LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Searching for Higher Order Cladding Modes in Fiber Optic Based Optical Levers

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1 Summary

Advanced LIGO uses fiber-coupled diode lasers as input to its optical lever system. The optical levers make up an auxiliary system that provides error signals in pitch and yaw in the first step of the lock of the interferometer. Currently, the optical levers contain noise which makes it harder to bring the interferometer into lock and sometimes provide false positives of seismic noise. A possible source of that noise is in the optical fibers; if excess light is coupled into the cladding of the otherwise single-mode fiber, the fluctuating higher-order mode could appear as beam wiggle and be interpreted as test mass motion. In addition, a small ring appears around the core of the laser spot at the end of its throw, decreasing the precision of the optical levers. In this experiment, we examined whether the single-mode optical fibers used could really be carrying higher-order modes, and if the ring around the core of the beam could be reduced or eliminated. Our analysis indicates that the optical fibers do not contain excess mode content, and the ring may be caused by diffraction in the optics of the optical lever telescopes.

2 Introduction

The Advanced LIGO detector uses optical lever systems to help control the pitch and yaw of the test masses in the interferometer. These optical levers consist of a fiber-coupled diode laser whose output is launched through a telescope. The telescope aims and focuses a beam onto the appropriate test mass and the beam is then reflected onto a quadrant photodiode for readout. By measuring the position of the beam using the quadrant photodiodes, the test masses can be kept stable.

Although the current setup works, there has been some noise observed at the sites. First, power shifts have been noticed on the photodiodes. Although a power shift itself would not be a problem since the system can normalize the power on the photodiode during analysis, the beam's pointing seems to change when the power changes. A second source of noise is a small ring of about four percent power around the laser spot on the photodiode. Eliminating, or at least minimizing these effects would greatly improve the sensitivity of the optical lever system.

The fiber used in this system is a single-mode optical fiber. This fiber should ideally clean the laser's output and only couple light where most of the power is in a core mode, thus producing a somewhat Gaussian spot. However, since the beam moves when the power changes, a good candidate for this noise source is the fiber optic system coupling additional light into the cladding of the fiber. This would then cause the fiber to produce some sort of pattern that varies with time at its output, especially when the fiber is moved. Because the laser and fiber system is sitting out in the open, it is not in the vacuum system, nor is it seismically isolated, it could be the case that simply moving the fiber causes this power shift. The fiber may also be related to ring produced, however that may also be caused by some other optical component.

Thus, the goal of this experiment was twofold. First, we wanted to measure the output of the fiber to determine if higher-order modes were being coupled into the cladding of the fiber. If it was determined that higher order modes might be a problem, we would look for ways to eliminate them. Second, we wanted to simulate the telescope system using beam propagation techniques to see if the ring would appear.

3 Profiling the Optical Fiber

In order to examine whether or not higher-order modes might be transmitted by the optical fiber, the output of the fiber had to be examined. In order to measure the light out of the fiber, we used a beam rotating slit-style beam profiler. In theory, the beam profiler should be able to measure the output of the fiber my simply pointing the fiber at the aperture of the profiler. In practice, however, there were several issues with this. First, the light coming out of the fiber has a very large angle of divergence. The angle of divergence out of the fiber ($\Delta\Theta$) is given by

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

where w is the core diameter of the fiber. As we were using a laser of wavelength 635 nm and a fiber with core diameter of 3.51 μm, the full angle of divergence out of the fiber is about 6.6 degrees. This made it challenging to use a lens to focus or collimate the beam since any small lens had to be placed very close to the fiber such that the beam did not fill the lens. This proved challenging because the beam had to be centered as perfectly as possible in the lens otherwise the lens would produce very noticeable aberrations in the beam. The other option was to simply place the beam profiler close to the fiber. This worked, but only after eliminating several reflections that were produced by the fiber output coupler.

Since the higher-order modes in this single-mode fiber were probably a small effect that only shows up in the tails of the profile, we took two separate measurements. One measurement was taken with the beam profiler's gain setting at a setting where the photodiode was never fully saturated such that the whole profile was visible. The second measurement was taken with the gain setting turned to the highest possible. This clipped the profile since the photodiode was saturated, however, it let us look at the tails of the profile. These two data sets could be then put together such that a more detailed profile was constructed.

Once an apparatus was constructed to measure the fiber's output, it was immediately clear that the fiber's profile was not Gaussian like that of a laser operating in the $\mathrm{TEM}_{0,0}$ mode. The fiber's profile was similar to a Gaussian near its peak, but while a Gaussian drops off exponentially in the tails, the fiber's profile dropped off more slowly. The output of the fiber can be seen fitted to a gaussian in Figure 1.

This behavior is expected. A 2D profile of the wavefront of a single-mode optical fiber is given by Equation 2.

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

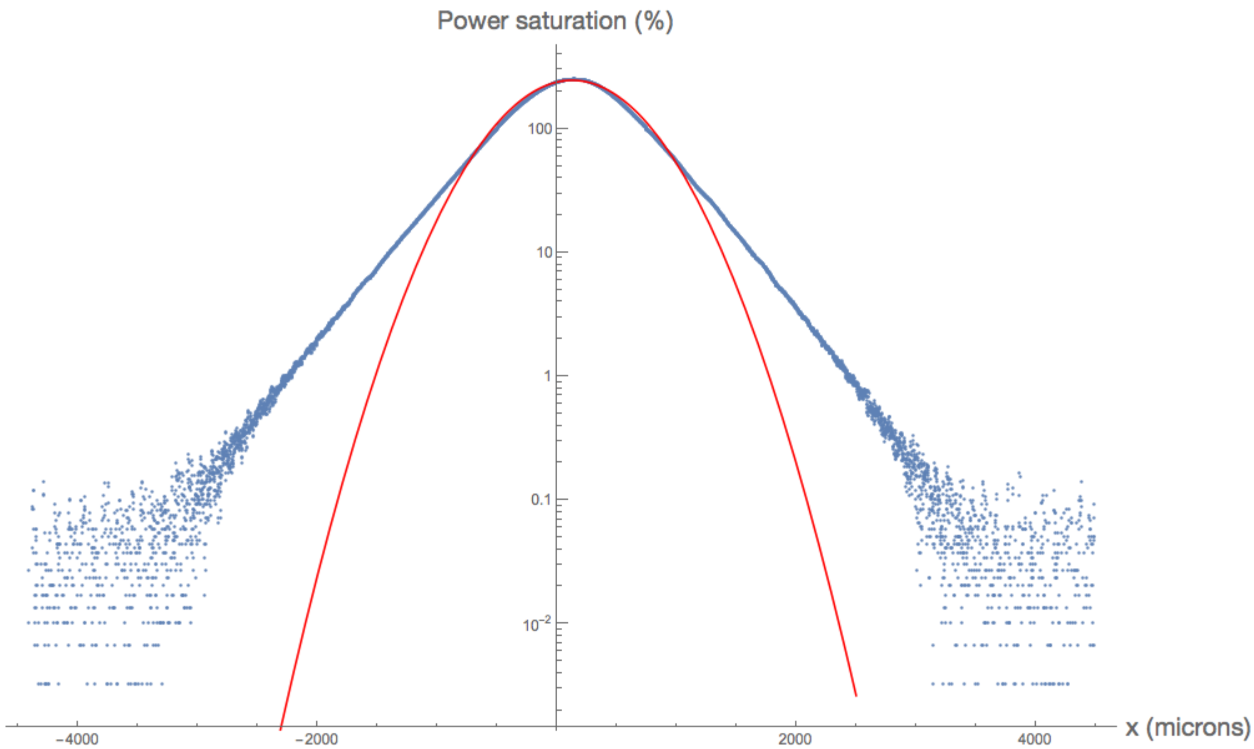

Figure 1: Experimental output of the singe-mode optical fiber compared to its best-fit Gaussian. The profile can be seen in blue and the Gaussian fit is shown in red. It is evident that the optical fiber's profile is not Gaussian.

Equation 2 is defined in terms of W, U, and V, where

$$W = \frac{\sqrt{a^2\beta^2\lambda^2 - a^2k^2\lambda^2\text{n1}^2 + 4\pi^2a^2\text{NA}^2}}{\lambda}, \tag{3}$$

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

and V is the "V number" of the optical fiber, defined as

$$V = \frac{2\pi a\text{NA}}{\lambda}. \tag{5}$$

In this notation, n_1 is the refractive index of the core, n_2 is the refractive index of the cladding, NA is the numerical aperture of the fiber, and k is the wavenumber of the light passing through the fiber. β is the propagation constant of the optical fiber, which is defined as $n_{\text{eff}}k$, where $n_1 \leq n_{\text{eff}} \leq n_2$. However, β is not well defined for optical fibers.

4 Searching for Higher Order Fiber Modes

If higher order cladding modes were present in the optical fiber, the profile of the output of the fiber would change if the fiber was moved. As the optical fibers in the actual detector are not in the vacuum system, movement of the fiber may cause the power shifts. To see if movement of the fiber could cause problems, I used the beam profiler to look at the profile of an optical fiber to create a baseline profile. I then took measurements with the optical fiber lying in different positions as well as while the fiber was moving. Measurements were made with the beam profiler looking directly at the fiber as well as with the beam profiler looking at the beam through a lens at the beam waist. The measurements made through the lens appeared to show a coma aberration, so the profile of the beam directly out of the fiber was not of much use. These measurements were compared against each other and the baseline, but there was no substantial difference between each profile, as shown in Figure 2. Repeated trials were carried out with several optical fibers of the same type as well with another type single-mode optical fiber.

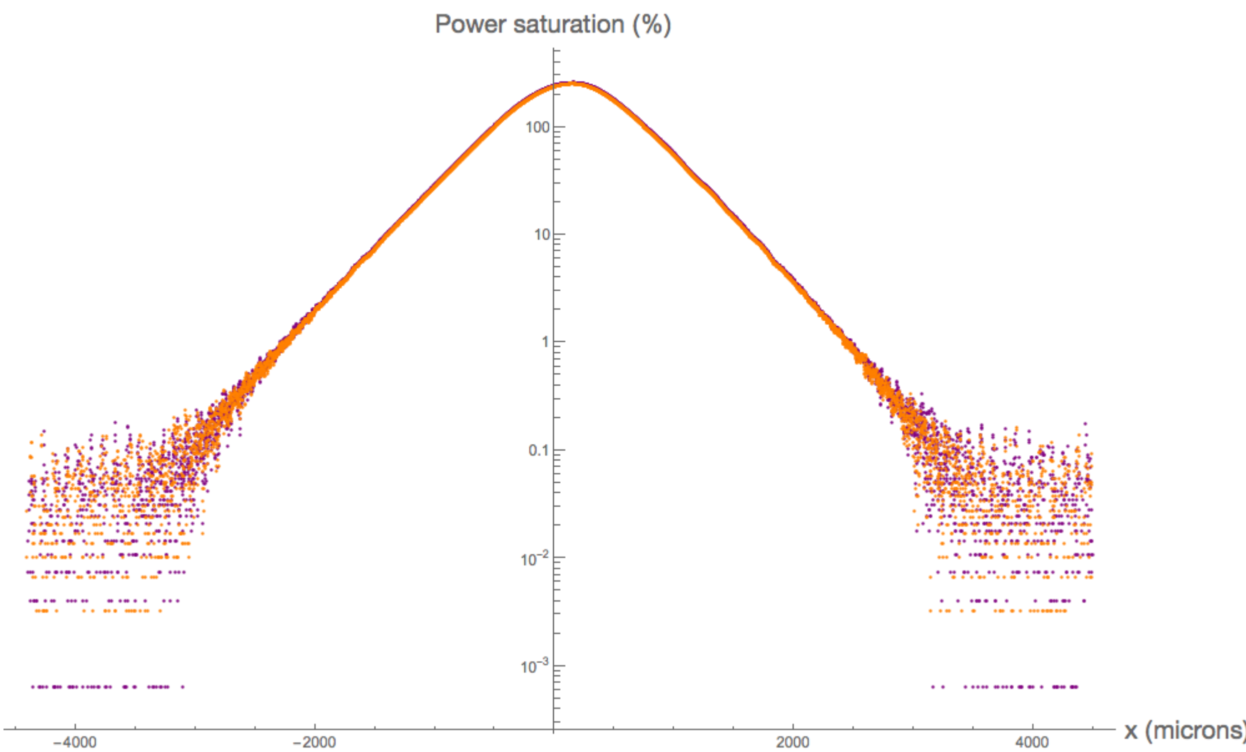

Figure 2: Profile of the same optical fiber in two different orientations. If higher-order cladding modes were present in this fiber, the profile of the fiber should change when moved.

Since the profile of the fiber's beam did not change when the fiber was moved, it seemed to suggest that excess light was not being transmitted through the cladding of the fiber. However, I was not certain that what I was seeing on the beam profiler was actually a true single fiber mode defined by Equation 2. Unlike a simple Gaussian, Equation 2 cannot be fit to experimental by a computer. Thus, in order to compare the experimental data to theory, the whole setup had to be simulated. This was accomplished by taking the theoretical field at the output of the fiber and propagating using Hankel transforms several centimeters to the beam profiler. The power of both the experimental and theoretical profiles was normalized since the overall shape of the profile is what is important. The result of this analysis can be seen in Figures 3 and 4.

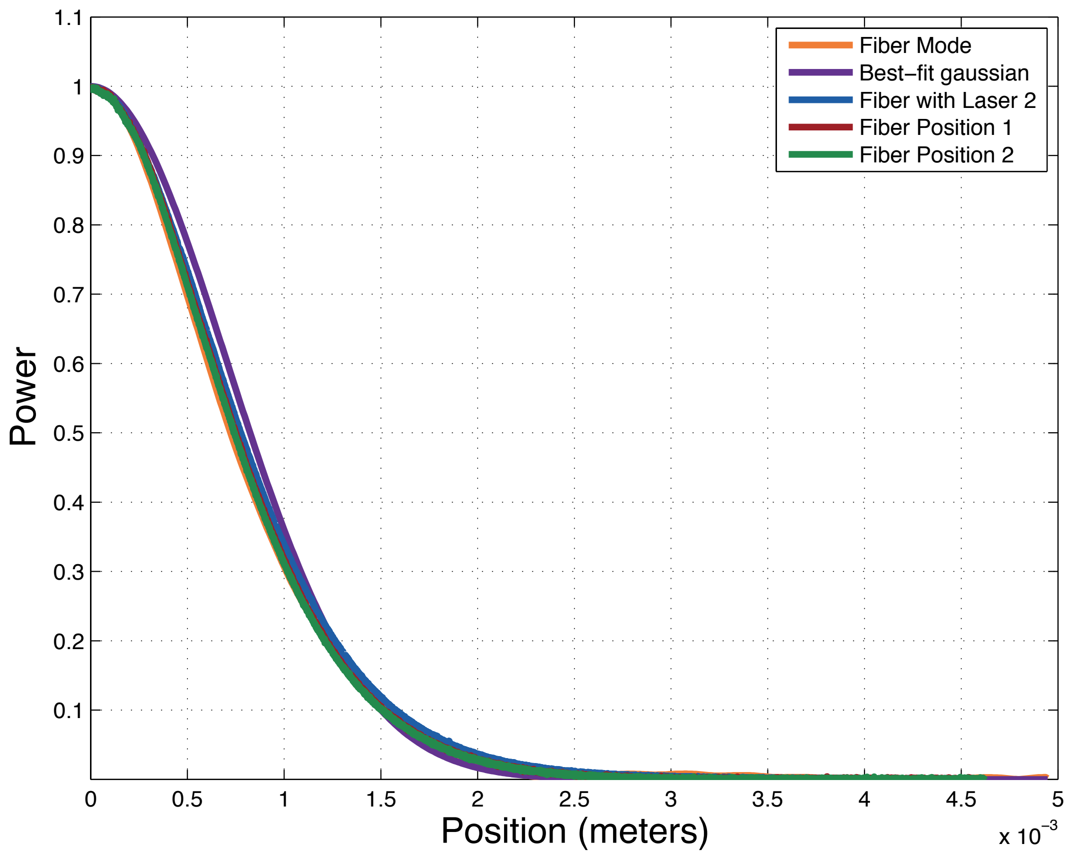

Figure 3: Profile of optical fibers in different orientations, a best-fit Gaussian based on ABCD beam propagation, and the propagated Fiber mode from Equation 2 on a linear scale. Notice that the fiber theory matches closely to the experiment.

Based on Figures 3 and 4, it seems as if what I was seeing on the beam profiler is a true fiber mode and not some other noisy mode. On the semi-log scale, the fiber mode appears to ripple near the tails of the beam. It is possible that this feature actually exists in the beam profile and it was simply not picked up by the beam profiler due to averaging or asymmetries in the beam. I believe that it is more likely that the ripple is due to a discontinuity in the theoretical fiber profile as a result of not knowing the propagation constant, β, exactly. Not knowing exactly what β is causes a discontinuity where the two portions Equation 2 meet, and this can be amplified by the beam propagation. Future work could include using a carefully calibrated translation stage and power meter to profile the beam out of the fiber. It might also be possible to construct an algorithm that searches for the β that makes Equation 2 continuous and seeing propagating still produces the ripple. Another possible factor in the

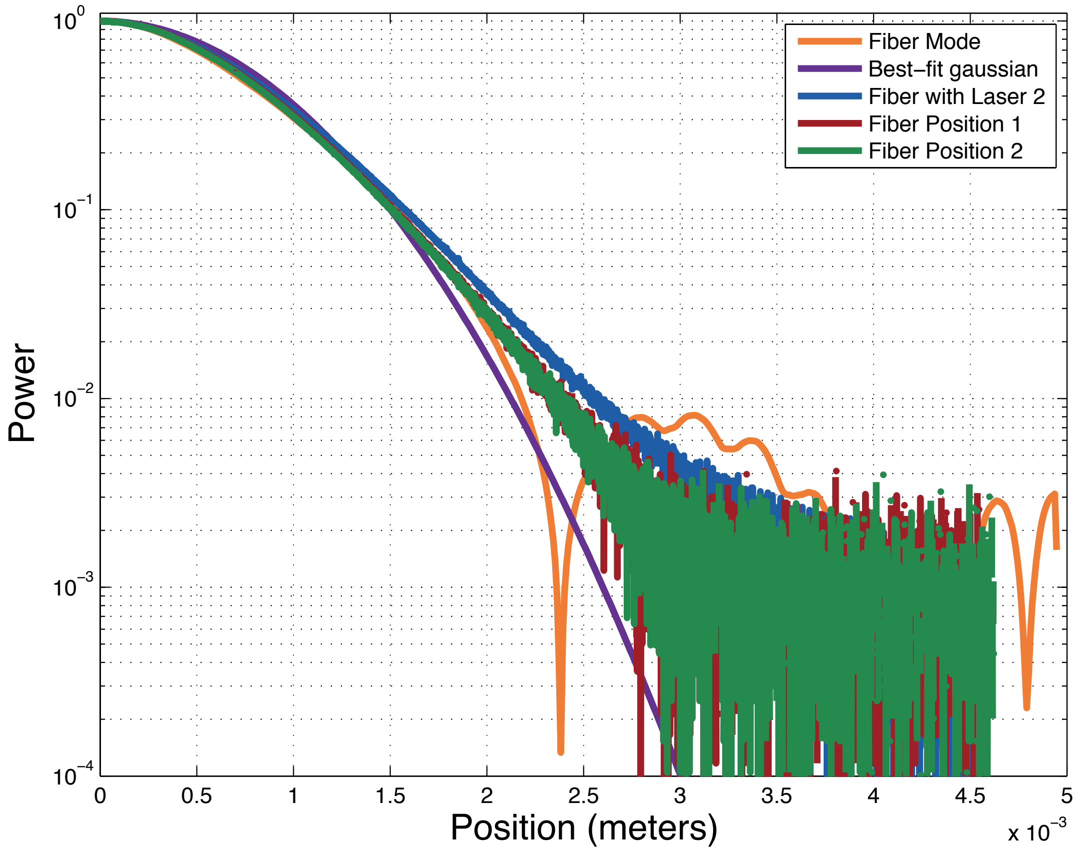

Figure 4: Profile of optical fibers in different orientations, a best-fit Gaussian based on ABCD beam propagation, and the propagated Fiber mode from Equation 2 on a semi-log scale. Notice that the fiber theory matches closely to the experiment down to several orders of magnitude. The discontinuities in the fiber theory might be due to a discontinuity in Equation 2 that gets amplified by the propagation.

ripple may be that the end of the optical fiber is not flat. If the end of the fiber isn't flat, the beam profile would be altered as the wavefront of the beam would be changed. Therefore, the ripple may occur if the fiber's face is flat, but it is not observed in our testing because our optical fiber has a more complex face.

Based on these results, it appears that higher order modes are not being transmitted by these optical fibers, or at the very least, the higher order mode content is not time-dependent. I was unable to find any evidence of power shifts or changes in the pointing of the beam out of the optical fiber, which is the true root of the problem. After moving the fiber around, coiling the fiber, using different fibers, and a second laser, I was not able to reproduce the problem seen in the actual interferometer. This problem may be a result of, among other things, sporadic fluctuations in the laser. Future study could involve replacing the diode laser with a more stable Helium Neon laser in the detector to see if the problem still occurs.

5 Simulating the Ring Patter

The other problem limiting the precision of the optical lever system is a ring pattern around the main spot of the beam of about 3-4% power that appears on the quadrant photodiode. The ring is shown in Figure 5.

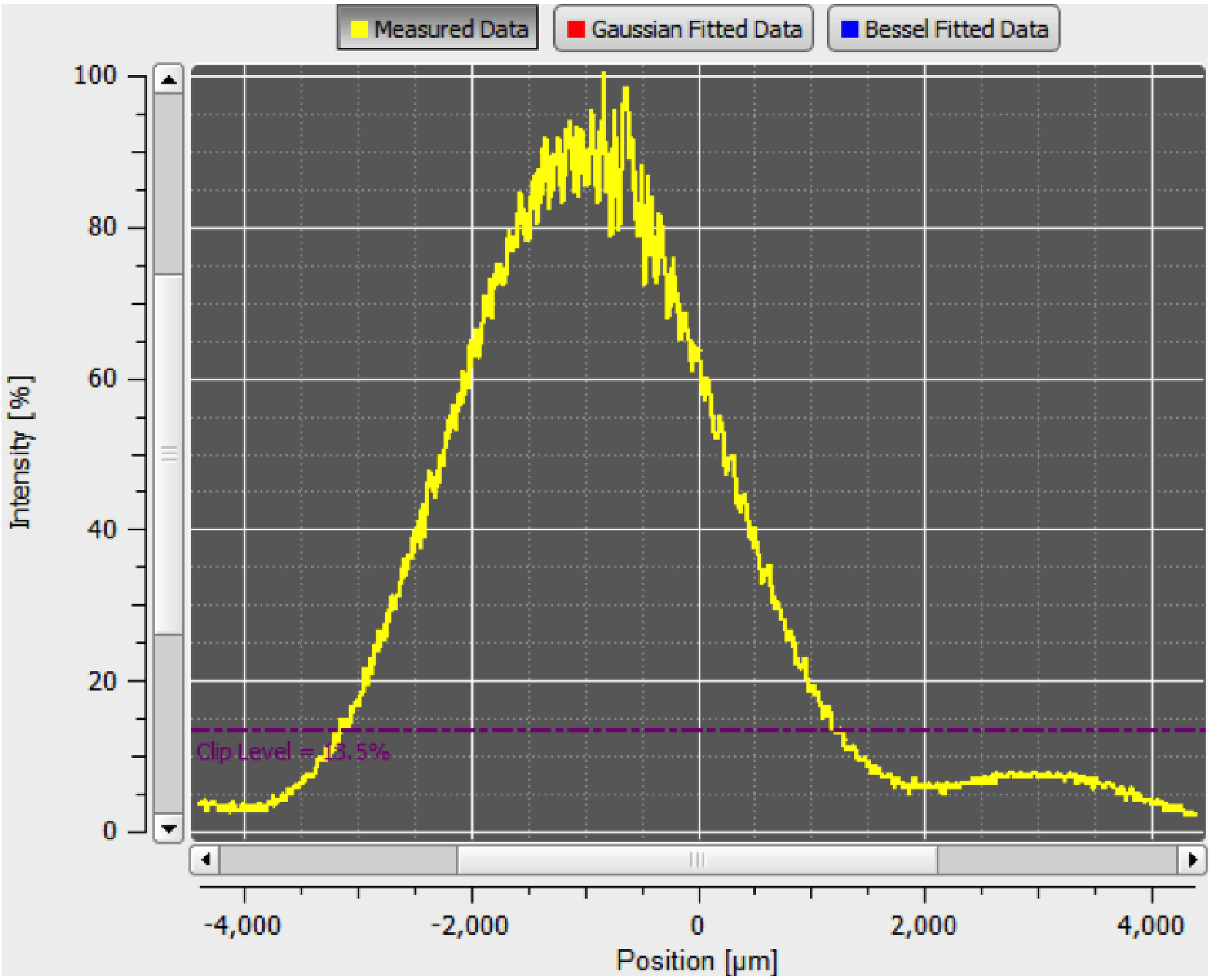

Figure 5: 2D profile of the beam in the optical levers system. The full optical setup consists of a fiber-coupled diode laser and a two element telescope that throws the beam up to 66 meters. The ring appears between 2000 and 4000 μm and is at about 3-4% of the peak of the beam.

This ring was observed by the designers of the optical lever telescopes[1]; my goal was to attempt to reproduce this result using a Fourier optics simulation. We wrote a program in MATLAB that simulated the telescope system using Fourier optics. This simulation assumed thin lenses and used Hankel transforms for beam propagation. The output of the optical fiber per Equation 2 was propagated through the two lenses in the telescope and to a far-field of 66 meters. The fiber's profile was compared to its best-fit Gaussian and a Gaussian using ABCD beam propagation to check the code worked. This propagation can be seen in Figure 6.

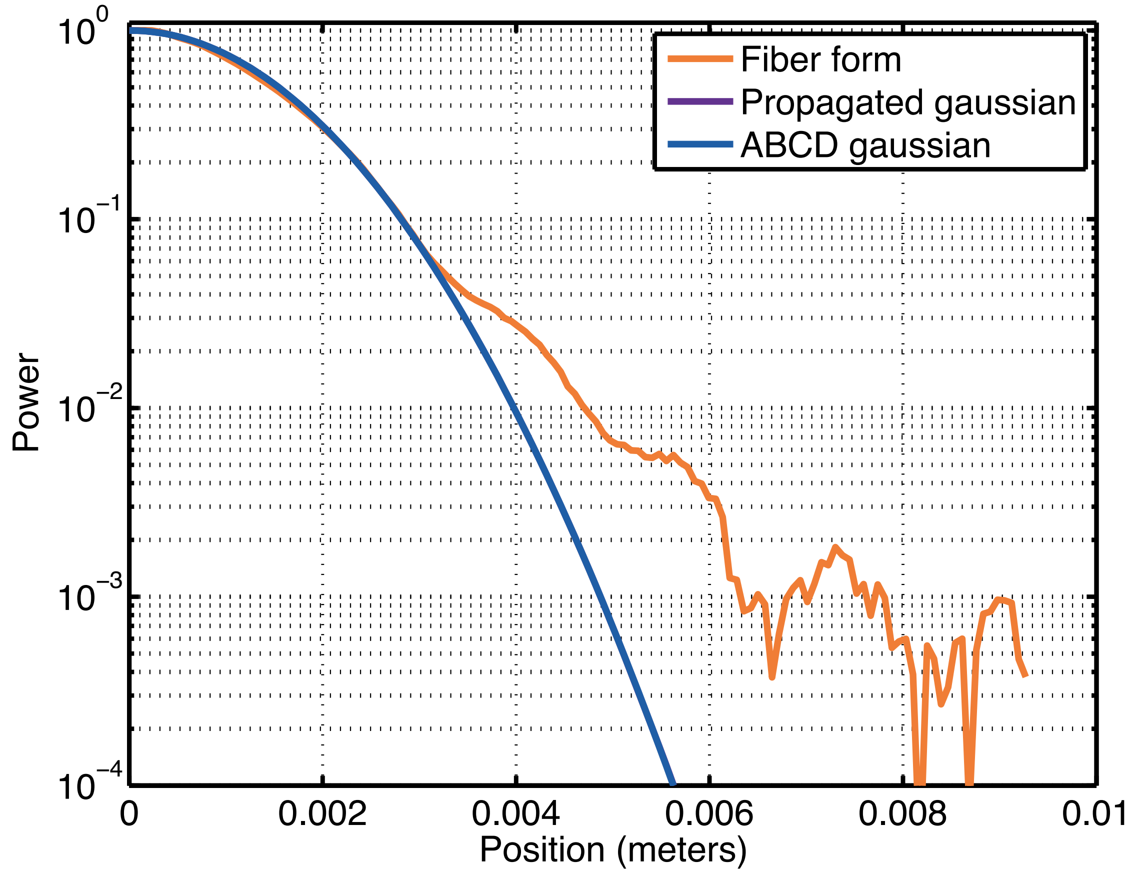

Figure 6: Profile of the fiber mode, best-fit Gaussian, and Gaussian whose width was calculated with ABCD beam propagation at 66 meters from the optical lever telescope. The fiber mode is not perfectly clean, but no ring appears.

Although in the far field the the fiber profile is not "clean" like the Gaussian, no ring is present. A bump in the profile appears, but it seems to appear closer to 3 orders of magnitude smaller than the peak, which is much smaller than the ring actually observed. It is possible that this simulation shows what would actually happen if we had thin lenses, but our lenses are actually thick and a thin lens is not a good assumption. When profiling the optical fiber using one objectives from the optical lever telescope, I noticed a coma aberrations. This aberration could be minimized, but the size and severity of the aberration was very sensitive to the positioning of the fiber. I tested whether these aberrations could be the cause of the ring by using data I had taken while profiling the fiber through an "eyepiece" lens and propagating it through the objective lens of the telescope, then on to 66 meters. These data are shown in Figure 7.

It appears as though a ring appears around the main beam spot after propagating the experimental fiber profile with a slight aberration through the the objective lens. Future work could involve finding larger lenses whose focal length is not close to their diameter and constructing a telescope out of said larger lenses. Larger lenses may reduce aberrations in

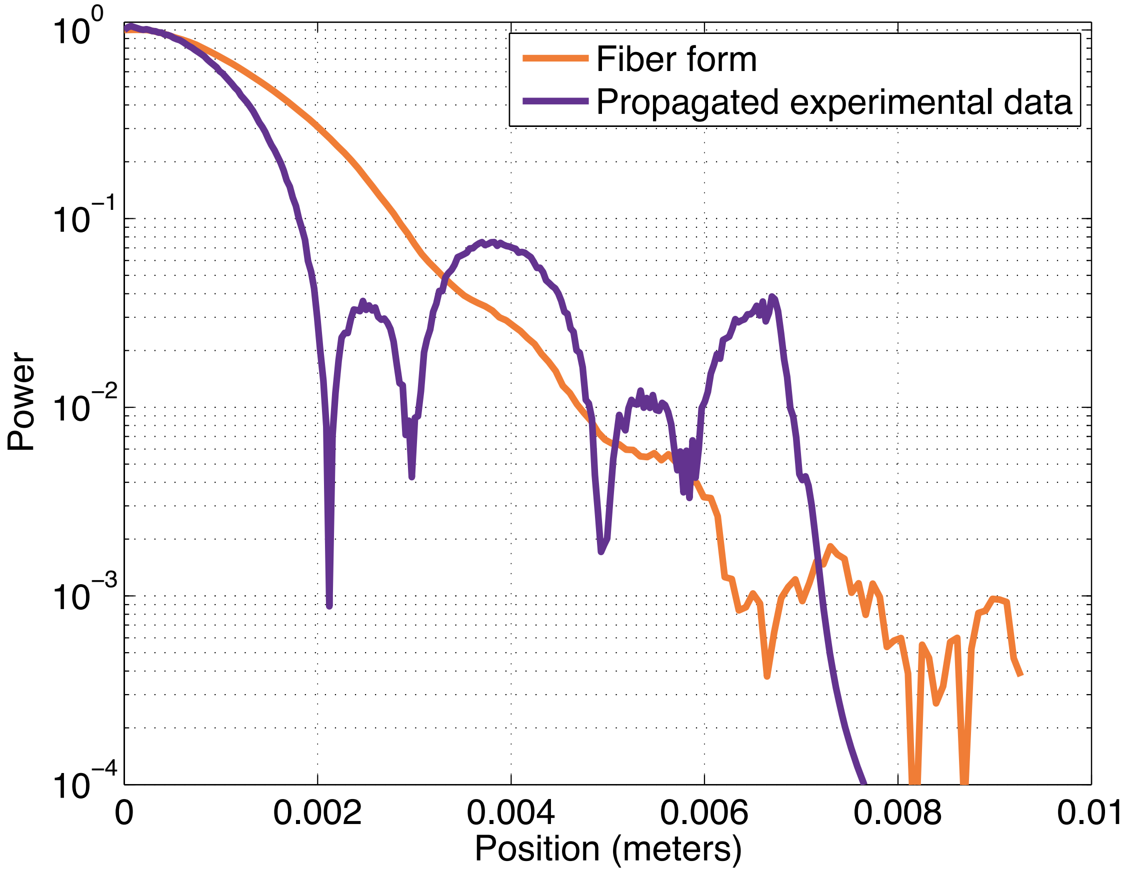

Figure 7: Profile of the fiber mode compared to the experimental fiber profile through a lens, then propagated to 66 meters. It appears as though a ring around the main spot of the beam appears.

the beam form and may reduce the ring seen. The telescope could also be simulated with thicker Plano-Convex lenses actually used in the telescopes.

6 Conclusion

The noise observed in the Advanced LIGO seems to not be related to the single-mode optical fibers used in the system. If the fibers were truly carrying higher cladding modes, when the fibers were moved, one would expect to see the power or pointing of the beam change, even if the shift was very small. Using a beam profiler, even at max gain, I could not reproduce this result. It is possible that the diode lasers used in the setup are simply noisy and the source of the noise is the laser. The ring around the beam observed after the beam is passed through a telescope and into the far field seems to be the result of the lenses and geometry of the telescopes. If the telescopes were ideal, no ring would appear; however, when actual data is injected, the ring shows up in our simulation.

References

[1] Engineering Note LIGO-E1300964-v1

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