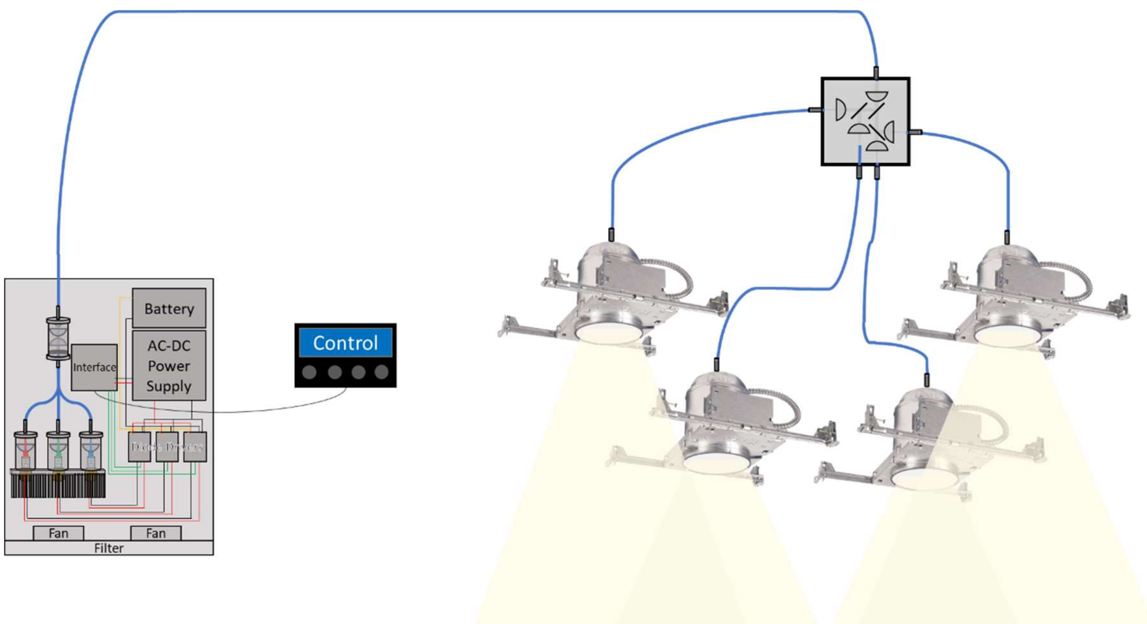
# Mixed and Distributed Laser Illumination System (MADLIS)




Group 26

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## 1.0: Executive Summary:

MADLIS is a new method to utilize the efficiency and power of laser diodes to create a lighting system that has added capabilities exceeding existing commercial lighting. The single light source unit is separate from the outputs and is connected by a single fiber optic cable. MADLIS is scalable in both function and magnitude. By utilizing a combination of different wavelength laser diodes combined into the fiber output from the source unit, the system can be configured for white light only for standard illumination, or additional wavelengths can be added for specialty purposes including security, sanitation, and agriculture. A basic system-level block diagram is shown in Figure 1 later in the paper.

MADLIS is different from existing lighting systems because the user-tunable light is distributed by fiber optics. This allows the entire system to be easily protected, electrically and optically redundant, electromagnetic pulse and electromagnetic warfare survivable, free from electromagnetic interference, and installed in wet, hot, cold, or other environments where electronic devices fail. Since the source unit can be separated by a significant distance, it can be placed in an area that is easy and safe to access for maintenance or control. The single fiber leading to the output area can be split into a required number of output modules, all with either an equal output, or the outputs can be customized by creating unequal outputs or different colors/intensities entirely by using a different source unit configuration with multiple 'channels' of lighting. This project has a base goal of creating a white-light illumination system that has user-controllable hues and intensities of light with four equally diffused output units.

### 1.1: Background:

During the maintenance of a United States Air Force satellite communication (SATCOM) system in 2013, it was questioned by Derek Daniels whether or not the same concept of combining, transmitting, and dividing/distributing signals in the microwave region of the electromagnetic spectrum could be done with visible light. The SATCOM system used a single waveguide to connect signals from multiple modems simultaneously to another building where the combined signal was transmitted. A received signal was a combined set of signals that could be divided back out to the individual modems. Through a single interfacility waveguide, the source of the signal was able to be physically separate from the output, allowing the source to be more easily climate controlled, physically protected, and controllable from a user-friendly position. As signals in the higher-frequency microwave region need to be transmitted over waveguides, optical signals can also be passed over waveguides in the form of fiber optic cables.

#### 1.1.1: Lighting/lasers

Most people take lighting for granted until their power goes out and they are back to using flashlights or candles. For a long time, most lighting relied on the usage of simple blackbody radiation of a piece of tungsten metal to provide light. Later down the road a technology called a light-emitting diode was developed (LED) which is now becoming the industry favorite for lighting applications. The LED was a major increase in efficiency from the previous incandescent design because of the broad spectrum of a blackbody radiator. LEDs operate over a smaller range of frequencies and use energy more efficiently than the previous designs. For our design project we were looking to further improve the efficiency by taking this progression a step further and replacing the LEDs with laser diodes (LD). The main differences between LEDs and LDs have to do with the mechanism of power gain, the spectral range of output light, the divergence of the light, and the efficiency of power usage. These will be discussed in more detail in the laser basics section.

When the topic of lasers is brought into light the issue of safety is usually the first topic of conversation. A major advantage to this design is that the source of the light will not be at the same location as the light output cannister. Intuitively, by having the light emitters in a separate secure location it becomes easy to consolidate them all together whereas for LED lighting there has to be an actual diode at each output location. LED lighting generally uses a large array of low output diodes whereas our design used a much smaller number of diodes, but each will be much more powerful. More specifically, we have about 7W of 450nm light, 4.4W of 638nm, and about 1W of 520nm. These levels of power are quite dangerous to the human eye and can even cause skin burns when focused down. This section will go in depth into the lasers themselves as well as the standards and safety protocol for dealing with high optical power.

#### 1.1.2: Laser Basics

Before getting into the safety concerns involved with operating lasers it is important to first understand some fundamentals to how lasers work in general. The word “laser” is an acronym meaning the “light amplification through stimulated emission of radiation.” In its most basic essence a laser system is made up of a cavity, a gain medium, and some form of energy pumping source.

Many lasers utilize a setup called a Fabry-Perot etalon to produce a good lasing cavity. A Fabry-Perot etalon in its most basic form is two flat mirrors facing on another, being parallel to one another, and having some characteristic reflection coefficients for different wavelengths. Assuming that the mirrors are relatively parallel there will inevitably be some light that bounces back and forth many times.

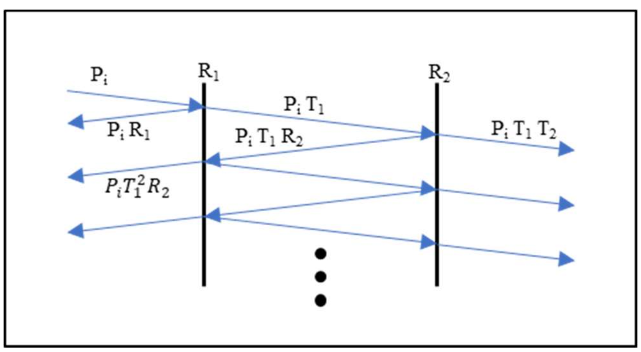



Figure 1: Basic Fabry-Perot etalon mirror setup.

Most of us have seen this effect when we use a mirror to look at our new haircut through another mirror; we see nearly infinite copies of the same setting in the reflection and this is an intuitive look at the Fabry-Perot etalon effect. A simple two flat-mirror Fabry-Perot etalon with both reflection coefficients being less than 100% is shown in figure 1. In the figure the initial incident beam of power hits the etalon setup at an angle causing all kinds of chaotic transmitted and reflected rays. Assuming there is a constant supply of incident energy these internal reflections should technically go on for as long as the cavity is physically and the number of reflected beams approaches infinity. If the incident beam is normal to the surface of the etalon, the mirrors flat and perfectly parallel, then all of the "trapped" light that gets caught bouncing between the mirrors will be taking the same exact pathway back and forth. This brings us to the concept of cavity resonance and round-trip travel time. To simplify the concept, when given a Fabry-Perot mirror cavity with a specific length (L) and index of refraction between mirrors (n) there are specific frequencies, called resonant frequencies, at which the etalon performs efficiently for. Figure 2 shows a good visual representation of any laser cavity with respect to what frequencies it would be useful for resonating.

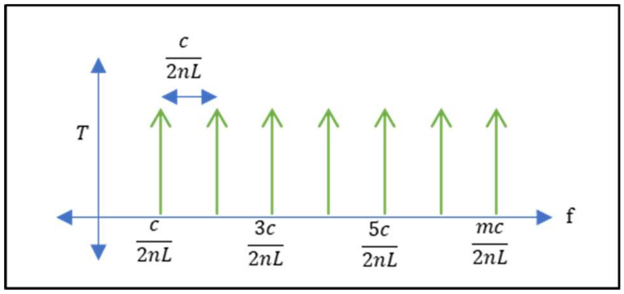


Figure 2: Fabry-Perot etalon resonant frequencies.

The modes of the cavity are separated by the amount c/2nL. This equation is the speed of light divided by double the product between the index of refraction between the mirrors and the length between the mirrors. At first glance this seems like a complicated equation requiring a lot of complex math to understand however, it is simply the inverse of the time it takes for light to travel a single round trip through the cavity. The speed of light in a vacuum divided by the refractive index of a medium is the speed of light in that medium. From basic first principles of physics one can find the time it takes for something to travel a certain distance by dividing the displacement of the object by the velocity of the object. Assuming that object's movement is periodically making round trips than the frequency would be the inverse of this value. The round-trip distance of the Fabry-Perot cavity is double the length of the cavity because the light travels distance L, reflects off a surface and travels that same distance a second time. The time it takes for the light to travel this distance once is the period and can be found from 2L/v, where v=c/n, or the speed of light in a medium of index n. This is how a Fabry-Perot cavity works in its most basic and general form and is not very exciting without the gain medium inside, which is the next part of a laser needing to be discussed [26] [25].

After understanding how a lasing cavity can resonate at specific frequencies the rest of the laser is just a matter of adding in some kind of gain medium and then giving that gain medium the energy it needs to lase. A gain medium is some kind of material that when excited by some kind of energy will emit a specific spectrum of electro-magnetic radiation depending upon many factors like the elements used, and some quantum fluctuations. To fully understand how this works one would have to get waist deep in quantum theory and the uncertainty principle but for the sake of this design project we will discuss the mechanisms in their most basic form for the purpose of use in comparing products. A gain medium spectrum, or the lineshape function, is a graph showing the change of gain with light frequency, an example of which can be seen in figure 3.

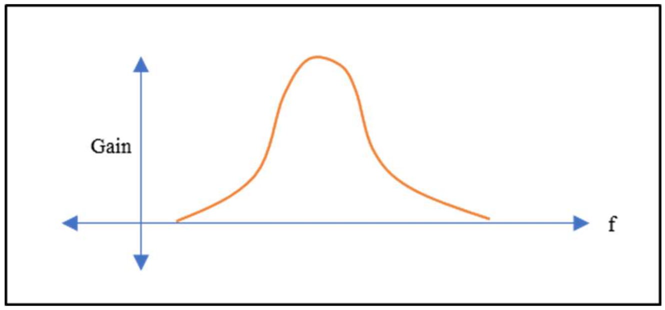



Figure 3: Lineshape function of some gain medium.

The y-axis of this graph is slightly misleading but allows for a better visual representation of some very complicated quantum physics concepts like the uncertainty principle. In the quantum view of light, it is thought of neither a ray nor a wave, but instead as a packet of energy or particle. In quantum mechanics theory a single packet of light, or a single photon, has an energy level directly proportional to the light particle's frequency – related by a constant known as Planck's constant. When looking into the gain medium itself we see that there are a number of possible energy levels that the valence electrons can be bumped up to. A simple visualization of this concept of energy levels can be seen in figure 4 with a simple 4-level lasing system [26].

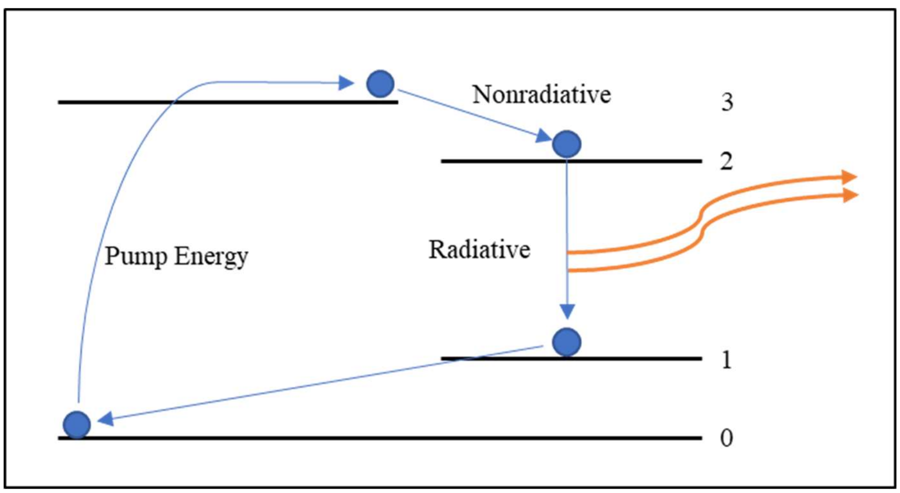



Figure 4: A simple 4 level lasing system.

When an electron is somehow given enough energy to get into the 3rd energy level for this system, there is first a nonradiative transition down to the second level and then another transition to the lowest level that is radiative. Not all laser systems operate like this with this number of levels but for the sake of explanation we consider the transition from energy level 2 to energy level 1. This decrease in energy that the electron experiences during this transition causes it to release a packet of light, or a photon, with the frequency corresponding to the energy loss divided by Planck's constant. Sometimes this emission can occur spontaneously if an electron gets excited to the required energy level and is known as spontaneous emission. When a photon is spontaneously emitted it has relatively random characteristics with respect to the phase and direction of propagation. A diagram of spontaneous emission can be seen in figure 5 and is simplified for the purpose of comparison.

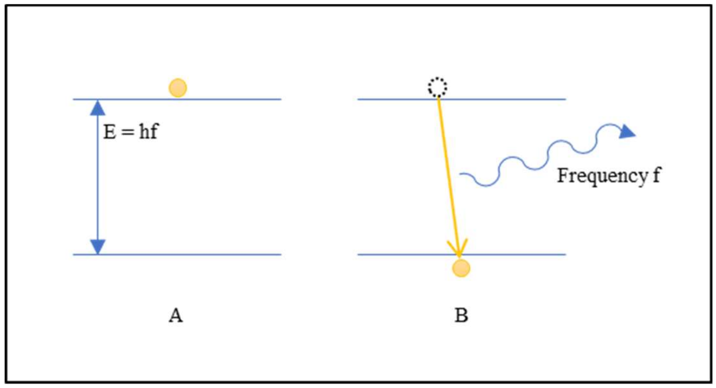


Figure 5: The process of spontaneous emission of light.

In the left part of the diagram (A) we can see an electron in some excited state then it falls down to the ground state (B) and spontaneously emits the light packet. This effect can be seen in things like glow-in-the-dark polymers where incident light energy throughout the day is absorbed by the material and is constantly released as the glow seen when viewed in the dark, or in a high contrast setting. There is another way that electrons can release light except in a “stimulated” or “triggered” manner. Stimulated emission is the process that really makes the concept of a laser possible and is similar to spontaneous emission. The process of stimulated emission can be seen in figure 6 and involves an already-excited electron as well as an incident light packet of equal or higher energy than said electron [26][35].

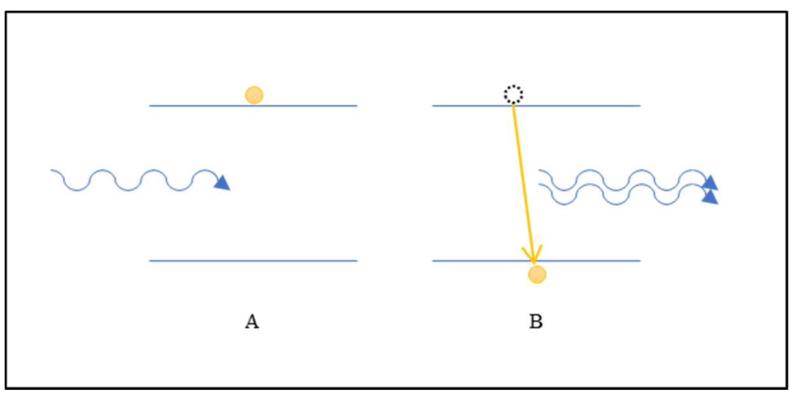


Figure 6: The process of stimulated emission.

The state of the gain medium before the stimulated emission (A) shows an excited electron in a higher energy level as well as an incident packet of light that happens to be of equal energy of the bandgap. The excited electron “sees” this packet of energy that is so similar in every way to itself and it falls down to the ground state (B) emitting a packet of light just like in spontaneous emission. The big difference in this case is the fact that the emitted photon is in phase with, traveling in the same direction, and of the same frequency of the incident light that stimulated the emission in the first place.

## 2.0: Existing Comparable Technology:

There are systems available including red, green, and blue (RGB) light-emitting diode (LED) lighting systems that use sets of RGB LEDs to control the colors that are emitted for an area. However, these systems are typically not transmitted over fiber due to the high fiber-coupling losses. LED fiber illumination systems exist for small-scale lab or medical use, but they use large bundles of fiber to attempt to increase light intensity, even for the short distances that they are used for. These systems are typically very expensive and not efficient. There are some laser-diode-sourced lighting systems available commercially, including some automotive headlights using a blue laser diode shining into a phosphorous to create white light. These systems are not hue-tunable without physically changing the phosphorous, or inefficiently adding filters. Blue laser diodes with phosphorous have been coupled into fiber for illumination with similar pitfalls. Because there has not been an identified prior art that nearly matches the utility of this project, a provisional utility patent was filed by Derek Daniels at 12:01PM ET on August 10, 2018 with the United States Patent and Trademark Office.

### 2.1: Market Research:

The lack of consistent standards with the innumerable types of light sources available makes direct comparisons with MADLIS difficult. A set of experiments were performed to analyze existing technology to ensure MADLIS exceeds most commercial lighting products available today. One product researched and examined was the Hyper Tough™ 4-ft LED Shop Light, purchased from Walmart for $16.87 plus tax. Clearly, this is a very inexpensive and bright option for lighting for our complex, expensive system to compare to. The light boasted 3200 lumens of output on 30 watts of power. To investigate these claims, the light was turned sideways and shined on a wall so that the area illuminated was approximately one square meter. Then, a commercial lux meter was used to measure lux levels across the illumination profile of the light. An illumination area of a square meter was chosen because one lux equals one lumen per square meter, so lux levels within one square meter would be equal to lumens. It was consistently shown that the peak lux reading was 3200 lumens, but only at the center of the beam. The output appeared to be gaussian in form, with the output lux levels quickly reducing to single-digit lux near the edge of the covered area. Therefore, the light would more accurately be labelled as 3200 lumens peak output since the light could not cover even one square meter with 3200 lumens of illumination. Next, the enclosure of the light containing the electronics for the LED strips was disassembled to analyze the input current and voltage supplied. By connecting an ammeter in series with the AC power from commercial power, it was determined that 371mA was being supplied to the light. Multiplying current by the RMS voltage of 120V, the light was shown to consume 44.5W, significantly higher than the specification. To analyze specific wavelength outputs from the LED strip, a single LED was isolated by covering adjacent LEDs and a Newport power sensor was placed directly over a single LED on the strip. Next, the power meter that the power sensor was connected to was set to a wavelength of 555nm, to match the wavelength that has the highest sensitivity to the human eye. A reading of 4.68mW was shown and multiplying the reading by 192 for the number of LEDs in the pair of strips, it was shown that the commercial light produced approximately 900mW of 555nm light. For the best-case scenario where the light emits at least the same wattage for the rest of the visible spectrum, a comparison to the wavelength-dependent sensitivity of the human eye can be performed.

To determine usable light emitted from a light source for illumination for use by human eyes, the wavelength-dependent sensitivity of the human eye curve must be used. A set of the points was taken from the National Physical Laboratory's Kaye & Laby Tables of Physical & Chemical Constants.

Taking the values used in the table of constants for the visible wavelength range for human eyes and fitting a gaussian function closely with the naturally unbalanced curve of human eye response, a plot was generated as shown in Figure 7 below. As shown, the wavelength that is most sensitive for human eyes is at 555nm, which is a slightly yellowish green color. On the shorter wavelength side of the plot, the blue light is much less sensitive to the human eye than the symmetric corresponding red light. If a light source with equal wattage across the visible spectrum was produced, to calculate the useable amount of light for human eyes, the integral under the curve would have to be performed after the level of wattage was scaled to the human eye response curve.

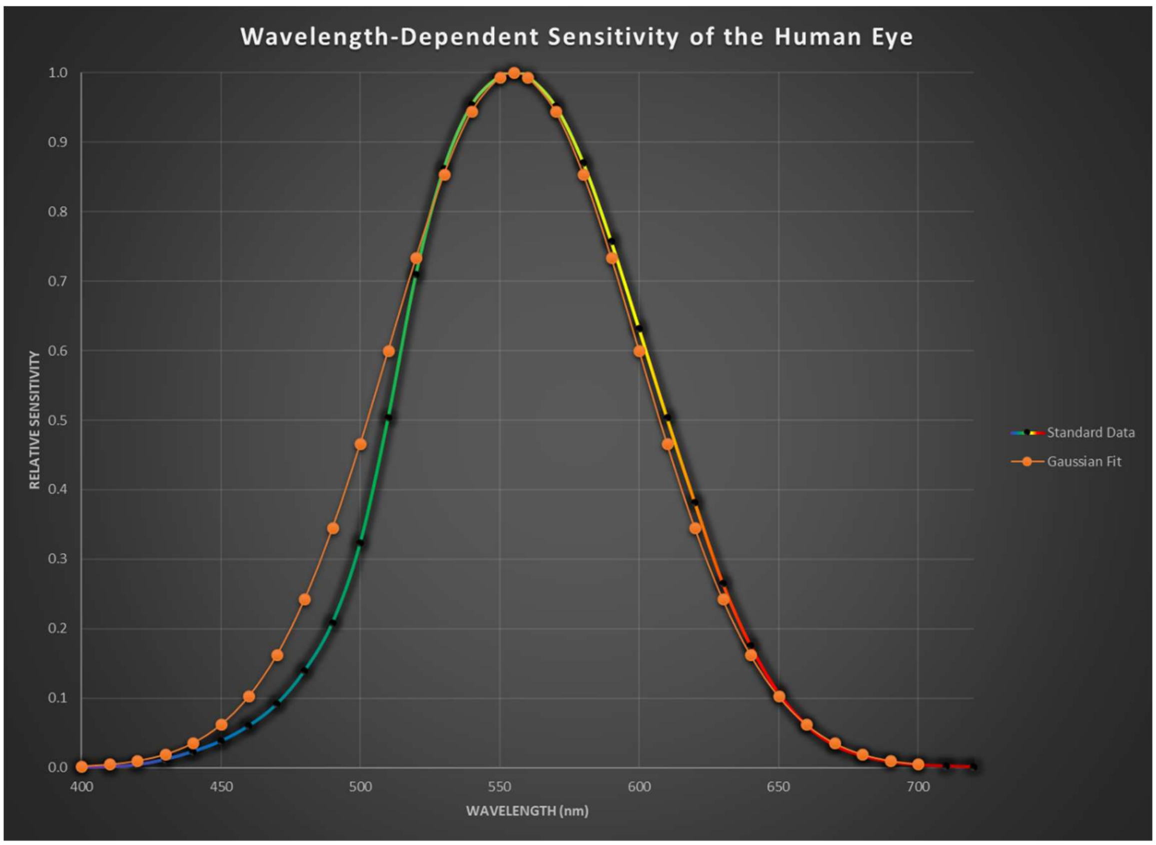



Figure 7: Wavelength-Dependent Sensitivity of the Human Eye, with Gaussian Fit

The equation for the gaussian fit shown in Figure 7 is $y = e^{\left(\frac{-(x-555)^2}{(63)^2}\right)}$. The integral under the gaussian fit is $\int_{-\infty}^{\infty} e^{\left(\frac{-(x-555)^2}{(63)^2}\right)} dx$ which is trivial using the Euler-Poisson Integral, which states that $\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}$. Therefore, the integral of the gaussian fit is $63\sqrt{\pi} \cong 111.665$.

The issue with assuming that a visible-spectrum flat-spectrum light source with an optical power of one watt at 555nm (and from 400nm to 700nm) would have a usable illumination power of 111.665W is that most power meters are not actually wavelength-selective. The power meter and sensor used to measure the 555nm power of the light from Walmart was not wavelength-selective with a defined spectral width. By selecting 555nm on the power meter, a slight adjustment was internally performed to the reading to compensate for the silicon's imperfect spectral response across the visible spectrum. However, silicon has a generally flat response across the wavelengths of concern for this experiment, and therefore the power reading acquired could be said to be the total visible-spectrum output power of a single LED in the strip. This assumption could be reinforced in that the human eye response of wavelengths further from 555nm quickly approach zero near 400nm and 700nm. If all these assumptions are correct, then the light from Walmart only had an output of approximately 0.9W of useable light for human eyes. To compare further to MADLIS, a 1W green laser will be used in a later experiment by spreading out the beam to a square meter in area, then taking lux measurements to compare to the '3200 lumen' LED light, which consumed nearly 45 watts to achieve what a laser might be able to achieve with a wall-plug wattage of approximately 3-5 watts.

A new style of light bulb that entered the market in mid-2018 is the "vintage LED" or "antique LED" filament light bulb. It utilizes a thin strip of LEDs that is positioned where the filament of a typical light bulb would be placed. The general purpose of vintage LED bulbs is to provide a nostalgic aesthetic while providing some of the benefits of modern LED illumination. A commercial example is the Philips ST19 Dimmable LED Light Bulb in "Vintage Soft White". Its specifications include an output of 350 lumens with 5.5 watts of power consumption, which equals a lumen per watt efficiency of 63.6.

To understand the real characteristics of a typical white LED, the emission spectrum of a white LED flash/flashlight on a Droid Turbo smartphone was recorded. The spectrum is shown in Figure 8 below:

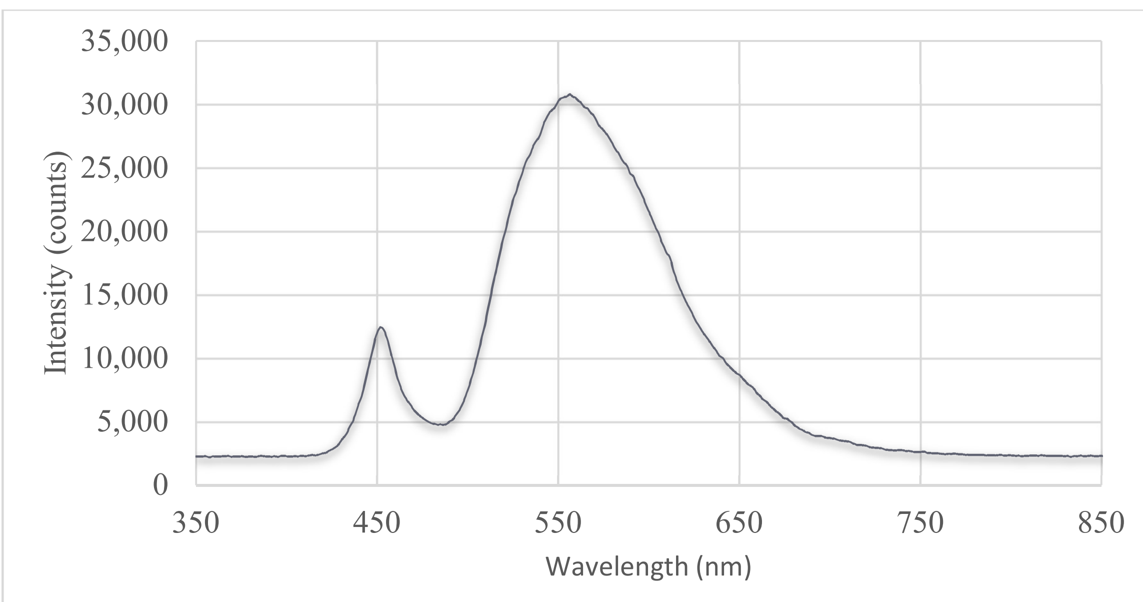



Figure 8: Emission Spectrum of the White LED on a Droid Turbo

The significant feature on the emission spectrum shown in Figure 8 above is the peak at 450nm. The small peak at 450nm is from the blue LED which is the actual source of the light energy in a white LED. The larger, wider peak in the spectrum is the phosphor material that fluoresces when placed above the blue LED and effectively creates the white light. Note the uneven distribution between the red, green, and blue wavelengths that would correspond to the primary cone response peaks of the human eye, as well as how they don't necessarily respond to a properly-adjusted distribution that would be an efficient set of wavelengths for human perception.

Another experiment that has introduced concern about the scaling to human eye spectral sensitivity is an experiment of nearly "pure" white light. The source used was a commercial computer monitor with a white screen showing. The white screen was a generated white image by setting the red, green, and blue values to 255, which is the peak intensity, and is known as a standard white color. A spectrometer took a sample of the screen's spectrum, plotting relative intensity (energy measured in an arbitrary unit of 'counts') to a scale of wavelengths in nanometers. The data from the spectrometer sample is plotted in Figure 9 below:

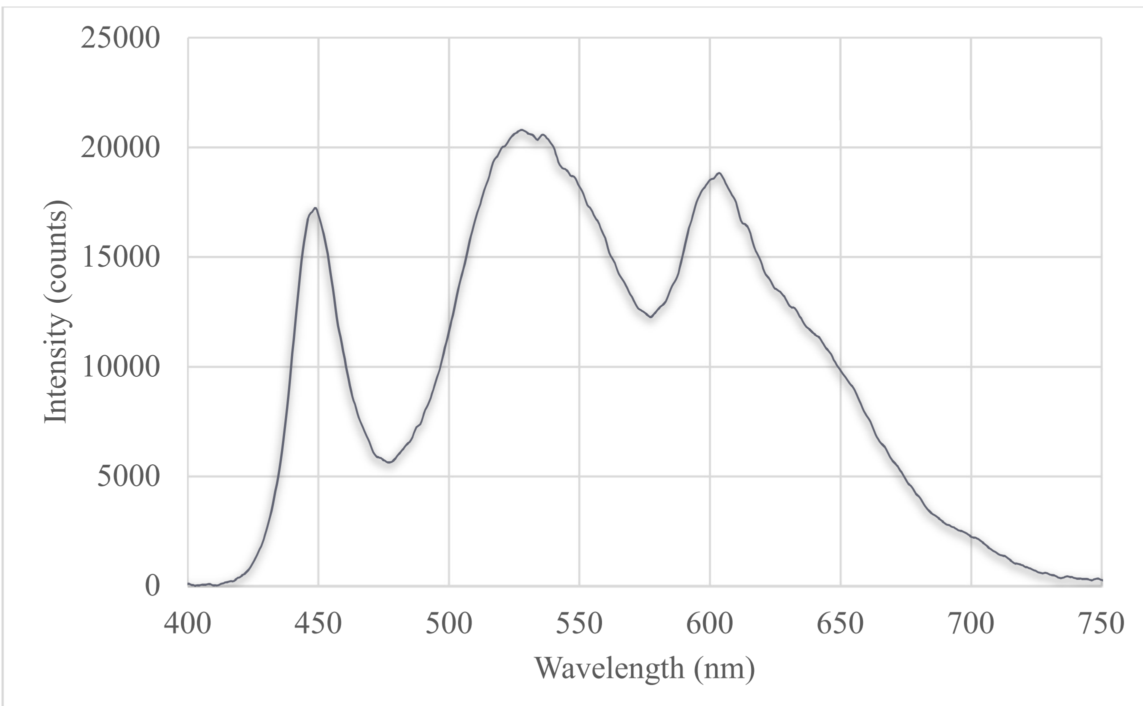



Figure 9: White Computer Monitor White Display Spectrum

The major finding of the white computer monitor display spectrum experiment was that the relative intensities were not only roughly the same, but the blue and red intensities are less than the green. This is counter-intuitive for what should be necessary to generate a perfectly even white light when the energies are scaled to the sensitivities of human eye cones. If a light source had a 1W output at 555nm, below in Figure 10 is a plot of the wattages and dBW required to have an equal perception of brightness across the visible spectrum for humans. Note the extreme values for the high and low of the visible range.

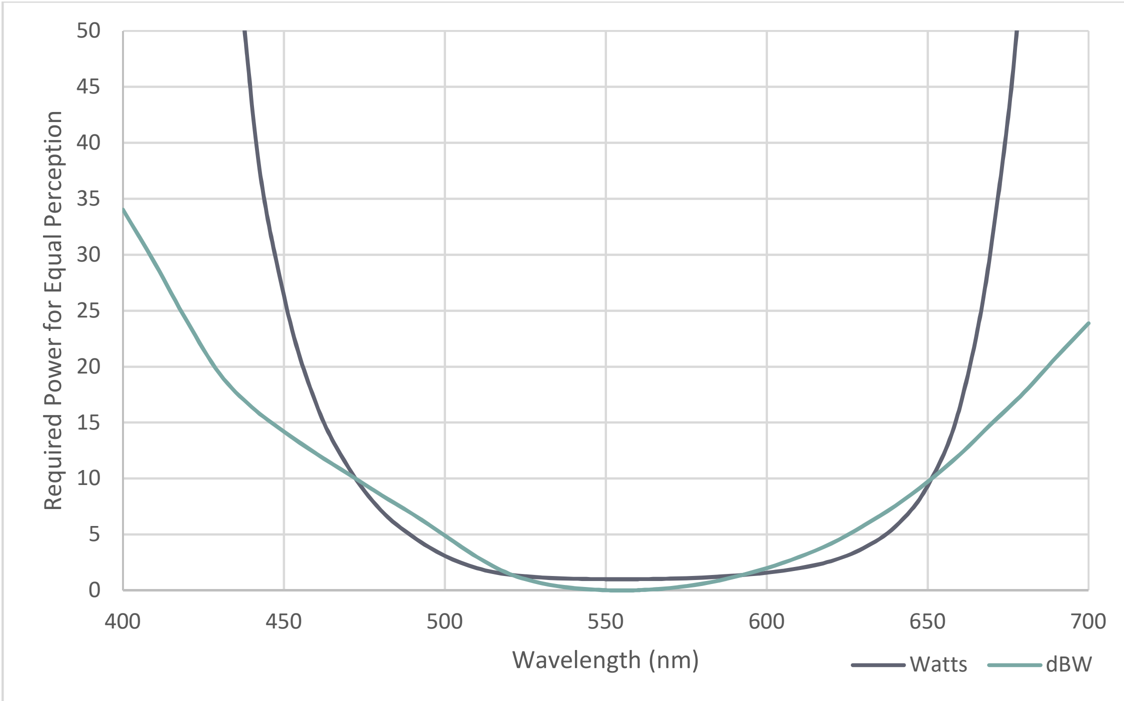



Figure 10: Relative Intensity Required for Equal Human Perception of Spectral Intensity

Clearly, the plot above in Figure 10 is not similar to the white light emission from the PC monitor in Figure 9. It appeared that only even energies are required spectrally to create an even white light for humans.

Luckily, with MADLIS, the initial prototype is a very macroscopic demonstration of an idea. Since the goal of the initial prototype is to illuminate an entire room using only a few laser diodes, and the system is designed so that anyone experiencing the effects of the prototype can view the optical path and method, the difficulty of presentation was trivial. Many research projects that are highly theoretical can be extraordinarily difficult to present due to the nature of the effect to show. Even multi-billion-dollar project like the Large Hadron Collider in CERN is difficult to show the effect that the system produces, even though the system itself is visually very impressive to behold. Many theories and ideas rely on computer or measurement equipment to display the effect to be presented, which can open the door to fabrication and falsification of results.

## 3.0: System-Level Block Diagram:

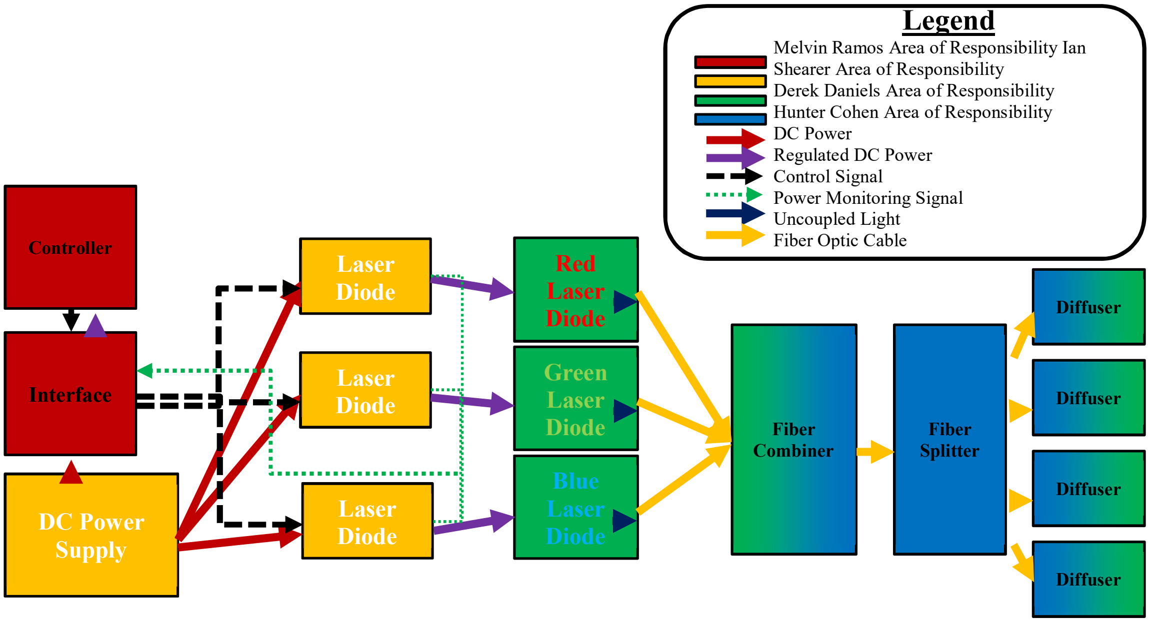



Figure 11: System-Level Block Diagram

## 4.0: Motivation and Goals:

By creating a properly functioning prototype of MADLIS, with quantitatively-measurable specifications, and by proving the marketable features, this project could scale and adapt to replace a large portion of the world's illumination systems. As shown below in Figure 18, the House of Quality, the engineering specifications near the bottom of the diagram include a goal of exceeding 100 lux/watt, which is a current standard for LED commercial lighting. However, additional research will be performed on commercial LED lighting to determine if the efficiency standards are based on the light output wattage or the wall-plug wattage.

The ability to present a working prototype of MADLIS would be vital for being able to secure more funding for further work in development. This initial project is similar to the initial 'breadboard' research for a new company project. Even during the research phase in a company, generally several prototypes of a new product would be developed before the product would even be considered to be in the development stage. Since this project contains a new method of applying generally well-established concepts, theory and simulation of the method is only as valuable as the credibility of the person or people presenting the method. Generally, high-end investors would not be interested in a project developed by undergraduate researchers that were working on their own idea without the direct guidance of a well-known professor. However, if someone or some group has a working prototype, persuading a potential investor is arguably only as difficult as determining if the product would be profitable after further development, regardless of who was working on it.

## 5.0: Claims:

MADLIS, comprising of a new method of providing illumination, has several claims pertaining to its features and operation. Some initial claims are included below and more will be added as new implications are discovered.

### 5.1: Tunable:

The primary claim of MADLIS is that it can be tuned or adapted to create any wavelength or mix of wavelengths in the visible, near-ultraviolet, and near-infrared range of the electromagnetic spectrum. This is accomplished by installing laser diodes or lasers of chosen wavelengths that can be coupled to the transmission fiber for mixing and distributing. For standard illumination applications, red, green, and blue laser diodes would be installed to create a tunable white light for mixing and distribution. Ultraviolet light could be distributed for sanitation in medical facilities where smaller or surgical rooms could be sanitized between patients where the room is unoccupied for a few minutes at a time. Since MADLIS would already be supplying the room lighting evenly for the room to be sanitized, the ultraviolet would be evenly covering the room during the sanitation process. For safety and convenience, the illumination lighting could flash red while the UV source light is activated. Infrared light could be used for a variety of purposes. One use for infrared light would be for nighttime surveillance when the primary illumination is turned off. The broad-spectrum cameras would have an even infrared illumination for monitoring the facility without the need for infrared LED sources around the cameras, which give away their locations to potential enemies. Since infrared laser diodes are very common and widely available, adding infrared capability to MADLIS would be less expensive than adding infrared LED sources to every camera coverage area.

### 5.2: Scalable:

The scalability in power is vast for MADLIS. Since there is availability of laser diodes in many power levels, and other laser types could be utilized for higher-power applications, the range in levels of illuminations for the system is only limited by cost and size. Very large applications such as stadiums or large warehouses could use an array of combined diodes to illuminate zones that would be individually controllable. Large-cored fiber optic cables can handle continuous-wave powers into the 10+ kilowatt range and pulsed powers into the megawatts.

### 5.3: Isolated and Hardened:

Since the source unit is physically separated from the output and distribution of the lighting, it can be isolated electronically and protected. The major claim from this capability is that by isolating the source unit electronically with a faraday cage and backing up the power within the faraday cage, the entire system is protected from electromagnetic warfare, electromagnetic interference (EMI), and power outages. Highly-sensitive laboratories where EMI is an issue with measurement electronics could utilize the fiber-carried illumination since zero current is carried over the fiber. MADLIS could be installed in systems that need to be undetectable by their electronics, such as modern stealth vehicles.

### 5.4: Agriculture Improvements:

In agriculture, the system could be tuned and adapted to emit only light that is usable for photosynthesis. What that means is that a facility could have a source unit that efficiently emits the needed light for a large-scale plant growth operation and have that light distributed to each of the plants. Not only would the light be very efficient by not wasting energy to unusable light, but the fiber optics are not susceptible to the moisture and temperatures used.

### 5.5: Reduced Cost:

As MADLIS is scaled to larger applications, the utilization of the near-linear current-to-output property of lasers increases. This means that for applications larger than an area that could be illuminated by a set of small LEDs, the combination of laser sources and low-cost distribution with fiber reduces the cost of systems that would otherwise require a large number of installed components and wiring. Besides the power needed for the source unit, no electric power would be wired to all the output units. This would save vast amounts of wiring costs in large facilities, since spools containing tens of kilometers of fiber can be purchased for less than one spool of a few hundred meters of commercial-grade wiring. Since the system is tuned so that all the generated light is within the useable spectrum for the application, no wasted light is generated that would reduce efficiency. Even though LEDs have improved efficiency over fluorescent systems and incandescent lighting, there are still wavelengths generated that are not useable for the system's purpose. Lasers are also highly directional and would require little to no reflectors to direct light in the desired locations. But requiring less reflecting, efficiency is increased. Fluorescent lighting, which is still the primary source of lighting for commercial applications, emits light nearly isotropically. Unless high-quality reflectors are installed above and around fluorescent tubes, much of the emitted light is wasted as heat, further reducing efficiency. Since MADLIS utilized direct radiation of particular wavelengths instead of blackbody radiation, wavelengths were selected to match the human eye response to particular bands of wavelengths, increasing perceived brightness.

### 5.6: Simplified and Safer Maintenance:

When the source unit is installed in an easy-to-access location, replacing, cleaning, or repairing becomes faster, easier, and safer. No longer would a technician need a lift or ladder to access a burnt-out bulb or light that was installed high on a ceiling, building, light pole, tower, or other raised location. Since the system carries no electric current once the light leaves the source unit, there is no risk of electrocution for the entire system besides the power supply. Additionally, since the power supply utilizes low-voltage direct current, the risk of electrocution is minimal there also. Instead of requiring electric power to be disconnected for the replacement of light sources, MADLIS can be configured to allow hot-swappable diodes, which would mean no loss of light to the user would be required for maintenance to replace parts. Since multiple laser diodes of the same wavelength can be coupled to the same fiber for transmission and distribution, inherent redundancy can be built into the system. Examples of applications where light should never be interrupted are prisons, secure areas, traffic lights, surgical rooms, escape routes, and laboratories with sensitive experiments. Since the source unit is all in one location, including a battery-backup option is simplified for the entire system. Battery backup would also benefit from the reduced wattage load of MADLIS compared to fluorescent and incandescent systems.

### 5.7: Physically Adaptable Outputs:

Although optical fibers can have thick protective coatings or layers of coatings, the core and cladding that carries the light is small in diameter compared to electric wiring for lighting. Therefore, the end of the fiber can be installed in most lighting output module forms. Examples of lights that could have fiber outputs installed are drop-ceiling lights, chandeliers, desk lamps, street lights, traffic lights, stadium lights, vehicle interior and exterior lighting, lighthouses, antenna tower beacons, searchlights, stage lighting, DJ lighting, runway beacons, microscope sample illuminators, holiday lights, and countless others.

## 6.0: Safety and Ethics:

Unless MADLIS is utilized in a configuration where the output power is less than a few milliwatts, the light-source laser diodes used will typically be high-powered Class IV lasers. When the source box is opened for maintenance, the risk of eye damage and fire increases, but is not immediately a danger unless the chamber where the optical axis where the beams are combined is opened while power is applied to the system. Even then, if MADLIS goes to a more mature commercial product, hot-swappable modules for the diodes could be implemented. Hot-swappable modules could be designed to be replaced with zero risk to the operator or maintainer.

The fiber optic portions of MADLIS carry some inherent risk to the user and operator if the system is modified or changed. There are certain safety precautions that should be taken by any installer, maintainer, or user of the system. The system should be powered off and have its power source removed before any fibers are disconnected from the source or the splitter. Additionally, power must be off and removed before any modifications to the output are made, including changing the diffuser, cleaning where the diffuser is removed, opening of the enclosure between the output fiber and the diffuser, or any case where the bare output of any part of the system is exposed.

Electrically, MADLIS is as safe or much safer than existing lighting technology. For systems that have the option of being powered off commercial alternating current, the typical risks with AC would be present until the power is converted to DC for the lasers and interface. Even with the risks involving the input AC, since the rest of the system operates on low-voltage DC, the risk of electric shock is nearly zero. Since the voltage needed to operate laser diodes is insufficient to cause electric shock in humans, there is no inherent risk of electric shock when replacing a burnt out or damaged source.

### 6.1: Safety

For this design there were a number of things to pay mind to when it comes to possible safety hazards in the building of the product. The biggest and most obvious safety concern for this particular system is possible damage to our eyes or skin as a result of high intensity laser light. Lasers can be very useful in cutting-edge research and new technology designs, but they also pose a major public safety concern so much so that there are standards for ensuring that people are kept out of harm's way. The American National Standards Institute (ANSI) has a comprehensive code on the use of lasers and how to be safe when operating lasers and laser systems.

The laser market began in the mid-1900s and ever since then there have been more and more types of lasers being produced with differing wavelengths, powers, and many other confusing specifications. This abundance of new laser technology called for a new standard of safe use to be developed specifically for these new powerful yet dangerous devices. A naming system was developed and refined over the years to accurately classify different types of lasers in the broadest yet most effective way possible. The current laser classification system in use is specified by the IEC 60825-1 standard and contains the following categories of classification:

Class 1 – The safest and lowest power of the lasers classified, not capable of causing any kind of tissue damage or eye damage even when focused down.

| | |
|---|---|
| Class 1M – | Similar to class 1 lasers except with enough power to cause damage when focused down to a point. |
| Class 2 – | A laser that is capable of doing damage to the eye while being focused down but usually does not cause harm due to the natural human reflex of blinking upon incidence. |
| Class 2M – | Similar to a class 2 laser except for the unfocused beam condition. |
| Class 3R – | Lasers that have a small chance of causing eye damage if exposed for longer than the maximum permissible time. |
| Class 3B – | Can burn the eye if beam is viewed directly but not powerful enough to cause diffuse reflection burns. |
| Class 4 – | Lasers that can burn most types of tissue with even a diffuse reflection. Should be handled with extreme caution and should also have some sort of lockout protocol (FDA/ANSI). |

Anyone who has picked up a laser pointer before has seen the yellow warning label that accompanies them. These warning labels go hand-in-hand with the classification system describes previously and usually contain the class of laser, the wavelength, and the power. Specifically, for lasers that actually can cause physical burning to tissue (class 2 and above) there is a triangular symbol that must be displayed on the product to let people know that it can cause harm to the eye if focused down to a point and viewed directly, an example of such a label can be seen in figure 12.


Figure 12: Example of a class 4 laser safety label (MySafetyLabels).

There were a handful of general safety precautions we have taken as well when it comes to actually working in the lab. When a laser is turned on it should be mounted firmly and pointing toward a beam block of some kind as to avoid it accidentally falling and blinding a person. There was also a need to make sure any kind of optical components that can reflect light (specular of diffuse) are firmly strapped down or screwed in because there was a possibility for something to fall at an angle that could cause eye damage. Assuming that everything was firmly strapped down there was still the issue of human error; particularly with metal watches or rings causing reflections. It is best to just remove any jewelry before working with lasers because these also pose possible risks when they reflect a beam toward a person's eye.

The biggest safety precautions we took in our project were having glasses as well as renting a storage unit off of campus for assembly. Due to the high power of our lasers we were not allowed to turn them on within campus property. Generally, an eye safe level of laser power for visible range is about 5mW, whereas we are dealing with 7 W of blue, 4.4 W of red, and 1 W of green. We found a storage unit facility with an in-door space that was 5 x10 feet and quite clean. This storage unit was where we constructed the laser coupling and beam splitting modules, as shown in the following figures below. When the final modules were completed they should be considered below class 2, assuming the coupling is efficient without much reflection.

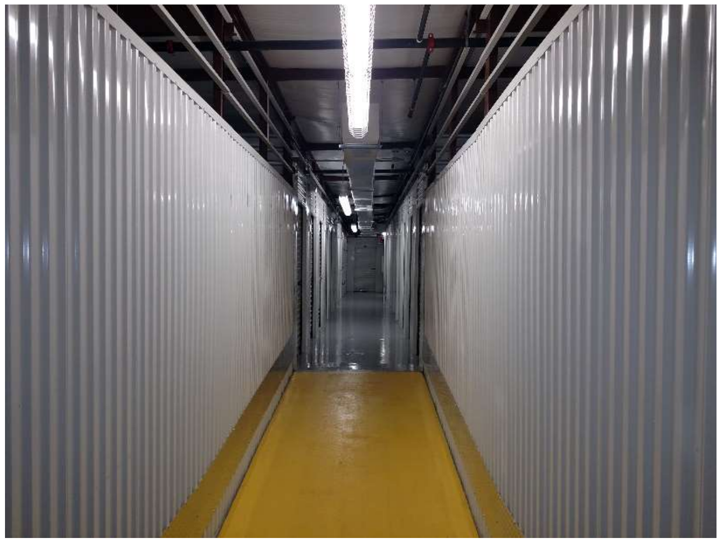


Figure 13: Hallway leading to the in-door storage unit laboratory.

As one can see this storage facility was quite clean and actually quite vacant as well meaning there was not very much traffic through the unit. The units themselves were also quite clean, with rubber-coated flooring and simple clean metal walls and ceiling. The metal walls might need to be covered up with some kind of non-reflective material in the case that a laser beam strikes the metal and causes a diffuse reflection.

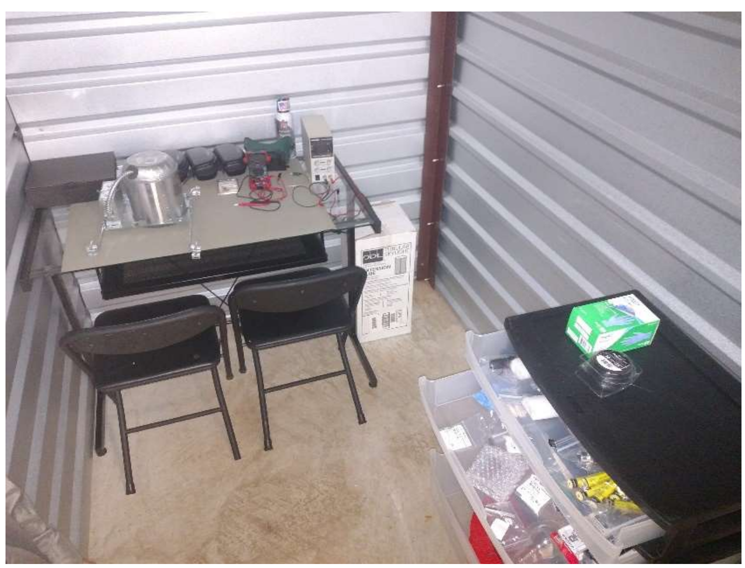


Figure 14: Storage unit laboratory / clean room setup.

For the selection of the glasses we really did not want to block out all of the visible light because it would help us to be able to see the light slightly while setting up the modules. For this reason, we had to hunt for the right optical density values for each color power that we are dealing with in order to block out enough to be eye safe but not block out so much that we cannot see the beam anymore. We decided to put in the purchase order for 2 pairs of Newport glasses for the red light, and 4 pairs of two different Thorlabs glasses for the green and blue lights, as is summarized in table 1.

| Description | Price Each | Quantity | Total Price | Wavelength λ (nm) | Laser Power (W) | Glasses OD at λ | Transmittance (%) | Final Laser Power (W) | Final Laser Power (mW) |
|---|---|---|---|---|---|---|---|---|---|
| Newport LV-F22.P4B05 | 208 | 2 | 416 | 638 | 1.8 | 2.6 | 0.251188643 | 0.004521396 | 4.521395577 |
| ThorLabs LG14 Glasses | 211 | 2 | 422 | 520 | 1 | 2.48036 | 0.33085675 | 0.003308568 | 3.308567505 |
| ThorLabs LG9 Glasses | 200 | 2 | 400 | 450 | 3 | 2.81894 | 0.151725997 | 0.00455178 | 4.551779911 |

Table 1: Glasses specs for power transmission.

Optical density is a value that ultimately determines how much light will be transmitted through some medium. The transmission coefficient for a specific medium at a specific wavelength unique to the OD number comes out to be $10^{-OD}$. The following figures are the datasheets for the optical densities of the three different glasses that was used in calculating the power that will be transmitted through. For the 7W blue with OD=2.818 there is only 0.152% transmitted through which amounts to about 10.64 mW.

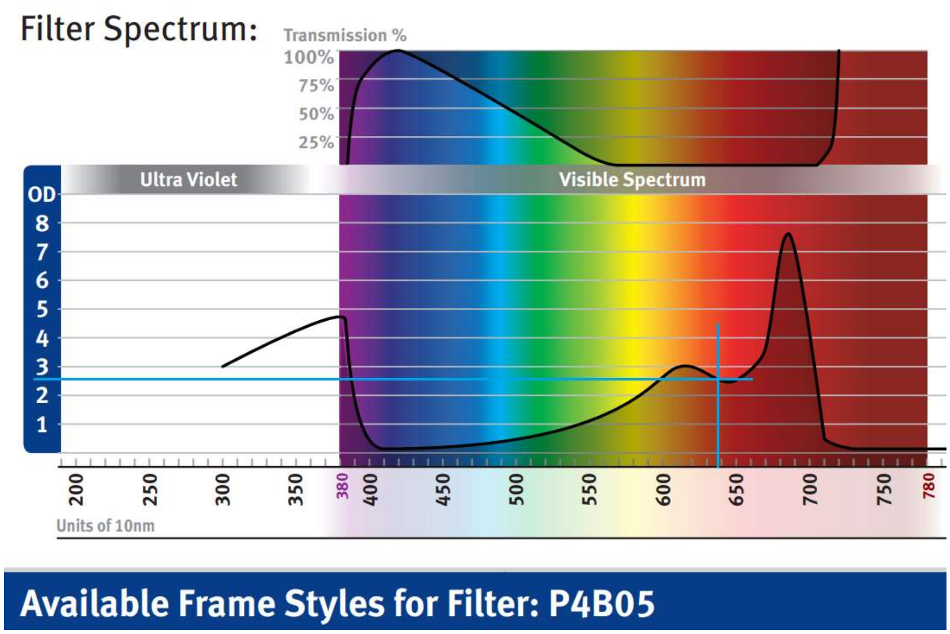



Figure 15: OD as a function of wavelength for the Newport LV-F22.P4B05 glasses.

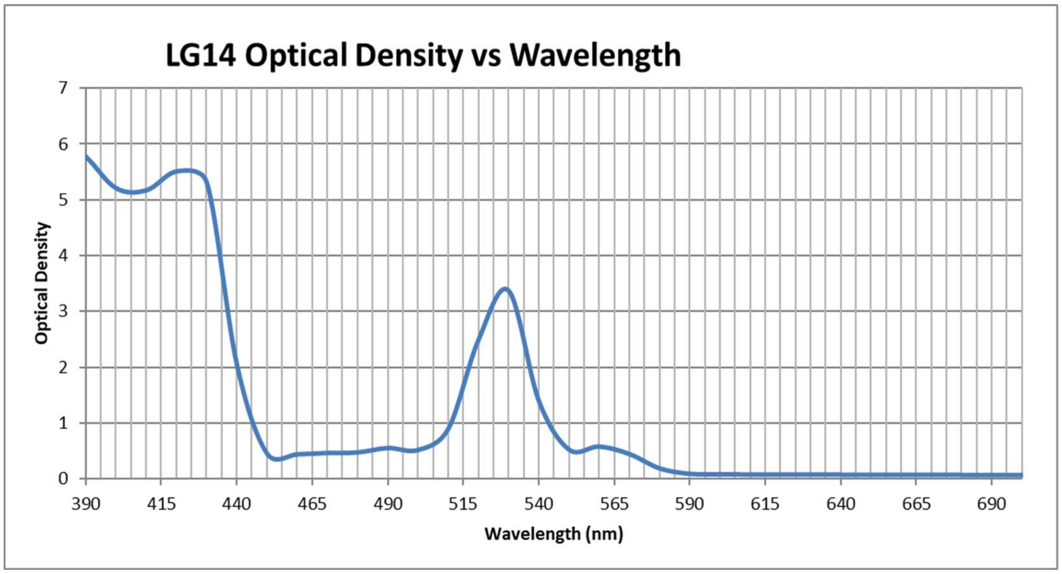


Figure 16: OD as a function of wavelength for the Thorlabs LG14 glasses.

For the 4.4W of red the OD=2.6 meaning that only about 0.25% is transmitted, or about 11mW. For the 1W of green the OD=2.48 which allows for about a third of a percent to transmit, bringing the green down to 3.3mW.

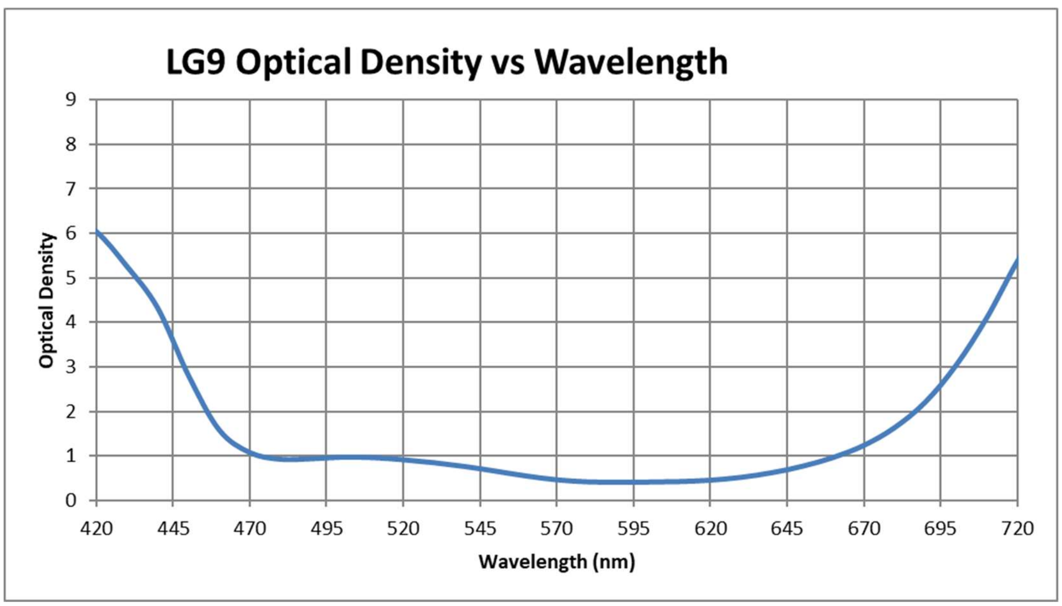
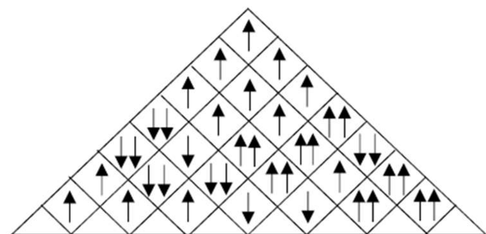


Figure 17: OD as a function of wavelength for the Thorlabs LG9 glasses.

## 7.0: House of Quality:

In the Six-Sigma (6σ) process for Quality Function Deployment to develop a quality product while considering the needs of the customer, a House of Quality (HOQ) can be created. Below in figure 18, a HOQ was created to help analyze the general features and goals of the project, as well as quantified specifications.



| | | Interface Color Control | Temperature Control | Power Supply Efficiency | Fiber Coupling Loss | Output Variation | Total Efficiency | Cost | Total Light Output |
|---|---|---|---|---|---|---|---|---|---|
| | | + | + | + | - | - | + | - | + |
| User Hue and Intensity-Tuneable Lighting | + | ↑↑ | ↑ | ↑ | ↓ | ↓ | ↓↓ | ↑ | ↑ |
| Active Temperature Control | + | ↑ | ↑↑ | ↑ | ↓ | ↓ | ↓↓ | ↑ | ↑ |
| High Power Efficiency | + | ↓ | ↑ | ↑↑ | ↑↑ | ↓ | ↑↑ | ↑ | ↑ |
| Low Optical Loss | - | ↓↓ | ↓ | ↓ | ↑↑ | ↓ | ↑↑ | ↑↑ | ↑↑ |
| Four Even Output Diffusers from One Source | + | ↓ | ↓ | ↓ | ↓ | ↑↑ | ↓ | ↑ | ↓ |
| More Efficient than Commercial LED Room Lighting | + | ↓↓ | ↑ | ↑↑ | ↑↑ | ↓ | ↑↑ | ↑↑ | ↑ |
| | | >= 4-bit | 25°C +20°C/-10°C | >80% | <10% | <10% | >100 lux/watt | <$2,000 | >5 lux/sqft; >200sqft |

Figure 18: House of Quality

## 8.0: Controls and User Interface

An interface on the very basic level is something that allows to input and output to a user. Interfaces are used in everyday electrical appliances, whether it be a simple light with a button, to a controller with many buttons and a screen, to a touch screen, to even voice commands with computer generated voice output. For this project, we needed an interface to allow for a user to interact with the settings of the devise, show the feedback of such settings, and show relevant information about the device.

There are plenty of possible configurations for an interface, but for our current project, a screen and switches are the best candidates. Most devices dealing with lighting interfacing are switches or buttons in combination with a screen or led lights for managing the lights. The simple LCD screen can convey the needed information to the user, while the buttons allow the user to navigate the settings and modify them. There are 4 buttons in total. The first button handles settings in said menu, the third and fourth buttons are for modifying the selected setting.

The LCD screen shows a menu with available settings to change within this menu. Each menu is for a specific category of settings. We currently have four categories for our menus:

- Color
- Temperature
- Luminosity
- Power

These four menus contain their own individual set of modifiable values that reflect what the controller has set for each category. Any modification by the user to these values will result in the modification of the settings currently in use by the controller, thus providing immediate feedback of these changes to the user.

The color menu displays the current red, green, and blue (RGB) values to the user. These values are displayed as integers in decimal (base ten), as this is a more understandable and commonly used base by the average user. The user can modify these values individually to change the intensity of each color, which will in turn, produce a variety of colors for the user to enjoy. The Temperature menu shows the current temperature or temperatures of the laser system. These temperature values will be displayed in Fahrenheit by default but can be changed to Celsius by the user. The Luminosity menu displays the current value of luminosity being produced by the system. The luminosity can be modified by the user in this menu to produce bright or dim lighting. The Power menu shows the power being used by the system and each individual laser. The user can set limits to the power consumption to save energy. In the figure 19, is a Unified Modeling Language (UML) diagram in which the layout of user interaction and how inner elements interact with each other is displayed.

### 8.0.1: Interface Stretch Goals

There are several stretch goals we would like to implement into our interface if our main goals are accomplished in a timely manner. These stretch goals include a more advanced looking interface, using a touch screen for both input and output, having a color picker, having an application that allows control via smartphone over a Bluetooth connection, a new menu to set up times for which the lights will be on and what color to change to, and another new menu for managing lighting profiles to save lighting settings.

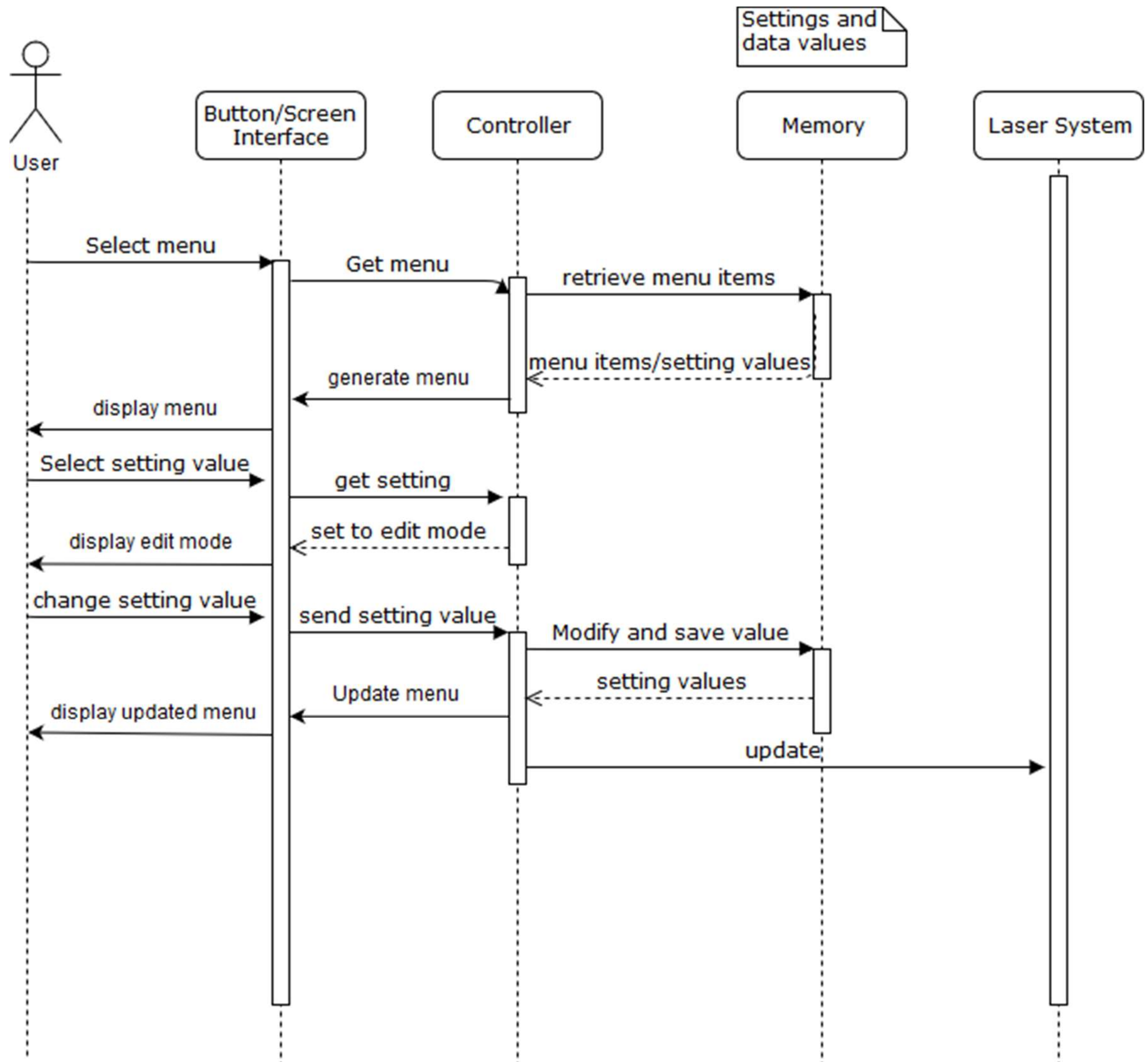



Figure 19: Unified Modeling Language (UML)

### 8.1: Input

The user input for this system is essential for operating the lighting. There are several forms of input devices to choose from. These input devices we wish to use are mechanical switches. The following is a list of switches that could work to fulfill our requirements:[1]

- Single Pole Single Throw
- Single Pole Double Throw
- Double Pole Single Throw
- Double Pole Double Throw
- Push Button
- Toggle
- Rotary
- Joystick

### 8.1.1: Single Pole Single Throw Switch (SPST)

This switch is perhaps the simplest type of switch, as it is the switch used for turning on or off the devices using one input contact and one output contact. Common uses for this type of switch are as a power switch to a device, such as a computer or other electronic devise. These switches are common on power strips, power supply units, home appliances like the vacuumed cleaner, coffee makers, lamps, light switches, wall switches, etc. Generally speaking, this is a widely used switch found commonly in electrical household products, as well as electrical devices in general.

### 8.1.2: Single Pole Double Throw Switch (SPDT)

This switch uses one input contact and two being output contacts. This switch allows to change between two outputs. This also contains an off position.
This Switch is often used in applications where the power must be switched from on device to another device.

### 8.1.3: Double Pole Single Throw Switch (DPST)

This switch is basically a doubled version of the Single Pole Single throw switch. It uses two input contacts and two output contacts. When the switch is toggled, both inputs are connected to their respective outputs.

### 8.1.4: Double Pole Double Throw Switch (DPDT)

This switch has 2 input contacts and 4 output contacts. It is like the doubled version of the Single Pole Double Throw Switch. When the switch is toggled the output for both SPDT are switched to the other output.

### 8.1.5: Push Button Switch

These buttons are a type of "momentary" switch. These switches have two states, the pressed state, and the released state. The switches, when in the "released state", are bridging the connection of the circuit which they reside on. When the button is pushed down to its "pushed state", the connection is broken. Thus, this switch uses an open circuit to produce a signal to indicate it's being pressed. This is also done in reverse, creating an open circuit in its "released state", and bridging the circuit in its "pushed state".

### 8.1.6: Toggle Switch

This switch is basically a different variety of the SPST, SPDT, DPST, and DPDT. This switch uses a lever to do the switching functions, and they come in a variety of sizes and designs.

### 8.1.7: Rotary Switch

This switch is used to connect one input to many other outputs. The switch usually used a knob for changing the outputs.

### 8.1.8: Joystick Switch

This switch is a special one, as it allows more than one axis of freedom in motion. Based on the direction the stick is positioned, different contacts are made to determine the directional output.

The joystick is used in many applications dealing with devices that move. Devices like construction vehicles, air planes, drones, RC devices, construction cranes, etc. This switch is also used as input for applications of computer games and simulation via specially made controllers, which would also contain many of the previously mentioned switches as well.

### 8.2: Choosing Input

Many of the settings for our project can be adjusted using a rotary switch type of input. This will allow the user to adjust settings such as the luminosity and colors. With the way the menu system is structured, we would require button switches to navigate. There is also the switch needed to turn on the device, which can be a button or a toggle switch. This means that there are many possible combinations of switches that can be used.

We can go for an all Rotary switch input. One rotary switch for cycling through the menus, another for cycling through the settings to select one. The third rotary switch for changing the value of the selected setting. The implementation for the menu cycling will have each menu category selectable by the switch's outputs. The switch that cycles through the setting will have a similar implementation as the first one. The switch that changes the value can be implemented with an incrementation value that increases depending on the direction the knob of the switch is turned.

The input can be acquired through the combination of four buttons. The buttons that will be used are a type of mechanical switch that is commonly used in electronics. Four buttons will be used to navigate and modify settings for the system. The first button navigates the menus, the second navigates the settings within each menu, the third and fourth to modify the selected setting.

The following shows how the input will be implemented:

- Button 1: Push to cycle through the menus
- Button 2: Push to cycle through the settings and select the setting
- Button 3: Push to Decrease the selected value or to cycle left in the selected setting
- Button 4: Push to Increase the selected value or to cycle right in the selected setting

The buttons were placed in order from left to right. These buttons were labeled for the user to be able to identify the functionality of each button. We can also go for a combination of rotary and buttons. Implemented in the following way:

- A rotary switch for the menu cycling
- A Button for selecting the currently highlighted selection

These 2 switches can be used to fully interact with the settings and changing the values. In fact, there are several 2 switch combinations that can achieve this:

- Rotary and Button
- Joystick and Button
- Button and Button
- Joystick and Rotary

With a modified implementation of how the input interacts with the controller, these combinations can be used and will minimize the amount of hardware used. A few good examples of implementing some of these combinations would be the following:

### 8.2.1: Joystick and Button

Using the Joystick and Button combination, we can have the Joystick be implemented as the navigator to cycle through selections on the screen. When the user has highlighted the element they wish to select, the Button will be the input the user will use to enter or select the element. If the user has selected a menu, then the joystick will still be used for navigating the options on screen, while the button will be used for selecting the element to modify. If the user has selected a setting to modify, then the joystick becomes the input for changing the value of the selected setting. Once the user has completed their modifications to the value of the selected setting, the button can be pushed to save the value and update the system to use this value. This will also de-select the setting the user had modified, and the joystick will be set back to its previous function of navigation and the button will be the selector.

### 8.2.2: Button and Button

Similar to the Joystick and button implementation, the first button shall be the ‘navigational button’ for cycling through the options on the screen, while the second button will be the ‘selecting button’ used to select the element. Once a setting is selected, the navigational button becomes the value editor. The nav button, when pushed, will cycle though the values available. If the nav button is held down, it will cycle at greater increments. Once the user is satisfied with the value, the user can push the selecting button to save and exit the selection.

### 8.2.3: Rotary and Button

The Rotary switch could be used as the navigator to cycle through the elements on the screen. The button will be the selector to select the element highlighted. When the user has selected a setting to change, the rotary switch then becomes the value modifier. The rotary switch could act as a dial that increments or decrements the value being modified.

### 8.2.4: Joystick and Rotary

The Joystick and Rotary implementation could be done as follows: Use the joystick to navigate through the menu. Any element that is highlighted can be modified by the rotary switch, no need to select or change input modes.

## 8.3: Output

We have several choices of how we can output the information to the user. Using a screen to display the information outputted to the user is the best way to implement this part of the interface. We have a few choices of what type of screen to use in this project:

- Cathode Ray Tube Display (CRT)
- Light Emitting Diode Display (LED)
- Electroluminescent Display (ELD)
- Plasma Display Panel (PDP)
- Liquid Crystal Display (LCD)
- Organic Light Emitting Diode Display (OLED)

#### 8.3.1: CRT

The Cathode Ray Tube Display is an old display technology that uses a vacuum tube with electron guns, which is a component that creates an electron beam, and a phosphorescent screen.[3]

#### 8.3.2: LED

The LED screen is a panel filled with arrays of light emitting diodes (LEDs). These LEDs are in groups of 3 colors, red, green, and blue. Using the 3 colors, the group is able to produce a wide variety of colors. These groups are what make up the array of LEDs on the screen. The changing of the colors of the individual clusters allow for creating an image on the screen.

#### 8.3.3: ELD

An Electroluminescent display uses an electric field to excite electrons on a special material to produce light output. The light comes from the photons released by the excited electrons. Using various types of material, the screen can be made to produce a specific color.[16]

#### 8.3.4: PDP

A Plasma Display Panel uses tiny containers that hold plasma, electrically charged ionized gasses, to produce a colored output. These containers are placed together in groups of 3, each filled with a different gas to produce a color. The three colors are red, green, and blue. These grouped containers make up the entire screen.[36]

#### 8.3.5: LCD

A Liquid Crystal Display uses liquid crystals along with a backlight or reflective surface. The liquid crystals are layered and act as polarized filters, not allowing any light to pass. The liquid crystals, when an electric field is applied to the crystals, change orientation, allowing light to pass through. This is how an image is produced in the screen.[7]

#### 8.3.6: OLED

The Organic Light Emitting Diode Display is a panel filled with a type of LED that is made of an organic substance. The Substance is a type of organic compound that when electrical current runs through it, light is emitted. These OLEDs come in 3 colors: red, green, and blue; and are grouped together in groups of the three colors combined.[9][37]\

| | CRT | LED | ELD | PDP | LCD | OLED |
|---|---|---|---|---|---|---|
| Durability | Low | High | Medium | Medium | Medium | High |
| Clarity | Low | High | High | High | High | High |
| Colors | RYB<br>Low Color Count | RGB<br>High color count | RGB<br>Low color count | RGB<br>High color count | RGB<br>High color count | RGB<br>High color count |
| Power Usage | High | low | low | High | low | low |
| Applications | Television set, PC monitor | Television set, PC monitor, advertisement, phone/tablets | Television set, PC monitor | Television set | Television set, PC monitor, phone/tablets | Television set, PC monitor, phone/tablets |
| Cost | Cheap | medium | low | high | low | high |

Table 2: Displays

Based on the information above, the Interface was constructed with an LCD screen for output to the user. The LCD screen chosen is small, low cost, and simple to implement. Our project requirements are easily met by this screen; to use a larger complex screen would be nice looking, but impractical for the small amount of user interfacing it will be used for. Both the Plasma display and the CRT display are outdated and consume more power and would be complicated to implement into our system. The OLED displays are, in general, quite expensive for what our system needs to display. The LED display would also be a bit pricy. The LCD accomplishes the important tasks needed to inform the user of useful data and settings, all while being much simpler to implement into the design of our system.

### 8.4: Touchscreen

The touchscreen is a more user-friendly interface for input. If we are able to meet our main goals, we could implement the touch screen as a stretch goal. Touch screens, in general, have the advantage of being both the input and output of an interface. Touch screens come in a variety of types, and by types, we mean different implementations. Touch screens have several different ways of being implemented to function with touch, so there are advantages and disadvantages to each implementation. The following are different types of touch screens:[6]

- Resistive
- Capacitive
- Surface Acoustic Wave
- Infrared
- Optical imaging
- Acoustic Pulse Recognition

#### 8.4.1: Resistive Touchscreens

The resistive type of touchscreen uses 2 layers of conductive material that are spaced out by little insulation points. This forms a layer separation between the two conductive layers of the screen. On the top of these layers would be some plastic layer, and on the bottom of these layers would be a glass layer. The plastic and conductive layer combo can flex under the pressure of being touched. The pressure, from touching, presses down the layer to make contact with the lower conductive layer. This contact is detected via the voltage change and allows for the location of touch to be found.

The advantages of a resistive touchscreen are:

- That it allows anything that touches the screen to be used as input.
- It can work with liquid or dirt on top of the screen.
- They are cheaper and easier to produce

The disadvantages of a resistive touchscreen are:

- Lower response rate
- Lower visibility of screen
- Does not generally register more than one touch at a time

#### 8.4.2: Capacitive Touchscreens

The capacitive type of touchscreen has a similar build to the resistive touchscreen. The top layer is a glass layer, which is then followed by a conductive layer, then a spaced off layer with insulated points. Then after the spaced layer, a conductive layer with a glass layer below. This construction uses electrostatic charges to detect touch. When touched by a finger or specially made material (conductive) some charge is transferred from the screen surface to the finger. This change in electrical charge is detected by the circuitry, and in turn, yields the location of the touch.[6]

The advantages of a capacitive touchscreen are:

- Clearer visibility of the screen
- Highly sensitive
- Accurate
- Very responsive

The disadvantages of a capacitive touchscreen are:
- Must use naked finger or special conductive glove or stylus
- Surface must be clean and not wet

### 8.4.3: Surface Acoustic Wave (SAW)

The Surface Acoustic Wave or SAW touchscreen uses soundwaves to detect touch. The build uses a glass layer as the top layer. Below the glass layer, we have a layer that consists of several transducers and several reflectors. Below that we have a sensor layer for detecting changes in the acoustic vibrations. When a user touches the screen, the acoustic waves are absorbed by the contact point, this change is sensed and determines the location of the touch.[20]
The advantages of the SAW touchscreen are:
- Clear visibility of the screen
- Great durability
- Able to touch with fingers or gloves

The disadvantages of the SAW touchscreen are:
- Must be touched by a finger or soft material
- Expensive

### 8.4.4: Infrared Touchscreen

The infrared touchscreen uses LEDs of the infrared spectrum to detect touch. The screen is incased in a frame with LEDs on one side and photodetectors on the other. When the glass is touched by the user the pressure from the touch blocks some of the light. This is detected by the photosensors and determines the location of the touch.
The advantages of the infrared touchscreen are:
- Durability
- Any touch is detectable

The disadvantages of the infrared touchscreen are:
- Sensitive to other light sources
- Expensive

### 8.4.5: Optical Imaging Touchscreen

The optical imaging touchscreen uses infrared lights and sensors to detect touch. The screen has a glass layer on top. Below the glass layer, infrared lights and sensors and reflectors are located in this layer. Once the screen is touched, the sensors detect the shadow of the blocked light, allowing the location of the touch to be found.
The advantages are:
- Accuracy
- Can use fingers or gloves

The disadvantages are:
- Does not support multiple fingers touching the screen
- Possible blind spots, unable to register touch in these areas

### 8.4.6: Acoustic Pulse Recognition Touchscreen

The Acoustic Pulse Recognition touchscreen uses acoustic sensors to detect touch. The build uses a glass layer on top and on the bottom, with sensors on the edge of the

middle layer. The sensors listen for the acoustic waves generated by the friction from the user touching the screen.
The advantages are:

- Durability
- Recognizes all forms of touch

The disadvantages are:

- Expensive

### 8.5: Choosing the Best Touchscreen

| Touch Technology Type | Resistive | Capacitive | SAW | Infrared | Optical Imaging | APR |
|---|---|---|---|---|---|---|
| Touch Reliability | high | high | high | medium | medium | high |
| Supports any material touch | no | no | no | yes | yes | yes |
| Supports multi-touch | no | yes | no | yes | no | yes |
| Screen Clarity | medium | high | superior | superior | superior | superior |
| Power consumption | low | low | low | medium | high | low |
| Durability against dirt/water | high | low | high | high | low | high |
| Durability against scratches | medium | high | high | high | medium | high |
| Price/Cost | low | medium | high | high | high | high |

Table 3: Touchscreen Options [12][4][30][13]

Of all the different touchscreens mentioned, the best candidates for this project are the resistive touchscreen, and the capacitive touchscreen. The other touchscreens are more complex, expensive, and sometimes bulky. Looking at the resistive and capacitive touchscreens, these technologies have been greatly improved upon over time. They are thinner, lighter, and cheaper to produce. They are practically used in almost all cellular phones in today's market.

The capacitive touchscreen has better accuracy in determining the location of touch, and responsiveness to the input is immediate. It's the most commonly used touchscreen in the top smartphones on the market, as they provide better visibility of the screen. The capacitive touchscreen also allows for multiple fingers to touch the screen for input of the device.

The resistive touchscreen is a cheaper alternative, with its advancements in improving accuracy to be just as good as the capacitive touchscreens. While the touchscreen may not be as visible as others, the screen can take any touch (with some pressure applied) as input. This allows any object or glove to not impede with interaction with the device. These resistive touchscreens are commonly used on lower end smart phones and devices, as they are cheaper.

Since our project will not deal with complex or detailed imagery to be displayed on the screen, the best candidate to use would be the resistive touchscreen. A simple backlit resistive touchscreen will achieve all the requirements necessary for the user interface of our project.

### 8.5.1: Touchscreen Input and Output

If we are able to meet our main goals, we could meet out stretch goal of bringing in a touchscreen for the interface. The touchscreen's display and input layout would be designed in the following manner. The screen would provide a menu of buttons, each being labeled as one of the following categories:

- Color
- Temperature
- Luminosity
- Power

Each of these categories, when touched by the user, will display a menu of the corresponding category that was selected.

### 8.5.2: Touchscreen Color Menu

The Color menu will have 3 color sliders to interact with. These color sliders would be for adjusting the RGB values for the outputting color of light. Along the side of these sliders will be a color previewer, displaying the color which results from the RGB values being used. An optional feature to add (one of the stretch goals) would be a color picker. Basically, a box with the full spectrum of colors that can be made. The user can pick the color they desire with this color picker by touching the color they desire. This can also display the values of the color selected to the user. The color picker could be made as a color spectrum bar, in which the user would select a section of color, then in a larger box would appear the different shades of the selected color for which the user can select from.

### 8.5.3: Touchscreen Temperature Menu

The Temperature menu will have the current temperature displayed and an adjustable slider for selecting the desired temperature range/fan speed. This will control the settings for the voltage of the fan or fans cooling the system. The temperature menu itself can display a background color to indicate how cool or hot the system is running by using cool colors (blue, cyan) to indicate cold temperatures, and using hot colors (red, yellow) to indicate hot temperatures.

#### 8.5.4: Touchscreen Luminosity Menu

The Luminosity menu will have an indicator on how bright the light is and a slider to adjust the luminosity value. The user can interact with the slider to adjust the luminosity of the output, which would also update the brightness indicator. The visual representation of the brightness of the system being outputted can be done using a progress bar which has the maximum brightness at the end and the smallest brightness at the beginning. The progress bar can visually show the current luminosity level by filling up the progress bar to the appropriate value.

#### 8.5.5: Touchscreen Power Menu

The Power menu shall display the total power consumption of the system, the power consumption of the individual lasers, and a slider to adjust the limit on the consumption of power. The visual representation of the temperatures in the system can be done using a progress bar, not unlike the one in the luminosity menu. The first bar would show the actual temperature of the whole system, the other bars would represent the temperatures of each sub-system. These can be listed horizontally or vertically. The value of each would be displayed above or next to each bar.

#### 8.5.6: Touchscreen Schedule Lighting Menu

This menu, if we are able to implement this stretch goal, would display settings for scheduling times in the day for which the lighting system output would change. This menu would be comprised of a set number of schedulable events for which a corresponding profile of settings will be applied to the system.

#### 8.5.6: Touchscreen Profile Menu

This stretch goal menu would be implemented to provide the user a way to save lighting settings as profiles. The implementation of the menu will be as follows: The list of currently saved profiles will be displayed, each one with the option next to them for editing. The editing option will bring up a window with the options of modifying the settings or deleting the current profile. On the profile menu would also be an 'add new profile' button. Upon pressing, a window will be brought up to modify and save the current settings.

### 8.6: Smart Phone as Interface

We have a stretch goal that gives us the option of having a smart phone act as the interface for the system. The System itself will have a simple interface for the settings, but the smart phone will have the more advance and easier to use interface. An application would be made for the smart phone to be used to interact with the controller. The controller will have a Bluetooth device for communication with the smart phone. Bluetooth is a widely used technology among smartphones and is not reliant on a middle man like the Wi-Fi radio is. Both the phone and our controller will communicate via Bluetooth.

The application for interfacing on the smart phone will have to be made usable on both Android and iOS to provide the best accessibility for users. This application will incorporate several design features that are similar to the touchscreen interface design. Features like the color picker, interactive value sliders, and manual entry will be implemented for manipulating the settings for the system. The menu system for this application will be set up with 4 buttons, Color, Luminosity, Temperature, and Power. Each button, when touched, will bring up their corresponding menu of settings.

Along with the interactive sliders, there can be an option to have manual entry for modifying the values for a setting. This could work with the virtual keyboard on the smart phone, entering the value desired into a text box. The other way this could be implemented is a dropdown list of values for the user to select from. Giving the user this option allows for an accurate entry for the setting the user wishes to acquire.

### 8.7: LCD Display Output

The LCD display is a simple character display with a back light for visibility at night. This display uses simple characters for interfacing; characters such as the carrots for arrows, a cursor for highlighting selections, and the whole ASCII character sheet. The menu system for the LCD is displayed differently than that of the touchscreen. The Screen starts with displaying a main menu, listing out the submenus of the 4 categories: Color, Temperature, Luminosity, and Power.

#### 8.7.1: LCD Main Menu

The main menu displays the title of the main menu on the top of the display. The mid to lower sections of the display hold the submenus as options to scroll and select. Depending on the size of the LCD screen, there are several options of how the listing of options can be implemented. The options we have are as follows:

- Horizontal listing
- Vertical listing
- Scrolling horizontal listing
- Scrolling vertical listing

Using Horizontal listing, all the items would be listed horizontally on screen along the width of the display. This option is limited to the width of the display in use. A smaller display would require abbreviations of the menu options.

The vertical listing option has the items listed vertically along the height of the display. This option is also dependent of the screen size, as a screen of small size would limit how many options can be displayed in the list, leading to the need to use a scrolling or page-oriented organization to list the menu options.

A scrolling list negates the limitations of a small screen. For both vertical and horizontal listings of the menu options. This form includes the use of arrows at the end of the currently listed options. These arrows are used to scroll/navigate to the next page or section of options. This essentially allows for as many menu options to be listed as needed regardless of screen size.

#### 8.7.2: LCD Sub-Menus

The sub-menus for the LCD screen are displayed in a similar manner as the main menu. The sub-menu title is displayed at the top of the screen; settings are listed in the mid and lower part of the screen. The listed items are horizontally listed with the option of scrolling for larger lists.

The color menu for the LCD contains the red, green, and blue values below the menu title. Depending on the screen size, we could implement progress bars to help represent the values of each color. These would be listed vertically, having the bars laid horizontally, with the color value either to the left or the right of the bars.

The Temperature menu displays the temperature of the system below the sub-menu title. Perhaps even the individual diode temperatures would be displayed as well.

The Luminosity menu displays the luminosity value of the system for the laser output. This can also have a progress bar implemented in a similar fashion to the color menu.

The power menu displays the power usage of the system below the sub-menu title. The power can be displayed as follows: have the total power usage at the top, then have each sub-system's power usage below it. The power usage of the subsystems can be displayed using percentage values to indicate the amount the subsystem is using out of the total system.

If we are able to, the stretch goal of having a schedule lighting menu for the LCD would be done by listing out the schedules vertically. There would be an option to add, modify, or delete a schedule. The option to add a schedule would be a plus symbol that would be located at the top of the list. The option to modify or delete a schedule would be given as two options next to each schedule.

The stretch goal for the profile menu would be implemented similarly to the schedule lighting system menu, the profiles would be listed vertically. The option to add a new profile will be on top of the list denoted by the plus symbol. The options to modify and delete would be placed next to each profile.

## 8.8: The Controller

The project will require a microcontroller. A microcontroller is basically a small, simple computer that is capable of small tasks and small computations. These microcontrollers are commonly used in embedded systems. Embedded systems are electronic systems, that include a microcontroller, that are used to control the functions of another system with user defined programs.[18]

There are several micro controllers to choose from that will fit our requirements for this project. The Micro controller's tasks consist of:

- Voltage regulation
- Voltage regulation of each individual laser diode (color control)
- Temperature reading
- Temperature regulation
- Power consumption regulation
- Having settings held in memory
- Outputting the current settings to the user via LCD screen
- Taking input via buttons

Several of the following microcontrollers are capable of completing these tasks:

- ATmega328
- MSP430
- ATmega32U4
- PIC16F877A

### 8.8.1: ATmega328

Atmel's ATmega328 microcontroller is a well-known and used technology. An easy to use microcontroller popularly used by Arduino. This microcontroller has 32 general purpose registers, 32Kb of flash memory that is both readable and writable, a Kilobyte of EEPROM, two Kilobytes of SRAM, 23 input and output lines, an RTC, 3 timers, a Watchdog timer, an USARTs, an I2C, an ADC, an SPI port, and power saving modes.

The ATmega328 has been used in many educational applications, and personal projects.[2d]

### 8.8.2: MSP430G2553

Texas Instrument's MSP430G2553 microcontroller is another well-known and used technology. This microcontroller is a low power controller commonly used in embedded systems that require a low power consumption. The controller comes with a 16 bit RISC CPU, registers of 16 bit, a digitally controlled oscillator, 16 bit timers, 24 pins for input and output, an analog comparator, a universal serial communication interface, and a 10 bit analog to digital converter.[29]

### 8.8.3: ATmega32U4

Atmel's ATmega32U4 microcontroller is another popular technology used in embedded systems. Similar to the ATmega328, this microcontroller is popularly used by Arduino. This controller comes with similar features to that of the ATmega328; 32 general purpose registers, 32 Kilobytes of flash memory, 1 Kilobyte of EEPROM, 2.5 Kilobytes of SRAM, 26 input and output lines, 5 timers/counters a USART, a 2-wire serial interface, an ADC, a temperature sensor, a watchdog timer, and an SPI Port.[1d]

### 8.8.4: PIC16F877A

Microchip's PIC16F877A microcontroller is flash microcontroller used in embedded systems. The microcontroller features a PIC16 core, a data bus of 8 bits, a max clock freq. of 20MHz, 368Bytes of RAM, 33 input and output pins, operating temps from -40C to 85C, I2C, SPI, USART, 3 timers, and 256 Bytes.[28]

| Specs | ATmega328 | MSP430G2553 | ATmega32U4 | PIC16F877A |
|---|---|---|---|---|
| Non-volatile Memory | 2KB SRAM | 16KB | 2.56KB | 256B |
| Memory | 32KB | RAM 0.5KB | 32KB | RAM 368B |
| I/O Pins | 28 | 24 | 26 | 33 |
| Clocks/Timers | 8-bit timer<br>16-bit timer<br>Oscillator | 32 kHz Crystal<br>2 16-bit timers | 8-bit timer<br>16-bit timer<br>Oscillator | 8-bit prescaler<br>8-bit timer<br>16-bit timer |
| Serial Port Communication | USART | UART | USART | USART |
| SPI | 2 | 2 | 2 | 1 |
| Cost (USD) | $0.90 | $2.20 | $2.89 | $5.09 |

Table 4: Controllers

### 8.8.5: Choosing the Microcontroller

Looking back at the comparison table (Table 4: Controllers) we are able to see the specifications side by side. According to our requirements, we will need a microcontroller with the memory capacity to handle the menu system and control interface. The PIC16F877A microcontroller falls short when compared to the memory sizes of the others; 256Bytes of ROM vs 2KBytes and more, 368Bytes of RAM vs 0.5KB and more. The fact that the PIC16F877A microcontroller has less memory and costs more than any of the microcontrollers, means that this microcontroller is not for us. The three microcontrollers left have more comparable features. Generally, both of Atmel's microprocessors have about the same memory, clocks/timers, SPI, and serial port communication types. The price difference between the two Atmel chips give way to the ATmega328 being the better choice of the Atmel chips. This leaves Texas Instrument's MSP430G2553 microcontroller and Atmel's ATmega328 to choose from. The biggest difference is the size of memory the MSP430 has vs the ATmega328. ATmega328 having the advantage of 32KB of memory vs the smaller 0.5KB of memory the MSP430 has. The ATmega328 has an easier to use input/output system vs the MSP430, as the analog inputs are easier to setup and are one of the important parts of our project. Then there's the price, the ATmega328 beats the MSP430 in that regard as well, being only $0.90 vs $2.20. Thus, the microcontroller to be used is the ATmega328, for it has an easier way to integrate analog input/output and superior amount of memory and value.

### 8.9: Color Control

There are several ways of implementing colors and how to adjust them. One way of doing this is simply using white lasers with a color filter in front. The light from the white lasers would pass through these filters, and based on the current filter, a selection of light waves would be blocked/absorbed by the filter, allowing only light of a specific range in wavelength through the filter. This would create the desired colored lighting but would be inefficient power wise. This setup would block a large amount of light produced by the laser diodes, waiting energy, and diminishing the light output greatly.

Another way of implementing color adjustment is through voltage modulation. Having the three colored laser diodes, red, green, and blue, we could change the color output of the combined lasers by changing the voltage being fed to each individual laser diode. Changing the voltage of red and green to a low amount would yield the color output to be blue. This technique is technically more efficient than the previous, but it is more complicated to implement. This would require proper tuning, which is a time-consuming activity, to get the color changing just right. This would still be somewhat inefficient compared to today's techniques.

Thus, the way we implemented color control in this project was through Pulse Width Modulation of each individual laser diode. Pulse Width Modulation is a special technique in which in the cycles of the waves of which the state of being "ON" is increased or decreased in length. This technique is used in many applications, but most importantly, to save on power consumption and adjust the light emitted by each laser diode. The technique uses a switch; during the change between on and off, the switch is consuming power, but it does so in a considerably small amount of time. The time is so small that the power consumed in this process is quite minimal compared to regular power delivery. By changing the length of the "ON" part of the cycle, we can effectively change the brightness of the laser light emitted. Increasing the length of the "ON" cycle, increases the brightness, decreasing the length, decreases the brightness. Using Pulse Width Modulation allows us to use a constant voltage for the laser diodes to produce quality lighting. Current modulation of the diodes would have been much more difficult to implement. The intensity of each color can then be adjusted via Pulse Width Modulation for each individual laser diode. This changing of the intensity of each color produces a larger range of colors output by the diffusers. We are using 3 colors: Red, Green, and Blue, which are the basic colors used in producing a large spectrum of colors. If we wish to make Purple, we bring down the pulse width for the Green diode to be near zero, while leaving the Red and Blue at 100% their intended operating pulse width. If we want to make Amber, we set the pulse width for Red to be at 100%, set Green to be at 75%, and Blue to be at 0%. Apple green can be made by having the Red to be 55%, Green set at 71%, and Blue at 0%. If implemented well enough, we could essentially have way more colors producible than originally planned. This would essentially give us a much higher color count than regular screen displays are capable of.[11][14][23]

## 8.10: Software

The Controller will be running software that we have programmed. The software has to perform the tasks of saving settings into memory. This software can be put together with potentially many different algorithms. The software can be broken up into system parts: Input System, Output System, Management System, and Monitoring System. These systems are what will run together on the microcontroller.

### 8.10.1: Input System

The input system will be responsible for accepting and interpreting inputs from the user. This can be done by coding either a polling function or an interrupt. Polling functions work by constantly checking for an input at the end of every predefined period. This is usually accomplished with a loop that contains a delay element to cycle through the loop to check if any input flags have been set. The delay element can be implemented via an empty loop that is executed a large amount of time; using this implementation of delay is not very accurate and is inconsistent on different clock speeds. Another way of implementing a delay element is using a predefined delay function from a library. Polling generally uses up more power and CPU to run. Interrupts, on the other hand, only become active when the event to trigger a flag happens. Using interrupts saves energy, as the microcontroller does not need to be actively checking for a change in input. In modern computers, interrupts are often used when detecting inputs from devices such as keyboards and mouse inputs. When the interrupt is raised it will call upon a function to respond to said interrupt. This function is what will interpret the input and determine what must be done based on the input.

### 8.10.2: Output System

The output system will be responsible for outputting data to the user via the screen, and the lasers. This will be done by using several functions to acquire the data for the message, assemble the message, and display the message. These functions can be separated into these three parts: Data Query, Message Assembly, Message Output. Data Query will be the function or functions that acquire the data that needs to be displayed to the user. Message Assembly will be the function or functions that put the data together into a meaningful way that is readable to the user. Message Output will be the function or functions that take the assembled message of data and send it out for display.

Starting off with the Data Query part, the Management System calls the function with a data query passed as an argument. This function then gets the requested data from the system and passes it on to the next function that is of the Message Assembly part. The data can consist of integers or ASCII characters. Depending on the data type, the corresponding function for Message Assembly will be called with the data passed in as an argument. The data can be acquired from the Color settings, Temperature settings, Power settings, and the Luminosity settings.

The Message Assembly part takes over and takes the data and converts it to a meaningful message. The data begins its conversion by first determining whether the data is of type integer or of type character, then the data is all converted to ASCII code, then converted to code that the screen will display as readable data. This conversion can be accomplished with a few different algorithms. One of these algorithms is a conversion table, where we have an array of code values to convert to, and a translation function for looking up the proper code value in the array to use.

The Message Output part takes the converted message data and sends it to the output screen for displaying to the user. The function or functions take in the message as an argument, then uses the appropriate output pins to send out the data.

### 8.10.3: Management System

The management system will be responsible for managing the input data and settings; this can be achieved using several functions. These functions would acquire the input data via the input system and adjust the settings according to the input data. These functions will be responsible for managing system settings, saving newly modified values to the non-volatile memory of the controller, and applying them to the running system.

This system pulls setting data from the non-volatile memory and applies the setting to the system at launch. The system can receive new values from the Input system, save the new values to the non-volatile memory, and apply the new settings to the lighting system.

This system also manages the Pulse Width Modulation based on the values for each color in the settings. Depending on the values set for each diode, the PWM is adjusted to accurately match those values to generate the proper output of light.

The Management system is also responsible for updating the power, temperature, luminosity, and color settings whenever there is a new value change in the settings.

### 8.10.4: Monitoring System

The Monitoring System is responsible for monitoring the power, temperature, and specific interrupts. There is a function that monitors the temperature. This can be done by setting up a timer to check the temperature periodically. The function polls the data at regular intervals. There is also a function for monitoring the power consumption of the system. The power monitoring system uses a time to check the power usage of the system.

The temperature monitoring system checks the temperature of the system, which includes: each individual laser diode, the onboard controller, and the power supply. The values it acquires are sent to the Management System for storage and use. The unit of measurement these values will be in are either Celsius or Fahrenheit.

The power monitoring system will be checking the power consumption of each part of the system. This system will acquire the measured values from the following systems:

- Laser diode system
- Interface system
- Controller system

The laser system's power values will measure the power of each laser diode. The Interface system power consumption will be that of the screen and input devices. The Controller system power consumption will be that of the microcontroller.

## 8.11: User Interface Standards and Common Practices

The interface in which an intended user interacts with is used everywhere in technology. Through many forms of input and output, interfaces vary widely; from the simple keypad and LCD screen on an ATM to a virtual reality headset with num-chuk controllers, we find a great many ways to create an interface for the user. In the many ways to make a user interface, there are bad practices and good practices. A clear, simple interface will always trump a cluttered interface with many features and gadgets. This is where good standards and guidelines for user interfaces come in to play.

### 8.11.1: User Interface Standards

User interface standards are guidelines designed by an entity (a company, a group, an organization, etc.) in which its product developers follow for the interfaces of their products. These guidelines specify the layout and organization of the user interface for their products. How should the buttons be placed? Where do the labels go? How elaborate is the menu on the display screen? Does the screen layout allow for scrolling? These are a few of the many questions the guidelines answer. These standards are developed to work best for the user end. Visibility and clarity of the interface are all made via the layout and design given by the guidelines created.

Individual entities develop their own user interface standards to best fit their product and end user. In consideration of these standards, it is the aim for a simple, yet effective implementation of user interface design. Things like symbols, colors, typography, and other visual graphics are taken into account to properly relay to the user what the entity wishes to convey. According to an article about communication via graphical interfaces by Suzanne Martin, communication through proper and clear visuals help to make an effective user interface. Using well-presented layouts and formatting along with other sensory outputs to the user can greatly enhance the interface experience. Clarity and organization in the layout presents a clear orderly presentation of the information to be conveyed to the user. Keeping the layout design consistent throughout the interface creates a familiar, easy to use environment for the user to interact with. Breaking that consistency will create confusion for the user. The navigation of the interface must be clear and organized, easy to extrapolate menus and sections of the visuals presented on the screen.

Colors are an important part of the visual interface, as the colors can generate a sense of organization in the layout. Using colors to organize different sections of the layout is an effective way to organize and segment off parts of the interface to the user. Colors can also be used to attract the user's attention and guide them to important information. The colors can be used to indicate or communicate to the user specific information. This is a form of symbolism using colors as symbols to communicate to the user.

Typography is the most commonly used form of communication in user interfaces. Choosing or creating a clean font style could mean the difference between having an easy to read interface vs a difficult to read interface. Changing the styling of the font can help convey to the user what kind of information they are reading. The way the text is organized and displayed can make or break readability.[27]

### 8.11.2: Common Practices

For many industries, there are commonly used practices to implementing user interfaces for their electronic devices. These practices are common, as they are familiar and easy to use and understand. Beginning simply with a screen for output and buttons for input, something anyone can easily interact with, are among some of the most commonly used parts to create an interface. Many have used a touchscreen instead, allowing for both input and output via one device. For all these devices interfaces, a screen is mostly involved. Thus, there are also commonly used visuals and graphics for these screen user interfaces.

Common practices for screens displays of interfaces is how it's laid out. The layout usually starts with the top part of the screen; this area usually has a title, a menu, navigation, or a combination of two or three of these. This helps to indicate the type of information the user can expect to see in the rest of the screen layout. The rest of the layout is typically the informational/main content of the interface.

According to usability.gov, common elements used in user interfaces are:

- Input Controls
- Navigational Components
- Informational Components
- Containers

The Input Control elements usually consist of a variety of input element such as: checkboxes, radio buttons, dropdown lists, list boxes, buttons, toggles, text fields, etc. These are for taking user input in various ways. The checkboxes are a list of options in which the user can make multiple selections by filling in the box next to the option via interaction. Radio buttons are another list of option similar to that of the checkboxes, except instead of boxes, we have circles to fill in via interaction and they are usually only allowed one selection at a time. Drop down lists are a form of list selections, they are usually a combination of a textbox, which contains the currently selected item, and a drop-down button for revealing the entire list to the user. The drop-down lists are a way of condensing listed information or options to make more room for other elements on the interface. List boxes are another form of list that are contained in a scrollable, fixed size box. This box list allows the user to make multiple selections via interaction. Buttons are perhaps the most commonly used element in user interfaces. These buttons can be used to generate an action upon the user's pressing of the button. The buttons are usually labeled with the intent of which action they provide. Toggles are a type of button that can toggle between different settings or actions, similarly to that of an on/off switch for a light. Text fields are another very commonly used element in user interfaces, as these elements provide the user the ability to type in a line or multiple lines of characters as an input.

Navigational Components are combinations of the previously mentioned Input Controls and other more graphical elements used in a fashion that allows the user to navigate the user interface. Search fields, bread crumbs, paginations, tags, sliders, icons, image carousels, etc. Search fields are components that contain a text field in which a user can enter a search query, usually by a search button, to which the results can be displayed on the user interface likely via a dropdown list element. This component allows for the user to potentially search for information or elements in the database that the interface is using. Breadcrumbs are a type of navigation tool usually implements by using clickable navigational elements that lead to places you came from. This element displays the path of navigation in which the user has taken; this also displays the current location the user is at. Paginations divide up the content into manageable separate sections or pages that are navigated via a row of clickable section/page numbers that lead to said section/page. Tags are a special element that are attached or associated with a specific category of information or content to which the user can search for content by. Sliders are a form of a graphical input that the user can interact with to adjust a value or setting. These sliders are often a bar with one or two movable graphical knobs that the user can interact with by sliding along the bar. This is often used for volume control, zoom, and brightness. Icons are a widely used graphic that is an image of which serves as a symbol. These icons are used for navigation, as they can symbolize the destination they navigate to. Thus, a common place for icon use is on button elements that navigate to the desired location. Image carousels are a more graphical form of navigation, as they provide images or icons that are in a horizontal scrollable list. The images/icons of said list are clickable navigators.

Informational Components are combinations of elements that inform the user of things like tool tips, messages, or any form of data. These elements are notifications, progress bars, tool tips, message boxes, modal windows, etc. Notifications in general are a message to update the user of an event that has taken place; things like receiving a new message, confirmation on a task, or an error occurring. The progress bar is an element that indicates to the user, graphically, of a progress of some task. This element is usually made in the form of a bar that is filled to the current point of said progress. Tool tips are simple elements that inform the user with information on how to operate a component or to give a hint on an item or subject. These elements come in the form of a text bubble that pops up near the item of question. Message boxes are another element by which informs the user of any sort of information. This comes as window that overlays on top, filled with the information, and usually has a button in which the user must click to confirm understanding of the information. The modal window is another form of the message box, except that it will require more user input before the user can interact with any other content. The input can be text fields and such.

Containers are a type of element that help segment and format data/content on the user interface. A specific element of this type is the accordion. This element is a type of list that contains topical elements along with hidden content in an organized fashion. When the user selects a topic in the list, the content, for said topic, extends downward from the selected element revealing to the user the content of the selected element. When first loaded, the accordion will have a pre-selected element with its content showing for the user to see.[24]

## 8.12: User Interface Prototype Parts Acquisition

For the prototype, we decided to acquire the parts necessary to make a simple working interface as a proof of concept. The parts need not be complex or expensive but must be able to implement all the base functions for this project. The following items are what have been chosen.

- Bread board
- LCD screen
- Wires
- Arduino micro board
- Potentiometer
- Push buttons
- Led indicators

Most of these are available in a special kit from Arduino, or can be bought separately. For budgeting reasons, we have opted to use a kit one of us acquired through a competition held by Thales. This is an Arduino experimentation kit, which included most of the items required for this prototype.

#### 8.12.1: Bread board

The bread board is used for testing out embedded designs. The board contains slots for which electronics and wires can be places and connected. There are two strips on each end for power supply and ground, two 5x30 blocks for placing electronics and connecting them. This breadboard has labeled rows and columns; rows are identified by number, columns are identified by letter.

#### 8.12.2: LCD screen

The LCD screen is an 84mm x 36mm x 14.5mm LCD character display module. This display comes with 16 characters per line, with there being two lines for a total of 32 characters displayable. This screen is also backlit via a green LED for visibility in a dark lit room or night time usage.

#### 8.12.3: Wires

The wires are simple jumper wires of 150mm. they come in different colors for identifying the use of the wire in this project. These wires can be placed on to the bread board for experimentation and testing of the embedded designs. Conventionally, red wires symbolize power output, black wires for ground, the other colors can be considered for data transfer.

#### 8.12.4: Arduino Micro board

The Arduino micro board contains the ATmega32U4 microcontroller, 20 input/output pins, 7 PWM channels, 12 analog input channels, a clock speed of 16 MHz, and 3 LEDs. It has a power input/data micro USB port, as well as a rest button.

#### 8.12.5: Potentiometer

The potentiometer is a type of dial that varies the voltage output using resistance. This particular model uses up to 10k ohms of resistance. By twisting the knob on the potentiometer, we can increase or decrease the voltage output. Starting from the input voltage and going down in voltage as we turn the dial.

#### 8.12.6: Push Buttons

The acquired push buttons are simple momentary switches that, when pushed, create an open or closed circuit to signal the push of the switch. We have about 4 in total for use.

#### 8.12.7: LED Indicators

The LEDs acquired are of two different colors: red and green. These Light Emitting Diodes can be used to indicate the powering of the system, and as update indicators.

### 8.13: User Interface Prototype Testing and Qualification

The parts we have acquired for the interface were tested to see if they are performing properly. After looking up information on the Arduino and the LCD screen, the information required to set up the and test the prototype interface was found on the Arduino site.

**8.13.1: Setup**

The LCD screen comes with 16 pins. These pins are connected and wired in the following way to run and use the screen:

| LCD Pin Number and Use | Arduino Mini Pin Connection |
|---|---|
| 1: VSS | GND |
| 2: VDD | 5V |
| 3: V0 | 5V -> Potentiometer ->V0 |
| 4: RS | D12/MISO |
| 5: R/W | GND |
| 6: E | D11 PWM/MOSI |
| 7: DB0 | None |
| 8: DB1 | None |
| 9: DB2 | None |
| 10: DB3 | None |
| 11: DB4 | D5 PWM |
| 12: DB5 | D4 |
| 13: DB6 | D3 PWM |
| 14: DB7 | D2 |
| 15: LED+ | 5V -> 220 Ohm ->LED+ |
| 16: LED- | GND |

Table 5: LCD Pins

For power, the LCD screen takes in 5 volts directly into pin 2; this is what provides power to the actual display. The LED back light is powered by 5 volts in series with a 220 Ohm resistor, producing a green light by which lights up the back, creating a contrast allowing visibility of the display. Unfortunately, we did not currently have that resistor, thus, several resistors of higher value were put in parallel to nearly match the 220 ohm resistance. The contrast of the display can be adjusted via the potentiometer that connects its wiper to pin 3 on the LCD.

For data, the LCD has several pins, about just over half of which is really needed. DB4-DB7 (pins 11-12) receive the character data to be displayed on screen. The RS pin (pin 4), also known as the Register Select, receives data on which instruction mode the LCD should be in. This mode determines how the data received by DB0-DB7 (pins 7-14) will be used. The LCD has two popular modes: Character mode and Instruction mode. In Character mode, the LCD will interpret the data received as data for characters to be displayed. In Instruction mode, the LCD will interpret the data received as instructions. These instructions could be to clear the display or move a cursor.

The Grounded pins VSS, R/W, and LED- (pins: 1, 5, 16) are for the most part grounded to complete the circuit. The R/W pin (pin 5) is set to ground as a low signal. This permanently sets the LCD to write mode, because we won't need to be reading what's written on the screen in this project.[17]

**8.13.2: Controller and LCD testing**

After setting up the Arduino and LCD screen using the instructions and pin layout data, The Arduino was programmed to output a sample menu to display. The following figure 20 shows the resulting output of the program. By using this program, we are able to test the functionality of both the microcontroller and the LCD display.

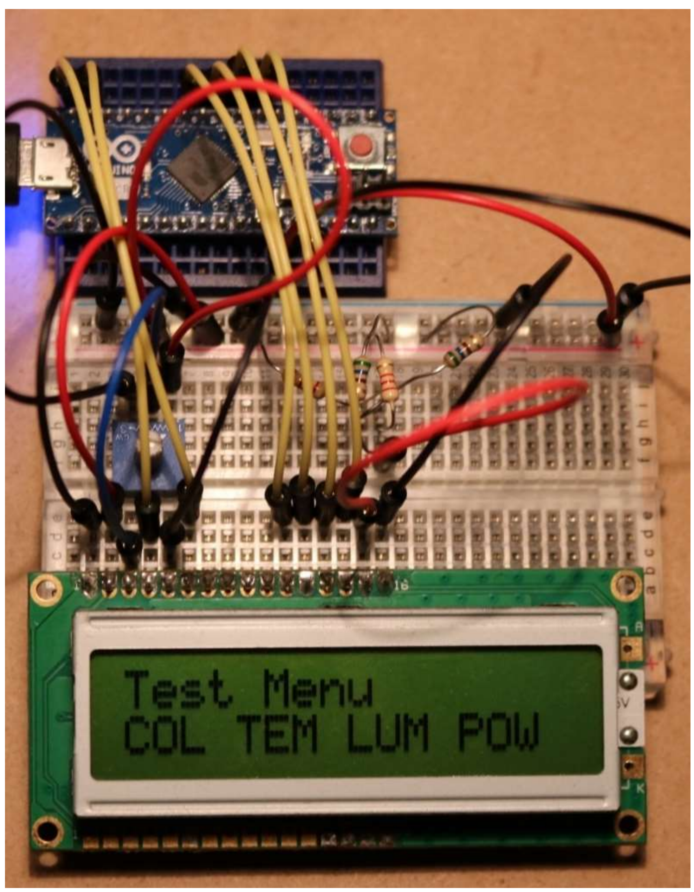



Figure 20: LCD

As the figure above shows, our LCD screen does in fact function and display the characters that were programed into the Arduino. The LCD inputs all function, including the one for adjusting the visibility of the characters. This input is connected to the potentiometer, allowing for adjustment of how dark or light the characters show up. Note that the character limitation of 16 characters per line, on this model LCD screen, has forced the use of abbreviations for each menu option. Color, Temperature, Luminosity, and Power have been abbreviated to COL, TEM, LUM, and POW respectively. Due to this limitation, menu items and setting elements will have to be small and shortly written, yet still understandable/readable to the user. Given that this is a prototype, some of the advanced menu parts may not be implemented here.

### 8.13.3: Controller Analog testing

The microcontroller is set up to be able to take analog signals as input. This is an important feature needed for implementing different controls schemes and designs for the interface and the controller. This is testable using a potentiometer. The potentiometer can be connected to the 5 volt source and it’s output to the analog input of the Arduino. The Arduino would be programmed to change the rate of which it flashes an LED. Swiping the potentiometer would increase or decrease the blink rate depending on the direction. This would test the potentiometer’s functionality and the microcontroller’s analog input.

### 8.13.4: Controller PWM testing

The microcontroller comes with the capability of Pulse Width Modulation. This allows us to control the duty cycle and frequency for the laser diodes, such that we are able adjust the overall brightness of each individual laser diode. Testing this feature is an important step in making our lighting system work effectively and efficiently. The test is a simple setup with a laser diode hooked up to the Arduino and running a program on the microcontroller that will increase and decrease the width of the “On” state of the duty cycle. This effectively brightens and dims the LED as a result of the change.

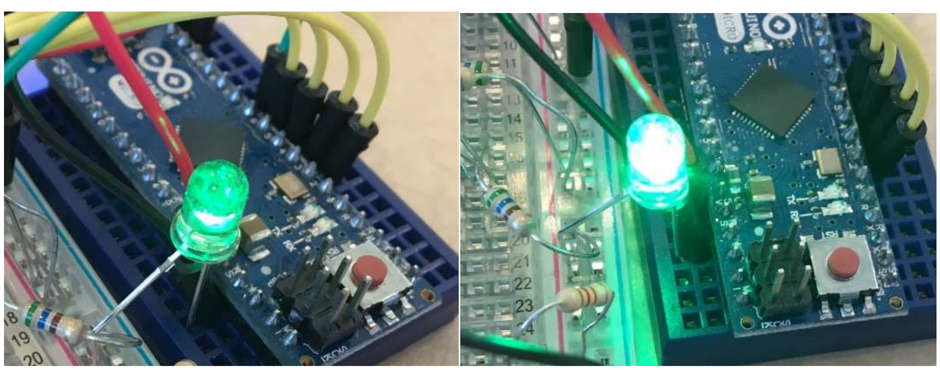


Photo 1: PWM Test

This test proves that the concept for changing the brightness via Pulse Width Modulation works. The LED consistently increases and decreases in brightness as the width increases and decreases respectively.

### 8.13.5: Input Testing

The push buttons we have acquired, must be tested beforehand to check for defects. To do this, each individual push button is placed into a circuit that is in series with a LED connecting to the Arduino board for power and completing the circuit. The button, when pushed, should turn off the LED indicator. This will indicate a properly functioning push button.

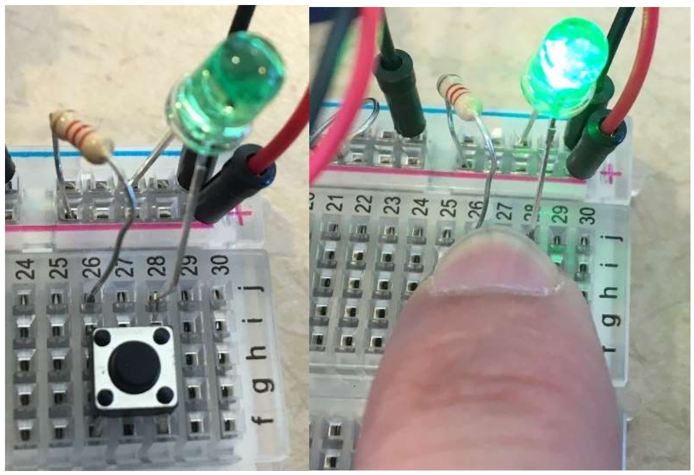


Photo 2: Button test

The results appear to happen in reverse; the LED is off when the button is not pushed but turns on when pushed. This means that the push buttons we have, bridge the circuit when pushed. This information is vital to properly implement these buttons to the interface.

## 9.0: Electronics:

Laser diodes are very similar to typical LEDs. For, the diodes to turn on correctly, they need to be biased with a current to be in a constant voltage. This system is typically done with a constant current source. This current source is done typically with a LED driver. The driver drives the current for the LED and creates a constant current even with a varied input. These inputs are usually around 5V to 12V but can vary anywhere in that range but no less.

With the design goal in mind to create different colors by using three different laser diodes, some control logic is needed to select the correct current required for the different brightness of each diode. This can be controlled with a microcontroller on a PWM signal to control how bright the diodes are. For this we would need a simple circuit to control each of the diodes.

Because the diodes need to have a different current for each type, each diode will receive their own driver. That can be tuned to its voltage but using the same voltage regulator which will allow for a simpler swap.

### 9.1: Diodes:

Diodes consist of semiconductor material that have a junction between two different types. These types cause some reactions to occur. In a normal everyday use diode, the control of current flow happens. After a certain threshold occurs, current can pass through the diode and into the next node it points to. All diodes follow this pattern and are privy to current instead of voltage.

With even just a small increase in voltage over the diode could cause the current in the diode to increase exponentially. This can be quite dangerous in these circuits and therefore cannot be powered on their own. For the most basic design of diodes, a current limiting resistor is placed in series with the diode. This resistor will take the rest of the voltage given from the source and therefore will limit the current in the node. However, this allows no control of the diode besides two states (On and Off).

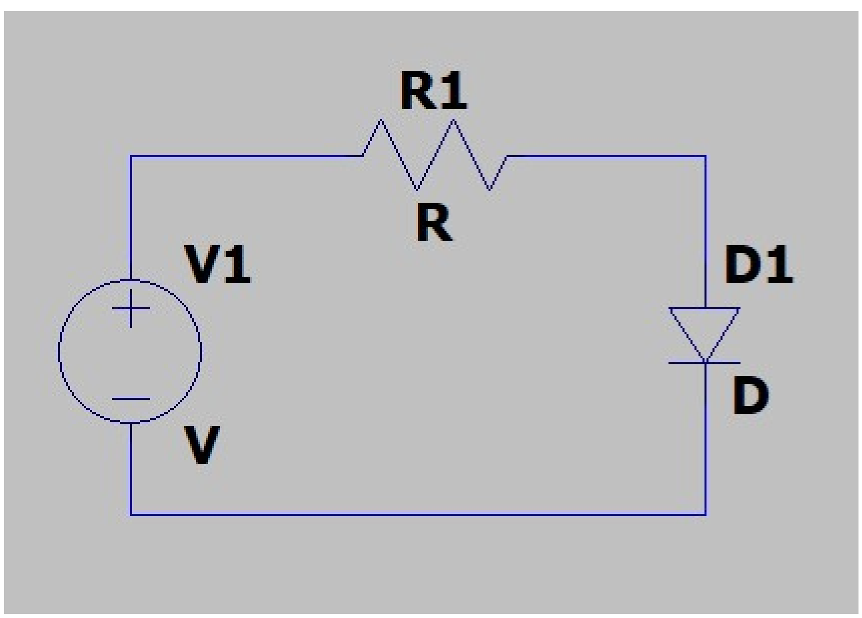



Figure 21: Basic Diode Circuit

Above is a basic diode circuit. This circuit has a diode in series with a resistor and a voltage source. While this circuit will work, it leaves something to be desired in terms of control and other sections. As discussed above, for the diode to be turned on a certain voltage threshold needs to be achieved, if any other higher threshold voltage is achieved, a current increase in terms of becoming exponentially larger is an issue. Therefore, a resistor is placed in series to limit the amount of current that goes through the circuit. As these components share the same current, and a certain voltage is required to turn on the diode, once that threshold is met the remaining current will go over the resistor. Of course, the amount of current desired through the diode is decided by the size of the resistor as Ohm's law determines the amount of current based on voltage here. This circuit is rather not efficient as well. As the resistor power is transformed into heat energy instead of any other use.[31] But the important thing to note is that the current needs to be limited in the diodes or damage to the circuit such as the wire, source, or even the diode itself can be costly and needs to be considered.

### 9.1.1: Laser Diodes:

Laser diodes work in the same way with a P and N type. These semiconductors are stacked on each other, with the P type wanting electrons and the N type wanting holes. This interaction can be created in a way that when the electron passes over the junction a photon is produced. Based on how the diode is made the photon produces a certain wavelength which can be in the visible spectrum. When a certain voltage or current is reached for the diode, it is focused and produces light. If more current is supplied or the current supply is staggered in waves (Such as a PWM signal), the brightness or number of photons that are being produced will change.

These diodes have two metal contracts on the ends of both the P and N type semiconductor. This is where the circuit connects to the diode. With a voltage applied over these plates the electrons are excited and pass through the band in between the P and N layer. However, due to the intrinsic nature of the diodes, they required a heavy amount of current to produce any sort of meaningful light for the application that is being used. At least 100mA is used to turn on the diode and any more from 100mA to 3 A can be used to make the diode even brighter. This amount of current is not used in the simple diodes as the resistors cannot handle this amount of power and will melt. This sort of higher current that is being used is something that needs to be considered when designing the circuit to power them.

## 9.2: Power

Voltage and current drivers are common to power most electronics. When designing some electronics on a PCB or other application, a certain amount of power is desired. To achieve this power a driver can be used to interface between the AC power or batteries and supply the correct amount of voltage needed. This type of circuit is called a power circuit or a driver circuit. [31]

In the case for this circuit, a smaller DC voltage is required along with a rather high current compared to most other low voltage circuits. There will be two ways to power this circuit:

1. Pull directly from the mains

2. Pull from a 12V battery

This design choice was created to have a safe way to keep the diode going if the power were to go out from the mains. If the power drops from the mains, a disconnection occurs and switches over to the battery for its power supply. With this voltage the driver that is used will be able to pull enough current and keep the lights going even when the power is off.

This adds some complication to the design of the circuit but for the added benefit that the product will be reliable and will continue to produce light. This will be done with some current sensing from the mains, once there is no current over a pull up resistor a MOSFET will allow current to flow from the battery and as MOSFETS have small resistances, the amount of power lost over the MOSFET will be small and insignificant to the rest of the circuit. Doing this analog instead of computer control allows for less complex code for a not so hard to implement circuit.

### 9.2.1: Diode Drivers

As discussed previously, diodes prefer a constant current compared to the constant voltage. As the slightest voltage change over the diode can drastically change the amount of current that passes through the diode. Therefore, creating a constant current source will be the best design in terms of powering the circuit.

For the laser diodes, to achieve this constant current a driver is used with an input of 12V that steps the voltage to whatever level is needed to produce a constant current. The current is produced at the output and can be connected directly the diodes.

#### 9.2.1.1: LED Drivers

For LED drivers and the laser diode driver that is being used has some connections that connect directly to a microcontroller. These connections are the Pulse Width Modulation and Status Output. The PWM pin is what will be used to change the brightness of the diode. As changing the current for the diode might make interfacing the diode with a computer much more difficult. For other types of adjustable current driver, a potentiometer could be used but this cannot be controlled through the microcontroller in any reasonable form. With using PWM, the internals of the driver will turn on an off the current being supplied to the diode and therefore will vary how much power is being outputted by the diode. If the duty cycle of the PWM signal is 50%, the diodes will be at half power compared to when the duty cycle would be around 75% which would have 25% more power than the 50% duty cycle. This wave can be controlled with the microcontroller and allows easier control. [31]

#### 9.2.1.2: Laser Diode Drivers

This driver works by taking the input voltage and based on the PWM signal will turn on and off the current that goes through a transistor. This transistor is based on a comparator which is compared to the reference of the output and the input. Based on the difference between these two voltages, a current will be produced to be close to what the reference voltage is.

This driver will be based on a constant current. As a variance in voltage can cause some serious damage to the circuit. With a constant voltage, a constant current can be created as well as seen from the circuit with the basic diode with current limiting resistor.

Some protections with this circuit are convenient. As the input impedance is rather high, if any sort of surge occurs, the diodes will not receive the current directly and therefore will not be broken during a surge and will only damage the driver itself (This is particularly useful as the diodes are rather expensive). There a different type of regulators. Linear regulator and switching regulators

Some laser diode applications where these drivers can be found are in Blu-ray devices. As they use the laser diode with the feedback to read information off of the disk, and as the feedback is very quick and is really fine, the information on the CD can be found very quickly. Some other applications with these types of drivers are with communications with the diodes. As the speed of light is very quick, the information is passed very quickly to the receiver.

#### 9.2.1.3: Switching Regulator

A switching regulator does exactly as the name says. With an input DC voltage, a voltage reference from the output, along with some Pulse Width Modulation causes a MOSFET to turn on and off very quickly. With the use of a comparator and a change in signal, this outputs a voltage that is AC but in a way that can be easily turned back into a DC voltage. With the modulator, at a certain point in the wave the MOSFET will be turned on, and at another point the MOSFET will be turned off. With this knowledge using some memory storage components will be helpful to pass along this current. An inductor is a component that does not allow the current to change instantaneously and will only change after time has passed. With this, an inductor can be used along with a capacitor in parallel with the output to create a DC voltage. A diode is also used so that once the FET is turned off, the current can continue in the loop instead of having an open circuit.

A switching regulator has a very high efficiency. This is due to less voltage loss over the component itself as the voltage drop over the FET is quite small. There is a very small resistance between the drain and the source (which is where the current passes through). And with using Ohm's law the voltage drop is quite small even with significantly high current passing through it. All the other components inside do not require much power and therefore do not produce as much heat as other components. The downside is that the circuit is more complicated, and inductors can run quite big compared to other types of regulator circuits. These diode drivers could be larger but typically they are quite small, and the inductor required to do the job and produce the DC voltage would present quite a challenge. [31]

Cost and complexity are something to consider here as well. As this design is more complicated than the linear regulator it costs more and as the need for a higher current than most circuits this component becomes even more expensive. For this design, at least 3 of these regulators are needed or 6 if redundancy is required.

While a higher efficient model is desirable, the efficiency for the design of this is the power efficiency over the diode compared to light energy. Not wall to diode power efficiency.

#### 9.2.1.4: Linear Regulator

A linear regulator is a much simpler concept compared to the switching regulator. An op-amp is used which has one end connected to some reference voltage and another end which is connected to the output voltage of the circuit, there is also a voltage divider of some kind to control the amount of voltage that is being regulated. As the op-amp terminals try to become the same voltage, the internals do their work and produce an output that will allow this to occur. This output current is then connected to a BJT. This BJT will be turned on with the voltage difference happening in the op-amp. This BJT is connected to the input of the circuit at the collector, the base is connected to the output of the op-amp, and the output is connected to the emitter current. With this, a higher voltage input can then be regulated to a voltage depending on the reference voltage and the voltage divider contented to the output.

The downside here is the efficiency of the input power compared to output power with this component is quite a bit worse compared to the switching regulator. The issue here comes from the BJT not being nearly as efficient compared to the MOSFET in the switching regulator. The input impedance being significantly higher and therefore causing a voltage drop over the BJT to occur that is much more significant. Issues here as this component takes quite a bit of power, lots of the power is converted to heat, in some extreme cases a heat sink is required for these components otherwise they will perform poorly or even become destroyed or damage other components around them on the PCB. [31]

Benefits come from the size of the component being quite small and the surrounding component being much easier to create. Typically, with some coupling capacitors on the input and output (to smooth out the DC voltage) and a few resistors on the output for the reference voltage and regulation of the circuit. This simple design makes these components quite desirable when efficiency is not an issue.

Cost and availability are a positive factor for these regulators as well. As they are not as complex as the linear regulator and are easier to manufacture, their cost per chip is significantly smaller compared to a switching regulator with the same output. As they are easier to manufacture there as well are more choices which drives down cost as well along with having a more varied choice in regulators to choose from (more constant regulators instead of having many dynamic/adjustable regulators.

Because of these benefits, the linear regulator for the constant current driver is the choice. As creating a constant current from a constant voltage is quite simple from a using a current limiting resistor or some other techniques. Their size and creation of less complicated circuitry around the diodes makes this a high priority. If power efficiency was the main issue, the switching regulator would be the key choice.

### 9.2.2: Mains Power

To drive this circuit, 12V DC is needed. To achieve this voltage from the wall some refinement needs to be done. In North America, socket power is delivered at 120V AC [12]. It is delivered at such a high voltage to increase the amount of efficiency with driving power over long distances. Therefore, this power needs to step down and transformed into DC.

The process of transforming AC into DC is called rectification. Using diodes, current can be funneled to the load of the circuit. There are two common types of rectifiers that are used here. Half-waver, and Full-wave rectifiers. Half wave is a rather simple type of rectifier, this requires just a diode to be placed in series with the load. As the AC voltage is positive, the current is passed to the load. When the AC voltage is negative no current is passed through. A capacitor in parallel with the load causes a more consistent voltage

(DC) to appear. As with the waveform being positive charges the capacitor, and when the waveform is negative, the capacitor discharges. Both charging and discharging times can be slow with the correct RC time constant and will give a DC signal

A Full-wave rectifier is slightly more complex. This will allow the current to go through even when the voltage is negative. This is done with a design called bridge rectification. The positive terminal of the input source is connected in between diodes that are in the same direction. And, the negative terminals are connected in between diodes in the same direction as well. The load of the circuit is connected in the middle of the circuit, known as the "bridge". With this layout a positive version of the wave is always outputted, even when the signal is negative. This is caused by the logical flow of the diodes. Again, the load can be placed in parallel with a capacitor to have a smooth wave form that is charged and discharged at a faster rate (double the rate) as a Half-wave rectifier.

This voltage also needs to be stepped down, this can be done before rectification, or after rectification. Before rectification an AC/AC step down needs to occur, this can be done with transformers. A transformer has two sides, each side has coils on it but with different turn ratios. Current is inputted in one side, this current because of the coil creates a magnetic field. This magnetic field then influences the other coil. And based on the ratio of the coils, a voltage will be produced. Therefore, for a 120V AC to 12V AC conversion a turn ratio of 10 is needed to step down the voltage to a lower side [12]. There needs to be some safety precautions as the power of this transfer ideally is not lost and therefore ten times the current will be produced on the other side.

These are the common ways that 48/24/12/5V DC voltages are achieved. Transformers are considerably more efficient than buck converters. With the high voltage change to low voltage change, just as it is done from distribution from power plants to consumer's homes [12]. If rectification, then using a buck converter is done. This can cause some very unsafe current levels and needs to be accounted for.

### 9.2.3: Batteries

Batteries are the other source of "Backup" power for these lasers. Batteries are a storage device that with a chemical reaction produce an electric current. This current of course is used to power the circuit. Batteries come in many different forms and have their various pros and cons to what should be chosen.

With the wide range of batteries, there are some that will be better for specific cases. Batteries come in a wide range of sizes, capacities, and power outputs.

#### 9.2.3.1: Deep Cycle Batteries

These batteries are common for car electronics. The purpose of these batteries in cars is that they power all the electronics in the car. Which nowadays is almost everything in the car from power steering, adaptive cruise control, to 12V outlets in the car. These batteries are particularly useful for long use cases and when lots of current needs to be applied. They can store a rather large amount of energy compared to other types of batteries but have a tradeoff being more expensive and quite large leaving less flexibility for space. Deep cycle batteries are made differently than traditional Lead-Acid batteries as the material in them is more dense than other batteries. Also due to the nature of the battery, they are less efficient than others [8].

### 9.2.3.2: Lithium Ion Batteries

Lithium Ion Batteries are another common type of battery. These batteries are typically seen to power laptops, flashlights, lasers, and even electric cars. A big benefit to these batteries is that they are rechargeable which is some major convince in terms of not having to replace these batteries [5]. Their size is another benefit as they are much smaller than some other long-life batteries such as the deep cycle batteries. Some issues that can occur is to use these batteries for a longer life the voltage needs to be checked as when the voltage reaches a certain level (that is low) the battery becomes useless and can no longer be charged.

### 9.2.3.3: Alkaline Battery

A very common type of battery typically used in small electronics such as toys or even some older cameras. This battery however has many negatives compared to its positives. The number of amp-hours that the battery has is quite small compared to the others and for its biggest negative that it cannot be recharged compared to the others. This battery has a lot to be desired for this project as, if there was a power outage for a short time, the batteries would drain faster than the others as they are less efficient and would have to be replaced in some fashion instead of recharging from wall power [21]. This of course would be different if there was no wall power near to recharge these batteries.

### 9.2.3.4: Battery Choice

With looking at many different battery types. The Lithium Ion Batteries are the choice to be desired. They can store enough energy that if the power were to go out, they could last for a significant amount of time without worry. They are quite reliable and used in many applications. The design impact with making this battery choice is that the voltage level needs to be looked at carefully to make sure it does not reach below the threshold. This can either be monitored digitally or analog and the decision was to do this with analog to allow full control of the microcontroller to the laser diode driving.

Another reason for these batteries is that if a change in voltage is required later, this leave some flexibility of the configuration to change and can place these batteries in parallel to increase the amount of current and therefore lifetime of the system being turned on. Because these batteries are so small compared to the deep cycle. Lots of batteries can be placed in the system to allow longevity of powering the system directly off these batteries.

### 9.2.4: Current Sensing Circuit

One of the design specifications is to have continuous power, even during a power surge or power outages. Battery storage was the method for when the power from the mains it is out can be used, or for the batteries to be the primary source of power. For this, a voltage/current needs to be checked if it is coming from the mains. If there is no current or voltage found from this circuit, it will switch the main power from the mains to batteries. This logic can be used with a simple transistor (a MOSFET for these purposes).

To sense the current in the circuit, the component conceptually must be "in" the circuit. As the voltage difference is something that can be measured externally very easily (in parallel), the amperage needs to be measured in series with the circuit. Therefore, a resistor commonly named as a shunt resistor is placed in the middle of an op-amp as a comparator. With the shunt resistor, the current going through the resistor will create a voltage across the two terminals (top part of the resistor and bottom part of the resistor). If there is a current going through the resistor, there will be a voltage drop and therefore will turn on the op-amp and produce an output. However, if there is no current going through the resistor, there will be no difference between the terminals in the op-amp and therefore there will be no output from the circuit. The shunt resistor is typically something rather small (somewhere in the milli-ohms range). As the current will not be affected by the size of the resistor, keeping the voltage as small as possible with a smaller sized resistor will decrease the amount of power loss in the circuit.

With using a MOSFET, the output can be connected to the gate of the FET. With this, the voltage can be outputted from the mains, and when the supply voltage stops from the mains, the FET will allow the current from the batteries to the load and will drive the rest of the circuits. The resistance over the drain to source is quite small and therefore will have a very small voltage drop over the MOSFET. This is quite useful as this circuit will require very little power to control and power on. The type of MOSFET that will be used is a P-channel MOSFET. As the shunt resistor will be placed through the current of the wall power, the current sensing circuit will be turned on and therefore have an output turned on. Therefore, the current will be supplied to the gate of the MOSFET, and as the connection for the current will run from the drain to the source with the connection of the battery, when a current/voltage is supplied to the MOSFET, the logic would be to have the switch open and a p-channel FET will achieve this through a voltage being applied will open the circuit instead of close the circuit like a n-channel.

The circuit shown in Figure below is the basic version of this current sensing circuit. As there will be some design decisions for these circuits to make sure that debouncing will not be an issue. Debouncing from the power change of the wall power to the battery is an issue as if the power is shut off for a period, this can shut off the microcontroller which then, the system will shut down and then be turned back on again. This reset is not something that is wanted. In many types of electronics where the battery can be charged or is gotten directly from wall power. Laptops have this type of debouncing to ensure that the power of the laptop is not shut off when going from the power of the wall to the battery power. Some ways to do this are with some memory storage elements such as using inductors and capacitors to store the energy in the system. This sort of circuit was discussed in the switching regulator, as the type of voltage that occurs from the input is seen from the output of the switching regulator. With the smoothing form an inductor would be very useful as the inductor will be charged up and once switched, the diode will complete the circuit and continue the current flow when there is no power for a short period of time. This time for switching is quite small (in the millisecond range) and therefore keeping these inductors and capacitors will keep the circuit flowing and not allow any significant change in current to get through the rest of the circuit. As size is not much of an issue for the Power PCB, the size of the inductor is less of an issue compared to the switching regulator. With this smoothing, and some capacitors in parallel with the out of the circuit, the power will be a much smoother DC and will continue to power the circuit. There will be some difference between the voltage of the wall and the battery but will not be significant enough for the circuit to notice any difference and will not behave differently.

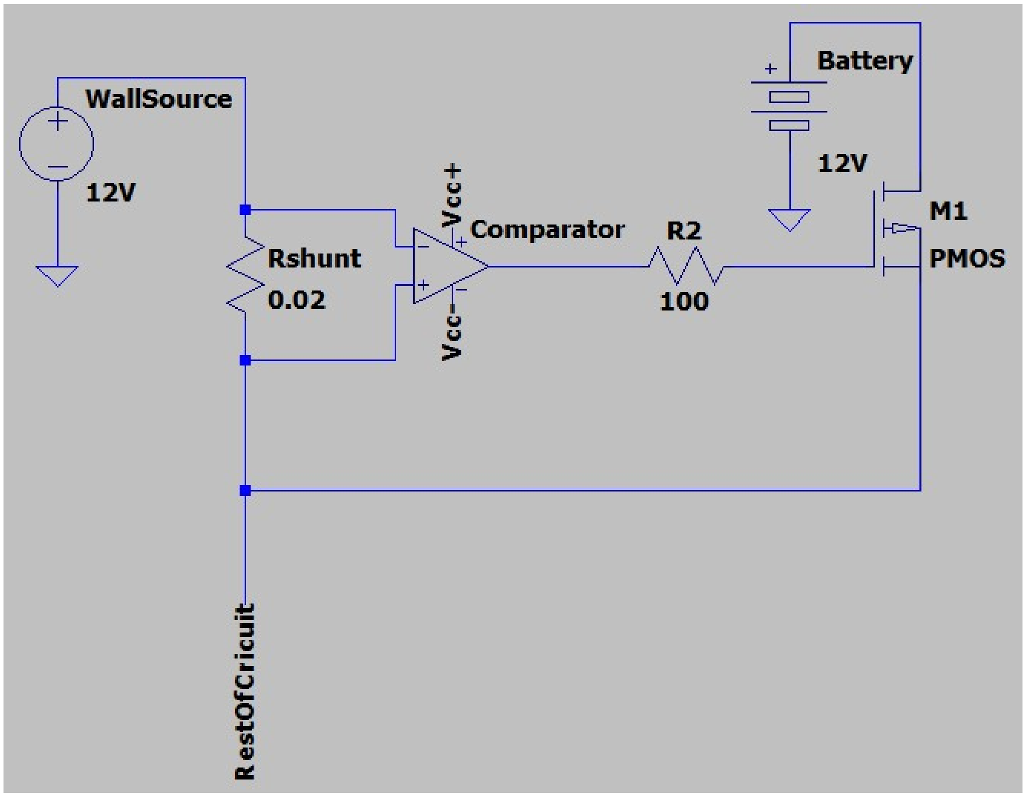


Figure 22: Simple Current Sensing Circuit

There are some issues that need to be addressed however, as the switch from the mains to the battery does not happen instantaneously, this can cause the whole circuit to lose power for a moment of time. There can also be an issue with a bouncing from the power supply. This bouncing can cause some damage to be done to the circuit and therefore needs some protection to make sure that this does not occur, and that if it does have a buffer that will not destroy the components.

### 9.3: Circuit Safety

Electrical safety is something as engineering should be thought of as the ethical and legal implications of designing a product that can cause some danger to its consumers. Safety can also be considered protecting some of the components in case of any dangerous activity occurs (water shorting out lines, open circuits occurring, etc.) so that the critically components are not destroyed.

A common type of safety component is a fuse. This component is put in series with the power source to the rest of the circuit. The fuse acts as a wire that once a certain threshold current is reach will break and therefore open the circuit. It's a cheap and easy to design in the PCB. In this case, anything more than 10 Amps going into the linear regulator can cause damage and therefore will be placed in series with the input of the regulator to protect the rest of the circuit. [31]

As the critical components of this project are the laser diodes, therefore having more protection before the diode is critical. The linear regulator itself creates a barrier to the diodes. As the input resistance for this component is high and therefore will be destroyed first instead of the diode and no current will get to the diode.

In terms of protection for the clients. There will be a case surrounding the circuit and will be inside the box once given to the client. This allows the client to not either poor water on the circuit. As there will be no direct contact with the circuit the client has less of a chance to hurt themselves with the electrify. This case also protects everything from its environment. If the system is outside or say even as pool lighting, the case will protect it from rain and water damage.

Heat, while not much of an issue in terms of fire is something that needs to be considered for the safety of the circuit itself. As if the components can get too hot they will be destroyed [31]. Or if they get hot enough, the characteristics of the components will change and therefore the circuit will not work properly. Heatsinks will be placed on the components to compensate for the heat that is created from the circuit components. These heat sinks are made from aluminum and have a large amount of surface area compared to volume. The higher the surface area the more heat can be dissipated from the component. The case that is housing the components will also have an active source of cooling using fans. These fans will be powered directly from the wall source. At ambient temperature this should be enough cooling to allow the circuit and its components (most importantly the diodes) to continue functioning normally for extended periods of time. Some other components besides the diodes need some passive cooling such as the FETs that will be used as they become quite hot over time even with their small power consumption. Linear regulators also have this issue of becoming quite hot as they are not very power efficient.

An easy to access switch will be placed on the outside of the case to ensure that if the power needs to be turned off quickly it can be (this is also for easy functionality to turn on and off the machine.

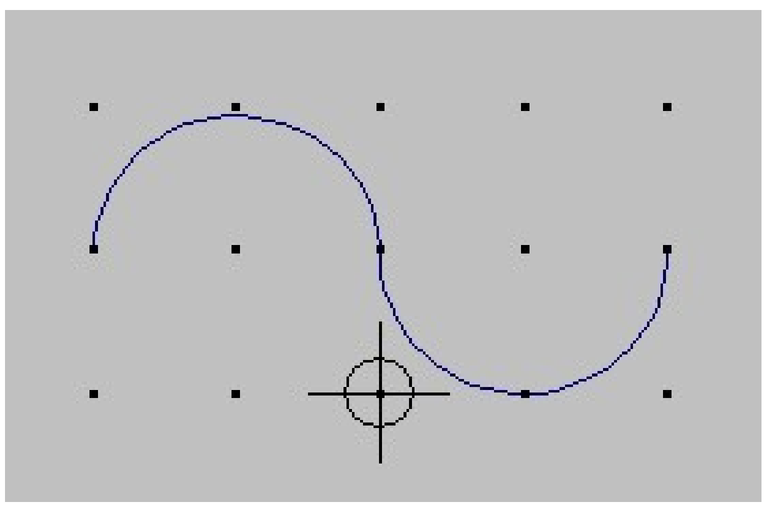


Figure 23: Fuse Symbol

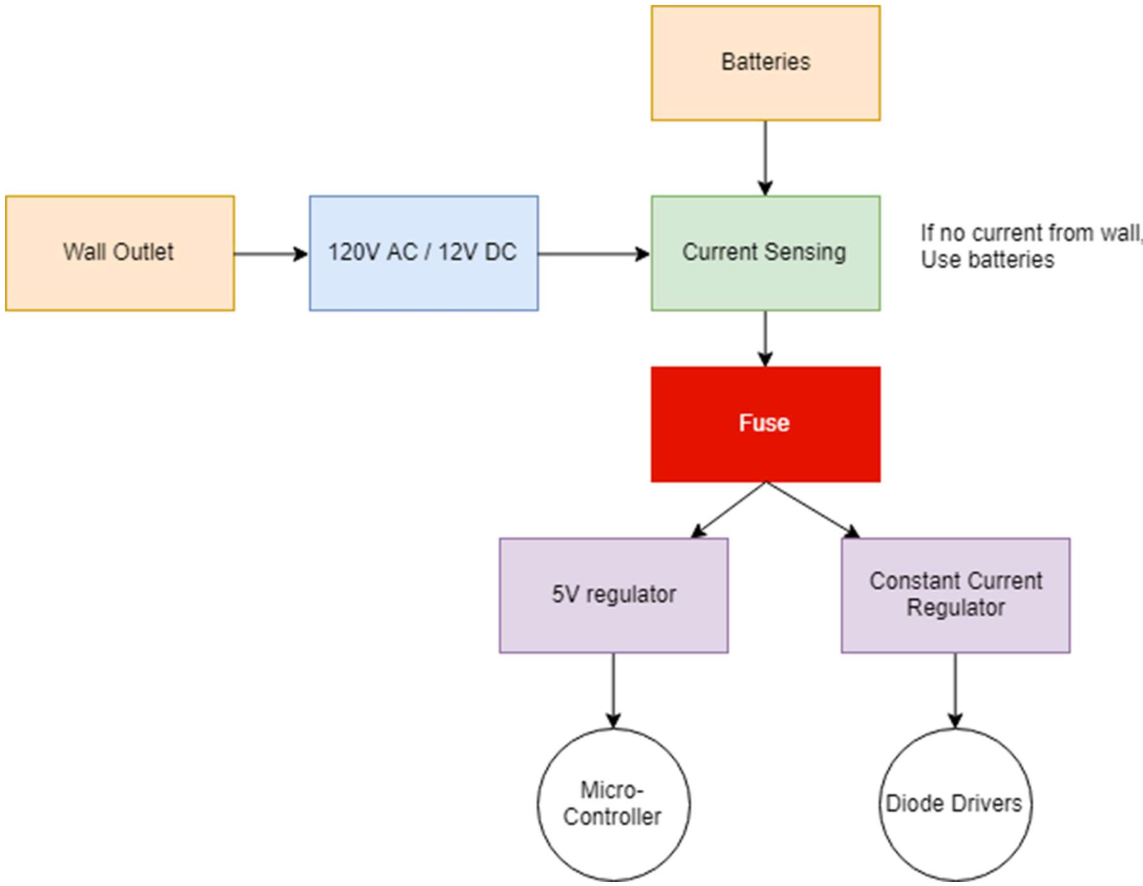


Figure 24: Power Layout

### 9.4: Power Layout

For the power layout, the two inputs are either the wall outlet or the batteries as the power sources as seen from the figure above come from the beige inputs. All power controlling besides the diode drivers will be done on this board. The most important parts of this board are the 5V regulator for the micro-controller and the constant current regulator for the diode drivers. The constant current regulator however will be on the diode driver themselves. For these circuits to work, the regulators need to work to be able to power the diodes and to power the microcontroller so that the control of the circuit can occur.

However, the 120 V / 12 V converter will not be placed on the board as it has their own separate controller along with the batteries of course not being placed on the board. They will be housed in their own section and have connections to the board. The batteries will have a container that connects the batteries in series and then those connections at the ends of the batteries will be soldered to the board or some other wired connection to the board. The converter will have a soldered or some other type of wired connection to the board as well.

Only one fuse should be needed for the whole circuit. Regardless of what power is being used, there needs to be a fuse that connected to the rest of the circuit. Therefore, where the wall or battery power meet is where the fuse will be placed. That way regardless of what power is being use the fuse will work in case the current is too high.

A switch will be placed right before the current sensing that will switch off both battery power and wall power of the circuit. The switch will allow easy access for the lights to be turned off and on physically and not through the microcontroller interface.

The current sensing circuit will also be powered from the wall. This will power the op-amp, and for the switch to occur, the output needs to be nothing and therefore when the power is off from the wall, the power will shut off from the op-amp and therefore will have the MOSFET switch closed and will continue the power from the batteries.

### 9.5: Hardware Layout

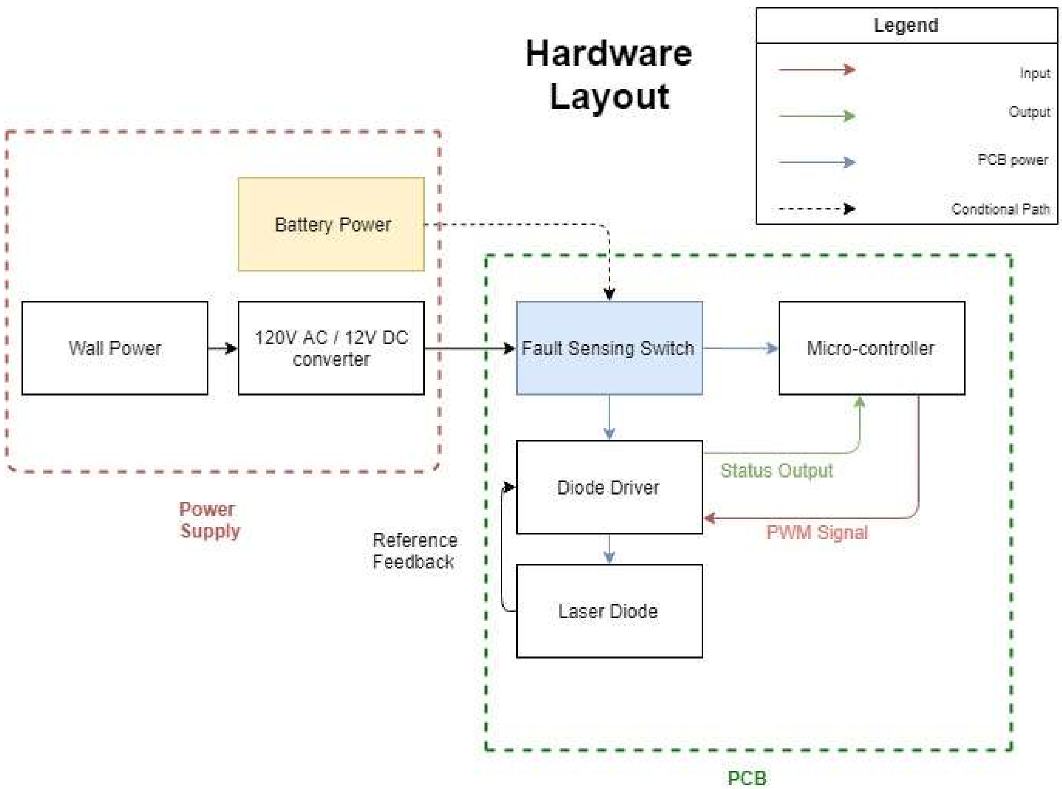



Figure 25: Functional Hardware Layout

The hardware layout took some careful consideration for some factors. Modularity, safety, and ease of set up. The power section is on a different board compared to the diode driving board. Inside a case that will house everything. The case will hold batteries in a section and allow plug in directly to the wall. There is also be a switch to allow the system to turn on and function. This section will be a PCB that feeds in electricity from the 120V AC / 12V DC converter. With this conversion, the fault sensing switch will be constantly reading if there is any current coming from the wall power and if not will switch over to the power. From this there will be connections made to all other sections. One more conversion will occur for the microcontroller as it needs 5V rather than the 12V coming form either source. The 12V will be used to power the laser diode drivers.

As seen in the figure above, the PCB for the diode driver will be on its own for each diode. As there will be a minimum of three diodes to obtain the full range of color there will be at least three connections from the power board to power these diode drivers. These drivers will be connected directly to the laser diode, power, and communication from the microcontroller. There are adapter cables that link power from the power PCB to other sections.

The design choice to have the PCBs for the diode drivers be separate for each diode was for flexibility and modularity of light choices. If one laser breaks or does no work properly or something on the PCB malfunctions. It can be quickly swapped out for another PCB and would not have to replace the whole system. These drivers can handle each different type of light emitting lasers and therefore has some flexibility for the user and to make it easier for the user to swap or fix on their own.

Microcontroller on a separate board is for simplicity/signal interference reasons. To ensure that the PWM signals that control the diodes. There was some discussion as whether to place the microcontroller on the power PCB. While this is something that could be done rather easily, it would be even easier to use a developer board for right now for proof of concepts. If this product were to go into production, the power PCB would be redesigned slightly to hold the microcontroller on it and have signal wire attachments for the PWM sections.

Each of the diodes will have some housing. This housing will hold the diode in a steady place and keep the heat sink on constant connection with the diode. The housing will allow for easy change as well. With the connection of the board power to this circuit to be a clipped in wire, this casing can be exchanged out if the diode breaks instead of having to touch the bare circuit, the user can just unplug from the circuit and exchange the housing with another ready diode.

## 9.6 Circuit Software:

**9.6.1 Eagle CAD:** Eagle CAD is a free to use software for schematic and PCB design. There are many different types of PCB software but most of them however Eagle has quite a large community and lots of information available as it is a software that has been around for quite a while and lots of parts manufactures have libraries that are built into the software or have libraries that you can download that have many different components to choose from. One of the best functions of this software is choosing components directly from the software that fit the needs specified in the search engine. Specifically, the type of component, the size, and the value of the component and Eagle will find in the libraries/online components that fit those specifications. There is a schematic to board builder as well, which will take the nets and components and bring the user to a board view where lots of customization can occur including manual tracing for the wires inside the PCB. Eagles ease of use and large community made it a prime choice for PCB design software.

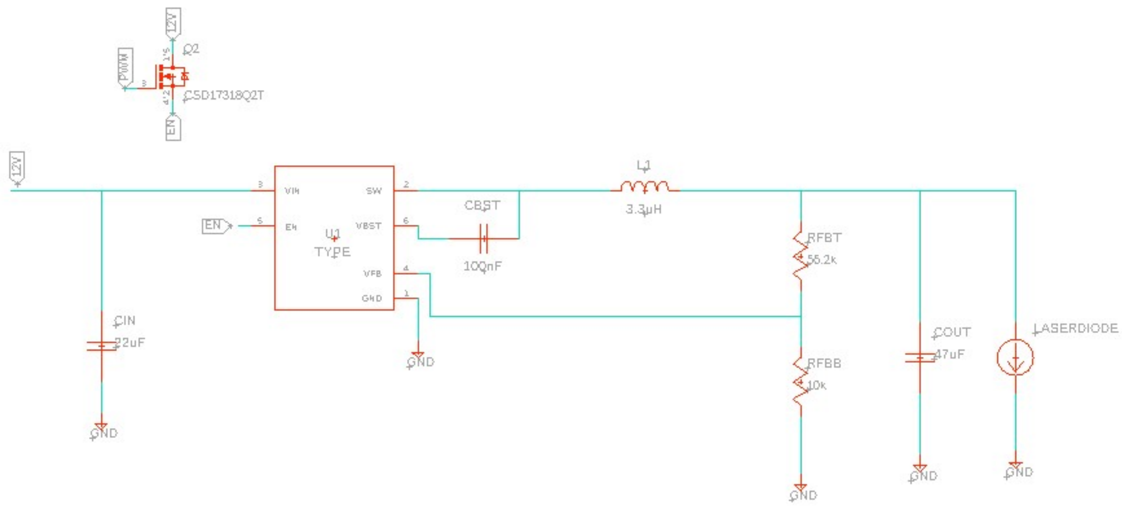



Figure 26: 4 A constant current driver schematic

## 9.7 Diode Driver Design:

The diode driver consists of a buck converter that takes 10-14V DC input with around 1.3A input current. The output of this converter is 5V DC and around 4A of output current that is driven to the laser diode [4d]. With this, there is plenty of energy for the diode to be driven to max or almost max depending on which driver it is. With this, this driver can be used with every type of driver as it does not exceed the maximum amount of power for the device and therefore can be safely used with each diode.

For the input of the circuit, there is 10-14V DC driving this circuit, this is in parallel with a capacitor to smooth the DC signal even further than it has been smoothed from the previous stage of mains voltage to 12VDC. DC voltage commonly have noise in them, and to smooth out the voltage to become more direct, capacitors will be placed in parallel with the source and the load. As learned about capacitors, they do not change voltage immediately and will change the voltage in less time. Therefore, with this concept, the bypass capacitor will take on the voltage noise and smooth out the voltage for the components in parallel as it will not change from the small voltage differences in the noise and will hold the mean value of the input voltage. Some circuits will have 2 or even 3 bypass capacitors to eliminate noise even further [31]. However, there will be no need for this and one bypass capacitor will do the job.

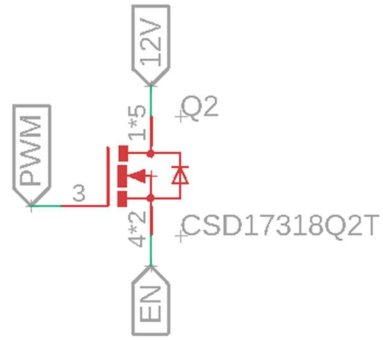



Figure 27: MOSFET with node symbols

For the next portion of the schematic, a MOSFET is used and is connected from the input power rail (shared with the IC used) and the enable pin with the gate voltage being controlled with a PWM pin form the microcontroller. To achieve the level of brightness desired with each diode, a frequency of square waves with the power turned on or off at a high kilohertz frequency with a duty cycle change. When a gate voltage is applied, the voltage from the power rail, goes to the voltage of the enable pin. Something important to note here is that this MOSFET when on is acting like a switch, and the voltage that goes across the drain and source is quite small as the resistance between these two terminals is quite small and therefore is modelled as an electronic switch. This MOSFET has a much higher efficiency compared to a BJT which works as an electronic switch but with a current instead of a voltage. Also, very important to note is that the voltage on the gate applied must be "logic level" [31] and can be seen on the data sheet. The logic level means that a voltage of either 3.3V or 5V must be used to turn on the MOSFET. 3.3V and 5V are common voltages for computing and therefore the FET can be driven from the outputs of the microcontroller.

Luckily for most students in this age, Integrated circuits designed by semiconductor manufactures do a lot of the heavy lifting for circuit design. The IC seen here does most of the conversion. This regulator is a switching regulator, which is why in the output of this circuit an inductor is used. Luckily the inductor size can be quite small in these cases and can fit on a PCB small enough for this design. Because of the switching in the regulator, the output current is in a waveform that does not resemble DC. The inductor does not allow quick changes in current to occur and therefore smooths the current out to a DC current through the inductor which is passed through the rest of the circuit. A connection from the output node and the VBST node needs to be made with a very small bypass capacitor, this connection turns on and off the FET inside of the IC. The same concept with the bypass capacitor used from the input is used with this FET as well. [4d]

Seen on the IC is something called voltage reference. The voltage reference is a connection from the output of the circuit done with a voltage divider. With two resistors a voltage divider can be created. The voltage divider uses the rules of Kirchhoff's Voltage Law (KVL), where the voltage of a closed loop is canceled out due to the laws of conservation of energy. The voltage of the bottom resistors divided by the sum of the resistors in series is the voltage divider. With this, a reference voltage can be sent back to the IC with the resistors being the ratio of the output voltage. These resistors can be chosen by the user to obtain the desired output voltage and therefore obtain the desired output current for the circuit. Values of 10k ohms or higher should be used for these resistors in order to decrease the amount of current needed to tell the IC what the reference voltage is but not a resistor value too large so that a small fluctuation in current would impact the voltage too much that the circuit would not work correctly. With these design decisions in mind, the resistor values can be easily taken for the current/voltage desired.

For the next section is again another bypass capacitor and possibly the most important bypass capacitor. As the current desired for the output here needs to be constant and smoothing the current even further is important to get a more consistent light out of the diode. Only one should be needed for this application, but if further smoothing is needed more bypass capacitors should be placed in parallel to smooth the voltage even further.

### 9.7.1 Microcontroller Power Design:

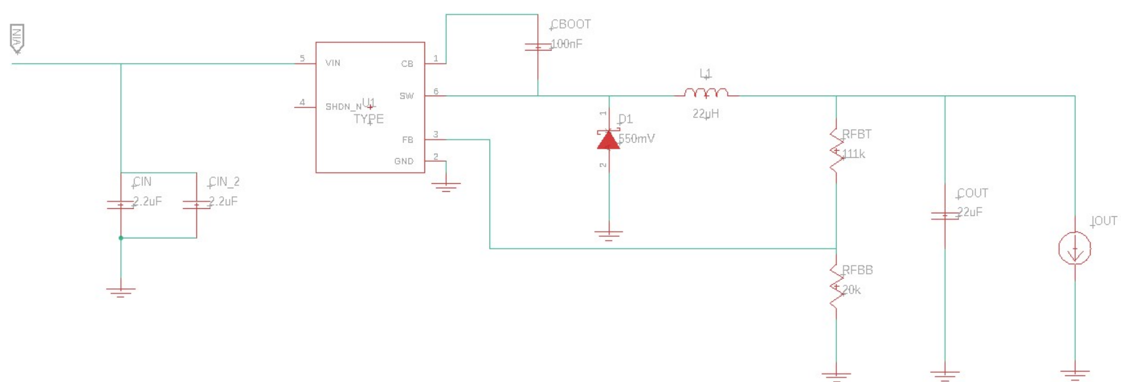



Figure 28: Constant Voltage Driver Schematic

Above is the schematic for powering the microcontroller from the mains voltage. This design is very similar to the diode driver as they both use the same type of regulator a switching regulator. This regulator above is a more traditional switching voltage regulator circuit. First of course are two bypass capacitors in parallel going into the input of the circuit. The same reasoning here is to smooth out the DC voltage coming into the circuit to reduce any noise that can occur. This also produces some shielding to the PCB to make sure that less damage will occur to the parts if any large influx of noise were to occur. [3d]

The difference in design for the Diode driver and this circuit is that this needs a constant voltage rather than a constant current. The diodes are the most consistent with a constant current as the voltage is driven by their current. For the microcontroller, a constant current can cause lots of damage to the board or produce lots of unnecessary heat. This heat as well can cause lots of damage to the board and should be avoided at all possible. But the constant voltage is needed for the circuit to turn on and then requires a small current compared to the other driver and therefore needed a different circuit to power the material.

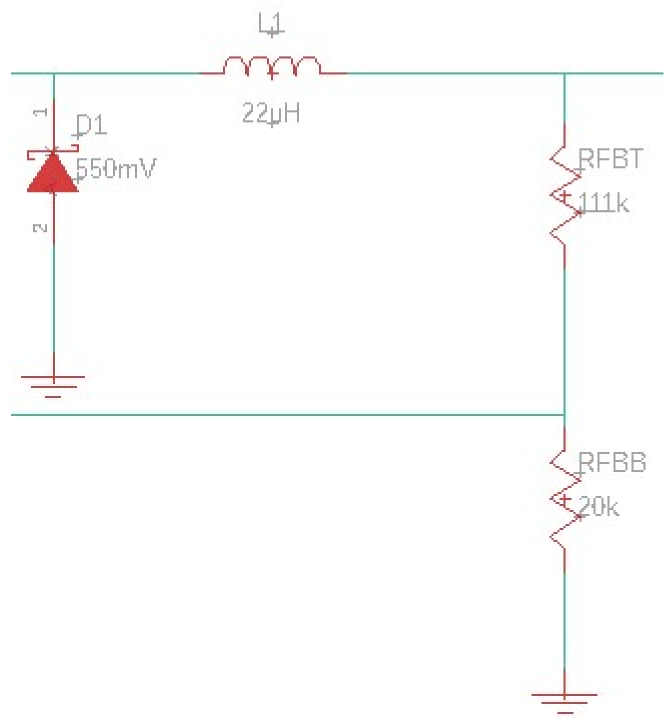



Figure 29: Switching Voltage Loop

The loop above is how the circuit differs here compared to the other section. The switching regulator does just as its name implies, switched on and off the voltage coming from the output of the circuit. After the initial cycle occurred from the loop, the inductor does not want to have the current change immediately and therefore trickles the current through the loop. The diode is a crucial component for this loop. If the diode is not there, the left over current from the inductor would trickle straight to ground and not provide any current going through the resistors. For this to be DC there needs to be current always going through the circuit. The diode allows this loop to occur throughout the circuit. With the position of the diode, it will not go directly to ground but will allow the current to complete its cycle and power those resistors. [31][4d]

The voltage divider there is to give a reference voltage in the circuit just like the other circuit but instead of giving a reference voltage that will give a constant current this reference voltage will give a constant output voltage. Again, these resistor values are somewhere in the middle to not take too much current to away from the load but also not too large to cause huge voltage differences to occur with small current changes.

Another bypass capacitor is placed on the output for the shielding reasons and to smooth that voltage even father. The value of this capacitor should be small (somewhere in the µF) as a larger capacitor will take longer to charge and cause issues with the circuit, a small value will be enough for what is needed, and if more is needed just add more capacitors in parallel with similar values.

### 9.8 PCB/Schematic Design Process:

How the schematic is laid out can make it easier or harder for the consumer to understand what the circuit is doing. Typically, larger circuits are separated by networks which serve specific functions. This separation in design while labelling your nodes allows for easier reading and even easier for the designer to understand and make changes later in the project. PCB's also have this design and the separation of components can lead to easier debugging or replacing of parts. Both practices are done with the EAGLE CAD software.

### 9.8.1 Schematic Design:

The first portion of designing the board is laying out the circuit in a schematic. This is typically to see the circuit at a lower level where specific parts are chosen, and values are chosen. At this lower level, this is where typical analysis is done and where the design process starts, this is usually done after the higher-level block diagrams take places understanding what network needs to accomplish and what the design in mind does.

For larger schematics, each network will have its own sections. Typically, a section with the power rail (in boards that have many different levels of voltages). A microcontroller/communication section. Signal filtering, Amplifying, and many other types of networks that can be used in the process.

An example of the design process can be seen with the buck converter schematic. This schematic is separated even from the other portions of the circuit where voltage changes are occurring (mains voltage to 12V DC, step down to microcontroller voltage powering, etc..). Even though the goal is the same as these other circuits, the values of voltage are different and therefore the way that they are achieved are different and are separated in the schematic to not confuse others in the analysis. Grouping these products on the same page can occur but clear space needs to be shown and no physical connections with wires on the schematic should be shown either (only connections with network tags should be shown to decrease any visual clutter).

Some other considerations should be the natural ways that humans read. With information being sent in data schematics, the information at the beginning should be at the left side of the schematic to where it ends at the right side of the schematic. Such as if a filtering system was placed in the schematic that has many layers and finishing it goes through a ADC. The ADC should not be on the left side of the schematic as it is the final form of the information that is being processed. This would be unintuitive and maybe make the reader think that the ADC is the first stage which then goes through filtering (Which makes no sense what so ever). Therefore, signals should always flow from left to right in a schematic for clearer reading. The same should be done for any processing for example with the 4A constant current source. The input voltage comes from the left side of the schematic and then is processed from left to right. Whereas, the output is at the right side of the schematic and is clear what the stages are for the process as the schematic flows from left to right.

In the design, there should be clear labels for the nets and not names that would confuse the reader. Such as the input voltage net should be named something such as Vin, Input Voltage, VIN, 12V, etc. This should not be named something such as just V, or Voltage. The more descriptive the names the easier it is to understand what each connection does. In larger circuits, there are many nodes in which name collisions can occur if similar names are chosen and therefore some connections that are not meant to be made are created.

Cluttered connections should not occur as well, do not have a schematic that has everything so close together that it is hard to read the information or see where all the connections go. Also, having lines that do not cross over other wires multiple times is good design to be not be confusing and should only be crossed if necessary. The solution to the cluttered issue can be seen in the 4A constant current schematic. The MOSFET schematic symbol was quite large and needed to be placed in between pins that have too small of a connection for the information to be seen. Therefore, this component was pulled away from that portion of the circuit and the nodes of the connections were then labeled to that component to see clearly where this component is connected. This took out any clutter that would be in that area and is easy to see where those connections go.

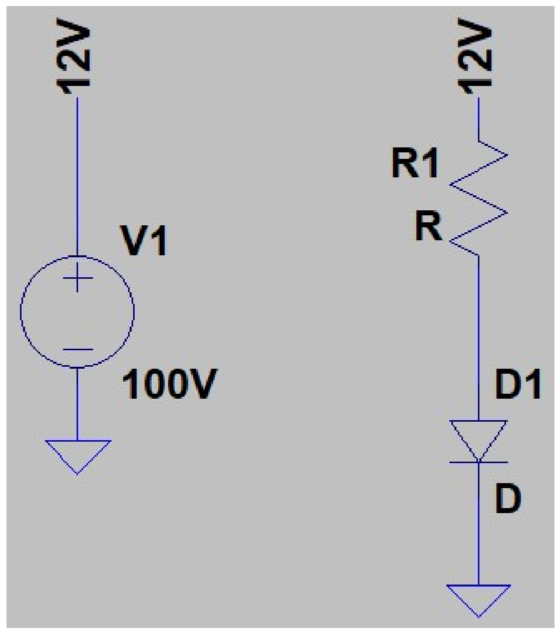


Figure 30: Poor labeling in schematic

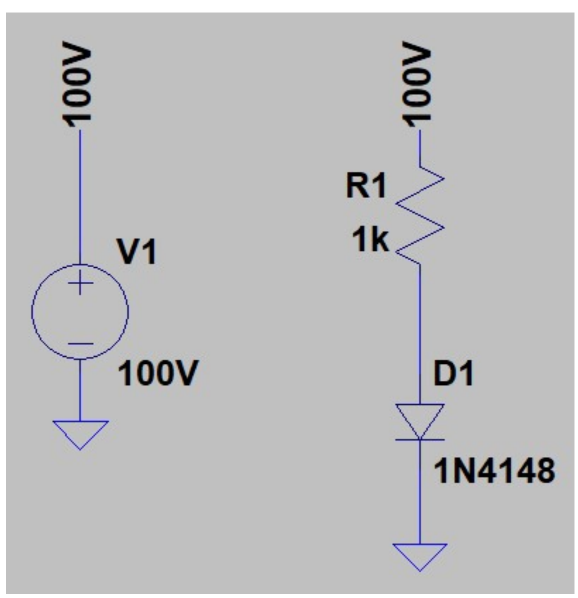


Figure 31: Clearly labelled schematic

### 9.8.2: PCB (Printed Circuit Board)

Printed Circuit Boards are common place in the electronics world today. From all consumer electronics to more industrial circuits PCBs are a more compact and clean way to make circuits. These circuits work the same as normal circuit, metal connections between components that power the device, send signals, etc. These boards however have multiple layers and can be much smaller compared to other circuits. With multiple layers, power lines and connections can be made between the components and in-between these plans have protection to make sure that nothing inside the board shorts out.

### 9.8.3: Components of PCB

There are 4 main layers to a PCB. Silkscreen, Solder mask, Copper, then Substrate. For very basic boards, 5-6 layers will be used in the order of, Silkscreen, Solder mask, Copper, Substrate, and Copper. With the bottom level copper being the ground plane of the circuit. [33]

**Silkscreen:** This layer is the top layer of the PCB and is what is seen by everyone. This layer has the color of the board and the information that is printed onto it. This layer has the written information that is sent in such as labeling what the resistor on the board is, what the IC is, power supply, and other areas. Other designs can be printed on these sections such as the university that created the board, names of the designers, other information such as what power rail is what and whatever other information is desired.

**Solder mask:** Another layer that is seen, this layer is typically on copper traces that are close to the top side of the board. It protects the traces having any interference from the outside sections of the board. This section is also used for the components to be soldered onto the board. The solder is connected directly to the copper traces inside the PCB, this allows the connections to occur between the different components.

**Copper:** The copper layer is the most important layer of the circuit. If there are any mistakes that occur in this section of the board could ruin some or all the functionality of the board. This is where all the connections from the solder layer of the board connect to other sections of the board. This is the “wire” of the circuit. Typically, a sheet of copper is used and then is etched with the copper design in terms of traces. These traces are the wires and conduct the current to each section, whenever there is a wire or node in the schematic, it is made with the traces in the board. In older PCBs these were made with copper wire and were hand drawn, now there are many ways for these traces to be created but are usually created with laser etchings.

**Substrate:** The separation of the copper layers is done with the substrate. If the copper layers were to be touching, shorting would occur, and nothing would work. Therefore, a nonconductive, high heat tolerant material is used as the separation barrier between different layers of the copper. This layer is not needed on the top of the PCB as the silkscreen/solder mask achieves this already and does not need to be in-between the solder marks and the copper as those connections need to be made.

### 9.8.4: Design of PCB

There are rules for PCB design that need to be done before the file is sent to a manufacture, and from manufacture to manufacture these rules can be changed slightly, choose the manufacture that can fit your needs and design around those rules. There are some rules that need to be followed regardless to ensure that the PCB design makes sense and works to the best it can.

**Rule 1, No 90-degree angles for traces:** This can be a rookie mistake to a lot of newcomers for in PCB design. While the right-angle traces might look clean, they can impact performance dramatically along with making tracing confusing. Most software will not even allow the user to make this angle in the traces as 45-degree angles should be used instead. If there must be a 90-degree angle, move the components to make sure that this does not occur in the circuit.

**Rule 2, Group related components:** Just as is done in the schematic, grouping related components is necessary for debugging and for the next rule. Grouping allows for easier debugging in finding parts that are not working in the current network. If a component is far off in the board it can affect performance of the board and make it confuse to others looking at the board.

**Rule 3: Use Short Traces:** The shorter the traces, the less energy that is lost in the circuit. While wires in a design setting have zero resistance this is not the case. With longer traces power can be lost and for data connections long traces can decrease the quality of the signal which can be crucial for some designs that use analog to digital converters. This practice also works well with the previous rule in that grouping the common components together will often lead to shorter traces in the PCB and therefore improve the quality of the board. This means that when separating networks and grouping them together, there should not be a large distance between the networks, they can be organized and not impacted length of the traces.

**Rule 4, Use Correct Trace Width:** The width of the traces is directly related to the amount of current that can pass through the traces. For any large current applications, the traces need to be much wider than typical applications.

**Rule 5 Use Heatsinks:** If your component gets hot after lots of use, make sure to use heat sinks on your devices. Not only could this hurt the component that gets hot, but it could even melt the board around it or damage the components surrounding the board. Proper heatsinks can increase the lifetime of the product. How to know if a component needs a heatsink is to check the data sheet for the temperatures of the device compared to what the voltages of the device will run at.

**Rule 6 Do Not Overlap Traces:** Overlapping traces can cause some serious issues. As stated, there is a copper level, then a substrate, then another copper level. If the traces overlap on the same level, they will make a connection to other components where connections are not meant to be made. Try and have a layout where the traces do not need to go to another layer, but if an overlap needs to be made, make sure that the trace goes under to another level and does not impact the circuit. However, Designing the PCB so there is no overlap is easier on a smaller PCB but where there are lots networks go to another level. [22]

**Component 1, Surface Mounted Device:** Surface Mounted Devices are exactly what the name is, these are components that are soldered on the top portion of the board (where the solder mask layer is). These components can be quite difficult to mount if the pins are smaller as the soldering happens directly on the board. These are quite common for resistors and capacitors and other such devices that need a heat sink pad on the bottom of the device. [32]

**Component 2, Through Hole Device:** The through hole is a much simpler device to solder through. On the PCB, the portion in which you solder it to the board goes directly through the board. The component then can be soldered on the bottom of the board as the component has pins that go through the board.

### 9.8.5: Sending PCB to be manufactured / Soldering

After the PCB has been designed in the software, lots of files need to be checked if they are correct and are ready to be created by the manufacture. These files that are sent are called Gerber files. This file contains the layout of the PCB with all the information (dimensions of the PCB, length of the traces, where the traces go, etc.). This format is universal and is used by all PCB manufactures.

EAGLE itself will have an error checker for both schematic and the Gerber file. If there are any missed connections on the schematic this can transfer over when moving to the board view of the circuit. But this will not catch everything and should be double checked when sending it in. The manufacture should have some sort of filtering to make sure that the information is correct such as traces not making their complete trace (something that can be easily overlooked as the screen for traces can be visually busy), if the widths are something that can be achieved or even if traces are too close. Lots of variables that can decrease the quality of the circuit that need to be checked before manufacturing.

```
Order list for C:/Users/Ian/Desktop/DiodeDriver.sch
Exported from EAGLE with DesignLink

Quantity        Value   Package Order code      Manufacturer    Manuf. Code     Availability    Price (from)    Description
1       100nF   0603    06R4873         MC0402X104M100CT        11703   0.016   MULTICOMP - MC0402X104M100CT - CERAMIC CAPACITOR, 0.1UF, 10V, X5R, 20%, 0402
1       22uF    0805    32K4516 KEMET   C0402C224K9PACTU        10000   0.091   KEMET - C0402C224K9PACTU - CERAMIC CAPACITOR 0.22UF 6.3V, X5R, 10%, 0402, FULL REEL
1       47uF    1206    61M2238         JMK212BJ476MG-T 45000   0.12    TAIYO YUDEN - JMK212BJ476MG-T - CERAMIC CAPACITOR, 47UF, 6.3V, X5R, 20%, 0805, FULL REEL
1       3.3uH   XAL6030 57AC7727                1255AY-3R3N=P3  1500    0.179   MURATA - 1255AY-3R3N=P3 - INDUCTOR, 3.3UH, 4.4A, 30%, WIREWOUND
1       WB_CURRENT_LOAD WB_CURRENT_LOAD unknown
1       CSD17318Q2T     TRANS_CSD17318Q2T       33AC4974                CSD17318Q2T     59      0.282   TEXAS INSTRUMENTS - CSD17318Q2T - MOSFET, N-CH, 30V, 25A, WSON-6
1       10k     0201    68R0221         RC0603JR-1310KL 20844   0.0040  YAGEO - RC0603JR-1310KL - RES, THICK FILM, 10K, 5%, 0.1W, 0603
1       56.2k   0201    07J4290 VISHAY/DALE     CRCW060356K2FKTA        0       0.016   VISHAY - CRCW060356K2FKTA - RES, THICK FILM, 56K2, 1%, 0.1W, 0603, REEL
1       TPS564201DDCR   DDC0006A_N      unknown
```

Figure 32: BOM (Bill of Materials)

Once the PCB is made, the components need to be ordered as well and is usually given in a file called BOM (Bill of Materials). This will have a list of each component and which manufacture has these components. On this, the size of each component, the type of component, and the values of the component should be checked to ensure that all the parts are correct and can be used with the board. EAGLE can do this for the user in a section called design link. This is where you can pick the parts and if connected to the internet can see the datasheet of these components, costs of these components, and more. With this file, it can be saved, and all the components can be ordered online or from other services that will order all the components for you.

After the Gerber file is sent and the instructions are received, the PCB will be created but what is sent to the consumer is just the traces and the silkscreen. It does not have the components on the circuit ready to go, this needs to be done by the user. This process is called soldering and there are many methods to making this process easy. [22]

Soldering is the process of taking a very hot iron and pressing it against solder to make physical metal connections between components. This material is conductive and allows electricity to flow through this material. There are different types of solder and some precautions should be taken for one’s health as breathing in the smoke that occurs from soldering is dangerous especially for and solder that has led in it.

Before any soldering occurs, the soldering tin needs to be tinned. Tinning is the process of placing solder on the iron while it is hot, this creates a better connection with the solder in future soldering. This should be done every time the iron goes cold again. Doing this will make the process much easier for heating up the solder everywhere else.

Reflow is a common process for components that are surface mounted. Reflow is the process of placing solder on a pad already, then while the pad is already hot, place the component on the pad and let the solder cool to have the connection in place. This is common for replacement of components as well, as the solder does not need to be replaced but only the component and therefore can re-use the solder that is already there.

The other type of soldering is placing new solder on the board or on the wire. This is done by placing the hot iron on the wire or the connection with one hand, and then placing the solder in the other hand. With the solder hand, move the solder tip towards the pin and location that is going to be soldered and continue to press the solder and the solder will fill up the location, take away the iron and the solder and the connection should cool very quickly.

### 9.8.6: Voltage Driver PCB designs

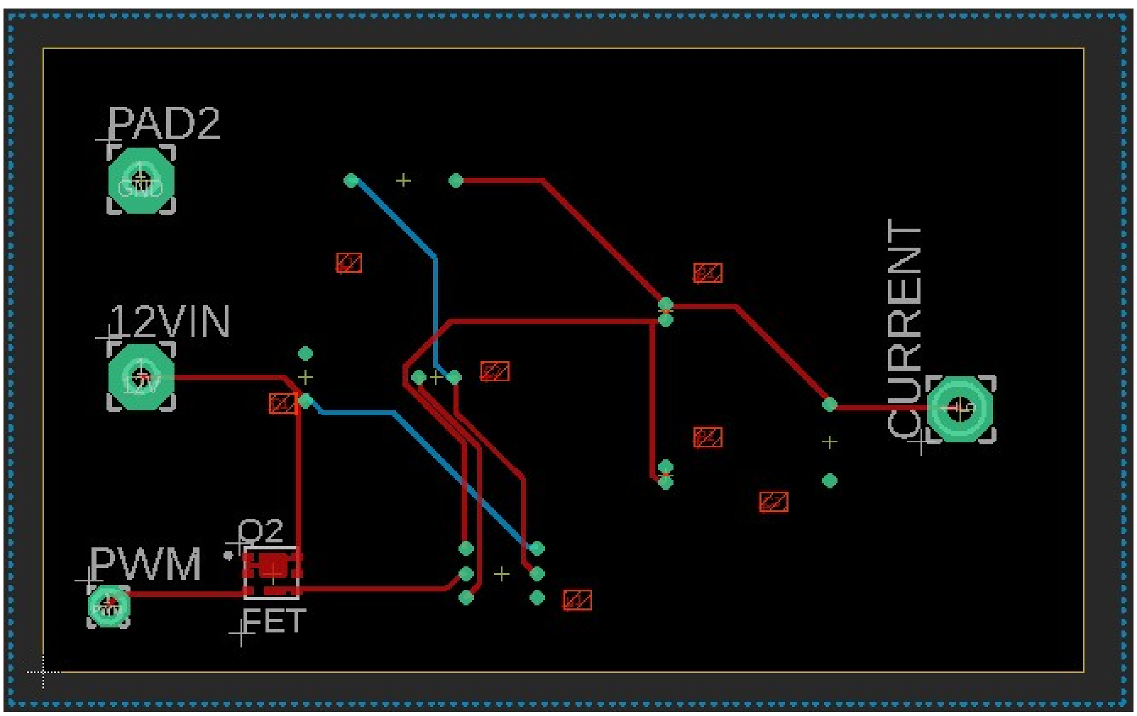



Figure 33: 4A current driver initial PCB design

Above is the first iteration of the PCB for the 4A constant current driver for all the laser diodes. As stated in the section about testing. The issue with testing this component is that the component is so small that it is very difficult to test from a bread board. There are some design flaws that will be changed to ensure a cleaner looking board and easier to read board.

The components go left to right based on what it is in the schematic. With input signals and power rails coming in the left side and output power on the right side of the component. The signal and power sections are all solderable wire parts, this will be changed with a much easier to connect section later in the design. But for testing and initial prototyping these wires will connect directly to those open spots for easy testing and interchangeability of different types of power sources, and easy to test nodes for probing.

As seen in the bottom middle portion of the PCB is the main switching regulator. This footprint has six closes together pins which is fine. However, the pins laid out could have been arranged in a better spot. The blue trace as seen above is a trace that goes to the ground portion of the board. This is because there cannot be any overlapping traces and therefore needs to find either a longer route or needs to go to a different layer of the board. While this is okay for the prototype and will work. This is bad practice as more time rearranging the board is worth it for unnecessary underside path traces.

While there are labels on the board. These labels are not silkscreened in and therefore will be difficult to see as they will be etched in instead. This is another easy fix that if more time was taken into creating the board any electrical engineer can clearly see what component goes where rather than having to look at the schematic and making educated guesses based on the pad size of the components.

The ground pin as seen with the PAD2 silkscreen could also be placed in a better spot and does not need to be as large as seen here. A simple, smaller connection is adequate for this section.

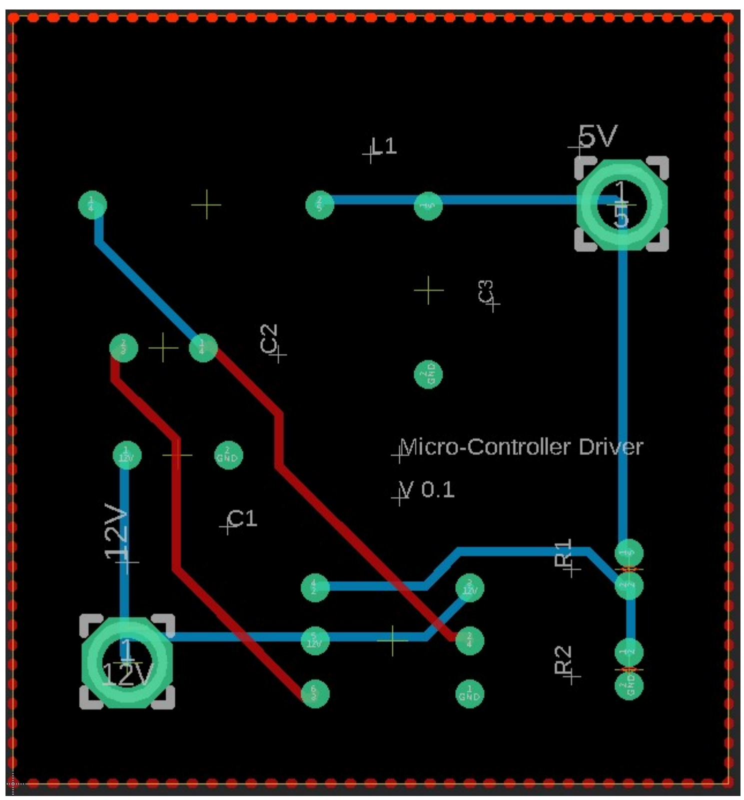


Figure 34: 5V Micro-controller driver

This is the first iteration PCB design for the Micro-controller driver. After learning from the mistakes of the first iteration 4A constant current driver the footprint of the driver is significantly smaller, the traces are the correct size compared to the current going through the traces. The power lines are more consistent to their traces. The components are all labelled on the proper level with the silk screen.

A small difference with the ground plane however, the choice was to use the top layer of copper rather than the bottom layer of copper. This does not really change much for the board and can be done either way.

This PCB uses a different switching regulator but has the same footprint and the same principals. The difference being the diode in this circuit.

| Description | Manufacture | Part Number | Quantity | Unit Cost | Total Cost |
|---|---|---|---|---|---|
| MOSFET | Texas Instruments | CSD17318Q2T | 4 | $0.47 | +$1.88 |
| 0.1uF Ceramic Capacitor | Murata Electronics | GRM033R6YA104KE14E | 10 | $0.061 | +$2.49 |
| 22uF Ceramic Capacitor | Murata Electronics | GRM21BD70J226ME44L | 2 | $0.510 | +$3.51 |
| 47uF Ceramic Capacitor | Taiyo Yuden | JMK316AC6476ML-T | 2 | $0.490 | +$4.49 |
| 3.3uH Inductor | Murata Electronics | 1255AY-3R3N=P3 | 2 | $0.480 | +$5.45 |
| 10kΩ Resistor | Yageo | RT0201FRE0710KL | 2 | $0.520 | +$6.49 |
| Step Down Switching DC-DC converter | Texas Instruments | TPS564201 | 2 | Sample | +$6.49 |
| 56.2kΩ Resistor | Vishay | CRCW020156K2FKED | 2 | $0.26 | +$7.01 |

Table 6: BOM for 4A diode driver (Incorrect sizing for components)

## 9.9 Testing Electronics

The testing process for the electronics was something quite simple but took quite a bit of time as there were some limitations and some issues that came up that needed special processes in order to test the components completely. As these circuits are mostly voltage regulators the same process would occur for them.

| | |
|---|---|
| Input Voltage | How would the variance in input voltage effect the output voltage of the circuit (or in some cases the output current of the circuit)? |
| Voltage Divider Resistance Tests | Choosing a voltage reference for a circuit is critical to getting the correct output voltage for a circuit. The datasheet |

| | |
|---|---|
| | provides different values of resistances that provide different output voltages. Testing if these values work. |
| Testing with Different Diodes | How does each individual laser diode react to the circuit? Each diode has a different diode characteristic and therefore has a different current depending on the forward voltage of the diode. Will the circuit work properly for each diode? Or does each diode need a different voltage divider combo for the same output wattage. |

Table 7: Diode Driver Testing Goals

A small goal was to create a circuit that would be simple for each diode that can be used interchangeably to reduce the amount of designs and therefore confusions when building the product itself. Having the same design but with different resistances for the voltage divider could increase some confusion and some precautions should be taken to ensure that the correct circuits go to the correct diodes. This could be solved by labelling the PCB with which driver goes to which laser diode. However, having every circuit will make it easier for any problem solving if there are any issues that occur with the circuit.

The testing process for the diode driver had some problem solving involved to test out the components. The driver is very tiny in size and cannot fit on a perfboard (This is an SMD component and cannot fit on a bread board either). Soldering a wire to each individual pin would be difficult as well. One of the solutions was to build a prototype PCB and test if the design works from this. Another solution was to buy an SMD to breadboard component PCB to test the component on a breadboard.


Figure 35: SMD Switching Regulator Tester

The decision was made to use the SMD to breadboard as this would be the simplest to test with differing resistors as stated by the testing plan. The part is soldered onto the board and the components in the lab can be connected and used for this circuit. The PCB was tried first but some incorrect trace widths and component size purchases were made and therefore could not be used to test the component as the PCB would falter under these conditions. Also, with the familiarity of testing components on a breadboard would make this testing environment ideal. Some precautions are used here as well, A power resistor is used as the load along with a laser diode to ensure that the diode will not be damaged with the amount of power going through these as the laser diodes are quite expensive in comparison to power resistors. Also, using the breadboard would require less soldering to be done and will save time in the long run if any wiring were to go wrong on a PCB design and will save more money.

The ranges of the input voltage will be based on what the ranges of the batteries will produce. From their max charge to their lowest charge for the input voltage. The battery configuration will be battery packs in series that go to a 12V voltage in parallel with lots of these battery packs. This will maintain the voltage for longer and allow more current to be produced in the circuit. Therefore, a voltage range of 14V to 10V will be tested to see if the configuration will work if the batteries have a little bit of overcharge (or extra batteries are placed in series) and to see how long the light will last with this battery configuration alone.

As stated before, the output voltage is based on the voltage divider created by resistor 1 and resistor 2.

$$V_{OUT} = 0.760 * (1 + \frac{R1}{R2})$$

Output voltage for 4A constant current driver [4d]

For a current needed in the diode, an output voltage of around 4.5V-5.5V is needed depending on the diode. Therefore, if a constant resistance for R2 is used, R1 can change to for testing. A resistance of 10kΩ is used for R2 as a base, this value is chosen to create the voltage at a stable level, not much current is needed for the voltage divider, but not large enough that a small change in current would cause a huge jump in voltage and make the circuit inconsistent. The values that will be tested based on this circuit are 49kΩ - 63kΩ. This should produce a voltage from 4.48V to 5.548V on the output. Based on the data sheet, these values are good enough to ensure that the output voltage is not in any territory where the voltage will destroy the laser diode due to overheating from the amount of power going into the laser diode.

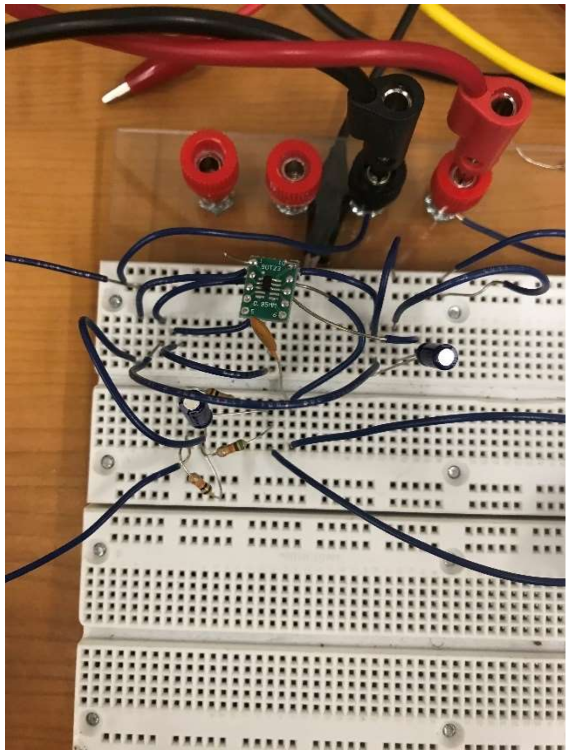


Figure 36: Bread testing circuit

Testing the circuit, wires were soldered to the pins so that connections to the breadboard could be made. With this, different loads were testing, different voltage dividers, and different voltages. All measurements were done over the load, as with the testing environment, there could be no lasers where we were testing this circuit and therefore could not test that load, but a power resistor was used to test if it could reach the higher current needed and that did but was only done for one test.

The first test was with different input voltages in the range from 10V-14V.

| Vin | Vout |
|---|---|
| 10 | 5.0023V |
| 11 | 5.0023V |
| 12 | 5.0045V |
| 13 | 5.0056V |
| 14 | 5.0071V |

Table 8: Input voltage versus output voltage

As seen above, the range of voltages in which the regulator will be operational provide the correct voltage done with the voltage divider seen in the schematic for this circuit. Regardless of our range, the circuit will output the proper voltage and current.

| R2 | Vout |
|---|---|
| 49000 | 4.501V |
| 51000 | 4.61V |
| 53000 | 4.8V |
| 55000 | 4.96V |
| 57000 | 5.003V |
| 59000 | 5.15V |
| 61000 | 5.401V |
| 63000 | 5.5V |

Table 9: Voltage Divider changes and output

The range of these values were taken from the datasheet as seen from the equation above. The output was rather close to the voltages stated from the datasheet. With the voltage divider providing a reference voltage back into the switching regulator a different output current is produced. And therefore, a resistance of 56.3k is chosen to give 5V for the circuit. But with this reference if a smaller voltage is needed to balance out the brightness of each laser diode, these resistance values can be used, or the equation can be used to produce the correct voltage as it works.

| RL | Vout |
|---|---|
| 10k | 5.04V |
| 30k | 5.01V |
| 50k | 5.002V |
| 75k | 5.03V |

Table 10: Load resistance and voltage output

Regardless of the resistive load for the circuit, the output voltage is rather close and the range of values between them is insignificant to cause any issues when the laser diode is used.

## 9.10 Electrical Standards

Standards to electronics are plentiful. However, many of the standards done by IEEE or ANSI can cost anywhere from $40.00 to hundreds of dollars. Many of these standards range from electronic communications to smart power grid design. For this project in terms of the powering of these components, not many standards are available or are applicable for low power/small voltage circuits.

The standards for supplying power to low voltage circuit come from UL 1310. UL is a standards company that make standards for electronics and other sections of engineering that are specific for the safety of design. UL 1310 is the standard for Class 2 Power units. Class 2 power units are designed as low voltage output design with some specifications that allow safety such as transformer isolation. The voltage cannot exceed 60V output DC or 42.4 Vpp for AC. As the maximum output for these circuits is 12V, the standards here. The Class 2 values were created from the NFPA 70 code, which is the national electric code. NFPA is the National Fire Protection Agency, as these electronics can be used in outdoor sections and if any sparks caused from shorting or other means can cause fires and therefore, this code was created to follow certain standards to ensure that less fires were created from electronics devices. This code has lots of electronic standards that ensure safety in devices. [34]

The types of converters are switching converters and are also called switch mode power supplies. These types of power supplies are under these standards. As the frequency that occurs in these switching regulators is high and provides isolation from the rest of the circuit for safety reasons and to ensure that the load of the circuit does not become damage or too high of a voltage (in the limit). As this application could be used in both indoors and outdoors, this standard works under those guidelines as well. This standard is common for toys, phone chargers, and anything else that is low in power.

There are some standards for the size of the SMD components. The company that created these standards is EIA. The sizes of these components are done in what are called package sizes and are the same for both resistors and capacitors. Companies can create their own standards for the SMD components but most of the companies use these package sizes as they are the most common and recognizable for most PCB designs. Some integrated circuits have different ways that they are mounted on a board. For integrated circuits that have many different connections a standard of a "Ball Grid Array" also known as solder balls are used and to be placed under the IC as to reduce the footprint and an issues with the connections being too close for the footpads of any other type of IC. [32]

IPC-J-STD-001 is a standard for soldering components onto a PCB board. These standards are typical for clients who want to work in manufacturing where soldering will be occurring quite a lot. Some of these standards are known to the public but to have the standard a course needs to be taken in order to obtain a certification under these standards. Some of the course points are, soldering SMD components, soldering through hole components, precautions in electrostatic discharge and much more. [24]

## 10.0: Laser Diodes and Fiber Coupling:

There is a set of laser diodes, each powered by a separate laser diode driver, since each laser diode will have unique current requirements. Even when there are multiple laser diodes of the same make and model, variations down to the quantum level up to the thermal level result in different requirements for power. To ensure each diode emits the desired amount of laser light, a reasonable level of thermal control is required. The base-level plan for cooling is to embed each laser diode in its own copper holder, that is then installed in an aluminum heatsink with computer fans blowing over the heatsink. Thermal compound was placed between the copper module and the aluminum heatsink. Initially, the computer fans will be driven at a constant speed with a balance of minimizing noise and power consumption and maximizing airflow over the heatsinks. A goal of maintaining airflow without the need of variable fan speed is to keep the entire system close to ambient room temperature. Since the idea of MADLIS is to keep the source unit in a location that is easier to control the environment, a goal of keeping the system at the ambient temperature of the room is a reasonable goal in most system applications.

Each diode is installed in an enclosure to both protect the diode from debris and to ensure the diode is physically stable enough to direct the output through the optics without significant variation. One method of both aligning and enclosing the laser diode/fiber coupling optics/fiber end is to use a short length of pipe. The laser diode shines into one end of the pipe, ensuring at the end of the alignment the area surrounding the diode is sealed so no dust gets into the pipe and no stray beams create a hazard for the user/technician. Next, a collimating lens system is mounted to the end of the laser diode in the pipe, and a positive lens is mounted near the center of the pipe using epoxy to ensure it does not move. Once the positive lens mounting epoxy cures, an end piece is mounted to the other end of the pipe that has a small hole drilled in very near the exact center of the piece. The end of the fiber to be coupled into is slipped through the hole and carefully positioned so that the focused laser beam hits the center of the core of the fiber. Epoxy is applied between the fiber and the hole, and as the epoxy cures the fiber is adjusted to ensure maximum power is entering the fiber. Quick-curing or UV epoxy can be utilized to hold the fiber in place while the primary epoxy cures. Although it seems efficient to have each diode coupled to an individual fiber, through laboratory experimentation, another method has been determined.

### 10.1: Single Tube Source Module:

By utilizing a single tube for the source diodes, a set of diodes can be directed into the transmission fiber. Installed in the tube would be a set of mirrors at angles that can direct the nearly-collimated output of the laser diodes, since the diodes each have a small set of optics installed to focus the beam. A basic diagram of the layout involving a tube and mirrors with the single positive lens is shown below in Figure 37:

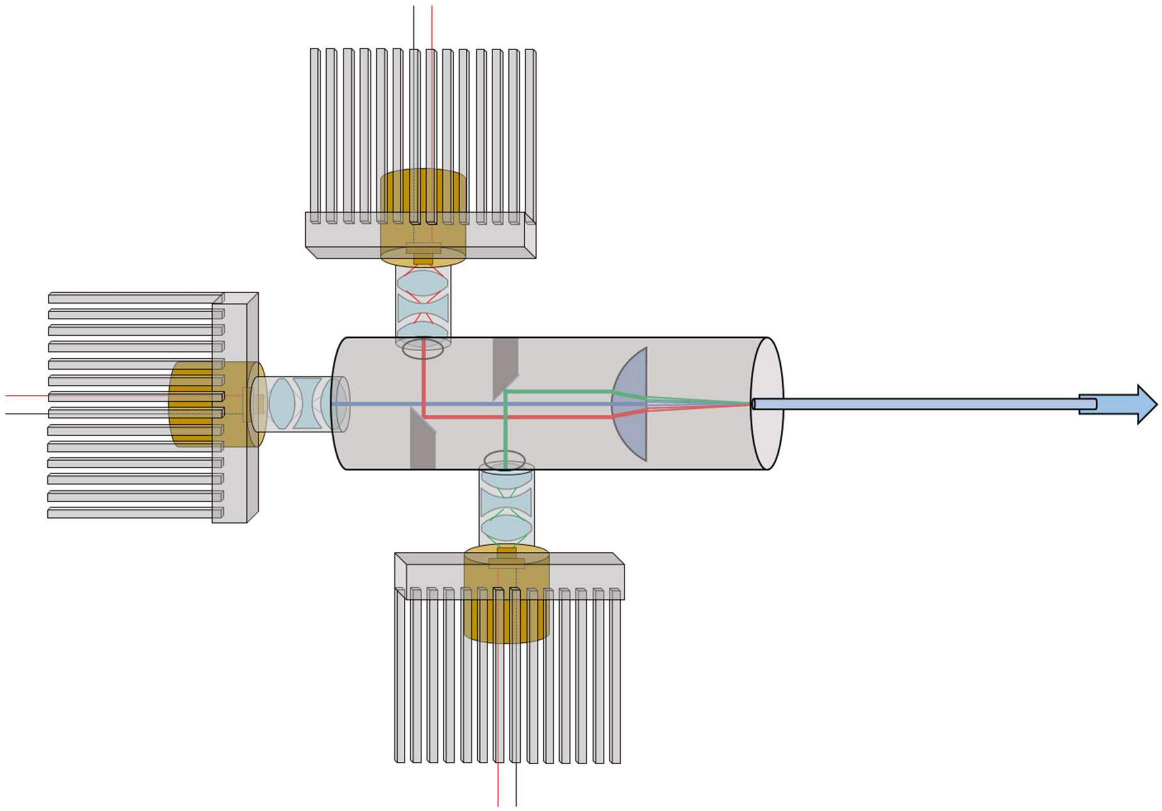


Figure 37: Tube Method of Diode-Fiber Coupling

The tube would be made of polycarbonate to ensure it stays very stiff while being transparent to aid in alignment and demonstration of the method. Polycarbonate is also easier to drill out, cut, and file down edges than glass would be. Plexi-glass would be too flexible as well as most clear plumbing pipes. The mirrors can be made by cutting a cylindrical piece of metal at a 45-degree angle and cutting a hole in the pipe, so the pieces can be positioned at the right rotation and depth, then bonded in place with epoxy. Before the metal piece is inserted, a mirror would be bonded to the angle. High-quality broadband coated lab mirrors could be used, but due to the high cost of these mirrors another solution was researched and will be utilized. Solar tubes are made of thin sheet metal and have a highly-polished silver coating on the inside of the tube. By cutting off small pieces of the solar tube and flattening the pieces of metal, small highly-reflective mirrors can be created for less than a few cents each. The mirrors are oriented so that the redirected collimated beams from the diodes are all directed as parallel to each other as possible. This creates a set of planar wavefronts for the positive lens, as if the light sources are effectively at infinite distance. When the wavefronts are planar oriented, all the beams will theoretically focus to the focal point of the lens. By placing the end of the optical fiber at the focal point of the lens, all the collimated beams from the diodes will be coupled into the fiber. Although the single positive lens will have a slightly different refractive index for each of the laser diodes since they have a different wavelength output, the change is focal point should be small enough to fit within the large core of the multimode fiber.

To ensure the focused beams can be effectively transmitted through the fiber, the angle of incidence created by the focusing positive lens must be less than or equal to the acceptance angle of the fiber. The acceptance angle can be set at a high value by utilizing a high numerical aperture fiber. A higher numerical aperture means the propagating waves in the fiber can have a greater angle to the inside surfaces of the fiber and still experience total internal reflection. If a positive lens with a longer focal length was used, the overall length of the tube would have to be longer, increasing the required size of the source unit. However, if the numerical aperture of the fiber is too high, collimating the output of the fiber for splitting purposes later becomes difficult. A high numerical aperture fiber would have an output with a wide cone of emission. This highly angled cone would have to be directed into an area less than the clear aperture of a high-diopter positive lens to collimate the output. The greater the angle of the cone, the higher-diopter the lens would have to be. There is also a point where the lens can't be more curved for its diameter and effective collimation would not be possible without a complicated set of lenses, increasing cost and reducing efficiency. A numerical aperture of 0.39 is commercially available for optical fiber and will be the fiber used for the demonstration since it is a good balance of acceptance angle and small enough angle of output cone for collimation.

The method of crossing the optical axis with side-mounted collimated diodes was realized after experimenting with an alternate method where the beams did not cross, as shown in Figure 38 below. There were a few issues with this method determined in the lab. One issue is that unless the mirror is very thin, the back side of the mirror will block the beam travelling down the tube along the optical axis of the system. Another issue is the difficulty in positioning the mounting the mirrors. The best method we could determine for mounting the mirrors in this alternate method would be to bond them to a thicker piece of metal to minimize flexing, then cut a slit at a 45-degree angle in the tube for the mirror to be placed in and epoxied to. Not only would this method severely reduce the structural integrity of the tube but would have a much more likely chance for error in the setup.

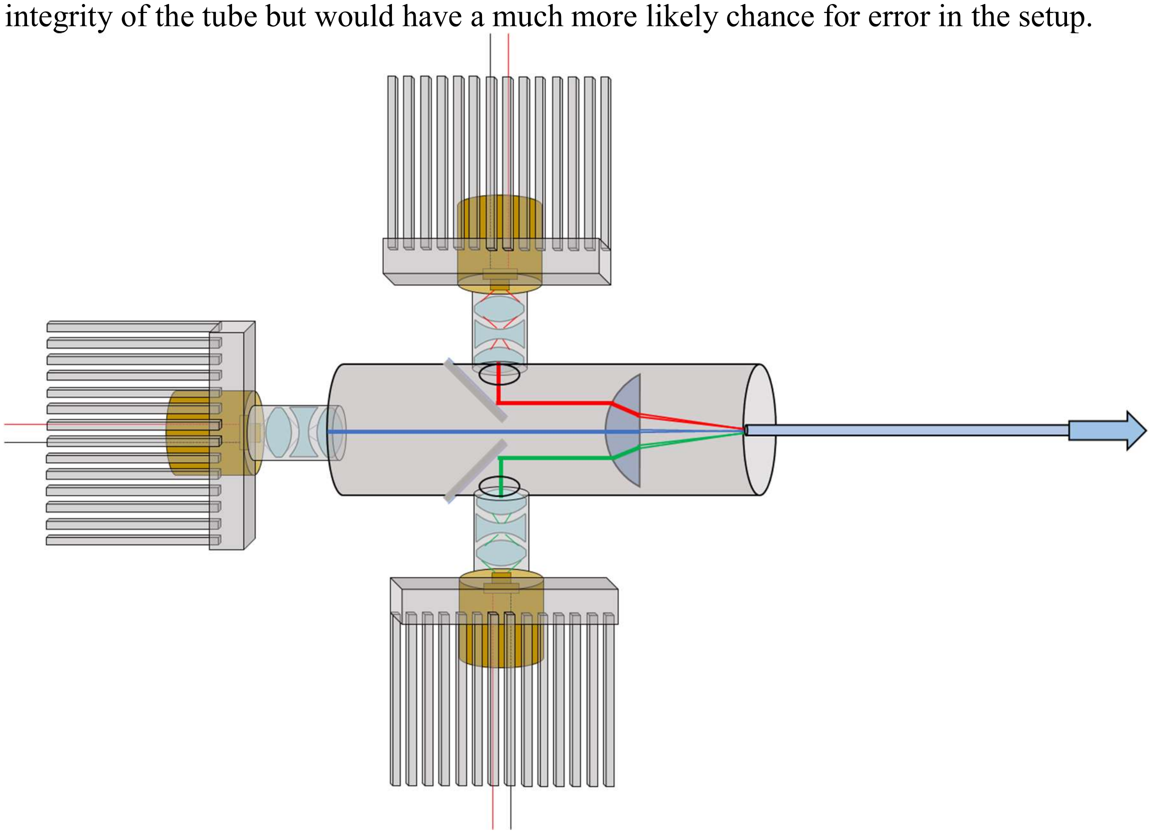


Figure 38: Alternate Method of Tube-Mirror Positioning (ineffective)

Below are Zemax OpticStudio models of the red, green, and blue wavelengths being focused down to a spot size small enough to fit within any multimode fiber optic cable that we would possibly use for the project. As shown, the spot size is smaller than 10 micrometers for any of the wavelengths, and since we are looking to use 300-400 micrometer core diameter cable, the positive lens we plan on using will be more than capable of providing the focusing power and quality that we need.

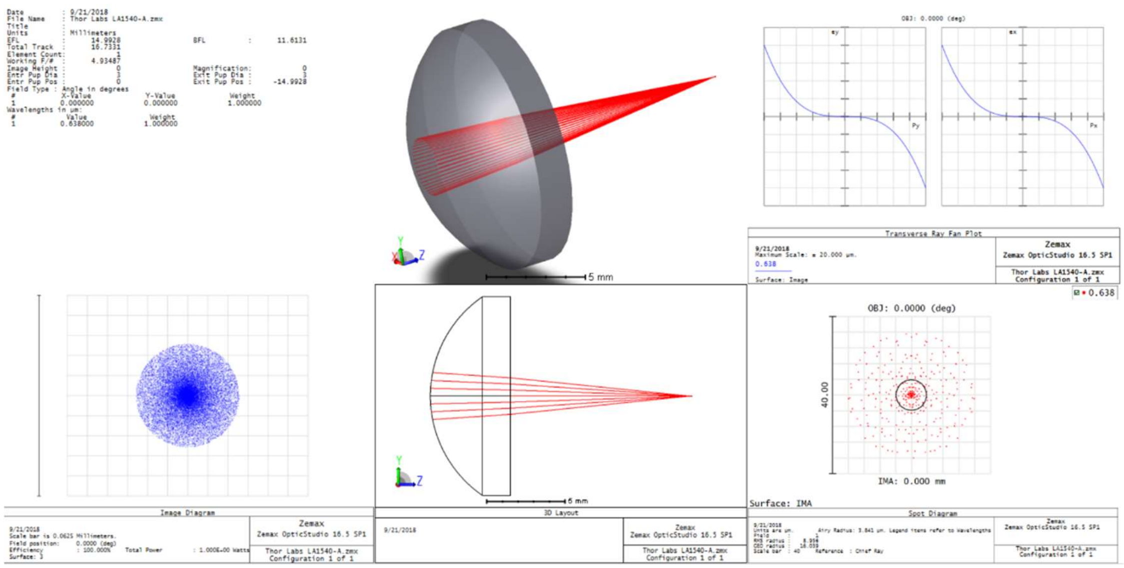


Figure 39: 638nm Focus Simulation

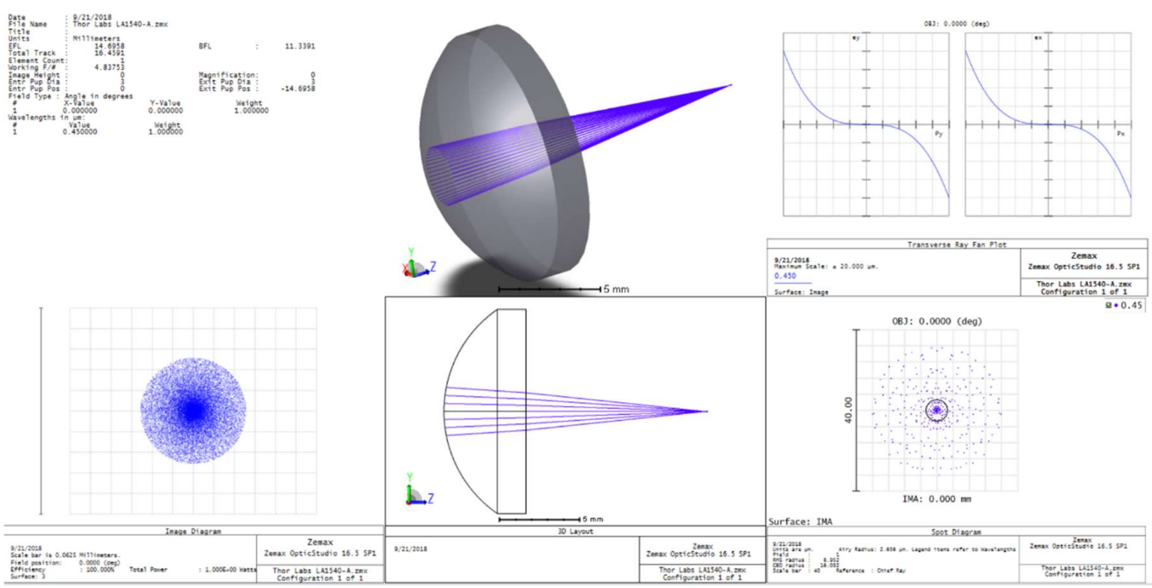


Figure 40: 450nm Focus Simulation

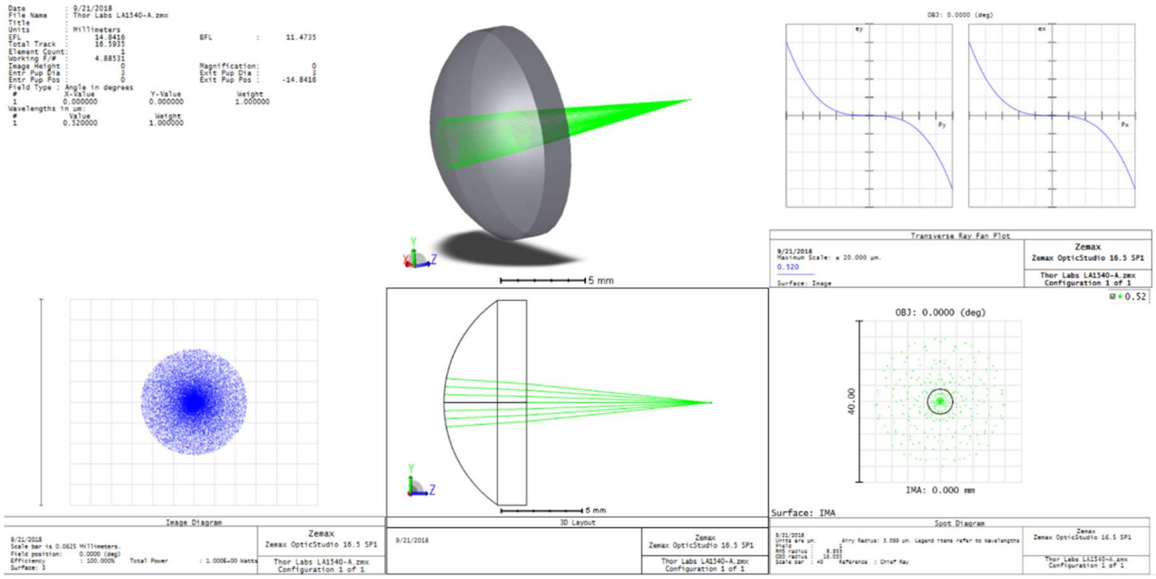



Figure 41: 520nm Focus Simulation

Below is a combination of the three wavelengths being focused by a single plano-convex lens concurrently. This is of particular interest because the various wavelengths that we plan on using in the prototype of MADLIS have a significantly large gap in nanometers between each of them. When two or more different wavelengths are focused down by the same lens at the same time, the focal points will be different for each wavelength. This is because all glass has a refractive index that is a function of wavelength, meaning the refractive index will change as the wavelength changes. There are specific coefficients that can be utilized to calculate a very close estimation of the refractive index of a lens for a particular wavelength, however, Zemax OpticStudio has these formulas and coefficients built-in to the software, as well as many of the Thorlabs lens options commercially available.

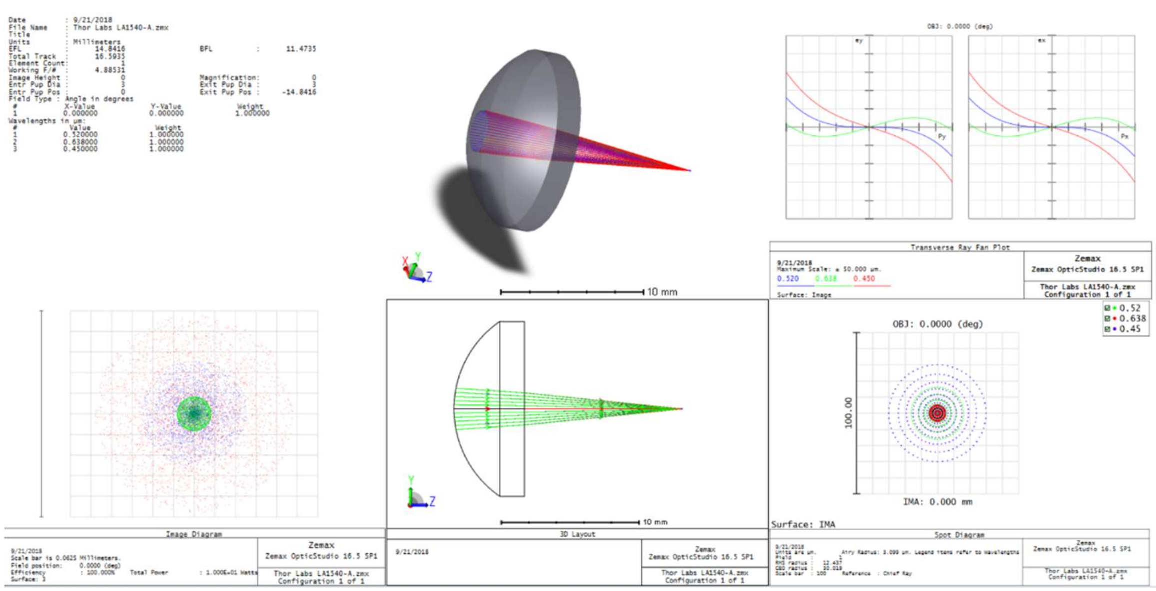



Figure 42: Combined Focus Simulation

Below is an example of a common commercially available infrared laser diode wavelength: 808nm. When this wavelength is focused by the lens, the effective focal length of the lens is slightly longer than the effective focal length of the other wavelengths. However, this is acceptable since the spot size at the cross-sectional location, or transverse cross-section where the other wavelengths used have their effective focal lengths for the lens is small enough to still easily fit within the cores of any multimode fiber optic cable that we plan on using.

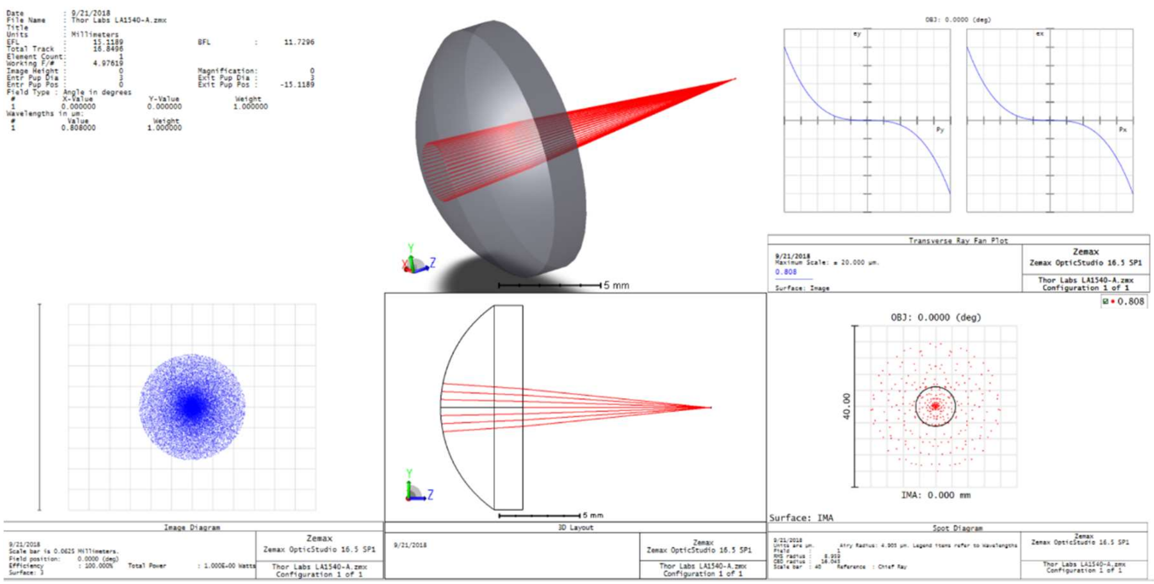


Figure 43: 808nm Focus Simulation

### 10.2: Commercial Availability of RGB Laser Diodes:

The availability of high-powered laser diodes in the visible spectrum has greatly increased in the last 10 years. Different industries have increased mass production of laser diodes with higher powers. The Blu-ray industry has greatly decreased the cost of the blue laser diode. Entertainment, projection, and novelty have increased the supply and technology of green and red laser diodes. Below in Table 11 is a comparison of commercially available red, green, and blue laser diodes.

| Description | Source | λ (nm) | Power (W) | Price |
|---|---|---|---|---|
| Oclaro HL63193MG | DTR's Laser Shop | 638 | 0.7 | $26.00 |
| Ushio HL63290HD | OE-Company | 638 | 2.2 | $165.00 |
| Ushio HL63290HD | Worldstar Tech | 638 | 2.2 | $98.00 |
| Nichia NUGM02 | DTR's Laser Shop | 520 | 0.9 | $95.00 |
| Nichia NUGM02 | Ebay: laserlandaustrailia2016 | 520 | 0.9 | $127.05 |
| Nichia NDG7475 | DTR's Laser Shop | 520 | 1.0 | $175.00 |
| Nichia NDG7475 | Ebay: techhood | 520 | 1.0 | $130.41 |
| Nichia NUBM44-81 | DTR's Laser Shop | 450 | 7.0 | $80.00 |
| Nichia NUBM44-81 | Opt Lasers | 450 | 7.0 | $197.00 |
| Nichia NUBM08 | DTR's Laser Shop | 455 | 4.3 | $50.00 |

Table 11: Comparison of Commercially Available Red, Green, and Blue Laser Diodes

The green laser diodes are typically more expensive since generating green light directly from a laser diode is a recently developed technology. In most commercial green lasers including laser pointers, green laser light is created by using nonlinear effects. An 808nm infrared laser diode is used to pump a small neodymium-doped yttrium aluminum garnet (Nd:YAG) solid-state gain medium to create 1064nm infrared light, then a potassium titanyl phosphate (KTP) crystal is placed after the output of the Nd:YAG crystal to double the frequency of 1064nm wavelength laser light to create a 532nm green laser output. This process has been mass-produced to vastly decrease cost. However, by utilizing a direct electron-to-photon laser diode, efficiency is improved, and stability and alignment is simplified. For very highly-scaled applications where hundreds to thousands of watts of light output are needed, the diode-pumped Nd:YAG KTP option is more viable since a single pair of crystals could generate laser light with pulsed powers into the gigawatts or higher with q-switching and/or liquid cooling. For the initial prototype of MADLIS, a direct-to-green laser diode will be used, since the 808nm diode would have to provide several watts to pump the Nd:YAG to be able to generate at least 1W of usable 532nm green light after the 1064nm output from the Nd:YAG is frequency doubled. Inherently, the solid-state method is less efficient due to imperfect anti-reflective coatings, imperfect alignment, incomplete coupling, imperfections in the Nd:YAG and the KTP crystals, and imperfectly collimating the output of the KTP crystal.

### 10.3: Alternative Lenses:

There are alternative lenses that could be utilized to couple the set of collimated beams into the end of the transmission fiber. Achromat and apochromat lenses could be utilized to equalize the refractive index of the lens for each of the coupled laser diode's wavelengths. To reduce cost for the initial prototype of MADLIS, a single plano-convex lens will be used. A multimode fiber optic cable with a 300-400μm core and a length of tens of meters is less expensive than an appropriately-sized achromat or apochromat lens from Thor Labs, Newport, or Edmund Optics.

### 10.4: Epoxies and Bonding Methods:

To allow the very slight adjustments that will be needed for the light source unit, high-quality epoxy will be needed. There are several locations where epoxy will be needed to position and hold parts in place. Once the set of collimating lenses are rotated to a position where the laser diode outputs are as close to collimated as possible, the rotating lens holder will need to be staked in place with epoxy to ensure it does not move during the rest of the alignment process. The laser diode modules will need to be held in place in their respective heat sinks with epoxy. The polycarbonate tube needs to have several holes cut for both the mirror holders and the laser beams. A metal rod would be cut at a 45-degree angle for the mirror to be mounted on with epoxy, then the rod would be inserted into a hole cut into the side of the polycarbonate tube, mirror first. When the rod is inserted to the proper distance in the tube, the rod would then be held in place with epoxy. After the laser diodes are prepared in their modules and heatsinks with collimated beams, they will need to be mounted to the polycarbonate tube. The diode module and heatsink will likely both require epoxy to hold them in place on the side of the tube opposite their mirrors with the collimated beam entering the tube through a cut hole. The plano-convex positive lens would be staked in place with epoxy approximately 1.5" into the end of the tube so the convex side of the lens is facing the angled mirrors. At the end of the tube with the lens, a flat thicker piece of polycarbonate would be epoxied to the tube. The flat piece will have a small hole drilled near the exact center of the end-circle of the tube, and the transmission fiber could be inserted in the hole. The fiber would be inserted slightly so that the end of the fiber is positioned at the focal point of the positive lens, and the fiber would be epoxied in place to the flat piece of polycarbonate.

Alignment of all the illumination elements would be performed as the epoxy dries. Therefore, a medium-to-slow-curing epoxy would be needed, as well as an epoxy with minimal out-gassing to ensure the optics and fiber stays clean. As the epoxy becomes more tacky, slight adjustments would be made to maximize coupling and alignment, re-positioning as necessary as the epoxy hardens. Ideally, a UV-curable bonding agent could be added around the long-curing epoxy to help hold parts in place during the curing process once a proper alignment and coupling is achieved.

### 10.5: Color Space and the Human Eye Response:

To be able to compare MADLIS to existing illumination systems, especially those that utilize mixed color sources to produce controllable hue and intensity, the analysis of color space and the human eye response to each color must be performed. Since MADLIS has a major claim of being a color-tunable illumination solution, a comparison of the performance of existing color-generating displays and illumination systems and how they are measured.

The color gamut is a representation of the combinations of red, green, and blue that can create the visible spectrum of colors visible to the human eye. The industry still utilizes the 1931 standard created by the International Commission on Illumination (CIE) called the 1931 CIE Color Space Chromaticity Diagram, as shown in Figure 44 below:

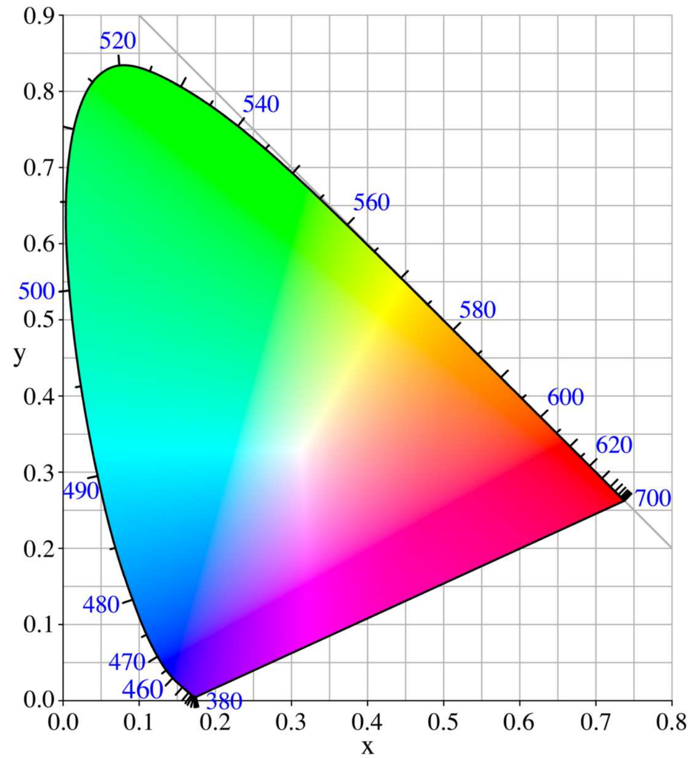



Figure 44: 1931 CIE Color Space Chromaticity Diagram

The edges of the chromaticity diagram show three-digit numbers in blue, which represent the corresponding wavelengths in nanometers. To be able to produce a color at the edge of the color gamut, a pure wavelength must be used. Therefore, most illumination systems and displays cannot fill the majority of the color gamut and must add additional color sources. When light sources of different colors are mixed together, each source can be placed on the color gamut and lines can be drawn between them to show the color possibilities that can be generated by changing the relative intensity of each color. The intensity mentioned in this case is the intensity relative to the spectral response of the human eye, therefore, the intensity must be scaled to that response and cannot be calculated using energy alone. The initial prototype of MADLIS utilizes three laser diodes, each with a very small bandwidth of wavelengths that each can output, referred to as linewidths. Since each diode is nearly a single-wavelength generator, especially compared to LED or other broadband sources, the colors they generate can be placed near the outer limit of the color gamut, as shown in Figure 45 below:

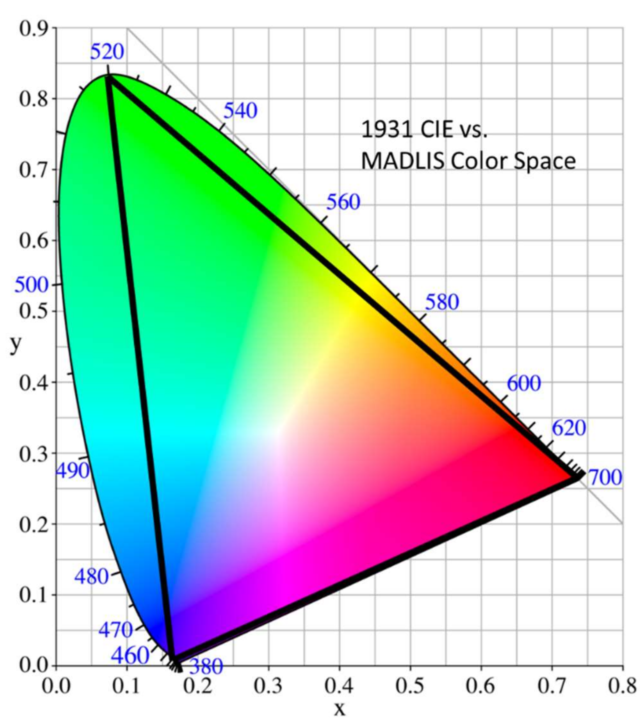


Figure 45: 1931 CIE vs. MADLIS Color Space

A feature to point out on Figure 45 is that the yellow hues are well covered, which is generally an issue for RGB-sourced displays since LCDs and LED displays have sources that are not on the edge of the color gamut and cannot cover much of the yellow section. Below are three diagrams showing MADLIS's performance in various color gamuts to compare with existing technology and research from CIE, all collected as Figure 46:

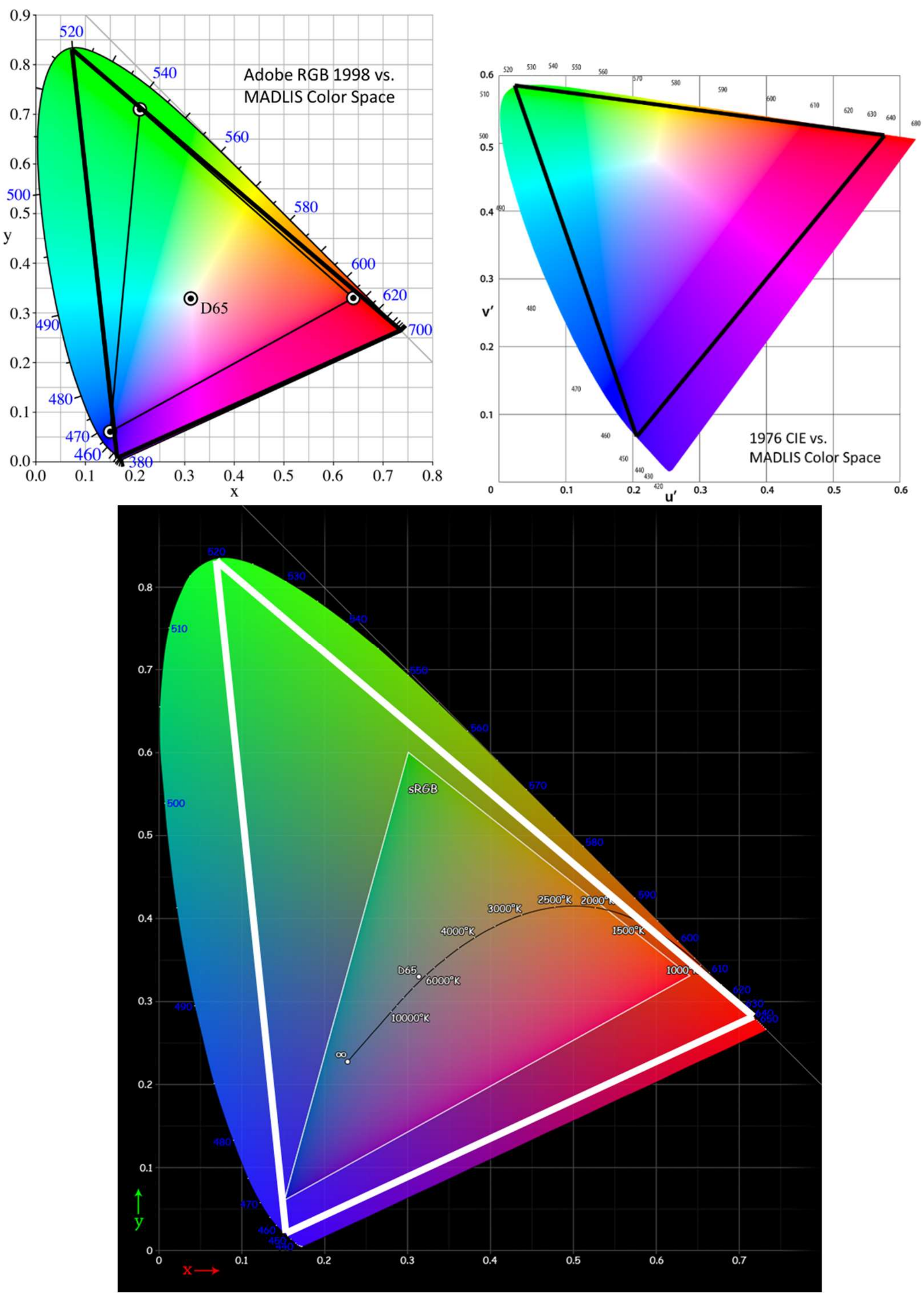
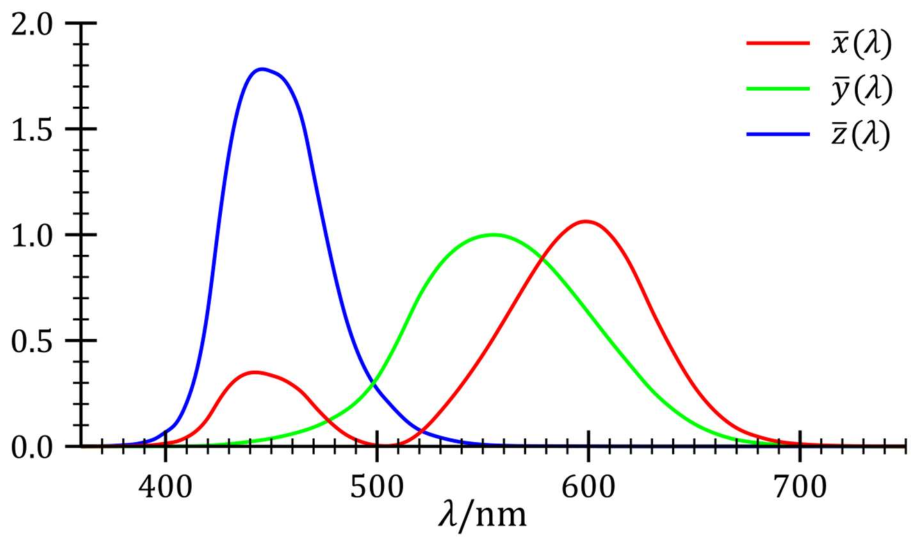



Figure 46: Color Gamut Comparisons to MADLIS
https://commons.wikimedia.org/wiki/File:Cie_Chart_with_sRGB_gamut_by_spigget.png

As humans, we have three cones that are used together to perceive color. One cone has a peak spectral sensitivity between 564-580nm and is designated “L” for long. A second cone has a peak spectral sensitivity between 534-545nm and is designated “M” for medium. The third cone has a peak spectral sensitivity between 420-440nm and is designated “S” for short. The cells within each cone have an interior nucleus with various mitochondria, which are the powerhouses of the cells. [Wyszecki, Günther; Stiles, W.S. (1981). *Color Science: Concepts and Methods, Quantitative Data and Formulae* (2nd ed.). New York: Wiley Series in Pure and Applied Optics. ISBN 0-471-02106-7.]

The CIE Color Matching Functions were generated by experimentation in the 1920s when William David Wright and John Guild had subjects adjust amounts of primary light colors until a light comparably matched a monochromatic light source. When the spectral power distribution (SPD) is weighed by the curves generated by the experiments, a spectrum of peaks related to the human eye color cones is generated, as shown in Figure 47 below:




[https://commons.wikimedia.org/wiki/File:CIE_1931_XYZ_Color_Matching_Functions.svg]
Figure 47: CIE Color Matching Functions

Since each cone in the human eye has a small range of wavelengths where peak sensitivity occurs, MADLIS can be optimized by using those peak-sensitivity wavelengths for the generation of white light. When other commercially-available illumination devices utilize a broad-spectrum source or set of sources, they effectively waste energy by generating wavelengths that the human eye is not sensitive to. With blackbody radiation, a certain temperature has a corresponding peak wavelength with a bandwidth spanning higher and lower than the peak wavelength. Wein’s Displacement Law relates different temperatures to a peak wavelength inversely. A graph showing the relative wavelength distribution of various temperatures is shown in Figure 48 below:

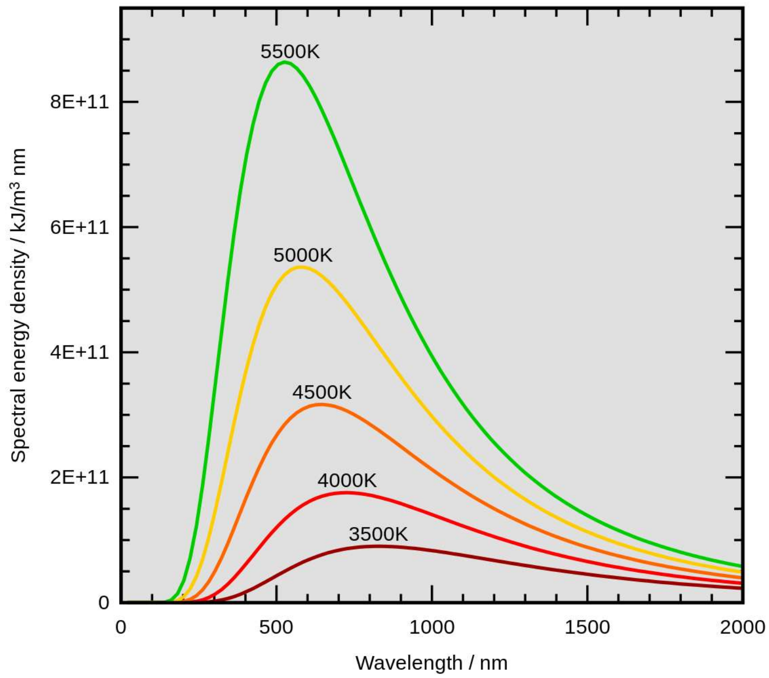



Figure 48: Wein's Law Wavelength Distribution Examples
[https://commons.wikimedia.org/wiki/File:Wiens_law.svg]

The Wein's Law relationship can be derived to a formula that can find the peak wavelength in nanometers with a given temperature in kelvin:

$$\lambda_{max} = \frac{hc}{x}\frac{1}{kT} = \frac{hc}{\left(\frac{hc}{\lambda kT}\right)}\frac{1}{kT} = \frac{2.897772914526216 \times 10^{6} nm \cdot K}{T}$$

Covering the concept of blackbody radiation is important since most commercial illumination devices compare their emitted spectra to a that of a pure blackbody. This is shown in specifications on commercial products in their equivalent "color temperature" such as "4000K". However, placing a color temperature equivalent to MADLIS's emission would not be accurate. Even though MADLIS can replicate the appearance of a blackbody radiator insomuch that it would be indistinguishable to the human eye, the actual energy/wavelength dependent spectrum of MADLIS's output would be very dissimilar. As shown in Figure 48 above, blackbody radiating devices generate wavelengths well into the infrared region of the electromagnetic spectrum. Since humans can only see wavelengths up to around 700nm, any wavelengths generated with a wavelength longer than 700nm is wasted as heat and not as illumination.

### 10.6: Parts and Supplies Needed for Light Source:

Every part and supply purchased or planned to purchase has been thoroughly analyzed in the effectiveness and efficiency of its utility. Some aesthetic features were considered only if it also added to the ease of assembly, commercial availability, or effectiveness of the demonstration by being easier to see the function of each of the components in the system.

#### 10.6.1: Source Unit Housing:

There are many form factors and spaces that the MADLIS source unit can fit in, depending on function and scale. For the demonstration in this project, it was decided that the source unit should fit within a small form factor desktop computer case. This was decided because of several inherent factors including but not limited to:

- Relatively inexpensive cost due to wide availability and mass production
- Wide availability of metal-based case; easy adaptation to a Faraday cage
- Built-in mounting holes and structures
- Designed to have inexpensive computer case fans mounted
- Typically, have mounting options for filters
- Clean appearance both inside and out
- Familiar appearance to the average consumer
- Ability to purchase with/add a transparent panel for interior viewing
- Blends in with existing household/business/medical/military technology

Since there is no standard size for a small-form-factor PC case, there was a lot of leniency in how small or large the housing would have to be. A currently available option that seemed to fit all the inherent factors above is the Silverstone ML05B Steel Body Media Center/HTPC Case, as shown in Figure 49 below:

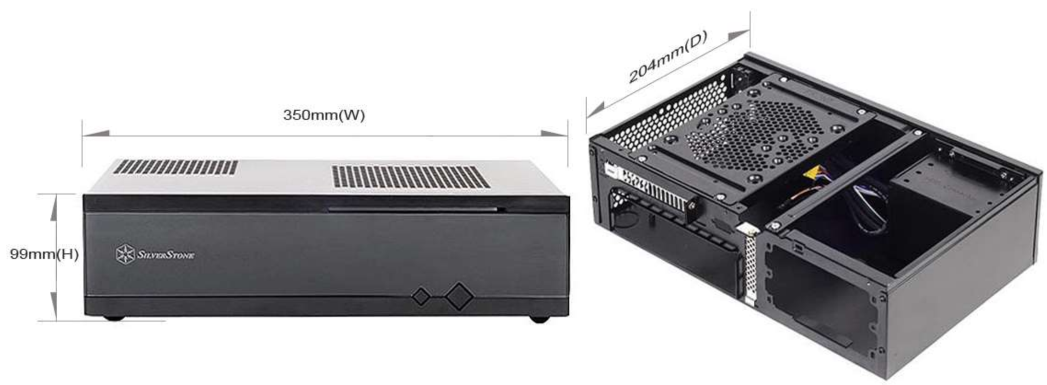



Figure 49: Silverstone ML05B

The specifications of the Silverstone ML05B are as follows:

- 0.8mm steel body
- Dimensions: 350mm (13.78”) x 99mm (3.9”) x 204mm (8.03”)
- 2 x 80mm fan slots on right side, 120mm fan slot on top
- Two external USB ports (which can be used for the external interface)
- Power and reset buttons
- Cost: $45.79, free shipping

#### 10.6.2: Optical Path Tube:

A method was needed to combine several laser diode beams into a single fiber optic cable, so the previously-discussed method of mounting components in and around a clear tube could be implemented. The material and size of the tube were the two major considerations that had to be considered. A convenient size that was chosen is an internal diameter of 1”, since the positive lens for coupling the light beams into the fiber has a diameter of 1”. A thickness of 1/8” was chosen since it was the thickest commercially available option for a price point that was reasonable for the demonstration. Several materials were considered and compared by cost, rigidity, durability, availability, transparency, thermal capacity, size choices, consistency, and more. Some comparisons between various materials are shown in Table 12 below:

| Material | Rigidity | Durability | Transparency | Consistency | Cost/ft. |
|---|---|---|---|---|---|
| Steel Pipe | High | High | None | High | $15 |
| Aluminum Pipe | Medium | Medium | None | High | $10 |
| Acrylic | Low | Low | High | Medium | $20 |
| PVC | Medium | Medium | None | High | $3 |
| Polycarbonate | High | High | High | High | $7 |

Table 12: Comparison of Tube Materials

Since all of the material characteristics compared in Table 12 above are significant for the performance of the combining and the ability for the demonstration to have easily viewable components, polycarbonate was the ‘clear’ choice.

### 10.6.3: Laser Diode Modules:

The material of the laser diode module, the enclosure that the laser diode is held in place with, is of great importance as it is the first material that starts to conduct heat away from the can of the laser diode itself. The primary characteristic of the material is the thermal conductivity, since the heat generated by the laser diode must be conducted away or the laser diode will not only decrease in performance but may burn out and fail entirely. A comparison of materials that could generally be used as a laser diode module are shown below in Table 13:

| Material | Thermal Conductivity (W/mK) | Density (g/cm$^3$) | Mohs Hardness |
|---|---|---|---|
| Aluminum | 205 | 2.7 | 2.75 |
| Copper | 401 | 8.96 | 3 |
| Carbon Steel | 54 | 7.85 | 4.25 |
| Diamond | 1000 | 3.5 | 10 |
| Gold | 310 | 19.3 | 2.5 |
| Silver | 429 | 10.49 | 2.5 |

Table 13: Material Property Comparison

Engineering ToolBox, (2003). Thermal Conductivity of common Materials and Gases. [online] Available at: https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html [Accessed 11/14/2018].

Since weight is not a general concern for this project, but cost and thermal conductivity are very important, either copper, silver, or diamond would be the best choices for the laser diode module material. Silver is an excellent thermal and electric conductor and is generally available commercially, but the cost per cubic centimeter is high. Diamond is one of the best thermal conductors known, and is concurrently one of the best electrical insulators, which would improve stability and reduce risk of electric discharge between unwanted conductors. However, diamond is very hard to machine or form into the shape necessary to encapsulate and hold securely a laser diode, and the cost of diamond is extreme, even if the diamond is artificially manufactured. The remaining choice from the list above is copper, which is relatively inexpensive for the quantity needed. Copper is an excellent thermal conductor and is not nearly as dense as gold and has a reasonable hardness that will hold its shape while still being easy to machine into the shape needed. The size of copper modules used are 25mm diameter by approximately 1" deep. The copper modules have been purchased from DTR's Laser Shop for approximately $15 each. The appearance of the modules is shown in Figure 50 below:


Figure 50: 25mm Copper Laser Diode Modules
https://sites.google.com/site/dtrlpf/home/diode-modules/25mm-copper-modules

The copper modules will effectively conduct much of the heat away from the laser diodes, but the copper itself will heat up over time and will need to have its thermal energy conducted away. The copper modules do not have a significantly large surface area, so convection cooling would not be sufficient alone. The solution to this thermal issue is to mount the copper modules within individual aluminum heatsinks. Copper heatsinks could be utilized and may be needed for higher powered systems, but the cost is prohibitive for this demonstration. The aluminum heatsinks are three inches by three inches, with a depth of approximately 1.5". By utilizing a heatsink, the effective surface area of the copper module is increased approximately 100 times. To improve the convection cooling for the heatsinks, several computer fans were mounted in the computer case to provide constant airflow.

To improve the conduction between the copper module and the aluminum heatsink, a method similar to how thermal energy is conducted away from computer central processing units and into their heatsinks was utilized. Thermal compound was placed around the copper module before the module was inserted in a hole that is cut into the flat side of the aluminum heatsink. The hole must be nearly precisely the same size as the diameter of the copper module, so that a complete contact is maintained between the module and the heatsink. To achieve this, a 31/32" drill bit was used to drill the initial hole in the heatsink, since 31/32" equals 24.60625mm. The slightly smaller hole will only require approximately 1/5 of a mm to be removed from all sides of the hole for a perfect fit of the copper module. Sandpaper was used to form the hole into a near-perfect size.

#### 10.6.4: Internal Source Beam Directors:

Within the source module beam combiner tube, the collimated laser beams must be directed so that the beams are parallel and as close to the optical axis as possible. This is a requirement since it would degrade the thermal stability to place the laser diodes next to each other, emitting their collimated beams down the optical axis together. As shown in Figure 46 above, the directors would be placed at 45-degree angles directly across from the laser diodes that are mounted to the sides of the tube.

Many options are available to change a beam's direction by 90 degrees, including:

- Total internally reflected prisms
- Silvered glass, either on the near side of the beam or the far side
- Silvered metal
- Coupled fiber bent in a 90-degree curve
- Gradient refractive index glass directing the beam
- Thin-film coated materials
- Non-linear beam self-refraction

Many of the beam directing devices can be acquired through optics and photonics lab supply sources such as Thorlabs, Newport, Edmund Optics, and others, but there are issues with getting the directors from lab supply companies. The first issue is cost. Even the simplest visible-spectrum mirrors cost more than similarly-sized plano-convex lenses when purchased from reputable optic supply companies. A second combination issue is the high cost of custom mirrors and the limited number of commercial-off-the-shelf sizes and shapes. A third issue, specific to this project, is the thickness of the mirrors and prisms. When we want to place a mirror at a 45-degree angle near the optical axis, the inherent spatial displacement of a thick mirror when placed at an angle becomes a problem.

Therefore, the solution to these issues could be to purchase a large extension solar tube that has highly-polished silvered metal on the inside. By cutting off small pieces of the tube and carefully flattening the metal that the tube is comprised of, custom-sized silvered metal mirrors could be created at a cost of pennies each. Experimentally, even crudely flattening the mirrors was sufficiently effective at redirecting the collimated laser beams along the optical axis and into the positive lens for fiber coupling. The experimental setup showing flat pieces of silver-coated metal is shown in Figure 51 below. Note the ability to place the reflective surface arbitrarily as close to the optical axis as possible without aperturing the beam that is sent straight through the tube from the rear.

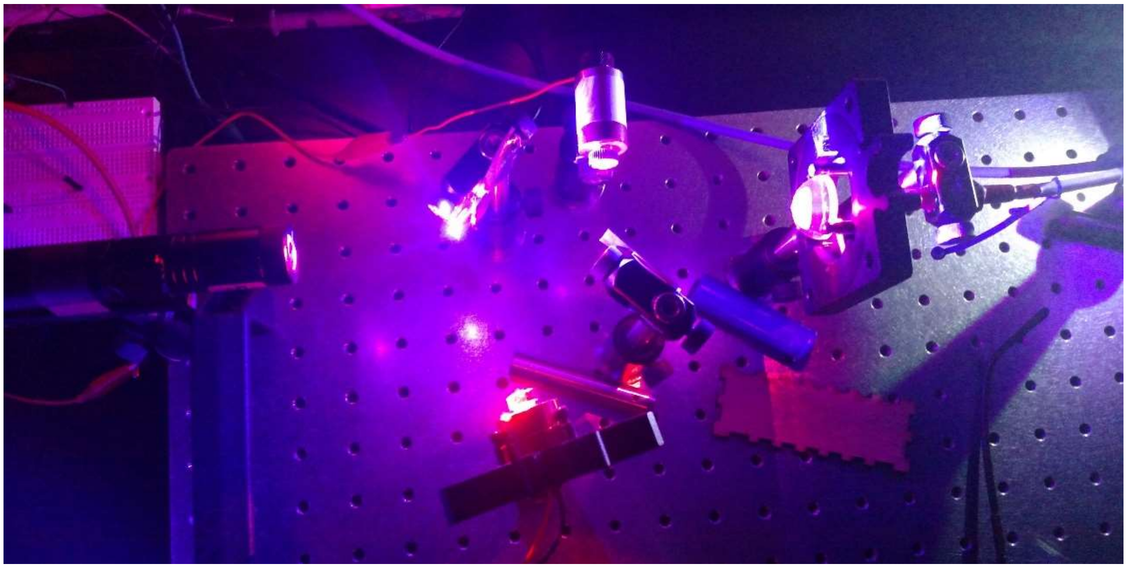


Figure 51: Experimental Setup to Test the Effectiveness of Solar-Tube Material

To mount the silvered metal pieces in the tube, they could be mounted to angle-cut steel rods with epoxy. The steel rod could be purchased from a hardware store and cut with a hacksaw or Dremel tool. After the angle is cut, the rod could be cut perpendicularly at the opposite end of the angle cut so that the rod length is slightly longer than necessary to insert the angled end into a hole cut into the polycarbonate tube opposite the laser diode that needs its beam redirected. The extra length is for the purpose of providing a point that can be adjusted from the exterior of the tube to position the reflector. After the position is established, the rod would be staked in place to the tube with epoxy.

The plano-convex lens used to focus the parallel collimated beams into the fiber would be mounted inside and near the end of the polycarbonate tube at a distance from the end just over the back focal length of the lens. The slightly longer distance is to account for the distance that the transmission fiber is inserted into a small hole drilled into a flat-bonded polycarbonate piece at the end of the tube.

After the components of the light source have been positioned and bonded in place, the light source could be bonded to the PC case with epoxy. The transmission fiber can be placed through a padded hole in the PC case to be sent to the output sections of MADLIS.

### 10.7: Multi-Tube Source

After many experiments both in the lab, simulations with Zemax OpticStudio, and thought experiments on paper, it was determined that the single-tube source/combiner offered too many chances for issues in fabrication and assembly. The original utility patent for MADLIS had shown separate, individual laser diodes being coupled into fiber optic cables. In the original drawings, the separate fibers, each carrying a different wavelength of light, were then combined together into one fiber for transmission to the output source by using some type of fiber combiner. Since commercial fiber combiners were either too inefficient, too expensive, or too fragile to handle the large optical powers that MADLIS required, the single-tube design was devised as a solution. However, as shown in section 10.8 below, a much simpler solution was determined to combine the fibers in a highly efficient, inexpensive, and high-power-handling method. Therefore, the initial idea of individually coupling laser diodes into fibers became the best method again. The general reasons why individually coupling laser diodes into fibers is superior are:

- It is much easier to couple a laser diode into a fiber to achieve the fundamental $TEM_{00}$ mode when the laser is allowed to directly shine on the center of the optics immediately before the fiber and have those optics shine on the center of the fiber without requiring a total angle upon the face of the fiber.
- The entire system is inherently more scalable, since many separate fibers can be combined together from many sources, and the combiners can be tiered once each fiber combiner has reached a maximum number of input fibers.
- Alignment of the laser into the fiber is much more consistent and straightforward when each fiber and diode can be aligned individually, instead of requiring a set of diodes to be collectively aligned to the same fiber.
- The absence of mirrors in the multi-tube setup reduces the cost and complexity of the system since optical mirrors are difficult to manufacture and cost much more than simple N-BK7 plano-convex lenses of similar sizes and power handling.
- Having shorter tube elements decreases the amount of flex over the length of the tube which increases the reliability and stability of the system.

Taking these considerations into account, the following coupling method was designed, as shown in Figure 52 below:

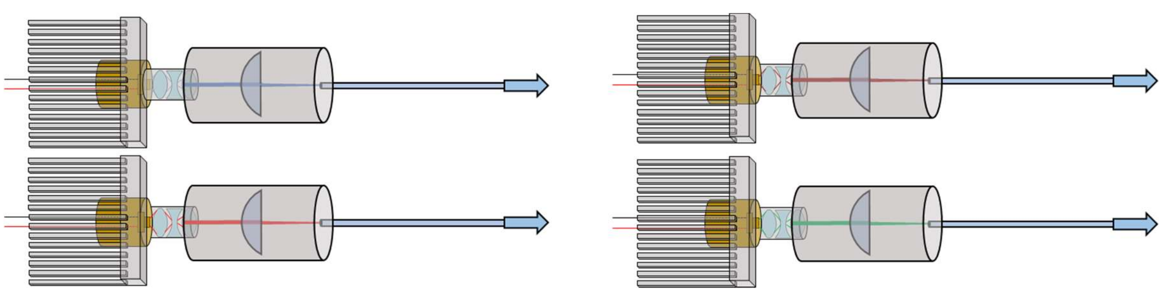


Figure 52: Multi-Tube Diode-Fiber Coupling Method

As shown above in Figure 52, each laser diode is housed in a solid copper module to draw much of the initial heat generated away from the diode. Next, each copper module is coated with thermal paste to aid in the conductive transfer of heat. Then, the copper module is wrapped in a thin layer of aluminum so that it can tightly fit within the aluminum heatsink. The aluminum heatsink has a 31/32" hole drilled with a 31/32" high-speed-steel drill bit, using WD-40 as a lubrication aid. The hole is then slightly widened by circularly pressing the bit on the side of the hole until the hole is just wide enough to tightly house the 25mm copper module. The wires from the diode are fed through the back of the heatsink to be attached to the electronics portion of MADLIS.

Each copper module has a set of lenses to collimate the beam by twisting a threaded lens holder in the module for proper focus. Once the beam has been collimated and the module is properly seated in the heatsink, both the rotation of the lens system and the module are epoxied in place by using 1-minute JB Weld clear epoxy mix. A 2" polycarbonate tube with a 1" interior diameter and a 1/8" wall thickness is bonded around the copper module directly to the aluminum heatsink with 1-minute JB Weld clear epoxy mix. Next a 1" outer-diameter N-BK7 plano-convex lens from Newport is mounted with the same epoxy within the 2" polycarbonate tube so that the planar side is a distance equal to the back focal length plus 3mm from the end where the fiber optic cable is to be mounted. The 3mm extra distance is for the fiber to stick out from its holder. The fiber is mounted by creating a disk of thicker polycarbonate with careful cutting and the drilling of a 1/16" hole in the center of the disk. The disk is then held on its side with a make-shift mount that allows the fiber to lay flat and straight so that the fiber is not bonded at an angle where the light is meant to be directly incident. The fiber is held in place with the clear 1-minute epoxy.

During initial experimentation of the single-tube sources, black 15-minute JB Weld epoxy was utilized to mount the fibers. It was theorized that black epoxy would help in determining if any epoxy had moved to the end of the fiber where it could have interfered with the laser diode light coupling. However, since the laser diodes used in this initial demonstration of MADLIS are of a comparably high power, there were issues with burning the epoxy during initial alignment. Even when the blue laser diode is run just above threshold to attempt to align with the minimum power possible, the blue laser diode is emitting approximately 300mW of highly-focused 450nm light. This light energy caused immediate smoking of the black epoxy which filled the cavity between the fiber holder and the plano-convex lens. This is a severe issue because any smoke on the optics can cause a catastrophic failure of the system. Proper alignment eliminates the ability for the light output to burn the epoxy around the fiber, but initial alignment requires the laser to be emitting light since the entire system is not physically aligned with micrometer accuracy. The initial tests of the method are shown below in Figure 53:

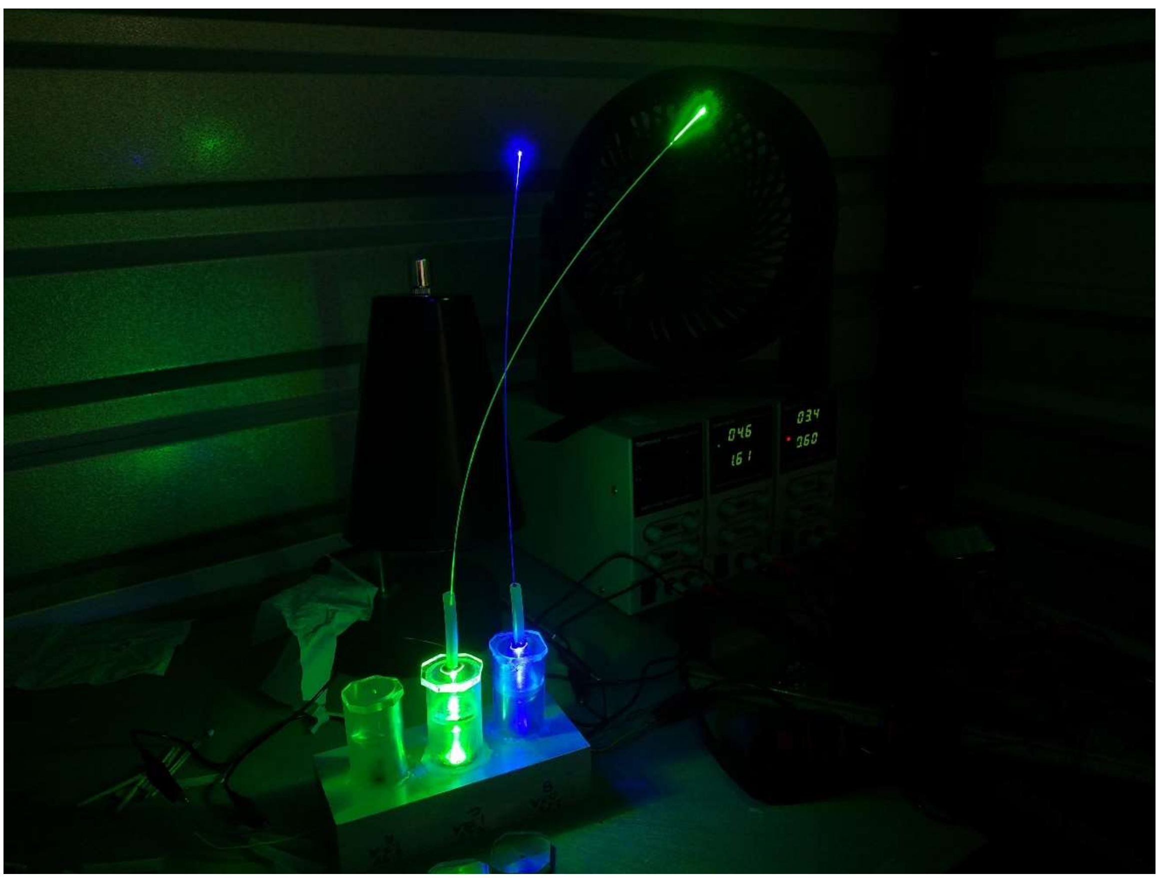


Figure 53: Initial Testing of the Multi-Tube Diode-Fiber Coupling Method

### 10.8: Fiber Combiner

After learning more about collimation of light leaving a fiber optic cable by using a plano-convex lens with the planar side facing the fiber, a different, much simpler method was determined for combining multiple fiber optic cables into a single fiber. Thinking back on the single-tube method for combining the beams, there were a few characteristics of the single-tube device that could be used instead for a fiber combiner:

- Each laser diode initially has a wide angular emission of light which must be controlled with a lens or a lens system. This could be applied in a similar method to light leaving a fiber optic cable, since the purpose of the lenses or lens systems is to collimate previously diverging light.
- The single-tube method had multiple collimated beams propagating parallel to a single optical axis to shine incident on a single plano-convex lens close to the lens's paraxial limit. Multiple beams could also be collimated by placing the ends of several fiber optic cables next to each other, shining in the same direction, to all be collimated near the paraxial limit of a single lens.
- The single-tube method utilized a single plano-convex lens to direct and focus many collimated beams into a single fiber optic cable. The same could work for several collimated beams that originate from multiple fiber optic cables instead of several collimated beams that originate from multiple laser diodes.

After considering the requirements for such a method and the distances, orientations, and lens characteristics, the layout of the combiner shown in Figure 54 below was devised:

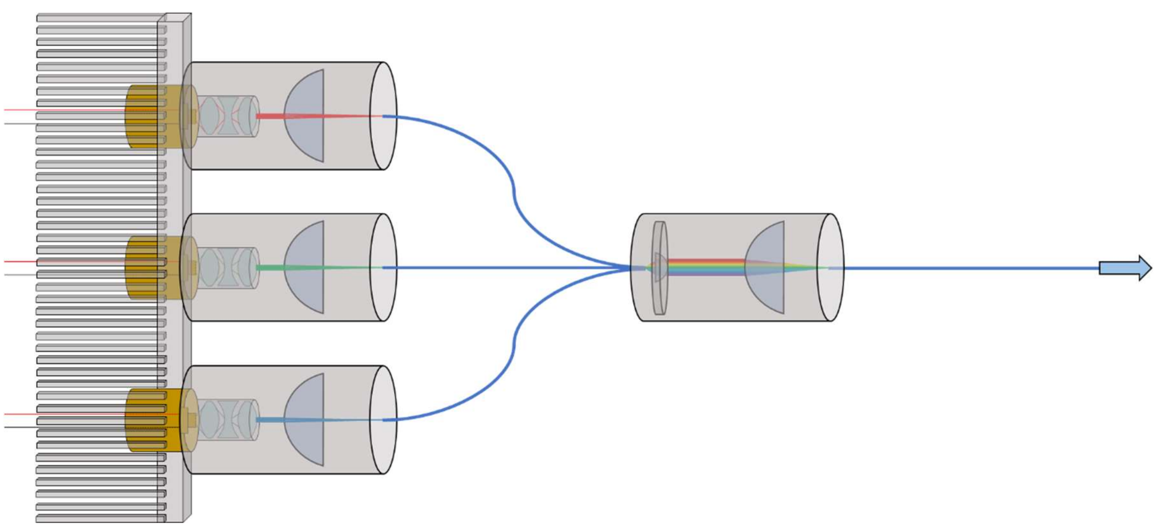


Figure 54: Fiber Combiner Method

Note that the three laser diode sources can now be placed in a single large heatsink, which simplifies assembly and removes the need to cut the heatsink into square pieces. Since the blue laser diode does not need to be powered at maximum output to generate pure white light, much less heat is generated that would need to be dissipated by a max-output diode.

As shown above in Figure 54, a smaller plano-convex lens is required for the collimation of multiple fiber optic cables because the back focal length of the lens must be significantly lower than the diameter of the lens. This is to ensure that the diverging light leaving the 0.39 numerical aperture fiber does not have enough distance to expand to the point where the light would shine incident on the outside portion of the lens or miss the lens entirely. A ¼" N-BK7 anti-reflective coated plano-convex lens with a back focal length of 2.8mm from Newport is used for the combiner since a lens with the required characteristics was not carried in stock by Thorlabs or Edmund Optics.

To hold the ends of the fiber optic cables together in such a way that they will shine straight out into the small lens near to each other as possible, the following method was used:

1. Strip the outer coating of the fiber back 1.5" with fiber strippers
2. Carefully remove the inner coating with a razor blade from the exposed fiber
3. Cleave the fiber ends with a high-end cleaver that utilizes precise tension and a diamond blade
4. Place the fibers ends next to each other and slide a small heat shrink over the fiber ends and heat the heat shrink to pull the fibers together
5. Place a 0.18" inner-diameter vinyl tube segment around the heat shrink
6. Carefully place the combined fiber bundle into a 1/16" hole that has been drilled in a thick polycarbonate piece placed the back focal length plus 3mm from the planar side of the ¼" plano-convex lens
7. Bond the fiber bundle to the polycarbonate disk using clear 1-minute JB Weld epoxy, ensuring no epoxy runs onto the ends of the fibers
8. Slide the vinyl tube down and place the tube against the polycarbonate disk so that the end sits flat, holding the fibers perpendicular to the disk
9. Bond the vinyl tube to the polycarbonate disk using 1-minute clear epoxy

After this method has been accomplished, the long transmission fiber is bonded to the other end of the combiner in a method identical to the diode-fiber couplers. The long fiber, as well as any fibers that are held in place with epoxy, will have heat shrink and vinyl tubing surrounding the bonding point so that the fiber is not highly prone to breaking by any angular moments applied to the fiber near the bonding point.

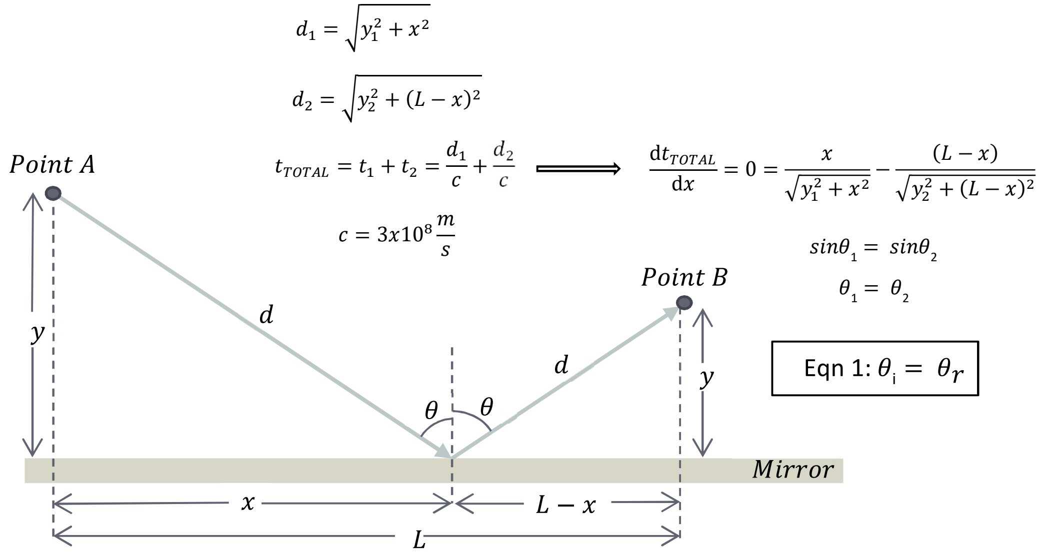
# 11.0: Fiber to Output:

After the collimated beams from the laser diodes have been focused and coupled into the transmission fiber, the light energy must be carried and distributed to become useful illumination for the prototype.

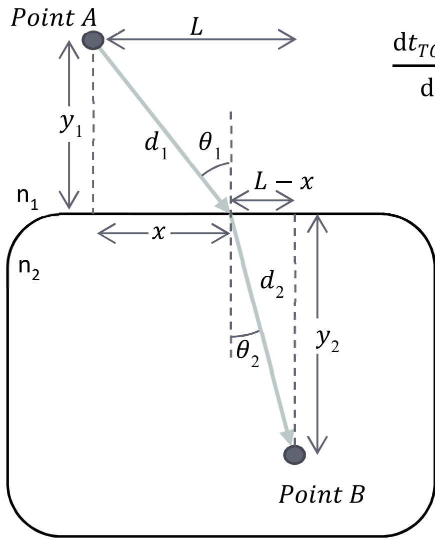
## 11.1: Photonics Basics

Since the use of light is heavily involved in this system it is important to look into the physics of what light actually is in order to get a better understanding of how to meet the engineering specifications that were established. In the field of optics and photonics there are generally 3 ways to define how light acts; It can act like a ray, wave, or it can act like a particle with quantum level variations and uncertainty.

The ray optics point of view states that one can assume that light travels in a straight-line path and uses simple trigonometry to trace through a system. Treating light as a ray allows for a very simplified and intuitive way of designing and analyzing optic systems. There are two very important concepts that must be understood with respect to ray optics; Fermat's Principle and Snell's Law. Fermat's principle is the idea that if light is sent from a point A to a point B, it will always take the most time efficient pathway between the points. From Fermat's principle both the law of reflection and refraction can be easily derived by finding minimizing the total time a ray takes to travel from one point to another:




From equation 1 we see that when a ray of light reflects off a flat surface the reflected ray angle is the same as the incident angle with respect to the normal. From equation 2 we get that when a ray travels from one medium to some different medium there is a bending or turning of the ray that occurs. This change of direction of the ray is caused by the difference in the speed of light in the different mediums. The index of refraction of a medium is the measure of the ratio of the speed of light in a vacuum to the speed of light in that particular medium.




$$\frac{dt_{TOTAL}}{dx} = 0 = n_1 \frac{x}{\sqrt{y_1^2 + x^2}} - n_2 \frac{(L - x)}{\sqrt{y_2^2 + (L - x)^2}}$$

$$n_1 \frac{x}{\sqrt{y_1^2 + x^2}} = n_2 \frac{(L - x)}{\sqrt{y_2^2 + (L - x)^2}}$$

*Snell's Law of Refraction*:

Eqn 2: $n_1 sin\theta_1 = n_2 sin\theta_2$

*Index of Refraction*:

Eqn 3: $n_i = \frac{c}{v_i}$

As index of refraction increases, the speed of light in the medium decreases, as is evident from the inverse relationship in equation 3. From these three principles we can deduce that when a ray of light travels from air to a medium with an index of refraction higher than 1, there is a ray that is reflected with an angle equal to that of the incident angle and there is another ray that is transmitted through the border of the mediums and bends towards the normal due to the change of speed. Intuitively, when light travels from a slow medium to a faster one, the transmitted (or refracted) ray is bent away from the normal, as seen in figure 55a. Traveling from a slow to a fast medium allows for a special case where all of the light is reflected back, and the refracted ray angle is 90 degrees, this case is called total internal reflection (TIR) and can be seen in figure 55b. The incident angle of a ray required for TIR can easily be calculated by simply using Snell's law (Eqn 2) and setting the second angle to be a right angle.

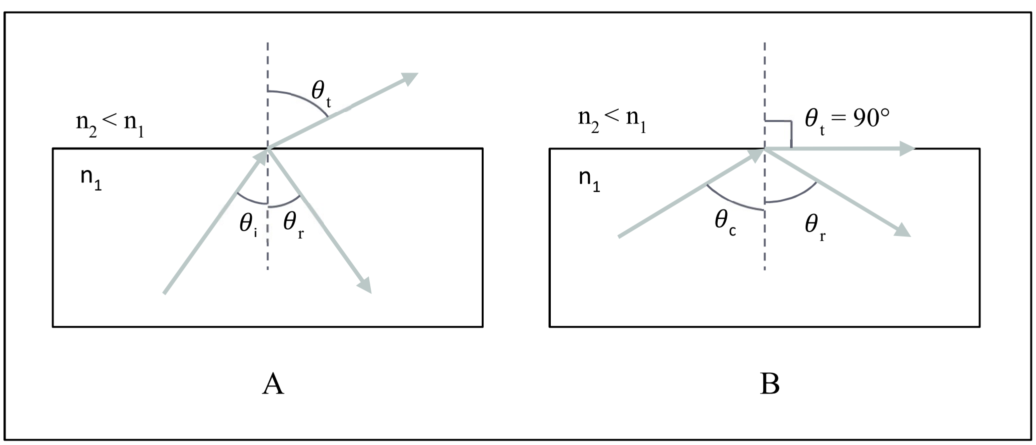



Figure 55: a) Incident angle is below critical. b) Incident angle is at or above critical [10].

It is important to note that this TIR assumption is at a specific interface between 2 different mediums and, in most cases, there needs to be further ray tracing to get the useful parameters, as is the case in fibers. In the fiber optics section this concept being put to use for designing will be discussed [10].

Now that the understanding of basic ray optics has been established there is a need to address the wave-like nature that light exhibits as well. Waves in general can be described with an amplitude, frequency, wavelength, and phase. The amplitude is the maximum value the wave reaches, and the phase is its shift in time relative to having no shift at all. The wavelength is the distance between the peaks of the wave and the frequency is how many times the wave repeats per unit time. The inverse of frequency is period, or the time that a single cycle takes to complete before repeating again. From the simple one-dimensional wave example pictured in figure 56b, we can deduce that the speed of the wave is the product of its frequency and wavelength. To understand what the units for these parameters when applied to light wave are, it is important to first understand the dimensionality of the light wave as well as what it physically is.

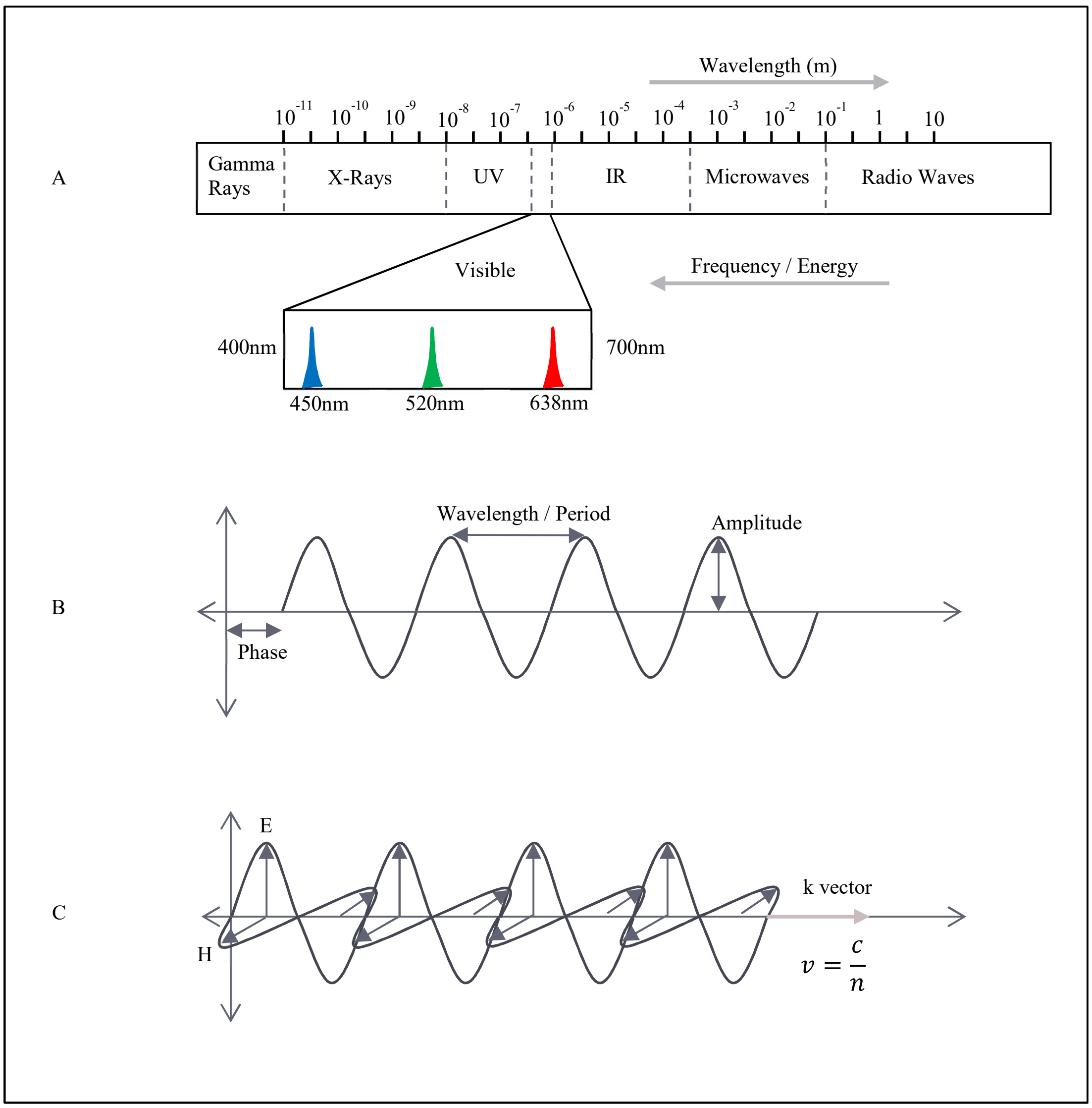



Figure 56: a) EM Spectrum b) A simple 1D wave c) An electromagnetic light wave

A light wave's direction is the cross product of orthogonal one-dimensional electric and magnetic fields known as an electro-magnetic wave (EM wave). There is a large spectrum of EM waves that range anywhere from low frequency radio and microwaves to extremely high frequency gamma or x-ray waves with only a very small portion in between that is visible to the human eye, shown in figure 56a. It is within this visible range where most of our lasers will operate. The visible spectrum ranges from about 400 nm to 700nm and we are using the red, green, and blue wavelengths from it (638nm, 520nm, and 450nm respectively). Similar to how RGB pixels can display a range of colors from different linear combinations of the three wavelengths used we plan to create general lighting for a study room that can be white light or some other color [19]. Waves follow a rule of superposition which means they can pass through one another without ultimately being affected. This also means multiple frequencies can be sent together as the linear sum of all the different waves and then separated again, a good example of which is the dispersion caused by a prism when white light is passed through. Another important characteristic of a light wave is something called polarization, a way of classifying the relationship of the electric field with the magnetic field. Polarization state can be linear or elliptical. Circular is often considered another polarization state, but it is really just a special case of elliptical polarization in which the minor and major radii are equal. An example of a light wave that is linearly polarized can be seen in figure 56c. By taking the sum of the electric and magnetic fields one can see the resultant vector oscillates back and forth on the same straight line at a 45-degree angle since the peaks are lined up and equal amplitude. This angle of linear polarization varies depending on the relative amplitudes of the electric and magnetic field vectors. Polarization states can be summed up as a linear combination of vertical and horizontal linear polarizations [19].

It is impossible to talk about the wave nature and polarization of light without mentioning birefringent crystals, dichroism, and Brewster's angle. Birefringent crystals are special media in which different directions of polarization experience different indices of refraction meaning the polarizations can separate from one another. If these special crystals are polished with the optical axis pointing in a specific direction relative to the incoming polarized light, the result could be a separation of vertical and horizontal polarization states after exiting the medium. This could potentially be useful to evenly split a randomly polarized beam into two separate beams of equal power and have them transmit parallel afterward (see figure 57).

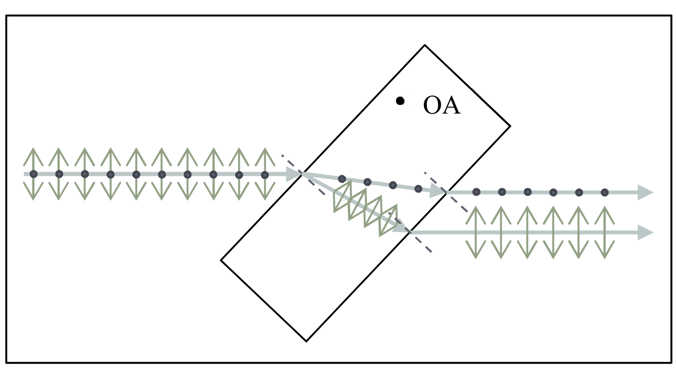



Figure 57: Birefringence causing an even split of randomly polarized light [19].

Some laser setups use something called a Brewster window on one end of the cavity which allows for the vertical component of light to pass while reflecting the horizontal component. This is not the case for our laser diodes meaning that the light from them is polarized in both horizontal and vertical axes in random amounts, otherwise known as randomly polarized light similar to that of sunlight except with a narrow linewidth and different peak wavelength. From this assumption of the laser light being randomly polarized we can assume that half of the power is polarized in the horizontal direction and the other half is in the vertical direction. This can be extrapolated simply from the concept of an even distribution between two characteristics meaning that each is weighted evenly. Theoretically it would be possible to use these birefringent crystals to split the transmission beam into two equal power beams, however a problem with this arises if we need to split those smaller beams. After the initial splitting via birefringence the two beams will both be linearly polarized. If those beams were to be passed through the same type of crystal the only affect it would have, besides the negligible absorption, would be the displacement of the linear beam and there would be no random polarization to filter. Due to this basic principle, splitting the transmission beam into more than two equal energy beams would be impossible. The use of a birefringent crystal is still a viable option for splitting the transmission beam into two but after that the splitting would have to be done by other means to be discussed in the splitting section.

### 11.2: Optical Fiber Distribution Network

In most buildings today, there are light bulbs in the ceiling and they generate the light with the power brought to each individual output location in an AC circuit. This design involves consolidating the light generators (laser diodes instead of light bulbs) in a secure location and then using fiber optic cables to mix and distribute the light to various locations. By transporting optical power instead of electric current there is no need to worry about or eliminate any electrical noise. The curbing of the issue of electrical noise in the power transportation is a nice perk to this design, however there are still losses to consider within and around the fiber distribution. In order to get into the losses involved with the fibers we must first look at how a fiber functions. The simple concept of total internal reflection discussed in previous sections is the fundamental mechanism that allows for waveguides in general to work. A fiber optic cable is generally made up of a core, a cladding, and a coating. The coating is just a protective layer to keep the fiber from being damaged or scratched. The core-cladding interface is where the total internal reflection must occur for the light to propagate through the guide correctly and with little loss; A single ray trace to this interface can be seen in figure 58a.

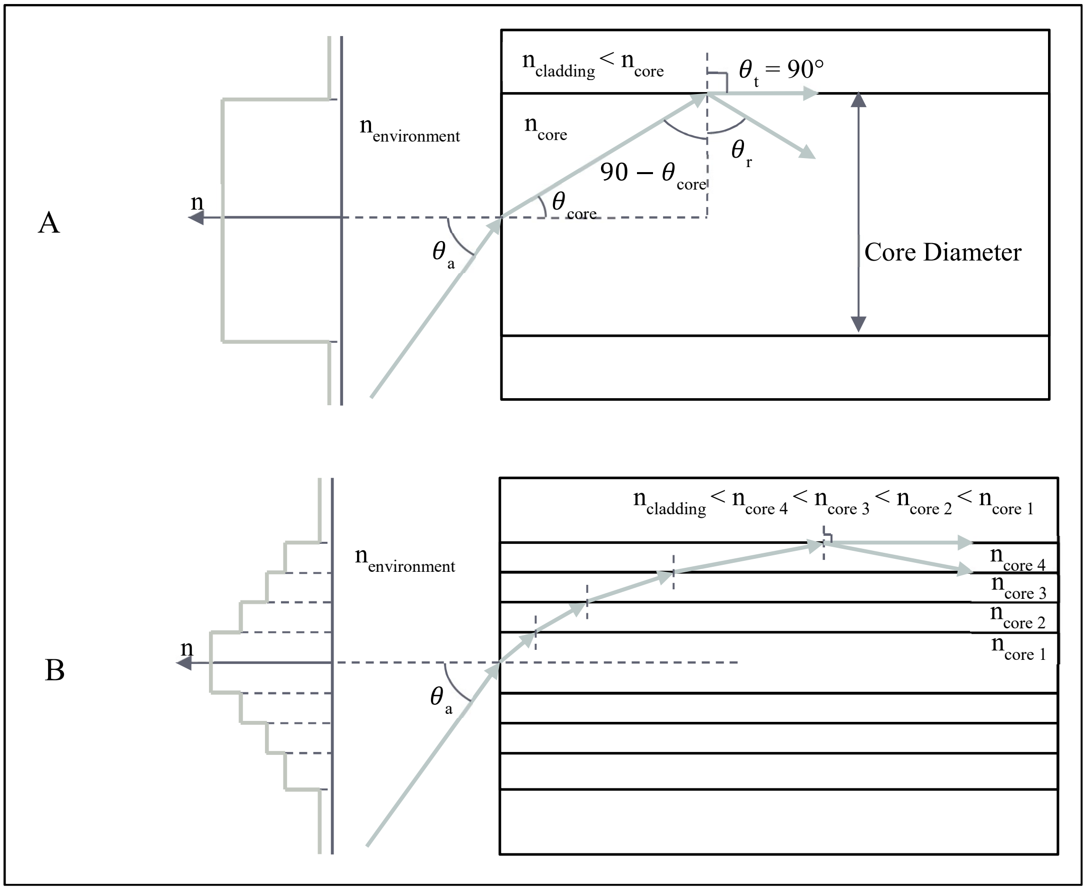



Figure 58: a) Simple 2 index step fiber b) More complex 5 index step fiber

Both of the fibers in figure 58 are called "step index" fibers because their constituent parts' indices of refraction have abrupt changes, similar to that of a step function. If we apply Snell's law of refraction at the core-cladding interface as well as the core-environment interface, we can combine the following 2 resultant equations to get the acceptance cone half angle of a particular step-index fiber:

$$n_{core}\sin(90 - \theta_{core}) = n_{clad}\sin 90 \qquad n_{core} = n_1$$

$$n_{environment}\sin\theta_a = n_{core}\sin\theta_{core} \qquad n_{clad} = n_2$$

$$\Rightarrow \quad \theta_a = \sin^{-1}\left(\frac{n_1}{n_{env}}\sin\left\{90 - \sin^{-1}\left(\frac{n_2}{n_1}\right)\right\}\right)$$

It is important to note that the environmental index of refraction could be different than air which would cause the acceptance angle to change. From this simple substitution of Snell's Law, we can see that the acceptance cone of a step index fiber depends only upon the index of refraction of the core, the cladding, and the environment. Evidently the core and cladding indices of refraction are key elements in the design or choice of what fiber to use for what application. Equation 4 is found by taking the acceptance cone angle equation a step further and quantifying the effective acceptance cone for a fiber that emits or collects in some medium with index of refraction $n_{env}$. A quick look at this numerical aperture equation shows us intuitively that the product of surrounding index and the sine of the acceptance angle is a constant for a particular fiber, which means if the environmental index of refraction is higher than the acceptance angle is smaller making it harder to couple into. This makes sense logically because if the surrounding index increases than the "power" of the first surface that the coupled light hits is reduced because it does not bend as much, as is evident by Snell's law [25].

$$Eqn\ 4\colon\ NA = n_{env} \sin\theta_a = \sqrt{n_{core}^2 - n_{clad}^2}$$

There is another kind of fiber called "graded index" in which the index of refraction profile is not made of step functions but rather some smooth variation. An example of a graded index fiber index profile and cross section can be seen in figure 59. When the index changes continuously instead of in discrete steps this allows for the light to take a sort of curved pathway instead of how it makes multiple turns in figure 58b. The graded fiber can almost be thought of as a step fiber in which there are infinite layers each with different indices that gradually vary from $n_{core}$ to $n_{clad}$ [25].

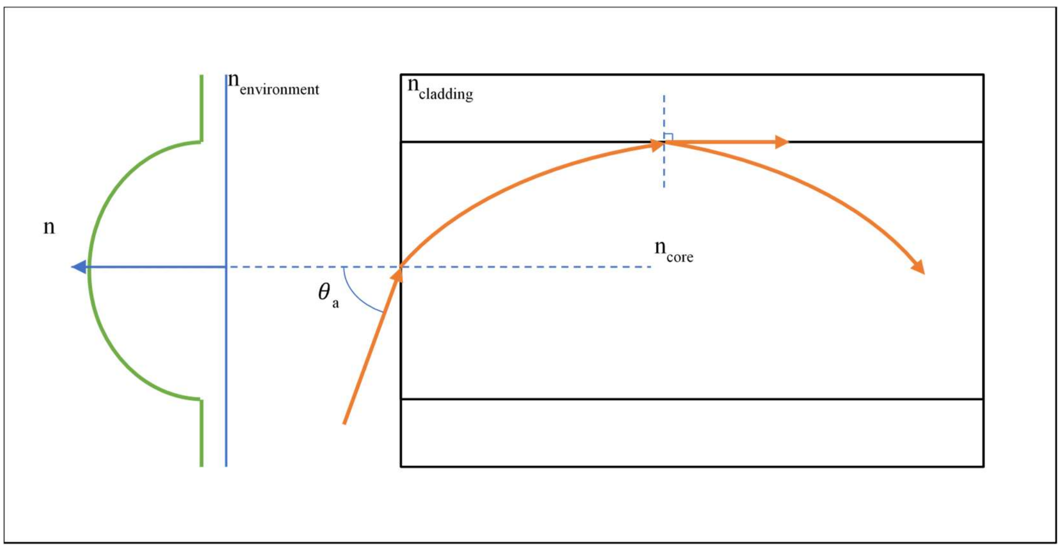



Figure 59: Graded index fiber cross section and index profile.

Since the ratio between the core and cladding indices is such an important characteristic of a fiber, it is important to discuss ways of representing how a fiber will treat light in terms of this ratio. The substitution of equation 5 into equation 4 will yield equation 6 under the assumption that the index ratio of cladding to core is very close to 1.

$$\text{Eqn 5: } \Delta = 1 - \frac{n_{clad}}{n_{core}}$$

$$Eqn\ 6\colon\ NA \sim n_{core}\sqrt{2\Delta} \qquad \Delta <\ll 1$$

### 11.3: Fiber Related Losses

There are a handful of ways in which light power is wasted or lost in a fiber transportation system, one of which is known as attenuation. Attenuation is generally loss of useful optical energy from either scattering or absorbing. The glass material itself is not perfect and contains some impurities and/or misaligned crystals. Sometimes the light will hit one of these impurities and a certain frequency will be absorbed and lost as heat depending upon what kind of impurity. Scattering is another major part of attenuation in a fiber and has to do with impurities causing a light ray to reflect or refract in a direction that does not allow for total internal reflection at the core-cladding interface. A diagram of how energy attenuates in a fiber can be seen in figure 60 and the equation describing the relationship between transmission distance (z) and input power ($P_i$) can be seen in equation 7. Accompanying equation 7 is the absorption coefficient for a particular fiber per kilometer of propagation.

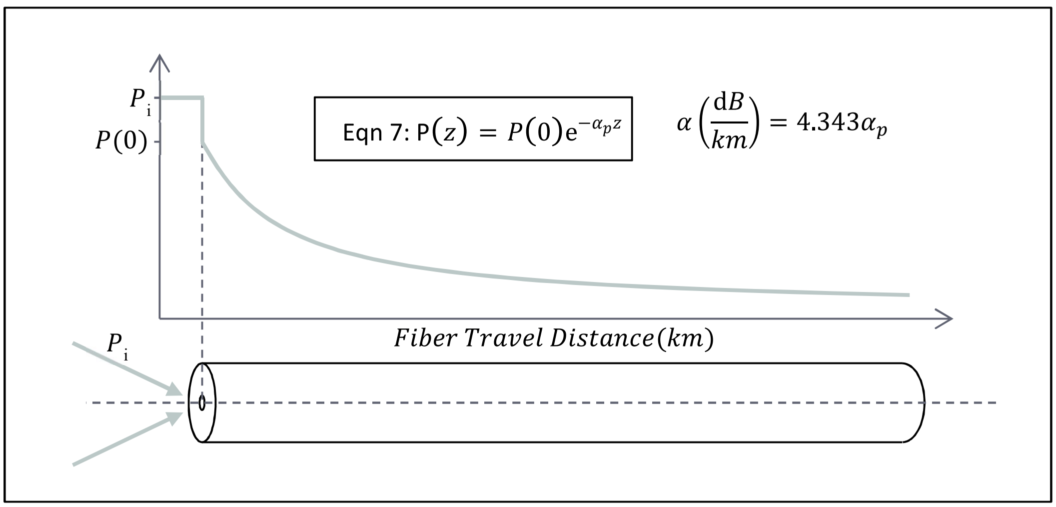



Figure 60: Optical Fiber energy attenuation over a distance z.

The distinction between graded and step index fibers is important to consider when looking for a fiber for a specific function, however a distinction that caries much more weight would be that between multi-mode and single-mode fibers. A single-mode fiber is a fiber in which there is only one real good pathway for light to propagate through without significant losses. These types of fibers generally have a smaller core radius and are harder to couple into efficiently. Multi-mode fibers have a large range of sizes and allow some engineered number of modes to exist, represented by M in equation 8. The number of modes allowed in a fiber increases exponentially with the V-number, which can be calculated from equation 9 with just the numerical aperture, core radius (a), and the desired wavelength. The issue of whether a fiber is single or multi-mode gets much more complex than this but for the sake of this design we chose to use a big diameter fiber meaning there is a plethora of modes allowed covering our broad spectrum of colors.

$$Eqn\ 8:\ M = \frac{v^2}{2}$$

$$Eqn\ 9:\ v = \frac{2\pi a NA}{\lambda}$$

For this particular design project there are many constraints to consider, the biggest of which would probably be the budget. After researching through different fibers and fiber combiners it is evident that the ideal fiber for what we are trying to accomplish would be through the roof on cost. It is for this reason that we are choosing to use a cheap 0.39 NA multi-mode fiber from Thorlabs. Another major reason we picked this particular fiber is because it is multi-modal and has a large core diameter of about 400um or higher. The budget constraint also limits our access to assembly technology and a larger core diameter would make it much easier to deal with the constant realigning during the glue drying process.

For this design project we chose to use a cheap Thorlabs multimode fiber with a large core and large numerical aperture. The experimental values for attenuation as a function of wavelength for the high-OH and low-OH versions of this fiber are shown in figure 61. For reasons discussed above we already decided that the best option for the sake of this demo with our time and money budgets would be a high NA and big core fiber. Attenuation was never really a major concern for us because most fibers are not only not designed for the visible range, but most of them are designed for operation over many kilometers of distance as well. For example, in the communications industry the 1550 nm wavelength is very popular for fiber optic communication network design so naturally there is a much higher demand for fiber that has low attenuation at that wavelength. When viewing the attenuation data for our fiber in figure 61 the first major decision that must be made is whether to get a low- or high-OH content fiber.

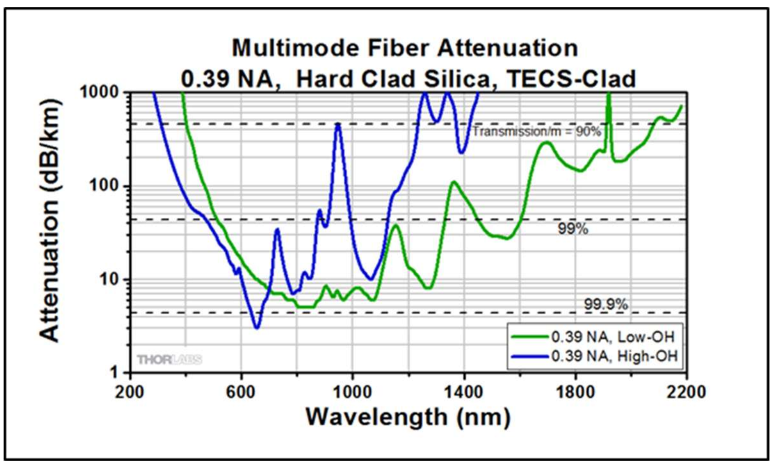


Figure 61: Attenuation data for Thorlabs

The biggest difference between low- and high-OH content optic fiber is introduced during the manufacturing process and generally the higher it is the worse the fiber will perform at certain wavelengths. The OH content, or the amount of hydroxyl ions, is introduced into the fiber unintentionally and is considered a contaminant to some degree. The large spikes in the graph of the high-OH fiber graph (blue) are clearly the biggest differences from the attenuation of the low-OH version of the same fiber. These large spikes in attenuation, or loss, are caused by some of the light being absorbed by the hydroxyl ions. This absorption is conveniently only a major issue at lower frequency (or higher wavelengths) and will not really affect the visible range much at all. Major spikes in the attenuation in the high-Oh fiber can be seen at around 750 nm, 950 nm, 1350 nm, and some higher wavelengths not in the window of the graph. For our demo we only care about the visible wavelengths, specifically the 450 nm, 520 nm, and 638 nm wavelengths. From the graphs we can see that the difference in attenuation for the visible range of the low- and high-OH fibers is nearly negligible over kilometers. For this design project we are most likely not going to use more than a few hundred meters of fiber so for these reasons we chose to get the high-OH fiber.

| Item # | Wavelength Range | Hydroxyl Content | Core Diameter | Cladding Diameter | Coating Diameter | Core / Cladding | Coating | Stripping Tool | Proof Test |
|---|---|---|---|---|---|---|---|---|---|
| FT300UMT | 300 - 1200 nm | High OH | 300 ± 6 µm | 325 ± 10 µm | 650 ± 30 µm | Pure Silica / TECS Hard Cladding | Tefzel | T16S31 | ≥100 kpsi |
| FT300EMT | 400 - 2200 nm | Low OH | | | | | | | |

| Item # | NA | Core Index | Cladding Index | Maximum Attenuation @ 808 nm | Bandwidth @ 820 nm | Max Power Capability | | Max Core Offset | Bend Radius | | Operating Temperature |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Pulsed | CW | | Short Term | Long Term | |
| FT300UMT | 0.39 | 436 nm: 1.466757<br>589.3 nm: 1.458434<br>1020 nm: 1.450174 | 436 nm: 1.406000<br>589.3 nm: 1.398200<br>1020 nm: 1.392306 | 14 dB/km | 15 MHz•km | 2.3 MW | 0.5 kW | 5 µm | 11 mm | 22 mm | -65 - 135 °C |
| FT300EMT | | 436 nm: 1.467287<br>589.3 nm: 1.458965<br>1020 nm: 1.450703 | 436 nm: 1.406000<br>589.3 nm: 1.398200<br>1020 nm: 1.392306 | 10 dB/km | | | | | | | |

Table 14: Thorlabs 300um core Multimode 0.39NA fiber attenuation and power handling data.

The losses with respect to attenuation are not a major issue for our design but there is still the issue of power handling capabilities. A few of the specifications for the low- and high-OH versions of the 300µm core diameter and 0.39 numerical aperture fiber from the Thorlabs website are shown above in table 14. They claim that this particular multimode fiber can handle 2.3 megawatts of pulsed laser power and 0.5 kilowatts of continuous wave laser power. We could technically go down either the pulsed or the continuous wave routes and still achieve our immediate goals for the design, but the more efficient way would be to pulse them for reasons having mostly to do with the human eye and mind. The differences between using the pulsed and continuous wave options in our design are somewhat negligible because of the distances and power levels that we are dealing with are quite small in comparison to a scaled-up version. Eventually, if we wanted to scale this lighting system up to a very large office building it might require a heftier fiber if we wanted to use a continuous wave because we might easily exceed the 500-watt continuous wave power maximum. Pulses would be much more practical than using continuous waves for a scaled-up version because not only would the smaller fiber be capable of handling a lot more total power, but also the maximum frequency of pulses the human eye can comprehend can be taken advantage of for the sake of improving efficiency.

Fiber splicing is another possible source of loss that mostly has to do with how well the fiber ends are cleaved and how well they lined up. Splicing can be done mechanically and for low cost by simply using an index matching gel or glue and a reinforced jacket to protect it. Splicing for this project could be useful for improving efficiency and catering to the needs of the individual wavelengths but that kind of design would require much more time and money. In this design the light is coupled into fibers by lenses and the fibers don’t need any breaks for repeaters so there is no need for any kind of fiber-to-fiber connecting required in the most basic form. Since there is going to essentially be a faraday cage around the laser diodes and backup battery supply we decided it would be convenient to have a fiber optic connector from the main transmission fiber to the fiber within the cage for more scalability. This would also allow for parts to be replaced more easily [19][25]. Even with a good connector there are certain fiber-to-fiber coupling losses to consider starting with the basics; angular, axial, and transverse alignment. Assuming that the fiber ends are perfectly cleaved, and they are of the same type of fiber, there should be no problem getting nearly 100% efficiency in the fiber-to-fiber connection if they are aligned angularly, axially, and transversely. When the connection is between two differing fibers there are more factors to consider, such as absorption coefficient, core radius, and numerical aperture. The following equations are some of the losses we must consider if we were to try and be more diverse and efficient with the fibers instead of using just one type of MMF:

$$\text{Eqn 10: } L(\alpha) = -10\log\left(\frac{\alpha_R(\alpha_E+2)}{\alpha_E(\alpha_R+2)}\right) \qquad \alpha_R \leq \alpha_E$$

$$Eqn\ 11\text{: } L(a) = -10\log\left(\frac{a_R}{a_E}\right)^2 \qquad a_R < a_E$$

$$Eqn\ 12\text{: } L(NA) = -10\log\left(\frac{NA_R}{NA_E}\right)^2 \qquad NA_R < NA_E$$

In eqns. 10-12 the subscript "R" means receiving fiber and the subscript "E" means the emitting fiber. Equation 10 is the loss as a function of each fiber's absorption coefficient. If the emitting and receiving fibers have the same absorption coefficient than the loss comes out to be -10log(1) = 0 dBm. If the receiving fiber has more absorption than the emitting fiber, then there is no loss due to the discrepancy. Equation 11 is the loss that occurs if the fibers have different core radii (a). Intuitively if a skinny fiber is coupling into a wider one there should be no loss attributed to the different radii because physically the smaller core one can fit within the bigger. It is when the receiving fiber is smaller than the emitting fiber that the difference in core radius must be addressed as a potential loss. The relationship in equation 11 is simply found by comparing the cross-sectional areas of each fiber as a ratio. There is another loss attributed to a difference between the acceptance cone angles of the fibers in a connection, described with equation 12. A larger NA corresponds to a larger acceptance cone angle and if the output of one fiber has a cone of light that partially falls out of the acceptance cone of the receiving fiber there would be lost light due to some escaping into the cladding and other layers.

Through the process of actually assembling some of this design we discovered the biggest loss of light by far will be that lost from the coupling into the fiber. There have been a number of issues that mostly stem from constraints surrounding the assembly of the coupling fiber holders themselves with precision needed for proper alignment. We had purchased some quick dry glue that can withstand up to 500 degrees Fahrenheit with the intention of holding the fibers in the holes steadily while the glue set. This proved to be problematic for a few reasons one of which being that the glue did not dry as advertised. The quick 1-minute setting glue was able to hold it in place properly but failed to get hard enough for no movement at all. We must have the fibers secure extremely well or else they will misalign, and a lot of optical power will not even enter the fibers. We tried another glue that takes 30 minutes to set but that turned out to be too long of a time to hold it in place. Moving forward we will rest the fibers and fiber-holders in some controlled fashion while glue dries. A few ideas for cheap methods of aligning the fibers in their holders were proposed but a simple block surface of the right height with clamps should work well enough for this design. A simple diagram shown below is a demonstration of a possible method to glue the fibers in and make sure they are perpendicular to the disk holders.

Figure 62: Fiber holder gluing apparatus.

A few assumptions are required for this mechanism to accurately work as intended. First of all, we need to assume that the "resting" blocks form a perfectly straight corner for the fiber to rest in or be taped down into. The block end that the disk is secured to must be perfectly perpendicular as well as flat as possible. Assuming that the disk holder has a flat side that can be pressed firmly against the end of the resting blocks and secured with some kind of tape or clamp (shown in yellow) this allows for us to ease the fiber through the hole and apply glue while it still stays in this configuration.

### 11.4: Transmission Beam Splitting

Once the lasers are coupled into the fiber, mixed, and transported the issue of splitting up the new mixed light evenly to their output locations arises. Originally the idea was to buy a commercially available fiber splitter that could be used to take the main mixed light transmission fiber and split it evenly to the outputs because there are some out there that do what we need with nearly 100% efficiency, but they are expensive. In the search for a cheaper way to split the light evenly with the efficiency level we need we decided upon the setup shown in figure 63. The setup makes use of simple 50:50 beam splitters and plano-convex lenses to first collimate the light from the emitting transmission fiber then split the power up however many times we want - to be focused down again by more plano-convex lenses into output fibers.

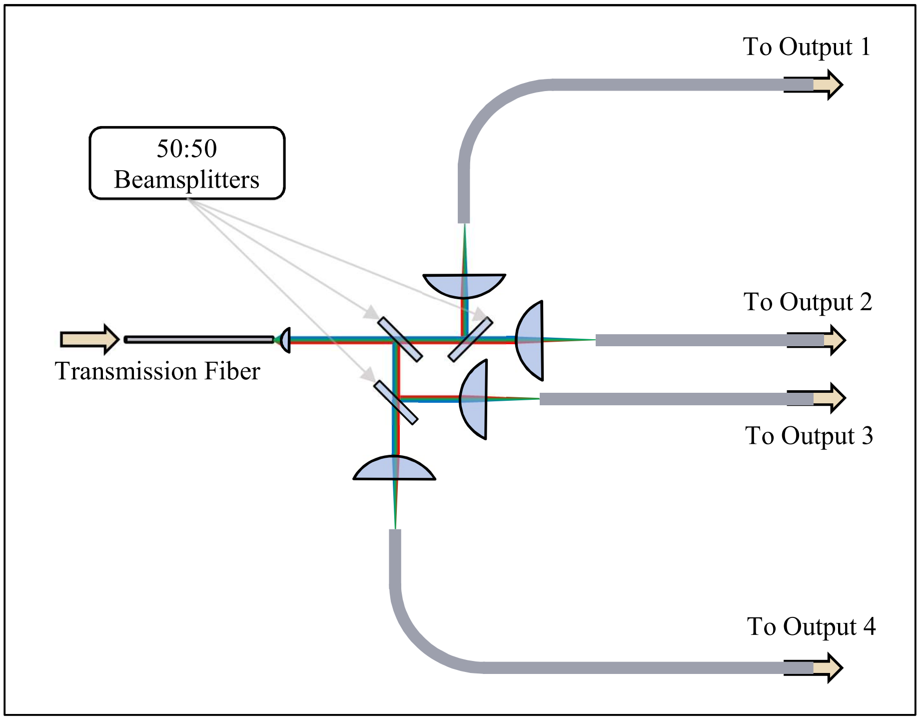


Figure 63: How the Transmission Fiber was Split Evenly Among the Output Fibers

So far, we used cheap Thorlabs 50:50 economy beam splitters that cost a measly $32.90 each. Beam splitters in general also act as parallel plates posing a possible problem with the displacement of the beams passing through however, these splitters are only a millimeter thick, so the displacement should be negligible. There are losses associated with each beam splitter that vary depending upon the wavelength. To figure out how much loss we are dealing with in the figure 63 setup we must consider each output individually and the losses associated with each of the three main wavelengths. Since the lenses' absorption is very small compared to the splitter losses we will ignore it for now and just assume the losses in the outputs all stem from the beam splitters. The light that takes the pathway to outputs 1 and 4 both experience the same loss. Figure 64 shows these pathways and how the original transmitted power must be multiplied by the transmission and reflection coefficients to get the output power.

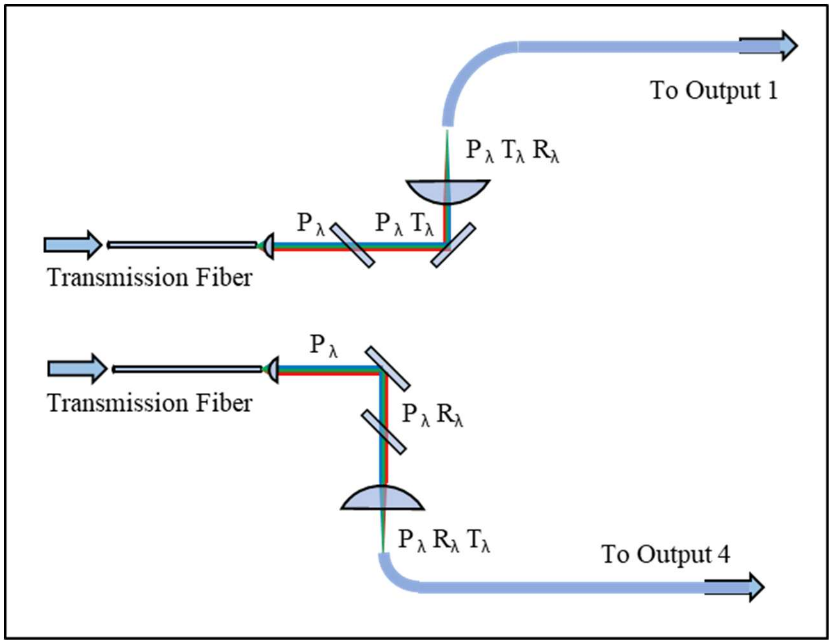


Figure 64: Light Pathway to Outputs 1 and 4 From Transmission Fiber

The 1st and 4th outputs have the same losses, as they both propagate through one splitter and they both reflect off another, just in reversed order. The 2nd and 3rd outputs each have unique losses since they transmit through two splitters and reflect off two splitters, respectively, as seen in figure 65.

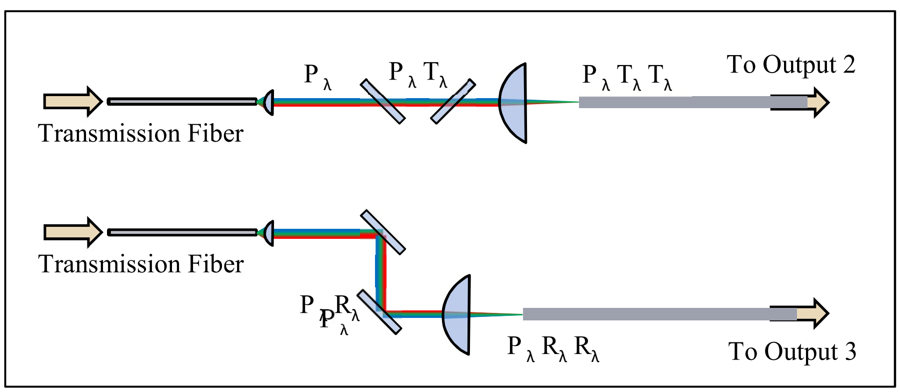


Figure 65: Light Pathway to Outputs 2 and 3 from Transmission Fiber

By using the Thorlabs datasheet for the transmission and reflections of the splitters we can see how efficient this setup is. The coefficients used for the calculations can be found in table 15. Table 16 shows a breakdown of the losses through each output for each wavelength.

| P λ (W) | λ (nm) | % T | % R |
|---|---|---|---|
| 4.4 | 638 | 45.73301 | 50.56379 |
| 1 | 520 | 47.11318 | 49.60828 |
| 7 | 450 | 45.65878 | 50.60305 |

Table 15: Thorlabs Data on Splitter Transmission and Reflection

| Outputs: | 1 (W) | 2 (W) | 3 (W) | 4 (W) | Loss (W) |
|---|---|---|---|---|---|
| 638nm | 1.0167872 | 0.921350144 | 1.12211 | 1.0167872 | 0.322965456 |
| 520nm | 0.23371271 | 0.22193521 | 0.24611521 | 0.23371271 | 0.06452416 |
| 450nm | 1.617373086 | 1.45938492 | 1.792464526 | 1.617373086 | 0.513404382 |
| White | 2.867872996 | 2.602670274 | 3.160689736 | 2.867872996 | 0.900893998 |
| | | | | Efficiency: | 92.73% |
| | | | | Total Power: | 11.499106 |
| | | | | Per Output | 2.874776501 |
| | | | | Standard Dev: | 0.227949917 |

Table 16: Losses in Watts for Each Output Totaled up in the Rightmost Column

Now that the theoretical setup of the beam splitter has been established we must address the practical side of the setup. The previous diagrams of the transmission beam splitter setup were not exactly to scale and only addressed the feasibility of it but included no physical dimensions or sense of size. For this demo we are aiming to do everything as cheaply as we possibly can, and size is not really a primary concern as of now. With more time and money, we could easily make the physical dimensions smaller by getting smaller beam splitters and lenses as there is a lot of material not being put to use in this setup as seen in the to-scale diagram in figure 66.

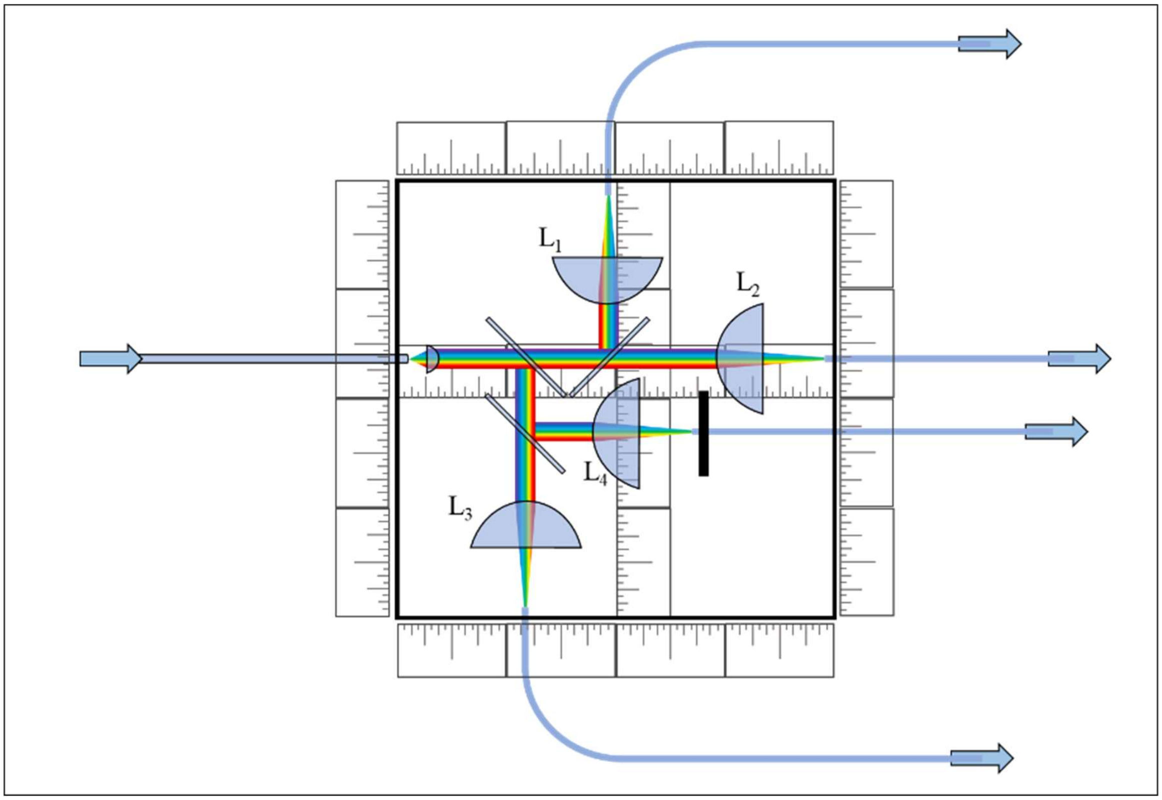



Figure 66: To-Scale Diagram of Transmission Beam Splitter Module

We are using Newport ValuMax Plano-Convex lenses with 1-inch focal length, 1-inch diameter, and about 13mm thickness. The beam splitters we are using are from Thorlabs and are 1 inch in diameter and about 1 mm thick. In the figure above these dimensions are represented to scale within a small enough margin for the sake of estimating the module size. The setup includes 3 beam splitters 4 lenses, a smaller collimating lens, the transmission and output fibers, and some kind of container to hold it all together. The output fiber that the lens 4 couples into will need to have some kind of stand within the walls of the module to hold it up whereas the other three output fibers can simply be held in place via a small hole in the wall of the container. With the splitters and lenses that we are using the smallest we can practically make the transmission beam splitter would be approximately 4 x 4 x 1 inch. This can be achieved by getting the first two adjacent beam splitters as close as possible to each other, with their lower edges touching slightly if we need to. The lower beam splitter could be as close to the first one as 1 inch * 0.5 * sin(45) but that would require the lens 4 to be in the beam pathway of another output. After the split plane wave beams have transmitted through the output coupling lenses the space needed is a matter of measuring 25.4 mm from the principle plane of the lens or finding the focus distance in other words [19].

Another problem that arises in this transmission beam splitting module is the fact that the beam splitters cause dispersion via the parallel plate effect. The parallel plate effect has to do with the fact that when a beam travels through some medium with a different index of refraction than the surroundings, then the output beam has some spatial displacement from the input beam. A parallel plate does not have any optical power technically because the surfaces are flat and parallel to one another, however the temporary change in optical path length as well as angle of the input beam causes it to have some displacement based upon the thickness of the plate as well as the index of refraction of it. This concept is better illustrated in figure 67, where the thickness of the plate has been exaggerated for the sake of spacing out the drawing a little more.

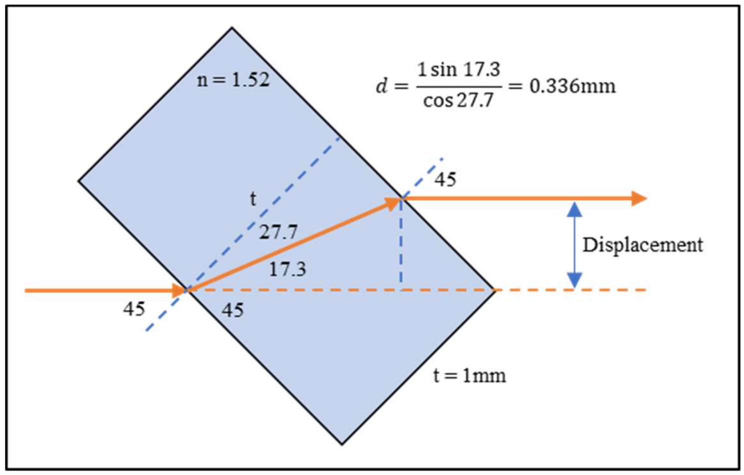



Figure 67: An Illustration of the Parallel Plate Incident Beam Displacement Concept

In the simplified figure above, we see something similar to what will occur when our beams transmit through the beam splitters. The incident angle of the beam is 45 degrees by necessity of the design and the approximate index of the material is 1.52 for the purpose of this proof. When the beam enters the parallel plate, it bends towards the normal by an amount proportional to the index ratio and when it exits the plate it bends back away from the normal by the same amount. During the propagation through the medium the change of angle of the ray causes the output beam to be displaced by a distance that is a function of the thickness and index of the plate. In this design, out plate has a thickness of approximately 1 mm making the displacement about one third of a millimeter. This is the most general case of parallel plate displacement and it ignores the fact that index may change based on wavelength. For our project we do not want the three laser diode wavelengths to separate, we want them to stay together as white light, and this displacement poses a possible threat to that. Since different wavelengths will experience slightly different indices of refraction, the while light hitting the beam splitter will experience some slight color separation. This poses a possible issue only at the lens 1 and lens 3 outputs. When following the four different pathways that the split-up beam will take there are only two in which this separation is an issue and that is due to only transmitting through a single beam splitter and reflecting off another, ignoring the order in which it happens. The light that takes a pathway to output 2 will transmit through two parallel plates that are perpendicular to each other. The following figure 68 shows how this pathway will not have any color separation at the output fiber because the displacement that occurs in the first transmission is undone in the second transmission. The light that takes the pathway to output 4 does not transmit through any beam splitters but in fact reflects off of two of them. Since the angle of reflection is the same as the angle of incidence regardless of wavelength in this case the fourth output does not have color separation issue either.

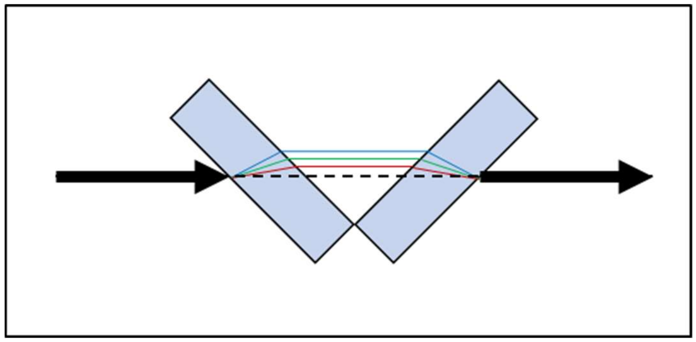


Figure 68: Color Separation Being Undone in the Pathway to Output 2 [19].

### 11.5: Diffusion of Output Light

The final stretch in the light's path from laser diode to tabletop is through that of the ceiling output setups. This area allows for some creativity and flexibility in the design and how it looks because of how easy it is to diffuse a bright light but there are still basic first-principle concepts that must be covered to ensure maximum efficiency. In optics there is a characteristic of refracting surfaces known as the power. The power of a surface has to do with its ability to either focus or defocus transmitted light (positive or negative power, respectively). Evidently a smooth surface has no power to focus rays and a set of parallel incident rays will reflect and still be parallel, as seen in figure 69a.

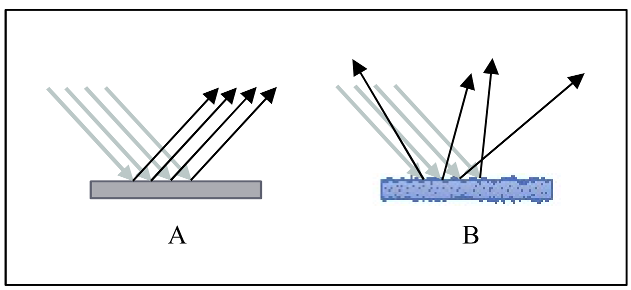



Figure 69: a) Specular Reflection b) Diffuse Reflection

The smooth surface that reflects the parallel rays back out still parallel is known as a specular surface and it does not scatter the incident light very much. One can take the smooth glass surface in figure 69a and blast it with sand to roughen it up and try the same reflection again, seen in 69b. When the glass surface is no longer smooth and consistent the rays that were parallel when incident on the surface each see slightly different incident angles causing them to all reflect in different directions - in an unpredictable manner if the roughness is evenly applied with sufficient randomness. When this happens, the surface can be categorized as diffusive and this is the reason why frosted glass causes images to be blurred when transmitted through them. The primary reason for needing to diffuse the output lights is because it is a potential safety hazard. Any visible light intensity above 5mW can irreversibly damage the human eye and we are dealing with whole Watts exiting a fiber tip that is only a few hundred microns in diameter. Ultimately the output fibers were placed in common light cannisters with a diffusive glass or plastic plate/lens at the end of the cannister, as seen in figure 70.

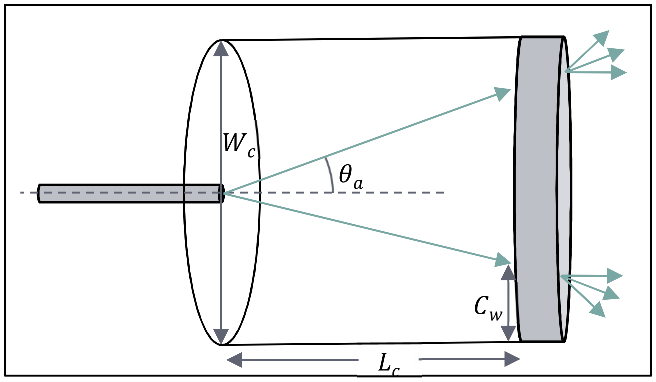



Figure 70: Ceiling Output Setup

When the transmitted light exits the bare fiber end it will do so in a cone with a divergence angle the same as the acceptance cone angle. This little detail is important when considering what length and width of cannister to pick because it dictates the relationship between spot size and cannister length. Ideally, we want the spot to travel through the cannister without having to reflect off the walls while minimizing the ring of wasted diffusive material denoted by the dimension $C_w$. A simple look at the diagram shows that the tangent of the acceptance angle is the ratio between the spot size radius and the cannister length. If we assume that the spot size will take up the whole diffusive surface, we find that this tangent ratio turns into just the cannister radius to cannister length. In the ideal scenario, 100% of the light exiting the transmission fiber would be diffused into the snack shop as usable light. The transmission through the diffusers in this best-case-scenario would look something along the lines of figure 71b. Figure 71a is the setup for just using a regular parallel plate or glass without sandblasting for roughness for comparison.

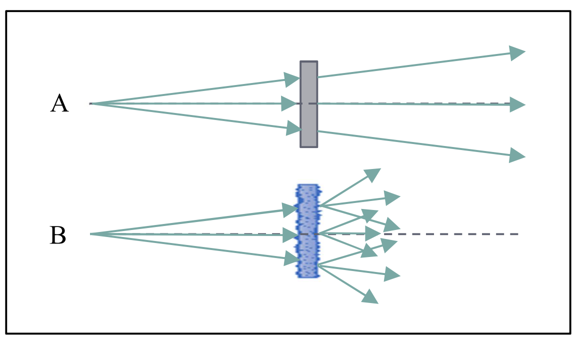



Figure 71: a) Smooth Surface Diffuser b) Rough Surface Diffuser

From the above figure it is evident that the rough surface diffuser would be good for this because it scatters the light – spreading out the somewhat-defocused beam into an even wider cone with less energy density. Even in the case where the whole spot size fits onto the diffusive glass there will still be some rays reflected toward the output fiber that need to be redirected in a useful direction. Figure 72 shows how if the cannister is either too long or too narrow the spot size would be bigger than the diffuser and some will bounce off the walls of the cannister and back into the diffuser.

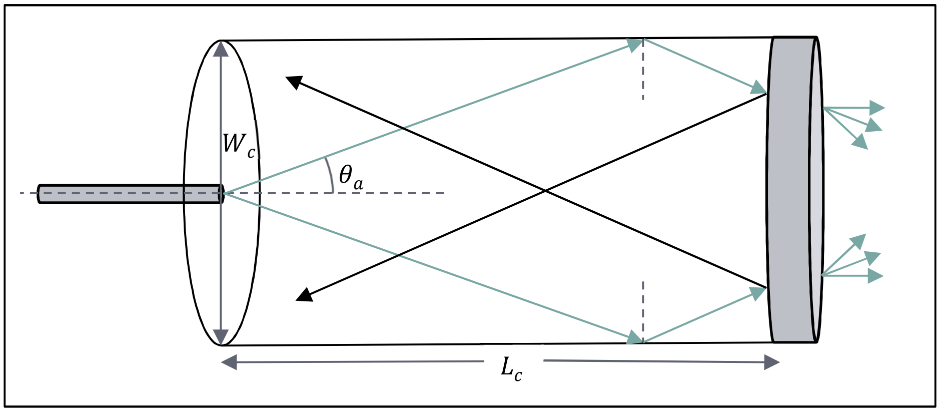


Figure 72: Output Light Cannister with Reflection Issues Drawn

This reflection off the cannister should not be a problem because they are highly reflective for visible for the sole purpose of reflecting stray light back into the diffuser, however there is still the issue of reflection off of the diffuser back toward the fiber. The black arrows in figure 72 represent the "problem" rays of light that must be saved from being wasted. One option that might work for collecting these wasted rays and directing them back to the diffuser would be that of a mirror surrounding the output fiber with a hole in the middle for the fiber end. This mirror could ultimately be of any power we want as long as it reflects the rays back in the general direction of the diffuser – they can be directed off the cannister walls as well with minimal loss. A simple flat mirror with a hole in the center would be the cheap and easy way to try and save some lost light however there are some other geometries of mirror to consider such as an array of corner cubes. A corner cube is a mirror configuration which takes incident rays of light and sends them back in the other directing parallel to the incident ray. A corner cube is basically three flat mirrors that make up the corner of a cube and are all perpendicular to one another. For the sake of explanation, a two-dimensional version of a corner cube is basically two mirrors with a dihedral angle of 90 degrees. A diagram showing how perpendicular mirrors in two dimensions can deviate an incident ray by 180 degrees is shown in figure 73.

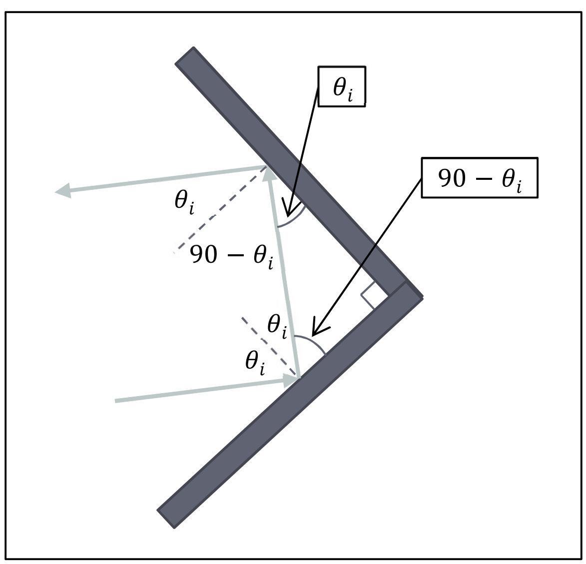


Figure 73: Corner Cube Proof of Concept in Two Dimensions

By adding on a third perpendicular mirror to the dihedral mirror shown in figure 26 we can see the formation of a corner cube. Since there will most likely not be much back-reflected light to worry about the mirrors of the corner cubes will not need to be extremely high quality. If we decided to try and use corner cubes we could just use pieces of solar tube that we are already using for other mirrors in the coupling stage of the design. These solar tube mirrors are quite cheap and have a good enough reflection for the visible range needed to this design.

## 12.0: Project Milestone and Budget:

During Senior Design 1, we a complete design planned, diagrammed, and calculated. A full part list with multiple options and sources for each part was completed. Any optically rigorous components were tested with real working parts to ensure they will work after system-level implementation. Many of the devices and parts were purchased during Senior Design 1 for analysis, planning, and adjustment of overall goals to ensure the prototype is physically possible and financially feasible.

For Senior Design 2, the current plan is to create a working prototype fairly early in the semester so that the logistics of presenting the working product can be thoroughly realized. A current option is to install the system in a 24-hour computer lab in the CREOL, which has been approved and encouraged by Mike McKee, the associate director of academic support services. This would allow a real-world application to be presented and the feasibility of MADLIS could be proven. For a main quantitative goal, the overall system should output over 5 lux per square foot in a room that is at least 200 square feet, with an efficiency of at least 100 lux per watt applied to the diodes.

Currently, the estimated project budget is $2,000.00, provided by Derek Daniels for any of the core components of the system included in the provisional patent. Any additional add-ons or new ideas implemented by the other three group members can be financed by the person with the idea.

### 12.1: Parts to be Used

Table 17 shows the list of items used in the initial prototype demonstration of MADLIS. Many other materials were used that were not included in the prototype due to failures during several trial-and-error processes used in the design process. Some other incidental :

| Description | Source | Quantity | Price Each | Price Total |
|---|---|---|---|---|
| Ushio HL63290HD 2.2W 638nm Laser Diode | Worldstar Tech | 1 | $98.00 | $98.00 |
| Nichia NUGM02 900mW 520nm Laser Diode | DTR's Laser Shop | 1 | $95.00 | $95.00 |
| Nichia NUBM44-81 7W 450nm Laser Diode | DTR's Laser Shop | 1 | $80.00 | $80.00 |
| 1" ID Polycarbonate Tube | Amazon | 1 | $14.53 | $14.53 |
| Plano-Convex Lens, 6.35mm Dia., 6.4mm EFL, AR | Newport Corporation | 2 | $53.00 | $106.00 |
| Plano-Convex Lens, 25.4mm Dia., 25.4mm EFL, AR | Newport Corporation | 8 | $27.00 | $216.00 |
| Multimode Fiber, 0.39 NA, High OH, 300μm Core | Thorlabs Inc. | 50 | $1.68 | $84.00 |
| EBS1 Economy 50:50 Beamsplitter | Thorlabs Inc. | 3 | $32.90 | $98.70 |
| JB Weld Plastic Bonder, Black | Walmart | 1 | $5.88 | $5.88 |
| JB Weld MinuteWeld, Clear | Walmart | 2 | $4.84 | $9.68 |
| PVC Junction Box, 4x4x2 in. | Home Depot | 1 | $7.09 | $7.09 |
| Silverstone ML05B Computer Case | Amazon | 1 | $45.79 | $45.79 |
| Lexan 10"x8" Polycarbonate Sheet | Home Depot | 1 | $4.98 | $4.98 |
| Optix 20"x32" Acrylic Sheet | Home Depot | 1 | $17.98 | $17.98 |
| 31/32" High Speed Steel Drill Bit | Victor Machinery | 1 | $18.42 | $18.42 |
| Aluminum Heatsink, 150x69x37mm | Amazon | 2 | $14.39 | $28.78 |
| ATmega328 Microcontroller | Digi-Key | 1 | $1.96 | $1.96 |
| Arctic Silver Thermal Paste | PXT Store | 1 | $6.67 | $6.67 |
| URCERI Handheld Digital LUX Meter | URCERI | 1 | $19.99 | $19.99 |
| Wire Spool, 18AWG, 35 ft., Black | Home Depot | 1 | $8.70 | $8.70 |
| 3/32" Heat Shrink Tubing, 8-Pack | Home Depot | 1 | $1.99 | $1.99 |
| 0.170" ID x 10' PVC Clear Vinyl Tube | Home Depot | 1 | $2.82 | $2.82 |
| Halo 6" Aluminum Lighting Housing | Home Depot | 4 | $7.49 | $29.96 |
| MOSFET CSD17318Q2T | Digi-Key | 4 | $0.47 | $1.88 |
| 0.1uF Ceramic Capacitor | Digi-Key | 10 | $0.06 | $0.61 |
| 22uF Ceramic Capacitor | Digi-Key | 2 | $0.51 | $1.02 |
| 47uF Ceramic Capacitor | Digi-Key | 2 | $0.49 | $0.98 |
| 3.3uH Inductor | Digi-Key | 2 | $0.48 | $0.96 |
| 10kΩ Resistor | Digi-Key | 2 | $0.52 | $1.04 |
| Step Down Switching DC-DC converter | Digi-Key | 2 | $0.00 | $0.00 |
| 56.2kΩ Resistor | Digi-Key | 2 | $0.26 | $0.52 |

Table 17: Complete Part List

The total price for the parts shown in Table 17 above is $1009.93, which is well below the initial budget allocation of $2,000.00. There were several factors contributing to the reduced cost of the prototype, including the ability to create the fiber combiner and splitter using relatively inexpensive optical components instead of purchasing a prefabricated commercial unit.

## 13.0: Photographs of Research and Experimentation:

Since the clearest way to understand much of the experimentation for this project is to see what was done, several photographs of critical stages of experimentation and development are added here and shown below in photos 3-10. Each photo has a basic description of what stage of the process is being experimented.

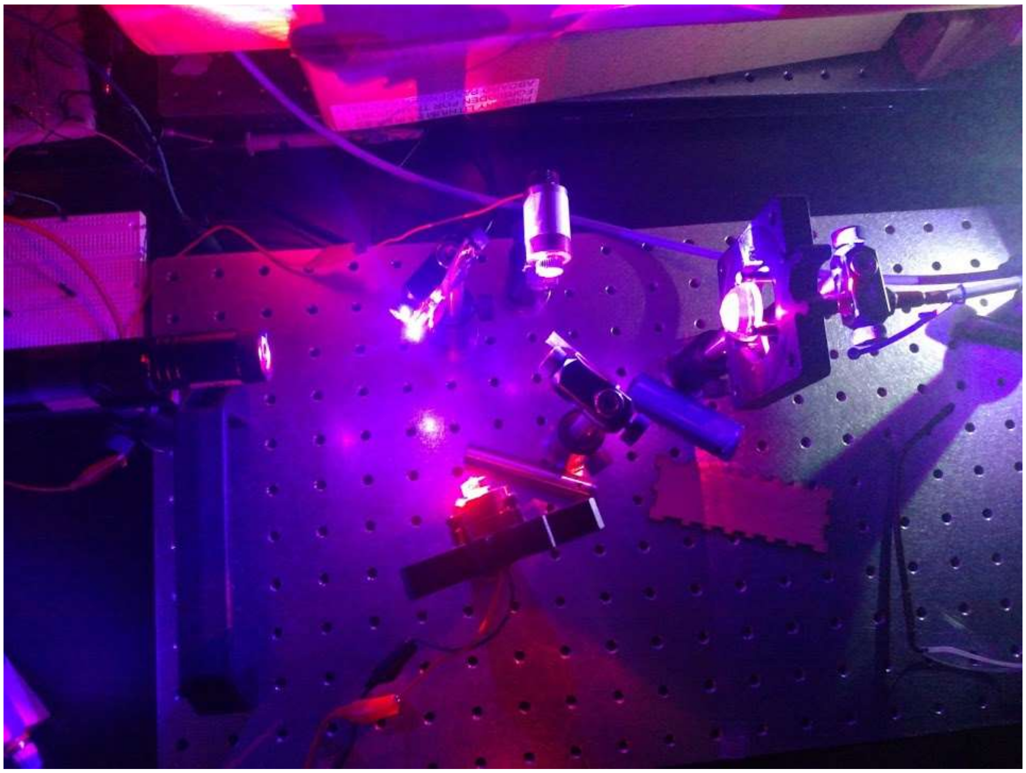


Photo 3: Free-space combined RGB coupling using mirrors

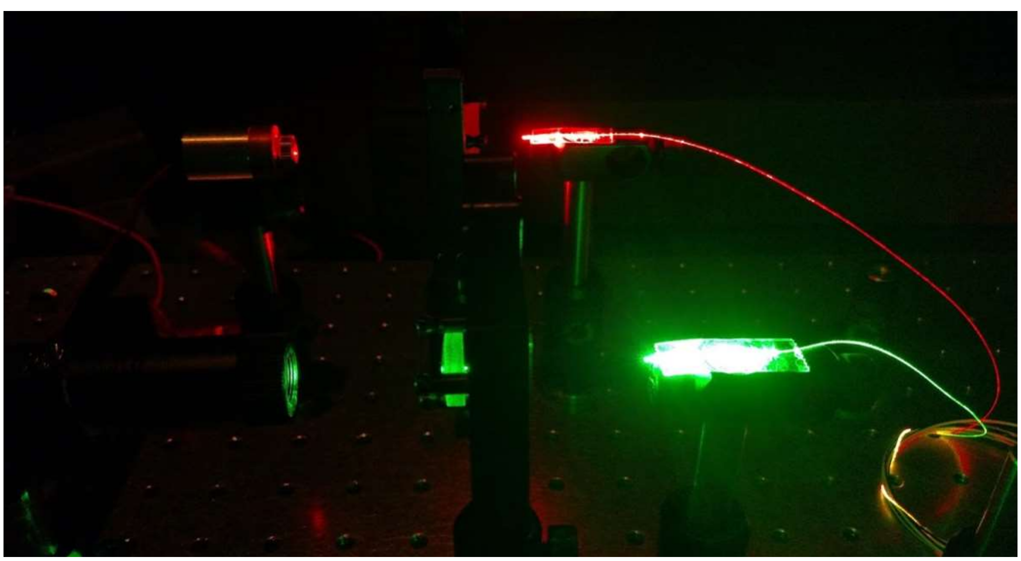


Photo 4: Inefficient results with commercial fiber combiner

Photo 5: First time achieving white light from a single multimode fiber

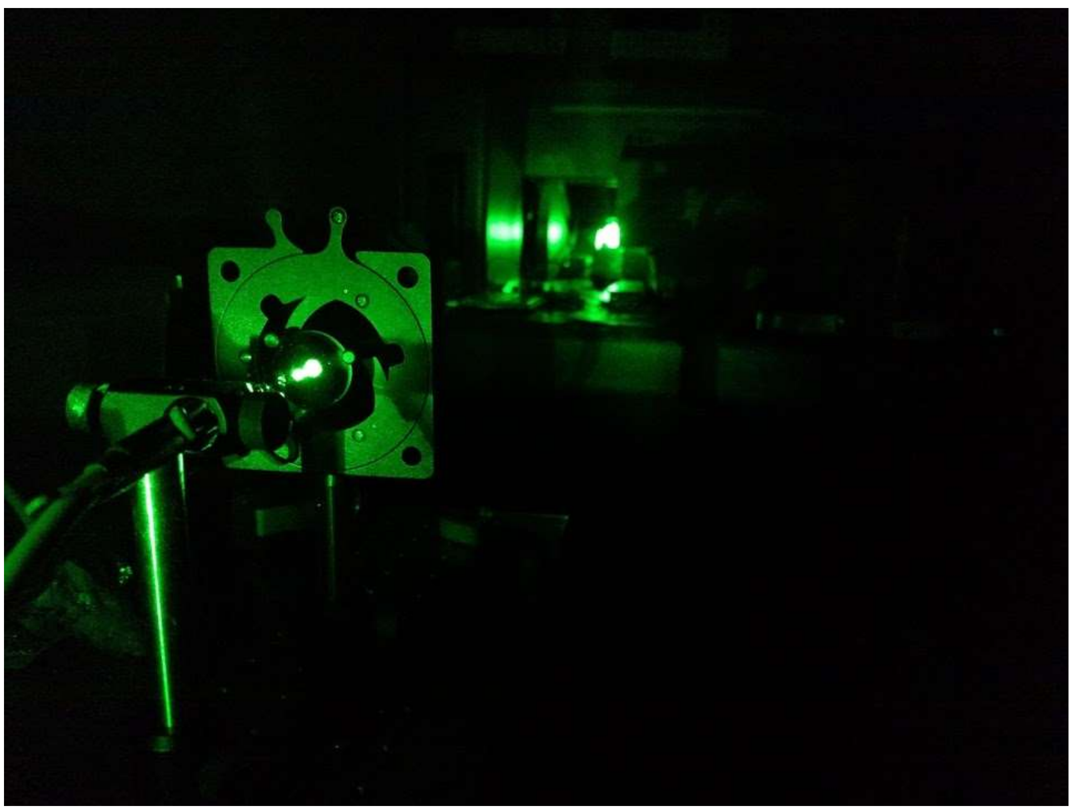


Photo 6: Testing beam collimation out of a fiber by using a plano-convex lens

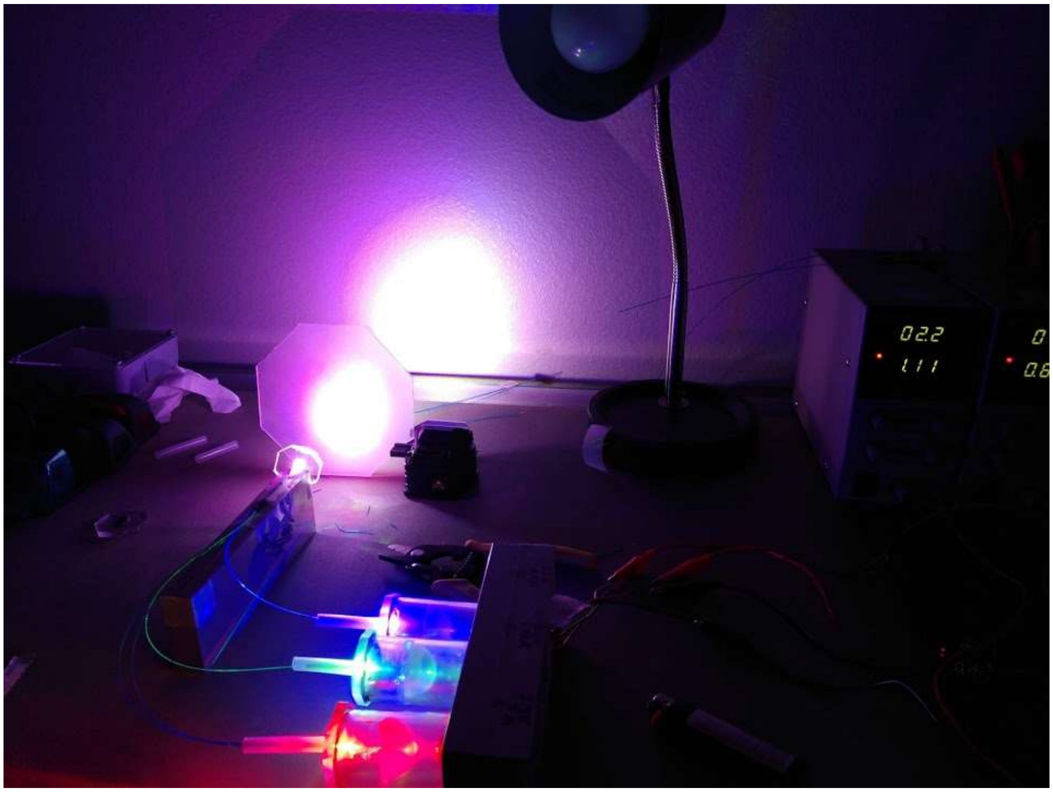


Photo 7: Achieving speckle-free white light from fiber-coupled laser diodes

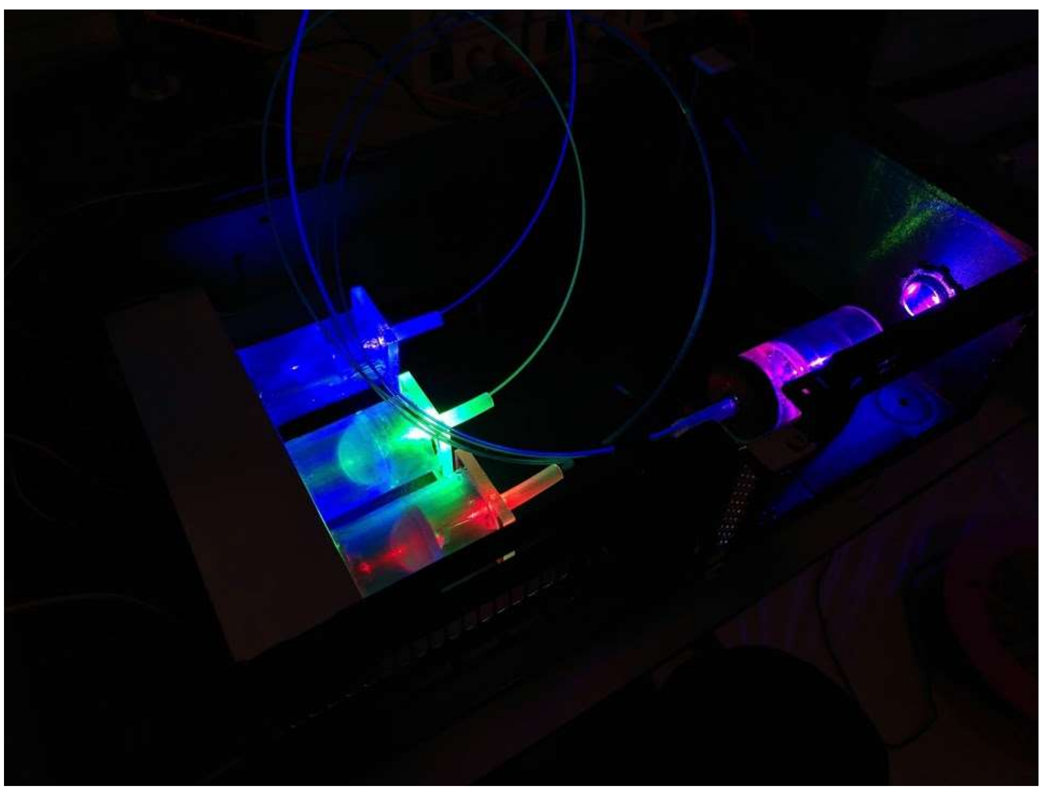


Photo 8: Utilizing deionized water in the combiner to reduce reflections

Photo 9: Testing the effectiveness of the splitter design

Photo 10: Achieving four even white outputs from the system

## 14.0: Final Project Changes:

Throughout the past couple semesters there have been many trials and errors in the overall project design and construction. Along the way there were some electrical issues as well as optical issues that could be, and in some cases were already improved upon.

The overall design of the user interface had little modifications, changes to the button functionalities and menu functions were made to fit the main requirements to make the controller work with the system. A custom coded menu system was made to more efficiently use the memory on the microcontroller, as other available menu systems would be filled with unnecessary variables that would eat up memory.

The Menus that were first proposed: Color, Temperature, Luminosity, and Power, were not all suitable, or so to speak, practical. The Temperature and Power menus were the least needed as they could be measured through other means, thus they were replaced with the Profile and Time menus. The Profile menu gave more customizability in how they wish for the lighting to operate at specific times of the day and gave an easy way of saving and loading custom colors assigned by the user. The Time menu allowed for accurate time keeping; letting the user set up the time to their local time. The Luminosity menu had its name changed to brightness to better appeal to all users, as well as the fact that the value shown does not reflect the actual luminosity value of the light output.

A few issues were encountered with the microcontroller. The Pulse Width Modulation pins on the controller don't all have equal steps of duty cycle frequency due to the fact that the timers on some pins were different in bit count, thus resulting in different levels of duty cycle frequency. The output of the pwm pins had to have the same frequency. Unfortunately, out of the 3 pins we had picked out, 1 did not match the other 2. Thus, the closest to our needed frequency was a lower frequency, about halfway. Fortunately, that did not affect the total outcome of the lighting output.

Other issues encountered were in the construction of the user interface. The input push buttons were, at first, not sending proper input to the controller due to how close the wiring was to the power line. Thus, to overcome any noise, we opted for a second separate cable to handle the input for the buttons. This not only kept noise out of the way, but it fixed the issue, allowing the input signals to get through.

Had we gotten extra time, we could have implemented wireless Bluetooth technology to send the signals wirelessly to the user interface, which in turn, would be battery powered. This would have allowed the UI to be placed anywhere, within a reasonable range, in the building.

Some changes were added to the electronics in the final project along with what changes should be made if a second version were to be created. The changes added into the final product were the configuration for the pulse width modulation mosfet, the current sensing and switching circuit, and some add-ons for the LCD and control section of the PCB.

For the pulse width modulation. The initial design used a p-channel mosfet. Originally not much was thought of for this design as the mosfet would achieve the same regardless of what type of mosfet it was. Well, after more research, realizing that this application would be more of a switching application, the n-channel had a considerably smaller rise and fall time for a decreased bottle neck in switching speeds. In terms of power over the mosfet, having a smaller resistance over the drain and source was preferred as 2.1A would pass through this resistance. N-channels (specifically a power mosfet) have lower resistance compared to p-channel mosfet. Therefore, in switching applications the n-channel was the one to choose. The original mosfet chosen was only rated at 300mA as well and would not work in this application. A small resistor (around 470 ohm) was used in series between the signal and the gate terminal of the mosfet along with a large resistance (around 1 megaohm) was placed in parallel with the gate and source terminals of the mosfet. This parallel resistance pulled the voltage down to ground in states that were supposed to be off, as when this resistance was not there the gate would sometimes be left hanging in logical hi.

The current sensing circuit became much simpler with an integrated circuit that reduced the footprint of the original design significantly and achieved more consistent results. This IC used the voltage from the primary source in series with a shunt resistor to then drive a mosfet off and not have any current leave the secondary source. Therefore, with the mains voltage being the primary voltage source and the battery source being the secondary source, whenever the mains voltage was on, the battery source was off and whenever the mains was off, the battery was on. A switch was placed on the output of the circuit and when off would provide no power to the circuit. This switch could have been placed in a better location as the battery would drain a very small current when off regardless if it was on or not and therefore would drain the battery over extended periods of time.

Headers were added to the LCD screen and UI to speed up the testing portion of this circuit. This proved to be correct as soldering the wires directly to the board added lots of mess, was less organized, and led to only one person working on the board when two could work on the board and LCD screen. Also, pulldown resistors were added for the buttons onto the board itself instead of having external resistors for easier cable management and better organization and consistency.

For changes in the next iteration of this board if the project were to continue go as follows listed in importance. Creating a more consistent current source for the diodes. Diode protection for over voltage and current spikes. Testing compatibility with the components and network connections. Testing voltage regulator with the expected loads. Using precision resistors for the voltage divider in the voltage regulator circuits.

As pulse width modulation was being used, a constant current supply to the mosfet would create some loss but would be able to consistently create the color needed. These diodes can be constantly powered with DC current and with the active cooling in the case this is not an issue. However, the improvement to be made is to either create a smoother current supply with a more carefully engineered switching regulator design or to decrease the efficiency but have an easier design with a smaller footprint and use a linear regulator. There are some current source integrated circuits that could be used as well with decreased efficiency but is something to be considered.

More protection for the diode should have been designed, these simple protections should have at least been over-voltage protection, current limiting, and using better fuses. For simple over-voltage protection a Zener diode in parallel with a breakdown voltage of what the close to maximum voltage over the laser diode should be. This way the Zener acts as a reference to ensure that the voltage across the laser diode never goes to a voltage that is dangerous. Current limiting would also solve this issue as overcurrent could destroy the diode as well. There are many designs for this and is something that should have been considered from the start to ensure that the most critical components of the design were protected. A faster fuse would have saved one of the diodes that were destroyed. The fuse originally designed was a slow act fuse which allowed too much current to the diode and destroyed it very quickly. A fast-acting fuse limited to the correct current would have saved lots of time and money for the component and a fuse is much easier to replace.

Testing these networks together with the loads attached would have saved more time in the PCB design. These circuits worked well on their own and consistently over time. But when attached to the other networks, more components were needed to be added due to the networks interacting with each other. Better preparation would have decreased significant time during the board testing stages.

Overall, on the optics part of the project, most of the ideas for the construction of the splitter and source unit went according to plan but some slight changes were made. For one we incorporated some water in the combiner and splitter designs in order to match refractive index a little better for the coupling down into the fiber to be possible. Having water on one side of a lens instead of air lowers the optical power of that lens and the beam in turn has a smaller diameter at the next surface making it possible to fit all the light within the optics that we bought. The fiber we used was a little bigger than the original fiber as well to make it a little easier on the gluing process to find the focus.

The splitter box originally was going to be within an electrical box but we decided that it would be much easier to 3D print a splitter (using our own plastic) that the lenses and splitters would be able to rest inside of while gluing. This print took about 48 hours and warped slightly but still worked within enough error for our proof of concept to work. Within one of the lense tubes on the box there is space for water to go on the transmission fiber input which reduced the divergence of the exiting beam that hits the beam splitters. This slight change caused a minification of 0.75 and made the beam fit on the splitters, helping us get more efficient light coupling into the output fibers. The output cannisters had a slight change made to them in that the reflective solar sheet that was originally going to be flat with a hole proved to not fit all too well and was not the best geometry to use. Instead we formed a cone with the solar sheet and had the small end of the cone over the cannister hole where the bigger end was the inside diameter of the cannister. This change allowed for more of the diffuse reflection within the cannister to be covered with more reflective specular surface, allowing for maximum usage of the light that bounces back up from the diffuser.

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# Appendix B - List of Figures

# Appendix C - List of Tables



# Appendix D - List of Photos