Designing and Developing an Incoherent Light Source for Ytterbium Ion Trap Testing

Jacob Thompson
Department of Physics, Middlebury College, Middlebury, VT
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Ytterbium ion trapping requires four lasers each producing a different wavelength of light. Lasers are both expensive and time-consuming to construct, and producing the proper precision required in the optical setup is a significant constraint. This makes ytterbium ion trap testing a painstaking process. To address these challenges, a prototype of a compact, incoherent light source was designed and constructed for use in ytterbium ion trap testing. The design is lightweight, easy to use, and can be adjusted depending on the desired wavelength of light. The device utilizes light from four LEDs which is coupled into a fiber-optic cable through the focusing of a variety of lenses. Ultimately, this prototype design was only capable of coupling on average seventeen micro-Watts of optical power into the cable. This is not adequate power for utilization in ytterbium ion trap testing. A future direction of this project would include redesigning the optical components or mechanical alignment of the device to increase the light coupled into the fiber.

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I Introduction

Ytterbium is the seventieth element on the periodic table, and it is often used in steel to strengthen the alloy and increase other mechanical properties. Recently however, ytterbium has been used in the construction of the first generation of quantum computers. One way of creating a quantum computer involves trapping and cooling singly charged positive ions [1]. Using a finely tuned laser, the ion may be excited into a state arising from the hyperfine splitting of the ground state — effectively storing a bit of information [3]. These ions are then strung together to create logic gates, which are necessary for the creation of quantum computers [1]. To study the encoding of information with ytterbium ions, the ions must first be trapped and cooled.

Trapping a ytterbium ion is done using both dynamic and static electric fields. Once the ion is trapped, it is cooled to its ground state energy. This involves slowing the velocity of the ion to remove any excess kinetic energy, ensuring the ion is in the ground state of its harmonic motion within the trap. Cooling the ion is frequently done using a technique known as Doppler cooling. In the Doppler cooling of ytterbium, a laser is used to excite an electron from the $^2S_{1/2}$ ground state to the $^2P_{1/2}$ excited state. The laser has a wavelength of $369\ \mathrm{nm}$ and has been slightly red-detuned [3].[1] This ensures that if the ion is moving toward the laser, it will absorb just enough energy to excite an electron and lose some kinetic energy in the process. Once this electron is excited, a photon is spontaneously emitted and the electron decays back to the ground state. In ytterbium, an electron in the $^2P_{1/2}$ state may, with 0.5% probability, decay to the meta-stable $^2D_{3/2}$ state rather than back to the ground state [4]. A $935\ \mathrm{nm}$ laser is needed to pump the electron up to the $^3[3/2]_{3/2}$ state where it can then decay back to the ground state. At this stage there is a chance of the electron decaying into the long-lived, meta-stable $^2F_{7/2}$ state [4]. A $760\ \mathrm{nm}$ laser is used to pump the electron into the $^1[3/2]_{3/2}$ state, where it will then decay to the ground state. A diagram of these energies and their respective decay processes is shown in Fig. 1. Using a $399\ \mathrm{nm}$ laser an electron in a ytterbium atom is excited from the ground state to the $^1P_1$ state. The electron is then excited to the point where it is no longer bound to the atom using a $369\ \mathrm{nm}$ laser [3]. This successfully ionizes the ytterbium atom.

This four-laser requirement makes the ion trap cumbersome and expensive to test. Having a compact piece of equipment in the lab which switches easily between the necessary wavelengths of light would be useful for testing the optical components of the ion trap.

[1] Red-detuning a laser involves adjusting the energy of the light such that it is slightly less than the energy required for the transition within the atom.

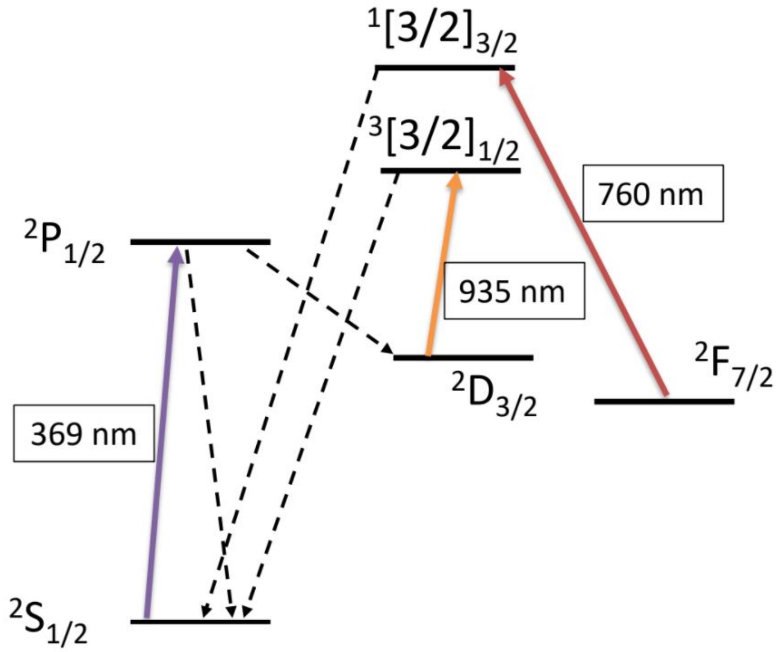

Fig. 1. The five energy levels of a ytterbium ion relevant for laser cooling. The solid arrows represent a laser pumping an electron into a higher energy state. The dashed arrows represent that electron decaying back to a lower energy state. [4]

II Objectives

Having an incoherent light source to test the optical pathways around the ion trap would be invaluable. This light source can be incoherent as it will not be used during the actual cooling process. The device must emit the four different wavelengths of light required for cooling a ytterbium ion ($369\ \mathrm{nm}$, $399\ \mathrm{nm}$, $760\ \mathrm{nm}$, and $935\ \mathrm{nm}$). It also must be compact (around six inches in length), easy to move, and durable. The incoherent light should be coupled into a fiber-optic cable so it may be easily transported long distances with little loss of power. The minimum required power for the light coupled into the fiber-optic cable is on the order of $0.1\ \mathrm{mW}$. Finally, the device should have the ability to couple multiple wavelengths of light into the fiber simultaneously. This feature will increase the speed of the testing process and ensure no artifacts arise when two lasers of different wavelengths are following the same optical pathway around the trap.

III Design Documentation

III. (i) Parts and Materials

LEDs with glass lenses were chosen as the incoherent light source because they are inexpensive, draw little current, and are easy to find in a multitude of wavelengths. The peak wavelengths of the chosen diodes are $375\ \mathrm{nm}$, $395\ \mathrm{nm}$, $760\ \mathrm{nm}$, and $930\ \mathrm{nm}$.[2] These are not the exact same wavelengths as those necessary for the Doppler cooling process, however, since LEDs are not completely monochromatic, and have a Gaussian distribution to their spectrum, the necessary wavelengths do fall within one standard deviation from the peak.[3] A glass lens, rather than an epoxy one, was chosen because the glass reduces the degradation of the lens over time, which protects the LED properties from alteration.

To prototype the housing and any other parts necessary, a resin-based stereolithography printer was used.[4] This prints to a high resolution and produces a strong, solid part. Out of convenience, the design also used some commercially available parts. These were square plates, known as cage plates, which secure a variety of components including lenses and fiber-optic cables. The plate can be mounted to metal rods which allow for easy translation in one dimension. An image of a cage plate is shown in Fig. 2. The four large holes on each corner are for mounting the plate using four cage rods. They also may be mounted to a lab table using a standard post for support. These parts offer adjustability and provide flexibility to the design. The cage rods come in a multitude of lengths, but six-inch rods were used to keep the design compact.[5] One cage rod is indexed in millimeters for easy adjustability of the optics' position relative to the LED array.[6]

A variety of lens sizes and focal lengths were used in the prototyping process. The NBK-7 substrate was chosen for the lenses as it offers a transmission range that encompasses the wavelengths of light in need of focusing [6]. More is said about the specific focal lengths and diameters of the lenses in section III. (iv). The fiber-optic cable chosen was multimode fiber with a $400\ \mu\mathrm{m}$ diameter and a numerical aperture of $NA = 0.5$.[7] This was the largest diameter and numerical aperture fiber available. Multimode fiber allows for more than one mode of light to enter at a given time, and therefore, more light is coupled. The numerical aperture relates to the maximum angle

[2]ThorLabs Part Numbers: LED375L, LED395L, LED760L, LED930L
[3]See specifications for each LED
[4]Model: Form Labs Form 2
[5]ThorLabs Part Number: ER6
[6]ThorLabs Part Number: ER6E
[7]ThorLabs Part Number: M124L02

of incidence of the incoming light that can be coupled into the fiber θ_{Max} in the following way:

$$NA = n \sin(\theta_{Max}), \tag{1}$$

where n is the index of refraction of the medium through which the incoming light is traveling. Solving Eq. (1) for θ_{Max} shows that light coming from an angle less than or equal to $\theta_{Max} = 30°$ will be coupled into the chosen fiber.

Fig. 2. A cage plate for holding one-inch optics from ThorLabs.[a] [b] The holes in each corner allow the plate to be translated along a cage rod or locked into place using a set screw. The optics and fiber-optic cable are held and aligned in the prototype device using these.

[a]ThorLabs Part Number: CP33

[b]Image taken from ThorLabs CAD rendering

III. (ii) Mechanical Design (LED Housing)

The first challenge in designing this device was designing a housing for the LEDs. The external dimensions were known because $30\ \mathrm{mm}$ cage plates were being used and this housing needed to align with those plates. The LEDs must be close together relative to their distance from the fiber-optic cable, and as close to the center of the housing as possible. This ensured they were close to the optical axis of the lenses mounted in the cage plates, a necessary condition for focusing light into the fiber-optic cable. After CAD modeling, and redesigning, a finalized prototype housing was produced. It is square and has the same dimensions as the cage plates. The end of the cage rod can be mounted to the face of the housing using 3/4 inch, 4-40 bolts. The housing splits into two pieces so an LED may be inserted into one of the tapered holes, held in place by friction, then clamped into place as the two halves are screwed together with 1/2 inch, 4-40 bolts. Two nubs sticking out of the inner face of one half, correspond to two holes on the other half. These ensure the two halves align perfectly when mated. The nut at the base of the housing locks in place as the two halves are screwed together. This allows for easy mounting on a post and attachment to the lab table. Figure 3 shows both the CAD rendering of this design and the 3D printed prototype. It also illustrates how the prototype is assembled.[8]

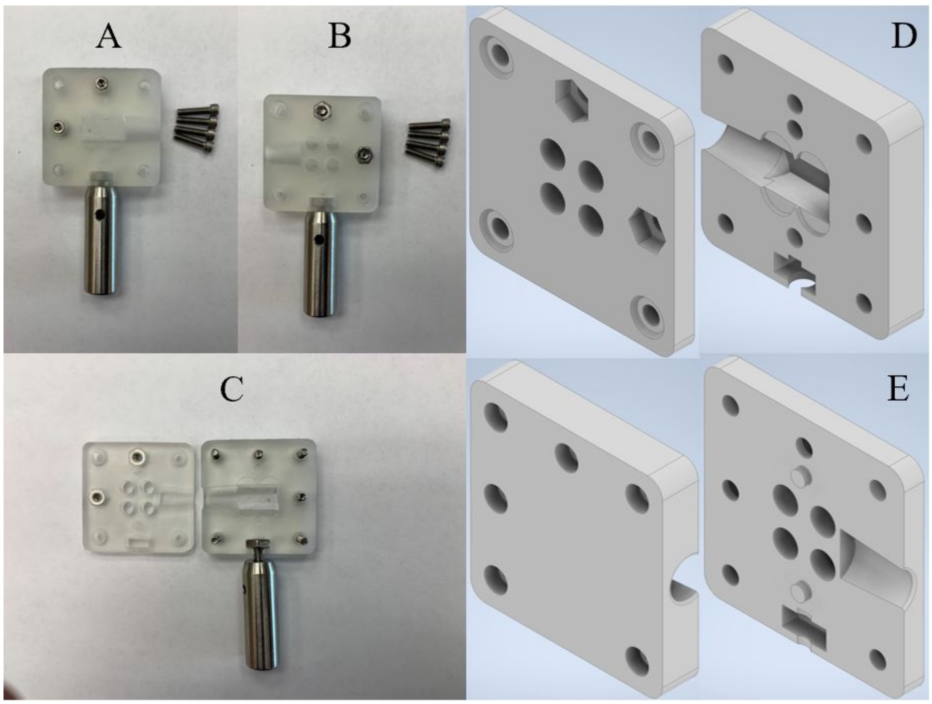

Fig. 3. Rendering of the CAD model (D and E), and the 3D printed housing for the LEDs (A, B, and C). Image A shows the back side, and image B shows the front side, of the assembled housing. Image C shows the housing disassembled with the inside portion of both sides facing upwards. Image D shows a CAD model of the housing disassembled from the front view. Image E shows a CAD model of the housing from the back view. The holes in the middle of the front face are where the LEDs will extend outwards. The cavity behind the LEDs allows for soldering space. This cavity uncovers just over half of the base of the LED leaving enough material to clamp the LED in place when the two halves are mated. The four screws shown in images A and B extend through the holes in each corner and screw into the cage rods. This secures the end of the cage rod to the housing.

[8]The print swells during the curing process meaning all tolerances must be increased by 0.07 inches before printing is commenced.

III. (iii) Electrical Design

The four chosen LEDs each have a different forward voltage and operating current specification. The forward voltage for each is under five volts, and the LEDs all specify a constant voltage power supply be used for power. This means standard USB power from a five volt power brick can be used as a power supply. Based on the objectives of the design, each LED should act independently, meaning, if multiple LEDs are turned on simultaneously, the brightness of each should remain unaffected. Therefore, the voltage across each LED must remain the same regardless of how many are turned on. This is achieved through wiring them in parallel. A parallel circuit splits the total current between each branch but supplies the power supply voltage across each branch. A standard five volt power brick is able to supply enough current to adequately power each branch of this circuit.

Wiring a circuit in the way described above would supply five Volts to each LED. This forward voltage would overdrive them and cause them to burn out. Therefore, a voltage drop is needed on each branch before each LED. The proper resistor value R such that the forward voltage V_F and current I match the LED specification sheet is given by

$$R = \frac{V_P - V_F}{I}, \tag{2}$$

where V_P is the power supply voltage [2]. For simplicity, the circuit design used resistors already stocked in the Hess Lab. Resistors with the exact resistance value necessary were not available, but there were many resistors with values less than what was needed. Through wiring these resistors in series, a total resistance value close to the calculated value necessary was obtained. This actual resistance value was higher than the calculated value necessary so the LEDs would not be overdriven. The calculated and actual resistance values used for each LED are given in Table I. With this information, the wiring schematic shown in Fig. 4 was generated. The electronics were then assembled according to this schematic.

The resistors were wired to a prototyping board to keep them neat and compact, see Fig. 5. They were then wired to four switches, one for each branch of the circuit. The four negative conductors for each branch of the circuit, and one positive lead, were wired to a nine-pin female DSUB connector mounted to the side of a 3D printed switch box. This switch box acts as an intermediate between the power supply and the diodes. The power supply plugs into one side, and the diodes plug into the other.

Another small prototyping board was used to solder the LEDs to a male DSUB cable, shown in Fig. 6. The LEDs were tested for any shorts before being placed in the housing. An image of the electrical components each in their respective housings is given in Fig. 7.

Table I. The calculated proper resistance value $R_{calculated}$ and the actual resistance value R_{actual} of the resistors wired into the circuit are shown for each LED. The tolerance of each resistor is $\pm5\%$, and because they are wired in series, the tolerance for the total resistance remains $\pm5\%$. The LEDs are designated via their peak wavelength λ.

LED λ	$R_{calculated}$	$R_{actual} \pm 5\%$
nm	Ω	Ω
375	70	77
395	75	77
760	64	67
930	74	77

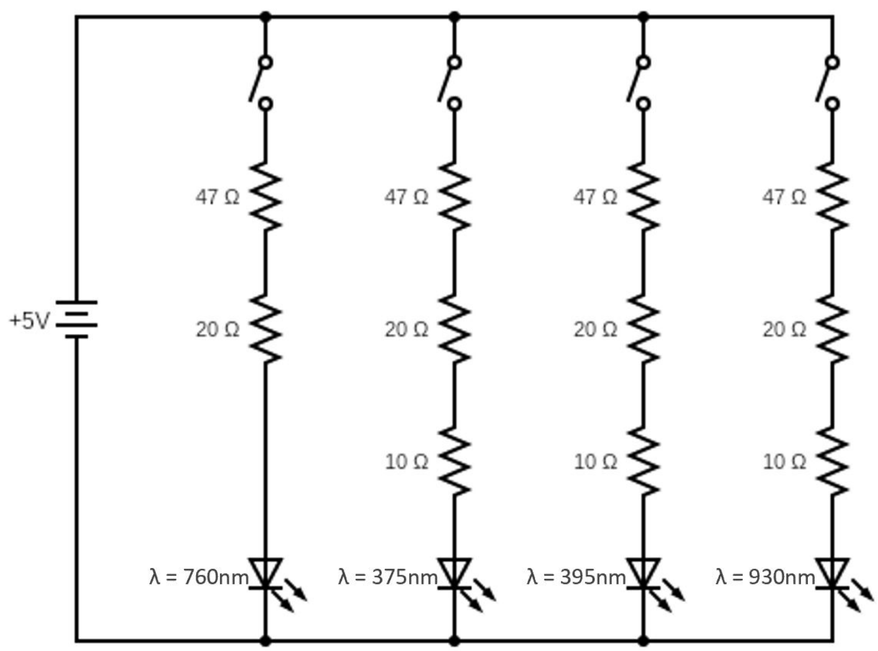

Fig. 4. A schematic of the wiring for the LEDs. Each LED is wired in parallel. Each branch also has a string of resistors wired in series and a switch before the LED. There are four branches total, one for each LED.

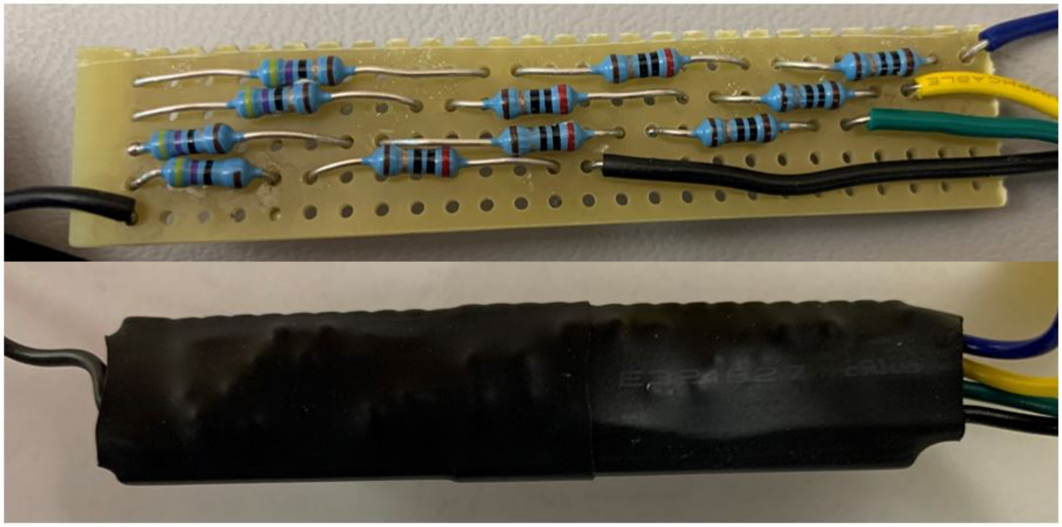

Fig. 5. The resistors are wired in series on the prototyping board. The finished product has been shrink wrapped to look neat and prevent shorts.

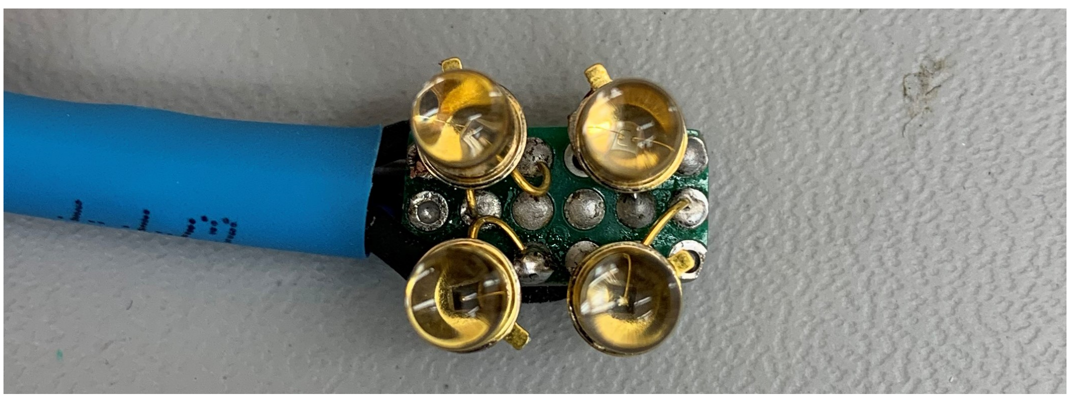

Fig. 6. The LEDs are soldered to the prototyping board, which is attached to a cable. On the other end of the cable is a male DSUB connector which plugs into the switchbox.

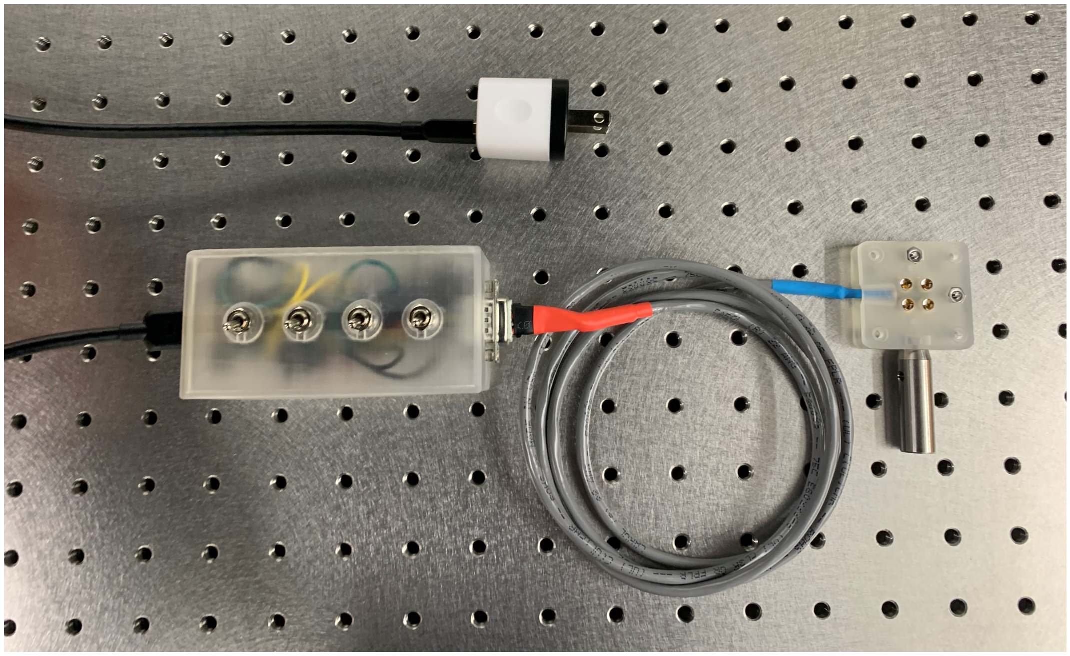

Fig. 7. The complete electrical system in working order. The USB power supply plugs into the left side of the switch box. Atop the switchbox are four toggle switches corresponding to the four LEDs. A DSUB connector plugs into the right side of the box and leads to the housing holding the LEDs.

III. (iv) Optical Design (One Lens)

The main challenge of designing an optical system to focus the LED light into the fiber-optic cable is that the LEDs are off-axis from the lens and cable. Thus the light cannot be first collimated then focused into the fiber. A lens is necessary for coupling the light into the fiber, as some preliminary measurements showed almost no light is coupled without one. A one-inch diameter lens is the largest lens that fits in the cage plates. The large diameter of the lens allows the lens to capture more light rays than a smaller diameter lens would at a distance far from the LED. Each of the LEDs has a different viewing half-angle, but they are all located $a = 5.4$ mm from the optical axis.[9] To capture the most light possible, the maximum distance x from the LED to the lens must be calculated. The LED with the largest viewing half-angle has an angle of $\theta = 20°$.[10] Simple trigonometry shows this maximum distance, as shown in Fig. 8, is $x = 20$ mm. The shortest focal length lens available with a one-inch diameter has a focal length of 25 mm.[11] The back plane of

[9]The viewing half-angle is the angle at which the light disperses from the LED relative to the normal.

[10]See specifications for LED model LED375L

[11]ThorLabs Part Number: LA1951

this lens was placed 28 mm from the LEDs to account for the lens thickness.[12] The position of the fiber was then translated along the cage rods to find the point at which the most light was coupled in. This point is located 42 mm from the LEDs and 14 mm from the back of the lens. This setup coupled in on average 17 μW of light.[13] This is better coupling than with no lens in the system, but the goal of at least 0.1 mW coupled is not achieved.

To focus the most light possible into the fiber-optic cable, the distance from LED to the optical axis was treated as an object. This object was then shrunk causing the entire LED array to be projected into the fiber. The initial object size is $a = 5.4$ mm as given in Fig. 8. Since the fiber has a diameter of $400\mu m$, a magnification of $M = 0.2mm/5.4mm = 0.04$ is needed. This is unfeasible to do with one lens because keeping the object distance reasonably sized requires that the lens's focal length be smaller than any lens commercially available at this time. Therefore, two lens options were explored.

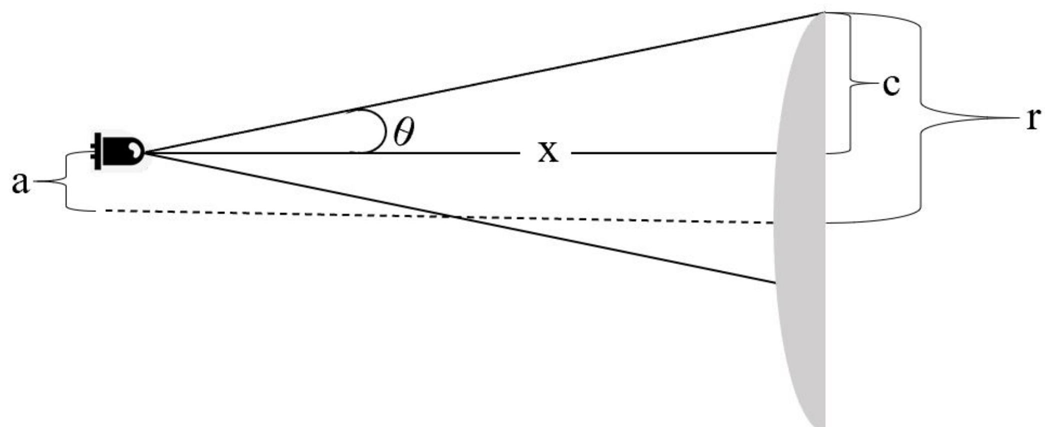

Fig. 8. The trigonometry necessary to calculate the optimal lens distance. Calculating x where $\theta = 20°$, $a = 5.4$ mm, and $r = 0.5$ in $= 12.7$ mm yields $x = 20$ mm.

[12]This thickness correction was calculated using the difference between the known focal length and back focal length of the lens.

[13]In this experiment, the object distance was within one focal length of the lens, causing the light rays to diverge. Two more experiments were conducted, one with the object located just outside one focal length, causing the light rays to converge, and one with the object located at the lens's focal point, allineating the rays. The 14 mm distance between the fiber and the back of the lens was kept constant because that distance still allowed for the most light coupling. These experiments yielded a similar result to the one described above. This is because fewer rays were captured by the lens and the ones that were focused were focused to a point other than the fiber tip due to the LED's distance off the optical axis.

III. (v) A Brief Foray Into Multi-Lens Systems

In a two-lens system, the effective focal length of a lens doublet F is given by

$$F = \frac{f_1 f_2}{f_1 + f_2 - d}, \tag{3}$$

where f_1 is the focal length of the first lens, f_2 is the focal length of the second lens, and d is the distance between the two lenses [5]. Plotting F with respect to d, as in Fig. 9, shows the effective focal length of the doublet F decreases nonlinearly with d. Also, Eq. (3) implies F decreases as $f_1 \times f_2$ decreases. Therefore, the condition to minimize the effective focal length of the lens doublet is: d, f_1 and f_2 be as small as possible. Furthermore, since the choice of f_1 and f_2 is arbitrary in Eq. (3), F is further minimized when $f_1 = f_2$. This focal length will be defined as f such that

$$f \equiv f_1 = f_2. \tag{4}$$

The image distance from the second lens in a lens doublet s_{i2} is given by

$$s_{i2} = \frac{f_2 d - f_2 s_{o1} f_1/(s_{o1} - f_1)}{d - f_2 - s_{o1} f_1/(s_{o1} - f_1)}, \tag{5}$$

where s_{o1} is the distance from the object to the first lens [5]. A diagram of these variables is given in Fig. 10 which illustrates a three lens system. Combining Eq. (4) and Eq. (5) yields

$$s_{i2} = \frac{fd - f^2 s_{o1}/(s_{o1} - f)}{d - f - s_{o1} f/(s_{o1} - f)}. \tag{6}$$

The total magnification of a lens doublet M_T is given by

$$M_T = \frac{f_1 s_{i2}}{d(s_{o1} - f_1) - s_{o1} f_1} \quad [5]. \tag{7}$$

Utilizing Eq. (4), Eq. (6) and Eq. (7), M_T is put in terms of just the object distance and the focal length of the lenses:

$$M_T = \frac{f^2}{f(f - 2s_{o1}) + d(s_{o1} - f)}. \tag{8}$$

Solving Eq. (8) for s_{o1} yields:

$$s_{o1} = \frac{f(M_T f - dM_T - f)}{M_T(2f - d)}. \tag{9}$$

This equation and the parameters outlined earlier are necessary for designing an optical system with a lens doublet.

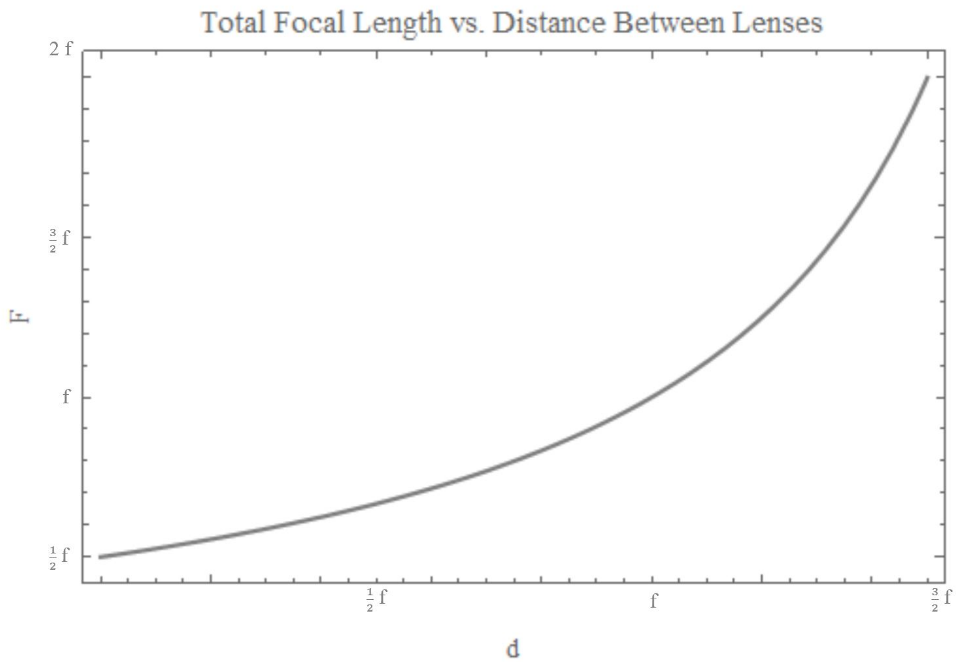

Fig. 9. The effective focal length of a lens doublet F is plotted as a function of the distance between the two lenses d. The axes are in terms of f where $f \equiv f_1 = f_2$ and is the focal length of the lenses in the doublet. The plot shows that the effective focal length decreases nonlinearly with the distance between the lenses.

III. (vi) Optical Design Part II (Three Lenses)

A one-half-inch diameter lens has a radius large enough to encompass the entire LED array and is available in focal lengths shorter than the one-inch lenses. The shortest focal length available in this size is $f = 15$ mm.[14] These lenses have a center thickness of 5.1 mm. If two lenses of this thickness are touching, the distance between the points from which the focal lengths are measured would be $d = 5.1$ mm. Taking $d = 6$ mm allows for some slight space between the two lenses while still minimizing the total focal length of the doublet. Inputting these parameters into Eq. (9) along with $M = -0.04$ yields $s_{o1} = 240$ mm.[15] This is far too long, as one objective is a length less than six inches or 152.5 mm. To address this, a third lens was added to the system.

A concave lens creates a shrunk virtual image. An elementary optics calculation using the thin lens equation, $1/f = (1/s_o) + (1/s_i)$, shows that an object one focal length away from a concave lens yields a virtual image halfway between the object and the lens. Furthermore, since

[14]ThorLabs Part Number: LA1540

[15]The magnification must be negative because the image created will be inverted.

the magnification M is given by: $M = -s_i/s_o$, the image will be upright and 1/2 the size of the object. Of the one-half-inch diameter concave lenses, 25 mm is the smallest magnitude of focal length available.[16] This concave lens (Lens 0) placed $s_{o0} = 25$ mm from the LEDs will create a virtual image halfway between the object and the lens. This virtual image will be half the size of the original object so a magnification of $M = -0.08$ is needed from the lens doublet (Lenses 1 & 2). Evaluating Eq. (9) with this new parameter yields $s_{o1} = 123$ mm. This lens system and its corresponding ray tracing are illustrated in Fig. 10, which is not drawn to scale. The final value in need of calculation is the distance of the final image from the last lens (Lens 2). Evaluating Eq. (6) yields $s_{i2} = 6.4$ mm, meaning the total distance from the LED to the second lens is $L = s_{o0}/2 + s_{o1} + d + s_{i2} = 150$ mm. This is within the goal of a length less than six inches. This system of lenses was carefully constructed and is shown in Fig. 11. Measurements of the optical power coupled into the fiber-optic cable were then conducted.

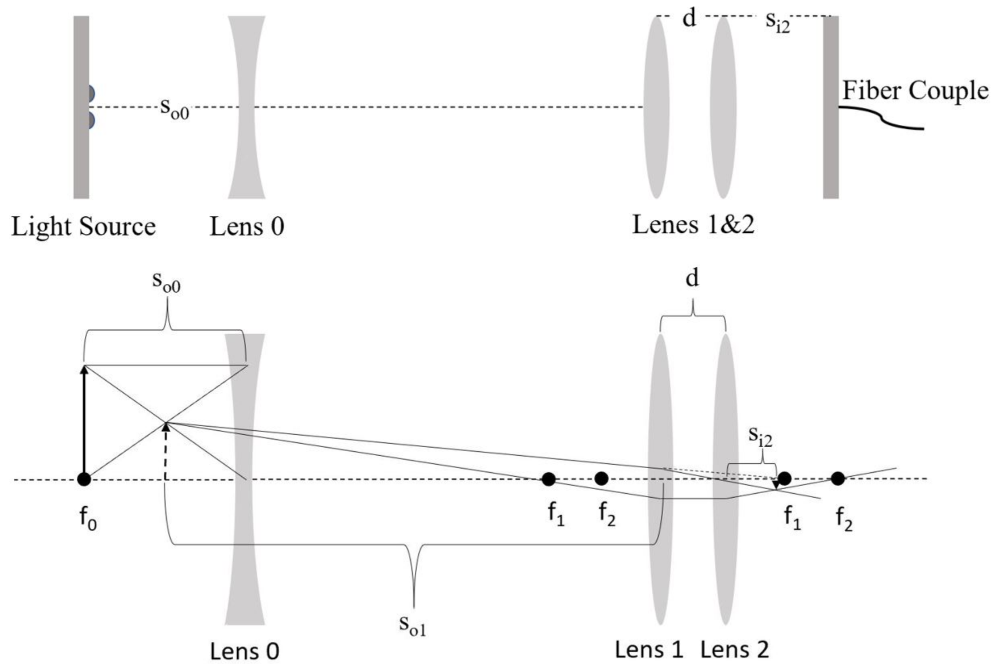

Fig. 10. A schematic of the three-lens system used in the final prototype (top) and a ray-tracing diagram for the three-lens system (bottom). The distance between lenses 1 and 2, d, is less than the focal length of either and equals $d = 6$ mm. Lens zero is a concave lens placed such that the object (in this case the LED array) is one focal length away. The ray tracing shows this "triplet" creates an extremely minimized, inverted, real image. This figure is not drawn to the scale of the actual lens system used in the device.

[16]ThorLabs Part Number: LC1054

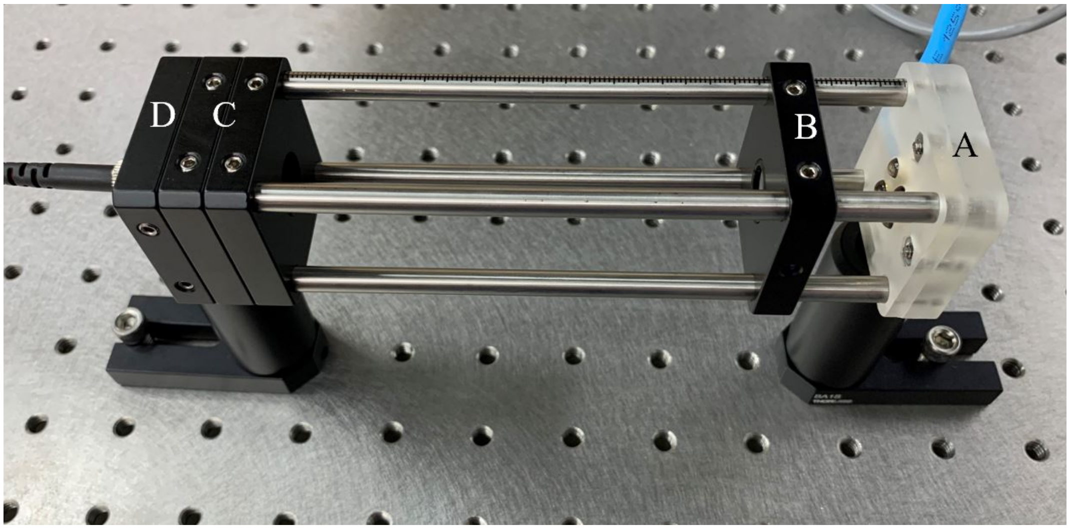

Fig. 11. The finalized prototype using the three-lens system. Part A is the LED housing. Part B is the concave lens with a focal length of $f_0 = 25$ mm. Part C is the convex lens doublet with each lens having a focal length of $f = 15$ mm. Part D holds the fiber-optic cable in place so the light may be coupled.

IV Data Collection: Procedure and Results

To measure the optical power through the cable, one end of the fiber was connected to the prototype and the other to an optical power meter.[17] The lights in the lab were turned off and the shades were shut to avoid any excess light skewing the results. Each LED was turned on individually and the power output through the cable was recorded. This power meter must be calibrated to the wavelength of light it is measuring. It was calibrated to the peak wavelength of each LED given by the LED's specification sheet. The fiber was then disconnected from the power meter and a wand that measures the optical power of ambient light was connected in its place. The power output of each LED was measured by holding the wand up to the glass lens of the LED. The optical power of the light that made it through the lens system was also measured by connecting the wand to the cage plate previously holding the fiber.

This procedure was conducted with no lenses. This hardly coupled any light into the fiber and motivated the creation of the one-lens system. The same data was collected for the one-lens system and the results are given in Table II. Finally, this procedure was conducted with the three-lens system and the results are presented in Table III.

[17]Model: ThorLabs PM400

Unexpectedly, there is little light coupled in with the three-lens system — even less light than was coupled in with the one-lens system. Only about 1-3% of the light from the LED made it through all the lenses. Most of this light loss can be attributed to the diverging lens (Lens 0). It is interesting to note that while the three-lens system did not couple the required light, it coupled a higher percentage of the light available than the one-lens system. The three-lens system coupled on average 14 times more of the light which made it through the lenses. This is likely due to the extremely small size of the image. A majority of the light available was still not coupled possibly due to the high angle of incidence of the light rays on the fiber. Conducting a simple trigonometric calculation yields a maximum angle of incidence of $45°$ which is 1.5 times larger than the maximum acceptance angle of the fiber.[18] Therefore, two-thirds of the light which made it through the lenses is lost just due to the fiber properties.[19] The average percentage of light coupled into the fiber from the light which made it through the lens system, for each system, is given in Table IV.

Table II. The optical power coupled for each LED through the fiber-optic cable P_{Fiber}, the optical power at the point of the fiber-optic cable $P_{Position}$, and the percentage of optical power lost through the lens system are shown for the one-lens system. The LEDs are designated via their peak wavelength λ and their power output P_{LED} is also given. The uncertainty in power was chosen based on how much the power meter fluctuated when the measurement was taken.

LED λ	P$_{LED} \pm 0.05$	P$_{Position} \pm 0.05$	P$_{Fiber} \pm 5$	Percent Lost
nm	mW	μW	μW	%
375	3.44	2610	12.30	24
395	8.84	6730	34.29	24
760	14.06	5690	11.53	60
930	12.08	4140	10.30	66

[18] Recall the maximum acceptance angle of the fiber purchased is $30°$.

[19] The calculation that two-thirds of the light is lost due to the fiber properties involves the assumption that light leaves the LED with equal power in every direction within its viewing half-angle.

Table III. The optical power coupled for each LED through the fiber-optic cable P_{Fiber}, the optical power at the point of the fiber-optic cable $P_{Position}$, and the Percentage of optical power lost through the lens system are shown for the three-lens system. The LEDs are designated via their peak wavelength λ. The uncertainty in power was chosen based on how much the power meter fluctuated when the measurement was taken.

LED λ	P$_{Position} \pm 0.05$	P$_{Fiber} \pm 0.05$	Percent Lost
nm	μW	μW	%
375	19.98	0.700	99
395	53.50	2.045	99
760	43.50	2.89	97
930	40.40	2.136	97

Table IV. The percentage of light coupled into the fiber-optic cable from the light available after transmission through the lens system, averaged over all four LEDs, is shown. $Percent\ Coupled = P_{Fiber}/P_{Position}$. The number of lenses N specifies the lens system.

N	Percent Coupled
1	0.35
3	5

V Conclusions and Future Directions

The mechanical and electrical portions of this prototype are both well implemented. The electronics are neatly assembled and function as desired. The LED housing is compact and well manufactured. The method of fiber coupling is in need of a redesign. Little light is coupled into the fiber with the one-lens system, and even less is coupled with the three-lens system. The three-lens system did couple a larger percentage of the light available after transmission through the lenses, but on average 98% of the light was lost due to this transmission. One assumption made in the design of the three-lens system was that the light rays lost through the system due to the small lens diameter and the diverging lens would be negligible. This proved to be incorrect. The optical portion of the prototype requires some rethinking and redesign, but the mechanical and electrical portions work as desired.

The redesign of the prototype could take the form of an optics redesign or a new mechanical design. By using powerful optics software to fit a certain system to the defined parameters, the optical system could be redesigned to couple in more light. Beyond this, a mechanical design might be necessary. One objective was the coupling of multiple LEDs simultaneously. By removing this objective, the LED can be placed on the optical axis of the lens and fiber. This makes the light easier to collimate and then couple in. A mechanical system can be designed which translates the fiber and lens onto the same axis as the LED. This would likely increase the power of light coupled into the cable and achieve a proper power output.

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