Tilt Measurements using a Monolithic Cyclic Interferometer

Joseph Porter

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Tilt Measurements using a Monolithic Cyclic Interferometer

A Thesis
Submitted to the Faculty
of
Rose-Hulman Institute of Technology

by

Joseph Porter

In Partial Fulfillment of the Requirements for the Degree
of
Master of Science in Optical Engineering

January 2020

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**ROSE-HULMAN INSTITUTE OF TECHNOLOGY**

Final Examination Report

**Joseph Porter**
Name

**Optical Engineering**
Graduate Major

☑ Thesis

**Thesis Title**
Tilt Measuring Using a Monolithic Cyclic Interferometer

☐ Non-Thesis

Project Title

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ABSTRACT

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January 2020

Tilt Measurements using a Monolithic Cyclic Interferometer

Thesis Advisor: Dr. Charles Joenathan

Measurement applications globally are demanding higher resolution measurements within a smaller footprint. The cyclic interferometer is a proven means of high-resolution tilt measurements while maintaining fringe stability. However, the cyclic interferometer commonly has many optical elements over a large surface area. In this thesis, a monolithic cyclic interferometer has been designed, constructed, and characterized. The monolithic system contains all the functionality of a typical cyclic interferometer, yet the optical elements are contained within a single glass optic. In doing so, the system attains a compact form factor and it is possible to complete measurements within a broader field of application.

Keywords: **Optical Engineering, Cyclic Interferometer, Monolithic, Optical Metrology**
You have given it all to me.

To you, Lord, I return it.
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1. INTRODUCTION

Optical tools for measurements in metrology have evolved from a scientific level to an industrial scale. Using light, tilt measurements can be performed from milliradians to nanoradians. The need for high-resolution tilt measurements is widespread in applications across many fields, from nano stage tilting of a Scanning Electron Microscope (SEM) to the testing of high precision tilt stages [1] [2]. While nanometer resolution has been achieved, there are still concerns regarding the stability of the measurement and the ease of repeatability, especially when using the interferometric technique in a real environment. Cyclic interferometers have recently shown to be stable in a laboratory environment because the counter-propagating beams travel identical paths, making the system invariant to external turbulences created by temperature and vibrations [3]. Even with such stability, the large-scale size and several moving parts of the interferometer preclude using it for on-site applications or in the real-world environment. However, one approach of using the cyclic interferometers for such applications is to develop a compact unit with few moving parts.

Efforts in making systems compact are found in other subfields of optical metrology, such as profilometry, using a Heterodyne Interferometry technique [4]. Another example of a compact optical metrology unit includes a Michelson interferometer combined with an autocollimator for simultaneous performance of linear and angular measurements [5]. A means of compacting an interferometer is to make it monolithic. Monolithic, meaning of one element, entails that the passive elements of a system are inherent to one single element of which the functionality of the previously unique passive elements are contained. For visible wavelength interferometric systems, the monolithic system most commonly consists of a single unit of glass with many unique features.
With the stability found in the cyclic interferometer being desired in areas outside of a lab environment, there is a need for a compact and unified system. Previously it has been shown that the cyclic lateral shear interferometer can be used to measure angles as small as 111 microradians [6]. The resolution can be increased using multiple reflections and phase stepping to that of 2 nanoradians as determined by T. Naderishahab in 2017 [7]. However, these systems are relatively large and find limited use. In this thesis, we have developed a monolithic cyclic interferometric system capable of being used in real-world applications with micrometer resolution.
2. INTERFEROMETRY

2.1 Introduction

Interferometry is the study of the superposition of electromagnetic waves. When waves interfere, destructive and constructive superposition of the waves occurs. In shearing interferometry, two waves that originate from the same coherent source interfere. The bright areas are formed when there is constructive superposition and dark areas formed when there is deconstructive superposition. These are commonly referred to as bright and dark fringes. An interferogram is the viewable manifestation of interference within the source area in which the fringes are contained. One of the first experiments showcasing optical interference was Young’s Double Slit Experiment which starts with a plane wave source traveling through two slits. Due to the wavelike properties of light, the uniform plane wave is diffracted by the two slits, creating respective point sources at the slit.

For a bright fringe, the two waves are perfectly overlapped, causing constructive interference if the path difference is a multiple of the wavelength. For a dark fringe to take place, the path difference between the two beams must be in odd multiples of half the wavelength of light. A simple rule is that the more fringes there are in an interferogram, the greater the difference there is in the path between the two waves.

There are several varieties of interferometric systems that exist in literature, but the ones relevant to this thesis are the Michelson and cyclic interferometers. The following chapter discusses the fundamentals of interferometry, the relevant interferometers, monolithic systems, and the final proposed system.
2.2 Michelson Interferometer

The Michelson interferometer creates optical interference by splitting the coherent beam of light into two beams, via a beam splitter, which traverses different paths and are recombined using the same beam splitter. The two beams interfere as they recombine to create the interferogram seen at the output. A schematic diagram of a Michelson interferometer is shown in Figure 1.

![Figure 1: Michelson Interferometer](image)

While intrinsically simple in design for the detection of differences in the path between the two beams, there are inherent instabilities. Since the two beams travel different paths, any movement caused by vibration or air turbulence will cause a change in the path difference and thus create essentially random changes in the resulting interferograms. This sensitivity can be exploited by eliminating all air turbulence and reducing vibrations in the system, thus causing the interferometer to be expensive due to the system requirements of a controlled environment. The LIGO system for measuring gravitational waves is an example of the exploitation of the
Michelson interferometer and the associated costs [8]. However, for most common purposes, the extreme sensitivity to the outside environment is a hindrance.

2.3 Cyclic Interferometer

An interferometer that is sensitive to the desired measurement and immune to the external environment will be a better tool for conducting tilt measurements in industry. One such interferometer is the cyclic interferometer, often referred to as the Sagnac interferometer. The cyclic interferometer splits the beam into two. The beams travel the same path but in the opposite direction (see Figure 2).

![Cyclic Interferometer Diagram]

Because each element interacts with both beams, any noise or movement will be nullified. Depending on the tilt of the mirror, noted as the Greek letter alpha in the diagram, the beam paths will be affected equally in opposite directions causing a difference in final beam location on the detector. From the resulting interferogram, the angle can be extracted. Prior research has been completed showcasing the high resolution, as noted in the introduction [7].
2.4 Compact Cyclic Interferometer

There are many ways to make an interferometer compact. Research has been completed employing the use of fiber optics or silicon-based photonic systems for compacting the components of an interferometer [9] [10]. While each approach offers a compact interferometric system, they do not allow for usage in many rugged field applications that require detachment from lab-based measurement equipment. With the use of items such as glass prisms and beam splitters, the structure is self-contained, rigid, and maintains the attributes associated with the larger cyclic interferometer. Work has been completed in creating a compact cyclic interferometer in this format [11]. However, what Cordero-Davila et al. created was meant for the testing of right-angle prisms. Both proposed optical systems are found in Figure 3.

Considerations for tilt measurement with the purpose of field applications was not present in the designs. In literature, the last mention of compact cyclic interferometry dates back to 1984 [12] [13]. These systems were used to test lenses and each of these publications mentions how the measurement technique is “immune to environmental disturbances and less prone to misalignment,” which boded well for high-resolution tilt measurements [13]. The results from
the work mentioned above show promise in the compacting of the cyclic interferometer using glass optics. However, as this thesis will show, the stability of a compact system without optical cementing proves to be noisy and not suitable for tilt measurements as previously theorized.

2.5 Monolithic Systems

In interferometry, most noise is from the small movements caused by vibrations and environmental changes, as has been discussed previously. Monolithic systems combine all the passive optical elements into a single optical unit. An example of a monolithic interferometer can be found in Harlander et al. work on an ultraviolet interferometer for the SHIMMER instrument on the STPSat-1 [14]. The monolithic instrument is part of a spatial heterodyne spectrometer used for the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMR). Figure 4 showcases the interferometer system used in the satellite before it was converted into a monolithic unit.

As seen in the schematic, there are several elements that are separate from each other in the non-monolithic system. In creating a monolithic system, the packaging of the unit, which is
meant to be in a satellite, is simplified to a few elements “rather than use a complex and massive mechanical structure to hold the optics individually…” [14]. Figure 5 showcases the monolithic unit and its elegant simplicity.

![Diagram of SHS configuration as a Monolithic Unit and Image of Final System](image)

Figure 5: Diagram of SHS configuration as a Monolithic Unit and Image of Final System [14]

While seemingly simple in design and implementation, many constraints and possible sources of noise or loss arise. As may be obvious, once a system is cemented or hewn in glass, only certain functions are now capable, and further adjustments are no longer possible. While this may be an issue in other interferometers depending on the application, it is a valued feature when using it for tilt measurements with a compact system. The sources of noise arise from the transmittance and reflectance of light at differing indexes throughout the unit. While an inherent disadvantage, they can be modeled within reason using tools such as the Fresnel equations, which will be shown in Section 4.1.

2.6 Compact and Monolithic Cyclic Interferometer

The work of this thesis is primarily focused on the creation of two systems, namely a compact cyclic interferometer and a monolithic cyclic interferometer with only one or two
moving components outside of the glass optics. Each optical component of the system that
passively interacts with the beam must be accounted for within the glass system. Based on these
premises, the guiding mirrors were replaced with right angle prisms and a cube beam splitter of
the same material.
3. COMPACT CYCLIC INTERFEROMETER

3.1 Introduction

To test the theoretical improvements of creating a compact cyclic interferometer and later a monolithic interferometer, fabrication and experimentation are the next logical steps. Throughout this chapter, the fabrication of the hardware for the compact unit, the monolithic unit, the software used, and experimentation are discussed in detail.

3.2 Hardware Fabrication

The first step towards the fabrication of a monolithic cyclic system was to develop a design. The new design was generated using a cube beam splitter and prisms based on the principles discussed in Chapter 2. To test the theoretical design, a set of prisms and a cube beam splitter were assembled to form a compact unit. In response to issues created by the compact design, the system was converted to a monolithic system. The following chapter will discuss the fabrication and testing of the compact cyclic interferometer and the monolithic interferometer, respectively.

3.3 Design and Construction of the Compact Cyclic Interferometer

The compact cyclic interferometer system has been designed and constructed as the first step towards making the system portable. In order to confine the beams within the glass optics, two 25mm N-BK7 right angle prisms were placed close to the 50.8mm N-BK7 AR coated beam splitter (see Figure 6). The 50.8mm beam splitter was chosen because of the size of the tilt mirror so that a larger diameter laser beam can be used. By extending the distance with the beam splitter, it creates a 12.5mm buffer between the glass and the target mirror. The need for physical spacing is to ensure no damage takes place due to contact with the optical elements. In addition
to the optic shown, to compact the entire system, a collimated 635nm laser diode unit from Thorlabs and a compact, monochromatic camera were used.

The focus of fabrication for the compact cyclic interferometer was on the construction of an encasement, as the optical elements were not cemented together. The key features to be considered were keeping the optical elements situated, safe, and capable of minor adjustment, along with the system being mountable to an optics post or tripod depending on the measurement requirements. The fabrication started with how to fit the beam splitter and two prisms together. An image of the initial base is found below in Figure 7. Due to the nature of Fused Deposition Model (FDM) printing, several iterations had to be completed to determine to what level of percent change in the dimensions of the print would be needed to house the optics.

The initial base included the need for 1mm of spacing between the optical elements so that there was no scratching or other physical interaction of the optical elements. Other elements of
this design were the thickness of the walls, the way the FDM printer would handle the corners as the plastic cooled, and the fluctuations in the plastic with regards to the desired dimensions.

The compact cyclic interferometer was then followed by a unit with higher raised walls and cutaways to better house the optics from possible damage and limit sources of ambient light, yet allow for the beam to traverse the optical elements (Figure 8). In this unit, dimensions for the laser diode were tested along with the FDM printer’s ability to handle vertical circles.
After several iterations to find the margin of fluctuation in the plastic, the next step was determining how to mount the system to an optical post or tripod. A tip-tilt stage from Newport was selected for its stability, flat platform, multiple screw mounts, and ability to be mounted to both an optical post and a tripod. Before creating a full system, as 3D prints can take several hours, a simple test base was designed to fit the screws and tested with the Newport mount (Figure 9).
Once the test base was verified to work, it was integrated into the next iteration of the compact cyclic interferometer encasement. For the next stage, camera and laser diode mounting were integrated to a higher degree, and alignment was tested, as seen in Figure 10. It was crucial that the mountings for the laser diode and camera had enough space to easily be placed in and taken out without much physical exertion to prevent damage without becoming off target. This design allowed for the first set of stable fringes to be seen, thus verifying the compact cyclic interferometers operation. However, extensive stability analysis was not completed at this stage due to the lack of full integration of each element.
After the alignment had been verified, the Odroid X-U4 and laser diode battery pack were integrated into the system along with the addition of space in front of the camera for a neutral density filter as seen in Figure 11. The neutral density filter is necessary for the camera to operate without saturation. It was desired to operate the unit using a single battery; however, due to the amperage requirements for the Odroid X-U4, this was not possible for a battery pack. Despite this, the Odroid X-U4 was kept for the sake of the laser diode.
After some initial testing with a compact unit encasement, the need for prism adjustment screws, an extended camera mount for better containment, and a means of containing the battery pack were added to the design. The final design used for the compact cyclic interferometer is shown in Figure 12. An image of the mount for the neutral density filter can be found in Figure 13. The final top view photograph of the system with all the elements in place can be found in Figure 14. The red line marks the beam path from the diode to the camera sensor. The white line shows the placement of the various elements. For a sense of scale, the target mirror is a 50.8mm square mirror.
Figure 12: Compact Cyclic Interferometer Encasement with Prism Adjustment Screw Mounts, Extended Camera Mount, and Screw Hold for Containing Battery Pack

Figure 13: Neutral Density Filter Holder
Items shown: Odriod XU-4 (1), QHY5-II Monochrome Camera (2), Neutral Density Filter Assembly (3), Thorlabs 633nm Collimated Laser Diode (4), Thorlabs 2” Beam splitter (5), Thorlabs 1” N-BK7 Right Angle Prism (6 and 7), Mad City Labs Nano-tilt Assembly (8).

The stability was measured by creating one single fringe or a null fringe in the overlapping area and studying the fluctuations in the intensity of the null fringe. By tilting the mirror, the fringes in the overlapping beams can be reduced and maintained at the null fringe level. However, a pinhole was placed in front of the detector, as shown in Figure 15, not only to ensure that one fringe was being detected but also to accentuate the fluctuations caused within the system. With the use of a single centered fringe, if the target mirror is tilted or if any of the optical components involved move, then the amplitude seen at the power meter will shift due to the fringe movement.
With the compact cyclic interferometer setup on the Newport tip-tilt stage and a single fringe present, measurements were taken over 30-minute periods with power values taken every second. For comparison, measurements were taken from the original cyclic interferometer and the Michelson interferometer that was set up in the same table location.

Following the completion of 3 sets of 30-minute runs from the compact cyclic, original cyclic, and Michelson interferometers, the following plot in Figure 16 was generated, showcasing the most stable data set for each system. It is important to note that the data has been normalized for stability comparison.
From Figure 16, the initial stability measurements of the compact cyclic interferometer did not compare well with the original cyclic unit and subjectively had more in common with the Michelson interferometer. With high stability being the sole reason for developing a compact cyclic interferometer system, this proposed a problem. With the theory of the cyclic interferometer being well vetted when it comes to the operation and stability, some form of environmental turbulence or innate issues with the optics used were causing problems. Thus, a study was performed to determine what the lack of stability was caused by.

It was determined that the back reflection from the index mismatch at each glass face was causing miniature Michelson interferometers to form at the system output. With several of these miniature systems forming, the total possible change at the output seen in Figure 16 becomes more reasonable and now has more of an objective relation to the Michelson interferometer.

With the problem determined, the resolution was to construct a fully monolithic system using an index matching cement placed between the prisms and the beam splitter. A more in-depth study comparing the stability of these two different units will be presented in Chapter 5.
4. MONOLITHIC CYCLIC INTERFEROMETER

In order to reduce vibrations and reflections caused by freely moving optical elements, a design to bond the elements with an index matching cement was contrived to fabricate a monolithic system.

4.1 Reflections in the Monolithic System

Before the monolithic design was created, it was observed that back reflection at each glass interface created a sizable amount of noise at the output. An air-to-glass interface, as predicted by the Fresnel equations, produces an approximately 4% reflection when the beam is directly incident on the surface. It was later observed that the noise seen at the output from these back reflections was in the form of an interferogram produced by a Michelson interferometer. To better understand this issue, this section was created to theoretically analyze the back reflections present in the monolithic cyclic interferometer. While it is impossible to eliminate every back reflection seen at the output, it is possible to reduce them greatly. To reduce the associated problems in the compact interferometer, the prisms were cemented with an index matching optical adhesive by Norland (Norland 65). Figure 17 shows the dimensions of the monolithic system.
It must be noted that the beam splitter has an anti-reflective coating that is designed for passing the beam from glass to air rather than from glass to glass. Efforts to remove the coating through various techniques were explored and are noted in the appendix. However, by the end of this experimentation, it was determined that the coatings must be kept in the cementing process, so as not to destroy the surface quality. By keeping the coating for the beam splitter at the cemented faces, a slight reflection due to an index mismatch will occur.

The interactions at each interface were predicted by assuming normal incidence when using the Fresnel equations. In addition, it was not possible to obtain the refractive index of the coating on the beam splitter from the company that manufactures it. However, in the future, for a good monolithic system, a beam splitter with no antireflection coating must be used; this will become apparent after the discussions in this section. What is known is the percentage of the beam power reflected and transmitted through the coatings which can be used instead of using the Fresnel equations. When a beam enters a different medium, there will be some form of loss due to absorption or reflection. As the beam traverses into the monolithic optic, there will be back reflections present due to the light entering a different medium. Figure 18 shows the
locations of the back reflections that will interact to create the compact Michelson interferometric arrangements in the output.

![Figure 18: Faces Responsible for Inherent Beam Reflection without the Target Mirror](image)

It is well known that the Michelson interferometer is highly susceptible to environmental perturbation as the beams travel unique paths. While these back reflections are of a small magnitude relative to the main beam being measured, they create a noise background across the surface, which might affect the measurement of the phase if they are not accounted for and reduced in the calculations of tilt.

Figure 19 labels the interactions of each place where the beam changes between mediums for beams traveling in the clockwise direction. The first five interactions, shown in orange, show the natural beam interactions with different interface glass inherent to the monolithic system. It is not until the target mirror is placed into the system that the second arm interacts with the beam path. Each cycle entails a total of 11 medium changes, as shown in Figure 19. It is important to note that interactions 3 and 9 are cemented sections of the monolithic interferometer.
The coating of the beam splitter is what creates a distinct transmission and reflection difference. Within the analysis, the metrics used to determine the percent reflected and transmitted are from the information published by Thorlabs for their visible wavelength cube beam splitters [15] [16]. Also, from the specifications provided by Thorlabs for the beam splitter, it can be seen that some of the light is absorbed by the beam splitter. Thus, the reflection and transmission percentages for both p and s polarizations do not add up to 100%. The same process was applied for the anti-reflective coatings on each face of the cube beam splitter. For the index of refraction of cement, the Cauchy equation was employed with data from Norland Optical [17] [18]. It was found that the index of refraction is approximately 1.52, leading to the difference in the percentage of power seen in reflections of less than 0.0001%. A final key assumption is the index of refraction of the N-BK7 glass which, was set to 1.515, as found in the Schott Glass Catalog [19].

The Fresnel equations are fashioned in a two-part sequence. The first part is to calculate the Fresnel coefficients. They are as follows for s-polarization and p-polarization as found in
equations 1, 2, 3, and 4. \( \theta_1 \) is set to be in the angle of incidence of the beam on the interface change. \( \theta_2 \) is the refracted angle of the beam after the interface change, which can be found using Snell’s Law (equation 5). The index of the initial medium is \( n_1 \) and the index of the new medium is \( n_2 \).

\[
t_s = \frac{2n_1 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \tag{1}
\]

\[
r_s = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2} \tag{2}
\]

\[
t_p = \frac{2n_1 \cos \theta_1}{n_1 \cos \theta_2 + n_2 \cos \theta_1} \tag{3}
\]

\[
r_p = \frac{n_1 \cos \theta_2 - n_2 \cos \theta_1}{n_1 \cos \theta_2 + n_2 \cos \theta_1} \tag{4}
\]

\[
\theta_2 = \sin^{-1} \left( \frac{n_1}{n_2} \cdot \sin \theta_1 \right) \tag{5}
\]

To determine the amount of power transmitted or reflected at each interface, the Fresnel Power Coefficients need to be calculated (Equations 6, 7, 8, and 9). These coefficients are what determine the values present in the following discussion of each interface interaction in the monolithic cyclic interferometer.

\[
T_s = \frac{n_2 \cos \theta_2}{n_1 \cos \theta_1} \cdot t_s^2 \tag{6}
\]

\[
R_s = r_s^2 \tag{7}
\]

\[
T_p = \frac{n_2 \cos \theta_2}{n_1 \cos \theta_1} \cdot t_p^2 \tag{8}
\]

\[
R_p = r_p^2 \tag{9}
\]
Table 1 and Table 4 summarize the results using the Fresnel equations to predict the reflection and transmission of a beam traversing through the monolithic unit within the first five interactions for both p and s polarizations through the left and right arms respectively. Note that both s and p polarizations start out at 100% to showcase how much of each polarization state is reflected and transmitted through the optic. The percentages seen are all in reference to the initial beam power present at the source. Tables 2, 3, 5, and 6 summarize the transmission of the back reflection as they return through the optic. The percentages of the transmission and reflection are in relation to the initial beam power. As can be seen in Table 1, after the beam splitter the power of the laser beam in the path of the left arm gives a better indication of how much power can be reflected at each interface for both p and s polarizations. It will be shown later that these reflected beams will form several Michelson interferometers of varying arm lengths along with the cyclic beam interferometer. While the transmission is a key factor for the final output and visibility, the reflection percentage is the focus for determining the noise. Note that at surface 4, since total internal reflection is assumed, the percent of the beam reflected is that of the previous transmission.

Table 1: Summary of Reflection and Transmission through Single Arm (Left)

<table>
<thead>
<tr>
<th>Interface</th>
<th>1 (Total Input)</th>
<th>2 (Beam Splitter)</th>
<th>3 (Left Arm)</th>
<th>4 (Left Arm)</th>
<th>5 (Left Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection (p)</td>
<td>0.13%</td>
<td>42.50%</td>
<td>0.06%</td>
<td>42.45%</td>
<td>1.78%</td>
</tr>
<tr>
<td>Transmission (p)</td>
<td>99.87%</td>
<td>53.22%</td>
<td>42.45%</td>
<td>-</td>
<td>40.67%</td>
</tr>
<tr>
<td>Reflection (s)</td>
<td>0.13%</td>
<td>46.22%</td>
<td>0.06%</td>
<td>46.16%</td>
<td>1.94%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>99.87%</td>
<td>50.55%</td>
<td>46.16%</td>
<td>-</td>
<td>44.22%</td>
</tr>
</tbody>
</table>

Notable from Table 1 is the difference in reflection and transmission present after interface 2. As stated earlier, this is due to the quality of the beam splitter. While small in regard to the total beam power, the reflection at interface 3 does create a notable percentage of the inherent back reflection present at the output. Interface 4 is assumed to be the total internal reflection due to the
nature of the reflection at a glass surface. The final values at interface 5 and 3 for the reflections of p and s polarized light are used for the starting value for the total reflection going back through the optic to the output. These values are notated as the transmission in the first columns of Table 2 and Table 3.

Table 2: Summary of Back Reflection from Surface 5

<table>
<thead>
<tr>
<th>Interface</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission (p)</td>
<td>1.78%</td>
<td>-</td>
<td>1.78%</td>
<td>0.95%</td>
<td>0.91%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>1.94%</td>
<td>-</td>
<td>1.93%</td>
<td>0.98%</td>
<td>0.94%</td>
</tr>
</tbody>
</table>

Table 3: Summary of Back Reflection from Surface 3

<table>
<thead>
<tr>
<th>Interface</th>
<th>3</th>
<th>2</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission (p)</td>
<td>0.06%</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>0.06%</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>

The analysis summarized in Table 3 follows the reflected light traversing back through the optic to the output. Once again interface 4 is held to total internal reflection but noted for the sake of bookkeeping. At the output there is a total of approximately 1.85% (combining s and p polarization) of the beam from interface 5 of the left arm alone. Reflection from surface 3 produces a total of 0.06% of the beam seen at the output for a total of 1.91% of the beam (combining s and p polarization) inherently present from the left arm with the potential of two miniature Michelson interferometers.

Table 4: Summary of Reflection and Transmission through Single Arm (Right)

<table>
<thead>
<tr>
<th>Interface</th>
<th>1 (Total Input)</th>
<th>2 (Beam Splitter)</th>
<th>9 (Right Arm)</th>
<th>8 (Right Arm)</th>
<th>7 (Right Arm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection (p)</td>
<td>0.13%</td>
<td>42.50%</td>
<td>0.07%</td>
<td>53.15%</td>
<td>2.23%</td>
</tr>
<tr>
<td>Transmission (p)</td>
<td>99.87%</td>
<td>53.22%</td>
<td>53.15%</td>
<td>-</td>
<td>50.92%</td>
</tr>
<tr>
<td>Reflection (s)</td>
<td>0.13%</td>
<td>46.22%</td>
<td>0.07%</td>
<td>50.48%</td>
<td>2.12%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>99.87%</td>
<td>50.55%</td>
<td>50.48%</td>
<td>-</td>
<td>48.37%</td>
</tr>
</tbody>
</table>

Table 4 shows a different amount of percentages present at each interface after the beam splitter than found in the left arm (Table 1). Once again this is due to the difference in the beam
splitters reflection and transmission abilities. Following the process of the left arm, the reflected values from interfaces 7 and 9 were used as starting values of transmission for analyzing the throughput summarized in Table 5 and Table 6.

Table 5: Summary of Back Reflection from Surface 7

<table>
<thead>
<tr>
<th>Interface</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission (p)</td>
<td>2.23%</td>
<td>-</td>
<td>2.14%</td>
<td>0.95%</td>
<td>0.91%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>2.12%</td>
<td>-</td>
<td>2.11%</td>
<td>0.98%</td>
<td>0.94%</td>
</tr>
</tbody>
</table>

Table 6: Summary of Back Reflection from Surface 9

<table>
<thead>
<tr>
<th>Interface</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission (p)</td>
<td>0.07%</td>
<td>0.04%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>0.07%</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>

While starting with different values of reflection at the respective surfaces when compared to the left arm (Table 2 and Table 3), the final percentage of power estimated at the output is the same. Because of the nature of the path, both beams receive the same interactions with the optics in a different order. The result is two miniature Michelson interferometers: the smaller having a total fluctuation ability of 0.12% and the second a total of 3.7%. Based on these values, and assuming there will be small tilt present in the cementing of each face, two fringe patterns of disproportionate relation will be seen with approximately 3.82% of the initial beam power.

When the target mirror is placed within the beam path to create the cyclic movement and the desired interferogram, another set of miniature Michelson interferometers are created. The most dominant of which is from the back reflection of the beam off interfaces 5 and 7. Figure 20 depicts the path of the reflection from interface 7; reflection from interface 5 is the same but with the exact opposite path.
As seen in the progression of light from the previous examinations of back reflections, the final amount of light present at the output is the same for each arm. What is different in Table 7 and Table 8 is the 1.69\% of the initial beam being reflected through each arm for a total of 3.38\% of the beam. What is expected is another fringe pattern to be present at the beam output overlaying the measurement. There is now expected to be a total of 7.2\% of the initial beam fluctuating in three separate, miniature, Michelson interferometers.
To complete the theoretical assessment of the monolithic cyclic interferometer, the beam completing a cycle through the optic is evaluated. The complete cycle of the beam and the tilt of the target mirror creates the optical path difference of which the interferogram derives. Since the first half of the interactions were summarized in Tables 1 and 4, Tables 9, and 10 show the complete path of the beam after reflecting off the target mirror and returning back through to the camera.

Table 9: Completed Summary of Beam Interactions of a Single Cycle (Left)

<table>
<thead>
<tr>
<th>Interface</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection (p)</td>
<td>40.67%</td>
<td>1.71%</td>
<td>38.96%</td>
<td>0.00%</td>
<td>16.58%</td>
<td>0.70%</td>
</tr>
<tr>
<td>Transmission (p)</td>
<td>-</td>
<td>38.96%</td>
<td>-</td>
<td>38.96%</td>
<td>20.76%</td>
<td>15.89%</td>
</tr>
<tr>
<td>Reflection (s)</td>
<td>44.22%</td>
<td>1.85%</td>
<td>42.37%</td>
<td>0.00%</td>
<td>19.61%</td>
<td>0.82%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>-</td>
<td>42.37%</td>
<td>-</td>
<td>42.37%</td>
<td>21.45%</td>
<td>18.78%</td>
</tr>
</tbody>
</table>

Table 10: Completed Summary of Beam Interactions of Single Cycle (Right)

<table>
<thead>
<tr>
<th>Interface</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflection (p)</td>
<td>50.92%</td>
<td>2.14%</td>
<td>48.78%</td>
<td>0.00%</td>
<td>20.76%</td>
<td>1.09%</td>
</tr>
<tr>
<td>Transmission (p)</td>
<td>-</td>
<td>48.78%</td>
<td>-</td>
<td>48.78%</td>
<td>26.00%</td>
<td>24.91%</td>
</tr>
<tr>
<td>Reflection (s)</td>
<td>48.37%</td>
<td>2.03%</td>
<td>46.34%</td>
<td>0.00%</td>
<td>21.45%</td>
<td>0.98%</td>
</tr>
<tr>
<td>Transmission (s)</td>
<td>-</td>
<td>46.34%</td>
<td>-</td>
<td>46.34%</td>
<td>23.46%</td>
<td>22.47%</td>
</tr>
</tbody>
</table>

The results in Table 9 and Table 10 show different values in the final percentages of the initial beam present at the output for each cycle. With the way the beam progresses through the optic, the left arm experiences two reflections at the beam splitter while the right arm experiences two transmissions. These differences in path at the beam splitter create large gaps with the different polarizations in each cycle; 9.02% for p-polarization and 3.69% for s-polarization which will affect the visibility of the fringes and the quality of measurement. For the measurable output, a total of 82.05% of the initial beam is present. Accounting for the noise present at the output within the primary back reflections mentioned previously, a total of 89.25% of the beam is accounted for, with the remaining 10.75% being lost in minor reflections throughout the optical interfaces.
It is key to note that the Fresnel equations only provide a coarse understanding of what may happen within the optic. The theoretical analysis using them provides an understanding of the major elements of noise present in the system, thus allowing for a greater understanding of the possible bounds of the monolithic unit or where noise sources may originate.

4.2 Construction of a monolithic system

4.2.1 Experimentation in Preparation of Cementing

Before attempting to cement the prisms to the beam splitter, different experiments and trials were run to garner as much knowledge of the process before finalizing the setup. In the theoretical nature of the system, several characteristics bring innate problems. The primary issue is the back reflections from the surfaces. If you recall from the second part of the proposed system section earlier in the thesis, the optics used in the final design are a coated N-BK7 beam splitter and two right-angle prisms which are uncoated.

To help determine the possible issues that may surface when cementing, two old optics with flat surfaces were used as a test. After cleaning the surfaces, a small amount of Norland 65 (the cement) was applied to the center of the two-inch square optic. Then, the two circular optics were placed on top. Pressing down on the circular optic allowed for the adhesive to almost evenly spread itself among both surfaces.

Figure 21: Cementing Test Process
At this point the primary issue was to reduce the air pockets in the adhesive between the two optics. Holding down the square optic and moving the circular optic in a circular motion moved the air bubbles to the exterior of the optical elements. Once this was accomplished, the bonded elements were then placed in the holder below the UV lamp for curing (Figure 22). To mimic the cementing of the beam splitter, the two optics were placed on their side. In doing so, a small amount of the cement pooled at the base of the optics. To accelerate the curing process, the lamp was turned on and left alone. According to the specifications, the cement normally takes 15 to 30 minutes to cure with a UV lamp, but the cement cured in 10 minutes [17].

Once the cement had fully cured, a beam was directed into the cemented optic at an angle to produce a “ghost” beam reflection in the middle can be seen due to the slight index mismatch between the glass and the optical cement. Because of this faint reflection, a low-frequency fringe pattern is observed in the overlapping region of the ghost beam reflection and the first surface reflection, as shown in Figure 23 (a) on the right side.
Figure 23 (b) shows the image of the front view of the cemented optics. By cementing the two prisms to the beam splitter, all three elements will now experience the same environmental effects. Thus, the structured noise projected onto the output from the miniature Michelson interferometers will be diminished to a more reasonable level, but not completely removed.

4.2.2 Cementing of the cyclic interferometer

Lessons learned from practicing cementing optics are incorporated into the final bonding of the elements for the monolithic cyclic interferometer. The index of the antireflection coating of the beam splitter, previously determined for the Fresnel reflection calculation, was the first step in determining the index of the bond. The second step to determine the index of the bond is to match the cement as close as possible to the glass of the prism. The final step in the bonding is to evaluate the thickness of the cement at each surface. If the thickness is mismatched along the surface, a Fizeau interferometer will set itself up between the prism and the beam splitter, causing a background low-frequency fringe pattern.

To accomplish the cementing of the optical elements, a cementing apparatus was created, as shown in Figure 24. The 16 screws are used to make small adjustments and keep the optics
tightly held in place as the cement cures. The blue objects are set up to press the optics together in the shape of the design. The walls of the apparatus were kept low to allow for the passing of a beam through the unit during the curing process to be sure of alignment. The apparatus is mountable to the Newport tip-tilt stage and allows for a target mirror to be used during the cementing process as well.

![Monolithic Cementing Apparatus](image)

Cement was then applied to each of the prism faces of which would be in contact with the cube beam splitter. Since the two prisms were being cemented at the same time, each prism face with cement was placed in contact with a piece of free glass as to smooth cement across the entire surface. These faces were then placed in contact with the cube beam splitter and shifted until air pockets were removed as best as possible.

To ensure alignment, a collimated laser was used and sent through the slowly curing system to reduce the wedge angle created in the bond. The fringes in the output of the cyclic
interferometer were monitored and reduced gradually to a null fringe by minimizing the wedge formation in the bonding layers. This was accomplished by adjusting the screws in the cementing system. Once the system was aligned, the UV source was turned on to cure the cement until the bond is firm.

4.3 Characterization of the Monolithic Cyclic Interferometer

After cleaning, the system was setup on a clamp-mount stage and examined (Figure 25). It was observed that small air pockets had formed in one arm of the unit. While this created a background noise in the beam output, the integrity of the measurement and stability was not compromised. Due to the larger collimated beam being used for alignment purposes, a slight vertical misalignment was missed and can be seen more clearly when the collimated laser diode is used.

Figure 25: Final Monolithic System
Using the larger collimated laser beam in the lab for analysis, the effects mentioned above can be seen more readily (Figure 26). Each arm was characterized by its power output and the data summarized in Table 11.

Table 11: Monolithic Beam Characterization

<table>
<thead>
<tr>
<th>Intensity (µW/cm²)</th>
<th>Beam</th>
<th>Right Arm</th>
<th>Left Arm</th>
<th>Back Reflection</th>
<th>Ambient Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>503.4</td>
<td>236.4</td>
<td>173.4</td>
<td>19.3</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Percent of Beam</td>
<td>-</td>
<td>47.0%</td>
<td>34.4%</td>
<td>3.8%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

A comparison of the theoretical and measured results are summarized in Table 12. While the noise compares well with the predictions of the Fresnel equations, the transmission of light at the output shows a drastic difference in the right and left arms. Specifically, the left arm has a much larger loss than predicted due to unknown causes.

Table 12: Monolithic Theoretical and Measured Data Comparison

<table>
<thead>
<tr>
<th>Intensity (µW/cm²)</th>
<th>Beam</th>
<th>Right Arm</th>
<th>Left Arm</th>
<th>Back Reflection</th>
<th>Ambient Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>503.4</td>
<td>236.4</td>
<td>173.4</td>
<td>19.3</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Measured Percentage</td>
<td>-</td>
<td>46.96%</td>
<td>34.44%</td>
<td>3.83%</td>
<td>0.34%</td>
</tr>
<tr>
<td>Theoretical Percentage</td>
<td>-</td>
<td>49.65%</td>
<td>42.45%</td>
<td>3.82%</td>
<td>-</td>
</tr>
</tbody>
</table>

Images of the beam at each output were observed. It was noted that the wedge formed in the bonding material could not be eliminated. Figure 26 shows the low visibility fringe pattern observed in the output.
Further analysis of the beam was completed using ImageJ software. Each image was smoothed then placed through two rounds of a Gaussian blur. Using a Gaussian blur eliminates the higher frequency components that raise the difficulty of analyzing the inherent fringes. A line profile was taken perpendicular to the orientation of the fringes, as shown in Figure 27.

The line profiles of the fringe pattern are shown in Figure 28 and Figure 29, respectively. The peaks of the fringe sets are distinguishable. The data in red represents the selection used to calculate the standard deviation of the fringes (and by extension, the percent change relative to
the maximum value in that selection). The reason for deriving a percentage change is to compare to the relative expected percent of power from back reflections.

Figure 28: Profile Along Right Arm after Gaussian Blur

Figure 28 shows the profile of the right arm beam corresponding to the yellow line shown in Figure 27. Using the process described previously, a standard deviation of 3.27 bits, which leads to a percent change from the max of approximately 3.0%, was found. The same process was applied to the profile of the left arm (Figure 29), which produced a standard deviation of 2.92 bits, which leads to a percent change from the maximum of approximately 3.8%. Comparing the values extracted from the profiles of each arm (Table 13), the theoretical values are close.
Figure 29: Profile Along Left Arm after Gaussian Blur

Table 13: Monolithic Beam Output Comparison

<table>
<thead>
<tr>
<th></th>
<th>Right Arm</th>
<th>Left Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Percentage</td>
<td>3.0%</td>
<td>3.8%</td>
</tr>
<tr>
<td>Theoretical Percentage</td>
<td>3.4%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Percent Difference</td>
<td>11.11%</td>
<td>11.11%</td>
</tr>
</tbody>
</table>

Inherent to the system as well as the back reflection at the output (Figure 30). There are several beam reflections present at the output, showing the known expected reflections at each index change. It is important to remember that these images were taken without a target mirror in place and represent intrinsic values to the monolithic system. Here it is easy to see the differences in the wedge angle and its orientation created in the bonding layer.
After an initial round of characterization had been completed, the system was packaged in a new unit, as shown in Figure 31. The Odroid X-U4 and battery pack housing were removed, and a housing for the Mad City Labs tilt stage was added. To secure the monolithic unit, the seating has triangular prongs at the front that keep it from shifting laterally, and a clamp is used in line with the front screw of the laser housing. An image of all the systems working together can be found in Figure 32 along with the clamp.
This complete package was then used for making stability measurements. Using the same format as previously described, a single fringe was generated, and an aperture was placed in front of the power meter to observe only the dark region of the single fringe. Slight structured
noise from the miniature Michelson interferometers was expected and was observed. To determine the reason for the fluctuations of the null fringe, a thermal imaging camera was used to analyze the heat generated in the system. From the image shown in Figure 33, a thermal gradient radiating from the diode laser and propagating through the optic and components is seen. Due to the nature of the thermal activity, movement in the air around the system can cause slight differences in the optic from each end as the glass expands and shrinks. This causes variations in the path difference, which can then be picked up by the Michelson interferometers created by the several back reflections, not the cyclic interferometer.

![Image of Monolithic Cyclic Interferometer](image)

Figure 33: Thermal Image of Monolithic Cyclic Interferometer

To determine if the noise may be suspect to other environmental turbulences, another cyclic interferometer was setup using a glass face of the monolithic system as the target mirror. In using the glass face of the optic, the packaging now becomes akin to the mounting of the target mirror. Stability measurements were taken, and the values were far lower that of the noise seen in the monolithic stability measurements. The results mean that the possible minor movements in the packaging and movement of the unit were not a prominent source of turbulence.
Using the diode laser and smaller camera, the system was characterized again. With the diode laser having a smaller beam width than that used for earlier characterization, the minor misalignment of the optics can be more readily seen. Figures 34, 35, 36, and 37 show the inherent background noise present in the null fringe. All these images were captured with the smaller camera observing the monolithic cyclic interferometer output. It is clear there is a lot of inherent noise in the output due to the construction process, which is more drastically seen with the smaller beam width. However, the fringes are still distinguishable, allowing for usage of the packaged system.

Figure 34: Monolithic Inherent Background Noise using Diode laser

Figure 35: Monolithic Null Fringe Using Diode Laser
Using Python scripts as described in Chapter 6, the images seen in Figure 38 and 39 were cleaned to show how the system is capable of measuring tilt despite the noise factors. The fringes were filtered using a low pass filter, eliminating the high-frequency noise present. In the processing, it is also assumed that the fringes due to the tilt are all oriented along the horizontal.
With the monolithic cyclic interferometer created and characterized, the next step was to determine its viability with stability measurements. To measure stability, the camera was removed allowing the beam to traverse to the system described in Figure 15. These measurements were accomplished and are discussed in Chapter 5.
5. STABILITY MEASUREMENTS OF INTERFEROMETERS

For testing and validating the compact and monolithic cyclic interferometers, several systems needed to be assembled and used for data collection. These systems include the original cyclic interferometer, the classical Michelson interferometer, the compact cyclic interferometer, and the monolithic cyclic interferometer. Throughout this chapter each system will be analyzed regarding the stability for the comparison of the monolithic cyclic interferometer.

Previously (section 3.3), the method of stability analysis was discussed for a compact cyclic interferometer. To measure the stability of each interferometer, a single fringe is created. An aperture was set in its path which only allowed a small selection of the fringe to pass through. A power meter was then setup in line with the aperture to monitor the changes caused by external turbulences (Figure 15). If there are instabilities within the interferometer measurement of the elements composing it, the single fringe will shift causing a change in the power meter reading.

Connected to the power meter is an Odroid X-U4 that contains Python-based scripts for recording the power measurements. Measurements were taken each second, and its value is transferred into a csv file with time stamps. From these files the stability plots are created. For the sake of comparison, the values are normalized, which allows for measurements from the various systems to be compared to each other. When comparing the data numerically, the fluctuation from the maximum and the standard deviation percentages are used. The fluctuation from the maximum is the measure of how much the power present at the output changes over the entire period of measurement as normalized to the maximum power reading seen. The fluctuation is used as a metric for how much the fringes move during the period of measurement, while the standard deviation is used to understand the noise present at the output.
With each of these systems, there are two sources used for measurement purposes. The first, which is used for the Michelson and the cyclic interferometers, is a Melles Griot HeNe Gas Laser with a 632.8 nm wavelength. The second, which is used for the pseudo monolithic and monolithic cyclic interferometers, is a Thorlabs collimated diode laser with a 633 nm wavelength. With the validity of the proposed system being contingent on stability, the stability of the lasers must also be observed as to determine a baseline for the system. As such, both sources were observed for 30-minutes. To accomplish this, the method using the aperture and power meter was employed with the change being that the direct beam was measured instead of a fringe pattern (Figure 40). The results of each of these measurements can be found in Figure 41 and Figure 42.

**Figure 40: Laser Stability Measurement Method**

**Figure 41: Thorlabs Collimated Diode Laser Stability Measurements**
As seen in Figure 41, the laser diode has a stable output with a maximum of 1.48% power fluctuation and a standard deviation of 0.32%. It is interesting to note the high fluctuations at the beginning of the measurements. These fluctuations could be due to a thermistor controlling the voltage across the laser diode.

![Figure 42: Normalized Melles Griot Laser Stability Measurements](image)

The Melles Griot laser also showcases a stable output with a peak fluctuation of 2.23% and a standard deviation of 0.52%. Seen in Figure 42 is the slow exponential change of the Melles Griot laser. While this slow exponential change with time is not well understood, it is believed to be a result of the cavity’s heating and cooling mechanism. When comparing to the Thorlabs Diode laser, the Melles Griot has slightly worse stability in both the fluctuation and the standard deviation.

5.1 Cyclic Interferometer

To make a comparison of the three different cyclic interferometers, the tabletop system was setup with the Melles Griot laser (Figure 43). Using the stability method described previously
(Chapter 3, Figure 17), the single fringe pinhole measurements were taken for 30 minutes at a rate of one measurement per second.

Figure 43: Cyclic Interferometer

Figure 44: Normalized Cyclic Interferometer Power Measurements

Figure 44 shows the slow exponential change of the output that has been previously attributed to the heat control mechanism of the Melles Griot laser. However, measurements were
also taken using the Thorlabs diode laser. The results from that measurement (Figure 45) showcase the same exponential curve that appears to be inherent to the system.

![Figure 45: Normalized Cyclic Interferometer Power Measurements using Thorlabs Diode Laser](image)

It is hypothesized that the change in the cyclic interferometer is due to the slow change in the micrometer screws holding the target mirror in its packaging. However, the true cause is unknown at the time of this thesis. Due to its consistency throughout the measurement sets taken, it is considered part of the nature of the cyclic system that will be compared. The three sets of data taken are summarized in Table 14.

5.2 Michelson Interferometer

While the cyclic interferometer sets the baseline stability for which the compact and monolithic versions will be judged by, the Michelson interferometer is a common interferometer which shows the “normal” environmental turbulences felt by a system. The system shown in Figure 46 was built and tested in the same format as described previously.
Data was collected for 30 minutes at a rate of one measurement per second and the data set with the best stabilization plot is shown in Figure 47. The collected data is summarized in Table 14.

What is interesting to note in Figure 47 is the high percentage of deviation seen in the measured values even while the vertical axis is stretched across 80% of the normalized space.
5.3 Compact Cyclic Interferometer

Stability measurements for the compact cyclic interferometer (Figure 48) were taken in 3 sets of 30-minute intervals. The plot of the set of data with the best stability is found in Figure 49 and the results of all three sets are summarized in Table 14.

While of the cyclic interferometer family, the measurements seen in Figure 49 provide a stark contrast to those found in Figure 45. With the compact cyclic interferometer, there is no
apparent exponential curve. The decreasing trend is due to creep in the plastic screws used to secure the optical components. There is a greater deviation in the measurements as compared to the original cyclic interferometer over a similar normalization range.

5.4 Monolithic Cyclic Interferometer

After characterizing and packaging the monolithic system (Figure 50), the same stability measurements of 3 sets of 30-minute measurement intervals were taken. The data set with the best stability is plotted in Figure 51 with the 3 sets summarized in Table 14.

Figure 50: Monolithic Interferometer
Figure 51 shows a similarity in both fluctuation and deviation to that of the compact cyclic interferometer measurements of Figure 49. This resemblance is to be expected due to the nature of using glass optics rather than silvered mirrors.

Following the comparison of the data sets contrived from the experiments described above, an extended analysis of the cyclic interferometer family was completed. In this extended analysis, 10 sets of 30-minute measurements were taken for each of the cyclic interferometers using the Melles Griot laser. The data is summarized in Table 15.

5.5 Stability Discussion

The standard deviations and fluctuations from the stability measurements of the four different interferometers are summarized in Table 14, along with the averages calculated from each of the systems. When compared, similarities can be found in the fluctuation between the cyclic based interferometers as expected, especially when held in contrast to that of the Michelson interferometer. What is interesting to note is that the monolithic cyclic interferometer is more similar to the original cyclic interferometer in the fluctuation of the fringes but similar to the
compact cyclic interferometer with regards to the noise seen in the standard deviation. This emphasizes the differences due to the use of glass optics predicted with the Fresnel equations; the glass optics would have higher noise due to back reflections, but the cementing will stabilize the fluctuations.

Table 14: Summary of Stability Measurements with Standard Deviation and Percent Fluctuation

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Fluctuation</th>
<th>Standard Deviation</th>
<th>Fluctuation</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclic [1]</td>
<td>20.85%</td>
<td>5.21%</td>
<td>Monolithic [1]</td>
<td>25.27%</td>
</tr>
<tr>
<td>Compact Cyclic [1]</td>
<td>17.07%</td>
<td>4.91%</td>
<td>Average</td>
<td>15.78%</td>
</tr>
<tr>
<td>Compact Cyclic [2]</td>
<td>8.54%</td>
<td>2.07%</td>
<td>Michelson [1]</td>
<td>67.22%</td>
</tr>
<tr>
<td>Compact Cyclic [3]</td>
<td>39.24%</td>
<td>5.83%</td>
<td>Michelson [2]</td>
<td>73.45%</td>
</tr>
<tr>
<td>Average</td>
<td>21.62%</td>
<td>4.27%</td>
<td>Average</td>
<td>74.94%</td>
</tr>
</tbody>
</table>

Visualizing Table 14, Figure 52, shows the fluctuation value of each data set with the standard deviation overlaid. Here it is easier to see the extensive fluctuation and noise present in the Michelson interferometer as contrasted to the family of cyclic interferometers. The original cyclic interferometer and the monolithic interferometer show a distinct correspondence in their characteristics, even when comparing to the compact cyclic interferometer. The compact cyclic interferometer has slightly higher fluctuation than that of the monolithic and original cyclic interferometers. When comparing the family of cyclic interferometers, if the compact cyclic interferometer data sets fluctuations were lower, there would not be such a notable statistical difference across the units.
Following the preliminary stability analysis, an extended analysis was completed with the additional 10 sets of data for each of the cyclic interferometers. Early on in the analysis it was determined the first set of each interferometer needed to be removed as there was induced instability from the data being taken before equipment had time to reach stability. The remaining 9 sets of data are summarized in Table 15, with the percent fluctuation from the maximum value, and the standard deviation. A bar graph of the summarized data can be found in Figure 53 to help visualize the data. It is good to note the scale difference between the y-axis of Figure 53 is nearly a fourth of the y-axis found in Figure 54. Overall, the data seen in Figure 53 is a direct improvement in both fluctuation and standard deviation from the data found in Figure 52. Looking at the contained values, it seems that the monolithic cyclic interferometer is an improvement from the original cyclic unit. The compact cyclic system attains the largest average change in fluctuation and standard deviation. However, these values are not largely different to make it notable outside of the factual basis.
To determine if there is a statistical difference between the three cyclic interferometers, the Kruskal-Wallis test was employed. The Kruskal-Wallis is a statistical test for two or more sets of non-parametric data that determines if there is a statistically significant difference between the medians of the data. The null hypothesis, which is being tested, is that all the medians are of equal value. The alternate hypothesis is that at least one median is different from the group. To have a statistically meaningful test, there needed to be at least 5 sets of data per factor.
The main output of the test that determines if the null hypothesis can be rejected is the p-value. The p-value is between 0 and 1 (100%) that showcases the probability that the data representing the event is captured in the null hypothesis or not. The lower the p-value, the more the data indicates that the null hypothesis is false. Depending on what the context is of the test, there are different thresholds for an acceptable p-value to make the determination of whether to reject the null hypothesis or not. Generally speaking, if the null hypothesis is below 0.05 (5.0%), then there is a strong indication that the null hypothesis is incorrect. If the null hypothesis is true, then the p-value will be larger than the desired confidence threshold. After completing the test, the resulting p-value was 0.55 (55%), which greatly exceeds the confidence threshold. Thus, the null hypothesis cannot be rejected meaning, that there is not a statistical difference between the three cyclic interferometers based on the fluctuation and standard deviation of the interferometric output. With the test being completed in Minitab, the following boxplot (Figure 54) was generated as well. The boxplot shows how the median values are within the inter quartiles of the other units.

Figure 54: Box Plot of Table 15
6. SOFTWARE DEVELOPMENT

The language used for this system was Python. With the versions 2 and 3 both were employed depending on the application. Data collection of power measurements or image acquisition comprises the first major functional part of the software. Its complement, data cleaning and analysis, comprises the second major functional part of the software.

The data acquisition portion uses two devices. The first, for power measurements, is a Newport 1931 – C power meter which takes RS-232 serial commands for manual data acquisition. The second, for image capture, is a QHY-5M-II camera that has a 2592 x 1944 monochrome array of 2.2-micron pixels and has communication lines along USB 2.0 and Ethernet.

For collecting data regarding the beam intensity, a script using Python 3 was created to communicate with the Newport 1931 - C power meter [20]. A wire connection from a USB 2.0 port on the unit used for data collection is connected to the RS-232 port on the back of the power meter via a USB to RS-232 converter. Using the serial library for Python, a virtual serial line is generated over a particular port and baud rate with specifics set for parity, stop bit, and byte size. Following initialization, a text file is created with writing privileges in a user specified location on the data collection unit. Once the text file is constructed, the user is prompted to respond in the command line. When the string “Measure Intensity” is sent, the user is then asked for how long in minutes. After a response is submitted, the script will begin to send the message of “PM:P?” to the power meter. The power meter will respond with the power value and magnitude. The value is then recorded in the text file along with the time of the measurement. Once the script is ended, by the user sending “Exit”, or another text file is opened, the text file with the data is closed and is ready for processing.
To capture an image with the QHY-5M-II monochrome camera, special steps must be taken before a script can be used to collect the image. The reason for this is QHY built their firmware only to be recognized by specific prompts from a device via the USB terminal. They regard open access to the firmware to be a company secret. Recently, however, the company released a simplified firmware set that allows the user to establish a crude communication line to receive image data and control the basic functionality of the camera. However, it appears that each flash of the simple firmware set is made temporary, and thus during startup, the firmware needs to be flashed again. Therefore, the following command must be sent in the Linux terminal to the known USB location of the device:

```
sudo fxload -v -t fx2 -s /home/odroid/qhyccdsdk-v2.011-Linux-Debian-Ubuntu-armv8/firmware/QHY5LOADER.HEX -I qhy5lii_v20170514.hex -D /dev/bus/usb/001/003
```

Once the firmware is applied, basic commands can be sent to the camera. To automate the process for data collection, a script using Python 2 was created. Using the usb.core and usb.util libraries along with the python version of OpenCV2, communication and image forming is possible. The script finds the camera via the supplied vendor and product ids and then sets an endpoint followed by an interface to get ready for data communication. Then, premade 16-byte commands are sent in hexadecimal format. These commands tell the camera how to initialize itself, what read frequencies to use, the desired image size, and to set up other basic camera functionality.

For a functional check, the script sends a command asking for the device’s information. Once that information is verified the script is ready to begin taking images. The essential process for creating the image is taking in the stream of data from the camera, assigning each byte a number,
then placing each byte of data into the grid as a pixel value. Once the process is complete, the image is created and saved.

When the power data collection process is complete, it is ready to be analyzed by the user. The data saved to the text file has the following format:

```
PM:P?
4.866459E-005
1566418043.7779825
```

Where “PM:P?” is the data request as described previously, the first numerical value is the intensity in W/cm², and the final value is the “true time” as set by the computer sensor. Recognizing this pattern and with the use of the Pandas library in Python, the text file can be systematically pulled apart using for loops and turned into a comma-separated values (csv) file. It is then saved as a csv and is ready to be analyzed by the user in Excel or similar programs.

To analyze an image with a computer, it must first be cleaned. While there is no set global cleaning process, there are general techniques that can be applied in succession that are common amongst the computer vision community. The process used in this thesis starts with making the image a gray-scale image that is in a recognizable format for the later processes. For example, if the image had 16-bit pixel depth, but the process requires an 8-bit pixel depth, then the image would need to be converted to be acceptable for the process. Once the image is properly setup, a binary threshold is applied to create a distinction between higher and lower intensity values, which separates the fringe areas from the background. An example of applying a binary threshold to an image of fringes can be seen in Figure 55.
The next step is to apply what is known as morphology to the image. There are two morphology techniques being used in the cleaning process: opening and closing. Opening and closing are both comprised of two morphology techniques known as dilation and erosion. Dilation is a process where the area of pixels around the pixels within the image that are 1 (created by the binary thresholding) are changed to 1 as well which works to fill in the gaps. By dilating, the small gaps of 0’s within the zones of 1’s are closed. Erosion is when the areas along the borders of where the pixels are 1’s are changed to 0’ which will then trim the filled gaps of the image. The difference between an opening and a closing is in the order of which they are applied to the image. In an opening operation, erosion is applied followed by dilation. A closing operation is when dilation is performed and then followed by an erosion. For the process used in this thesis, a set of openings followed by a set of closings completed the cleaning process.

Figure 55: Image Cleaning Process and Fringe Counting

Once cleaned, the fringe counting process is started. Fringe counting is a fast process that only requires a few steps further than cleaning. However, fringe counting is limited to the
resolution derived from its nature: counting the fringes shown in the image. To count the fringes, there is a “draw contours” operation within the Python CV2 library that will denote separate regions of 1’s into singular objects and then “draw” a white line around it creating a contoured object. In this operation, there is also an object count, which provides how many objects that the process drew around. Using this count, the number of fringes in the image can be determined.

Also, by overlaying the contours onto the original image, the fringes recognized by the script can be seen, as shown in Figure 55.

Another method to determine tilt is Fourier Spectrum Filtering. This method requires the two-dimensional Fourier transform of the image, filtering it with a mask, then reverse transforming to uncover the fringe frequency. The method can be seen in Figure 56. The mask used is simply a rectangle that will encompass the possible frequencies of the fringes. Each pixel represents an approximate frequency value starting with zero in both x and y directions at the origin of the image.

![Figure 55: Two Dimensional Fourier Transform Filtering Method](image)

![Figure 56: Two Dimensional Fourier Transform Filtering Method](image)
7. CONCLUSIONS

A monolithic cyclic interferometer has been designed, constructed, and characterized. Comparisons to the original cyclic interferometer, which is the current threshold for high-resolution tilt measuring interferometric systems, along with a comparison of the Michelson interferometer and compact version of the cyclic interferometer have been completed. Through those comparisons discussed in Chapter 5 and summarized in Table 14 and 15, it has been shown that compacting the design of the cyclic interferometer using glass optics is viable and indiscernible from the original cyclic interferometer. At the cost of a slight addition of noise created by miniature Michelson interferometers and an increase in fringe fluctuation, the compact cyclic interferometer is an honorable concept. However, the compact cyclic interferometer would not remain stable in the tumultuous environment outside of a lab. By cementing the glass optics, thus creating a monolithic system, both noise and fringe fluctuation is lowered, yet not completely mitigated as seen at the interferometric output.

A 3D printed packaging unit and Python-based computer vision scripts have been developed to showcase that the monolithic system is capable of being used outside of a lab environment and free of the “a complex and massive mechanical structure to hold the optics individually…” normally required for optical interferometric science along with mitigating some of the structured noise issues inherent to the monolithic system [14]. Using computer vision scripts, some of the noise issues generated in the construction can be nullified. Regardless of the post-processing, improvements can be made to the shape and construction of the monolithic optic to reduce the structured noise created by the miniature Michelson interferometers created due to index mismatch.
One improvement requires creating a seamless optic during the original manufacturing for the attachment of the prisms to the beam splitter. Constructing the system of one optic from the start by means such as using two rhomboid prisms would remove the interfaces causing back reflection and make the final construction process simpler. A simpler process would make the unit less prone to error due to construction. Another means of reducing the noise due to back reflection would be to apply anti-reflective coatings to the faces of the prisms directed toward the target mirror.

The monolithic cyclic interferometer attains the qualities of the cyclic interferometer within a compact form factor with only a minor cost of noise at the output. If the noise can be mitigated through post-processing as shown, or if the application does not require instantaneous phase measurements of the fringes, then the monolithic unit is superior when compared to the original cyclic interferometer for a wider variety of applications. The monolithic cyclic interferometer, if the improvements recommended are applied, shows great promise for applications requiring a reduced form factor or an environment outside or even inside the lab.
8. LIST OF REFERENCES


9. APPENDIX

9.1 Software

9.1.1 Image Cleaning and Fringe Counting

Created on Mar 21, 2019

@author: joe porter

```python
import time
import cv2
import sys
import scipy as sp
import numpy as np
from scipy.fftpack import fft, ifft
from scipy.fftpack import fftn, ifftn
import matplotlib.pyplot as plt
import matplotlib.cm as cm
import matplotlib.image as mpimg
from skimage import data, img_as_float, color, exposure
from skimage.restoration import unwrap_phase

def main():
    """Main entry point for the script."""
    null = cv2.imread(r'C:\Users\porterjr\OneDrive\Graduate School\2 - Thesis Work\Summer_Measurements\Fringe Pictures\null_fringe_3.jpeg',0) #test_null.png
    fringes = cv2.imread(r'C:\Users\porterjr\OneDrive\Graduate School\2 - Thesis Work\CCI_Fringes\single_frame_6.jpeg',0) #100_micro_test.png)6_Fringes.jpeg
    filter_mask = cv2.imread(r'C:\Users\porterjr\OneDrive\Graduate School\2 - Thesis Work\Summer_Measurements\Fringe Pictures\filter_10.png',0)

    print('Enter your commands below. 

    * Insert "exit" to leave the application."

    user_input=1
    while 1 : 
        # get keyboard input
        #input = raw_input(">> ")
        # Python 3 users
        user_input = input(">> ")

        if user_input == 'exit':
            exit()

        elif user_input == 'STR':
            STR(null,fringes,filter_mask)

        elif user_input == 'CTR':
            CTR()

        elif user_input == 'SIR':
```

elif user_input == 'CIR':
    CIR()
else:
    print('Command not understood... Please try again.')

def STR(a,b,c):
    print('Single Tilt Reading selected...')
    sigma = 8
    threshold = 1
    maxvalue = 255
    kernel = np.ones((20,20),np.uint8)

    img = b.copy()
    thresh = cv2.threshold(img, 19, 256, cv2.THRESH_BINARY)[1]
    # Remove small white regions
    open_img2 = cv2.morphologyEx(thresh, cv2.MORPH_OPEN, kernel)
    # Remove small black hole
    close_img2 = cv2.morphologyEx(open_img2, cv2.MORPH_CLOSE, kernel)

    fringe_count = 0
    contours,h = cv2.findContours(close_img2,1,2)
    for cnt in contours:
        cv2.drawContours(img,[cnt],[0,(255,255,255)],10)
    fringe_count += 1

    print('Number of fringes: ', fringe_count)

    img2 = b.copy()
    filter_mask = c.copy()

    f = np.fft.fft2(img2)
    fshift = np.fft.fftshift(f)
    magnitude_spectrum = np.log(np.abs(fshift))
    filtered_spectrum = fshift*filter_mask
    filtered_spectrum_img = magnitude_spectrum*filter_mask
    f_ishift = np.fft.ifftshift(filtered_spectrum)
    filtered_img = np.fft.ifft2(f_ishift)
    filtered_img = np.abs(filtered_img)
    remapped_img = exposure.rescale_intensity(filtered_img, out_range=(-2*np.pi, 2*np.pi))
    wrapped_phase_img = np.angle(np.exp(1j * remapped_img))

    # Plots
    fig1, axs = plt.subplots(2, 2)
    figtitle = 'Total Fringes: ' +np.str(fringe_count) + '    Estimated Tilt: ' +np.str(fringe_count*10)+ ' microradians'
9.1.2 Image Capture

```python
import sys
import usb.core
import usb.util
import cv2
import numpy as np
import time
import serial

vendor_id = 0x1618
product_id = 0x0921

dev= usb.core.find(idVendor = vendor_id, idProduct = product_id)

# See if the camera is there
if dev is None:
    print("There seems to not be anything connected...")
    sys.exit(1)
```
else:
    print("The camera does exist and we are connected.")

#Open the comm line just incase kernal is blocking
if dev.is_kernel_driver_active:
    print("Detaching kernel driver...")
    dev.detach_kernel_driver
    print("Detached.")

#Configuration
print("Configuring device...")
dev.set_configuration()
print("Configured.")

#get endpoint
print("Setting endpoint for communication...")
configuration = dev.get_active_configuration()
interface = configuration[(0,0)]
epo = usb.util.find_descriptor(interface,
    custom_match = \
    lambda e: \
    usb.util.endpoint_direction(e.bEndpointAddress) == \
    usb.util.ENDPOINT_OUT)
epi = usb.util.find_descriptor(interface,
    custom_match = \
    lambda e: \
    usb.util.endpoint_direction(e.bEndpointAddress) == \
    usb.util.ENDPOINT_IN)

# print ep.device
# print ep.bEndpointAddress
print(epi.bEndpointAddress)

print("Endpoints set.")

#Initialize Streaming Mode
A0_SR =
[0xA1,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00]

#Initialize Single Frame Mode
A0_SF =
[0xA1,0x01,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00]

#Set 12MHz Readout
A1_12 =
[0xA1,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00]

#Set 24MHz Readout
A1_24 =
[0xA1,0x01,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00]

#Set 48MHz Readout
A1_48 =
[0xA1,0x02,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00,0x00]

#Set 2592x1944 image
A2 = [0xA2, 0x00, 0x00, 0x20, 0x00, 0x00, 0x07, 0x98, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Exposure_1s
A3_1s = [0xA3, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Exposure_20ms
A3_20 = [0xA3, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Exposure_16.63ms
A3_16_63 = [0xA3, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Exposure_1ms
A3_1 = [0xA3, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Exposure_0.5ms
A3_0.5 = [0xA3, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Gain to 2
A4 = [0xA4, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x20, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set USB Traffic Speed (0 to 255)
A5 = [0xA5, 0xC8, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x20, 0x00, 0x00, 0x00, 0x00]

A6_go = [0xA6, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A6_stop = [0xA6, 0x11, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A6_sleep = [0xA6, 0x22, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A6_wake = [0xA6, 0x44, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A6_reset = [0xA6, 0x66, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A7 = [0xA7, 0x01, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

A8 = [0xA8, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00]

#Set Resolution
#dev.ctrl_transfer(0x40, 0xD1, 0, 0, A2, 1000)
#time.sleep(0.02)

#Camera Info Check
info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
print info

#Start Stream
#dev.ctrl_transfer(0x40,0xD1,0,0,A6_go,1000)

img_data = []
usr_cmd = 'Start'
while 1:
    usr_cmd = raw_input('>> ')

    if usr_cmd == 'Stop':
        exit()
    elif usr_cmd == 'A0_SR':
        dev.ctrl_transfer(0x40,0xD1,0,0,A0_SR,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A0_SF':
        dev.ctrl_transfer(0x40,0xD1,0,0,A0_SF,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A1_12':
        dev.ctrl_transfer(0x40,0xD1,0,0,A1_12,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A1_24':
        dev.ctrl_transfer(0x40,0xD1,0,0,A1_24,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A1_48':
        dev.ctrl_transfer(0x40,0xD1,0,0,A1_48,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A2':
        dev.ctrl_transfer(0x40,0xD1,0,0,A2,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A3_20ms':
        dev.ctrl_transfer(0x40,0xD1,0,0,A3_20,1000)
        info = dev.ctrl_transfer(0xC0,0xD2,0,0,64)
        print info
    elif usr_cmd == 'A3_16.63ms':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A3_16_63, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A3_10ms':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A3_10, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A3_1ms':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A3_1, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A3_0.5ms':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A3_0.5, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A4':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A4, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A5':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A5, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A6_go':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A6_go, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A6_stop':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A6_stop, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A6_sleep':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A6_sleep, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A6_wake':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A6_wake, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'A6_reset':
dev.ctrl_transfer(0x40, 0xD1, 0, 0, A6_reset, 1000)
info = dev.ctrl_transfer(0xC0, 0xD2, 0, 0, 64)
print info

elif usr_cmd == 'Status':
info = dev.ctrl_transfer(0xC0,0xD2, 0, 0, 64)
print info

eelif usr_cmd == 'Read':
data = epi.read(262144, 8000)

info = dev.ctrl_transfer(0xC0,0xD2, 0, 0, 64)
#print data
print len(data)
print info

eelif usr_cmd == 'Single Frame':
flag = 0
frame_check = [0,0,0,0,0]
device = [0x40,0xD1,0,0,A0_SF,1000]
device = [0x40,0xD1,0,0,A6_reset,1000]

device = [0x40,0xD1,0,0,A5,1000]
device = [0x40,0xD1,0,0,A3_0_5,1000]
device = [0x40,0xD1,0,0,A1_24,1000]
device = [0x40,0xD1,0,0,A2,1000]
device = [0x40,0xD1,0,0,A6_go,1000]
data_0 = epi.read((2592*960),1000)
info = dev.ctrl_transfer(0xC0,0xD2, 0, 0, 64)
print 'array('''B''', [170, 17, 204, 238, 207])'
print len(data_0)
data = []
data.extend(data_0)
img = np.zeros((960,2592))

count = 0
for i in range(959):
    for j in range(2591):
        img[i,j] = data[count]
count+=1

array = np.resize(data[0:((960)*2592)-1],(960,2592))
cv2.imwrite('single_frame1.jpeg', array)

9.1.3 RS232 Data Capture

import time
import serial
# configure the serial connections (the parameters differs on the device you are connecting to)
ser = serial.Serial(
    port='/dev/ttyACM0',
    baudrate=38400,
    parity=serial.PARITY_NONE,
    stopbits=serial.STOPBITS_ONE,
    bytesize=serial.EIGHTBITS
)

f = open(r'/home/odroid/Documents/Data 8/MellesGriot_30min_2.txt', 'w')

ser.isOpen()

print('Enter your commands below.\nInsert "exit" to leave the application.')

input_v=1
while 1:
    # get keyboard input
    #input = raw_input(">> ")
    # Python 3
    input_v = input(">> ")
    if input_v == 'exit':
        ser.close()
        f.close()
        exit()
    elif input_v == 'Measure Intensity':
        print("How long in minutes?")
        input_v = input(">> ")
        time_mins = int(input_v)
        time_seconds = int(time_mins) * int(60)
        total_measurements = time_seconds / int(1)
        for j in range(0, int(total_measurements)):
            serialcmd = 'PM:P?'+chr(10)
            ser.write(serialcmd.encode('ascii'))
            out = ''
            time.sleep(1)
            while ser.inWaiting() > 0:
                out += ser.readline().decode('ascii')
                if out != '':
                    print(">>>" + out)
                    f.write(str(out))
                    f.write(str(time.time()) + chr(10))
    # Python 3 users
    # input = input(">> ")
    else:
        # send the character to the device
# (note that I happen a \r\n carriage return and line feed to the characters
- this is requested by my device)
ser.write(input(">> ") + '\r\n')
out = ''
# let's wait one second before reading output (let's give device time to answer)
time.sleep(1)
while ser.inWaiting() > 0:
    out += ser.read(1)

if out != '':
    print(">>" + out)

9.1.4 TXT to CSV File Conversion

import pandas as pd
import numpy as np
df = pd.read_csv(r'/home/odroid/Documents/Data/test.txt')
(length_rows,length_columns) = df.shape
count_power=3
count_time =2
mat = np.asmatrix(df)
Power = []
Time = []
for i in range(0,length_rows):
    if count_power ==3:
        Power.append(mat[i,0])
        count_power = 0
    if count_time ==3:
        Time.append(mat[i,0])
        count_time =0
    if count_power!=3:
        count_power = count_power+1
    if count_time!=3:
        count_time = count_time+1
data = {'Power': Power, 'Time' : Time}
df_data_total =pd.DataFrame(OrderedDict(data))
df_data_total=def_data_total.astype('float')
df_data_total.dtypes
print((Time[0]))
mat1 = np.asmatrix(df_data_total)
for k in range(0,len(Time)):
    mat1[k,1] = float(mat1[k,1]) - 1528481642.16

df_data_total.head(20)
df_data_total.to_csv(r'/home/odroid/Documents/Data/test.csv')

9.2 Anti-Reflective Coating Removal

There are two popular means of removing an anti-reflective (AR) coating from an optic. The first is the use of Isopropyl alcohol to weaken the AR coating then removal with an edged surface. The second is the use of a buffered oxide etch (BOE), which is a mixture of distilled water, ammonia, and hydrofluoric acid. Both processes were explored and are discussed in the following sections.

9.2.1 AR Removal with Isopropyl Alcohol

To test removing a coating with isopropyl alcohol, several lenses designated for destructive testing were soaked in the liquid for 10 minutes, 30 minutes, and over an hour. In the attempt to not damage the glass surface, a plastic squeegee was used to rub the coating off. After a concerted effort, there was no effect. Next, a new razor blade was used. While this removed the surface, due to the edge not being of high-grade manufacturing, the surface was covered in scratches. To avoid scratching caused by the metal edge, a ceramic blade was used in the final attempt. While removing the coating, the lens was scratched, and parts of the blade broke apart,
creating an uneven edge, which led to uneven removal of the coating. Images of the results can be seen in Figure 57.

![Figure 57: Optic Before (Left) and After (Right) Isopropyl Coating Removal Attempt](image)

9.2.2 AR Removal with Buffered Oxide Etch (BOE)

With the failure of the Isopropyl alcohol in removing the coatings, the secondary option of using the BOE was then examined. With a set of infrared band AR-coated optical flats available, tests were made in the Rose-Hulman MiNDS lab to remove the coatings with BOE. Three lenses were placed in the BOE for approximately 10 seconds, 20 seconds, and 30 seconds (Figures 58, 59, and 60). With the results shown below. The 10-second etch was not long enough to remove the coating as can be seen. The 20-second etch removed a majority of the coating without any visual damage to the optic surface. The 30-second etch removed the coating and showed no visible damage to the optic.

![Figure 58: Optic After 10-Second BOE](image)
With success found in the infrared AR coatings, lenses with visible wavelength AR coatings were then tested in the same 10, 20 and 30-second process. It was found that longer etching times would be required to remove the AR coating. Another 30-second etch was applied to the previous 30-second test optic and the coating was removed. Upon removal, an investigation was started to determine how long it would take before damage to the optic occurred. It was found that after approximately 5 minutes of etching, extreme damage would take place.

With the above in mind, it was determined that the beam splitter and coated prisms should go under a BOE to remove the coatings on select surfaces shown below highlighted in red (Figure 61). The process determined to complete the BOE of the optics was to first coat the other
surfaces in photoresist and then bake it to seal off those faces from being etched. Following the baking process, the faces set to be etched were placed in the BOE for periods of 30 seconds.

Figure 61: Selected Surfaces for Coating Removal

Figure 62 shows the results of the 30-second BOE on the beam splitter. What can be seen is the failure to remove layers evenly from the faces of the optic. From this point, each optic was dipped for 30 seconds at a time until the coatings were removed. However, with the surfaces continually not showing any sign of completely removing the coatings, the use of a q-tip was recommended in massaging the surfaces with the BOE.

Figure 62: Result of Initial 30 second BOE
What resulted from the use of the q-tip and BOE can be in Figure 63. The coating was removed, but the surface of the glass was also etched. This was unexpected at the time due to the various tests completed showing that etching of glass did not occur until five minutes of BOE had taken place. It appears that the massaging of the surface in the BOE sped the process up.

![Etched Beam Splitter](image)

Figure 63: Etched Beam Splitter

Now that the main beam splitter had been destroyed along with a set of prisms, the cementing process became the focus of the research. It was determined that even with the films meant to impedance match air, it would still be best to cement the optics together making a unified system. The issues created by the films would be nullified in that they would be held at a measurable constant.