text{nm}$$

Even the smaller photodiodes have widths of about 1mm. And from these equations, knowing that we are focusing a collimated beam to a point 1f away, and that we want to keep our device relatively small and handheld, it should be clear that the diffraction-limited spot size is not a concern for this setup. There should not be too much difficulty in getting the beam focused down to the size of a photodiode.

One issue that this fails to address, however, is that we want to measure the output power of our laser, which emits in the UV spectrum. The ThorLabs photodiode that we were looking at does not read properly in the UV, and so another photodiode had to be found. We have settled on the S12698-04 series photodiode by Hamamatsu. This photodiode can read across the entire 200 nm to 350 nm UV range that we wish to be capable of generating, and also has a decently large active area. This means that it will be less sensitive to misalignments of the laser cavity. Another issue that comes up when designing the UV portion of this device is that standard N-BK7 lenses don’t transmit UV. Instead, UV Fused Silicon is a next standard that isn’t extremely expensive (though it is quite a step up from N-BK7). Due to this step up in prices, smaller lenses will be used for the UV portion of the project to save money.

5.2.5 Second Harmonic Generation

A crucial part of getting our project to its point of application is getting the VIS light to convert to UV light. This is done by focusing the light into a NLO crystal that can perform SHG on VIS light. The process of SHG absorbs two of a given energy photon and emits one photon of twice that energy (half that wavelength). These processes can happen for multiple wavelengths from a single crystal, but require precise angle-tuning of the crystal to get your specific wavelength to frequency double. For this, it would be advisable to get a crystal custom-cut so that the frequency that will undergo SHG normal to the surface of the crystal is approximately in the middle of your device’s range. So we should try to get a crystal that will perform SHG at normal incidence with

550nm light. I have also heard from multiple sources that BBO is a good crystal for this, for which SHG can work well past the VIS spectrum in both directions.

In our final project, we had obtained a piece of BBO cut for SHG of 800nm to 400nm at normal incidence. This would allow for SHG across the visible spectrum by only angle-tuning of the crystal. More on the testing (and limits to testing) of this part of our system can be seen in the prototyping sections below.

5.2.6 Main Optical Train

Every lens used in the main optical train will be a plano-convex lens. This is because every lens here will either collimate an expanding beam or focus a collimated beam. Plano-convex lenses serve this purpose well when the flat surface is on the side of the collimated beam, allowing that wavefront to strike flat across the surface of the lens, causing that interface to have no net optical effect on the system apart from axial OPL.

As mentioned before, the beam exiting the preferred laser cavity design will have a spot size of .8875 mm and will be diverging by a half-angle of 5.317°. The most diameter-limiting component in the main optical train is the beam sampler. It has a diameter of 12.7 mm, is 3 mm thick, and must be oriented so that a collimated beam will strike it at 45°. This results in a remaining face of about 6.8589 mm in diameter to work with. Seeing as this sampler comes right after the beam is collimated out of the laser cavity, this means that the expanding beam out of the laser cavity cannot be allowed to reach this maximum diameter before it is collimated. A lens of focal length 36.96 mm would result in exactly this diameter, and any shorter will result in a shorter collimated beam diameter. Smaller lenses can be used to get shorter focal lengths, which would allow us to collimate the beam sooner and keep the diameter smaller. However, this would also result in using very small ROCs which can result in larger spherical aberrations, smaller lenses which give us less room for misalignment error, and less space in front of the laser cavity to use as wiggle room for both adjusting the cavity and removing it. As such, we have decided to stay at a 1” diameter lens as was previously decided before more information was obtained. The smallest focal length lens of such criteria offered by ThorLabs is a 25.3 mm focal length lens, which would give us 20.52 mm between the lens and the cavity, and would result in a collimated beam of diameter 4.696 mm.

Because one of the principal planes on plano-convex lenses lies on the curved surface, and the other inside the lens, by having the non-collimated beam intersect with the curved surface, it intersects with one of the principal planes, simplifying the setup. This simplifies it to lining up one part of the beam with the curved surface of the beam and just making sure there is space on the other side for the actual thickness of the lens. The thickness of the lens mentioned above is 11.1 mm, and because the beam after it is perfectly collimated, the distance to the beam sampler is insignificant and can be placed practically as close as one would like.

After this, another 25.3 mm focal length lens should be used to focus the light back down to create a tight spot size for a NLO crystal. Using Edmund Optics' NLO crystals for a size reference, the most restricting size is a 15 mm long crystal with a cross-section of a square with side length 3 mm. The beam focused by the 25.3 mm focal length lens is small enough in diameter and shallow enough in angular convergence/divergence to fit fully inside this crystal. This crystal is also quite long for our purposes seeing as ones this long would likely double our project cost.

After this, lenses that work in the UV must be used. Additionally, the small size of the 3 mm diameter lens in the optical power meter must be taken into account. To keep the beam diameter at least somewhat small in comparison to the lens size, I decided to use an identical lens to collimate the light after the NLO crystal. This lens is a plano-convex lens, 3 mm in diameter, and has a focal length of 9 mm. This makes the total length between the focusing and collimating lenses around the NLO crystal 34.3 mm when the crystal is not in place. If the crystal were placed so that the beam stays small and focuses well inside the crystal so as to generate higher intensities (quite often required for NLO effects to take place), then this distance would increase. After this UV collimating lens goes the UV beam sampler (again at 45°) to sample off some of the UV light for power sampling. The rest of the beam is collimated and can simply continue out the front of the device. This collimated beam has a diameter of 1.67 mm.

Figure 18 below shows a to-scale sketch of the optical layout with beam diameters, distances, focal lengths, and lens numbers included. The object on the far left is the laser cavity size. Additionally, figure 19 below shows a ray tracing simulation of this design implemented using Ray Optics Simulation.

Figure 18 - Sketch of Main Optical Train

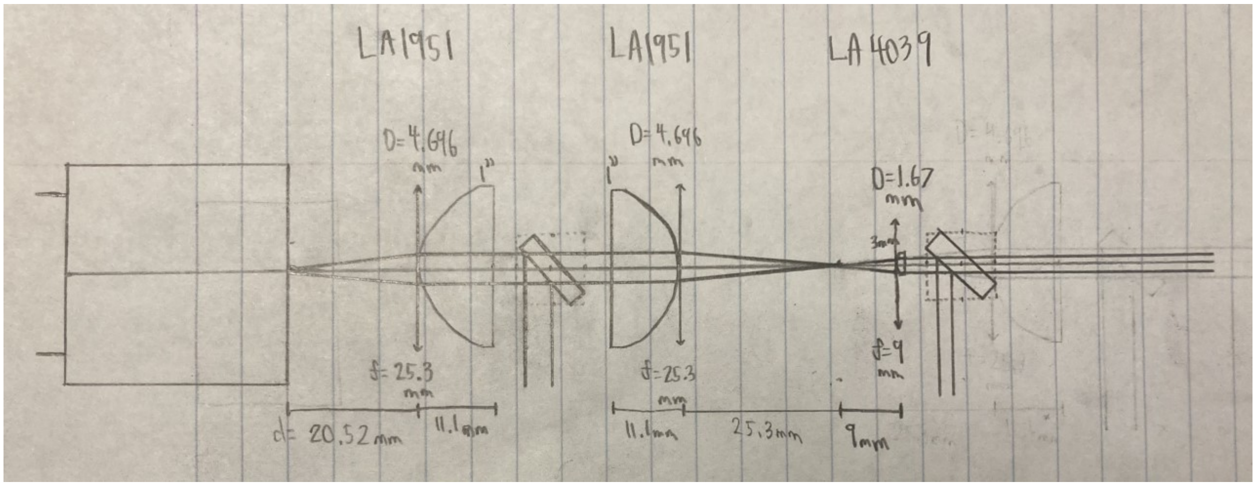
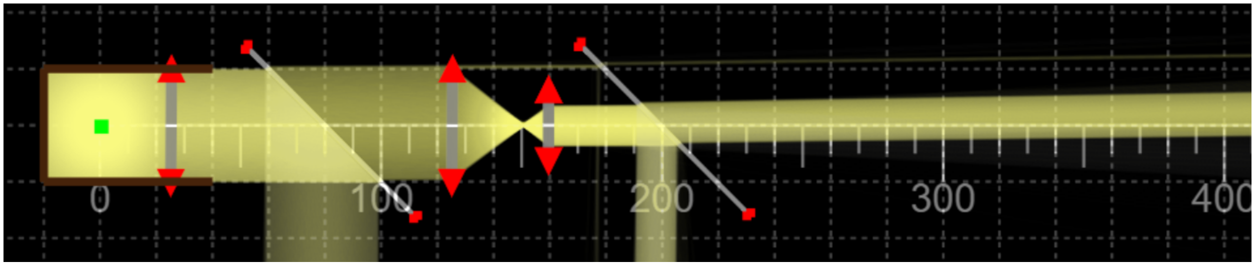


Figure 19 - Main Optical Train Simulation



One issue that was brought up to me after this project's completion via consulting with others in CREOL was that it would be more optically efficient to have faced each plano-convex lens' curved surface towards the collimated end of the beam (whether that be input or output to the lens at each location). I had taken it on advice from previous years that it is more optically efficient to design a system with the curved surface of these lenses towards the focused end. This is still not something I am sure about now after having received opposing advice. This is something that could and should have been tested well in Zemax to get a more grounded answer for. However, with the college's limited access to Zemax, and with my personal computer (through which we were able to get Zemax) broke during senior design 1, and I was not able to get a new computer until a decent bit into senior design 2. This prevented Zemax from taking a part in the design process which showed issues in prototyping and caused me to not gain valuable experience with the software in relation to this project.

5.3 Electrical Design

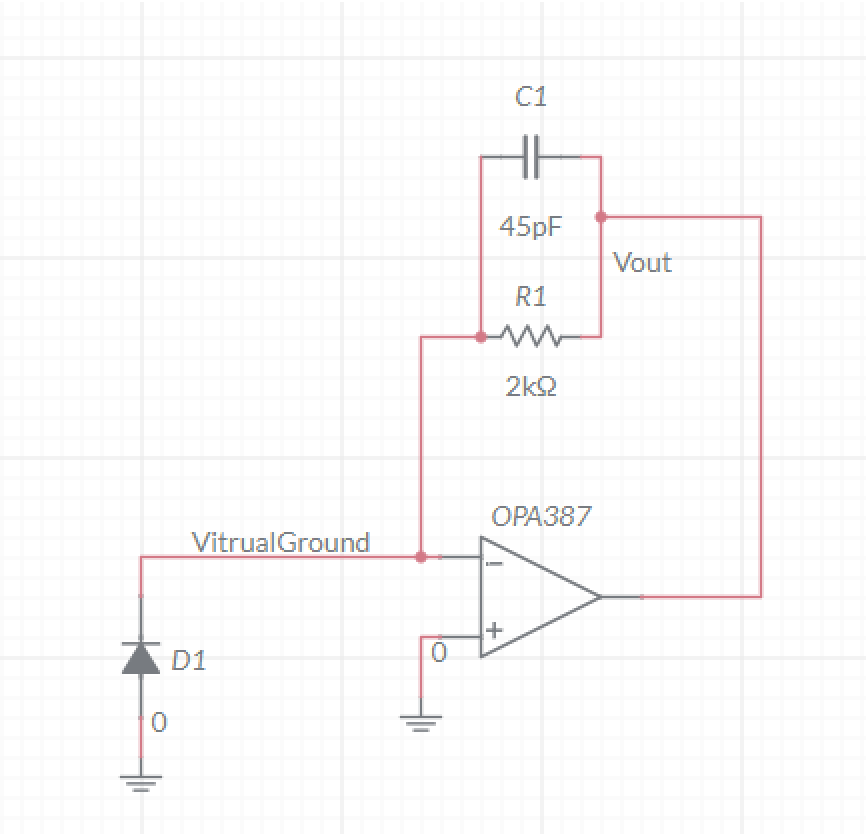
5.3.1. Sense and Display Subsystem Design

The Sense and Display Subsystem (SDS) will measure physical phenomena, read them into the embedded computer, evaluate functions with the read values, and display them on the LCD. It does these things in the order presented. This process is meant to be completed periodically. It is limited in this fashion to conserve the batteries' energy. Using something as cheap and easy-to-implement as push buttons, this feature can be modified. The SDS will be one the most far reaching of the subsystems because it will rely upon components located far away from each other. The four tasks will be described in greater detail in the following paragraphs.

The photodiode will be placed in the transimpedance amplifier circuit located in Figure 20. It will be in the place of D1. The amplifier is in photovoltaic mode. This ensures the dark current is as low as possible (ultimately reducing noise). We expect the radiation to have a nearly constant amount of power (and frequency), making reverse biasing unnecessary. The resistor value was chosen to be 200 Ohms.The maximum optical power received by the photodiode is expected to be less than 10 mW. The resistor could be absorbing greater than 0.1 W of power. A power resistor is required to properly dissipate this power. It is also significantly less than the shunt resistance of the diode as is recommended. A feedback capacitor will be placed in parallel with the resistor to stabilize the output and its value can be calculated using the equation below. There are many elements that cannot be seen in this diagram but they contribute to the output. For example, the traces in the PCB will need be designed so the power supply will not cause additional leakage,

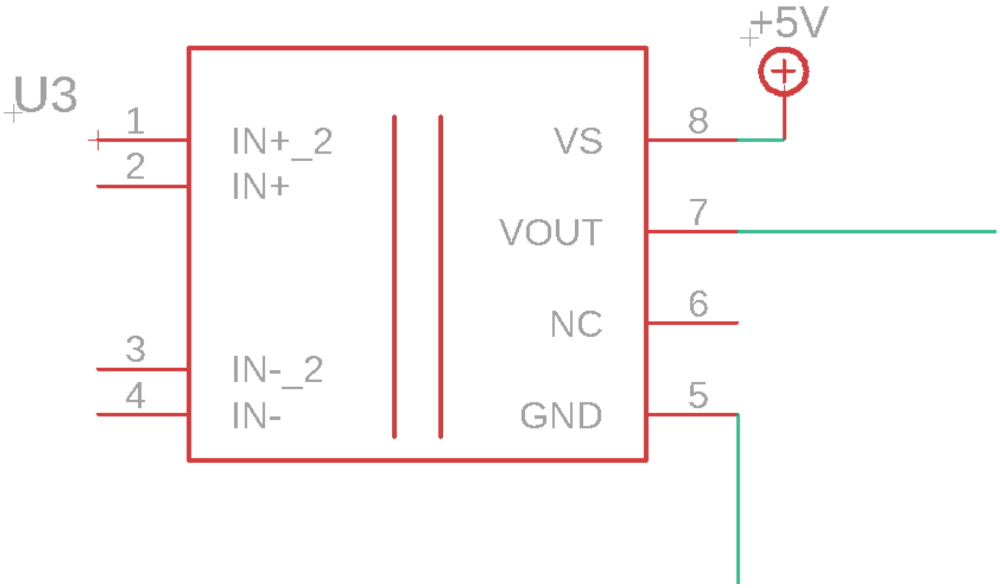
$$C_{feedback} = \frac{1 + \sqrt{(1 + 8*\pi*R_{feedback}*C_{junction}*GBW)}}{4*\pi*R_{feedback}*GBW}$$

Figure 20 - Transimpedance Circuit



The ammeter's internal circuitry will closely resemble the circuit below. It has available gains of 50 mV/A, 100 mV/A, 200 mV/A, and 400 mV/A. It is necessary to know the expected current from the battery and the specifications of the ADC to determine the needed gain. If the gain is too large, the input voltage could exceed reference voltage. The ammeter draws current to operate and will also affect the current drawn from the battery. This current along with others in the circuit can affect the magnetic fields in the device and lead to inaccurate current measurements. We planned to add a shield to the current sensor to reduce the noise from the other currents. Figure 21 presents an ammeter that has not been connected to the battery. The protection plate was not included in the schematic. Vout connects to a port located on the microcontroller. Vs is 5 V and within the recommended supply listed on the manufacturer's website.

Figure 21 - Ammeter without input

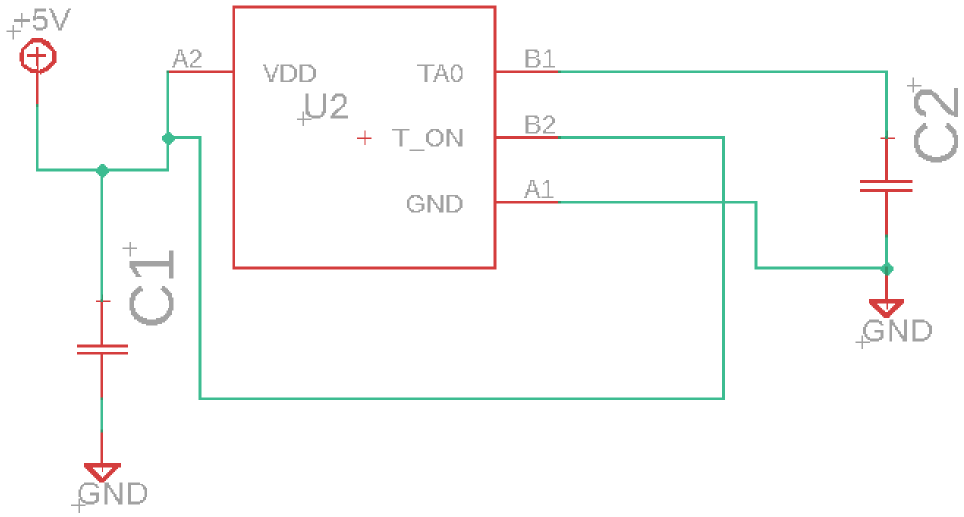


The values will be read into the microcontroller using the ADC that is found in the microcontroller. There will be a need for op amps prior to the ADC. This is needed to calibrate the system and create functions for the function. There are 3 resolutions available. We used the highest resolution available (12-bits). Testing will determine the variation that can be seen when all conditions are the same and the ADC is creating values. This may result in a change in the resolution. For example, when measuring we see the first two bits changing consistently between activation, it may be best to change the resolution to 10-bits. The settings for an ADC module will not affect the other modules. If the same analog signal was measured with the other modules it may provide a different digital signal. The values that are from the ADC module will then be stored in integer variables.

The functions for the optical values that will be used by the microcontroller are determined by testing the laser at different modes of operation. The raw data used to obtain the responsivity curve was made available by the manufacturers. The microcontroller will calculate the current through the photodiode and divide by the responsivity to find the actual power. To find the responsivity, the frequency is needed. The frequency can be found by using the results from the spectrometer. Creating an approximation function (with frequency as the independent variable) would require the microcontroller to perform very intensive calculations (consuming more memory and wasting energy) . It will be more efficient to use tables for the responsibility. This will be implemented using a series of else-if statements. Testing will be done to determine the max current seen by the photodiode and find the average of it and the dark current (nearly zero).

The thermometer will be needed to monitor the temperature of the batteries. It will be easier to measure the temperature of the hottest battery and report those values. The hottest batteries will be the ones located closest to the center of the holder. We anticipate the operating temperature of the thermometer will be between 20 °C (room temperature) and 42 °C (maximum allowable temperature of the battery). This range is small and a range that some components have been designed to minimize the error in. A reference value will need to be obtained before estimations are made. The reference voltage value is dependent on the operating conditions of the thermometer and a test will have to be done to determine the one for our thermometer. Knowing the reference value and gain will enable us to determine the temperature. The output voltage will not need a gain because a typical temperature sensor will have a high enough gain to distinguish a 0.5 °C temperature difference. This will reduce noise from additional traces and op amp-induced error. Thermal vias assist in connecting the thermometer to the thermal conductor (aluminum). Figure 22, includes the thermometer circuit.The supply voltage is the same as the supply voltage in the ammeter circuit to reduce the need for additional power supply circuits. Overall, decreasing the area of the PCB, lowering noise, and reducing cost. This decreases the area of the PCB and Capacitors have been added to protect the thermometer from high frequency noise.

Figure 22 - Design of LMT70 thermometer circuit



The total power (power absorbed by the voltage regulator) function will be the current multiplied by the input voltage of the switching regulator. This current max current divided by 2 will be the base current. This means that when that current is being drawn from the battery, the voltage measured by the ADC will be Vref (the digital signal will be all zeros). This means there will be an offset number. The offset will be added to the digital to find the correct current.

The optical power meter was operating as intended. It was not soldered to a PCB. It's values were very similar to a calibrated optical power meter found in the lab. It operated well within the 10s of microwatts range. The thermometer and the ammeter were removed because we decided they would not be important to any user of the device and only increase the cost of the device. Also,the batteries did not exhibit a considerable rise in temperature. This is likely due to the open housing and lower than expected current draw. We were never able to get the spectrometer working due to issues with level shifting, the ADC being too slow, and noisy pulse signals. We have a new design for a spectrometer.

5.3.2 Cooling System

$$Q = \frac{A*(T_{battery} - T_{thermometer})*Conductivity}{d}$$

A piece of aluminum will be molded in the shape of the gaps between the batteries in the holder. This shape piece will also suspend the PCB with the plastic plate. Thermal epoxy will be used to adhere the batteries to the aluminum. This prevents the battery from moving creating temperature errors due to air being the thermally conducting medium (air is a poor thermal conductor) but creates minimal risk of short circuiting due to the batteries' terminal covers. This is important to avoid but to increase the rate of heat transfer the area covered on battery needs to be maximized. Attached to the piece in the battery holder, will be a rod that becomes a plate to be attached to the thermal vias. The case and traces must be carefully designed so the aluminum does not create a short. The battery will have overcurrent protection but wont function properly. The batteries' terminals will need to be shielded by highly resistive material and the traces should be located away from the aluminum. The thermometer should be located towards the end of the board to limit the interference with trace routing for other components. Wires will be needed to prevent traces from coming into contact with the thermal vias. Figure 23 is a computer generated 3D models of the batteries and the battery thermal contact. In Figure 24,more of the thermal contact can be seen.The pictures do not accurately display the anode/cathode covers because the software used is not easily capable of displaying them but they will be noticeable in future renderings.

One fan located at the top of the device will remove the hotter air. Since hot air is less dense than cold air, it will move towards the top of the housing. The cold air will be pushed into the housing by the bottom fan. There will need to be additional screws to fasten the fan to the top. The fans are less than 0.5 pounds, meaning that gravity will be applying approximately 4.9 N of force on the object. The force acting in the opposite direction will come from the screws/housing. We want to avoid plastic deformation or braking in both the housing and the screws. The screws will be placed normal to the direction of the gravity to place the minimum amount of stress on the internal thread. The drill holes need to form a square-like pattern (most fans have square faces) and they need to be on a surface that will allow the fan's screws to be equidistant. The best surface for this is a flat surface. A flat surface will also allow the internal threading to cover more of the screw's surface area (extra strength).

Figure 23 - View from a different angle of battery holder with aluminum contact in place. The black lines are the cathode/anode covers but the top of the battery holder was left off.

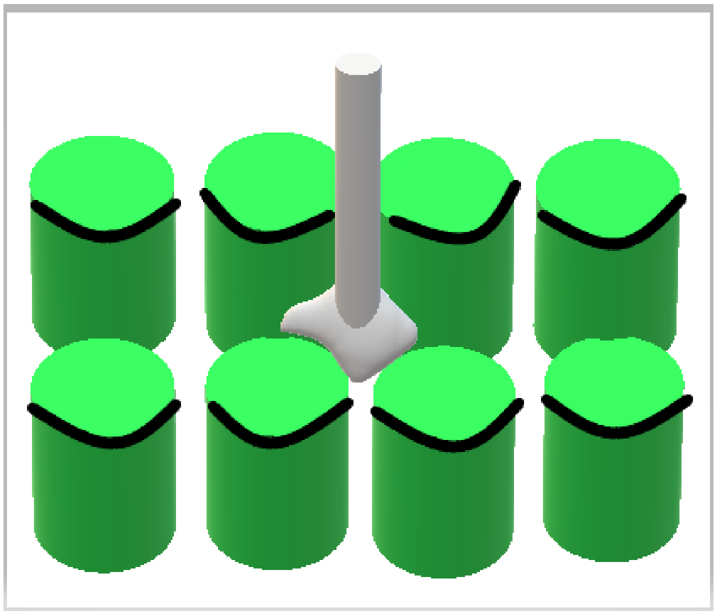
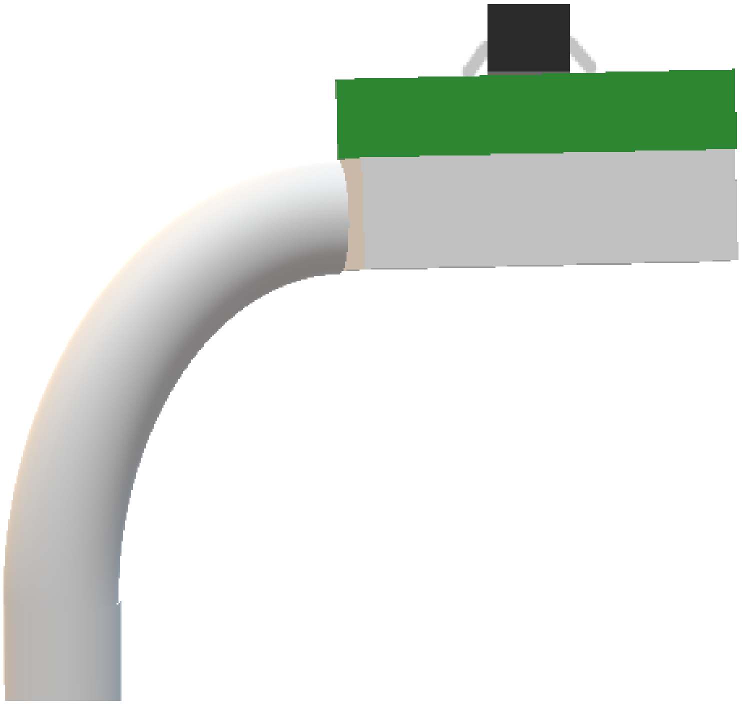


Figure 24 - The aluminum is making contact with thermal vias of the PCB (green colored shape). The thermometer is black and is located at the top.



The Cooling System had major changes since we removed the thermometer and kept only the fans. Batteries were not adhered to aluminum. No housing was designed for the power supply and therefore temperature control was not a real problem.

5.3.3 Power Supply/Batteries

5.3.3.1 Power Supply Design

In order to have a successful project we had to design a power supply capable of delivering power at a constant specific voltage no matter what load is required, or how much power is being drawn from it. When thinking about what kind of power supply to use for our electronic device there were two obvious options available which were the traditional 120 VAC outlet, or batteries.

There are advantages to powering our laser device with an electrical plug outlet. The advantages are the constant voltage and current which provides unlimited runtime, and the fact that the batteries in the device would not need to be charged. When it comes to the device being battery powered the advantages would be the portability and no need of power grid.

When we were thinking about the design of our device, we really wanted to have a portable device. The portability of the device was more appealing to us and therefore the choice was obvious when it came to choosing the power supply. After choosing batteries as the power supply, we had two choices again which were disposable or rechargeable batteries. Primary cells would have to be replaced constantly and would not be cost effective, thus again the choice was clear, and we chose secondary cells.

The power supply is composed of rechargeable batteries that were meant to deliver power to the pump source through a voltage regulator and circuit to vary the current, but the pump source was omitted in design due to not being able to find an adequate diode on time. The power delivery system powers the spectrometer which is a 1D array sensor, power meter transimpedance circuit to operate the photodiode, microcontroller, cooling system, and the display. The power supply components are the battery holder case, the Li-ion rechargeable batteries, voltage regulators and cooling system.

5.3.3.2 Batteries

Our team wasl deciding on which is the most viable battery option for our device. We took two options into consideration which are Lithium-Ion and Nickel Metal Hydride (NiMH), and made our decision based on Lithium-ion's battery arrangement, voltage, capacity, charge time and self-discharge rate and weight. The variables that we considered are cost, safety, nominal voltage, weight, capacity, charge time, self-discharge rate, battery arrangement among other factors.

Lithium-Ion batteries have advantages that contribute to our design which are nominal voltage, capacity, weight, charge time and self-discharge rate. We wanted our device to be portable and Lithium-Ion batteries have the advantage when it comes to weight since less batteries need to be used. Capacity is a significant advantage for Li-ion batteries with a nominal capacity of 3400mAh compared to NiMH average of 2200mAh. Lithium batteries have a nominal voltage of 3.6/3.7 volts per cell which is 3 times that of a NiMH battery with a nominal voltage of 1.2 volts per cell. Li-ion batteries' charge time (about 1-3 hours), and the self-discharge rate are both lower than NiMH; these factors contribute to the reliability and usability of the device.

NiMH batteries on the other hand had advantages on cost, and safety. When it comes to cost, NiMH has a significant advantage, helping with the budget of the design as well as when batteries need to be replaced. Materials for NiMH are less active than Li-ion batteries which contributes to the safety of the device. Li-ion batteries usually have circuits to check for voltage and temperature, but that does not take away from the factor that they can react and generate lots of heat, and subsequently blow up. The standards found in the fabrication of lithium batteries do take away from its highly risky chemistry, and in addition by abiding by other standards for the proper use, enclosure, removal and storage of these batteries.

Our team was leaning more toward the Nickel Metal Hydride battery since we believed it possessed the best battery chemistry for the laser. 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, but after considering the two options and determining that we wanted to use a battery monitoring system we ended up choosing Lithium batteries (The BMS was later omitted when we determined our power requirements). When looking for a BMS for NiMH we could not find any and other ICs would come up that would not offer the desired features. We determined that the number of batteries we needed was only two batteries in parallel and was decided by the current/power requirements for each component. We wanted to provide the user with at least 500 charge cycles before needing to replace the batteries, but our batteries have a cycle life of greater or equal to 300 charge cycles which is still considerably satisfactory.

Factors like weight, charge, and self-discharge rate in Li-ion make the product more reliable and easier to use. Even though NiMH batteries would have helped with the budget, Li-ion batteries have a higher nominal voltage that decreases the number of batteries needed in series in comparison to NiMH. Our lithium-ion batteries also have a higher capacity which reduces the number of batteries needed in parallel. Our lithium-ion batteries have a nominal voltage of 3.7V and we kept our power supply at the same voltage to prevent us from using batteries in series and therefore having a more simple arrangement.

When acquiring the lithium ion batteries precautions were taken. New cells found in the market can be fake cells coming from deceiving sellers which will have lower capacities and that might not abide by the required standards. When procuring our cells we used digi-key which is a reputable and well known electronics distributor. The manufacturer for our lithium-ion batteries is ultralast. The Li-ion batteries have a typical nominal capacity of 3400mAh, nominal voltage of 3.7V (charging cut-off voltage of 4.2V and discharge cut-off voltage of 2.5V), maximum continuous discharging current of 3000mA, and operating temperature of charge 0～45℃ and discharge -20～60℃. The Li-ion batteries used in our project are also RoHS compliant.

5.3.3.3 Battery holder case

The battery holder case was decided to be acquired since the battery arrangement was simple and different ones were available for purchase. We wanted the battery holder case to use the least amount of space on the PCB, but decided to actually keep it separate from the PCB design since it would have taken about half the size of the whole PCB design. Instead we decided to connect the battery holder case to wires in parallel that would connect to a switch coming from the positive side. The switch is intended to turn on and off the device. Wires coming from both positive and negative ends connect to pinheads on the PCB. The battery holder allows the user to easily swap out the battery.

5.3.3.4 Voltage Regulators

Buck controllers and Boost converters are employed to optimize the power supply to meet our requirements like step-down voltage, step-up voltage, or to reach a level of output power. The step-down controllers or step-up converters are concentrated in the power supply circuit. The power supply circuit includes resistors, capacitors, and inductors as well. The selection of the type of voltage regulators required was determined by the voltage and current needs of each component. Our power supply had a range from 4.2V (charging cut-off voltage) to 2.5V (discharge cut-off voltage).

The first voltage regulator designed was a step-up 5V regulator coming directly from the batteries. The 5V regulator used was the LM2698MM-ADJ/NOPB IC and was designed through TI Webench Power Designer. Texas instruments requires some parameters like input voltage minimum and maximum values, output voltage and current, and Iq Typ range in µA. Once all these parameters are completed a search is done and several options become available. The current problem with Webench is that it gives you different circuits that you could use as buck, boost or boost-buck converters, but it does not check for availability of the actual IC of the voltage regulator. We managed to find one boost converter that had actually had the IC voltage regulator available for purchase online.

The next 3.3V regulator was not found through Webench after searching through all output options in the website. We managed to find the IC circuit by looking through electronics distributors and inputting desired parameters. The buck 3.3V controller uses the XCL210C331GR-G IC and comes from the 5V regulator output voltage connection. The last regulator was a 12V boost converter that uses the XC9143B10DER-G IC and is connected directly to the 3.7V power supply. The 12V regulator was also found after looking through several electronics distributors due to voltage regulators suggested in Webench were out of stock. The 3.3V and 12V regulators were designed with the aid of datasheet directions and specifications.

5.3.3.5 Battery Monitoring System

The battery monitoring system was meant to be designed or bought depending on our power/current requirements that determined our battery arrangement. Once the arrangement was decided the bank covered a voltage range, output a maximum continuous discharging current, had a certain capacity in Ah, and a nominal energy in Wh. If our battery arrangement would have been different then providing power to the device could have had certain problems. If the battery bank discharges it can be charged with a proper constant-current and constant-voltage method. While charging, not all cells will show the exact same voltage, since not every cell is chemically identical, and they will contain slightly different capacities. Due to this chemistry battery factor the bank will charge up faster which can lead to misalignment in the voltage of the cells and eventually in the destruction due to over voltage.The problem only applies to battery packs and this feature is not needed if the batteries are charged with a commercial charger that would charge the batteries properly. The battery monitoring system can provide short-circuit, overcharge, and over discharge protection, as well as balance charging.

We stated that there were two options when acquiring a BMS which are buying or designing one. Commercial BMS have different specifications and we could have chosen the ones that pertain to our device. Most of these BMS have a PCB which is divided into three groups. To start the PCB has a bunch of components which are the closest to the balance connector which connect to each battery cell. The components in this group will be capacitors, resistors, two transistors, and an IC and protect each cell from overcharge, overdischarge, and overcurrent by using two transistors to cut the cells connection to the load.

The second section in this PCB has a bunch of passive components, a transistor, and another IC. This section is used to balance charge. The battery cell will be discharged by the transistor through a resistor if one of our batteries goes above a certain voltage value. After charging our battery bank all cells should be up to the same voltage requirement. The last group of this PCB has passive components, N-channel power MOSFETs, and transistors. If the battery draws more than the maximum current there are large resistors which will act as a current shunt and there will be a voltage drop high enough across this shunt that will activate the passive component network and turn off the MOSFETs. Once the MOSFETs are turned off the current flow will cease.

Another option from buying the commercial BMS is to purchase it from Texas Instrument which offers a wide selection of features and that can be designed according to our needs. The battery monitoring ICs that can be obtained through the Texas Instruments website can measure cell voltages, current and temperature and perform cell balancing to monitor and protect the cells. For battery packs small to medium passive cell balancing is typically used similar to the commercial battery monitoring systems previously described.

When considering buying or building a BMS, the price was deemed as one of the major factors. Commercial battery monitoring systems are relatively cheap while building a BMS will require a lot of components that would have to be individually bought which will raise the price pretty quickly. One of the positive factors of building our own BMS is that it could improve our power supply system by adding other features that might not be available with the commercially bought one. To build a BMS would probably take a lot of research and time that can be dedicated to other parts of the design of our device so this is another negative factor for the DIY one. Lastly, the final product of a built BMS would require a high current supply from our battery which would not be feasible for our system.

When designing the power supply system, we did not know the arrangement of the battery bank and were being really careful about safety. After determining our battery arrangement, we concluded that we did not need a BMS. We decided to use a commercial charger, so we did not need to worry about balance charging or protection from overcharge. After looking for a BMS for our arrangement it was discovered the parallel configuration did not need a BMS. This is because our configuration count as a single voltage cell and only arrangements with batteries in series require a BMS, but if we would had chosen one it would have been the commercial option due to being economical, having lots of protection features, drawing a low current in μA, and not requiring assembly besides connecting it to our battery bank.

5.3.3.6 Power Delivery and Requirements

When designing our power supply for our device we calculated our total power load by adding all the individual power requirements for each individual component. To calculate the power drawn by each component we used the datasheet and looked at its nominal value and the highest current requirements. The formula used is the normal power formula P = V x I. Table 7 contains the components that are powered by the power supply system including voltages and currents.

Table 7 - Component Requirements

Component	Part and Description	Voltage	Current
Microcontroller	MSP430FR6989 Active mode, FRAM (0%)	3.3V	375μA at 1 Mhz to 2675μA at 16 Mhz
LCD Display	C162D-BW-LW65	5V	2.5mA
Pump Source	PIL-1064-100, 1064 nm, 300mW	N/A	N/A
Spectrometer	TCD2557D	12V	33.33mA
Power Meter	UV-015	12V	Testing on the transimpedance circuit needed to be done and low current expected
Cooling System	Two fans MF40100V1-1000U-A99	5V	2 x 136mA

The microcontroller requires a voltage of 3.3V and the max current at unified memory is 1845 μA at 16 Mhz which represents the typical program execution, but for power calculation we want to use maximum current to have a better estimate. The maximum current possible at 0% cache hit ratio with a frequency of 16 Mhz is 2675 μA. When multiplying the input voltage of 3.3V and the maximum current possible we obtain a maximum power consumption by the MSP430FR6989 of 8.8275 mW. We don't believe we require 16 Mhz frequency at 0% cache, but to be on the safe side we use this value in our equation to calculate the total power draw.

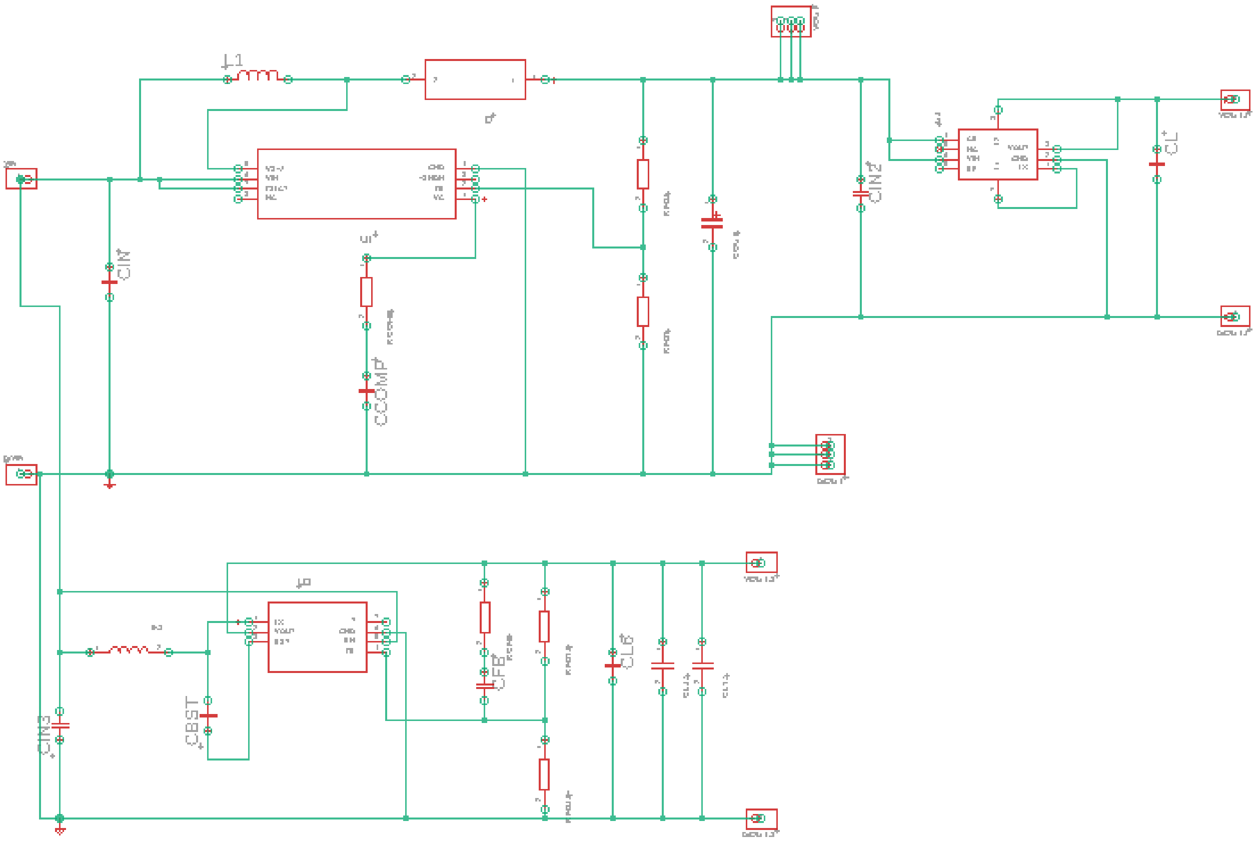
For the LCD display used is the C162D-BW-LW65 which requires a voltage supply of 5V and a current supply of 2.5 mA. When we multiply these two values we get a total power draw of 12.5 mW. The Pump source, Thermometer and Ammeter were omitted from the design of our device for different circumstances and therefore are not included in the total power calculations.

The Spectrometer uses the TCD2557D 1D-Array sensor which requires an input of 12V and a current supply of 33.33 mA. The total power consumed by the 1D-Array sensor is 400 mW. The cooling system is composed of two fans which require a 5V input and draw a current of 136 mA each for a total of 272 mA. The cooling system total power after calculations is of 1.36 W

After adding all power values, we get a total power load of 1.781 W. We are missing the power meter photodiode current draw and therefore the power cannot be provided for this component. The photodiode uses two op-amps and a transistor which are not expected to draw a lot of current, so the power is not expected to be much higher. The total maximum continuous discharging current for each battery is 3000 mA. The total current consumed by the load is 310.5 mA (missing the current consumed by the transimpedance circuit). The reason for such high discharging current in the power supply is because we were going to power the pump source laser diode which was supposed to draw 640.1 mA, as well as the thermometer and Ammeter which were discarded. Another factor to take in account are losses in the system. These can be heating losses due to resistivity or impedance. The losses could take place in the power supply, internally in the battery, the elements in the printed circuit board, in the connections and others.

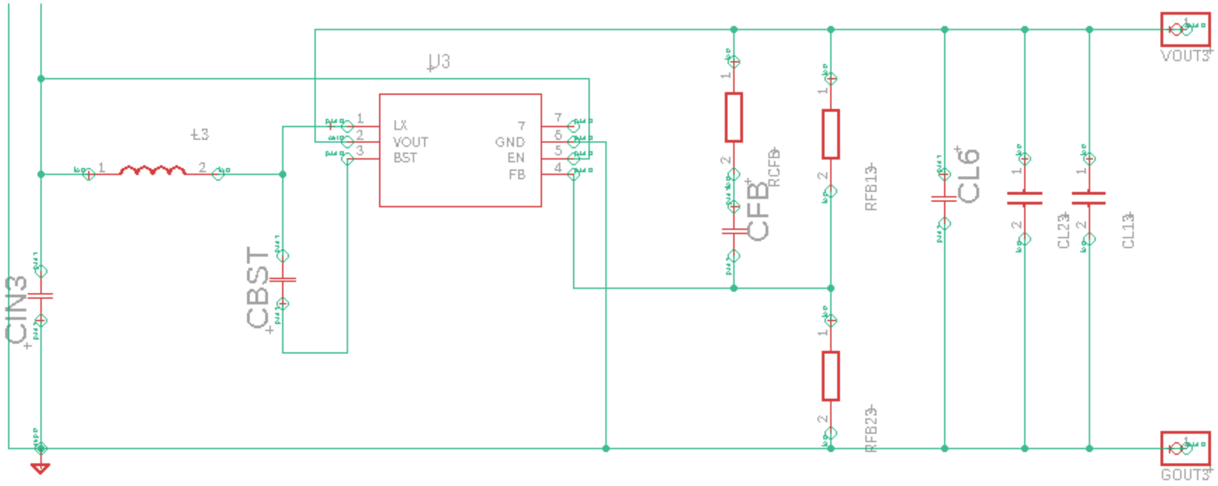
The DC-DC voltage regulators will supply power to different components. The 3.3V regulator powers the MSP430FR6989 microcontroller DVCC and AVCC pins. The 5V regulator will supply voltage to the two fans in the cooling system and the LCD display. The 12V regulator will supply power to the transimpedance circuit for the photodiode used as the power meter as well as the 1-D array spectrometer. The pump source was going to be powered by a 1.8 voltage regulator along with a circuit and potentiometer in order to vary the current from the desired maximum of 640.1 mA and lower. The power supply’s PCB is composed of all voltage regulators (3.3V, 5V, and 12V) and all related parts. The schematic for the PCB’s design is shown in Fig 25

Figure 25 - Power supply PCB’s schematic



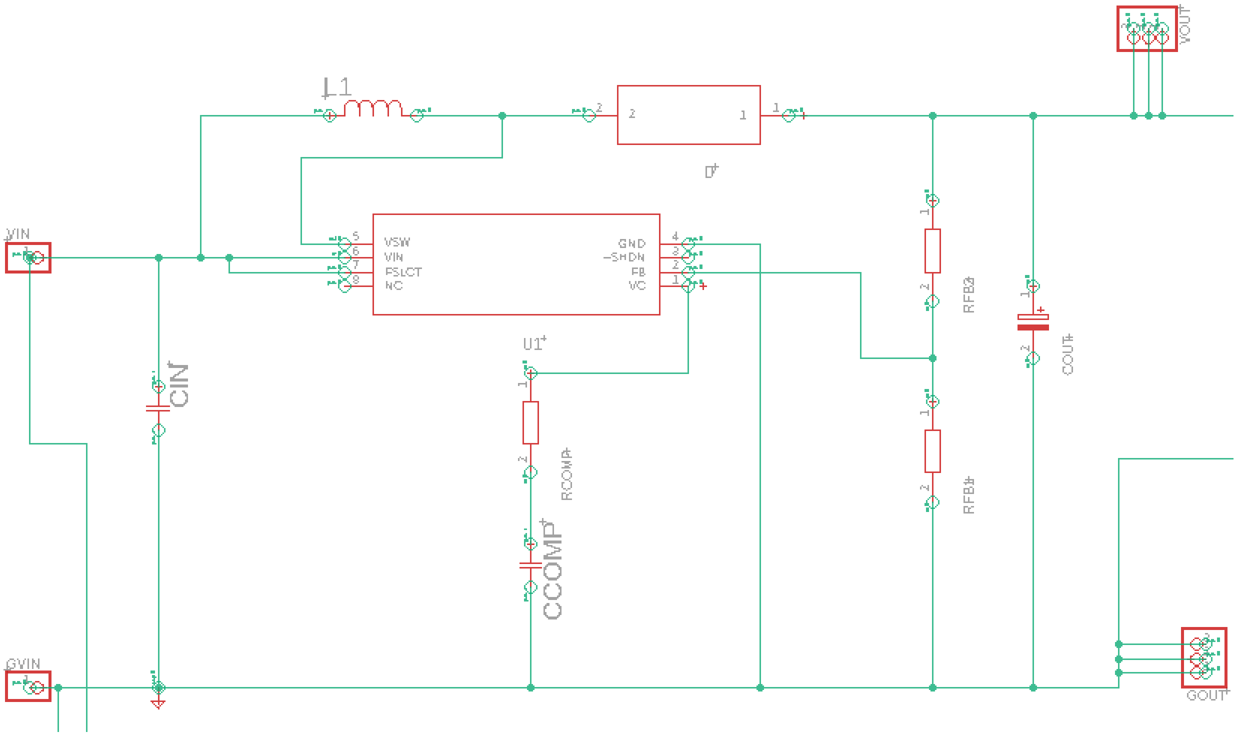
The 12V boost converter is intended to power the two operational amplifiers and a transistor in the photodiode’s transimpedance circuit, as well as the 1D-Array sensor. The total cost of the boost converter is $3.75. The boost converter is composed of the XC9143B10DER-G IC, capacitors, resistors and an inductor. The 12V converter is connected directly to the 3.7V Power supply pin headers. The schematic of the 12V boost converter is shown in Fig. 26

Figure 26 - 12V Boost Converter Circuit Schematic



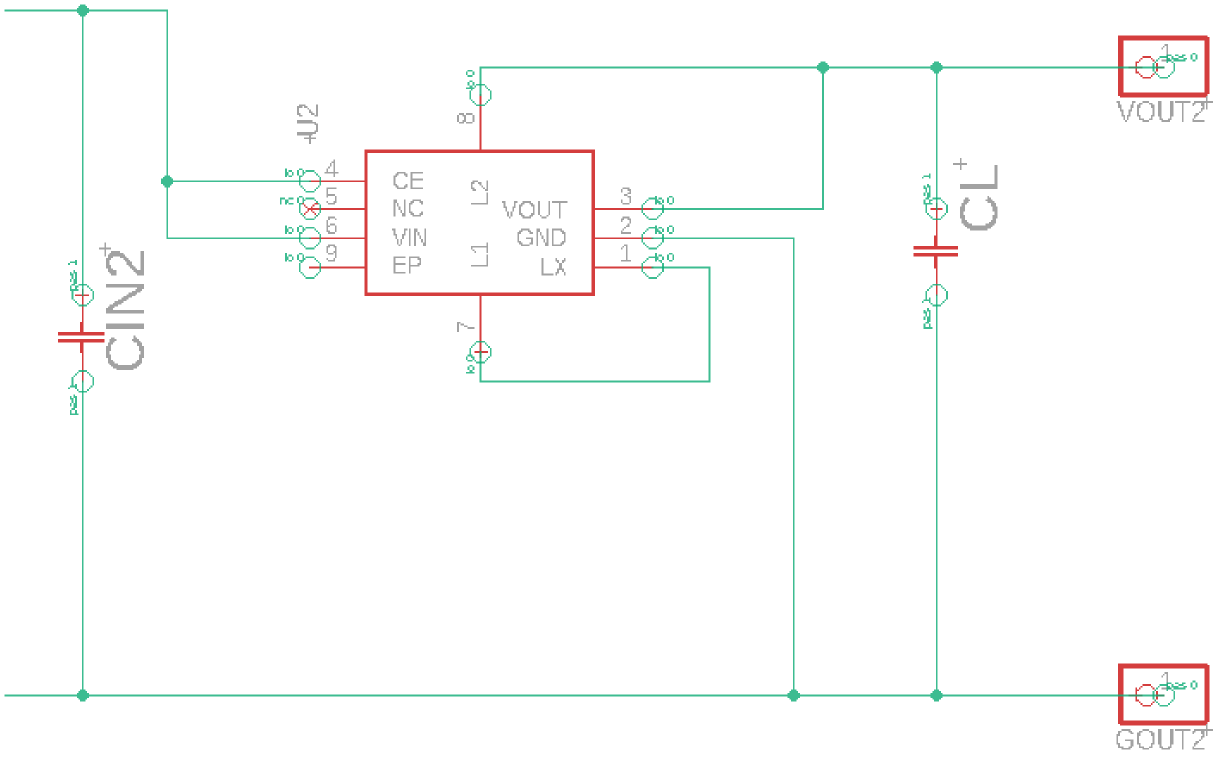
The 5V boost converter is intended to power the display and two fans in the cooling system. The total cost for the boost converter is $8.44. The boost converter is composed of LM2698MM-ADJ/NOPB IC, capacitors, resistors, a diode, and an inductor. The 5V converter is connected directly to the 3.7V Power supply pin headers. The schematic of the 5V boost converter is shown in Fig. 27

Figure 27 - 5V Boost Converter Circuit Schematic



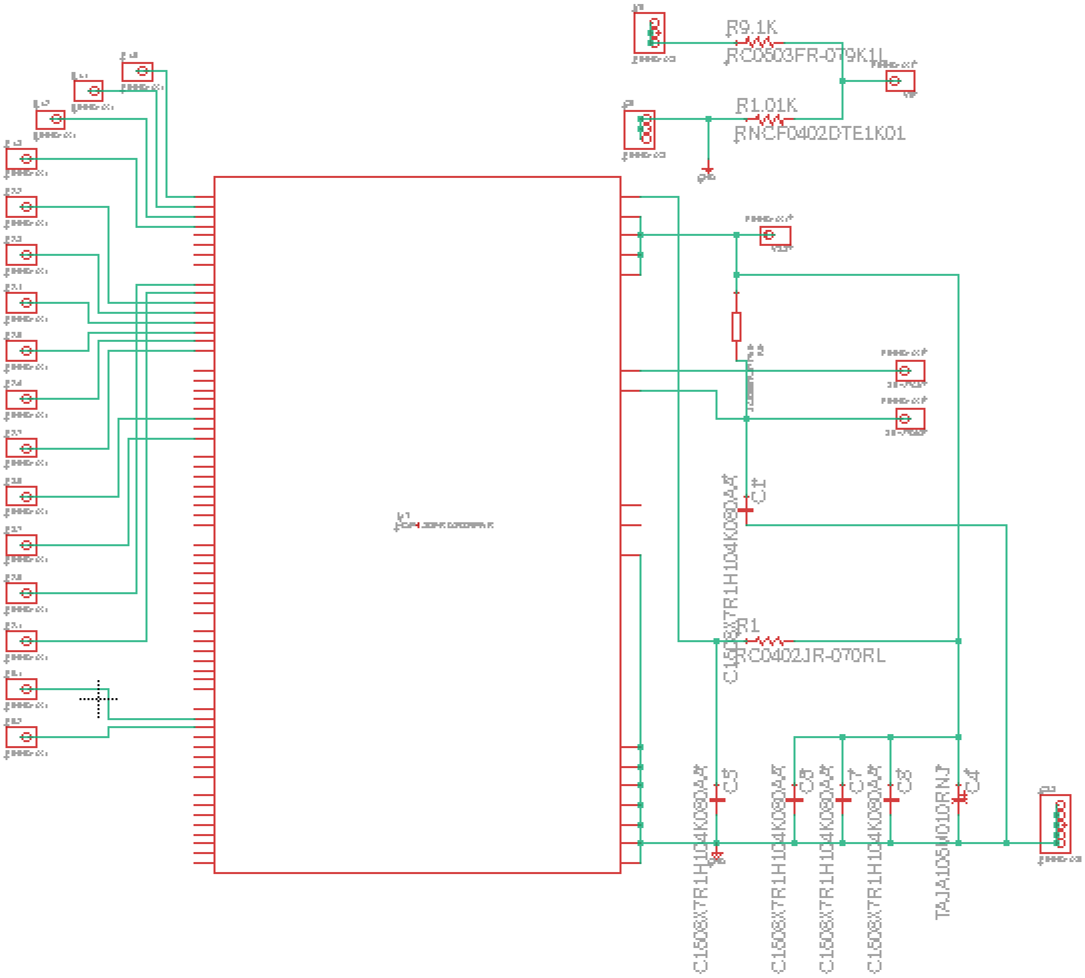
The 3.3V buck controller is intended to power the MSP430FR6989. The total cost for the buck controller is $3.21. The buck controller is composed of XCL210C331GR-G IC and two capacitors. The 3.3V buck controller is connected directly to the 5V boost converter output nodes. The schematic of the 3.3V buck controller is shown in Fig. 28

Figure 28 - 3.3V Buck Controller Circuit Schematic



The 3.3V output connects to the PCB of the microcontroller. The schematic of the microcontroller contains the MSP430FR6989 IC, all pins used have dedicated pin header, and the power circuit connection to be able to supply to the AVCC and DVCC pins. A voltage divider is also include in the schematic for the display connections. Schematic is shown in Fig 29

Figure 29 - 3.3V Microcontroller Circuit

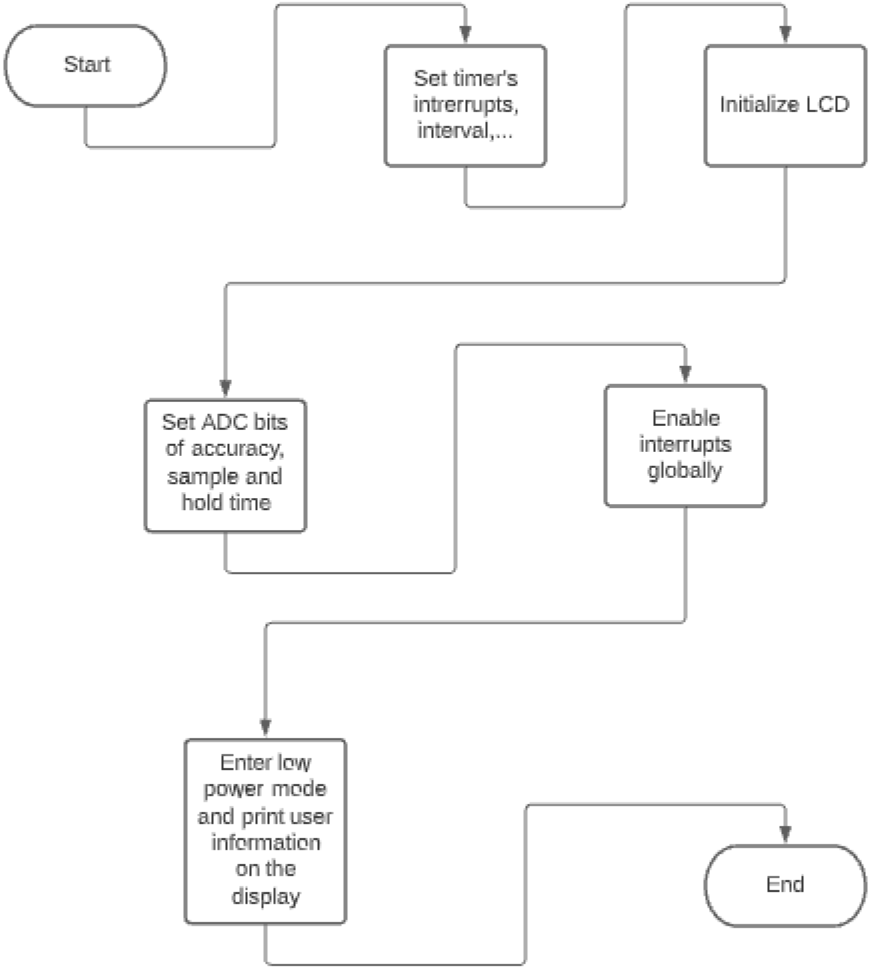


5.4 Software Design

5.4.1 Main Function

We intended to program using C in our MSP430FR6989 with its unique functions and variables Figure 30 shows the flowchart for the main function. The flowchart does not reveal every aspect of the main function or code that must be created for it to execute. Its header files will need to be included in the preprocessor. There will also need to be a header files for the display. Additionally, defined constants will be present as well. Then, functions will be initialized and global variables will be declared.The register values need to be set even though many were already set by the initialization functions. The meaning of the individual bits will be determined by using the manufacturer provided user guides.. The main function will instruct the MSP430FR6989 to enter low power mode 4. Allowing the button and timer to interrupt to re-enter it into the high power state.

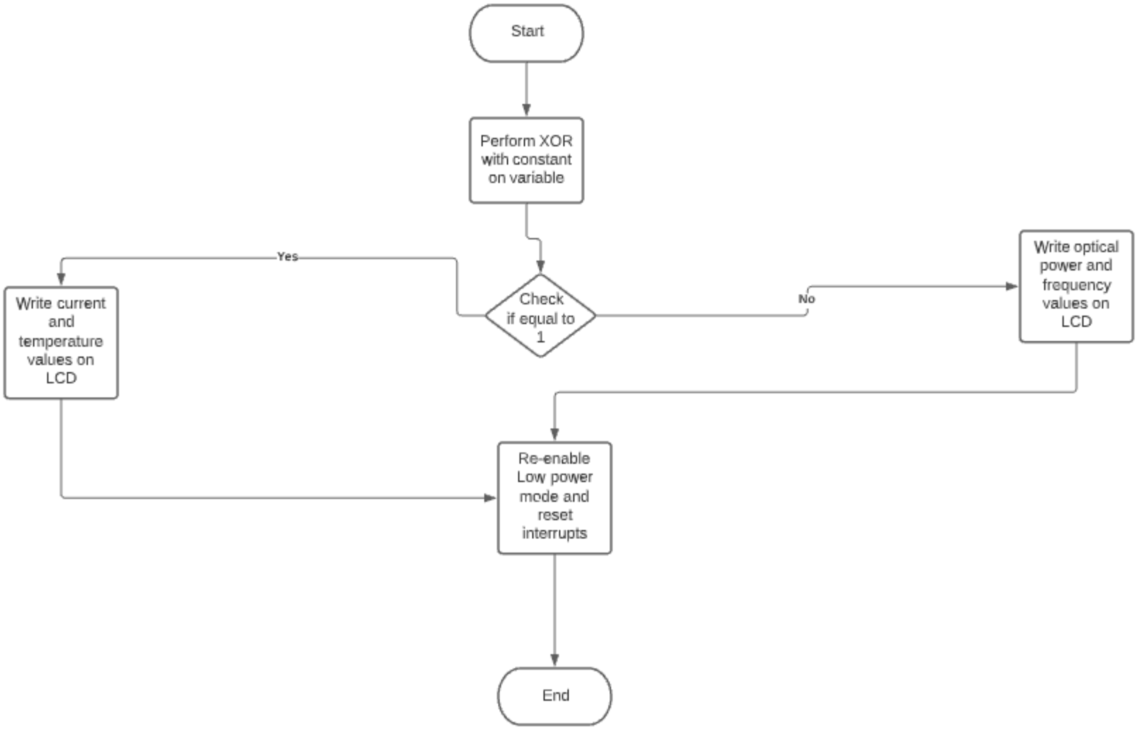
Figure 30: The main function's program flowchart



5.4.2 Button Interrupt

The push button will be used to change the information displayed on the display. Figure 31 shows the flowchart for the button interrupt. A global variable will be initiated as zero and have an XOR operation performed on it by a constant.The constant will be 1 to make the bit alternate between 1 and 0 .The variable The main function will initialize with the user setting being output to the display. This means the global variable equaling 0 will indicate user information is being displayed and equaling 1 one will indicate the opposite. Code will have to be created in the main function to ensure this pattern. After the display has had its information changed, interrupts will need to be reset. Then low power mode will be re-entered. Disabling interrupts is unnecessary because the MSP430FR6989 automatically disables interrupts when an interrupt is started.

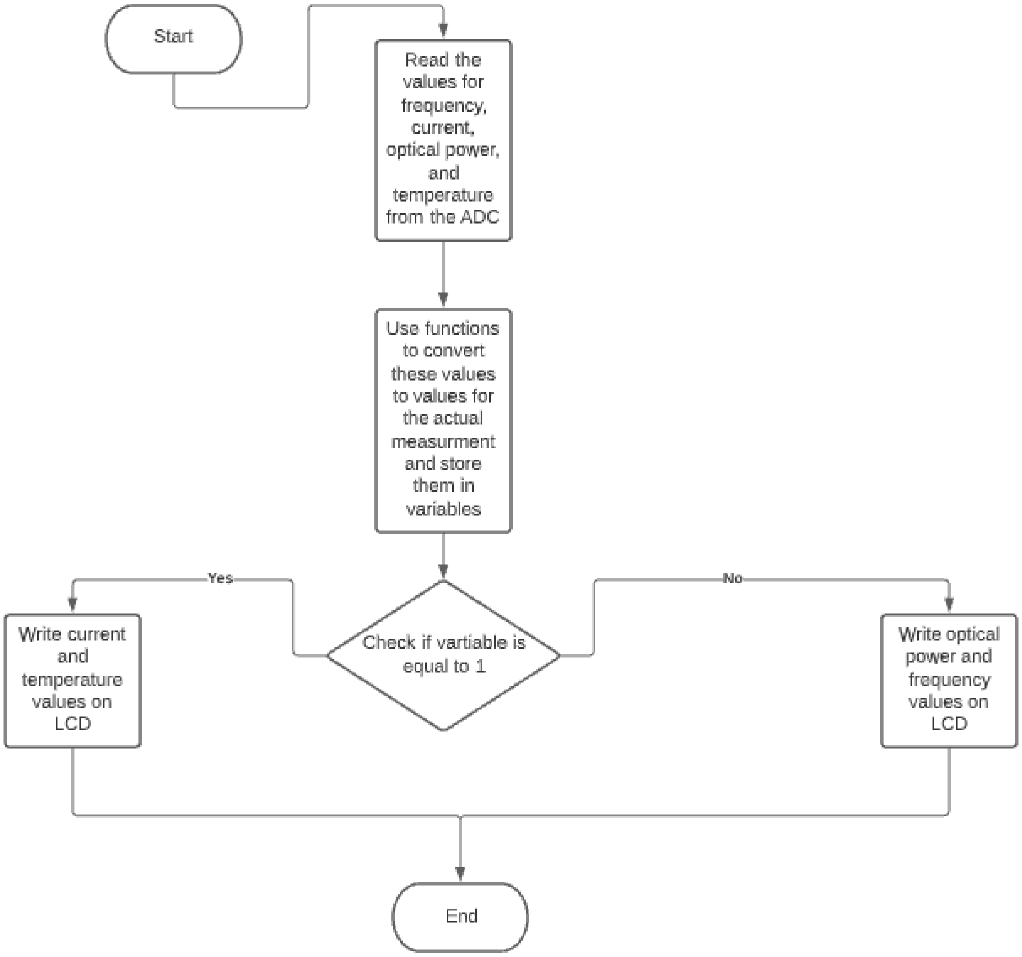
Figure 31: The button interrupt's program flowchart



5.4.3 Timer Interrupt

The timer will regularly make interrupts to update to the values on display. Figure 32 shows the flowchart for the timer interrupt. The ADC must create digitized values using all of the input by using the single-ended mode calculation method. After the digitized values are found, they will be used to calculate the approximate value. Some components need to be calibrated by adding offsets. The sensors will be linear over the range of values we are measuring and will make calculation possible using basic arithmetic. It must now check if the global variable used in the button interrupt is 0 or 1. It will then print the information that corresponds with that value. The timer used will have its interrupt automatically reset. The MSP430FR6989 will re-enter low power mode.

Figure 32: The timer interrupt's program flowchart



The push button was not used because the microcontroller was not soldered to a PCB. We instead decided to display data and have the microcontroller cycle between displayed values/units at a constant rate. It still allows the user to see optical information regularly. The timer still updates the values regularly.

5.5 Mechanical Design

5.5.1 Beam Blocker

The purpose of the beam blocker is to protect the user and the user's surroundings from potentially harmful radiation. It will be located at the front of the device where the radiation is emitted. We recommend turning the laser off before manipulating the beam blocker. The beam blocker was designed to be modular. A user could replace the electrically conductive medium and the component that stores the elastic potential energy.

The component that attenuates electromagnetic radiation will be a circular piece attached to a hinge located at the front of the laser. The circular piece and hinge will be made of the same material as the housing. Multiple layers of aluminum foil will envelop the front (part facing outward) of the circular piece. Glue will be used to adhere the aluminum to the circular piece. The aluminum will be 3 skin depths of the radiation with the longest wavelength emitted by the device. The aluminum foil can be easily replaced by pulling off the layers added for the original design and adhering new strips to the circular piece. The top and bottom of the housing will feature threads. The tips, that the threads are embedded within, will protrude from the housing to limit the size of the front piece There will also be a thread within the circular piece. When these threads are aligned , the user can use a thumb screw to fasten the circular piece to the housing.To hold the beam blocker in the open position (does not attenuate the radiation), a user must fasten the circular piece to the top of the housing. To hold the beam blocker in the closed position (attenuates the radiation),a user must fasten the circular piece to the bottom of the housing. Only one screw is needed to perform both actions.

Figure 33 shows the front of the housing but the blocker is not present. The blocker will need to be added along with a hinge. The blocker displayed in Figure 34 will be attached to the front using a metal pin. After the metal pin has entered the holes. an internal thread will be created so a screw could be entered. This screw will prevent the metal from moving out of one side. The other side will not have a hole and it would not be able to leave that side. Attaching fins to the pin and making placing holes for the fins will stop the pin from rotating. Rotation could drive the screw out but calculations would have to be done to determine the amount of force required.

Figure 33 - The front of the housing

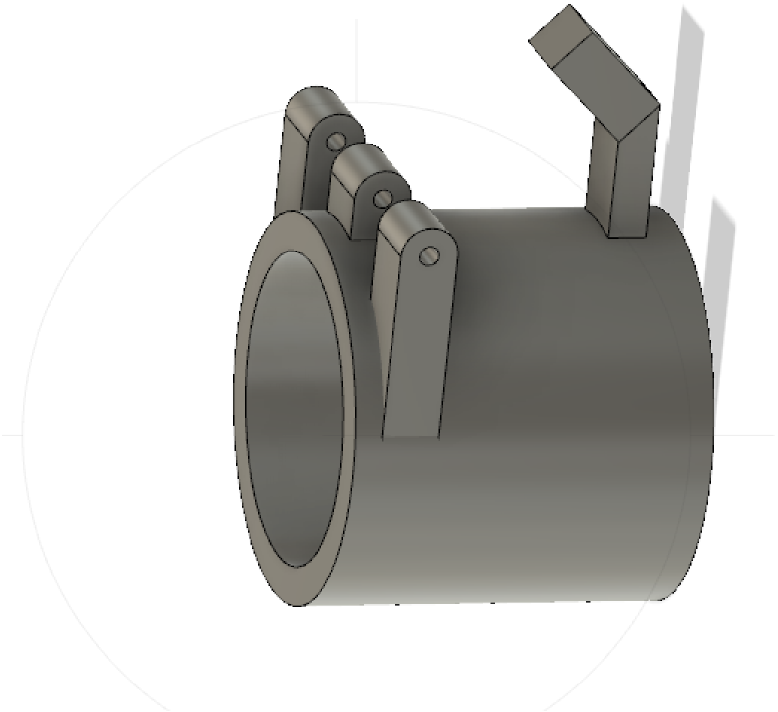
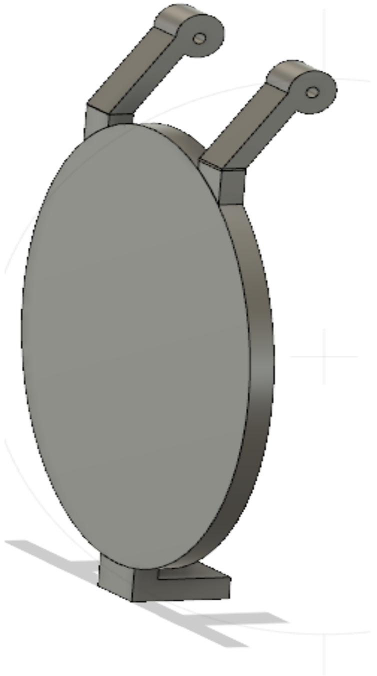


Figure 34 - The beam blocker



We did not use this beam blocker in the final design. We did not observe any flaws in this design and it may still work but it needs to be adjusted to fit the current housing.

6. Prototype Construction and Coding

6.1 Housing

As has been mentioned before, the housing for our design was custom-designed and 3D printed. This decision was reached largely because we wanted to bring our project to the point of being a proper tool, and not some large, temporary, table-top setup. To do otherwise would also stray from one of the primary goals of this project, which is to make this laser easy to use. Designing a 3D model of our laser will take more time than we anticipated, in part due to computer malfunctions that have led to the loss of easy access to engineering software that is capable of doing this.

There were 6 major compartments to our housing design. These included the main optical train, the spectrometer, the optical power meter, the power systems, the computing system, the cooling system, and the control system. The 3 main optical systems must be blocked off from each other so that no diffusely reflected light off of optical surfaces interferes with the readings in either the spectrometer or optical power meter. Each of these will receive their optical input orthogonal to the main optical beam path by beam samplers that will split off approximately 5.5% of the incident laser beam light at each location.

The spectrometer will occupy a mostly 2-dimensional area spanning just over 6.4cm x 6.4cm. The transmission grating is the cause of this 2-dimensionality. It will split the VIS spectrum from 400 nm to 700 nm off by a central angle of 33.37°, keeping in mind that this is already split off by 90° from the main optical beam path. This additional 33.37° could be oriented in any direction, but we have oriented ours pointing back towards the cavity so as to try and fold the spectrometer compartment back towards the electrical compartments in an attempt to keep the parts outside of the main optical beam path closer together. Doing this will also keep the image sensor closer to the computer and power system.

The optical power meter only required approximately 3.5 cm of length by 1 cm each in longitudinal space. This is because this system is in the UV (therefore using smaller lenses for the sake of cutting prices) and reads with a single photodiode. The lens is 3 mm in diameter and the photodiode housing is 9.1 mm in diameter. This system is also going to receive its optical input 90° off from the main optical beam. From there, the system could be folded further so that it could run parallel with the optical beam, but this would require the purchase of a UV mirror, which would only add to our costs. Instead, this meter will be a protrusion further down near the laser output. The only other prominent protrusion that far down the device was supposed to be the hinge to the UV beam blocker.

One concern that had been noted by some is the whether the plastic that the campus 3D printers print in will be resistant enough to heat to prevent warping. This concern can manifest itself in one of 2 forms: electronics and stray laser beams. The latter of these is easily dismissed since a properly working laser does not have stray beams that could strike the housing surface to heat it in the first place. The one beam that could cause an issue is the half of the cavity laser power that would exit back out of the input to the device. This would propagate back to the input laser light source. Since some laser systems cannot withstand feedback of this sort, such laser systems may not be advisable to use with our final design. The electronics are the other concern. Batteries are infamous for heating up over strenuous or extended use. In our case, it is the mere power requirements that may cause such a heat up. Since we want to keep this device cordless, the batteries will need to store enough power for the device to operate for an extended time without being plugged in. This results in potentially high temperatures, which could cause concern for the stability of the housing. The solution to this is that we have engineered a cooling system to prevent the electronics from overheating. This will, in turn, aid in the structural stability of the housing that holds the entire project together.

6.2 Optical Setting

Some senior design projects involving lenses and optics rely on mounting their optical equipment on an optical table/rail. This makes for an easier setup since any kind of mount one could need is made to fit the area, and some even to work together. However, in order to make our device handheld and easy to use, it needs to be free to be moved around, and not locked to a table at all times. Additionally, it was difficult to get table-mounts as close together as we would need them for our project. We have multiple optical components that are to be positioned only centimeters away from each other. There simply isn't enough room on an optical table to cram everything so close together. Especially if one then wants to adjust the position or orientation of any parts.

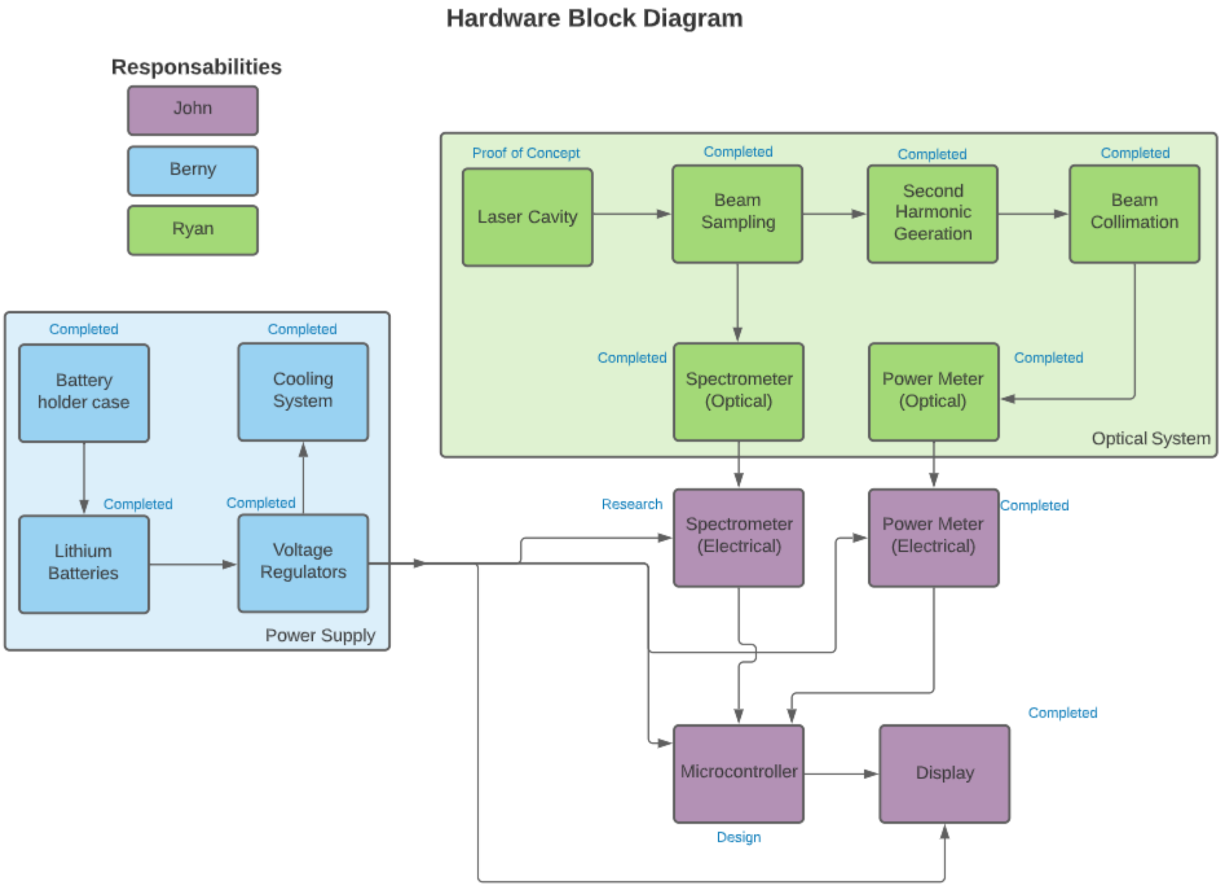
As has been mentioned before, we made a cylindrical concave divot wherever a lens will be necessary. We may then test the positioning of each optical component in sequence, making sure each part works individually and as a whole before attempting to fix it into the project. For each piece, when we were confident that we have the positioning right, we were going to use super glue (though epoxy would make a suitable alternative) to fix the component to the concave divot. The raised divots for smaller diameter components will be taller than those for larger diameter components out of necessity to fix all optical axes on a level plane. This height is not a factor that can be easily adjusted by hand during the fine-tuning of the positioning of optical elements, and as such will be reliant on the 3D design to make sure their heights are correct.

Some components, such as the laser cavity and the VIS to UV NLO crystal require the ability to adjust their orientation during or between uses of the final product. To meet this requirement, these components would be fixed to rotation mounts which are fixed to the housing. This allows for the cavity and crystal to orient themselves based on the cavity's specific defects (resulting in otherwise off-axis lasing angles) and the necessary incidence angle for SHG to occur in the crystal. We knew that the cavity mount will be a kinematic mirror mount. This is because they are a standard component for orienting optical components. Additionally, they allow for the setting of an inner diameter to the mount. In our case, there is a designed ring on the cavity that will be slid into the mirror mount so that the set screw on the mount can tighten down and hold the cavity in place. The NLO crystal also came in a 1" diameter mount made for the same kinematic mount holders that we obtained for use with the laser cavity. The issue discovered was that the kinematic mount we had was too large for the system. The other optics were all too close together. To remedy this, we printed a hole in the baseplate of the optical mounts and stuck a small rod to the bottom of a basic 3D printed ring-holder for the BBO mount. This would allow it to sit in its proper position and rotate for angle-tuning between different input laser wavelength requirements.

7. Prototype Testing

Due to multiple systems being kicked from the design, our final project block diagram is significantly different from how it started. In figure 35 below, you can see the updated block diagram for our final model. Each of the systems involved are discussed to some degree in this section, including what went wrong and where we finished for them.

Figure 35 - Final Block Diagram



7.1 Optical Testing

7.1.1 Optical Components Testing

Lenses

We should have tested the focal distances of each lens that we obtain. Typically, the listed focus of a lens is close enough to the actual focus so that testing is not necessary in a lab. If the focus is slightly off, you simply use a translation stage to adjust the distances. However, in our project, we fixed the lenses to the housing so that they cannot be adjusted. This, along with the fact that we built a very small optical setup for how many components are involved, means that very small distances matter a great deal and should have been tested for precision. These could have been tested on an optical table with the use of collimated light and translation stages for most of our lenses. This is because most of our lenses serve to collimate a diverging beam or focus a collimated beam. These are plano-convex lenses, and tend to work quite well for the job. The other type of lens that is used in our project is a bi-convex lens. It is used to focus the light that passes through the transmission grating in the spectrometer onto a

1D image sensor. Even though a plano-convex lens would technically work here, bi-convex lenses are an advisable lens for diverging-to-converging setups. This lens could have been tested either by sending white light through a monochromator and into a transmission grating, or skip the monochromator. Either way, such a setup would provide us with everything we need to see how the lens is focusing different wavelengths of light and where (if anything) something is going wrong.

Transmission Grating

The transmission grating can be tested much in a similar way to how we could test our bi-convex lens: with a monochromator. Since we care very deeply about making sure the different wavelengths are being split up in a predictable and consistent manner, there is value to testing different wavelengths independently. This is where the monochromator comes in. It would let us send small bandwidth signals to the transmission grating, one at a time, so that we could observe the exiting angle of each color.

Because the transmission grating is one component that we decided to go cheap on, it was also important that we test the stability of the grating. By this I mean to point out that professional gratings are coatings on glass or mirrors. Our grating, however, is on thin plastic. This means that it is much more susceptible to physical movement or vibrations. This physical stability should have been tested to see how far (if at all), the diverted spectrum will change angles, both laterally and vertically. The issue here is that the plastic of the transmission grating is not very taught, and so it is prone to bending. This bending changes the incident angle of the white light, which means it will change the exiting angle of each wavelength. This can not only blur the system, but it can also move the focused light entirely off of the 1D sensor. This is one such reason why we had been advised to consider changing to a 2D sensor and using some software to determine at any given point just what pixels are representative of what wavelengths. This testing should have been performed across the visible spectrum from 400 nm to 700 nm.

Mirrors

The only mirrors used in our optical design were used in the laser cavity. Therefore, they are some of the most important components to test since they are what's going to make this device work as a laser. You can test a standard flat mirror by simply striking it with a small collimated laser spot and observing its deflection angles at different angles. One could also check to make sure the beam stays collimated for such tests. However, we are not using a standard flat mirror. We are using concave mirrors. And even more problematic for testing, spherical mirrors. One test that can be performed on concave mirrors is to send light through their foci and observe the light focusing at the opposite foci. However, a spherical mirror has only 1 such point: its center of rotation. This point would need to be the emitting location of a point source and we would need to be able to measure the light focusing back to said point. This can be attempted, such as with an LED small enough to fit up to the mirror's focus while still being able to observe a small dot forming on a barely misaligned location.

The simpler way to measure the focus of a spherical lens, though it is still not perfect, is to shine a large collimated beam at the mirror and observe with a pin the point(s) of focus in front of the mirror. A pin (or similar tool) must be used so that the light hitting the mirror is not fully blocked. This focus should be imperfect, but it can be a simpler way to test a concave mirror.

Then there is the hot mirror. This mirror is supposed to reflect most IR light and transmit above 85% of visible light. The actual percentages are heavily dependent on wavelength, ranging from 85% to 99% transmittance. Again, as with the transmission grating, the specific transmission and reflectance of the hot mirror can be tested using a monochromator for the visible light, and a 1064 nm source for the pump light, reading the transmitted and reflected powers for each wavelength. This was instead only tested for 1064nm and 532nm light due to the fact that we were already quite sure that the hot mirror was going to be scrapped from the system due to flaws in the design discovered during prototyping on the same day.

Beam Samplers

Our beam samplers are supposed to reflect 1% of P-polarized light that hits it at 45°, allowing the other approximately 99% to transmit through, and reflect 10% of S-polarized light that hits it at 45°, allowing the other approximately 90% to transmit through. This can be tested with a collimated beam, a linear polarizer, and a power meter. You collimate a beam at a diameter smaller than that of the sampler's 45° cross section and send the light through a polarizer. Making sure you know the orientation of the polarizer, you can then force P- or S-polarized light to the beam sampler and read the power levels that transmit and reflect. If so desired, the reflecting angle can also be measured. Due to the fact that these specific angle-dependent reflections did not come up as significant enough to consider by the time we have circuits ready to test the optical power meter, we did not perform this test. Additionally, since the linear image sensor for the spectrometer was never completed, the exact sampling rate was not tested for the VIS sampler either. This is more excusable for the VIS sampler since the spectrometer would only care about relative intensity by wavelength, which would be preserved regardless of polarization.

KTP

The main two things that need to be tested for our KTP crystal are conversion angle and its conversion efficiency (which is partially dependent on angle). NLO crystals can be finicky with the angles that they will perform SHG at. KTP is one of the nicer, easier to work with crystals. Nonetheless, it is important to check at what angles you can actually get 1064 nm light to convert down to 532 nm light before you glue it to your mirror. Additionally, it would be of value to find the conversion efficiency so that you can better predict what your laser cavity's actual output power will be. The first of these tests can be performed simply by having the KTP on a kinematic mount with a 1064 nm beam pointed at it and seeing when you get green light. The latter will require that we separate the residual 1064 nm light from the 532 nm light so that their powers can be read separately. The ratio of 532 nm power after the KTP over the 1064 nm power before the KTP is your crystal's conversion efficiency. This value is intensity-dependent. Higher powers will have different conversion efficiencies than lower ones. But it would be good to at least have a baseline when we don't yet have our full 100 mW Nd:YAG laser, but can test weaker lab lasers on it.

During the early stages of senior design 2, it was discovered through correspondence with professors in CREOL who had access to SNLO software that the conversion efficiency through KTP would be very low, on the order of 10^{-4}. Though we were unable to test the actual efficiency through the crystal, this was confirmed through the difficulty we had getting any visible 532nm out of the ktp when hitting it with dozens of milliwatts of 1064nm light. This was one of the leading factors that lead to a redesign of our laser cavity during senior design 2.

NLO Crystal

Finally is the NLO crystal that will be used to convert the VIS wavelengths of the laser cavity down to UV wavelengths for absorption testing. In the same way as with the KTP, the conversion angle and efficiency are both valuable data to have. However, it is a bit more complicated when working with VIS to UV as opposed to IR to VIS. One must obtain a UV optical power meter to look for proper conversion at all since we can't see UV light. What is technically an alternative for qualitative measurements is that one can take a UV sensitive material and place it behind the crystal. Many chemicals fluoresce when illuminated with UV light, which you would be able to see if the yellow laser light was successfully converted down to UV. One such material is cotton, which can fluoresce when illuminated with UV, but does not fluoresce when illuminated with VIS.

Again, knowing the conversion efficiency would be valuable for laser classification, but it is not necessary for the application. We care about being able to detect a difference between the UV powers before and after a substance, but we don't technically care what order of magnitude those values are.

Due to larger input powers needed to get a proof of concept for a dye laser cavity working, we had to use a more powerful laser to really test some of the components in our system. This was also used for testing our BBO NLO crystal. Because of the limited access to this powerful source, though we were able to clearly observe frequency doubling happening through the crystal at phase-matched angles, we were unable to measure the conversion efficiency. Most of this being due to the fact that the UV sensitive spectrometer we were using to detect the VIS and UV separately was being saturated in the VIS. As such, we could not compare the VIS light to the generated UV in quantity.

7.1.2 Optical Systems Testing

Dye Laser Cavity

The pump source and dye laser cavity were the parts of our optical system that caused us the most issues. The first things that were tested were just the individual parts. In doing these tests, we discovered that the conversion efficiency for 1064nm down to 532nm via SHG in KTP was very low, and on top of that, the absorption of 1064nm in our Rhodamine B and methanol solution was about 20% across 1cm of solution. This meant we needed to try and figure out a way to get more 532nm light into the cavity and not have to rely on SHG in our own cavity to generate it. This solution was looked for in prior designs early on in senior design 1. However, at that time, we were still looking for very specialized optics that would transmit 532nm and reflect 590nm at 0 degrees of incidence. This was not something we ever came across for any kind of reasonable price. During this prototyping stage, however, we did find dichroic mirrors that would reflect 532nm and transmit 590nm as per what we would need for this general cavity layout.

Making this change would allow us to get more 532nm light into the system using a low power 532nm source than we were getting into the system with a higher powered 1064nm source. Nonetheless, it still wasn't enough to get our .6mM solution lasing. The 532nm was being absorbed in the first millimeter of solution, and not penetrating deep enough to allow for lasing. Another issue, though not visible, was that the CW operation of the pump source was (according to professors in CREOL) problematic for dye laser systems with non-flowing dye. We tried to pulse the system at up to 900Hz (thus was the fastest we could get in the lab with the equipment we had easy access to), though this was not fast enough to get the system to lase either.

We did get access however to a more powerful, faster pulsing, 532nm laser system in a graduate lab. This access was limited, and the operation of the laser was restricted to the person running the lab. With his guidance and our striving, we were able to get two proofs of concept for dye laser cavities at the very least. The first of these was that, with this pump source, and a much lower concentration, special laser cavities (like the one we designed) can work like a charm. The powers to get them to work, however, are so high that he was not willing to let us try to use our optics for our specific laser cavity design. The second of these proofs of concept was that we were able to show that with higher concentration solutions (like the one we had prepared), simply pumping the cavity with enough power pulsed fast enough can get lasing between the solution and cuvette wall. This lasing light comes out the side of the cuvette, though very dispersive and foggy. The former would be a more optimal proof of concept, though we were not permitted to use our own optics for such.

Because of all of these issues with getting the dye laser cavity to lase, we had to chuck it from the final design. This results in not having our own dye laser cavity or pump source, and not needing to power a pump source. Removing these systems from our device turns our project from a completely independent dye laser system emitting in the

UV, to a modular system that one could add to the front of a VIS laser to sample its VIS wavelength, convert it down to UV, and sample its UV output power. This system could still be used for testing UV absorption of sunscreen, but we did not get so far as to be able to complete said application test.

Spectrometer

As stated before, the optics of the spectrometer system have been operating decently since the midterm demo of senior design 1. We have been able to show that when collimated light is input to our sampling system, we are able to get wavelengths hitting where the linear image sensor would go at the approximate locations that they were designed to strike. We were not able to view all the way to the extremes of 400nm and 700nm due to the low light levels we were able to get through the monochromator used for this testing.

Because the circuit for the linear image sensor was never completed, we were unable to test the resolution of the spectrometer, and are only really able to surmount it to a spectroscope.

Optical Power Meter

Though the testing for this system was very last-minute, we were able to get successful testing and calibration of the optical power meter completed, testing at 650 nm. We should have tested this at UV wavelengths for the best calibration, though two things got in the way of that. First was that I had not thought about how a VIS filter that is transmissive to UV would be needed to separate the VIS leakage through the BBO and the UV generated by it. Additionally, due to the limited access we had to the powerful pump source that would be needed to get a sizable amount of UV out of the system, we were not able to calibrate the system in the UV.

With the testing that we were able to complete, however, we successfully used our optical system to direct some laser light off to the photodiode, read the photodiode circuit for a voltage correlated to the amount of incident light, and display the amount of light exiting the system to the display.

Housing and Mounts

The original design that we had for the optical mounts was to simply print up mounting rings from a baseplate at the designed locations to permanently affix all optical elements where they needed to be. The first issue that we came across was that the support material for the arches in the rings were very disruptive to the shape of the ring, preventing the lenses from fitting. They were printed as well without the support material, though these rings did not come out circular. The next prototype was to try printing the rings themselves separately. Though this allowed for very nice circles that the lenses fit into fantastically, they were then impossible to properly position on the baseplate by hand. Finally, a third design was drawn up. This third design was to have the mounts printed up from the baseplate, but have material fitting the shape of each optic from the bottom, but not from the top. This allowed for the optics to fit snugly where they should.

Two issues came up with this final model. The first was that the larger plano-convex lens used to focus the VIS light onto the BBO was large enough and close enough to a full hemisphere that it kept wanting to rotate out of position. It did not want to rotate far enough forward to properly guide light to the UV lenses. As such, it had to be left unattached from the system so that it could be removed for testing later parts of the design. The second issue was that the designed distance between this lens and the collimating UV lens was not perfect. The light exiting the system diverged heavily, and did not produce a well, confined beam. This distance would have been better determined in Zemax if I had access to it when I needed it. Additionally, I could have messed with the distances on the baseplate manually if I had more time to do so.

A housing was printed and completed for this remaining system. The system, when capped, consists of an input hole, the VIS spectrometer, a focusing and collimating system with an angle-tuneable BBO inside, the UV optical power meter, and an output hole. There were holes in the walls to the housing for the linear image sensor (in the case that such circuit could be completed in time) and the photodiode. Additionally, there is a hole in the top of the housing through which a printed screw could be attached to the top of the BBO since a user would need to be able to angle-tune the crystal during operation and between using different wavelength inputs. The final mounting baseplate and cover can be seen in figures 36 and 37 below.

Figure 36 - Optical Mounting Model

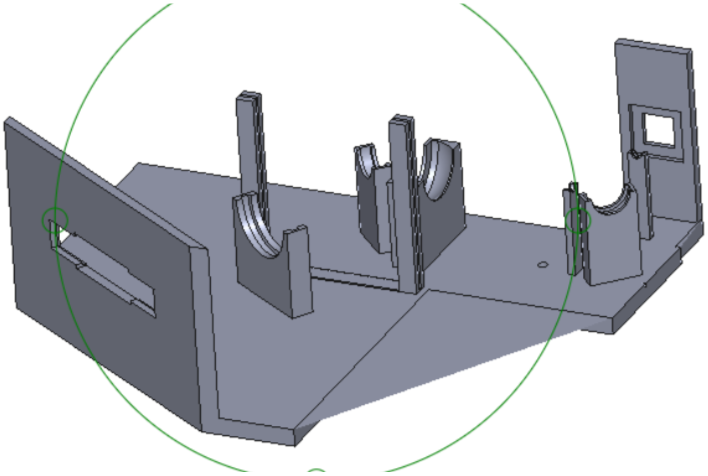
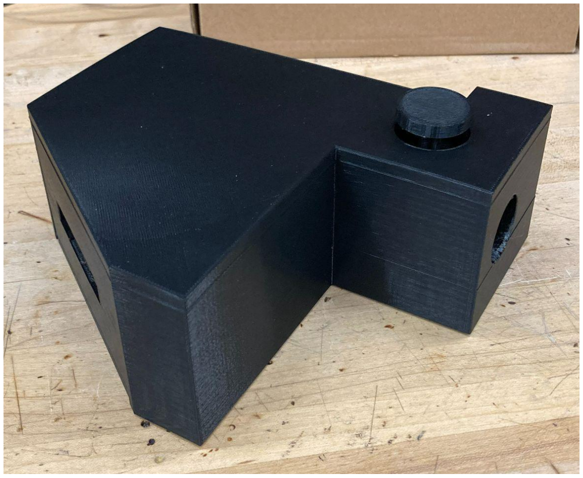


Figure 37 - Optical Covering



Application

Our project has been a technology-push project rather than an application-pull one from the beginning, sprouting from the idea of the ease of use of a self-contained dye laser cavity as opposed to standard dye laser systems. The application that we believe we have settled on to display a use of this system is UV absorption testing of sunscreen. Sunscreen is designed to absorb mainly UVA and UVB rays of sunlight that would otherwise be harmful to human skin under prolonged exposure. UVC is typically ignored due to the fact that most of it is absorbed by the ozone layer.

The testing for this is quite simple. First, the laser is pointed at a piece of thin plastic and the transmitted power is read by a photodetector on the other side. This should be done over time to get a better average of the power, especially since the photodetectors we are accustomed to using have a large variation of read power over time. This pattern repeats though, so an exposure of a minute or two can be taken for a good average.

Next, a piece of the same type of plastic is coated in the sunscreen being tested and allowed to dry for the specific brand's recommended drying time. The same experiment is then performed on the piece of coated plastic. If the sunscreen really does absorb UV light, then we should see a significant decrease in the transmitted optical power.

A disadvantage to this form of sunscreen testing is that it only tests one wavelength (or a few in a very short linewidth) at the same time. To effectively scan the full efficiency of a sunblock, one would need to prepare multiple dye cavities for this device to convert down to multiple UV wavelengths to test over a wider range of wavelengths.

M-Squared

When building a laser, one of the major questions asked is the m-squared value of the device. For most purposes where a precise or clean laser beam is desired, a Gaussian is picked as the “optimal”. Other applications, like laser cutting of large materials can care more so about the output power and less about if the beam looks pretty. The m-squared value in simple terms is an index for how closely your laser beam approximates a perfect Gaussian profile. An m-squared value of 1 means it matches a Gaussian beam perfectly, and the higher the value, the further it is from a Gaussian.

The method for testing the m-squared value of a laser has been made into a standard and rewritten multiple times over the years because of just how precise you have to measure such a sensitive detail. The overall process involves mapping out your laser beam into a grid of multiple discrete regions. You then measure the optical power at each said region and create a discrete representation of the profile of your beam. This is matched to a Gaussian profile, and the larger the disparities, the larger the m-squared value.

The mathematical details of this process have not been obtained yet seeing as this is an industry standard (and those cost money to view). However, a simple way to test this is to mount our device in an x-y positioner and point it at a power meter with a small square blocking aperture on it. This will allow the power in a small square of the profile to transmit through and be read on the power meter. After allowing for a timed average of the reading at a certain point, the laser can be translated so the next region of the beam transmits through the aperture, and measurements are taken again. This can be performed for the full grid of the laser profile. By the point of testing, the mathematical data on calculating an m-squared value should be acquired, and we can then calculate the m-squared value of our laser.

M-Squared testing was not something that we got around to with our project due to both the issue of how late we were getting around to so much in our system and the chucking of the laser cavity subsystem. A similar, and still significant test to perform (given we had time) would be to analyze the point-spread function for our specific system. Since it is a modular system now that could be added to the front of a VIS laser, it would be valuable to know how neat a laser point will come out of our system.

7.2 Electrical testing

7.2.1 Hardware

Voltage Regulators testing

When the PCB arrived parts had to be soldered to it. Problems can arise from several reasons like defective design, and soldering mistakes like bridges, disturbed joints, starved joints and others. After our PCB was soldered we proceeded to testing. The first testing of just measuring the voltage at each voltage regulator output was done. All regulators output voltages were correct and worked as intended. The next test was to put a load at each regulator. The 5V boost converter was connected to the two fans of the cooling system and both fans operated as intended. The 3.3V and 12V regulators output pins were connected to resistors. The 12V boost converter unfortunately was connected to a load that was too big to handle. The design had an expected output current of about 200mA, but when loaded with 120mA the resistor overheated and the 12V regulator IC burned out. Another PCB had to be soldered and tested and precautions with current were taken. The 12V regulator was hard to find and we were not worried about the output current since the components that required this regulator would had not taken more than 100mA.

Housing

The housing will be made of ASB. The airflow must be sufficient for the fans to remove enough heat. The fans will be tested by measuring the effects they have on objects when blowing behind the housing and directly in front of the object.. The beam blocker should be able to reduce the power (leaving the front) by over 50%. The housing will be tested based on how it withstands falling from at the height of a typical human shoulder. It should protect the components and not break. Being dropped in the upright position is the only position of interest for us. It would be unusual for an individual to drop it another way.

The housing used a different material and we decided not to drop it to avoid breaking it before the demo and final presentation.

Sensor testing

After the thermometer, additional circuitry, and coding has been configured it will need to be tested for accuracy. The thermometer terminal will be connected to a breadboard and powered using an external power supply. The microcontroller will be replaced by its launchpad equivalent. The base of the aluminum probe will be placed in a cup of ice water. The places that would not be in direct contact with the batteries' will be covered with plastic to emulate the level of thermal insulation in the air. The temperature reported by the microcontroller would need to be within 5 percent of 32 °F (30.4 °F - 33.6 °F) to be considered accurate. It would also need to be stable no more than 30 seconds after it was submerged in the water. Stable means the value does not change by more than 3% in a 5 second interval. An accurate digital thermometer can be used to verify that the water is 32 °F. Once the thermometer has been verified to be working correctly, it will be assumed to be correct and its reported values will be accepted as the actual values. This is needed to determine the correctness of the other sensors, which are affected by temperature, because they will not be tested in the housing. Knowing the actual temperature inside can help us to create functions to compensate for these non-ideal effects. However, it should vary greatly considering the housing is expected to be slightly warmer than room temperature.

The ammeter's circuit can be tested by using a very low tolerance resistor and an external power supply. The power supply will supply power for the resistor and the ammeter. The ammeter will be powered by that external power supply as well. Using Ohm's law the current through the resistor can be determined. The values should be compared with the values reported by the microcontroller. The value reported by the microcontroller should be within 10 percent of the predicted value to be considered correct. It will initially be tested without the electromagnetic field protection plate. Measurements will be taken with and without the plate to determine its necessity.

These components were not included in the design.

Cooling system testing

The cooling system was tested by connecting the two fans to the 5V regulator. The fans ran at a constant speed and operated as intended without stopping for 1 hour before we disconnected them. The original design testing was intended as follows, but changed due to changes in design. The cooling system will use a fan operating at a constant speed. The speed will vary by the DC voltage applied to it. To determine the required fan speed, we planned to configure all components and assemble the housing to properly assess the performance of the fans. The properly functioning thermometer will be used to analyze the batteries' temperature. The batteries will be discharged until they have 10 % of their charge left (starting from 100 % charge). The goal is for the batteries' temperature to remain less than 40 °C during this entire time. The fan speed will be decreased until this cannot be achieved. This is done to reduce the power requirement or maximize efficiency.

BMS testing

We removed the BMS from our design, but the following is the original intended plan for testing. Testing the BMS should be done especially if we buy it from a commercial seller found on the internet that is not from a recognized brand like Texas Instruments which tailors the BMS to our needs. If a commercial battery monitoring system is obtained, several types of tests should be done to simulate all conditions that could occur during operation of the laser. A DC power supply unit like the one we use in the lab can emulate our battery power supply. The DC power supply unit is equipped with functions to test and validate our BMS. Battery short circuit , overcharge, and over discharge can be mimicked and tested for the BMS by using this DC power supply unit. If the features offered by the commercially bought battery monitoring system function as expected, we can move on to use it with our actual battery power supply.

7.2.2 Software Testing

The software was tested after all of the hardware had been configured and functionality had been verified via testing. The software was tested for things such as the accuracy of the timer, accuracy of the push button, correct output when interrupt-triggering events occur closely with respect to time, and correct output over the recommended ranges for each phenomena being measured. The correct outputs over the recommended ranges were verified by testing the components. The microcontroller must digitize those values and report them on the display. A multimeter was used to measure the output voltages of the sensor circuits and they will be used to calculate the corresponding digital value.

The values printed on the display should match these values. If the requirements were not met the code would have been rewritten.

The timer should update the display every 5 seconds. Iteratively, the code executed in the timer interrupt would add 1 to the previous number. The number was then printed on the display. We planned to use a stopwatch to confirm it is switching every 5 seconds. After this we intended to use a more accurate method to determine the time. The microcontroller was used to display the value in the timer's counting variable.The program was written to display the number in the timer's counting register at the end of the interrupt and reset to zero. The delay caused by the processor is negligble. Using the frequency of the clock, the exact time elapsed was determined.

The button will alternate between the types of information displayed. The button can be tested by printing a value on the display and having it change when the button is pressed. It should not do anything unless the button is pressed. A tester should hold the button for an extended period of time, press it rapidly, and partially release the button before pressing the button firmly again. None of these ways of manipulating the button should result in a change in the value.

Occasionally, multiple interrupts are triggered almost simultaneously. In this case we want to ensure that they still provide the desired output. For example, the button is pressed 5 seconds after the timer updates the values. The timer should display the opposite information until the button is pressed again. If the code is functioning as desired, the button should be able to change whenever it is pressed. This includes when the timer is executing the interrupt code. It could be nearly impossible for a human to wait until the code is executing and strike the button at that exact time. To test it, a person will wait until nearly 5 seconds has elapsed since the last update and quickly strike the button. Doing this many times will make it more likely that you struck it while it was executing the interrupt code. If it always alternates the code after 20 to 30 tries, then one can be confident there are no strange effects around the execution time.

To test how the microcontroller handles multiple interrupts, we started an interrupt and then we prolonged it using a timer. Since interrupts on the microcontroller are not preemptable, it did not begin executing the code in the next interrupt until the currently executing interrupt ended.

8. Administrative Content

8.1 Conclusion

We set out at this project’s onset to create a self-powered laser system sampling its own wavelength and power for the user. Over the course of two semesters, we were able to complete a self-powered spectroscope and optical power meter reading and displaying output laser power to the user. These systems were still not completely unified in a single model though. Multiple setbacks were hit, there were parts that broke, and prototypes that failed. Our overall system is still something that could be used for our original application however: UV sunscreen absorbance testing. It would still be a module used in a testing lab with lasers, though in this model, the user would need to provide a pumping VIS laser.

When developing the power supply system availability of parts became an issue. Voltage Regulator ICs were in very short supply for our application and most had really high lead times, but in the end we managed to find all the parts to complete our power supply circuit and test it. The power supply can deliver all desired output voltages and currents required by each component. Housing for the power supply was not completed due to time constraints. Completion of the housing needs to be finalized for the safety of a user that is not familiar with our power supply.

As we reflect on our project, we contemplate moments or decisions that we wish were different. We had an alternative idea for the spectrometer that used a moving photodiode propelled by a linear actuator. We also thought of using a slide potentiometer to track its position. This would have allowed us to avoid issues with the timing of the pulse signals for the image sensor.

8.2 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 slowly transitioned from the research of how to design these systems to the actual design process of them. The first systems that needed to 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 hoped to be trying to wrap up the design process as November approached, and proceed to begin gathering parts for project demos. Working on project demo construction was to take place through most of November. Of course, there would be many changes to the project design as we ran 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 also came up over the course of senior design 2, during which we continued with the purchasing of parts, construction, and testing. Additionally, over the course of senior design 2, we tried 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 8.

Table 8 - 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

8.3 Budget and Costs

When estimating the budget for the device, we knew from the start that optical components would be expensive and would cover a big fraction of the budget. We set our budget at $1000 for the project and expect the optical components to be an expense of over $900. Most electrical parts tend to be low in price and we estimate that our electrical components will be around $100 which would give some lead way to allow us to stay under budget. At the beginning of the semester, we decided to split the cost, but after making some optical calculations and seeing how expensive this portion of the project would be, Ryan decided to ask his parents to sponsor the optical components portion to build the laser. The electrical components expenses will be split in half between Berny and John to cover the rest of the budget.

Due to the fact that the dye laser cavity and pump source were kicked from the design in the end, the costs for such do not appear below.

Table 9 - Parts Breakdown & Costs

Item	Supplier	Item #	Quantity	Price in $	Total in $
Super Glue	Walmart	N/A	1	5.62	5.62
VIS Beam Sampler	ThorLabs	BSF05-A	1	40.31	40.31
UV Beam Sampler	ThorLabs	BSF05-UV	1	40.31	40.31
Diffraction Grating	Arbor Scientific	33-0990	1	3.75	3.75
Photodiode	Edmund Optics	#57-510	1	66.50	66.50
1D Image Array	West Florida Components	TCD2557D	1	10.40	10.40
VIS->UV Crystal	Edmund Optics	#11-167	1	570	570
Plano-Convex Lens	ThorLabs	LA1951	1	25.14	25.14
Plano-Convex Lens	ThorLabs	LA4039	2	65.00	130.00

Bi-Convex Lens	ThorLabs	LB1471	1	25.04	25.04
Microcontroller and circuit	Texas Instruments	MSP430FR6989	1	9.32	9.32
Display	Focus LCDs	C162D-BW-LW65	1	13.70	13.70
Switches	NTE Electronics, Inc	54-874	1	0.51	0.51
Batteries	Ultralast	3145-UL1865-34-2P-ND (2 batteries pack)	1	21.99	21.99
Voltage Regulators IC and other parts along	Texas Instruments and Digi-key	XCL210C331GR-G LM2698MM-ADJ/NOPB XC9143B10DER-G	3	3.21 8.44 3.25	14.90
Fans	Sunon Fans	MF40100V1	2	5.50	11.00
Battery Charger	Ultralast	ULLIONCHG	1	12.99	12.99
Battery Holder Case	Keystone Electronics	1048	1	6.80	6.80
Operational Amplifier	Texas Instruments	OPA2387	1	1.15	1.15
				Total Cost	$1009.43

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 9. Also some items have been removed from the list like the beam splitter. Currently optical parts have a total cost of $917.07 and electrical parts at around $92.36 coming to a grand total of $1009.43. Our budget just went over the $1000 expected budget.

8.4 Sources of Reference

Though we did not keep great records of our references throughout the course of senior design, we would like to reference here some valuable sources that we pulled from. Some of the following are companies, websites, or books that had valuable information, and some are people who we were able to get advice or assistance from who we would like to acknowledge.

Dr. Abichar, Zakhia

Dr. Delfyett, Peter.

Dr. Horton, Chad.

Dr. Kuebler, Stephen.

Dr. Mhibik, Oussama.

Dr. Richie, Samuel

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9 Final Project Operation

9.1 Device Usage

Our device is a module that you can add to the front of a VIS laser that emits between 490nm and 700nm. The lower limit is imposed by the efficiency of optical coatings inside the device, and the upper limit is imposed solely by the degree to which we wished to design this device for. The system will sample your VIS wavelength, which can be seen through the rectangular opening on the trapezoidal protrusion from one side of the device. This is operable at this point as a spectroscope. The module will then send your laser light to a BBO crystal, which you can angle tune with the screw protruding from the top of the device. The module will finally sample off the UV light generated by the BBO and display the output UV power on the LCD. The output beam will exit on the opposite side from the input beam.

An image of the device can be seen in figure *** for reference.

9.2 Optical Alignment

To align the module, you should first place a straight reference edge (two screws will also work) along the long-straight side of the module, opposite that of the trapezoidal protrusion. This edge is aligned to be parallel with the main optical train internal to the device. The module may then be placed in front of your VIS laser source that you wish to use. You should make sure the input is centered vertically and laterally so that the output beam comes out as neat as you can get it. This output beam, due to failures in the system, may not be well collimated. Because of this, it is advised that the operator is very cautious during the optical alignment process. Once you have this aligned properly, the spectroscope and optical power meter should be well aligned.

The remaining step is to manually angle-tune the BBO inside the device via the screw protruding form the top of the housing. Using SNLO or similar software is advisable to find a likely position to start from to convert your VIS wavelength down to its SHG wavelength, though it is not strictly necessary. As you approach the optimal angle, the displayed UV power on the screen should go up, indicating that you are getting more output power. When you find a maximum, leave the screw where it is, or remove it if so desired. Your system is then sampling wavelength in the VIS, converting some of the VIS down to UV, and sampling power in the UV.

9.3 Optical Power Meter

The optical power meter needs to be configured to create a positive voltage at the ADC's input terminal. A negative voltage could damage the ADC.Connect the cathode of the photodiode to the negative input of the op amp and the anode to ground. Connect

Port 9.2 to the output terminal of the op amp and the ground port to ground. It is recommended the op amp have 5V and -5V volts at its rails to provide voltages for the entire spectrum of optical powers. The negative supply voltage can be created by using a separate set of batteries with the 5V regulators.

The software will require calibration depending on the frequency of the light and other characteristics of your system. The gain can be tuned by taking the value measured by a calibrated power meter and dividing it by the microcontroller's reported value. Multiply the gain in the code by this number and repeat if necessary. If you are not able to reach the correct value, make sure you are using a stable power source and adjust your feedback resistors or capacitors.

9.4 Power Supply

To start operation of the laser, batteries should be positioned in the battery holder case in parallel by matching positive and negative markings. Once the batteries have been positioned correctly in the battery holder case, turn on the device by pressing the switch. After operation, turn off the switch and remove the batteries from the holder case. Batteries should be stored away from sunlight, heat, and humidity.