ECE476: Electro-Optics
Summer, 2021

Coupling to a Single Mode Fiber

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6/13/2021

Abstract— This paper discusses the attempt to couple a .5 mW He-Ne laser beam to a single mode optical fiber without the use of commercially available connectors. This was achieved through a micro positioner from ThorLabs and a standard magnification lens.
Through this coupling, we were able to demonstrate the Gaussian profile of the .5 mW He-Ne laser, as the optical fiber being smaller than the magnified laser beam acts as a form of sampling mechanism when the laser light propagates through the fiber onto an optical power meter. Interestingly, we also discuss how the single mode fiber has a Gaussian intensity pattern as well. This paper will discuss the findings of this coupling experiment and compare our primitive coupling methods and techniques to the commercially available coupling methods and techniques that exist. This paper will also dive into some of the fundamentals of wave propagation and transmission, discuss their practical use pertaining to signal transmission, and also discuss some future related experiments that can be done. We will conclude with an elaboration of some of the shortcomings of this paper's experimental findings and provide some rationale for these shortcomings, as well as discuss ways in which these shortcomings could have been improved upon.

Introduction

In order to understand coupling to a single mode fiber and the complexity of such a process, it’s good to first understand the general principles relating to optical fibers and signal transmission through these medians. This introduction will begin with a discussion of waveguide propagation in an optical fiber, followed by a discussion of single mode versus multimode coupling and the advantages and disadvantages of each. It will then transition into a discussion of how single mode fibers are used today in the real world and some of their current applications. Finally, this introduction will outline the basis for the performed experiment and give a basic rationale for such an experiment.

Background on Waveguide Propagation and Coupling

Optical fibers can be treated as step-index optical fibers of cylindrical shape with both a core, that has its own index of refraction , and a cladding, that has its own index of refraction . Typically, and are very similar in value, keeping the normalized index of refraction very small. Ensuring that this is greater than means that a beam of light can undergo total internal reflection, presuming that the incident light into the fiber is less than the maximum acceptance angle of that fiber. If the incident light enters the fiber at an angle greater than the maximum acceptance angle, the light would propagate both through the core and the cladding and eventually be absorbed, leading to a device that transmits signals very poorly. We will discuss more on this maximum acceptance angle later on.

When light enters into the fiber, we can envision many individual waves propagating through the material. Each of these waves has a vertical component and a horizontal component, and we know that these waves will constructively and destructively interfere. All propagating waves are either transverse electric (TE) or transverse magnetic (TM) and we know that the TE waves have an effective velocity in the direction of propagation through the fiber because their electric fields sum in that direction, whereas TM waves have their magnetic fields sum in that direction and their electric fields are perpendicular [1]. These relationships can be further explained using Fresnel's equations, but we will not go into that as it is not too relevant for our discussion. It is important to note, however, that the incident angle of a light beam on an interface using Fresnel's equations determines the magnitude of the reflective coefficients and the phase change of the incident wave. This becomes relevant when intensity, reflectance, and transmittance is concerned, and the principles of Fresnel's equations are the reason that a fiber can achieve total internal reflection.

Returning to the idea of light propagating through an optical fiber, the propagating waves can be broken down into two types, meridional rays and skew rays. Meridional rays are rays of light that enter the fiber through the fiber axis and transverse through the fiber always crossing the fiber axis. A skew ray enters the fiber off the fiber axis and therefore propagates in a helical path around the fiber. These two types of rays in a step-index optical fiber lead to guided modes. The issue with these guide modes is that a phenomenon called intermodal dispersion occurs, explained by multiple modes propagating at different group velocities. What this means for a fiber used in a real word device is that when there are multiple modes, there is a broadening of the input pulses as the distance of propagation increases; this limits the potential bandwidth of signal transmission as distance increases [1].

A solution to this limitation would be to limit the number of modes that can propagate in a fiber. This can be achieved when the V number is less than 2.405 [1]. In this instance, only one mode can propagate through the fiber, and we call this single mode fiber propagation.

Typically, in order to achieve single mode operation, the radius of the cylindrical fiber has to be decreased; this can obviously be a challenge. Single mode propagation has a much more precise bandwidth than a multimode fiber propagation, however, which is one of the clear advantages of single mode fiber propagation. A disadvantage of a single mode fiber is that its multimode fiber counterpart tends to be more energy efficient. This can perhaps be explained by some of the power in a wave being lost into the cladding at a higher rate for a single mode fiber than for a multimode fiber, as the radius of the core for a single mode fiber is significantly smaller. What this means for practical applications is that a multimode fiber can transmit data over a larger distance with the same amount of energy, even if the rate of the data transmission must be slower. Single mode fibers do have longer transmission capabilities, however, despite requiring more power because a single mode fiber does not disperse like the multimode fiber does.

Another clear limitation of a single mode fiber setup is that the range of working wavelengths for the fiber is much narrower. This may not be a problem as long as the traversed wavelength of light falls within the acceptable range for a certain fiber, but it does limit a single mode fiber to only serial applications. Multimode fibers have been able to transmit signals in parallel over a single optical fiber [2]. This is made possible because a larger range of working wavelengths means that multiples different frequencies of light can be traversed over the same fiber at the same time and be separated at the end of the fiber, something that is not achievable with the smaller range of working wavelengths in a single mode fiber.

Interestingly, one way to verify if a fiber is in single mode is to check the intensity profile of the fiber. A single mode fiber follows a Gaussian intensity, similar to the He-Ne laser. Hence, if one of the various techniques were used to measure the profile of our coupled optical fiber in this paper, one would see that it is in fact a single mode coupling; measuring the intensity profile of a at the end of the fiber is therefore without a doubt one technique to validify if a certain fiber is single mode coupled or not. A multimode fiber would have a more complex intensity pattern. This more complex intensity pattern can be useful, however. It has been shown that increasing the number of modes has some useful applications in imaging, where the higher the number of modes, the higher the resolution of the collected image through the multimode fiber [3].

Current Applications of Single Mode Fibers

Single mode fibers are used in a seemingly uncountable number of applications. They recently have been used in high-sensitivity temperature sensing, which can have some potentially very interesting applications [4]. They were also recently shown to be used successfully in a displacement sensor [5]. The key takeaway here is that single mode fibers have many applications and that there are definitely some overlaps regarding the possible applications of multimode fibers and single mode fibers. When it comes to determining what fiber is best for a specific application, the ideas discussed above really come into play, but for many instances, the two different fibers can be relatively interchangeable for a task. For example, in some instances, a single mode fiber might be the best fiber for signal transmission, as it lends itself to a better bandwidth, but device manufacturers and engineers might opt to use a multimode fiber because they tend to be a cheaper fiber with comparable performance. There are even such fibers called few-mode optical fibers that too have some interesting applications including mode division multiplexing, among other unique applications [6]. Ultimately, single mode fibers have many applications and are especially useful for their low dispersion in comparison to any multimode fibers.

With respect to the goals for this project, coupling to a single mode fiber can be a difficult task, and coupling two single mode fibers together can be even more difficult. Real world techniques exist in order to ensure coupling between fibers. Without these techniques, single mode fibers would be impractical. The task of coupling two single mode fibers together is called Fiber Optical Fusion Splicing.

Fusion is the use of high temperature heat generated by an electrical arc, two glass fibers, end to end, fused together in order to make the fiber core precisely aligned. The tips of the two fibers are connected to each other and heated to melt them together. This is usually done with a splitter, which mechanically aligns the two fiber ends and then applies a spark at the fiber tips to fuse them together. The method is the same as coupling to a single mode fiber. It requires the end of the fiber to be flat and polished so that both sides of the fiber could transmit the light well. [10]

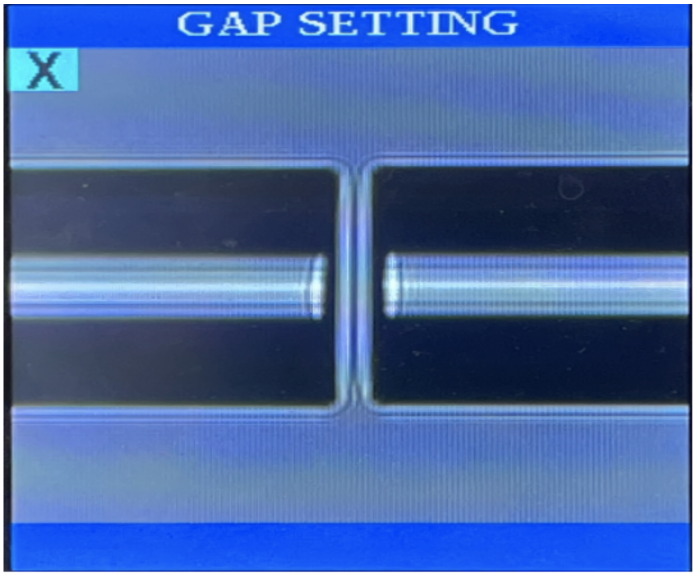


Figure 1: Fusion Splicing two single mode fiber

Optical fibers are terminated with a particular connector and the connector endface preparation will determine what the connector return loss, also known as back reflection, will be. The back reflection is the ratio between the light propagating through the connector in the forward direction and the light reflected back into the light source by the connector surface. Minimizing back reflection is of great importance in high-speed and analog fiber optic links. [11]

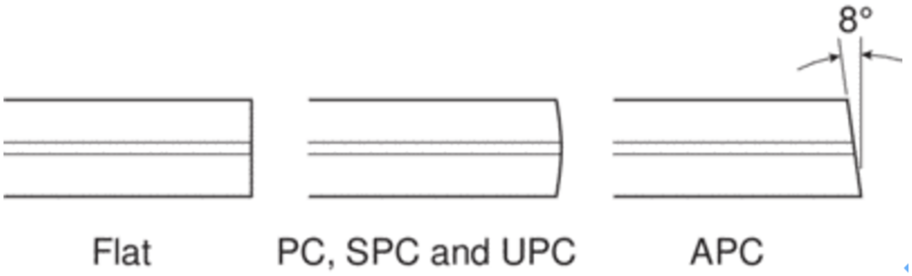


Figure 2: Connector Endface graph

Some different heads of the connectors will be discussed. Physical Contacts (PC) are a micro spherical polished insert with a slightly spherical surface and the fiber core at the highest point of the bend, which effectively reduces the air gap between the fiber components and allows the two fiber ends to make physical contact. Ultra Physical Contacts (UPS) are not completely flat, but have a slight curvature to achieve a more accurate docking, UPC is based on PC to optimize the polishing and surface finish, the end face looks more domed. Angled Physical Contacts (APC) are called a beveled physical contacts, where the fiber ends are usually ground to an 8° bevel. 8° angled bevels allow the fiber ends to be tighter and reflect light through their beveled angle to the cladding rather than directly back to the light source, providing better connection performance. These varying performance levels matter depending on the application of the fiber optic in any desired system.

Applied Knowledge to Experimental Setup

For this paper we took the ideas presented of coupling to a single mode fiber and using that information, we aimed to experimentally determine the intensity profile of a .5 mW He-Ne laser. We know that if the propagating laser's diameter is larger than the diameter of our fiber core, when shining the laser light onto the core, assuming that the angle of incident is less than the maximum acceptance angle, the fiber would propagate only the light that entered into its core. Using this knowledge, we know that if the light on the center of the laser enters into the fiber, this high intensity light would propagate through the fiber until the end. We also know that minimal dissipation or absorption by the material will occur as the single mode fiber will have total internal reflection when the entering light is incident at an angle less than the maximum acceptance angle. It should be noted that it was decided to magnify the laser in order to make this task a bit easier knowing that this should not affect the intensity profile. We know this because since intensity is power divided by area, evenly magnifying or dispersing a laser beam should only affect the individual measurements, not the overall intensity profile itself. We also know that passing any light through a medium decreases the power, but again, this should be negligible regardless of if the beam was focused or not and if it wasn't negligible, it should be relatively constant across the beam, meaning that the intensity profile should be unaffected.

As we know that the maximum occurs at the true center of the laser beam, hence, we know that we can manipulate a micro positioner holding a single mode fiber until a maximum occurs on our power meter on the opposite end of the fiber, and then take incremental measurements outwards to derive experimentally the intensity profile of a laser. The more precise methods in which we conducted this experiment will be discussed later, but it's important to understand that we ultimately used this single mode fiber to sample different parts of a He-Ne laser beam in order to calculate its intensity profile. We then compared and contrasted our findings to the expected intensity profile of a He-Ne laser beam which can be found below.

Technical Background

This section of the report will cover the background of certain components of this lab such as topics of acceptance angle and lens magnification.

Acceptance Angle

The acceptance angle is the maximum angle at which a ray of light can enter a fiber from one index to another and allow the ray to stay contained within the fiber; this occurs because the ray of light undergoes total internal reflection within the fiber. If the incidence angle of the light is higher than the acceptance angle, then the ray will be shot out of the fiber. The picture below is a visual representation of what was just discussed.

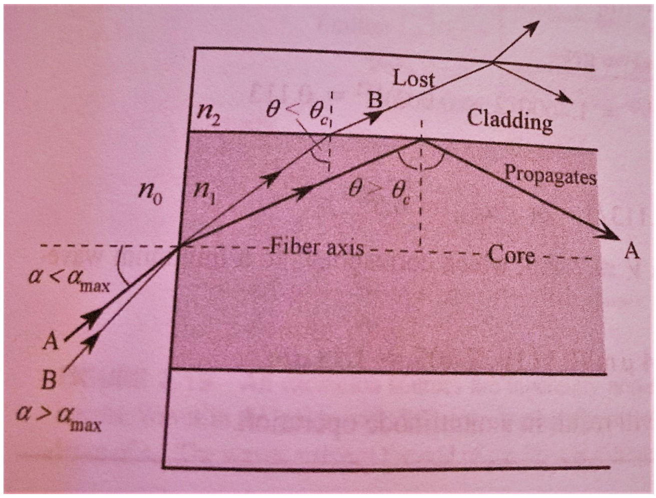


Figure 3: Visual representation of the angle of incidence and total internal reflection [1].

The equation for finding the maximum acceptance angle follows:

$$sin(\alpha_{max}) = \frac{NA}{n_o}$$

Where NA stands for numerical aperture, simply a characteristic parameter of optical fibers, which has the relationship defined by:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}}$$

Where n_1 is the refractive index of the cladding and n_2 the refractive index of the core.

It should be noted that n_0 in the maximum acceptance angle equation refers to the refractive index of the medium in which the light propagates through prior to propagating through the fiber. In the case of our experiment, this value is 1, as air has an index of refraction of 1. This is not always the case, as we know, and should be considered when working on other projects.

For this project, we obtain the maximum acceptance angle for the F-SV and F-SA optical fibers from Newport Corporation. The data sheets for each fiber states that the numerical aperture follows .10-.14 [7], [8]. Therefore, using the above equation, we know that our maximum acceptance angle for the two fibers falls between ~5.74° - ~ 8.05°.

We also used a another fiber for our first experiment from Newport corporation that was labeled as F-SS-50, however, we could not find a data sheet for this fiber, hence, we could not calculate the maximum acceptance angle, as we did not know the refractive indexes of the core and cladding, nor the numerical aperture for the fiber.

Lens Selection

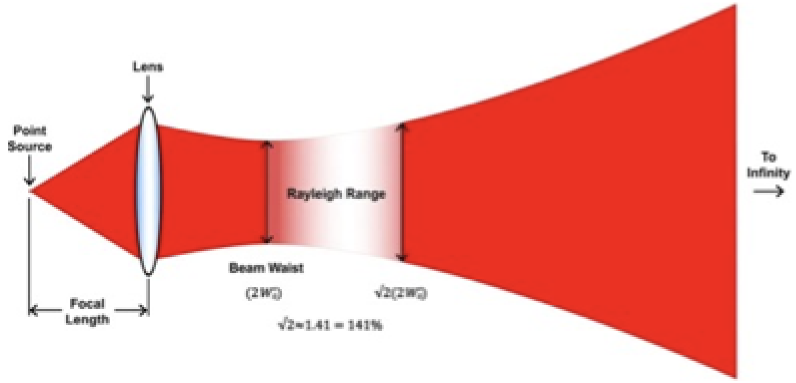


Figure 4: Spot size and lens magnification diagram

Spot size is typically defined as the radial distance from the center point of maximum irradiance to the point where the intensity drops to 1/e^2 of the initial value. The focused spot size of an ideal lens can be calculated by using wavelength (λ), the focal length of the lens (f), the input beam diameter (D), the refractive index of the lens (n), and the beam's M factor (assume = 1), which represents the degree of variation from an ideal Gaussian beam. [12]

$$\phi = \frac{4\lambda M^2 f}{\pi D}$$

For this experiment, however, we will assume a linear relationship. We neglect this precise calculation of spot size, opting for a more trigonometry based calculation which will follow.

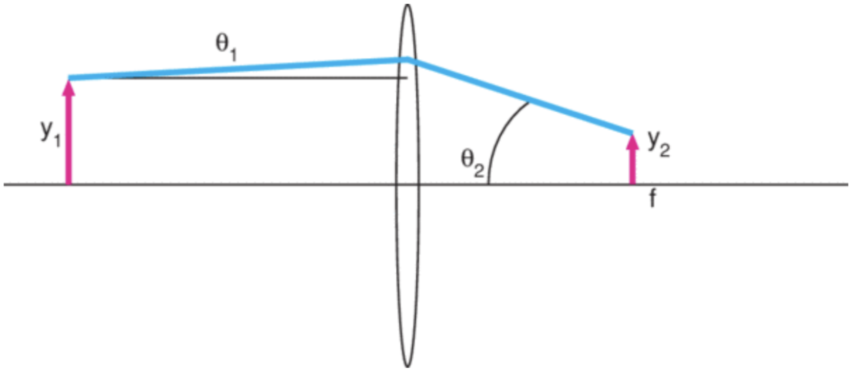


Figure 5: Diagram of focusing a laser beam to a small spot [9].

We can visualize our simplified problem in Figure 5. Making use of basic trig and small angle approximations, we know that: $\theta_2 = y_1/f$ and $y_2 = \theta_1/f$

We do not know f, as the lens manual did not provide it, but we do not need it. We solve for θ_2 with respect to θ_1, eliminating f from the above equations and are left with: $\theta_2 = (y_1/y_2)\ \theta_1$. We say that y_1/y_2 is the magnification, M.

We acknowledge that this may be an invalid approximation, as it assumes linear magnification and an ideal lens, but since we are working over very small distances, we believe that it should be sufficient in producing a good estimation. We will choose a magnification much smaller than our calculated maximum magnification in our actual experiments to avoid this uncertainty.

We know that $\theta_1 = 1.7$ mrad from the user manual for the .5 mW laser. We also know that $y_1 = .48\ (\mathrm{mm}) / 2$ from the same manual, but this does not matter as we are trying to solve for the maximum acceptance angle based on the lens magnification.

We know that our smallest maximum acceptance angle is 5.74° from above, when our NA is .1. Hence, we solve for the maximum lens magnification, M, that can be used through:

$5.74° = M*[\{1.7\ (\mathrm{mrad})\}*\ \{1\ (\mathrm{rad})/(1000\ (\mathrm{mrad})\}*\{180°/(\pi\ (\mathrm{rad})\}]$

So, $M = 58.92$

Since $M = y_1/y_2$, we can solve for the smallest y_2

$y_2 = \{.48/2\ \ (\mathrm{mm})\}/\{58.92\} = 4.073\ \mu\mathrm{m}$

This is larger than the core radius of both of the fibers that we use in this project, hence, it is impossible to ensure that all of the incident light enters the core of the fiber, however, using a magnification of less than 58.92 ensures that whatever light is incident on the fiber core will not be absorbed by the cladding, but will be subject to total internal reflection. This enables us to use the process coupling to our single mode fiber as a way to sample the Gaussian intensity profile of the .5 mW laser, as light absorption by the fiber core or cladding should be negligible when properly coupled. This is why we chose to use a lens magnification of 20X for the .5 mW laser, as this magnification was a comfortable distance away from our maximum calculated magnification.

The 4 mW laser has a beam divergence of 1 mrad and a beam diameter of .8 mm, so repeating the above calculation we find a maximum magnification of M = 100.17. We chose to use a lens magnification of 10X while working with the 4 mW laser, and this is well below the ~100X maximum allowed.

Method

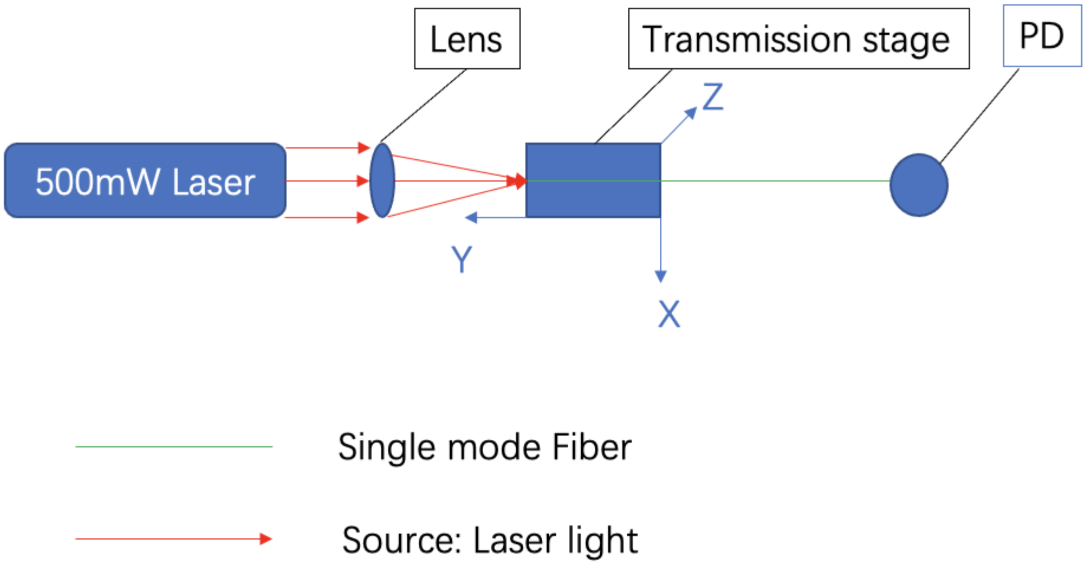


Figure 6: Setup diagram

The experimental setup can be summarized in Figure 6. In this project a 0.5 mW He-Ne laser was mounted to the optics table and was fitted with a magnification lens. The magnification lens was selected using the process indicated in the lens Selection section. Next a micro-positioner created by Thor labs was set up to hold a piece of fiber directly into the laser beam which could be manipulated by the 3 knobs located on the micro-positioner allowing you to move the fiber in the X, Y and Z direction. The light traveling through the fiber was then fed into the optical power meter allowing the intensity to be measured.

Experiment 1 - Poorly Cut Short [F-SS-50] Fiber

First, a fiber was cut intently to have a very poor surface structure along the fiber's edge. A pair of rusty pliers were used and upon inspecting the cut under a microscope (seen in the figure 7.a) it was evident that the fiber suffered some cracking and splitting, making it a poor transmitter of light. This is derived in part from the angle of incidence discussion above.

Figure 7.a: Poorly cut fiber.

We then began by mounting the poorly cut fiber into the micro-positioner with a 20 times magnification lens and manipulated the fibers position within the beam with the goal of finding its highest output on the optical power meter - this highest output was our starting value for measuring the intensity profile. We assumed that the profile would be Gaussian, hence, the point of maximum intensity would be the beam center.

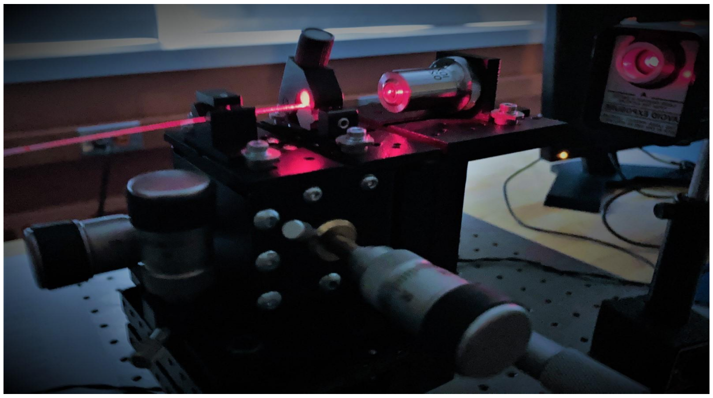


Figure 7.b: Acceptance angle threshold met.

Once the highest value was found we began to rotate the fiber horizontally by increments of 50 micrometers and recorded the output on the optical power meter until the fiber no longer transmitted light. The results of this can be seen in the graph below.

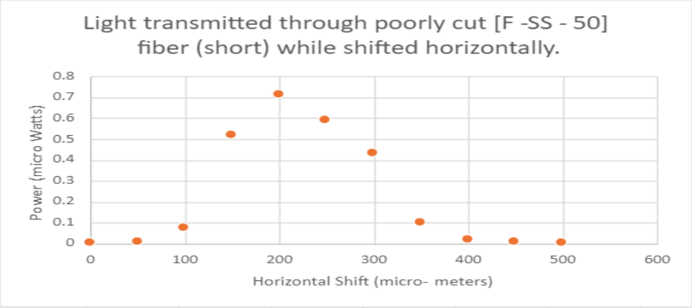


Figure 7.c: Poorly cut fiber output.

Experiment 2 - Clean Cut Short [F-SV] Fiber

The process discussed above was then repeated but for a cleanly cut fiber, cut via a specialized fiber cutting tool called a Fiber Cleaver. This tool used a high carbon steel rotating blade to cut the fiber more smoothly. The fiber can be seen in the picture below along with a graph of our outputs from the test.

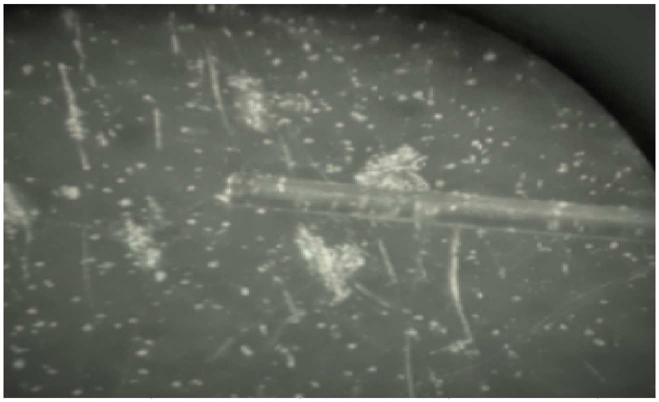


Figure 8.a: Image of the clean cut fiber.

The process for the clean cut short fiber was very similar to that of the poorly cut short fiber. The fiber was set up into the micro-positioner with a 20 times magnification lens. Then manipulated in the x and y direction until the maximum output was recorded on the optical power meter. From that point the fiber was shifted by increments of 50 micrometers in the horizontal direction until the value on the optical power meter reached approximately zero. The results of each experiment can be found in the analysis section below.

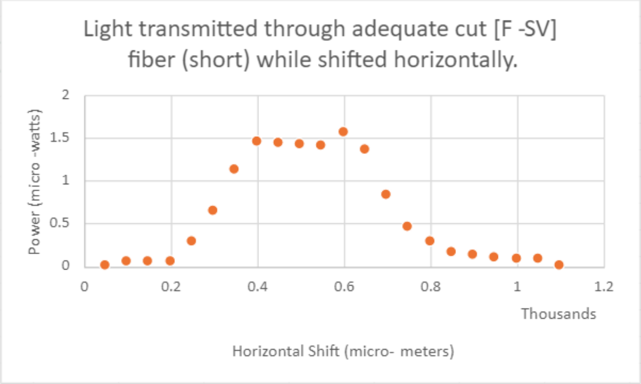


Figure 8.b: Clean cut fiber output.

It should also be noted that the power recorded was recorded at an approximate max of 1.56 microwatts. While the previous short poorly cut [F-SS-50] fiber had a recorded approximate max of 0.71 microwatts. We can assume that the difference in max power recorded was due to the clean cut fiber having a relatively smooth and level surface for the laser beam to enter. While the rough cut was more fractured which means that the less of the laser beam was actually allowed to enter the fiber.

Experiment 3 - Clean Cut Long [F-SA] Fiber:

The process for the clean cut long [F-SA] fiber was slightly different compared to our other tests performed. For the previous tests we used the 0.5 mW laser, but we realized that it was very likely that the collected data in the previous experiments was contaminated by light propagation through the cladding. To eliminate this, it was proposed to repeat the above experiments, but with a longer fiber. This was done with both the F-SS-50 fiber from experiment 1 and the F-SV fiber from experiment 2, but coupling was not successfully achieved for either fiber. We then decided to use the F-SA fiber and with this fiber, coupling was achieved, but the optical power meter was giving unreliable readings, as it was picking up too much noise from the environment. This noise persisted even with a cardboard box covering the optical sensor to prevent ambient light from entering. We therefore decided to try to couple to the F-SA fiber, but using the 4 mW He-Ne laser in the lab.

From there the process remained greatly the same. We mounted our new fiber that was approximately half a meter in length into the micro-positioner with a 10 times magnification lens. Then manipulated the fibers position until the max output on the optical power meter was found. From there we shifted the fiber horizontally by increments of 5 micrometers and recorded the results. We then repeated this process by shifting the fiber vertically through the beam at increments of 5 micrometers. In the end, we successfully coupled to the F-SA optical fiber that had a length of about 1.5 meters, and we were able to record the intensity profile of the 4 mW laser seen below.

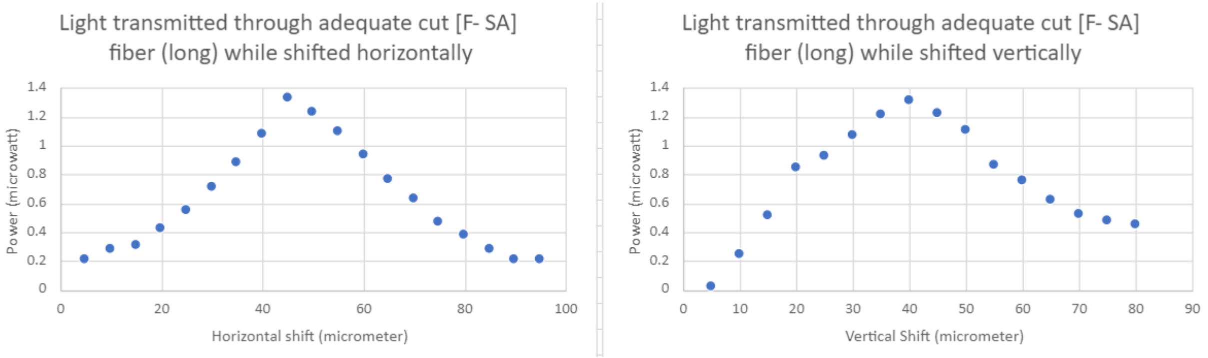


Figure 9: Clean cut long fiber output shifting, Horizontally (left) and Vertically (right).

Challenges:

This section's purpose is to describe some of the changes faced throughout completing this project. One of the most common challenges faced was when it came to properly cutting the fiber and having there being a clean surface devoid of fractures and with a perpendicular face. The reason why this was so difficult was because the fiber is very brittle. In the early stages of our project we tried to use a tool similar to the ones used to cut glass sheets, as seen in Figure 10, but they proved ineffective which is why we were forced to use a cutter with the high carbon disk blade.

Figure 10: Original fiber cutting tool.

It should be noted, however, that the carbon circular blade had its own challenges, such as it required the just right amount of strain on the fiber to work correctly. If the strain was too great, then the fiber would snap off in the wrong place and fracture. If the strain was too little, the blade would only scratch the surface and have to be gone over several times.

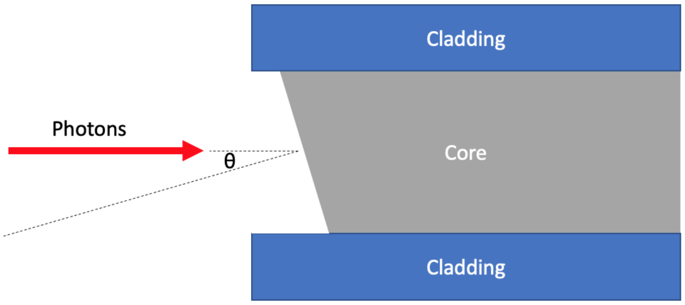


Figure 11: Illustration of the importance of a clean cut

The importance of having a cleanly cut fiber can be shown in Figure 11. If the cut is not flush, it is possible that the irregularities in the cut can prevent any light from achieving internal reflection through the fiber. A simplified, idealized, example if this is shown in Figure 11. If the fiber is cut at an angle that is not flat, despite the laser being incident at 0° to the traditional normal of the core, if θ is larger than the maximum acceptance angle, propagation of light is impossible at perfectly normal incidence, and possibly in general. This is a simple example that demonstrates the importance of having a cleanly cut fiber, which for this experiment, proved to be quite difficult.

There is another method to check if the end of the fiber is good. Using the same set up as seen in figure x and given a Fiber-Coupled LED, there should be a nice, unified beam pattern as shown in Figure x if there is a flush cut. If the beam pattern is out of focus and not spherical, it means that the fibers end is not cleanly cut. [13]

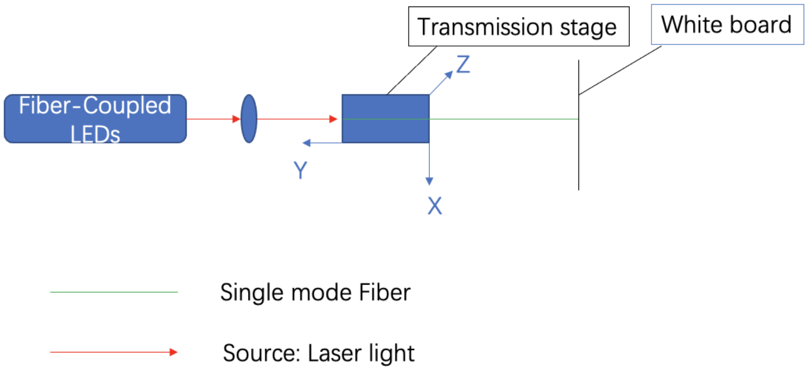


Figure 12: Fiber-Coupled LED Experiment

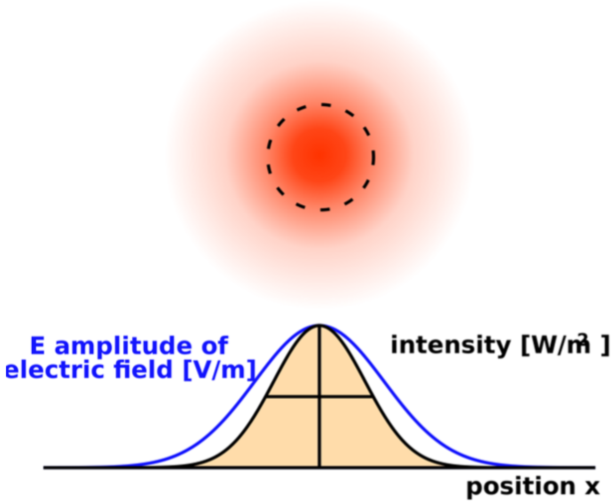


Figure 13: Nice, unified beam pattern of a flush cut

Another issue we faced was making sure that no ambient light from the surrounding room interfered with our reading. We had to make sure all of the windows were covered and had to try not to move around the room too much after we zeroed in our optical power meter so as to not change the ambient light entering into the sensor. At one point in our project we used a cardboard box with a cut out slit for the fiber to cover the sensor in order to help this issue.

One of the more frustrating challenges faced occurred when we were trying to test the cleanly cut long [F-SA] fiber. Originally we intended to measure the power output while the fiber was several meters long. But this was deemed untenable after many attempts to measure the output. The power meter was unable to detect any light traveling through the fiber even though it was clear that coupling occurred, evident through being able to see red light fully propagating through the fiber and being omitted at the end. Our solution to this was to shorten the fiber by approximately half a meter and to then upgrade our power from the 0.25 mW laser to the 4mW laser, which can be seen in our third experiment outlined above.

Analysis and Conclusion

As light enters one end of the optical fiber and shoots out the other, its intensity diminishes. This means that as the optical signal travels through the fiber, some of its energy is lost. This means that there is something in the fiber, or for some reason, blocking the light signal from passing through. There are many reasons for optical fiber attenuation, Absorption loss, Scattering loss, Dispersion loss, Radiation loss, Coupling loss. Light power propagating in a fiber decays exponentially with length due to absorption and scattering losses. Attenuation is the single most important factor determining the cost of fiber optic. For a given fiber, these losses are wavelength-dependent which is shown in the figure below. The value of the attenuation factor depends greatly on the fiber material and the manufacturing tolerances. The typical fused silica glass fibers we use today have a minimum loss at 1550nm. That's the reason why we need a fiber wavelength matching the laser wavelength, because it can give a minimum loss. [14]

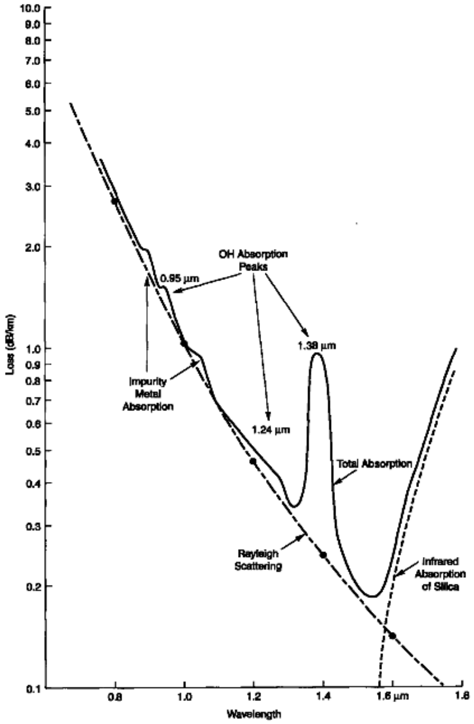
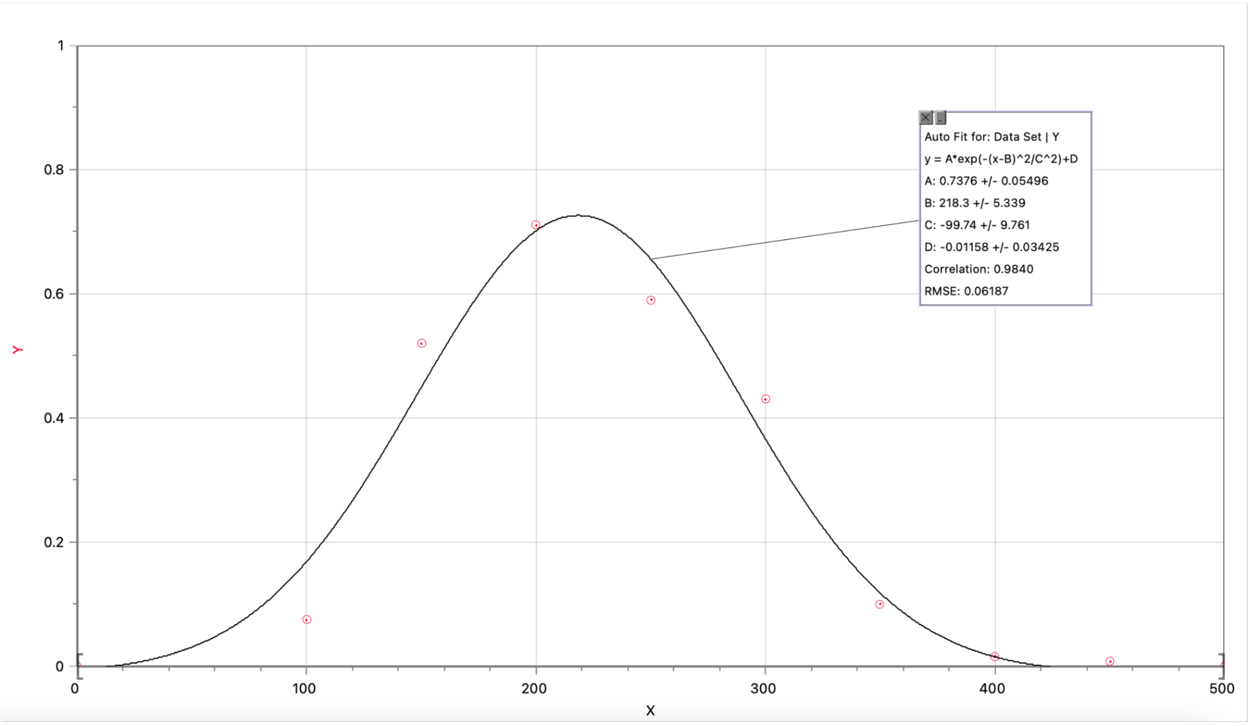


Figure 14: Silica glass fibers' loss vs wavelength

Looking back at our data for this paper, we can conclude that both the .5 mW He-Ne laser and the 4 mW He-Ne laser have a Gaussian intensity pattern.



Auto Fit for: Data Set | Y
y = A*exp(-(x-B)^2/C^2)+D
A: 0.7376 +/- 0.05496
B: 218.3 +/- 5.339
C: -99.74 +/- 9.761
D: -0.01158 +/- 0.03425
Correlation: 0.9840
RMSE: 0.06187

Figure 15: Gaussian plot of experiment one in LoggerPro

This is supported by our data in all three experiments. In order to verify the Gaussian relationship of our data, the data from each experiment was inputted into LoggerPro where a Gaussian best fit curve was plotted and a correlation calculated. An example of this can be seen in Figure 12. The correlation of the data with a Gaussian curve, from experiment 1 to experiment 3, following data as presented chronologically in this paper, was of 0.9840, 0.9808, 0.9943, and 0.9511 respectively. We can therefore conclude that our data follows a very Gaussian pattern, as predicted, and we can use this information to validate our hypothesis that the light of a He-Ne laser beam propagates with a Gaussian intensity profile.

Examining our data, we see that power in experiment 2 is greater than that of experiment 1. We believe that this can be attributed to the fact that the fiber used in experiment two had a cleaner cut fiber than the fiber used in experiment 1. As stated above, we believe that this led to undesired diffusion in the fiber and a lower power reading in the optical power meter.

We also see the power readings in experiment 2 against experiment 3 to be slightly increased as well, and this is the case despite an 8 times more power laser being used in experiment 3. We believe that there are two possible explanations for this. First, since the fiber used in experiment 3 was much longer than the fiber used in experiment two, it's possible that some attenuation occurred throughout the fiber. Given what we know about attenuation in a fiber, however, we know that this probably contributed to some negligible difference only. We believe that the greater discrepancy occurred because in both experiments 1 and 3 there appeared to be some propagation through the cladding of the fiber. Since the fibers in experiments 1 and 2 were very short, this propagation altered the readings on the power meter to a pretty noticeable extent. Comparing this to the longer fiber used in experiment 3, visually, we could not see light diffracting through the cladding at the end of the fiber, and as it was a longer fiber, it is obvious that the light incident on the cladding at the end of the fiber was much weaker in comparison to the other experiments. We believe that this is the major reason for the differences in power readings between experiments, with experiment 3 most likely having the most reliable data. Unfortunately, experiment 3 was also the most susceptible to noise while messing, and we attribute this noise to the sometimes abrupt changes in the data as well as the power reading not actually approaching zero while the fiber was vertically or horizontally shifted to the extremes. Improvements relating to the measurement quality might be conducting the experiment in a more controlled environment with respect to the ambient light of the room, as well as perhaps using a more precise optical power meter, as the power we were working with was very small and noise had a significant effect on the meter's readings.

Returning to a practical application standpoint of coupling to a single mode fiber, we ultimately see that based on the experiment results, adjusting the incident beam's angle and position can improve the coupling efficiency of light into a single mode optical fiber. There are unexpected variables that could impact the results such as reflection, scattering and absorption loss. For maximum coupling efficiency into single mode fibers, the light should be an on-axis Gaussian beam with its waist located at the fiber's end face, and the waist diameter should equal the Mode field diameter. This situation would lead to the greatest efficiency of propagation, with the only real limitations stemming from the span of wavelengths from the laser source itself and the attenuation losses through the fiber over any distance. When efficient coupling to a single mode fiber is achieved, however, these fibers provide a unique advantage in their minimum dispersion in comparison to their multimodal counterparts.

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