NOISE-FREE INCORPORATION OF MULTIMODE FIBERS
INTO ABSORPTION SPECTROSCOPY EXPERIMENTS

by

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This project develops and evaluates alternative methods to the traditional way of detecting light transmitted through optical fibers in spectroscopy experiments. The main motivation behind this work is to develop an alternative that allows for (1) use in harsh environments (e.g. combustion engines) where glass optical fiber is among the few materials that can survive, (2) use in multi-beam experiments where space is extremely limited, and (3) large throughput with minimal noise yielding high signal-to-noise ratios.

Several alternatives are identified and tested with varying results. A fiber bundle based image guide was found to produce undesirable noise but had physical characteristics that, if properly defined, could be changed to produce more desirable results. To demonstrate the potential for fiber bundle approaches, a linear array of single mode fibers was tested and shown to produce good results.

The most significant finding in this work is that very careful installations of standard multimode fiber were found to reduce mode noise to near other limits (e.g. shot noise). This result provides a solution that meets all the needs outlined above with a low-cost solution.
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# TABLE OF CONTENTS

Abstract ..................................................................................................................................... i  
Acknowledgments ................................................................................................................... ii  
Table of Contents ................................................................................................................... iii  
Table of Figures ....................................................................................................................... v  
List of Tables .......................................................................................................................... vii  

**Chapter 1. Introduction** .................................................................................................................. 1  
1.1 Background ................................................................................................................ 1  
1.2 Motivation ..................................................................................................................2  
1.3 Objective .................................................................................................................... 3  
1.4 Thesis overview ......................................................................................................... 5  

**Chapter 2. Testing Setup and Methods** ....................................................................................... 7  
2.1 Receive Fiber Test Setup ........................................................................................... 7  
2.2 Testing Procedure ...................................................................................................... 8  
2.3 MMF Testing ........................................................................................................... 10  
2.4 MMF Alternatives .................................................................................................... 11  

**Chapter 3. Circular Image Guide** ............................................................................................. 12  
3.1 Initial Assessment .................................................................................................... 12  
3.2 Microscopic Evaluation of the Image Guide ........................................................... 13  
3.3 Additional Issues with the Image Guide .................................................................. 15  
3.4 Characteristics of an Ideal Image Guide .................................................................. 16  
3.5 Conclusions .............................................................................................................. 18  

**Chapter 4. Linear Fiber Array** .................................................................................................. 19  
4.1 Initial Assessment .................................................................................................... 19  
4.2 Microscopic Evaluation ........................................................................................... 20  
4.3 New Hypothesis About Noise .................................................................................. 20  
4.4 Testing the New Hypothesis .................................................................................... 21  
4.5 Conclusions .............................................................................................................. 26  

**Chapter 5. Careful MMF Installation** ........................................................................................ 27  
5.1 Eliminating Noise Sources is Key for Success ......................................................... 27  
5.2 Solutions for Reduced Moise MMF Setup ............................................................. 28  
5.3 Implementation of Noise Reduction Solutions ....................................................... 32  
5.4 Quantitative Noise Analysis .................................................................................... 35  
5.5 Sources of Remaining Noise .................................................................................... 37  

**Chapter 6. Conclusions and Future Work** .................................................................................. 41  
6.1 Conclusions .............................................................................................................. 41  
6.2 Future Work .............................................................................................................. 42
## TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Schematic of current method for performing absorption spectroscopy</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Engine access ring model to be used in two-dimensional absorption spectroscopy experiment. A portion of the laser beam mesh is included in the figure.</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Setup for detecting signal in an absorption spectroscopy experiment without using optical fiber. Detector is positioned immediately next to the test article.</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>LaVision’s optical spark plug that allows optical access to the combustion chamber. The encircled area is where the pitch and catch are located as well as a mirror for redirecting the beam.</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>Schematic of the test setup for examination of MMF alternatives.</td>
<td>7</td>
</tr>
<tr>
<td>2.2</td>
<td>Vibration mechanism for test fiber. Encircled area is where the fan blades contact the tab on the fiber. This is the only portion of the fiber that vibrates.</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>Signals from the test fiber detector (blue) and reference detector (red) with the MMF in the test fiber position. Figure 2.3(a) shows the effects of vibration and Figure 2.3(b) shows the effects of temperature variation, i.e. wavelength variation.</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>Output end of the image guide magnified at 50x illuminated with 650 nm laser light. The ‘line’ of focus is roughly the area encircled. Above and below, the cores are muddled and blurry.</td>
<td>13</td>
</tr>
<tr>
<td>4.1</td>
<td>Signals from the test fiber (blue) with the reference detector (red) for the array in the test fiber position. For these tests, the input to the fiber array was a 1:16 splitter with eight adjacent fibers connected. With the fiber array positioned within the 165 µm required to avoid interference, Figure 4.1(a) shows the effects of vibration and Figure 4.1 (b) shows the effect of temperature variation, i.e. wavelength variation. Then with the fiber</td>
<td></td>
</tr>
</tbody>
</table>
positioned further than 165 µm away from the detector, Figure 4.1 (c) shows the effects of vibration and Figure 4.1 (d) shows the effect of temperature variation, i.e. wavelength variation.

Figure 4.2- Signals from the test fiber detector (blue) with the reference detector (red) while vibrating the test fiber. Figure 4.2 (a) shows the array end close to the detector and Figure 4.2 (b) shows the array end further from the detector.

Figure 4.3- Rms noise levels and DC signal level versus position for the array to array test fiber.

Figure 5.1- Active surface from a Thorlabs PDA10CF detector. Circles of diameters 500 µm, 400 µm, 320 µm, and 300 µm are superimposed for reference.

Figure 5.2- Exploded view and assembled view of the clean positioning mechanism. Figure 5.2 (a) shows the individual parts of the positioning mechanism and Figure 5.2 (b) shows the actual assembled clean positioning setup.

Figure 5.3- Signals from the test fiber detector (blue) with the reference detector (red) with the MMF in the test fiber position with the vibration active. Figure 5.3 (a) shows the MMF in the “close” and Figure 5.3 (b) shows the MMF in the “far” range.

Figure 5.4- The uniformity scan results of the GAP500 photodiode used in the Thorlabs PDA10CF detector. This scan was performed by GPD Optoelectronics. Notice the tab on the right side of the scan.

Figure 5.5- Fiber mode noise calculator from the Center for Hyperspectral Photonics website. The inputs are shown above the “Calculate” button and the output is shown below it.

Figure 6.1- New SMA connector with the protruding MMF fiber. The fiber protrudes 1.5 mm past the end of the ferrule. This will screw into the new fiber holder shown in Figure 6.2 and hold the fiber more securely than tape.

Figure 6.2- New fiber holder that will still fit inside SM1ZM while holding the new SMA connector from Figure 6.1. The new holder will still allow the fiber to come in close proximity to the photodiode.
LIST OF TABLES

Table 1- Listed are the characteristics of an “ideal” image guide that would minimize
noise from crosstalk, exterior interference length, and etalons.................................. 17

Table 2- Outlining the differences in the properties between the linear array and the
image guide. ...................................................................................................................... 19

Table 3- Quantitative analysis of specific sources and values of noise in the setup. ........... 35
CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

A common implementation of near-infrared absorption spectroscopy in combustion articles uses a standard single mode fiber (SMF) to deliver sensor light to the test article and a multimode fiber (MMF) to receive light from the test article and deliver it to a photoreceiver as illustrated in Figure 1.1.

![Figure 1.1- Schematic of current method for performing absorption spectroscopy](image)

Multimode fiber allows for high-throughput collection of light due to the large core diameter. The large core, however, gives rise to high numbers of modes propagating in the fiber (hence the term multimode) and, in turn, a ‘speckled’ intensity distribution in the fiber. Typically thousands of speckles are present [1], and the speckles move with perturbations such as fiber vibration and wavelength tuning. When the moving speckles are incident on any imperfect surface, the result is a noise known as ‘mode noise’ as detailed by Bartula [1].
1.2 MOTIVATION

A key motivation for this work is a project in which the goal is multi-beam two-dimensional absorption spectroscopy. Among other experiments in which using a noise-free MMF would be useful, this is the specific experiment that triggered the investigation into alternatives to the current method of using a MMF to transmit sensor light from the test article to the photoreceiver.

![Image of engine access ring model](image.png)

**Figure 1.2- Engine access ring model to be used in two-dimensional absorption spectroscopy experiment.**

A portion of the laser beam mesh is included in the figure.

The goal of the project is to improve upon the current method of single beam line-of-sight measurements, which provide only path-integrated gas property information along a path. Eventually, 2-D tomography using numerous laser beams will allow images of gas property data, in this case, in an engine cylinder. The model in Figure 1.2 shows the engine access ring that will be used, including a partial mesh of the laser beams that will be directed through the cylinder in order to gather information about the gases contained within. In all, there will be thirty laser beams, fifteen in each of two perpendicular directions, each with its
own pitch and catch ports. Each pitch uses a SMF with a fused lens and each catch uses a MMF with a fused lens. The goal is to end up with a 225-pixel image (4 mm pixel size) detailing the gas temperature in the cylinder. Precision and accuracy of the measurements at each pixel is strongly dependant on the noise level of the data gathered by each of the laser beams. This is why noise reduction in the multimode fiber is an important goal.

1.3 OBJECTIVE

The principle objective of this work is to design fiber strategies for absorption spectroscopy that have reduced or zero mode noise. We also want to be able to use multiple beams to gather data from harsh environments where only glass fiber is able to go.

Previously, many researchers concerned about mode noise have attempted to circumvent the noise by avoiding the use of MMF altogether. One method avoids the use of optical fiber completely by positioning the detector immediately next to the test article [2], the test article being an engine as shown in Figure 1.3. This approach works for the particular instance where it is used, satisfying the objective of no mode noise while facilitating a single beam through the test article. However, the space available is very limited thereby disqualifying it from use for our purpose of using multiple beams. In addition, because the detector is so close to the test article, the area requires cooling so that the heat does not affect the electronics in the detector. This adds an element of complexity that would not be needed if an optical fiber was used in the same spot.

Another method of avoiding MMF uses an optical spark plug that incorporates a single SMF as both the pitch and catch fiber [3]. Figure 1.4 is a picture of this spark plug.
Figure 1.3- Setup for detecting signal in an absorption spectroscopy experiment without using optical fiber. Detector is positioned immediately next to the test article.

Figure 1.4- LaVision’s optical spark plug that allows optical access to the combustion chamber. The encircled area is where the pitch and catch are located as well as a mirror for redirecting the beam.
This method also has no mode noise. However, the reliance on SMF results in lossy measurements, often yielding a lower signal-to-noise ratio than desired.

Given all the above information, it is clear that a more suitable alternative is worth pursuing since none of the current alternatives are able to successfully fulfill the objectives of an all fiber, multi-beam, high signal-to-noise ratio setup.

1.4 THESIS OVERVIEW

The progression of this thesis is as follows:

Chapter 2 lays out the test setup and testing procedure that allows data gathering on the different fibers. It displays and describes the issues with noise while using MMF and proposes two alternatives to MMF, a circular fiber bundle and a linear fiber array.

Chapter 3 examines and tests the circular image guide. Examination under a microscope is discussed and the resulting observations and conclusions stated. Then there are changes in the characteristics that we believe would improve performance outlined for possible future investigation.

Chapter 4 moves to the linear fiber array and shows that the noise behavior seems to be better than that of the image guide. Then, it is postulated that special conditions exist where the noise can be eliminated. It is then proposed that these conditions be tested with other types of fibers.

Chapter 5 attempts to apply the special conditions discovered in Chapter 4 to MMF. Elimination of the noise sources by taking careful steps proves to be successful and the process is outlined in this chapter.
Finally, Chapter 6 outlines the conclusions of the entire thesis with a review of the major points. There are also future projects outlined and proposals for other future work.
CHAPTER 2. TESTING SETUP AND METHODS

2.1 RECEIVE FIBER TEST SETUP

In order to test different possible receive fiber alternatives, we built a receive fiber test station as illustrated in Figure 2.1. The test station consists of a 1351 nm distributed feedback (DFB) diode laser coupled into a 90/10 splitter. The 10% leg is directed to a reference detector to record the baseline noise level. The 90% leg is coupled into the test fiber. The output of the test fiber is then directed on to a detector identical to that of the reference detector. The detectors used (Thorlabs PDA10CF, window removed) have an active InGaAs diameter of 500 µm. Since mode noise is generally driven by receive fiber vibrations and/or variations in the input wavelength, our test station had provisions for simulating these noise sources. The test receive fiber was vibrated, when desired, using the small fan shown in Figure 2.2. A tab was taped onto the fiber and secured in order to position the tab in the path of the fan blades as they spin around. When the tab is struck by the blades, the motion is transferred to the fiber causing consistent, constant vibrations. To make sure that any noise observed is caused exclusively by vibrations, on either side of the vibrating region, the fiber
was secured to a solid surface so that the vibrating region was isolated to a small portion of the fiber.

![Vibration mechanism for test fiber. Encircled area is where the fan blades contact the tab on the fiber. This is the only portion of the fiber that vibrates.](image)

Any vibration transferred to the connectors or end facets could result in extra noise that would be attributed to factors other than that which are being investigated; isolating the vibrations avoided this problem. The other source of mode noise, wavelength variations, is reproduced by varying the laser temperature.

### 2.2 TESTING PROCEDURE

In order to compare all the alternatives to the MMF fairly, the first step in the procedure is to match the DC level of the reference and test detectors with variable optical attenuators (VOAs, not shown). The level that these signals were manually maintained at was ~8 V. This level was maintained to yield maximum signal-to-noise ratio while avoiding detector saturation.
Figure 2.3- Signals from the test fiber detector (blue) and reference detector (red) with the MMF in the test fiber position. Figure 2.3(a) shows the effects of vibration and Figure 2.3(b) shows the effects of temperature variation, i.e. wavelength variation.
After matching the DC signal levels, the AC portion of the signals are recorded using a 100 MHz, 14-bit digitizer (National Instruments PCI-5122) in a LabVIEW environment. Figure 2.3 (a) and (b), are examples of the AC-coupled signals recorded in this investigation. By examining the AC-coupled signals we can tell more about the changes in the noise that come from vibration and wavelength variation. In these figures, the red trace represents the reference signal, that is, the signal from the laser light without any outside noise influencing the signal. It should be noted that the reference (red) trace fluctuates slightly as the temperature of the diode is changed. This can be seen in all subsequent figures in my thesis where the laser temperature is varied. The blue trace represents the test fiber signal; that is, the signal from the laser light that is sent through the test fiber experiencing the effects of the vibration or wavelength variation.

2.3 MMF TESTING

To demonstrate the necessity of finding an alternative to a standard MMF implementation, a MMF was inserted into the test fiber position. With the fiber (Polymicro, FIP300330370, Ultra-Low OH, 300 µm Core) in place, a test was performed. Figure 2.3 displays the results of the test. The reference detector signal shown in Figure 2.3(a) is steady while the test fiber signal shows a large amount of noise as a result of the vibration. The reference signal in Figure 2.3(b) shows a small variation due to wavelength variation, but the test fiber detector signal exhibits much more drastic changes. In the end, the test fiber signal variations were due to some combination of dirt on the end of the MMF, detector surface, or surfaces of the lens coupling the two components, and spatial clipping on the lens apertures. Chapter 5 will
show that the noise can be largely eliminated by paying careful attention to such factors. Such result highlights the need for an alternative to the standard MMF receive fiber.

2.4 MMF ALTERNATIVES

We tested two alternatives based on arrays of SMFs: a circular image guide based on a stack-and-draw process and a linear fiber array based on etched SMF laid in V-grooves on a silicon substrate. Both alternatives were chosen with the thinking that arrays of SMFs provide the low-noise benefits of SMF along with the high-throughput benefits of MMFs. The image guide we chose (Sumitomo IGN-035/06, angle polish) consisted of six thousand, 2.16 µm-diameter cores bundled into a 315 µm-diameter circular image guide. The core spacing was roughly 4 µm. Each core had an N.A. of ~0.35. The linear fiber array (Auxora G3 20 Fiber Array) consisted of twenty standard SMF fibers spaced by ~55 µm. For the tests we performed with the linear array, only eight adjacent fibers were used to prevent overfilling the PDA10CF detector used.
CHAPTER 3. CIRCULAR IMAGE GUIDE

3.1 INITIAL ASSESSMENT

There are three effects that have been identified and addressed in sections 3.1 and 3.2:

- Excess core transmission
- Far-field core-core interference
- Crosstalk

We first measured the throughput of the image guide. We expected a result of 28% based on the area fill factor of the image guide input facet (ratio of total core area to total input facet area). However, we measured a throughput of ~50%. We do not know the source of this discrepancy. We initially used two matched aspheric lenses to focus the output of the image guide onto the detector. Using this method, it was clear that the signal was quite noisy and sensitive to vibration and wavelength changes (similar to MMF), while the overall throughput varied from 40-60%. The amount of light reaching the detector was somewhat puzzling considering the calculated fill factor for the image guide of 28%. This led us to believe that the light could be guided by other interfaces in the fiber structure rather than by the cores themselves. We also looked at the output in the far field and it appeared as a MMF would appear. Projection onto a plain white sheet of paper looks full of speckles because of the interference among all the cores.
3.2 MICROSCOPIC EVALUATION OF THE IMAGE GUIDE

Examination under a microscope shows the light is guided only by the cores. 650 nm (red) light was used to visually examine the output of the fiber bundle. A picture of the magnified output end of the image guide is shown in Figure 3.1.

![Figure 3.1](image.png)

Figure 3.1-Output end of the image guide magnified at 50x illuminated with 650 nm laser light. The ‘line’ of focus is roughly the area encircled. Above and below, the cores are muddled and blurry.

It must be noted that only very near the output facet are the speckles observed in the far field absent. Further visual examination hints at the sources of noise in this image guide.

The center of Figure 3.1 displays clearly the individual cores of the fiber. On the edges, however, there is muddled, blurry light meaning the focus was inexact in that region, and the light from adjacent cores is interfering. Since the fiber is angle polished it was difficult to position it perfectly parallel to the microscope objective. This raises concern as to whether
the fiber facet can be held everywhere in the focal plane of the aspheric lenses used to focus the image guide output onto the detector. Typically, in our microscope images, the focal plane of the microscope objective intersects with the end facet plane in a line, and the result is the ‘line’ of focus seen in Figure 3.1.

Our next step was to try focusing the input light into just one core at the input facet to the image guide to see if this helped remedy the situation. The thinking was that it would be easier to focus light coming out of much fewer cores than light coming out of the entirety of the cores. What we found was that even when the light was focused into one core, or very few cores, there was significant crosstalk between cores. Under the microscope again, we noticed that while much of the light came out of the single core or cores of origin, a significant amount of light was seen in nearby cores. This led us to believe that somewhere within the image guide, the light is leaking from core to core. Sometimes, up to at least \(~50\%\) of the light was observed to emanate from these neighboring cores. A somewhat systematic pattern to this core-to-core crosstalk was observed: ‘branches’ of the light centered roughly at the cores of origin were observed. In addition, when light incident on the input facet was directed into the ‘dead’ space between cores, for some reason there was still noticeable light coming through the fiber in several cores. With the light coming out of very few cores, fringes are visible on the edges of the main image guide area where light comes out. This becomes a problem when focusing on the detector. As fringes move from vibration or wavelength tuning they will move off and on the edge of the detector providing a source of noise in the measurement.
The image guide turned out to be very sensitive to vibration. By touching or even just having an air current move the fiber, a large amount of noise was observed. Also, when allowing the wavelength of the light to change, large amounts of noise were observed. Not only can this be seen on the detector signal but under the microscope as well. Vibration clearly causes movement in the light in the individual cores and violently moves the speckle observable under the microscope. As described before, this is a source of noise when speckles move on or off the detector. Wavelength tuning also affected the noise. Observable movement took place when the temperature was allowed to change, i.e. wavelength was tuned. This is a problem for all of the above mentioned reasons. As an added measure, since infrared light would be used in absorption spectroscopy experiments, light from the 1351 nm laser was coupled into the image guide. A handheld infrared viewer that allows the human eye to see what is normally undetectable was used to examine the output of the image guide under the microscope. The result was telling in that even when the light was focused into fewer cores, it looked as though the whole image guide was illuminated and blurry. It was near impossible to focus the light and to find the cores the light was coming out of. The crosstalk seemed to cause the light to leak throughout the whole image guide at the longer wavelength.

3.3 ADDITIONAL ISSUES WITH THE IMAGE GUIDE

In addition to the issues with the actual image guide, a source of noise we discovered could also be the manner with which we got the light from the end of the image guide to the detector. Initially, we thought imaging the end of the guide on to the detector using two aspheric lenses would be the best way. This ended up being more difficult than we thought since a perfect focus across the entire fiber end facet is required in order to avoid noise. The
first obstacle was the 15° angle polish on the end of the image guide. Focusing the end of the fiber on the detector meant we needed to position the fiber end at an angle in order for it to be parallel to the lens, which is extremely difficult to accomplish with the accuracy needed for low noise and an exact focus. The angle also meant that the light did not come straight out of the fiber. There exists a small launch angle which needed to be accounted for. The launch angle turned out to be a problem when aligning the lenses. The small size of the lenses resulted in the light clipping the edge of the lens producing fringes that caused interference resulting in noise at the detector. When using a flat polished fiber, the issue of the launch angle goes away, but then there is an etalon formed and even then, lens clipping still may be an issue. Vibration issues arose even without separate lens mounts, but especially with them. With a fiber mount, a lens mount, and a detector mount all independent of each other, vibrations affecting each separate component became a noise source. Consolidation or elimination of parts may help reduce the effects of vibration on alignment pieces of the setup.

3.4 CHARACTERISTICS OF AN IDEAL IMAGE GUIDE

Outlined in Table 1 are the characteristics of an “ideal” image guide. These characteristics are such that many of the above mentioned noise sources could be greatly reduced or eliminated. The arrows represent the change in the values of the specified characteristic that we believe would reduce the noise contribution due to the individual causes: crosstalk, exterior interference length, and etalons. An ‘X’ in a box means that we do not think that any change in that particular characteristic will affect the noise contribution from that particular cause.
Table 1- Listed are the characteristics of an “ideal” image guide that would minimize noise from crosstalk, exterior interference length, and etalons.

We think that crosstalk, light leaking from one core to another or several others, may be reduced by changing several characteristics. Using a fiber with a lower N.A. would reduce the chance of crosstalk. The shallower angle associated with a lower N.A. means that the light is much less likely to leak from the core. Larger core spacing would allow any light that escapes the cores to be absorbed by the filler material between the fibers. This would eliminate the crosstalk that stems from light leaking from the cores. A shorter length image guide would leave less space for the light to leak from one core and migrate to another which would reduce crosstalk. Increasing the length between the position where the light exits a core and interferes with light from an adjacent core will help reduce noise by reducing the chances of speckles forming. By reducing the N.A., the light exits the fiber at a smaller angle and propagates further before interacting with light from an adjacent core. More space between cores allows more space for the light to travel before interacting with light from adjacent cores as well. Etalon noise could be eliminated by polishing the fiber end facet at an angle or fusing a lens to the end of the fiber. Both of these methods would reduce parallel
surfaces in the system. Reducing the N.A. would also reduce etalons by making it harder to attain the exact parallel alignment needed for an etalon to form.

3.5 CONCLUSIONS

We think all these attributes of an “ideal” image guide would result in low noise, high throughput measurements. However, in conversations with manufacturers, we discovered the cost for these “ideal” image guides would be at least $50,000. While we believe the “ideal” image guide would have been the best solution, the amount of money required disqualified their use at this time. This is an excellent candidate for future research.
CHAPTER 4. LINEAR FIBER ARRAY

4.1 INITIAL ASSESSMENT

The next step in the search for a MMF alternative was using the setup with a linear fiber array as the test fiber. We chose the linear fiber array because its characteristics more closely resemble our ideal image guide and it was available at a lower cost than the ideal image guide.

<table>
<thead>
<tr>
<th>Property</th>
<th>Linear Array</th>
<th>Image Guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>N.A.</td>
<td>0.14</td>
<td>0.35</td>
</tr>
<tr>
<td>Core Spacing</td>
<td>~55 µm</td>
<td>~4 µm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>9 µm</td>
<td>2.16 µm</td>
</tr>
<tr>
<td>Angle Polish</td>
<td>8°</td>
<td>15°</td>
</tr>
</tbody>
</table>

Table 2- Outlining the differences in the properties between the linear array and the image guide.

Table 2 compares the properties of the linear array and image guide. The only problem is that it is a linear array instead of a circular array so there will be a low throughput due to the large core spacing and low number of fibers. Using only eight adjacent fibers so as not to overfill the detector, the initial tests were done with an array whose fibers were connected to a 1:16 splitter. Even with all the promising points, the initial tests showed that there was actually significant noise when the fibers were vibrated. Since these fibers are single mode, mode noise cannot exist so there had to be another source of the noise. This was somewhat troubling and further investigation was needed.
4.2 MICROSCOPIC EVALUATION

Under the microscope, the linear array is a much simpler structure than the image guide. It is much easier to focus on a line of fibers than a whole plane. Visually, using 650 nm light, the array seemed to look much better than the image guide while the focus was exact. There were not any fringes or light in cores that weren’t being focused into. This was very promising. Then to see what would happen when the light from adjacent cores overlapped, the microscope was slowly defocused so that the focus was in front of the end facet of the array. The light got blurry but stayed relatively uniform until the individual spots began to overlap and then, fringes formed in this region. A small amount of vibration, touching the fibers away from the ends, causes these fringes to shake which is similar to mode noise. The shaking of the fringes when the fibers are touched is thought to be a result of the changing optical path length of each beam as it travels through the fiber. All it takes to affect an interference fringe is a change in the path length of half a wavelength, so even a small change in the bend radius of the fiber will end up changing the fringe. Even though this is SMF and mode noise cannot occur, the core-to-core interference causes a different noise that behaves in similar ways. Examination using infrared light directed through the array fibers yielded the same conclusions. Since this was the case with both the visible and infrared light, something had to be done which led to an idea about a method to avoid noise no matter what type of fiber is being used.

4.3 NEW HYPOTHESIS ABOUT NOISE

Based on the observation that interference of light from adjacent cores causes noise, we came up with the hypothesis that if the light reaches the detector before it can interfere with the
light from an adjacent core, noise can be avoided. To test this hypothesis, we had to get the array end extremely close to the detector. The constraints for this problem are that all the light has to fall on the detector, and the light from adjacent cores cannot interfere. So, using the detector size of 500 µm in combination with the linear array parameters (core spacing of 55 µm, the core diameter of 9 µm, 99% N.A. of 0.14), the maximum distance was calculated to be 165 µm. Note: This value is different than the value that would allow all the light to fall on the detector; that value can be calculated to be 375 µm. The distance of 165 µm is the furthest array-to-photodiode distance that ensures the light from adjacent cores will not interact, meaning the test signal and reference signal should match, no matter the vibration or wavelength variation. In order to actually test this, an array was fixed on a mount using a fiber clamp and the detector was mounted with adjustment allowing 5 degrees of freedom. The mount will allow for not only X-Y-Z adjustment, but rotation of the detector which will allow for adjustment of linear-array-to-photodiode-surface parallelism.

4.4 TESTING THE NEW HYPOTHESIS

The initial test for the new hypothesis used a 1:16 splitter and an array whose individual fibers were connectorized allowing only eight adjacent fibers to be utilized. Then, using the 5 degree of freedom positioning system, the detector was centered on the fiber array. As the detector was moved closer and closer to the array, small adjustments were needed to maintain an optimized signal. When the detector was getting close to the array end, there was a procedure implemented to the positioning.
Figure 4.1- Signals from the test fiber (blue) with the reference detector (red) for the array in the test fiber position. For these tests, the input to the fiber array was a 1:16 splitter with eight adjacent fibers connected. With the fiber array positioned within the 165 µm required to avoid interference, Figure 4.1(a) shows the effects of vibration and Figure 4.1 (b) shows the effect of temperature variation, i.e. wavelength variation. Then with the fiber positioned further than 165 µm away from the detector, Figure 4.1 (c) shows the effects of vibration and Figure 4.1 (d) shows the effect of temperature variation, i.e. wavelength variation.
That procedure was as follows: detector moved closer with Z-direction, X-Y-direction adjusted to center, the two rotation degrees of freedom adjusted to optimize signal level, then moved closer again in the Z-direction and repeat. This procedure was repeated until the DC signal level reached a plateau. Once this happened, it was safe to say that all the light coming out of the fibers was falling on the detector. Next, the noise on the AC-coupled signal was examined. Examination of the noise yielded some positive results in that the test signal could be made to follow, nearly exactly, the reference signal. This is shown in Figure 4.1 (a) and (b) as the test and reference signals are virtually identical, i.e. the array does not introduce any new noise above and beyond that of just the laser. This is very promising for continuing tests. As a check, the array was moved outside of the “safe” zone to see if the noise changed as expected. As seen in Figure 4.1 (c) and (d), there was a much different situation as the test signal did not match the reference at all. The next test setup consisted of inserting a fiber array spliced to another fiber array instead of an array connected to a fiber splitter. In order to get enough light into the fiber array, a cylindrical lens (Thorlabs, LJ1598L2-C) was used to focus the light into the array. The cylindrical lens focuses light to a line where the spherical lens focuses light to a circle. With a cylindrical lens, the ratio of fiber area to laser beam area is high which means more light is available for transmission. Using the spherical lens reduces the ratio significantly, drastically reducing the light available for transmission.

After the input to the array was optimized, the output had to be positioned using the same positioning procedure as described for the splitter/array positioning. Then more data was taken and is shown in Figure 4.2. Again, the results were exactly as expected. There is noise when the array is positioned further away as in Figure 4.2 (b) and the noise vanishes when
Figure 4.2- Signals from the test fiber detector (blue) with the reference detector (red) while vibrating the test fiber. Figure 4.2 (a) shows the array end close to the detector and Figure 4.2 (b) shows the array end further from the detector.
the array is positioned closer to the detector as in Figure 4.2 (a) even though the fibers are vibrating under both conditions. Observation of the signals while the array-detector distance was being reduced yielded an interesting discovery. As the distance was reduced, we could watch as the noise got less and less until the two signals matched exactly. Another interesting observation was that once the array was close enough that the signals matched, the behavior remained constant no matter how much smaller the array-to-photodiode distance became. The linear array appears so have significantly better noise performance than the MMF as long as the array is able to be held close enough to the detector so that all the light is falling on the detector and none of the light from adjacent cores is interfering.

In order to verify our conclusion that we indeed were closer than the 165 µm distance, one more test was conducted. During this test, the detector was moved and optimized as close as possible to the array and several values were recorded: the DC signal, rms noise level, and micrometer reading on the dial that controls the Z-direction positioning. The detector was moved away from the photodiode in increments of 20 microns and the same numbers were recorded. A graph of the results is shown in Figure 4.3. The position reading is on the X-axis and to the right is closer to the detector. So as shown in Figure 4.3, the DC signal and the rms noise plateau as the array is moved closer to the detector. From this, we can conclude that we are indeed within the “close” region. Another discovery is that we have lowered the noise attributable to the array below the shot noise level. As the DC signal drops the detector translated away from the array, out of the region where the light from adjacent cores does not interfere. This should cause the noise to increase; however, the rms noise level stays constant for a distance after this. If a lower shot noise limit was obtained in this
experiment, a more accurate picture of what is happening as the array crossed this “close”
distance could be obtained.

![Graph showing Rms noise levels and DC signal level versus position for the array to array test fiber.](image)

Figure 4.3- Rms noise levels and DC signal level versus position for the array to array test fiber.

### 4.5 CONCLUSIONS

Even though testing the array resulted in a successful reduction of noise compared to the MMF, it is likely not a candidate for replacement of the MMF in the two-dimensional absorption spectroscopy experiment. The observed behavior of the linear array proves that the ideal image guide would in fact be very advantageous to use. We have to disqualify it from use, however, on the basis of cost.
CHAPTER 5. CAREFUL MMF INSTALLATION

5.1 ELIMINATING NOISE SOURCES IS KEY FOR SUCCESS

We learned a lot of lessons while studying the image guide and linear fiber array. We learned that we want to avoid using aspheric lenses because of alignment, vibration, and lens clipping. All these issues introduce undesirable noise in the eventual measurement at the detector. Instead, we discovered that positioning the fiber end right near the detector is a more advantageous method. We learned that the end of the test fiber must be parallel or very close to parallel in order to make sure that the light falls where we want it to and so there are not path length differences to avoid interference. Perhaps the most important lesson is that we want all the light to fall on the detector active surface. Once this condition is met, if there happens to be some interference structure in the light, the intensity fluctuations would be contained to the active surface area and not moving on and off the detector causing fluctuations in the signal. When this is the case, noise is minimized.

The above lessons are directly applicable to the transfer to using MMF. On the other hand, the lesson of moving the fiber facet into an “interference-free” position is not applicable because all the light in MMF has interference from the interacting modes. This fact stresses the need for the condition of all the light falling on the detector. Another concern arises when using MMF that was not present before and that is dirt. Any dirt present on the fiber end facet or detector will cause mode noise.
The return to MMF was done because the ideal image guide was cost prohibitive and although it had desirable noise levels, the linear fiber array was little more than proof that if we could get a fiber bundle with the ideal characteristics we would be better off. Therefore, like with the other alternatives tested previously, the objective was to eliminate the MMF noise sources. This meant that the fiber must get close enough to the detector so that all the light fell on the detector. This only takes care of one of the noise sources, however. The noise is not only caused by speckles moving on and off the detector, but also by moving on and off any dirt or defects on the detector or fiber output facet. This noise generating mechanism is not a concern with the linear array because the fibers of the array are SMF. It follows that if all the speckles fell on a uniform, clean detecting surface, the mode noise could be reduced or eliminated. Special care must be taken to prevent any contamination by protecting during fabrication and shipping. The positioning system must also maintain a contaminant-free environment.

5.2 SOLUTIONS FOR REDUCED NOISE MMF SETUP

Obtaining and maintaining a clean multimode fiber facet was relatively straightforward. Ordering the MMF with the end polished from the manufacturer was an easy order to fill. The specification for the polish according to the manufacturer was stated as, “0.3 µm mechanical polish, defect free at 40x magnification.” The manufacturer also shipped the fiber with the polished end sealed in a Class 100 clean room bag.
The clean detector required some extra investigation. First, a regular PDA10CF was examined under the microscope to gauge how clean it was without any extra precautions taken. The photodiode is shown in Figure 5.1. It didn’t take long to see that they were actually pretty dirty and had some particles on the active surface. In addition to the particles, it must be noted that the tab on the bottom of the active surface is not part of the active surface. According to the datasheet for the PDA10CF detector, the active surface is 500 µm in diameter, highlighted by the outer red circle in Figure 5.1. It is clear that the entire circular area cannot be used because of the tab. This means that less area is available and measurement using the microscope software says that the distance from the top of the tab to the top of the circular area is 400 µm. The 400 µm diameter is now where the light must fall.
In conversations with the company that manufactures the photodiodes, GPD Optoelectronics, it was stated that near the edges of the photodiode, the surface may not be completely uniform. This is a potential noise source so, based on the conversations, we set a buffer zone of 10% of the total diameter (40 µm) effective on the radius. This brought the total usable active surface diameter to 320 µm. The total usable active surface area is the second-smallest red circle on Figure 5.1. The core size of the fiber used was 300 µm, highlighted by the smallest red circle on Figure 5.1, so as illustrated there was not much room to work with.

With all these reductions in the diameter of the active surface, the maximum fiber-to-photodiode distance to keep all the light on the photodiode went from 443 µm with a 500 µm diameter active surface available, to 44.3 µm with a 320 µm diameter active surface available. The close proximity requires positioning devices with sufficient sensitivity to be able to move that close but also enough sensitivity to allow for human error in the positioning without the fiber end hitting the detector. After a search, a positioning mechanism, consisting of two purchased parts and one fabricated part, was developed that would allow for such positioning. The purchased parts (Thorlabs, SM1ZM and LM1XY) allow for three degrees of freedom so that the fiber can be centered and brought close to the detector surface. The fabricated part was a holder for the fiber that had to be designed so as to fit inside the other two parts for ease of positioning.

In Figure 5.2, the setup is shown including the detector and the three parts. The parts LM1XY and SM1ZM are purchased directly from Thorlabs and screw on the front of the PDA10CF. The LM1XY allows for movement in the X-Y plane and centers the fiber on the detector.
Figure 5.2- Exploded view and assembled view of the clean positioning mechanism. Figure 5.2 (a) shows the individual parts of the positioning mechanism and Figure 5.2 (b) shows the actual assembled clean positioning setup.
This part has positioning dials that have a sensitivity of 250 µm per revolution which allows for sufficient precision in centering the fiber. The part SM1ZM allows for movement in the Z-direction and adjusts the distance between the detector surface and fiber end facet. This part has a sensitivity of 500 µm per revolution which is sufficient to move the fiber end facet close enough to the detector active surface without touching that same surface.

5.3 IMPLEMENTATION OF NOISE REDUCTION SOLUTIONS

After some dialogue with the detector and photodiode manufacturers about the cleanliness of the assembly process, we decided to have GPD, the photodiode manufacturer, send us the photodiodes directly with the windows removed and tape over the hole where the window would have been. Once received, the excess tape was trimmed away from the areas that Thorlabs needed access to for insertion into the detector housing. After shipping to Thorlabs for final assembly, a process for clean assembly was implemented. It was agreed on that each detector would be individually assembled with great care taken to not expose the active surface of the detector. Once the photodiodes were inserted into the detector housing, assembly was complete and they were shipped back to us.

The next hurdle was assembling the positioning mechanism in a clean environment. We gained access to a clean bench, which is a lab bench with a hood that is continuously purged with filtered air to ensure there are no particles that could contaminate the detector or fiber end facet. After assembly of the mechanism, tape was used to cover the outside of the assembly so no dust could get in once it left the clean bench area. This would be sufficient to ensure cleanliness and therefore satisfy all the requirements for eliminating the noise sources.
Once assembled, the fiber was aligned and centered on the detector. This was done in a systematic fashion, similar to the procedure used to optimize the fiber array. While the vibration fan was operating, each of the three positioning dials was adjusted so that the DC signal level continued to rise and the AC signal trace was observed. Eventually the DC signal level started to plateau, meaning the fiber was near to the desired position. At the same time, the rms value of the AC signal began to fall. This was very encouraging because it was a sign that the objectives were near to being realized. Once the DC signal stopped rising, we knew the position was near the ideal. From here, the X and Y adjustments were made to optimize the light to the center of the detector. Then, the fiber was moved away from the detector while observing the DC and AC signals. The AC signal would get noisier and noisier and when it stopped increasing, that was considered the “far” position. Data was recorded here for comparison later on. The fiber was again positioned close to the detector and when the DC signal stopped rising and the AC noise signal stabilized, this was considered the “close” position and data was taken again. This data is shown in Figure 5.3. From these figures, it is clear that the new method of using MMF is an extremely effective way of reducing noise in the signal from the light exiting a MMF. There is a stark visual difference between the “close” and “far” positions. The next section details the quantitative analysis of this noise.
Figure 5.3- Signals from the test fiber detector (blue) with the reference detector (red) with the MMF in the test fiber position with the vibration active. Figure 5.3 (a) shows the MMF in the “close” and Figure 5.3 (b) shows the MMF in the “far” range.
5.4 QUANTITATIVE NOISE ANALYSIS

<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Experimental Noise</th>
<th>Calculated/Expected Noise</th>
<th>Reference Signal Value</th>
<th>SNR&lt;sub&gt;expt&lt;/sub&gt;</th>
<th>SNR&lt;sub&gt;calc&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Scope</td>
<td>85 µV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>72 µV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>8 V</td>
<td>94118</td>
<td>111111</td>
</tr>
<tr>
<td>(2) Detector (+ Scope)</td>
<td>415 µV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>2 mV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>8 V</td>
<td>19277</td>
<td>4000</td>
</tr>
<tr>
<td>(3) Shot (+ Detector, Scope)</td>
<td>0.840 mV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>1.04 mV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>8 V</td>
<td>9524</td>
<td>7692</td>
</tr>
<tr>
<td>(4) “Close” MMF w/ Vibration (+ Shot, Vibration, Scope)</td>
<td>2 mV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>-</td>
<td>8 V</td>
<td>4000</td>
<td>-</td>
</tr>
<tr>
<td>(5) “Far” MMF w/ Vibration (+ Shot, Vibration, Scope)</td>
<td>22.5 mV&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>-</td>
<td>8 V</td>
<td>356</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3- Quantitative analysis of specific sources and values of noise in the setup.

Analysis of the actual numbers that this investigation has yielded gives a more specific look as to the improvement that the new MMF setup has provided. In order to clarify the comparison between the reference and test signal behavior, Table 3 was assembled to piece together the individual components contributing to the overall levels of noise in both.

‘Experimental noise’ refers to the measured noise calculated in the LabVIEW environment. This is an rms value that is directly calculated from the signal that is received in the data acquisition system. The calculated/expected noise is the number given in the datasheets of the individual parts in the system, i.e. the scope and detector, or it is the calculated noise from the principles of that particular component, i.e. shot noise. The reference signal value is
the DC component of the overall measurement in order to normalize and compare each noise value. Signal-to-Noise Ratio, SNR, values are simply the reference signal value divided by the experimental or calculated/expected noise value.

First, let us consider red trace of Figure 5.3, the reference trace. In Row (1) of Table 3 is the scope noise. This is the noise that exists when everything but the scope is off. The experimental noise is slightly larger than the expected noise taken from the datasheet of the data acquisition card. This noise is small comparatively but the point is that it is small and does not contribute much in the way of overall noise levels. When the detector is turned on, there is roughly a 5 times increase in the observed noise level. This level is actually the scope noise plus the detector noise. The values in Row (2) show that the experimental noise is much below the expected value that is from the datasheet of the detector. So the Thorlabs detector was performing much better than the specification which is helpful in examining noise levels especially at the low levels we ended up observing. Row (3) outlines the shot noise which is essentially noise that arises due to the fact that laser light is impinging upon the detector surface. The level observed is actually the scope noise plus the detector noise and the shot noise. These are the components of the red reference signal. These components are also present in the test signals and are the ideal case for the test signals. If the test signal matched the reference signal there was no noise components added by the test fiber, as was the case with the array to array signal in Figure 4.2 (a).

For the final MMF setup, the noise described above is present along with the mode noise that differentiates the test from the reference as shown in both Figure 5.3 (a) and (b). In Row (4) of the table, the experimental noise is exhibited to be over twice that of the shot noise of the
raw laser signal. While this may not seem to be a positive result, compared to the values from Row (5), it is a success. Comparatively, the noise has nearly been eliminated. This is obvious visually, and is confirmed through examination of the actual numbers from measurements.

5.5 SOURCES OF REMAINING NOISE

There is still noise in the signals for the MMF in both the “close” and “far” cases. In the former, most of the noise has been eliminated by reducing the distance between the fiber end facet and the detector below a certain amount. Even with this condition filled there is a source or sources of noise that have yet to be determined. One of those possible sources is non-uniformity in the detector surface. Some investigation into this had been done and there is data provided that is somewhat helpful. The results of the uniformity scan are shown in Figure 5.4. The results are helpful in that it seems that for the most part the detector active surface is uniform. They do not address the questions about what is happening on the immediate edges of the detector active surface. Fine scale uniformity data is needed to calculate exactly the uniformity on the edges possibly predict the noise contribution of the non-uniformity. Another possible source of noise is the possibility of the detector having some dirt or dust on it. Since the microscope used for previous investigations does not have the capability to be used in a “clean” environment, we cannot visually inspect the surface of the photodiode at this time. In both these cases, there is a way to predict the degree of non-uniformity or the size of contaminants. Using the equations from Bartula [1], the Center for Hyperspectral Photonics website has put together a fiber mode noise calculator [4]. Using
this calculator, the sources of the remaining noise can be speculated upon given certain assumptions. A view of the calculator is shown in Figure 5.4.

Figure 5.4- The uniformity scan results of the GAP500 photodiode used in the Thorlabs PDA10CF detector. This scan was performed by GPD Optoelectronics. Notice the tab on the right side of the scan.

Non-Uniform Detector Response: Given the Table 3 Row (4) condition where the SNR=4000, and assuming that half the detector is “bad” meaning that 50% of the detector area is not uniform, the calculator can be used to predict the degree of non-uniformity in the detector. Using the terms of the calculator, the desired number was the transmission, T, of the obscured area and the target number to be calculated was the relative noise output of the calculator. The target for the relative noise was the inverse of the SNR, or 0.00025. By trial and error, the transmission of the non-uniform area can be calculated to be 98.3%. This
means that to get a SNR of 4000 and all else being equal, if light falling on the uniform area has intensity of 1, that same light falling on the non-uniform area will have an intensity of 0.983. The noise in the measurement then comes from the speckles moving between the uniform and non-uniform areas.

Percentage of detected space that is unobscured, $P_{\text{perfect}} [%]$:

![Percentage of detected space that is unobscured](image)

Transmission, $T [%]$:

![Transmission](image)

Fiber numerical aperture:

![Fiber numerical aperture](image)

Fiber core diameter [$\mu$m]:

![Fiber core diameter](image)

Wavelength sent through fiber [$\mu$m]:

![Wavelength sent through fiber](image)

Relative noise (standard deviation / mean) = 0.000258742158452521

Figure 5.5- Fiber mode noise calculator from the Center for Hyperspectral Photonics website. The inputs are shown above the “Calculate” button and the output is shown below it.

Detector is not perfectly clean: Given the Table 3 Row (4) condition where the SNR=4000, and assuming there is one dust particle with zero transmission and the detector is otherwise perfect, the calculator can be used to predict the size of that one particle causing the noise. Using the terms of the calculator, the desired number was the percent of the detector unobscured and the target relative noise again was 0.00025. Through trial and error, the percentage of the detector unobscured was found to be 99.992%. This means that the particle covers 0.008% of the detector. Assuming the detector area is 500 $\mu$m and a circular particle, the area of the particle can be calculated and from that, the diameter. These calculations yield a particle diameter of 4.4 $\mu$m. This means that to get a SNR of 4000 and all else being equal, a 4.4 $\mu$m diameter particle would have to be somewhere on the detector surface.
obscuring the light. This is a very small particle and is a good demonstration of how well the detector surface was kept clean.
CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

We set out to find a suitable alternative for MMF as a catch fiber in an absorption spectroscopy setup. For our purposes, there was too much noise associated with the traditional MMF setup so an alternative was sought. We needed a catch fiber with a reduced noise level and a high enough signal level to get a favorable signal-to-noise ratio. We tested and compared MMF, a fiber bundle image guide, and a single mode fiber linear array. The MMF had noise that we knew was there before but the image guide also had undesirable noise levels. We think there are characteristics of an image guide that have the potential to eliminate some noise in the measurements, however, the costs to implement this solution are extremely high, making this alternative cost prohibitive. The linear array seemed to behave the best and similar to what we expected. The array was promising but not applicable to the two-dimensional absorption spectroscopy experiment due to space constraints. From the array, though, a new idea was born. Finally applied to MMF, a clean, close proximity fiber setup was eventually used to show that MMF can be used in a low-noise manner. This further investigation into MMF provided a low-noise, low-cost solution that did not exist prior to this investigation. Since, for most cases, cost is an issue, and for the two-dimensional experiment, space was an issue, the new clean MMF setup is far and away the best alternative to the old MMF setup when high throughput is desired but mode noise is not tolerable.
6.2 FUTURE WORK

Use of the noise-free MMF setup developed in this thesis is already set to be facilitated. As described in the introduction, the modified MMF setup will be inserted in the two-dimensional absorption spectroscopy experiment. Several small changes in the manner with which the fiber is held have been made since the data was taken. In order to hold the fiber more securely, the MMF will be housed in a new SMA connector, shown in Figure 6.1, with ~1.5 mm of fiber protruding out the end. This SMA connector will screw into a sleeve that is inserted into the new fiber holder design shown in Figure 6.2. The fiber holder will fit into the SM1ZM just as the old one did. This will hold the fiber more securely than just using tape.

In addition to the two-dimensional spectroscopy experiment, there is a flame absorption spectra experiment that will be facilitating the new setup. In this experiment, a flame that is 88.3 cm long will have a laser beam pitched through it and on the catch end a MMF is needed because of the high throughput. The new setup will allow for more accurate measurement than would previously have been possible. The reduced noise will allow for more accurate spectral fitting to gain information about the properties of the hot gas in that flame.

Investigating the source or sources of the remaining noise is also a possible future investigation. Gaining knowledge as to what exactly is causing the remaining noise in the measurements would be useful in potentially eliminating the noise.

Other than future experiments using the new setup, I think that future work can involve further investigation into other types of fiber, i.e. circular image guides and linear fiber arrays.
could prove useful in developing high throughput, low-noise alternatives to MMF where they are desired.

Figure 6.1- New SMA connector with the protruding MMF fiber. The fiber protrudes 1.5 mm past the end of the ferrule. This will screw into the new fiber holder shown in Figure 6.2 and hold the fiber more securely than tape.

Figure 6.2- New fiber holder that will still fit inside SM1ZM while holding the new SMA connector from Figure 6.1. The new holder will still allow the fiber to come in close proximity to the photodiode.
REFERENCES


