Progress Report 2: Improvement of Fiber Optic Based Optical Levers By Elimination of Higher Order Cladding Modes

Brian Charous[1,2]

[1)] *California Institute of Technology, Pasadena, CA 91125*

[2)] *Carleton College, Northfield, MN 55057*

(Dated: 1 August 2014)

I. INTRODUCTION

At the time of the last progress report, I had made measurements on a Helium-Neon laser to determine its mode structure, especially near the wings of what should be a Gaussian distribution if the laser was operating in $TEM_{0,0}$. I then tried to do the same with the fiber-coupled diode laser, but was having problems looking at the output due to extraneous reflections. I thought that a collimating lens might help me see the output of the fiber.

II. TASKS COMPLETED

Once I received lenses with short enough focal lengths, I tried to observe the mode structure of the optical fiber. The fiber I was looking at was a Thorlabs S405-XP custom patch cable without a jacket. I found that the angle of divergence of the light out of the optical fiber using

$$\Delta\Theta = \frac{\lambda}{\pi w}, \tag{1}$$

where w is the core diameter of the optical fiber, and λ is the wavelength of light coupled into the fiber. I estimated that the full angle of divergence is 7.22 degrees as the diameter of the core of the S405-XP fiber is 3.0 μm and the wavelength of the laser is 635 nm. Based on this angle of divergence, I estimated that I could use a lens with focal length of 50 mm or possibly greater without filling the lens, as the spot size 50 mm away from the fiber would have a radius .27 inches and the lenses I had were 1 inch in diameter. However, I would not want to let the spot size get much bigger since I'm really interested in looking at the wings of the power distribution.

I then attempted to make measurements of the output of the fiber using the lens, but I found that since the lenses I was using had such small focal lengths compared to their diameter, the radius of curvature of the lenses was large, and thus if the beam was not perfectly centered on the lens, I would see an aberration where the beam looked like a comet and I could not get a good look at what the profile actually looked like. I spent a couple or days tweaking the setup so that I could finally look at the mode structure of the fiber. I located a mount that let me control the positioning of the lens precisely in 3 degrees of freedom. This helped a lot, but it was still not perfect. I also took some black electrical tape and black felt and shielded any surface that I thought might reflect light. Eventually, I aligned the lens and took some data. However, after shielding everything, I was actually able to look at the output of the fiber directly by placing the output couple of the fiber right next to the aperture of the beam profiler. As with the HeNe laser, I took two data sets, one where the beam profiler was saturated so that I could look at the wings of the power distribution and another where the entire profile could be seen. I ran it through my script to stitch the two data sets together and got a good look at the profile. The output of the fiber is shown in Figure 1.

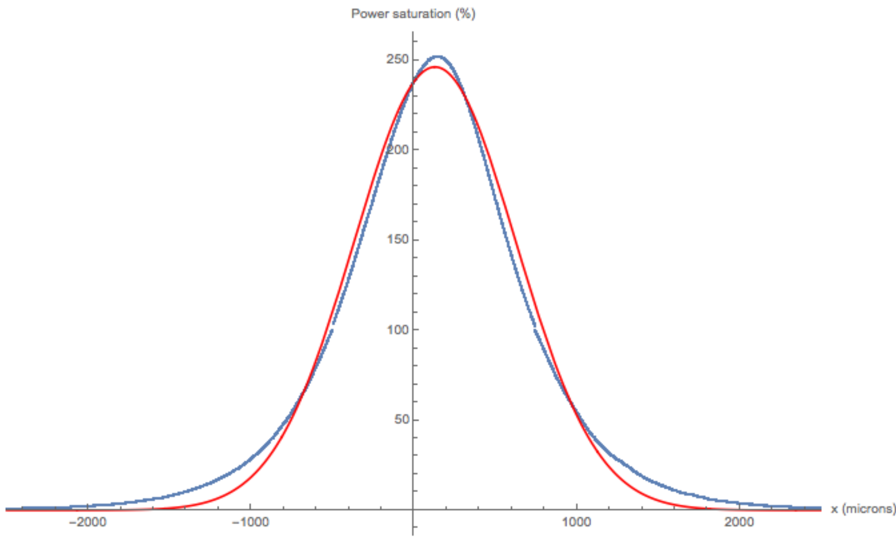

FIG. 1. Output of the step-index single-mode optical fiber coupled diode laser. The profile can be seen in blue, a Gaussian fit is shown in red.

It's clear that the output of this fiber is not gaussian, especially in the wings, as the gaussian falls off way faster. The question is whether this is what the core mode of the optical fiber looks like or are there other modes being coupled through the fiber. It seems like this may just be what the core mode of the fiber looks like. To investigate this, I took measurements of the fiber with a loop of fiber sitting in several different orientations, and even while I was shaking the fiber. The output was almost identical in each of these data sets. In a semi-log plot, it looks like the fiber is actually doing a really good job since it takes about 4 orders of magnitude before the data starts to look noisy. A semi-log plot can be seen in Figure 2. In that plot, it's even more clear that the fiber's profile doesn't look like a gaussian.

We thought that maybe the S405-XP fiber was just a better fiber than the jacketed one used in the optical lever system, so I looked at the profile of a jacketed single-mode step-

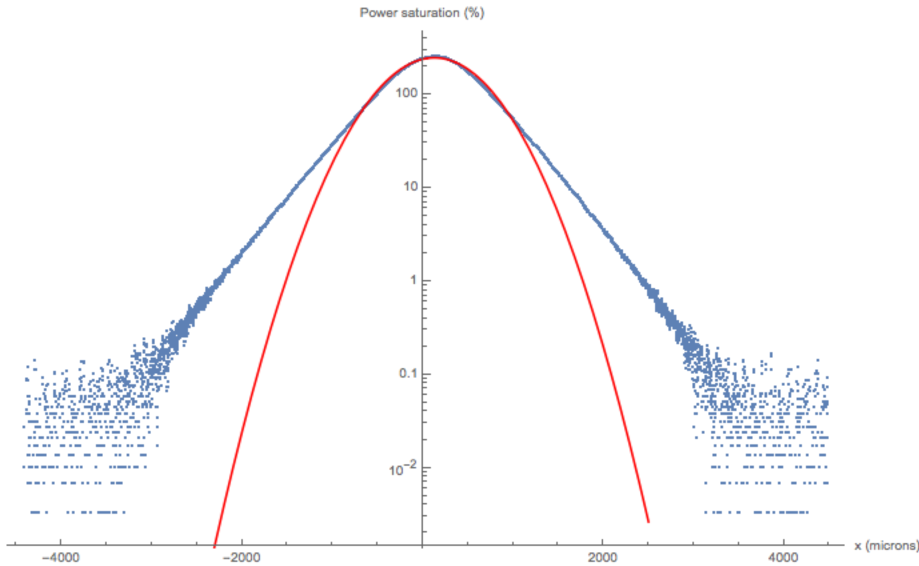

FIG. 2. Output of the step-index single-mode optical fiber coupled diode laser on a semi-log plot. The profile can be seen in blue, a Gaussian fit is shown in red.

index optical fiber, this one a Thorlabs P3-630A-FC-5. This time, I also took measurements of the fiber after it had been reflected off a mirror and through a 24.5 mm plano-convex lens. The mirror was used to make it easier to align the light through the lens. An image of the setup is shown in Figure 3.

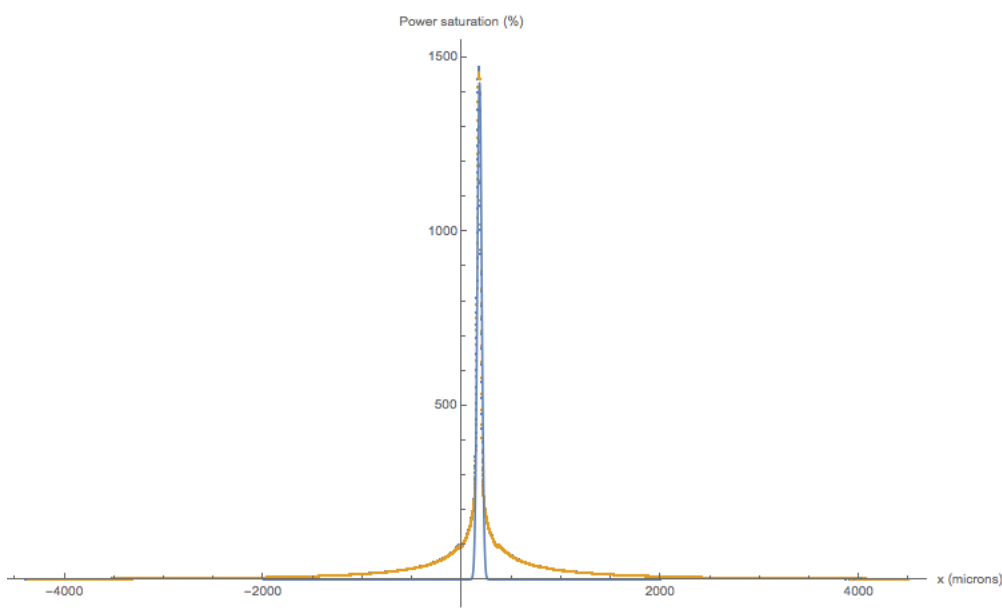

FIG. 4. Profile of the jacketed optical fiber (at the beam waist) in two different orientations. The two orientations are right on top of each other. A gaussian fit is shown in blue.

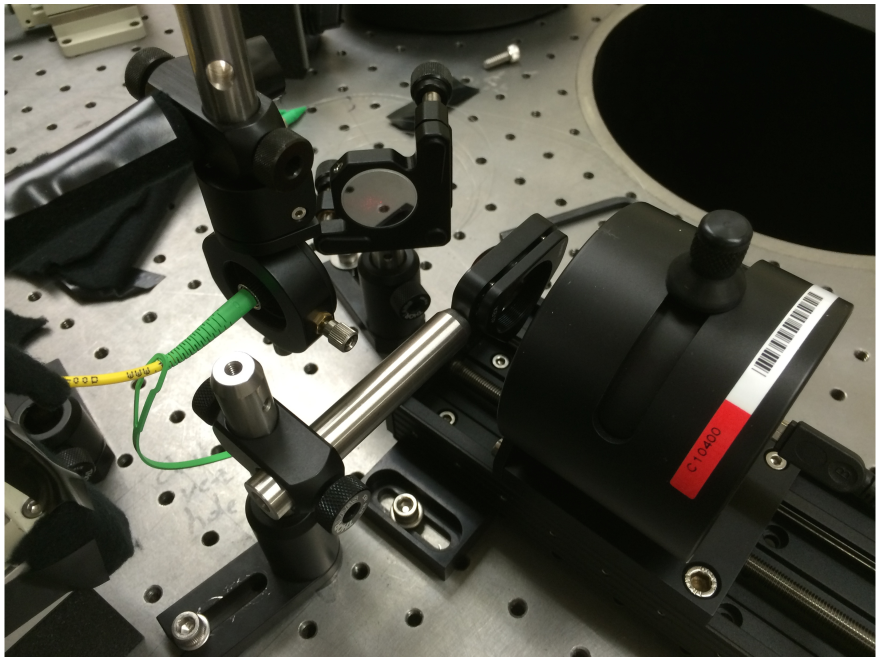

FIG. 3. Setup used to profile the fiber. The light out of the fiber is reflected off a mirror and through a 24.5 mm lens onto the beam profiler.

I looked at the profile at the beam waist so that I could really see the wings. I took data with the fiber sitting in different orientations. These data can be seen in Figure 4. The different orientations are lying right on top of each other indicating that there probably isn't some higher order mode being transmitted by the cladding. A gaussian is fitted to these data, and it is very evident that the fiber's profile is not gaussian.

I compared the output of the jacketed fiber to the output of the unjacketed fiber that I had been using earlier using the same setup. These data are shown in Figure 5. The jacketed and unjacketed fiber's profiles look very similar. The unjacketed fiber's profile is shifted over, but this is due to a slightly different alignment of the setup. The unjacketed fiber also seems to transmit slightly more power, but that may be due to differences in the fiber's construction or materials used.

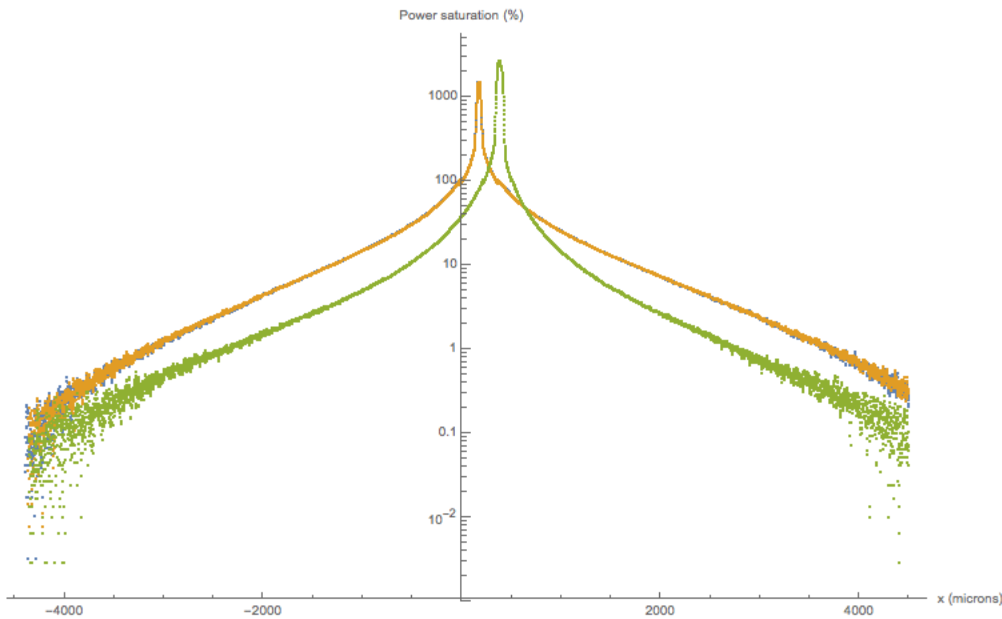

FIG. 5. Profile of the jacketed optical fiber (at the beam waist) in two different orientations and the output of the unjacketed fiber from earlier. The two jacketed fiber profiles are shown in orange and blue. The unjacketed fiber is shown in green.

We eventually found what the actual output of the fiber should look like. The field of the fiber should be of the form

$$H_{x0} = -\sqrt{2/\pi}(\epsilon_0/\mu_0)^{1/4}\frac{W}{aVJ_1(U)}\sqrt{n_2 P}\begin{cases} J_0(U\frac{r}{a}) & : r \leq a \\ \frac{J_0(U)}{K_0(W)}K_0(W\frac{r}{a}) & : r \geq a \end{cases}, \tag{2}$$

2

where

$$U^2 + W^2 = V^2 = (n_1^2 - n_2^2)k^2a^2, \tag{3}$$

where n_1 is the index of refraction of the core of the fiber and n_2 is the index of refraction of the cladding of the fiber and k is the wavenumber of light through the fiber. Also,

$$U = (n_1^2 k^2 - \beta_s^2)^{1/2}a. \tag{4}$$

Another aspect of this project is to simulate the telescope used in the optical lever system. Using Fourier optics, I am trying to simulate the telescopes mathematically and see if I can produce the ring that occurs in reality. I took some Matlab code to do this calculation and rewrote it in Mathematica since I am more familiar with Mathematica. I was able to produce identical results in Mathematica to the Matlab code when propagating a Gaussian beam through free space. I then tried to propagate a Gaussian through a lens. I was not so successful at this, though. I used the book *Introduction to Fourier Optics* to find a density function for my plano-convex lens. I found the density function to be

$$\Delta(x,y) = \Delta_0 - R + \frac{x^2+y^2}{2R}, \tag{5}$$

where Δ_0 is the maximum thickness of the lens and R is the radius of curvature of the lens. I then found that the phase transformation of light through the lens to be

$$t(x,y) = \exp\left(ik\Delta_0\right)\exp\left(-ik(n-1)\right)(\Delta_0 - R + \frac{x^2+y^2}{2R}), \tag{6}$$

[1]

where n is the index of refraction of the lens and k is the wavenumber of the light being passed through the lens. However, I found that the Gaussian gets wrecked if it is propagated through the lens. This probably a bug in my code or a math error. This should not be a hard fix.

III. TASKS TO BE COMPLETED

1. Fix propagation code
2. Propagate through telescope and see if I can reproduce the ring
3. Fit fiber profile to field of Equation 2
4. Strip off cladding on one of the fibers, place index-matching fluid on it, see if anything changes

REFERENCES

[1]Goodman, Joseph W. *Introduction to Fourier Optics*. New York: McGraw-Hill, 1968

[2]Loss Analysis of Single-Mode Fiber Splices. *The Bell System Technical Journal* 56: 703-718, 1977