Mixed and Distributed Laser Illumination System (MADLIS)

Hunter Cohen, Derek Daniels, Melvin Ramos, and Ian Shearer

Dept. of Electrical Engineering and Computer Science and the College of Optics and Photonics, University of Central Florida, Orlando, Florida, 32816-2450

***Abstract* — MADLIS is a new, patent-pending 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.**

***Index Terms* — Color, diode lasers, driver circuits, lighting, optical fibers, programmable control.**

I. Introduction

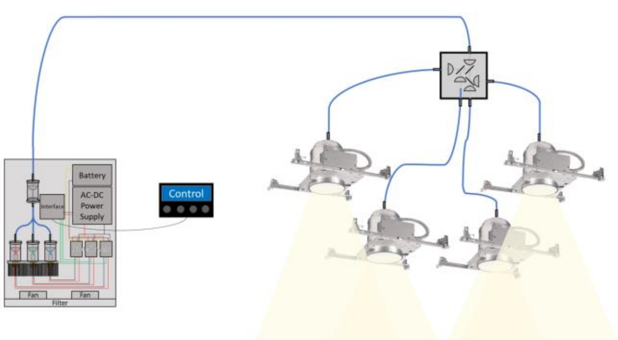

Fig. 1. Estimated relationship between the time an author spends reading these instructions and the quality of the author's digest article.

As shown in Figure 1 above, MADLIS is different from existing lighting systems because the separately-located, user-tunable light source 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.

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.

II. Safety

For this design there are 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 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 2:

Fig. 2. Class 4 laser safety label (MySafetyLabels).

There are a handful of general safety precautions we will have to take 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 is 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 is a possibility for something to fall at an angle that could cause eye damage. Assuming that everything is firmly strapped down there is 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 have taken in our project are having laser safety glasses as well as renting a storage unit for initial assembly and converting a residential room to a cleanroom off campus for more advanced assembly and alignment. Generally, an eye safe level of laser power for visible range is up to 5mW, whereas this prototype of MADLIS uses up to 7 W of blue, 2.2 W of red, and 1 W of green. During the assembly and alignment process of MADLIS, a various set of laser safety glasses were worn, which each reduced the laser power incident on the user's eyes by approximately 1000 times. When the final modules are completed they will not be considered lasers since the fiber output is encased within a diffusing can with an output diameter of several centimeters and a divergence on the order of a radian. Therefore, the nominal ocular hazard distance (NOHD) from the output is less than zero, meaning there is no hazard for human eyes from this project.

III. Controls and User Interface

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 LEDs 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 and second buttons handle navigating to different menus, the third button handles selecting the available settings in said menu, the fourth button for navigating back or back to the main menu.

The LCD screen displays 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

- Brightness
- Profiles
- Time

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 Brightness menu displays the current brightness value for the output of the system. The Value of the brightness is used as a ration to modify the overall value of the output of the laser diodes. The brightness value can be modified to instantly change the lighting. The Profiles menu contains the profiles of color values and the time which the said colors will be applied to the output of the system. The user can load a profile's color setting, change the profile's color settings, set the time of which the system will use the profile settings, and enable or disable the time of activation for the profile. The Time menu contains the means to change the current time of the device (the hours and the minutes).

A. The Controller

This project uses 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.

The Micro controller's tasks consist of:

- Time keeping
- Pulse Width Modulation of each individual laser diode (color control)
- Having settings held in memory
- Outputting the current settings to the user via LCD screen
- Taking input via buttons

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.

B. 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 an essentially 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 decided to implement color control in this project is 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, as we would have to do stuff. 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 can produce a larger range of colors outputted 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.

IV. 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.

For the power layout, the two inputs are either the wall outlet or the batteries as the power sources as seen in Figure 2 come from the beige inputs. All power controlling besides the diode drivers is 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, is 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 are 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 are 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 is placed. That way regardless of what power is being use the fuse will work in case the current is too high.

A switch is placed right before the current sensing that will switch off both battery power and wall power of the circuit. The switch allows 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.

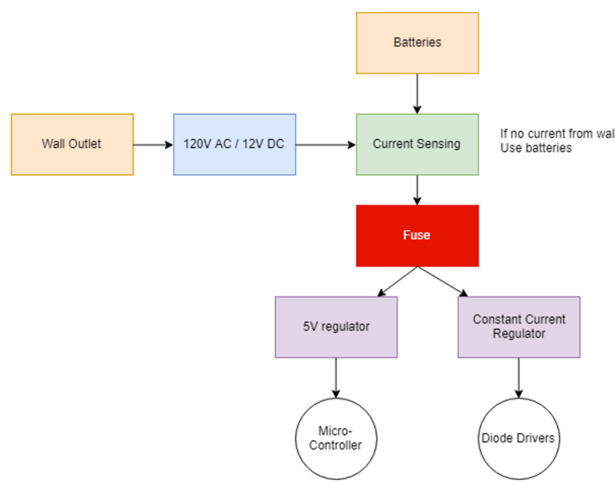

Fig. 3. Estimated relationship between the time an author spends reading these instructions and the quality of the author's digest article.

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 is a PCB that feeds in electricity from the 120V

AC / 12V DC converter. With this conversion, the fault sensing switch is constantly reading if there is any current coming from the wall power and if not will switch over to the power. From this there are connections made to all other sections. One more conversion will occur for the microcontroller as it needs 5V rather than the 12V coming from either source. The 12V is used to power the laser diode drivers.

As seen in Figure 4 below, the PCB for the diode driver is on its own for each diode. As there are three diodes to obtain the full range of color there are three connections from the power board to power these diode drivers. These drivers are connected directly to the laser diodes, 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 not 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.

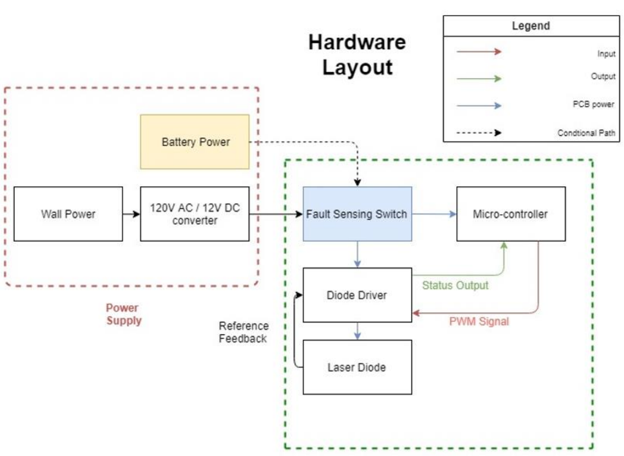

Fig. 4. Hardware Layout

A. Electrical Standards

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 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]

V. Laser Diodes and Fiber Coupling

There are 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. Each laser diode is in its own copper holder which is then installed in an aluminum heatsink with computer fans blowing over the heatsink. Thermal compound is placed between the copper module and the aluminum heatsink. The computer fans are simple 80mm 12VDC fans which are wired in series with the 12VDC power supply so that the fans are running at half of their operating voltage and approximately half of their nominal speed. This is to decrease noise and power draw while still maintaining some airflow.

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 Figure 5 is a comparison of commercially available red, green, and blue laser diodes.

Description	Source	λ (nm)	Pwr (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

Fig. 5. Comparison of commercially-available red, green, and blue laser diodes.

This prototype of MADLIS utilizes the HL63290HD red, NUGM02 green, and the NUBM44 blue laser diodes. From the distributers they come preconfigured with a simple collimating lens, which helped in the process of coupling into the fibers. A simple anti-reflective coated plano-convex lens was placed after the laser diodes to focus the beam down into the fibers.

VI. Fiber Combining

The fiber combiner became much more complex than the initial theoretical design through experimental iterations of the design. By modeling basic lens theories in Zemax OpticStudio and minimizing the size of the image which would be placed on the end of the transmission fiber, the following layout was devised, as shown in Figure 6 below:

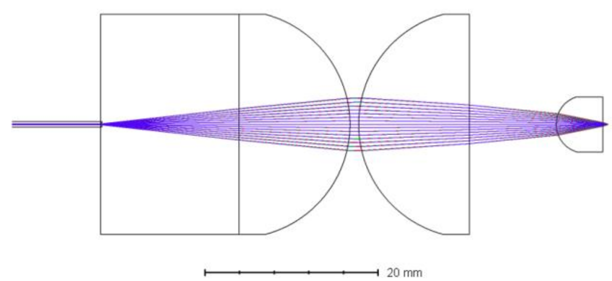

Fig. 6. Fiber combiner optic model. The left-to-right order is: a bundle of fibers is bonded tightly together into the end of a tube so that they protrude into water, where the beam travels through water until it strikes the planar side of a plano-convex lens, which then collimates the set of beams which then are focused down by another plano-convex lens onto the convex side of a small plano-convex lens, which minifies the image of the fiber bundle onto a single fiber optic cable.

The fiber combiner is held together by a polycarbonate tube and the lenses are held in place and water-tightened by a two-part clear epoxy. The water used is deionized and purified to ensure the beam has little attenuation and the optics stay clean.

VII. Fiber Splitter

The fiber splitter was designed as a new product since existing commercial fiber splitters were either too expensive, not efficient enough, could not handle the power MADLIS uses, required fiber splicing, had too large of a minimum order for a reasonable cost, or were not designed for the wavelengths MADLIS uses. After several versions were attempted, the final design used is shown below in Figure 7:

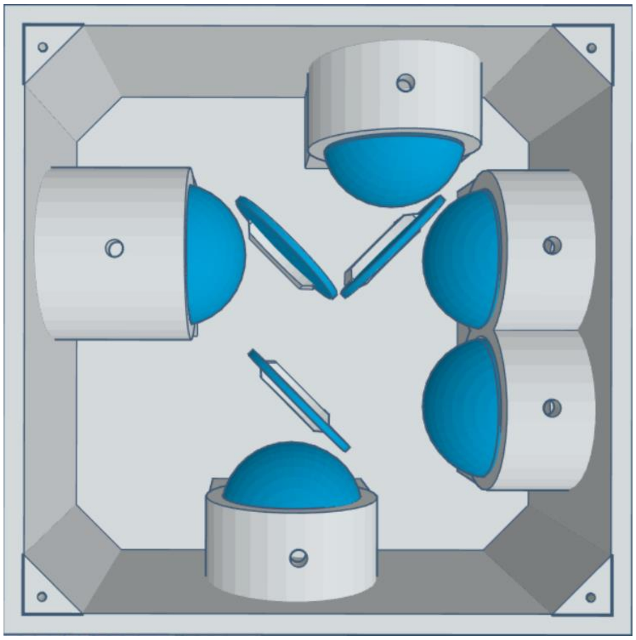

Fig. 7. Fiber Splitter. The layout shows the larger tube on the left side which is filled with water with the transmission fiber entering from the left side of the box. The longer tube has a plano-convex lens which collimates the light exiting the transmission fiber. The collimated light then strikes three beamsplitters which split the collimated light into four collimated beams. These four collimated beams then each strike the four plano-convex lenses on the smaller tubes where the light is directed into four fiber optic cables.

The fiber splitter has a clear panel placed on top which is sealed with epoxy and a thin strip of electrical tape to attempt to seal out dust from the free-space optics within.

VIII. Outputs and Diffusers

After the four fibers exit the splitter, they each carry slightly less than one-fourth of the transmission fiber's power to four ceiling can light fixtures. A hole is drilled in the top of the ceiling can where the fiber enters and is fixed in place so that it emits nearly directly downward. A highly-reflective silver-coated metal sheet is cut into cones that are placed around the fiber output within the can to efficiently return reflections from the diffuser at the bottom of the can. The diffuser is a piece of polycarbonate that has been sprayed with frosted glass paint. This acts as a finely-featured diffuser that breaks up the coherence from the laser light and effectively recombines speckling into a smooth, consistent output. The diffuser is bonded in place on the end of the can, the can is bonded to a hole cut in a drop-ceiling tile, and trim is bonded between the bottom of the can where the diffuser is bonded and the bottom of the ceiling tile. The thorough amount of bonding is to ensure that the bare end of the fiber is not able to be viewed directly by a user unless the entire output fixture is broken apart. By adding a fixed diffusing unit to the system, the output of the system changes from what could be a class 4 laser if the output is maximized to less than a class 1 laser. The main reasons why the diffuser makes the system safe for human eyes is that the diffuser greatly increases the output aperture from the fiber's 600µm core to the diffuser's 4-inch diameter, and the fiber's tighter divergence to the diffuser's divergence of over one radian. When these diffused variables are utilized with standard laser-classification formulae, the formulae show that there is no hazard for human eyes. For example, a common formula for Nominal Ocular Hazard Distance is shown below in (1):

$$N.O.H.D. = \frac{1}{\theta}\sqrt{\frac{4 \cdot P_0}{\pi \cdot M.P.E.} - (2 \cdot w)^2} \quad (1)$$

where θ is the divergence of the beam in radians, P_0 is the power of the source in watts, M.P.E. is the maximum permissible exposure in watts/radian, and w is the waist of the beam in meters. By solving for what the M.P.E. of the beam would have to be for a NOHD of zero with the values used from the MADLIS diffuser output, the M.P.E. becomes 31.8 watts/radian, which is far lower than typical commercial lighting, which means the safety standards would have to be so strict that no light source with an emission divergence of 1 radian could be more powerful than 31.8 watts, which is not the case. For a NOHD of 1 meter, which is a more standard use of the MADLIS system since most users will not be placing their eye on the diffuser, the M.P.E. becomes 1.2 watts, which is an even more unrealistic standard for lighting since it is equivalent to the brightness of a dimly-lit room.

VIII. Conclusion

The process of creating the prototype Mixed and Distributed Laser Illumination System included dozens of failed attempts across the various components. The final result could be improved in several ways by utilizing higher-quality parts and alignment procedures, however, for a proof-of-concept approach to creating an initial prototype by mostly utilizing hand-crafted, hand-aligned, and hand-bonded parts, the result is more than satisfactory. As shown below in Figure 8, we were able to achieve nearly even color and power output from four fiber optic cables that had a single light source of three laser diodes. Considering that there are approximately 26 surfaces that the light must pass through from the laser diode to the final output, the ability to create any amount of illumination with all hand-aligned parts was a greater achievement than expected.

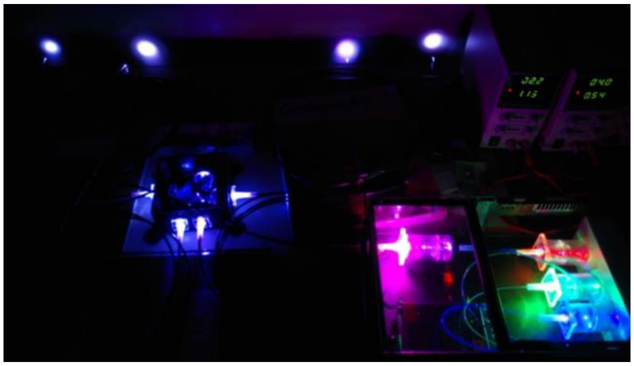

Fig. 8. Final assembly before fiber outputs were installed into the diffuser ceiling tiles. Note the four circular white beams emitting from the four output fibers near the top of the picture.

It is also worthy to note that all fiber optic cables were cleaved using a fiber cleaver bought off Amazon for approximately $30.00. Typical production or laboratory-quality fiber cleavers can easily surpass $10,000.00 plus all of the support equipment required. The entire project had an initial budget of $2,000.00, and the final cost was under budget at approximately $1,600.00.

ACKNOWLEDGEMENT

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