Title: Free space coupling of single-mode fiber

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Physics 410

Abstract: In this lab, we study single-mode fiber optic cables and how to couple light efficiently from free-space. We characterized the fiber and through mode matching the input Gaussian beam parameters of the He-Ne laser, we achieved a maximum of 73% coupling efficiency.

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Introduction:

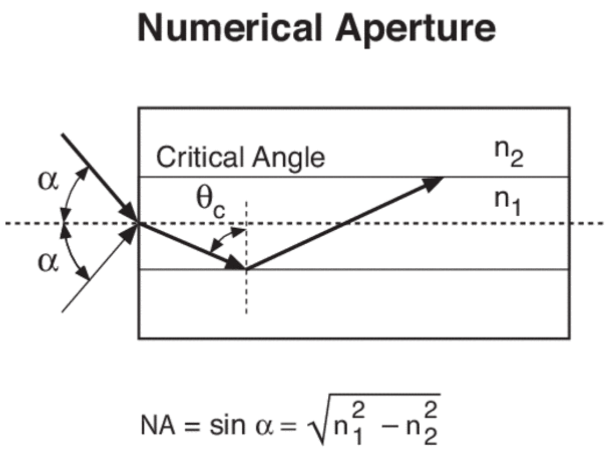
Fiber optic cables are everywhere. Most data processing centers, high-tech businesses, and all internet content is sent through fiber optic cables laid along the ocean floor, connecting every continent in one large network. These cables must be extremely strong to handle the stress and pressure at the depth of the ocean, but many would be surprised to hear that that actual core of the fiber was on the order of a few micron diameter. These cables going thousands of miles and carrying the entire data communications of a country are actually a few single-mode fibers collected in a strengthened outer shell (ITU). These cables only allow the propagation of a single transverse mode, that of a Gaussian, through the core. To attain a strong signal over large distances, a high coupling efficiency must be achieved. The study of the Gaussian profile of a single-mode fiber and HeNe laser source, with an emphasis on efficiency, is conducted in this lab. To get the maximum light output from the fiber optic cable for a given laser power, the incident transverse Gaussian laser beam must match that of the fiber.

Single-Mode Fiber Optic cables:

This lab involves efficient coupling of light into a single-mode fiber and involves two important aspects of light physics: first, an understanding of single-mode fiber optic cables and how light propagates through, and secondly, the use of Gaussian wave physics to accurately match the modes of the fiber and laser.

The central part of a fiber optic cable is the core. It's usually made from silica waveguides and additional elements, called dopants. Doping the fiber gives the fiber certain characteristics such as changing the index of refraction, absorption, dispersion, and are exploited to give the fiber extremely low attenuation across larger distances (source: 3,4). The next layer is the cladding, which provides an index of refraction much lower than that of the core and provides the difference in indices required for a high critical angle, Θc (2,8). This is all surrounded by a strengthening outer layer. The ends of the fiber are then cleaved to present a smooth interface for the light with minimal scattering. A fiber cleaver makes it easy by holding the fiber under tension and delivering a score that cleanly snaps the fiber giving that flat interface (6).

The accepted angles of incident light that can couple to the fiber are related to the critical angle and numerical aperture, NA. The critical angle comes from Snell's law going from a material with a high index of refraction, n_1, to a material with low index of refraction, n_2. At a certain angle, Θc, we find no light escapes the interface and the ray is fully internally reflected. This critical angle is related to numerical aperture, as the maximum angle of incidence that can be coupled to the fiber from free-space.



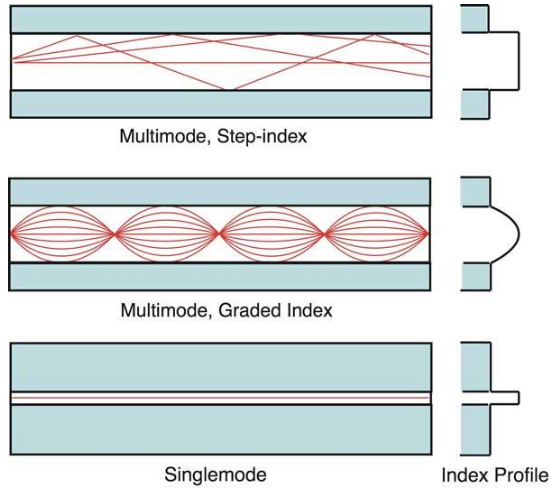


Figure 1a: Numerical Aperture gives the maximum acceptance angle for input light rays. Figure 1b: Single-mode fibers have such small core diameters that only a single transverse mode can propagate (Source: 8, 2)

Standard multimode fibers work by matching the NA of the fiber with the NA of an objective lens to make sure every incident ray is internally reflected; however, single-mode fibers work slightly differently. Instead, we must match the transverse Gaussian profile of the TEM_{00} mode of the fiber with that of the Gaussian beam entering the fiber. Let’s look at how to characterize Gaussian beams.

<u>Gaussian Beams:</u>

The ray optic picture is incomplete when dealing with small features and the high precision of single-mode fibers, so a different approach is needed. A Gaussian wave has a transverse Gaussian profile and can be described by figure A for the transverse direction and figure B for the longitudinal.

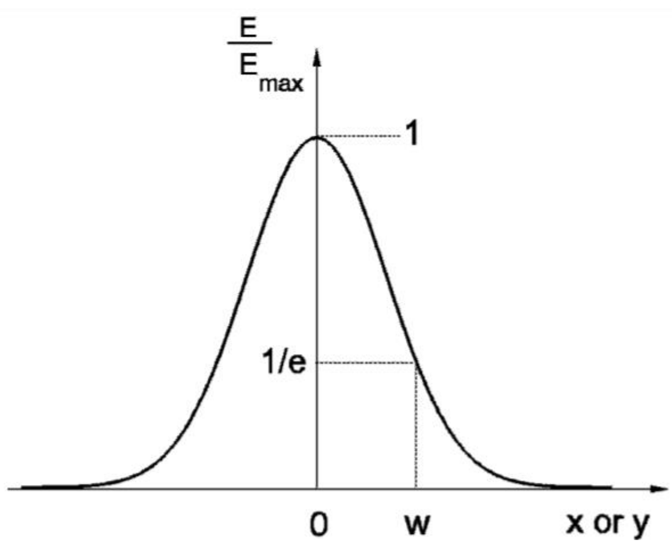


Figure 2a

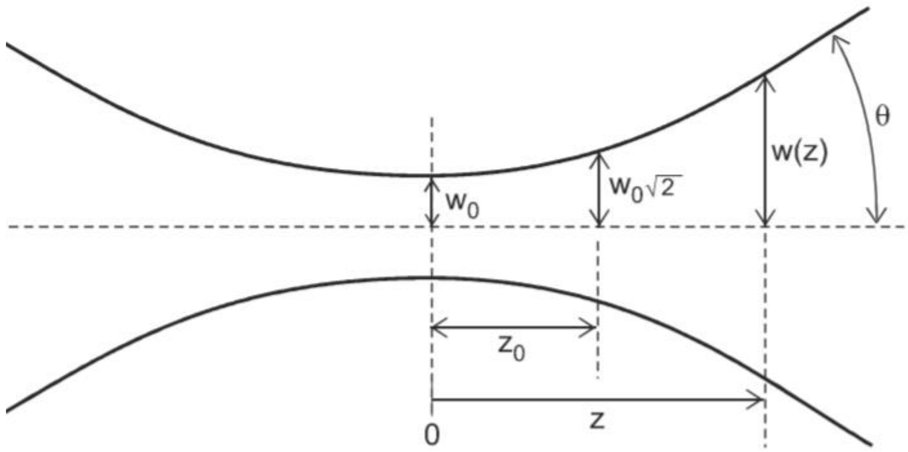


Figure 2b

Figure 2a: Shows the transverse profile of the Gaussian TEM_{00} mode that me match between fiber and laser. Figure 2b: Gaussian beams propagate through free-space as shown and are defined by the focus, ω_0 (Source: 10)

Where the first plot shows the transverse Gaussian profile of the TEM_{00} mode, the only mode allowed in these single-mode fibers. The second plot shows how a Gaussian beam propagates in the z-direction. The important parameters are the waist, ω(z), and the Rayleigh range, z_0. All other parameters are calculated from these quantities and are dependent on each other.

From these variables, we gain information on the divergence angle, the radius of curvature, and the waist, ω_0, at the focus. You can see how all the variables of the Gaussian beam can be described below. We use these and our understanding of optical lenses to manipulate the beam waist and focused spot size to match that of the single-mode fiber core.

Rayleigh length, z_0:	$z_0 = \frac{\pi\omega_0^2}{\lambda}$
Waist, $\omega(z)$:	$\omega(z) = \omega_0\sqrt{1 + {z^2}/{z_0^2}}$
Radius of curvature, $R(z)$:	$R(z) = z(1 + {z_0^2}/{z^2})$

Together with the knowledge of Gaussian beams and single-mode fibers, we can carefully study how the beam enters and exits the fiber to maximize the overall coupling efficiency.

Experiment:

There are three main parts to this experiment. First, we measured the Gaussian profile of our single-mode fiber, then measured the Gaussian profile of the HeNe laser, and finally used this information to optimize free-space laser to single-mode fiber efficiency. Each setup centers around measuring the transverse Gaussian beam profile of the fiber or laser. Our main measurement tool is a beam profiler, which accurately measures the Gaussian intensity distribution, and fits a Gaussian profile at a location, z. Then using the equations for a Gaussian beam, we can calculate all other parameters.

Let's begin by characterizing our single-mode fiber. First, the V number. This describes the difference between single- and multi-mode fiber optic cables and is described by,

$$V = \frac{2\pi a}{\lambda_0} NA$$

for a core of radius, a, and numerical aperture, NA. This describes the number of modes able to propagate in the core and a $V < 2.405$ describes the condition for a single-mode propagation only.

Using the beam profiler, we measured the Gaussian beam at several locations near the exit facet of the fiber. With the full-width-half-max (FWHM) of the transverse Gaussian profile, given by;

$$U(\rho) = e^{-\rho^2/\omega(z)^2} = 1/2$$

with $\rho = \sqrt{x^2 + y^2}$, we can get the waist $\omega(z)$ at this location. That is,

$$\omega(z) = \sqrt{\frac{-\rho^2}{\ln(1/2)}}$$

Where $\rho = \frac{1}{2} * FWHM$. We also know from standard parameters of a Gaussian that,

$$z = z_0 \sqrt{\frac{\omega(z)^2}{\omega_0^2} - 1} \;\; ; \;\; z_0 = \frac{\pi \omega_0^2}{\lambda}$$

for the location of the waist given the waists, $\omega(z)$ and ω_0. Since we only know the waist $\omega(z)$ and the relative difference between sample locations, $\Delta z = z_2 - z_1$, we need to write this in terms of Δz, $\omega(z)$, and ω_0;

$$\Delta z = \frac{\pi \omega_0}{\lambda} [\sqrt{\omega_2^2 - \omega_0^2} - \sqrt{\omega_1^2 - \omega_0^2}]$$

Then using Mathematica, we wrote a program that solves for ω_0 in the above equation, and in turn, can calculate all other dependent variables of our Gaussian beam.

The next experiment is measuring the Gaussian beam parameters of the HeNe laser. We used an f=25mm lens to focus the laser and measured the transverse Gaussian using the beam profiler; again, measuring the FWHM at a couple locations and using the same Mathematica program to give the focused beam waist, ω_0. Using the information about the focused waist and focal length of the lens, we can calculate the spot size of the laser beam before the lens, and compare it to the focused spot of the microscope objective. The focused spot waist needs to be on the order of the fiber's Gaussian wais,t or as close as possible for the necessary efficiency. Looking at the equation for a Gaussian beam focused through a lens, we see, in the far-field limit of the laser, R_1>>f → R_2=-f,

$$\omega_0' = \frac{\omega}{\sqrt{1 + (\frac{\pi \omega^2}{\lambda f})^2}} \approx \frac{\omega}{\frac{\pi \omega^2}{\lambda f}} = \frac{\lambda f}{\pi \omega}$$

We say $1 \ll (\frac{\pi \omega^2}{\lambda f})^2$, so we can approximate the denominator. This describes how the waist of the laser incident on the lens, ω, gets focused to a spot, ω_0', by a certain lens of focal length, f, and wavelength of light, $\lambda = 633nm$ for the HeNe laser.

The final part of this experiment uses the full setup; a 10X microscope objective to focus our culminated laser into the single-mode fiber and a photodetector to measure the incident and output power. Maximization of the output power was conducted with a goal of 90% efficiency.

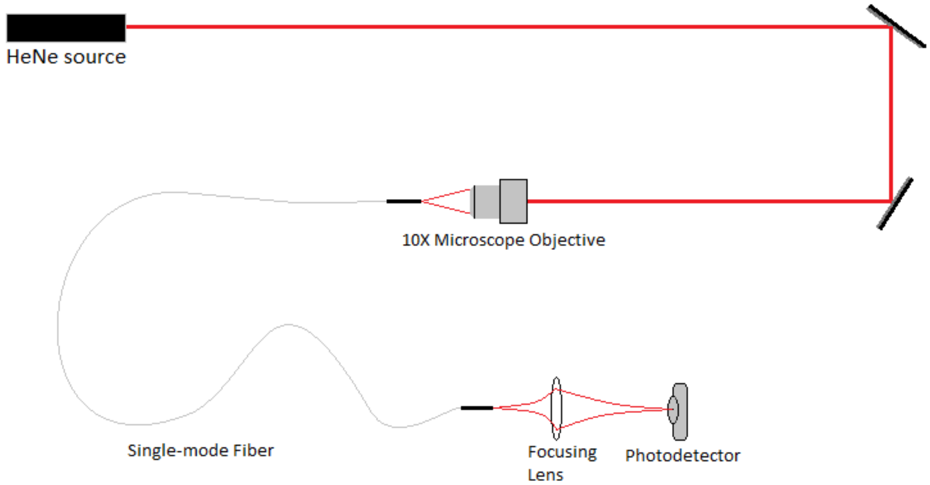


Figure 3: Final optical setup for optimizing the power output through the fiber optic cable.

Data:

First let's calculate the V number for our fiber, *Newport FS-V*. Newport gives the Mode Field Diameter as 3.6-5.3µm, or when the intensity of the Gaussian drops to $1/e^2$ on either side (when $\rho = \omega$), and is given to be 28% larger than the core diameter. The core diameter is therefore between 2.8-4.1µm. That along with an NA=0.10-0.14 gives a calculated V number of 1.4-2.8 (7, 8). This is on average <2.405, but each fiber will have slight variations.

For part 1, measuring the Gaussian profile of the fiber, we obtained a FWHM (shown below, left to right) of 1.0mm, 1.5mm, and 2.0 mm for locations z= 0mm, 5mm, and 10mm respectively.

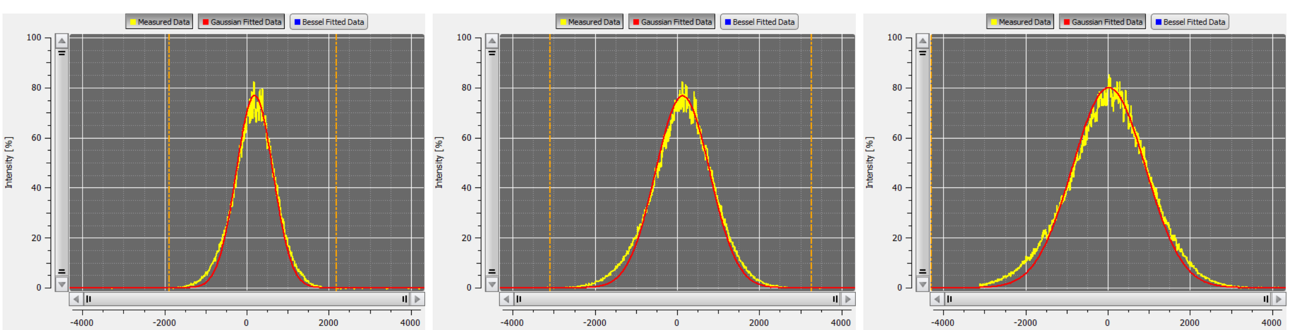


Figure 4: Gaussian profiles of at the exit facet of the fiber.

This gave the waist $\omega(z)$, at a couple relative distances, z, away from the focus. Using the equation described in the "Experiment" section, we obtained the following Gaussian parameters for our single-mode fiber:

Newport FS-V fiber:
$\omega_0 = 3.4 \pm 0.1 \times 10^{-6}\ m = 3.4 \pm 0.1\ \mu m$
$z_0 = 5.6 \pm 0.1 \times 10^{-5}\ m = 56 \pm 1\ \mu m$
$\theta_0 = {}^{\omega_0}/_{z_0} \approx 3.4°$

Next we measuring the Gaussian profile of our laser beam. We did so with an optical path length $\approx 2\ m$, through an f=25mm lens. With the beam profiler, we got a FWHM of 1.75mm, 2.3mm, and 2.6mm for locations z=0mm, 10mm, and 15mm respectively. Using the Mathematica script to solve for the focused Gaussian parameters of the beam after the lens, we get:

HeNe laser source:
$\omega_{0,1} = 5.92 \times 10^{-6}\ m;\ \omega_{0,2} = 6.10 \times 10^{-6}\ m;\ \omega_{0,3} = 5.59 \times 10^{-6}\ m;$
$\omega_{0,avg} = 5.9 \pm 0.3 \times 10^{-6}\ m = 5.9 \pm 0.3\ \mu m$

The averaged focused waist was $\omega_{0,avg} = 5.9 \pm 0.3\ \mu m$ through the f=25mm lens. Using this, we got a laser waist of $\omega(z) = 0.85 \pm 0.4\ mm$ at the location of the objective ($z \approx 2\ m$). Our microscope objective has a focal length of 16.5mm, and gives us a final focused waist radius of $3.9 \pm 0.2\ \mu m$ (5).

For the final experiment of achieving the highest efficiency though our single mode fiber, we used all calculated variables to help us achieve maximum coupling efficiency. We got a fiber maximum of 134mV at the exit facet and a laser maximum power of 204mV using all the optical lenses in the setup to account for their loss. This gives an efficiency of around, $\frac{P_{fiber}}{P_{laser}} = 66\%$.

<u>Analysis:</u>

While we obtained an efficiency of ~66%, shy of the 90% goal, we need to see what accounts for these additional losses. First, our V number was slightly above the threshold, $V < 2.405$ as our calculated value was $1.4 < V < 2.8$. Newport's website gives our fiber $V = 2$, but the slight differences in core diameter and numerical aperture give a larger range than the website shows. This means a higher order mode could exist at certain points in the fiber, but these modes will not propagate much further than these variations. We are still within range for single-mode propagation, but the V number has a larger range than expected.

The end facets of the fiber also need to be as flat as possible to minimize scattering. We can assume this surface is perpendicular to the fiber (even though it is closer to a few tenths of a degree), and using the Frenal relations, we can estimate the reflection, and loss, at each interface. Assuming $\theta = 0$, and a core of silica, $n = 1.457$ for $\lambda = 633nm$ (source: RefractiveIndex.INFO),

$$R = |r|^2 = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2$$

Thus, for each air-silica interface the reflectance is 3.5%. Therefore, we have a total of 7% laser power reflected at the two fiber interfaces.

There is also attenuation inherent of the fiber and wavelength of light used. These total scattering and absorption losses are based on the material and dopants used in the fiber core. From Newport's website; we have an attenuation of 15dB/km for our fiber, which is the ratio $^{P_1}/_{P_2} = 31.6\ km^{-1}$, or a 96.8%/km loss. For a length of ~2m, we have ~0.1% loss. Not a significant amount due to our short length and is not our main source of losses.

When we compare the single-mode fiber's waist, to the data given on Newport's website, we find that our calculated focused waist of $\omega_0 = 3.4 \pm 0.1\ \mu m$, shows that our data is a slight overestimate of the field radius in the fiber, which should be between 1.8 – 2.7 @633nm. This means our fiber has a minimum 22% greater Gaussian waist than given on the website. Our fiber is therefore characterized to have an above average mode field radius.

The next value we calculated was the spot size of our focused laser beam. We got a focused beam waist of $\omega_0' = 3.9 \pm 0.2\ \mu m$ after the microscope objective. This is ~15% greater than the calculated field radius of the fiber optic cable, and at least 37% greater than given on Newport's site. Since our focused spot is much larger than the field radius of the fiber, we experience significant losses where the tails are cut off the Gaussian profile of the incident laser.

The optical path length is very important for this measurement. At first, we measured the Gaussian profile with a path length ~2m, but had our objective <1m away from our laser. This didn't give our HeNe laser enough time to diverge to our measured beam waist, so some adjustment was necessary to get the correct optical path length. There is an inverse relationship between laser waist and focused spot size, so increasing the optical path length further to increase the total laser divergence, or adding another lens, would both work to reduce our focused spot size even more and match the fiber's field radius better.

<u>Conclusion:</u>

Even with our mismatched Gaussian field diameter of the single-mode fiber and focused laser of 15%, we obtained a maximum power of 134mV exiting the fiber. Including our lenses used, we had a "before" power of 204mv with an additional ~7.1% loses for the fiber end facet reflections and attenuation, giving a total efficiency of 66% + 7.1% = 73%. This is a total efficiency of 73% coupled from free-space into the single-mode fiber considering all losses.

This is impressive when considering the rudimentary fiber optic mount and 3-D translation stage used, the non-perfect cleaved ends of the fiber, and the best alignment we could accomplish. At such short lengths of fiber optic cables, we run into very little attenuation, ~0.1%, but for long distance communications and undersea cables, these losses become very significant. Therefore, wavelengths are chosen as to minimize the attenuation as much as possible. Our fiber with 15dB/km loss is very high when compared to undersea cables of 0.5dB/km (source: The Fiber Optic Association).

Much of the efficiency losses came from misalignment and the fiber ends much more than the attenuation in the fiber. To minimize this, a more sophisticated mount or fiber connector would be used, as well as cleaving the fiber ends at the Brewster angle to minimize reflections.

This lab showed us how to work with fiber optic cables in real world experiments and use Gaussian beam optics when high precision is necessary. We learned how to calculate and manipulate the Gaussian beam to get the correct dimensions for the waist and focused laser spot. These skills will be very helpful when working on fiber optics and single-mode fibers in the future, as well as any system that requires the extreme precision, carefully calculated parameters, and the high efficiency of many optical experiments. This lab tests the patience of those unprepared for the relentless fine tuning needed for maximum efficiency, and while we only achieved 73%, this is considered very good considering the conditions and laboratory equipment available.

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