Coherence Length Measurement System Design Description Document

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Authentication Block

Rev	Description	Date	Authorization
A	Initial DDD	1-22-2018	All
B	Edited System Overview	2-05-2018	All
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	Added New Results		
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	Added new results		
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	Added Customer Instructions		
	Added to Code		

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Vision Statement:

This projects' goal is to design and assemble an interferometer capable of measuring and reporting information regarding the coherence length of a laser. The device will be used to characterize the lasers used in the semiconductor industry to improve the performance of lithography systems.

Project Scope:

Interferometer Design:

Our responsibilities include the design and development of a working prototype interferometer capable of measuring and reporting visibility measurements of a laser over a path length difference of 500 mm. This system should be capable of calculating visibility of the interference pattern every 10 um of path length difference and be able to calculate a visibility of at least 0.01. The device must be able to analyze multispectral lasers.

Additionally, the system is to be housed in a maximum enclosed area of 1 m x 1 m x 0.5 m and is to operate in a lab setting. The laser will be introduced to the system from an optical fiber and the gathered data will be exported to a connected computer. We are not responsible for vibration isolation. The budget for our system is $5,000.

Delivery of Device

In addition to the building the prototype interferometer, our team is responsible for the delivery of the system to our customer. This will be done by mailing:

1) The breadboard with all the mechanical components still mounted on the breadboard, but with the optics removed
2) All optics in their original cases
3) The detector

ASML will pay for the shipping of all the components.

Theoretical Background:

The "coherence" of a source, describes the degree to which there exists "a fixed phase relationship between the electric field values at different locations or at different times" [1]. Characterizing the coherence of a source is important, as it is indicative of the lights ability to interfere. When two coherent waves are combined, the result is an interference pattern, where the relative phase relationship of the waves at different locations, results in fringes (areas of maximal and minimal intensity). On the other hand, when two incoherent waves are combined, the lack of a relative phase relationship, results in no distinguishable fringes and rather a uniform intensity pattern. It should be noted, that in reality no source exists that is entirely coherent or incoherent; all physical sources have varying degrees of coherence that depend upon how long a relative phase relationship can be maintained [2].

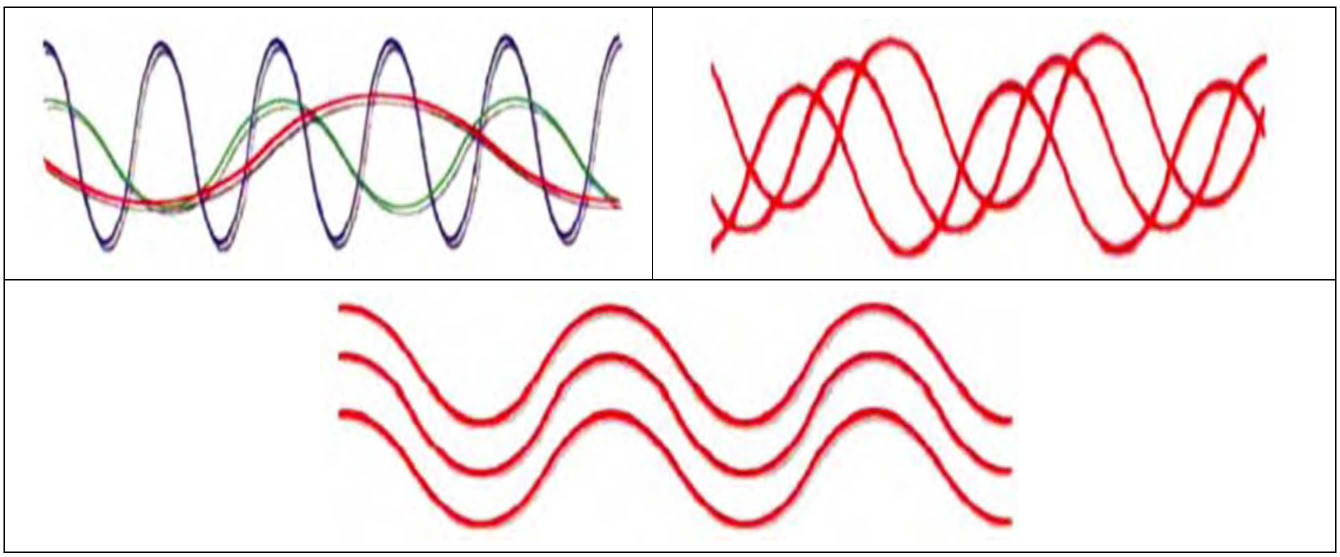


Figure 1: Top left is a representation of the phase relationship of polychromatic light. Top right is a representation of the phase relationship of low coherence monochromatic light. On the bottom is a representation of the phase relationship of high coherence monochromatic light [3].

The term used to describe the longevity of the phase relationship is temporal coherence. Temporal coherence can be quantified in terms of coherence time which relays the maximum delay in which a wave can be combined with a copy of itself and still produce an interference pattern. The coherence time, can be expressed in terms of coherence length, where Coherence Length equals the Coherence Time multiplied by the Speed of Light. In words, it can be expressed that the "coherence length is a measure of the largest optical path length difference two waves can sustain before they can no longer interfere" [4].

One way to determine the coherence length of a source is by using a Michelson Interferometer. A Michelson Interferometer is an amplitude splitting interferometer, that takes a collimated beam and divides it into two paths. Part of the light goes towards and is reflected back by the mirror in the measurement arm and the other part of the light goes toward and is reflected back by the mirror in the reference arm. The two beams are then recombined to create an interference pattern. To determine the coherence length, the optical path difference (OPD) between the two arms is increased until interference is no longer observed. Instead of relying on a subjective approach to estimate when the source is no longer coherent, the strength of the interference pattern can be quantified using the metric of visibility.

The visibility of a source is the difference in the maximum and minimum intensity, divide by the sum of the maximum and minimum intensity. A visibility of 1 indicates complete coherence, while a visibility of 0 indicates complete incoherence. While different values of decay can be used to quantify the coherence length, the most common value used is when the fringe visibility is 1/e or approximately 37% [5]. It should be noted, that the Fourier Transform of the source irradiance, can be used to determine the interferograms visibility [4].

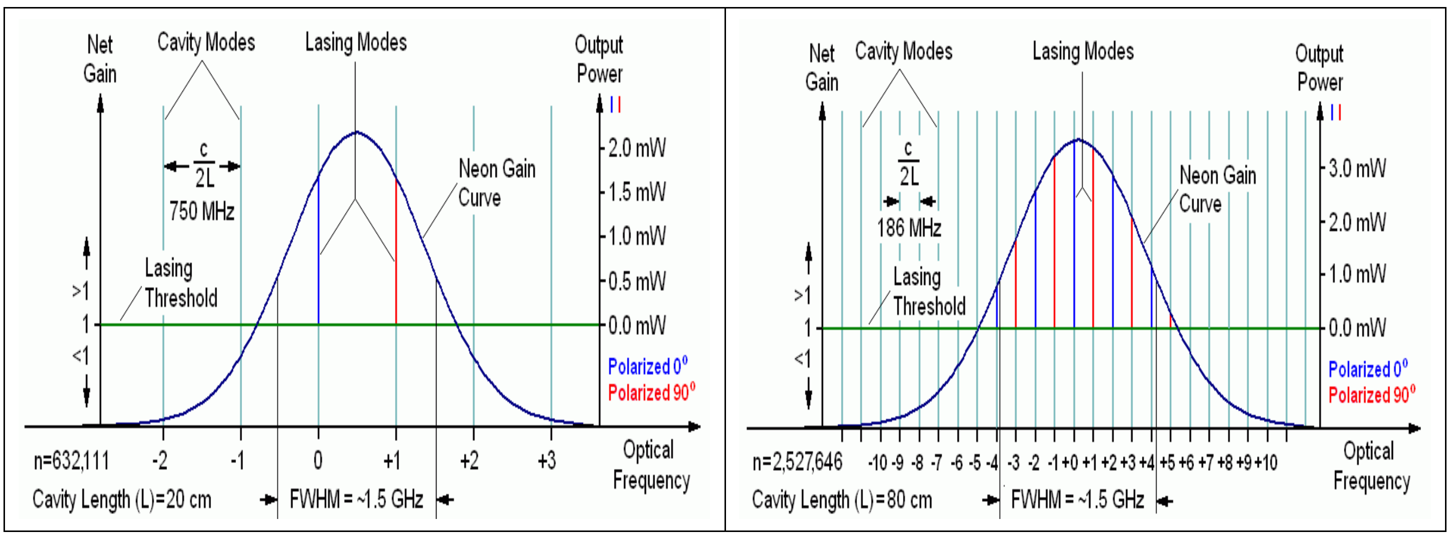


Figure 2: On the left is an image of the longitudinal modes for a HeNe laser with a cavity length of 20 cm. On the right is an image of the longitudinal modes for a HeNe laser with a cavity length of 80 cm [6].

With the concept of coherence length established, the source properties that influence this metric can now be discussed. Directly addressing laser sources, there exists a strong degree of coherence, on account of stimulated emission creating photons that have a fixed phase relationship. The coherence length of a laser, depends upon the number of longitudinal modes (which are modes determined by the axial dimensions of the resonant cavity) and therefore the shape of the spectrum curve [2]. A narrow bandwidth results in a longer coherence length and a broad bandwidth results in a shorter coherence length. Additionally, lasers that sustain multi-longitudinal modes have resurgence peaks of visibility.

In a multimode helium-neon (HeNe) laser, the typical coherence length is about 20cm. However, in a singlemode HeNE lasers, the typical coherence length exceeds 100 m [4]. A standard laser diode usually has a shorter coherence length of less than a millimeter. A standard light emitting diode (LED), would have a very short coherence length on the order of microns.

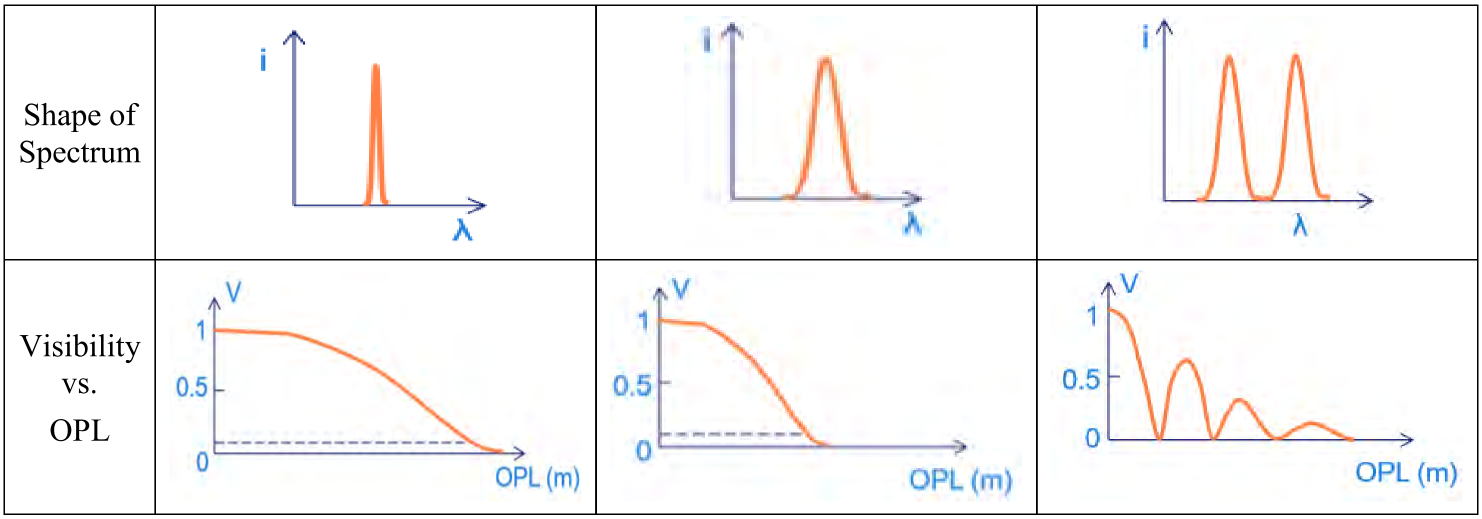


Figure 3: Depiction of how the shape of the spectrum influences the visibilty as the optical path length is increased. Going left to right is a narrow spectrum source, a broad spectrum source, and a multi-spectral source [7].

System Overview:

Design and Performance Constraints:

1. Path difference range: 500 mm
2. Path difference incrementation: 10 µm
3. Minimum visibility measurable: 0.01
4. Wavelength range: 500-900 nm
5. Interface: FC/PC connector
6. Data output: raw data of visibility over entire measurement range
7. Packaging size: 1 x 1 x 0.5 m

Final layout of the Device:

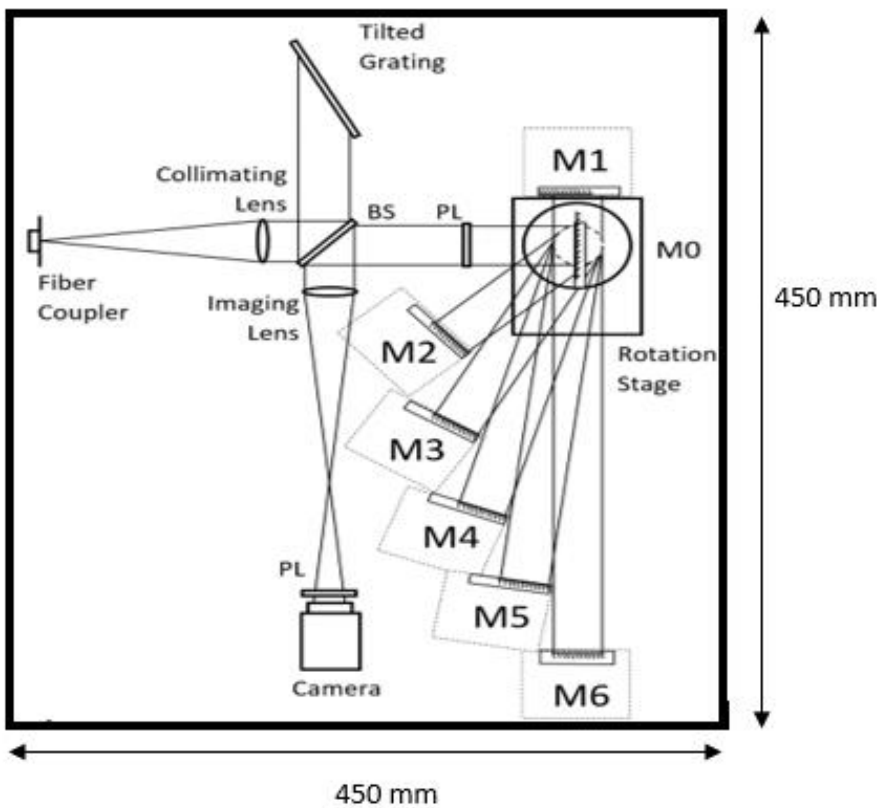


Figure 4: Set-up of current interferometer design.

Looking at Figure 4, the final dimensions of our interferometer can be seen to be 450 mm x 450 mm. A total of 7 mirrors are used in the system and are labeled M0 through M6. In Figure 4, BS indicates a beamsplitter and PL indicates a polarizer.

In one arm of the interferometer, hereafter called the grating arm, is a 25 mm x 50 mm grating with 31.6 grooves/mm and a blaze angle of 63°. This grating is tilted by 63° to be in the Littrow configuration, such that light is made perpendicular to each line of the grating and, therefore, reflected back with fine steps of OPL information (See Figure 5). Additionally, the grating is also given a very small vertical tilt which allows for a continuous measurement of OPD through each grating step. For the final design, on account of the grating being tilted, the maximum OPL that could be achieved from the furthest beam reflected back by the grating, in comparison to the closest beam reflected by the grating, was 44.6 mm. Of this information, only 40 mm was considered since the light from the edge of the grating proved to not be as useful.

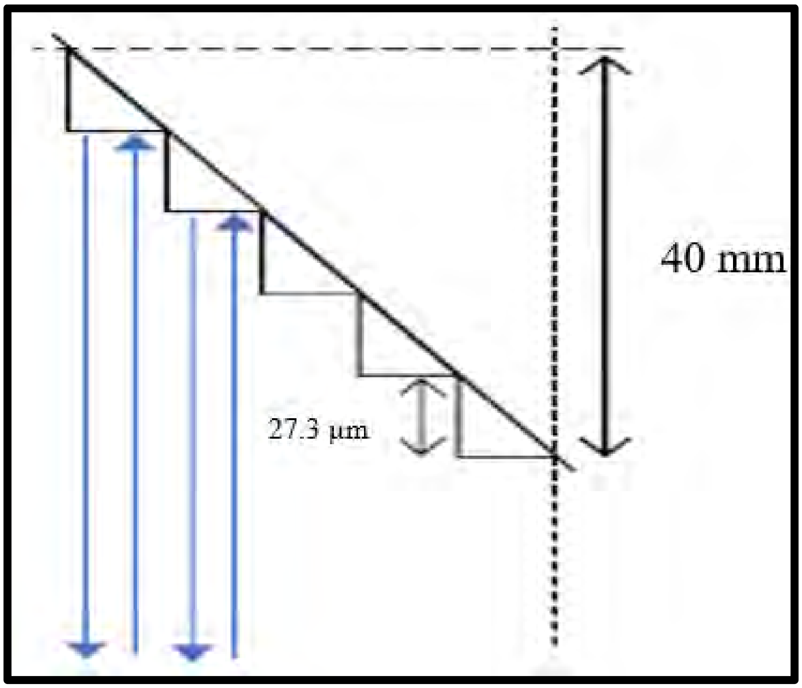


Figure 5: Drawing of how grating act as a staircase reflector.

In the other arm of the interferometer, hereafter called the measurement arm, is a seven mirror configuration. By rotating M0 towards the other mirrors, it is possible to measure the visibility over the entire measurement range. This is accomplished by placing M0 such that it and the top of the grating are at an equal path length from the BS. Since the interference of M0 and the grating gives visibility information over a ΔOPL range of 0 mm to 80 mm, M1 is placed 40 mm from M0. When M0 is oriented towards M1, the interreference pattern created between M1 and the grating will therefore give visibility information over the ΔOPL range of 80 mm to 160 mm. This process is continued with all subsequent mirrors to give a maximum ΔOPL measurement of 560 mm (See Figure 6).

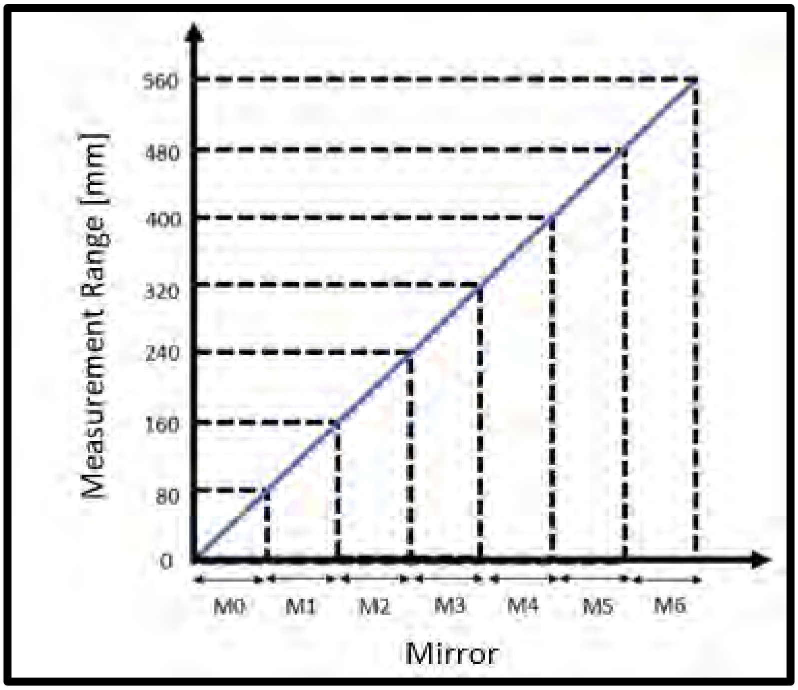


Figure 6: Drawing mathematically depicting how measurement arm extends measurement capabilities over desired range.

In order to resolve the discrepancy between the light intensity from each arm, on account of the fact that the mirrors in the measurement arm are more reflective than the grating in the grating arm, our design uses a two polarizer approach. A stationary polarizer is placed in the measurement arm and a rotatable polarizer is placed in front of the detector. By rotating the polarizer in front of the detector it is possible to make the detector receive approximately equal strength beams from the two arms of the interferometer.

<u>Enclosure and Mounting:</u>

The device will be mounted upon its own breadboard and enclosed by a carboard box to prevent stray light from entering the outside environment. This entire system will be mounted onto a vibration isolation table by the customer.

Cost Analysis:

Optomechanical Components:

Part	Company	Product Number	Qty.	Cost per Unit	Total Cost
Collimating Lens Mount	Thorlabs	FMP1	1	$ 16.12	$ 16.12
Imaging Lens Mount	Thorlabs	FMP1	1	$ 16.12	$ 16.12
Beam Splitter Mount	Thorlabs	KM100S	1	$ 80.58	$ 80.58
Grating Mount Part 1	Thorlabs	FP90	1	$ 67.83	$ 67.83
Grating Mount Part 2	Thorlabs	KGM40	1	$ 134.64	$ 134.64
Grating Mount Part 3	Thorlabs	KM100	1	$ 38.70	$ 38.70
Mirrors 0, 1-5 Mounts	Thorlabs	KM100S	6	$ 80.58	$ 483.48
Mirror 6 Mount	Thorlabs	KM100	1	$ 38.70	$ 38.70
Rotation Stage	Thorlabs	ELL8K/M	1	$ 391.68	$ 391.68
M6 Cap Screws (Pack of 25)	Thorlabs	SH6MS12	1	$ 8.11	$ 8.11
20 mm Posts (Packs of 5)	Thorlabs	TR20/M-P5	2	$ 21.33	$ 42.66
20 mm Posts (Single)	Thorlabs	TR20/M	3	$ 4.74	$ 14.22
100 mm Post (Single)	Thorlabs	TR100/M	1	$ 5.87	$ 5.87
Clamping Forks (Packs of 5)	Thorlabs	CF125-P5	2	$ 42.45	$ 84.90
Clamping Forks (Single)	Thorlabs	CF125	4	$ 8.95	$ 35.80
20 mm Post Holders (Pack of 5)	Thorlabs	PH20/M-P5	2	$ 35.15	$ 70.30
20 mm Post Holders (Single)	Thorlabs	PH20/M	3	$ 7.03	$ 21.09
75 mm Post Holder (Single)	Thorlabs	PH75/M	1	$ 8.27	$ 8.27
Post Holder Base (Pack of 5)	Thorlabs	BE1/M-P5	2	$ 47.43	$ 94.86
Post Holder Base (Single)	Thorlabs	BE1/M	4	$ 9.49	$ 37.96

Breadboard	Thorlabs	MB4545/M	1	$ 273.36	$ 273.36
Fiber Plug-in Mount	Thorlabs	FMP1	1	$ 16.12	$ 16.12
Fiber Plug-in Port	Thorlabs	S1FC	1	$ 29.58	$ 29.58
Glass Windows for Polarizer	Edmund Optics	84-455	4	$ 125.00	$ 500.00
Fixed Polarizer Mount	Thorlabs	FMP1	1	$ 16.12	$ 16.12
Rotating Polarizer Mount	Thorlabs	RSP1	1	$ 86.19	$ 86.19
Detector Mount	Thorlabs	XT34TR3/M	1	$ 42.84	$ 42.84
					$ 2,656.10

Table 1: Cost breakdown of optomechanical components.

Interferometer Components:

Part	Company	Product Number	Qty.	Cost per Unit	Total Cost
Collimating Lens	Edmund Optics	49-361	1	$ 96.50	$ 96.50
Beam Splitter	Thorlabs	BSW26R	1	$ 294.78	$ 294.78
Blazed Grating	Thorlabs	GE2550-0363	1	$ 223.38	$ 223.38
Mirrors 1-5	Thorlabs	PFSQ10-03-P01	5	$ 53.30	$ 266.50
Mirror 6	Thorlabs	PF10-03-P01	1	$ 52.02	$ 52.02
Rotating Flat Mirror	Thorlabs	PFR10-P01	1	$ 83.39	$ 83.39
Wire Grid Polarizing Film	Edmund Optics	34-254	2	$ 55.00	$ 110.00
Detector	High Point Scientific Inc.	ASI183MM	1	$ 629.00	$ 629.00
Imaging Lens	Edmund Optics	49-361	1	$ 96.50	$ 96.50
					$ 1,852.07

Table 2: Cost breakdown of interferometer components.

Complete Cost Analysis:

Component	Final Cost
Optomechanical	$ 2,656.10
Interferometer	$ 1,852.07
Total	**$ 4,508.17**

Table 3: Cost breakdown of combined components.

Spring Semester Timeline		
January	1/21-1/27	• (1/25) Met with customer to discuss direction of project. • (1/26) Met with advisor to discuss current design concerns and questions posed by customer. • Decision made to pursue interferometer design utilizing a blazed grating.
	1/28-2/3	• Assembled a simplified version of current design to gain insight into design practicality issues. • Investigated possibility of a custom made grating via diamond turning.
February	2/4-2/10	• Investigated algorithm to optimize visibility measurements. • Investigated best mounting method for grating. • Learned basics of and began modelling with FRED. • Began testing the use of multiple mirrors in reference arm.
	2/11-2/17	• (2/14) Met with customer to provide update on project. • (2/16) Met with advisor to discuss design and lab set-up. • Investigated use of OAP mirror for large beam collimation. • Investigation of alternate way to divide up reference arm. • Modeled current set-up with FRED.
	2/18-2/24	• Updated lab set-up and began testing the rotation mirror method. • Updated FRED analysis by creating a new grating and implementing a more detailed/realistic source.
	2/25-2/28	• Used FRED to determine test if rotation stage possessed adequate specifications. • Found suitable achromatic doublet to replace OAP mirror.
March	3/1-3/3	
	3/4-3/10	• (3/5) Met with Advisor to discuss ways to improve system design and methods of data analysis. • Investigated using a tarp as a “soft” enclosure. • Started writing code for data analysis.
	3/11-3/17	• Spring Break.
	3/18-3/24	• (3/23) Met with customer to provide an update on progress and ask a few questions. • Updated lab set-up to test if manipulation of polarization characteristics could create equal output beam intensity from both arms.
	3/25-3/31	• (3/30) Met with Advisor to discuss a finalization of components. • (3/31) Met with Professor Eastman to discuss detector choice.

<table>
<tr><td></td><td></td><td>• Decided on the two polarizer method to balance the two arms.
• Decided on a detector.
• Performed final mathematical calculations for spacing of components on breadboard
• Finalized BOM.
• Continued refining code to analyze visibility.</td></tr>
<tr><td rowspan="5">April</td><td>4/1-4/7</td><td>• (4/1) Sent completed BOM to customer for ordering.
• Continued refining computer analysis method to determine visibility</td></tr>
<tr><td>4/8-4/14</td><td>• Measured coherence length of a short coherence length source
• Continue refining computer analysis method to determine visibility</td></tr>
<tr><td>4/15-4/21</td><td>• (4/17) Received confirmation from customer that parts were delivered to him and that they are currently in transit to the U of R.
• (4/19) Received all parts except for detector
• Roughly assembled prototype components</td></tr>
<tr><td>4/22-4/28</td><td>• Calibrated and determined angle for rotation stage
• Performed fine adjustments of prototype set-up
• Began tolerancing prototype
• Began writing customer instructions for operation</td></tr>
<tr><td>4/29-4/30</td><td rowspan="2">• Printed poster for Senior Design Day
• Continued testing prototype
• Finished writing customer instructions
• (5/4) Senior Design Day</td></tr>
<tr><td rowspan="2">May</td><td>5/1-5/5</td></tr>
<tr><td>5/6-5/12</td><td>• Package and ship materials to customer</td></tr>
</table>

Table 4: Spring Semester Timeline

Lab Results:

Final Testing Set-up:

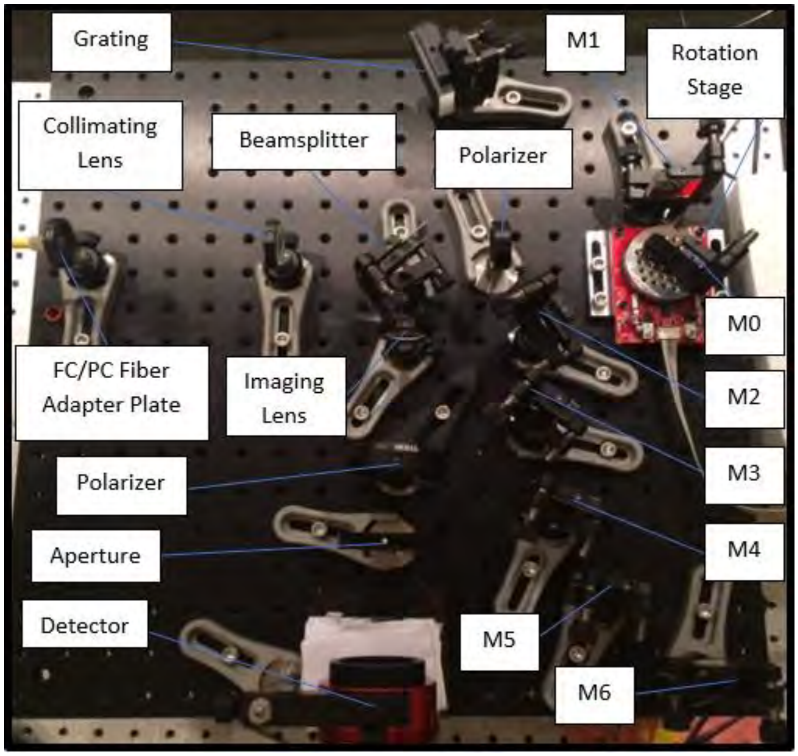


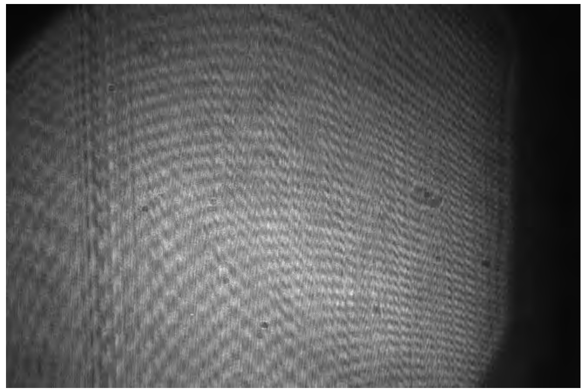
Figure 7: Image of testing set-up.

The system tested was the final prototype, with all of the components specified in the above listed cost analysis. Also, used was an aperture that was borrowed from the teaching lab. The source used to run the experiment was a fiber-coupled red laser with a wavelength of λ=650 nm.

The purpose of this final experiment was to produce the best images possible, in order to determine the limits of our system. One major factor in producing these best possible images, was the fact that our ordered detector, which had a significantly higher resolution, had arrived. Another factor in yielding the best images possible, was that in a previous experiment our group noticed that part of an additional unwanted diffraction order from the grating was making it to the detector. To eliminate this light, our group used an aperture to block out this light. Additionally, our team re-checked and improved the degree of collimation of the light, by using a shearing interferometer.

The procedure of our experiment followed how the interferometer is intended to be used. First, the rotation stage was put into the M0 orientation and a power meter was used to measure the power from each arm. The rotatable polarizer was adjusted until the two arms were balanced. Next, the mirror was rotated into the various path length configurations and images were captured. Finally, the images were processed using the visibility code.

Final Results:

Mirror	Image
M0	
M1	
M2	

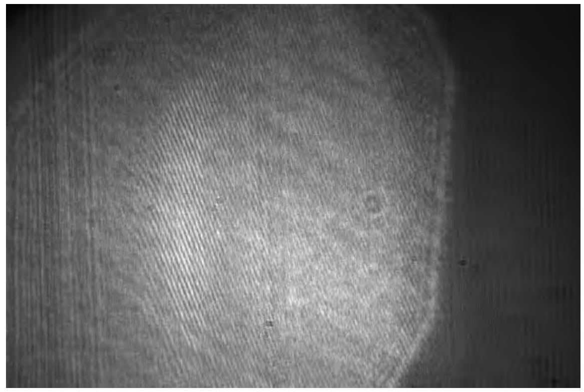
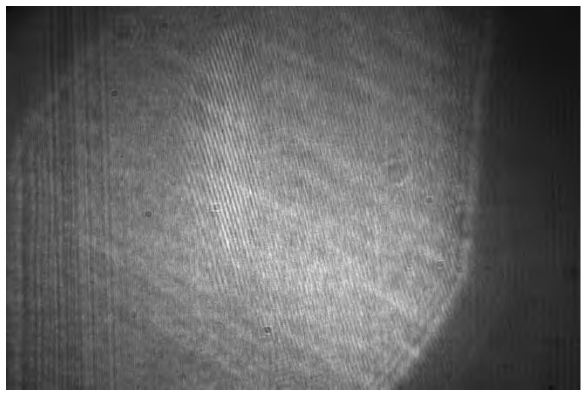
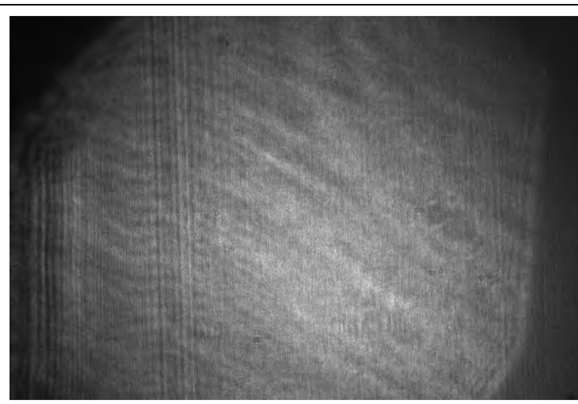
M3	
M4	
M5	
M6	

Table 5: Images of interference patterns created by interferometer in the various mirror configurations.

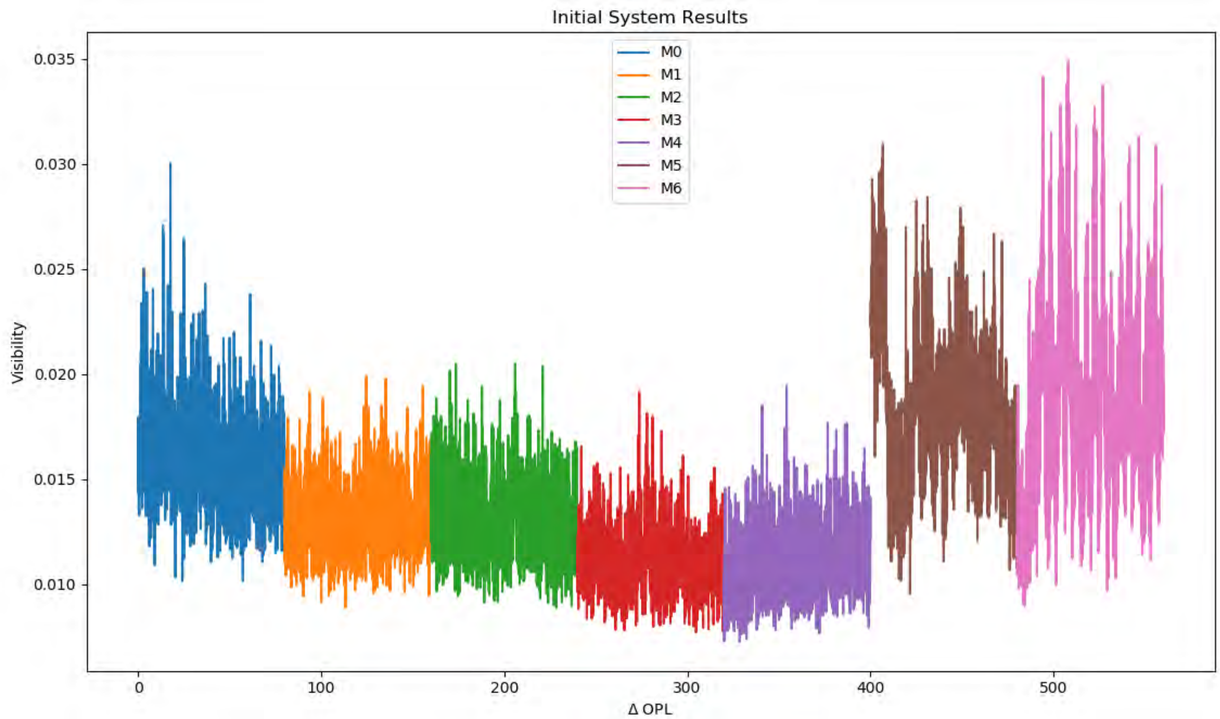


Figure 8: Plot of Visibility vs. ΔOPL. Image was created by applying the analysis code described in Appendix B, to the images in Table 5.

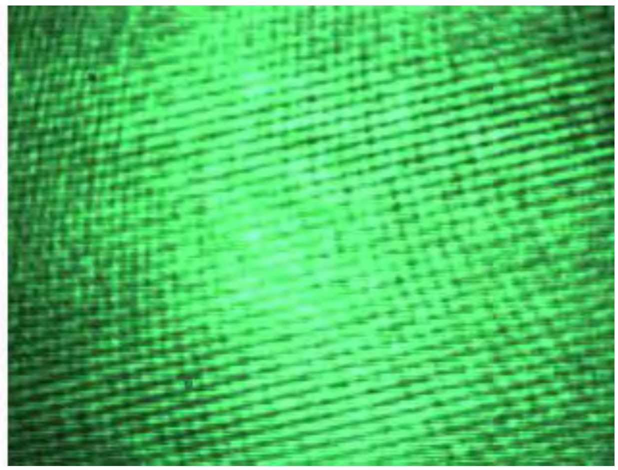
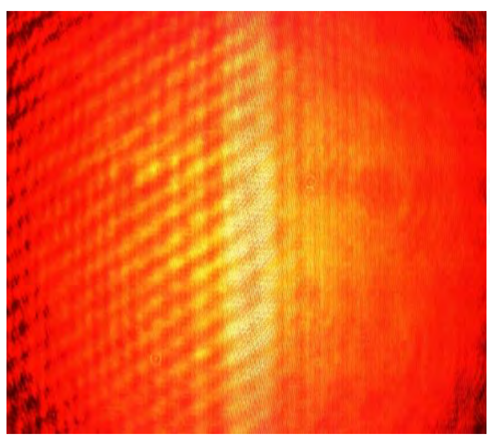
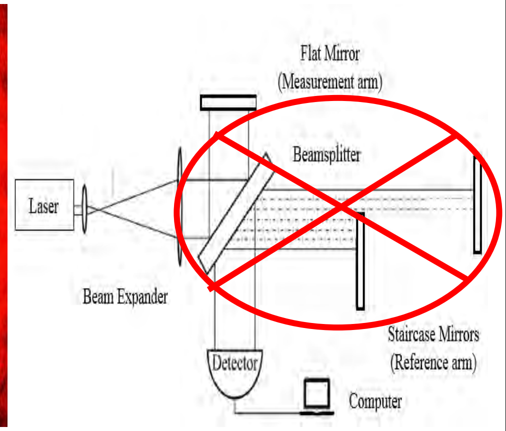
From looking at the images contained in Table 5 and the plot presented in Figure 8, their exist a couple of points to be discussed.

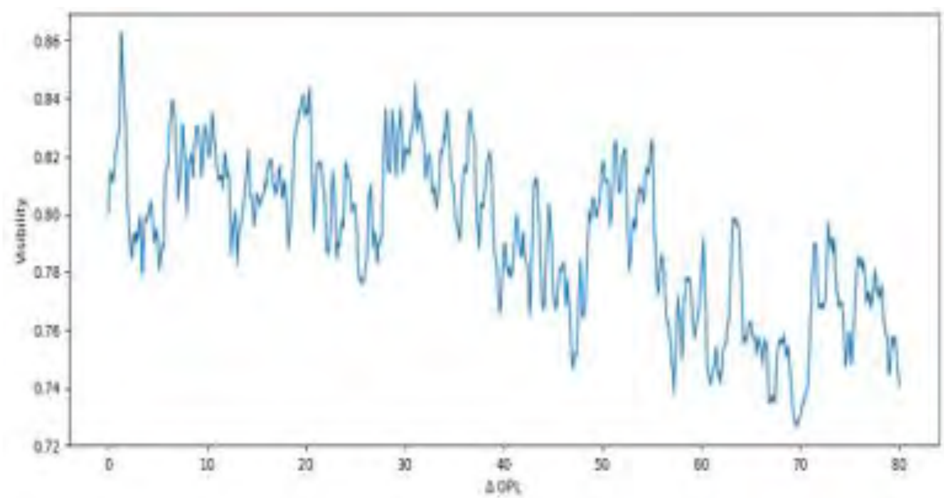
First, it is important to observe global decay in fringe visibility that can be seen as the OPD is increased. In regard to subjectively viewing the fringe contrast shown in Table 5 by eye, M0 clearly has the best contrast, while M2, M3, and M4 show a decay in fringe visibility, and, finally, M5 and M6 display no fringes at all. This observation is mostly confirmed by Figure 8, in that the visibility decays from M0-M4; however, M5 and M6 show a spiked visibility that is clearly not indicated by our images. We attribute this strange result to be a byproduct of our visibility code picking up on artifacts within the M5 and M6 images, which represents a new problem that will need to be addressed.

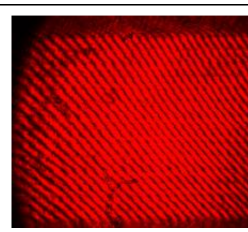
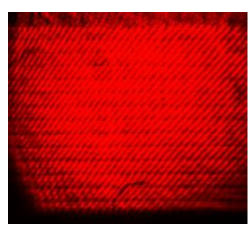
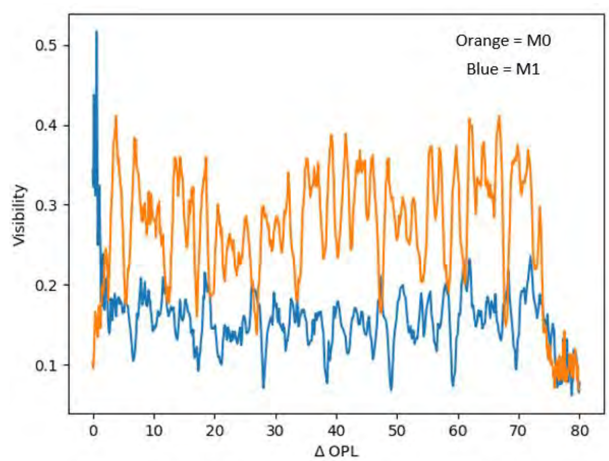
Second, it is important to note the high level of noise that exists over each mirror measurement region. We attribute a significant portion of this noise be a result of our fringes having a strange bend. Despite all of our attempts at adjusting the mirrors so that the fringes would be very straight, we could not eliminate this deformation of the fringes. As soon as any adjustment to move past the point of inflection was made, the large bend would appear and distort the fringes. This in turn, negatively impacted our visibility plot, as a uniform frequency of the fringes is a necessary condition for achieving good results with our visibility code.

Summary of Significant Results from Earlier Lab Sessions:

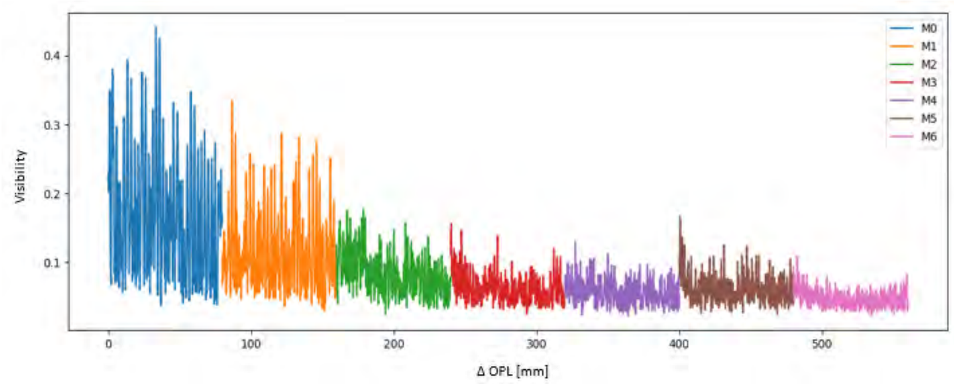
The following table is a condensed summary of our most important results from our lab sessions. If desired for reference, all relevant images captured in the lab are attached in appendix A.

Date	Testing Conditions		Significant Images and Discussion
1/28-2/3	Light Source	532 nm Laser Pointer	 The purpose of this initial lab session was to test the possibility of producing interference fringes using a reflective grating. In the above image it can be seen that our initial tests were promising in that they did yield the creation of prominent interference fringes.
	Grating Arm Reflector	Blazed Grating (20 grooves/mm, 26° 45′ blaze)	
	Measurement Arm Reflector	Single Flat Mirror	
2/11-2/17	Light Source	633 nm HeNe Laser	  The purpose of this lab session was to test the possibility of using a tiered reference mirror structure. Our results indicate that this design will not work for our system, as the interference patterns from each reference mirror were not observable at the same time. Additionally, the portion of the detector where the two reference beams overlapped became unusable.
	Grating Arm Reflector	Blazed Grating (20 grooves/mm, 26° 45′ blaze)	
	Measurement Arm Reflector	Two Flat Mirrors	

<table>
<tr><td rowspan="3">3/18-3/24</td><td>Light Source</td><td>633 nm HeNe Laser</td><td rowspan="3">

The purpose of this lab session was to further confirm our initial positive results seen when using the rotation mirror method and also to produce high-contrast fringes that could be used for image analysis. In the lab, we were able to create very straight and vertical fringes that became the first images from our system that we were actually able to analyze using our code.</td></tr>
<tr><td>Grating Arm Reflector</td><td>Blazed Grating (20 grooves/ mm, 26° 45′ blaze)</td></tr>
<tr><td>Measurement Arm Reflector</td><td>Three Flat Mirrors in Rotation Method Configuration</td></tr>
<tr><td rowspan="3">4/8-4/14</td><td>Light Source</td><td>Red Laser Pointer</td><td rowspan="3">M0 
M1 


The purpose of this lab session was to test a version of our final design with a short coherence length source. In a global sense, our results were promising in that our system did capture how the visibility was decreasing with greater OPD. On a more local scale, the visibility analysis of each image by itself, was found to be hindered by excessive noise that we attributed to vibration and the non-ideal quality of the lab equipment.</td></tr>
<tr><td>Grating Arm Reflector</td><td>Blazed Grating (20 grooves/ mm, 26° 45′ blaze)</td></tr>
<tr><td>Measurement Arm Reflector</td><td>Three Flat Mirrors in Rotation Method Configuration</td></tr>
</table>

<table>
<tr>
<td rowspan="3">4/22-
4/28</td>
<td>Light Source</td>
<td>Fiber-Coupled Red Laser</td>
<td rowspan="3">

The purpose of this lab session was to test the capabilities of our completed prototype except for the detector, which had not yet arrived. Similar to the results achieved using a short coherence length source, the global trend of visibility decreasing as OPD increased was observed, however on a local level our visibility for each individual mirror was still filled with excessive noise. Our group attributes this noise to unwanted diffraction in our system and also to the low resolution of the camera as our ordered detector had not yet arrived.</td>
</tr>
<tr>
<td>Grating Arm Reflector</td>
<td>Blazed Grating (31.6 grooves/ mm, 63° blaze)</td>
</tr>
<tr>
<td>Measurement Arm Reflector</td>
<td>Seven Flat Mirrors in Rotation Method Configuration</td>
</tr>
</table>

Table 6: Summary of key lab results.

FRED Analysis:

Early concerns regarding both the propagation of light and the impact of diffraction in our system pushed us to model our system using FRED.

Our first FRED model was a very simplified version of our system consisting of a collimated light source, a beamsplitter, one mirror in the measurement arm, and a blazed grating with approximately 20 grooves/mm and a 26° 45’ blaze, that was tilted at 26° 45’. The purpose of this initial model, was to continue getting familiar with modeling in FRED and as a basic proof of concept. We were unsure if we could see fringes or if diffraction from the grating would dominate the system. The initial FRED model gave us confidence that our design would produce results.

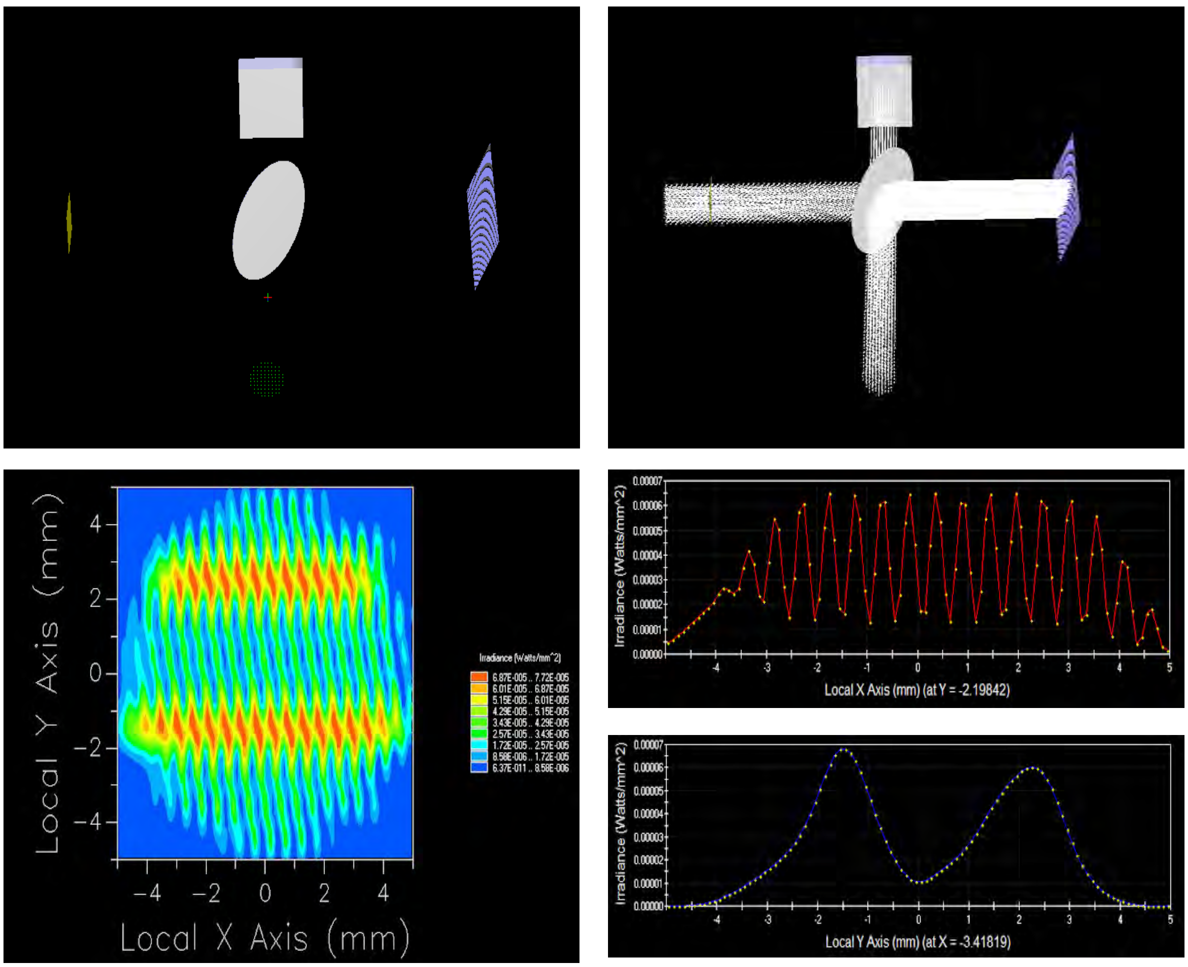


Figure 9: Shows a simplified model of our system in FRED. The top figures show the physical system. And the figures below show the irradiance pattern observed by the detector (the yellow object in the upper figure)

The next model that was created was a more realistic representation of our system. This model utilized a non-trivial light source which was collimated. The component used for collimation was a parabolic mirror, that we had intended to use at that time. Two mirrors were used in the measurement arm to simulate the rotation stage mechanism and a blazed grating with 31.6 grooves/mm and a 63° blaze was placed in the grating arm and tilted 63° to be in the Littrow configuration. This model proved useful as an aid to developing our system and also as a means to corroborate our lab results. It allowed for tolerancing and the ability to quickly make theoretical changes to our system and see immediate results.

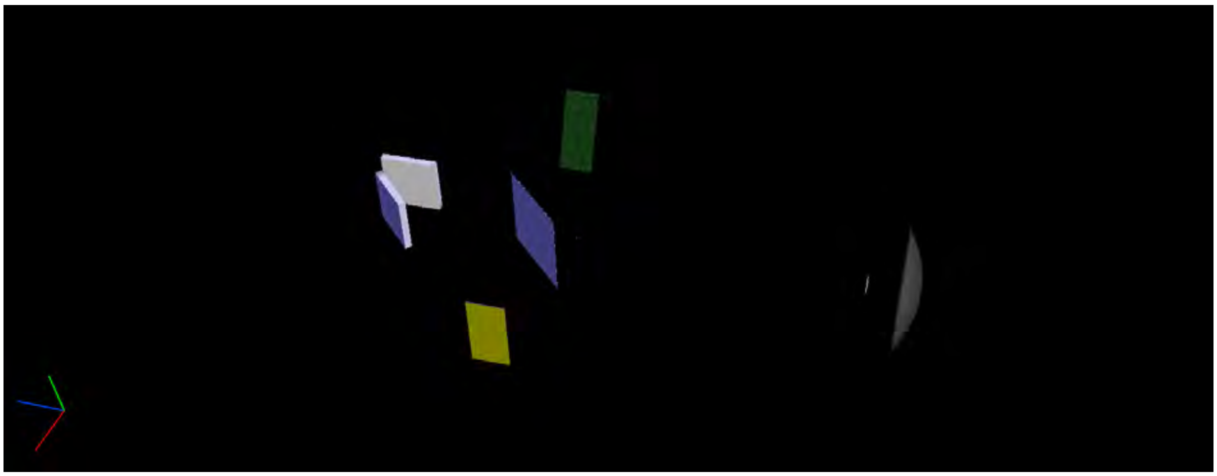


Figure 10: Model of current set-up. This model includes the grating of 31.6 grooves/mm and a 63° blaze angle that we intend to use, a realistic source collimated with a parabolic mirror, and a CCD detector with a glass cover plate.

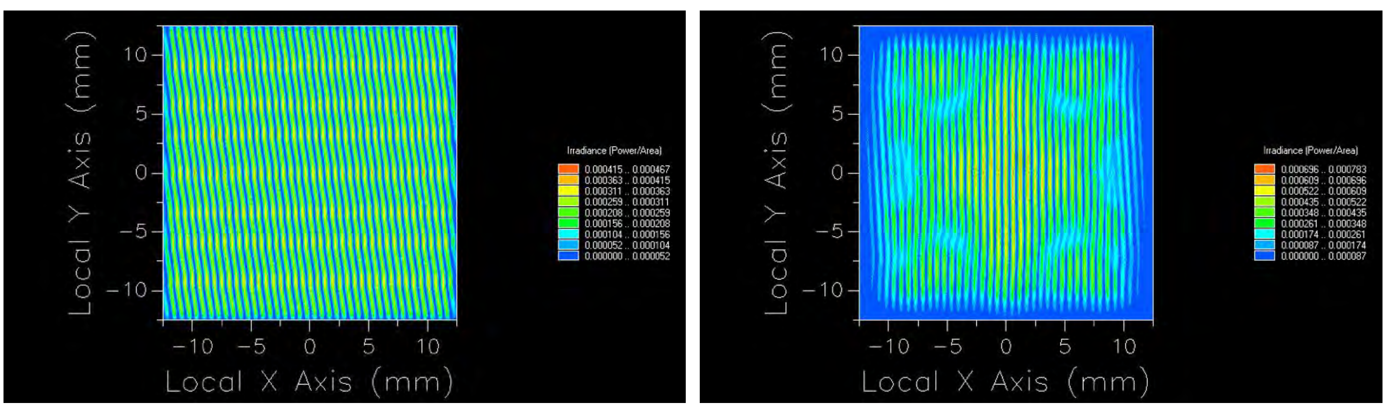


Figure 11: Results from a plane wave and a gaussian source modeling a HeNe laser.

.

The next model that was created was a model to test how the error of our selected rotation stage would impact results. After applying the maximum possible error of the rotation stage, no noticeable change occurred to the imaged interference pattern. This led to the conclusion that our selected rotation stage was accurate enough to be purchased.

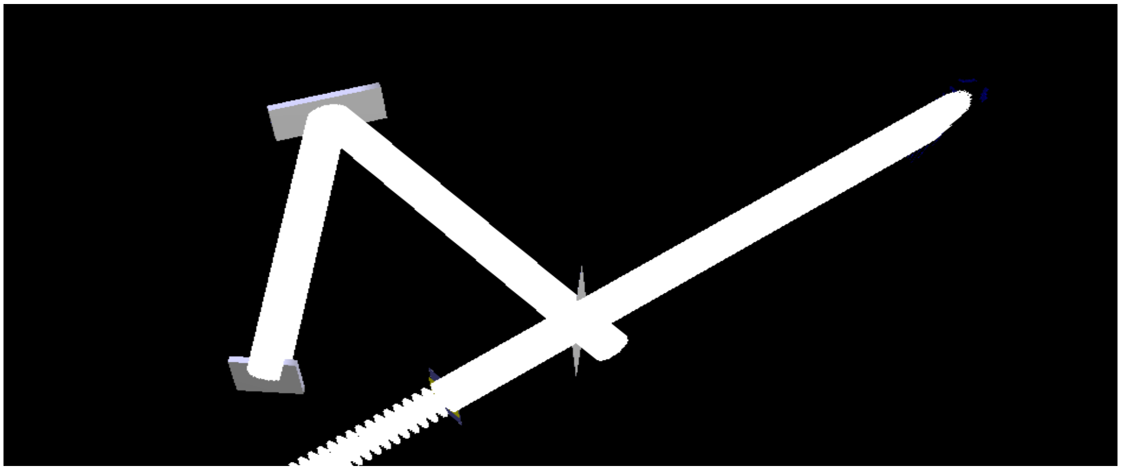


Figure 12: A visualization of our model used to check if the repeatability of our rotation stage would cause any problems.

The final FRED model created was a model of all the optical components used in the prototype. Compared to previous models, this includes the addition of a collimating and imaging lens and the additional mirrors used in the measurement arm.

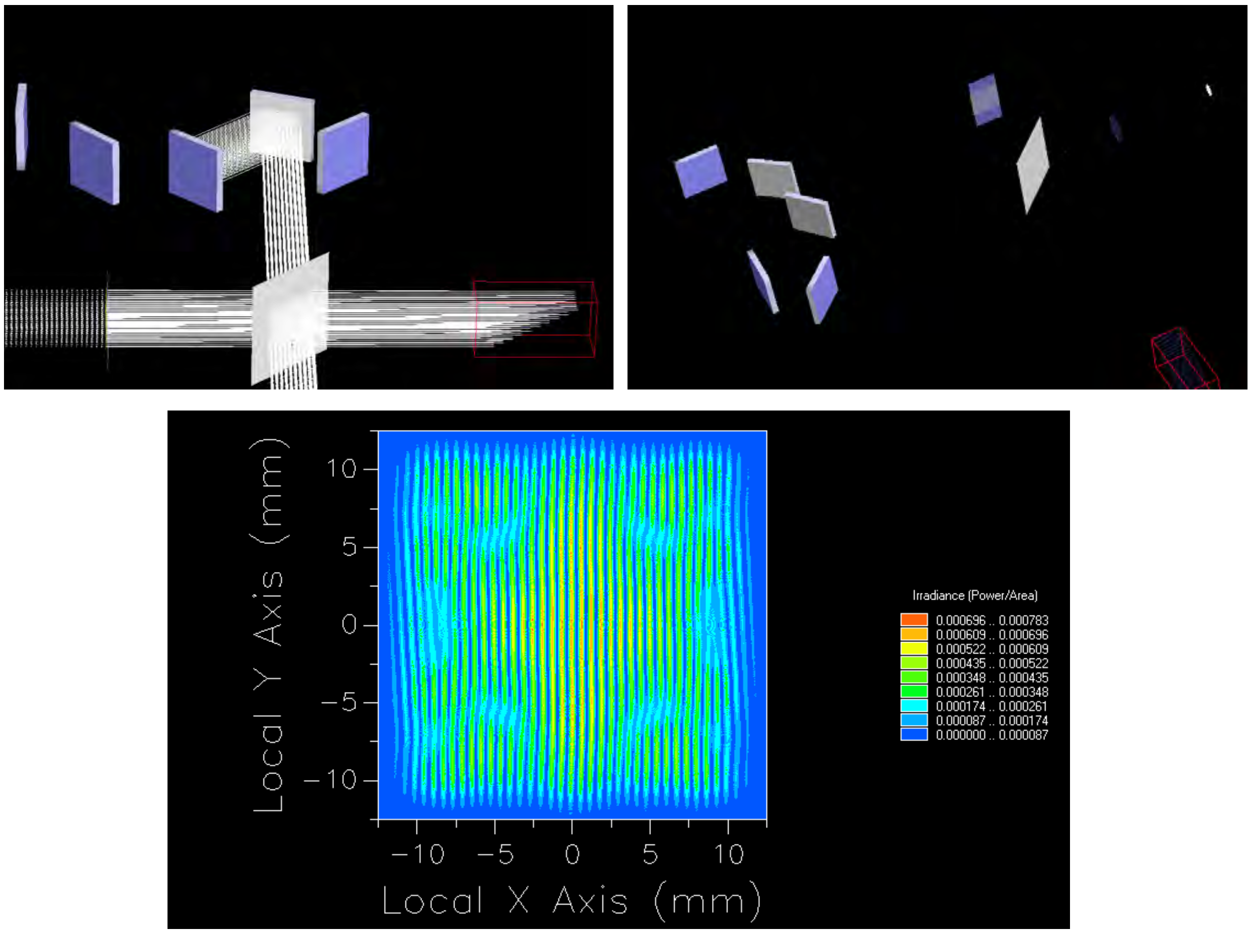


Figure 13: Our final system modeled in FRED. The top figures show the physical system. The bottom image shows the modeled interference pattern observed from using a Gaussian laser beam source with a spectrum modeled after that of a HeNe laser.

Visibility Analysis:

This section illustrates the software analysis method that was used to create a plot of the visibility as a function of optical path length difference through calculating the image along each line of the grating and though calculating the grating line. For the full code see Appendix B.

Once an image is collected, the visibility is calculated by taking the Fourier transform of each grating line. The visibility of a fringe pattern can be determined by taking twice the amplitude of the fringe frequency and dividing it by the zero order frequency. The FFT of the system was obtained in python with the use of the numpy toolbox command FFT:

```
FringFft = np.abs(fft.fftshift(fft.fft(fft.fftshift(FringeArray))))
```

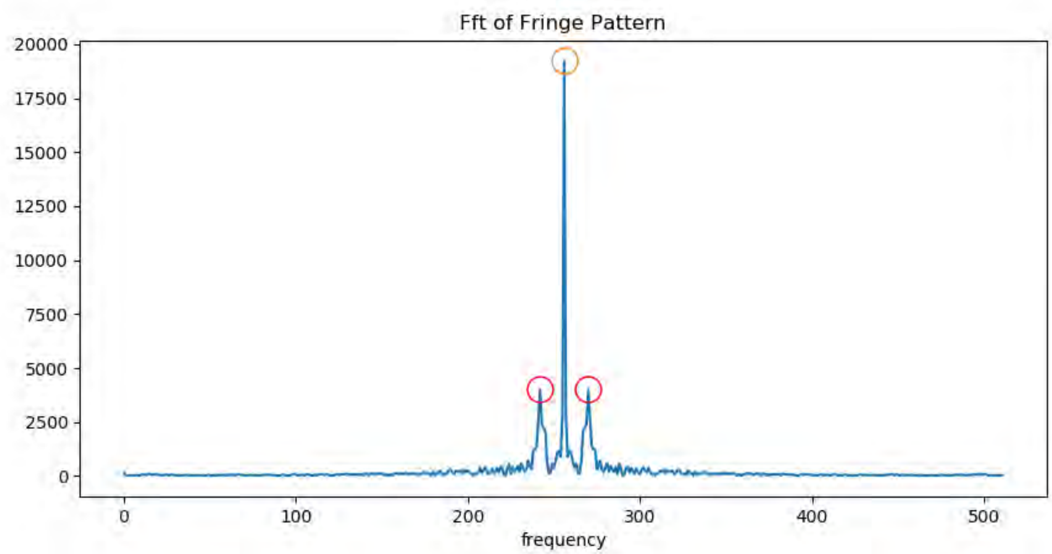


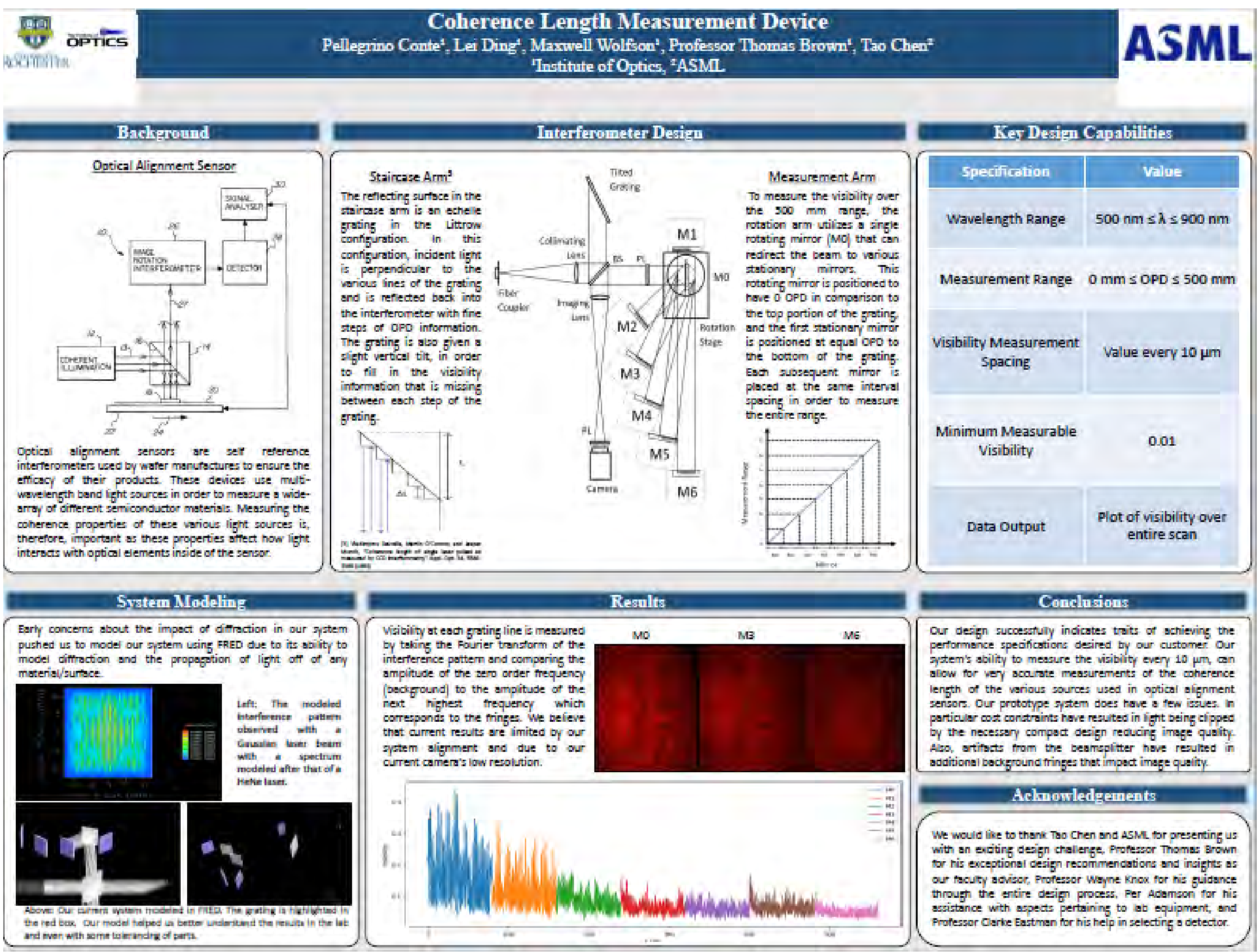
Figure 14: The fast Fourier transform of a 1-dimensional array along the line of the grating. Circled in orange is the shifted zero order frequency peak. Circled in red are the secondary peaks that correspond to the fringes.

Design Day Description:

Our design day presentation consisted of two parts:

1. Our Prototype Interferometer
   - This interferometer was attached to a red-fiber coupled laser that could be turned on to help demonstrate how light propagated through the system. We also demonstrated how the rotation stage was programed to quickly rotate to the different angles necessary for extending the measurement range of our device.

2. Poster



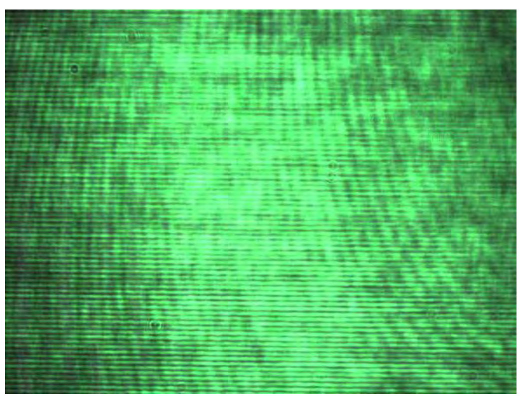
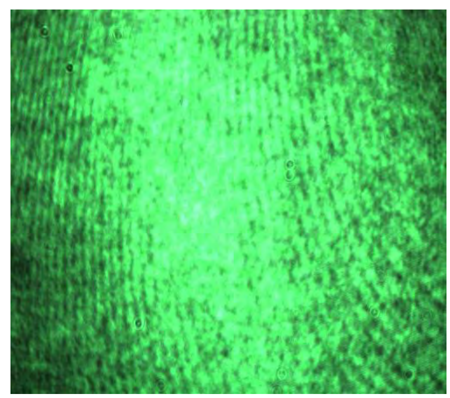
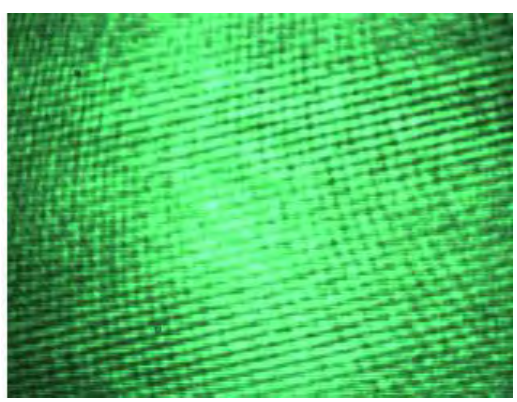
Conclusions and Future Work:

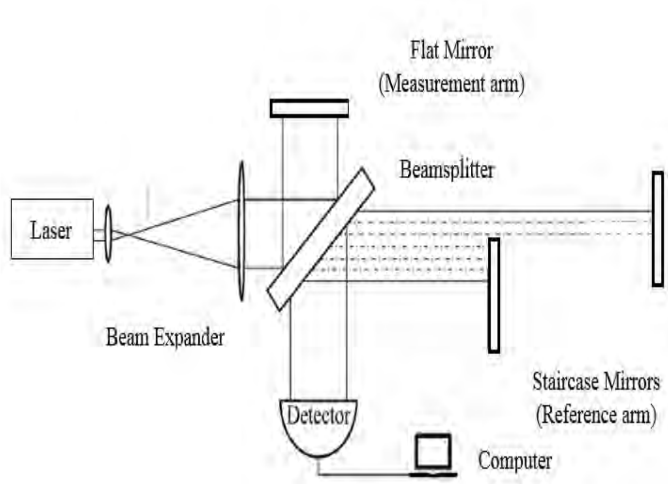
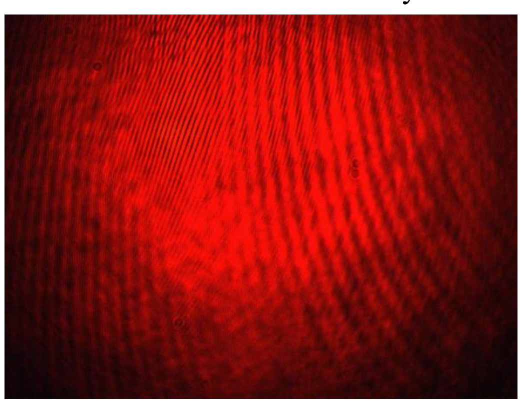
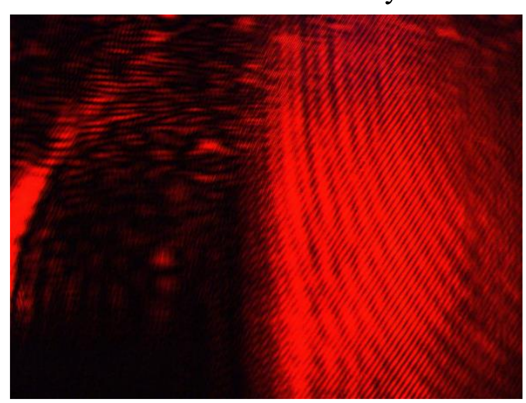
Our final prototype interferometer is promising in its design, but currently lacking in practical implementation. Theoretically our design meets and exceeds the major design restraints that made the customer unable to measure the coherence length of his various sources. Our system is able to outperform a traditional Michelson interferometer, in that the grating allows for a measurement value of the visibility in increments less than 10 μm. Also, our system can outperform a spectral analysis method of the coherence length, in that the mechanical nature of our device does not obfuscate lower visibility values.

However, when trying to physically test the prototype our team encountered issues that led to excessive noise in our results. Problems with our system set-up resulted in warped fringes that yielded undesirable results. A number of factors, probably working together, may have caused the distortion of our fringes. The thinness of our beamsplitter and rotating mirror, along with the type of mount being used upon them, may have resulted in these components being bent and therefore impacting fringe quality. One way to eliminate this concern regarding the mirror, would be to fix it to a more solid base and then mount that component. In regard to the beamsplitter, it may be necessary to use a different type of mount. Another factor impacting our results, could be unwanted reflections caused by the beamsplitter and additional orders reflected by the grating. A new design that takes into account this factor of unwanted light when positioning optics may be needed to improve fringe quality. An additional factor that impacted our results, was the quality of our lenses. A future design could be made with better quality optics in order to avoid issues with aberrations, nonuniform brightness, and vignetting that negatively impacted our image quality. Another possible avenue to explore in improving fringe quality, is to perhaps initially use a smaller collimated beam and then a beam expander in the grating arm to cover the grating. By doing this issues with the large beam being clipped and diffracted by mounts and other optics could be avoided. Also, a future avenue for improvement of image quality, could also be to create a custom made grating with a larger step spacing and a higher accuracy in step-size uniformity. Another possible future design change, could be to use another spatial filter set-up in addition to the fiber coupler, to improve the quality of the collimated beam. In support of this design change, is that our best lab results occurred during the 3/18-3/24 lab week, when a spatial filter was being used. In addition to these mechanical concerns, our visibility code is also in need of improvement. While the visibility code can report the visibility when fringes exist, in the presence of artifacts and the absence of fringes our code produces results that do not follow what is experimentally observed.

Ultimately, our prototype is a unique type of interferometer that shows promise in achieving the capabilities desired by the customer. Hopefully, with some modifications of this prototype design, the issues that impact fringe quality can be eliminated and the device can, subsequently, be implemented to ensure the efficacy of the systems used to measure wafer quality.

Appendix A: Table of All Lab Results

<table>
<tr><th>Date</th><th colspan="3">Results</th></tr>
<tr><td rowspan="4">1/28-
2/3</td><td>Equipment Specifications</td><td colspan="2">• 532 nm Laser Pointer
• Blazed Grating (20 grooves/mm, 26° 45′ blaze)</td></tr>
<tr><td>System Layout</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">Images</td><td>Grating Arm Only
</td><td>Reference Arm Only
</td></tr>
<tr><td colspan="2">Interference of Two Arms
</td></tr>
</table>

<table>
<tr><td rowspan="4">2/4-
2/10</td><td>Equipment Specifications</td><td colspan="2">• 633 nm HeNe Laser
• Note: Used three flat mirrors. Two in the reference arm and one in the measurement arm.</td></tr>
<tr><td>System Layout</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">Images</td><td>Measurement Arm Only
</td><td>Reference Arm Only
</td></tr>
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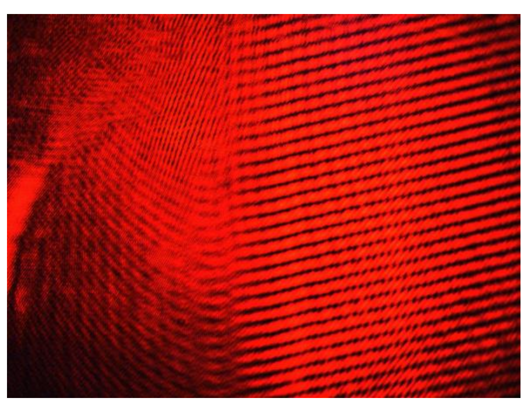</td></tr>
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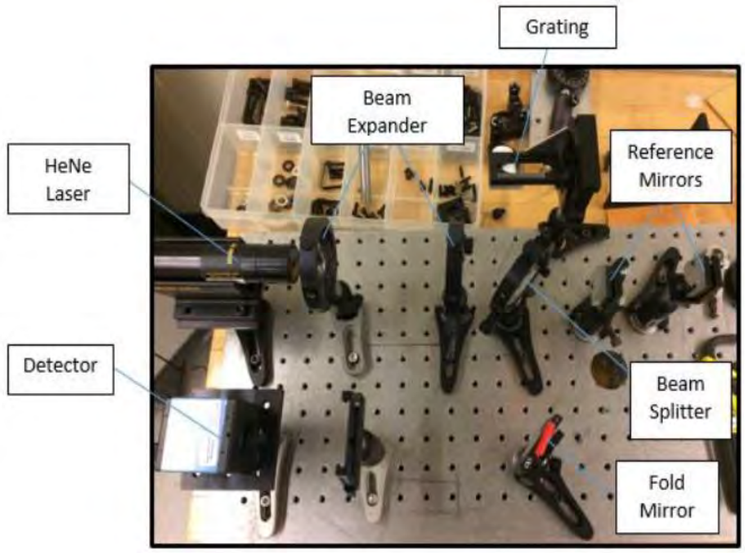
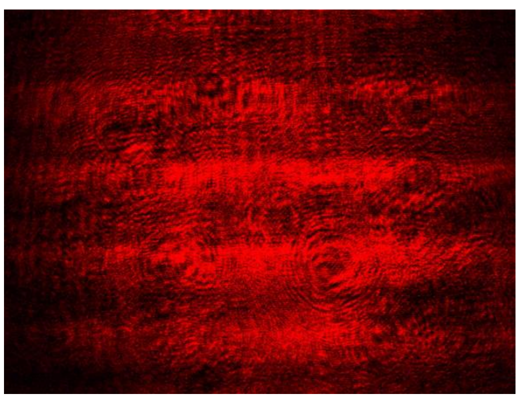
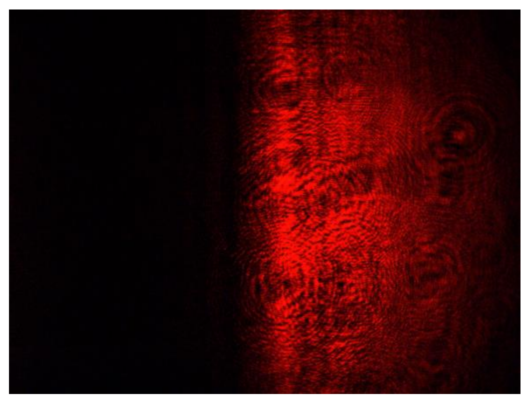
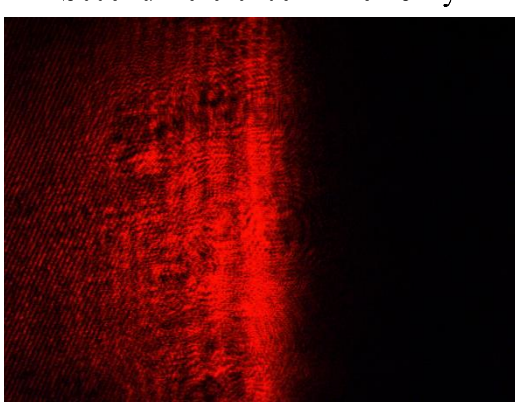
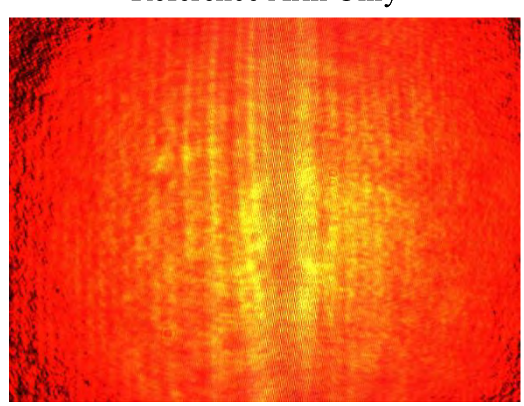
<table>
<tr><td rowspan="4">2/11-
2/17</td><td>Equipment Specifications</td><td colspan="2">• 633 nm HeNe Laser
• Blazed Grating (20 grooves/ mm, 26° 45′ blaze)</td></tr>
<tr><td>System Layout</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">Images</td><td>Grating Arm Only
</td><td>First Reference Mirror Only
</td></tr>
<tr><td>Second Reference Mirror Only
</td><td>Reference Arm Only
</td></tr>
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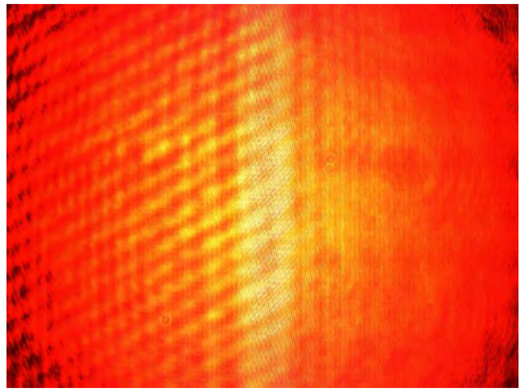
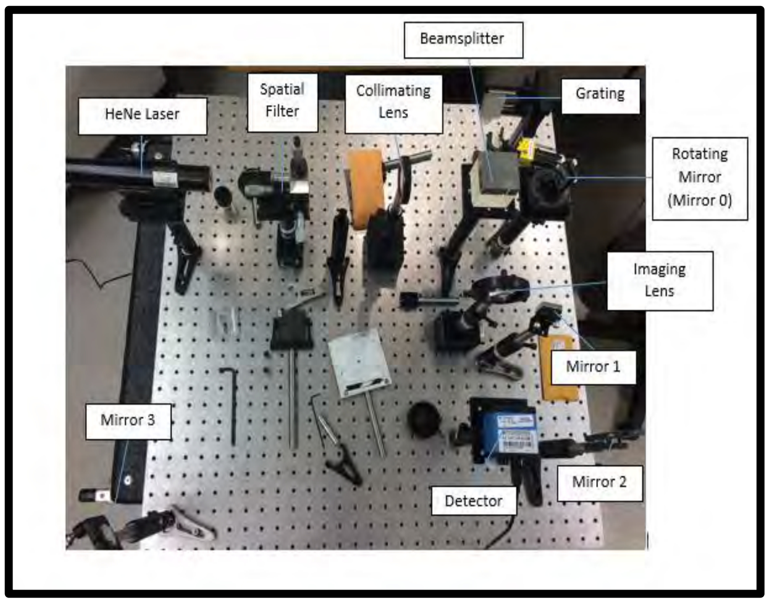
<tr><td></td><td></td><td colspan="3">Interference of Two Arms
</td></tr>
<tr><td rowspan="3">2/18-
2/24</td><td>Equipment Specifications</td><td colspan="3">

- 633 nm HeNe Laser
- Rotation stage method.
- OPL values: Grating Top=158mm, Grating Bottom=140mm, Mirror 0=130mm, Mirror 1=284mm, Mirror 2=750mm, Mirror 3=1540mm

</td></tr>
<tr><td>System Layout</td><td colspan="3">
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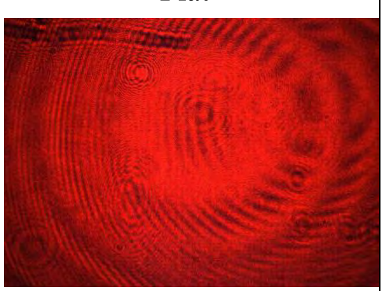
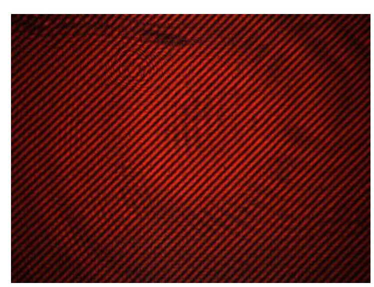
<tr><td>Images</td><td>Measurement Arm Only Flat
</td><td>Mirror 0 Only
</td><td>Interference of Flat and Mirror 0
</td></tr>
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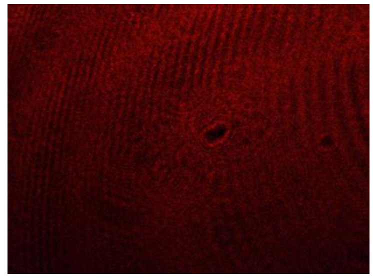
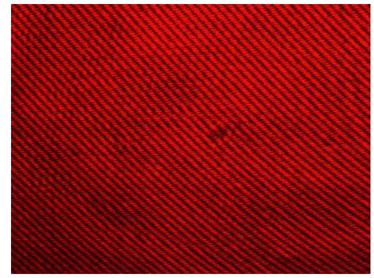
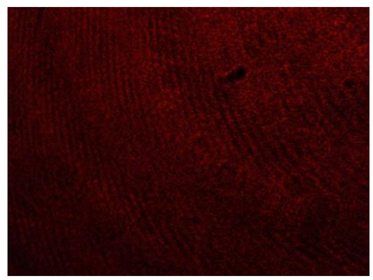
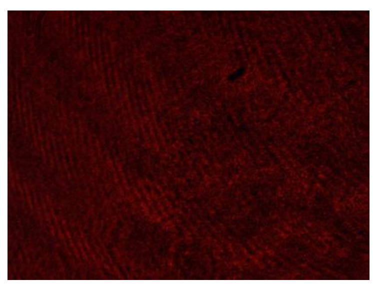
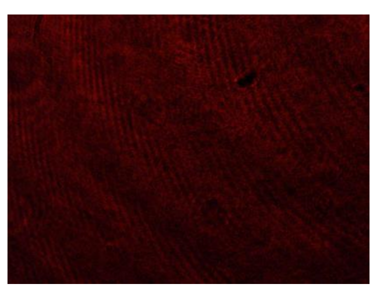
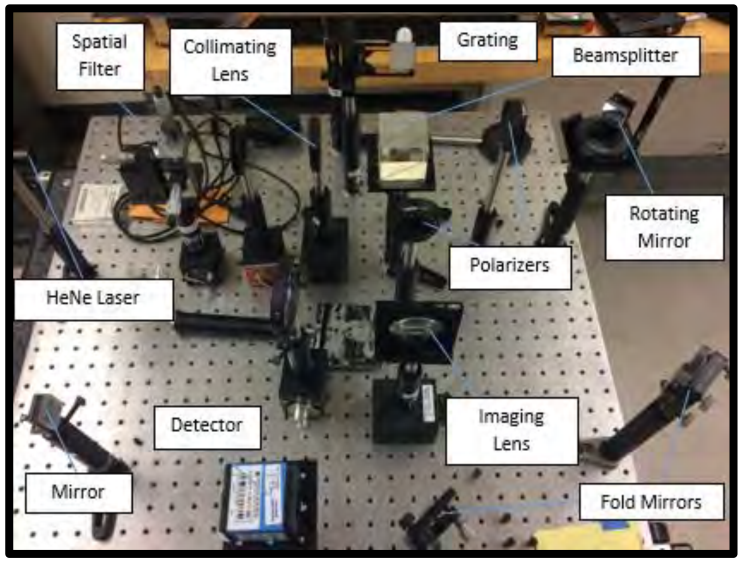
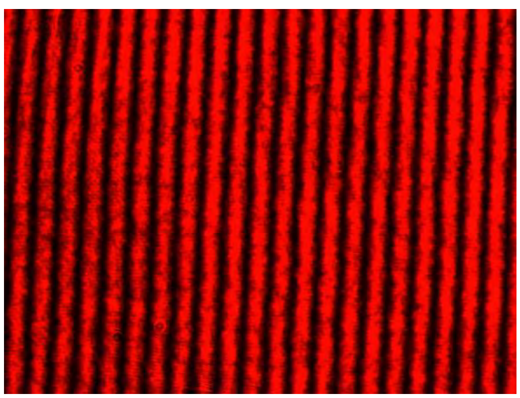
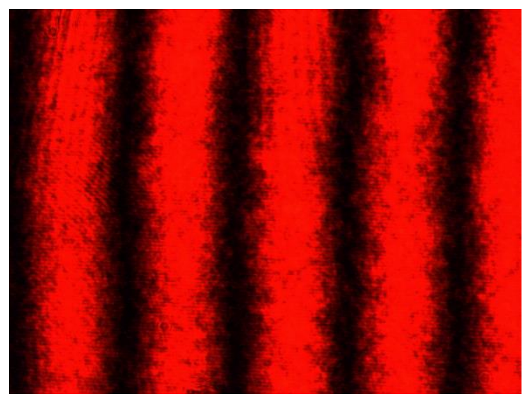
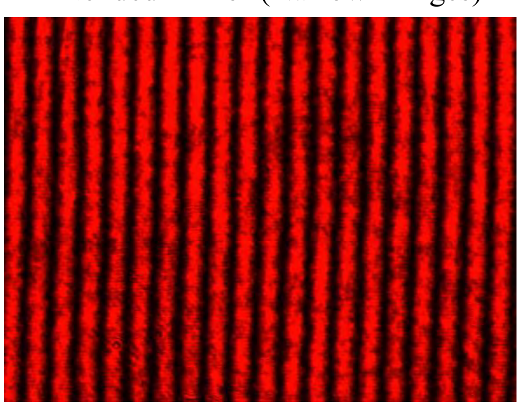
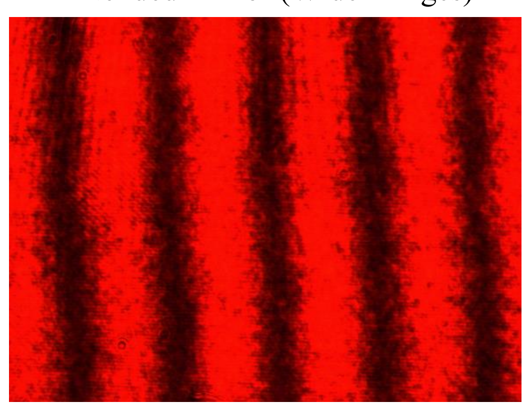
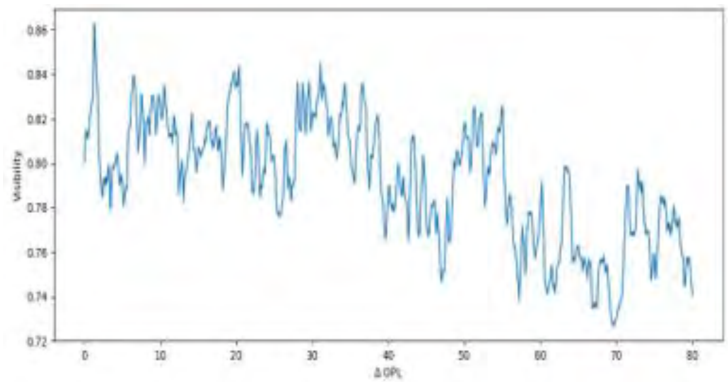
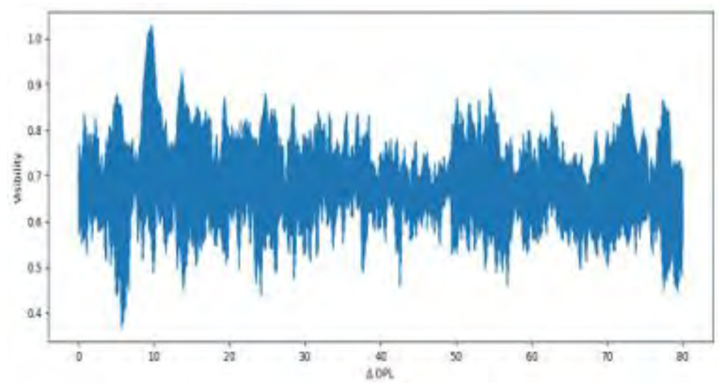
		Grating Arm Only 	Mirror 0 Only 	Interference of Grating and Mirror 0 
		Grating Arm Only 	Mirror 1 Only 	Interference of Grating and Mirror 1 
		Grating Arm Only 	Mirror 2 Only 	Interference of Grating and Mirror 2 
		Grating Arm Only 	Mirror 3 Only 	Interference of Grating and Mirror 3 

<table>
<tr><td rowspan="5">3/18-
3/24</td><td>Equipment Specifications</td><td colspan="2">• 633 nm HeNe Laser
• Rotation stage method</td></tr>
<tr><td>System Layout</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">Images</td><td>Interference between Grating and Rotating Mirror (Narrow Fringes)
</td><td>Interference between Grating and Rotating Mirror (Wide Fringes)
</td></tr>
<tr><td>Interference between Grating and Extended Mirror (Narrow Fringes)
</td><td>Interference between Grating and Extended Mirror (Wide Fringes)
</td></tr>
</table>

<table>
<tr>
<td rowspan="2"></td>
<td rowspan="2">Visibility Plots</td>
<td>Visibility determined Once per Grating Line



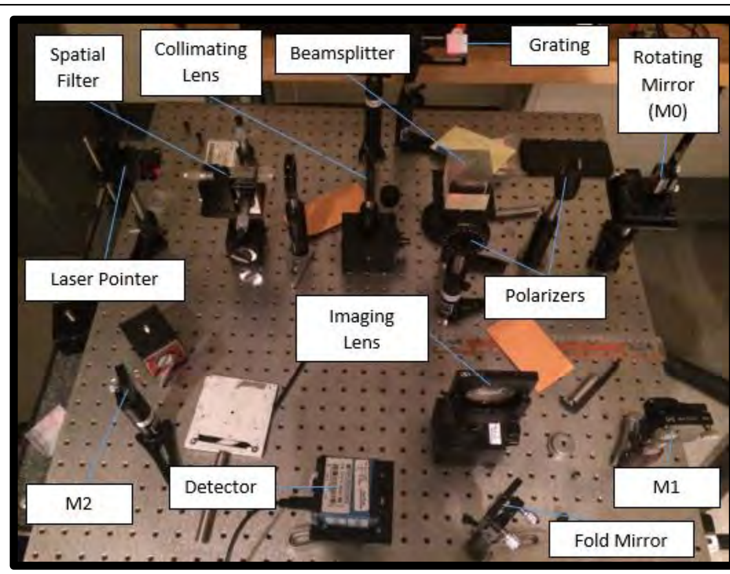
</td>
</tr>
<tr>
<td>Visibility determined Multiple Times per Grating Line



</td>
</tr>
<tr>
<td rowspan="2">4/8-
4/14</td>
<td>Equipment Specifications</td>
<td>

- Red Laser Pointer
- Rotation stage method
- Base-to-Base OPD values: Mirror 0 = 0 cm , Mirror 1 = 50 cm, Mirror 2 = 130 cm

</td>
</tr>
<tr>
<td>System Layout</td>
<td>



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</tr>
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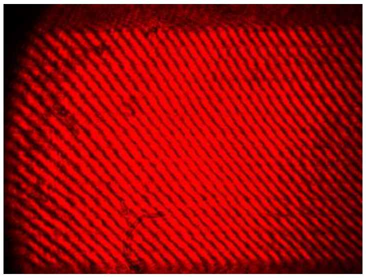
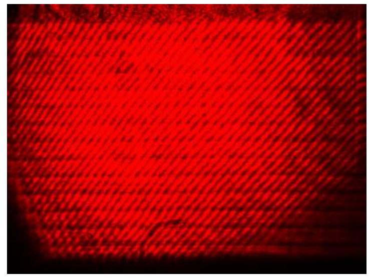
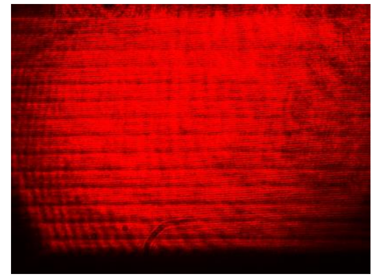
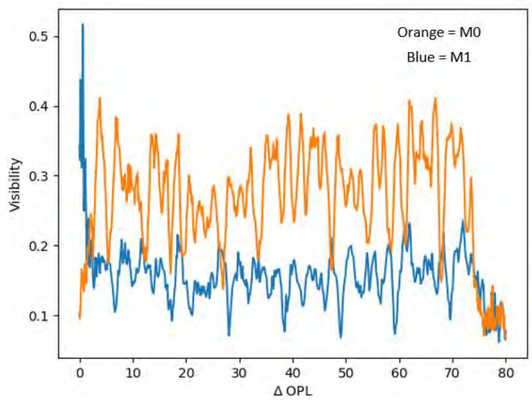
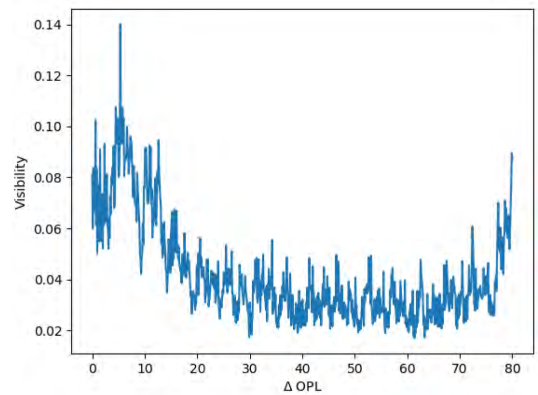
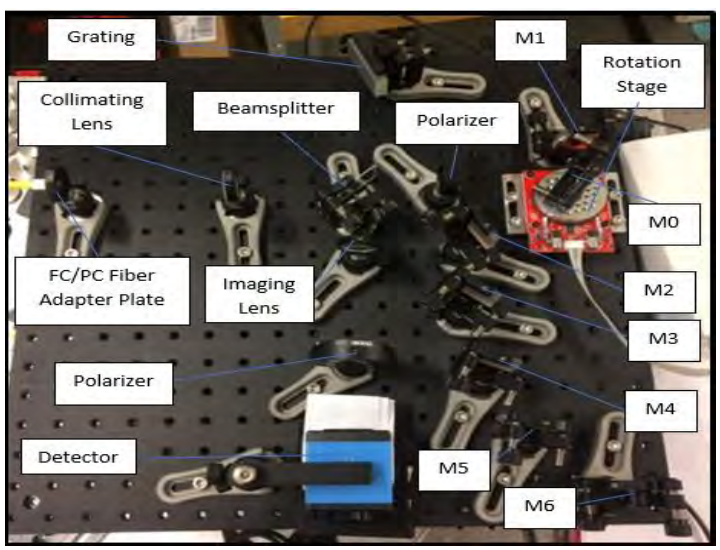
<table>
<tr><td rowspan="2"></td><td>Images</td><td colspan="2">Interference between Grating and M0
</td><td>Interference between Grating and M1
</td><td>Interference between Grating and M2
</td></tr>
<tr><td>Visibility Plots</td><td colspan="3">Visibility of M0 and M1 Configurations

</td><td>Visibility of M2 Configuration

</td></tr>
<tr><td rowspan="2">4/22-4/28</td><td>Equipment Specifications</td><td colspan="4">

- Fiber-Coupled Red Laser Pointer (λ=650nm)
- Complete prototype except for detector
- OPD Ranges Mirror 0 = 0-40 mm , Mirror 1 = 40-80 mm, Mirror 2 = 80-120 mm, Mirror 3 = 120-160 mm, Mirror 4 = 160-200 mm, Mirror 5 = 200-240 mm, Mirror 6 = 240-280 mm

</td></tr>
<tr><td>System Layout</td><td colspan="4">
</td></tr>
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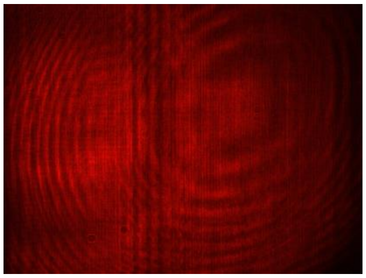
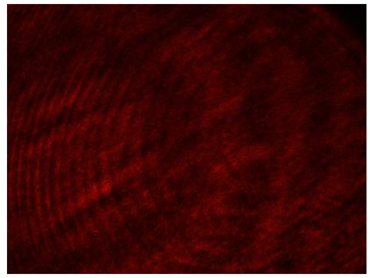
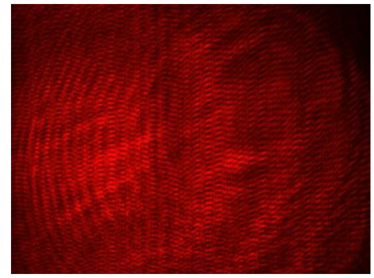
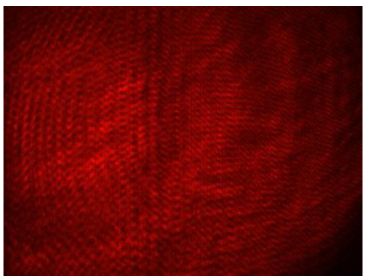
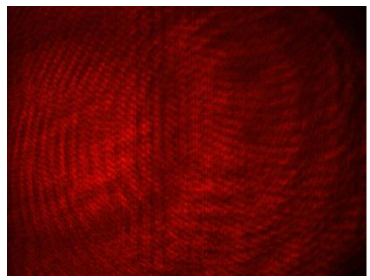
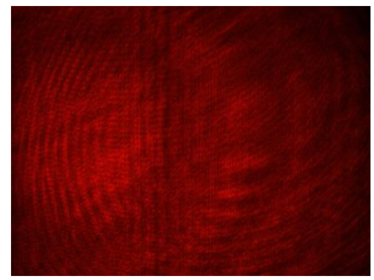
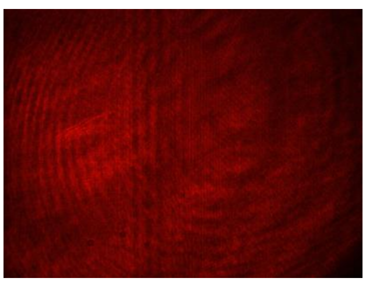
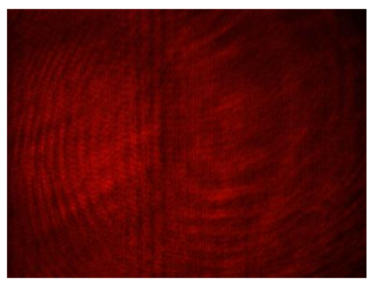
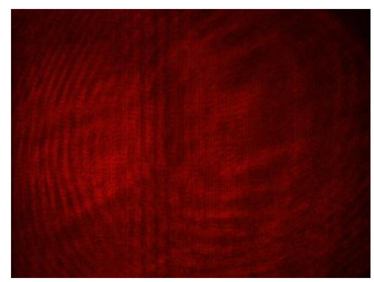
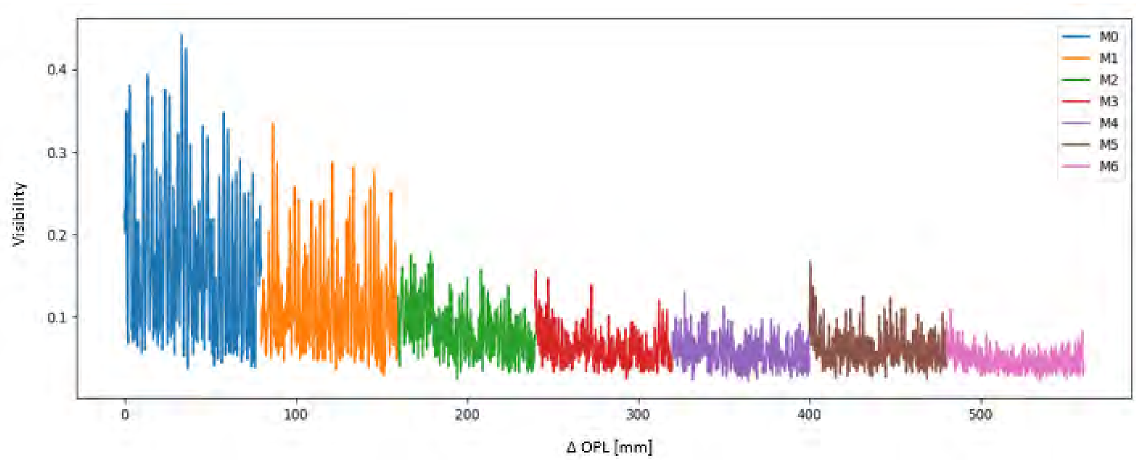
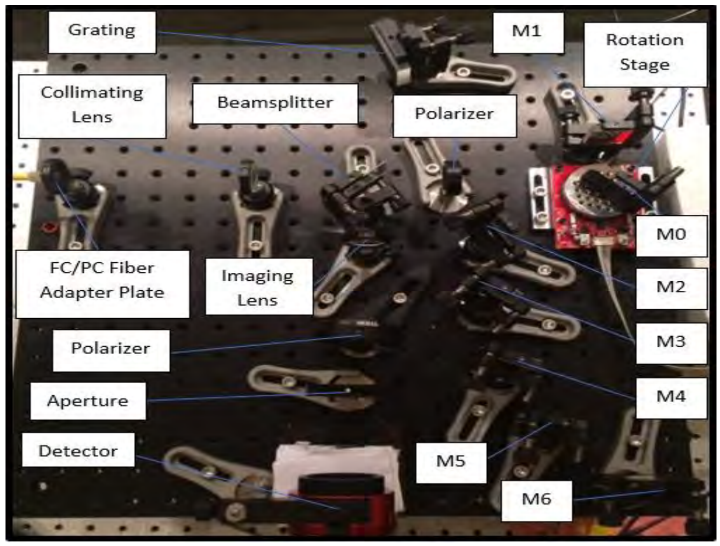
	Images	Grating Arm Only 	M0 Only 	Interference between Grating and M0 
		Interference between Grating and M1 	Interference between Grating and M2 	Interference between Grating and M3 
		Interference between Grating and M4 	Interference between Grating and M5 	Interference between Grating and M6 
	Visibility Plot	 		

<table>
<tr><td rowspan="3">4/29-
5/5</td><td>Equipment Specifications</td><td colspan="12">

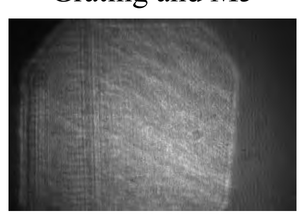
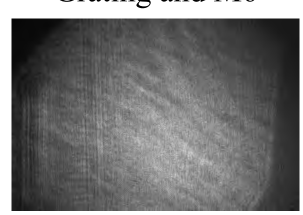
- Fiber-Coupled Red Laser Pointer (λ=650nm)
- Complete prototype with detector and a borrowed aperture
- OPD Ranges Mirror 0 = 0-40 mm , Mirror 1 = 40-80 mm, Mirror 2 = 80-120 mm, Mirror 3 = 120-160 mm, Mirror 4 = 160-200 mm, Mirror 5 = 200-240 mm, Mirror 6 = 240-280 mm

</td></tr>
<tr><td>System Layout</td><td colspan="12">



</td></tr>
<tr><td>Images</td><td colspan="12">

<table>
<tr><td>Interference between Grating and M0
</td><td>Interference between Grating and M1
</td><td>Interference between Grating and M2
</td><td>Interference between Grating and M3
</td></tr>
</table>

<table>
<tr><td>Interference between Grating and M4
</td><td>Interference between Grating and M5
</td><td>Interference between Grating and M6
</td></tr>
</table>

</td></tr>
</table>

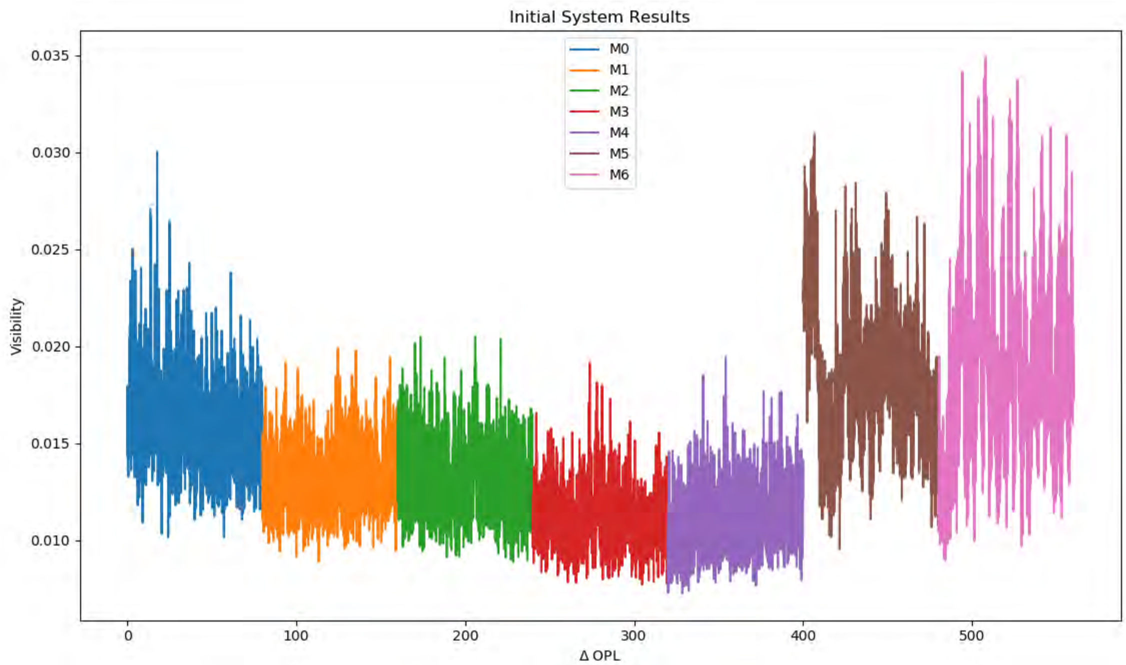
	Visibility Plot	

Table 7: Record of all lab results.

Appendix B: Visibility Processing Code

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-

"""
Created on Fri Mar 30 17:05:40 2018
@author: pellegrinoconte
"""
import PIL
import os
import numpy as np
import matplotlib.pyplot as plt
from numpy import array
from numpy import fft
from PIL import Image
from scipy import ndimage
print(os.path.realpath(__file__))
os.chdir("/Users/pellegrinoconte/Desktop/310/53")


def getv(name):
    img = PIL.Image.open(name +".png") #.convert('LA')
    arr = array(img)
    ar = arr #[:,:,0]


    v = np.empty(0, dtype = float)
    j = 0
    for each in np.transpose(ar)[::-1]:
#         j+=1
    #    print(each)

        segm = each
#         [int(i*np.shape(each)[0]/roll):int((i+1)*np.shape(each)[0]/roll)]
        altimg = np.abs(fft.fftshift(fft.fft(fft.fftshift(segm))))
#         if j == 100:
#             plt.plot(altimg)
        m1 = (np.amax(np.abs(altimg[:int((altimg.shape[0]/2 -
altimg.shape[0]/50 ))])))
        m2 = (np.amax(np.abs(altimg)))
        vis = 2*m1/m2
```

```
        v = np.append(v, vis)

    return v

fig1 = plt.figure()
ax = fig1.add_subplot(111)
ax.invert_xaxis()

nums =0
v = getv("M0")
x = np.linspace(nums, nums+80, np.shape(v)[0])
fig1 = plt.figure()
ax = fig1.add_subplot(111)

p7, = ax.plot(x, getv("M0") , label = "M0")
v = getv("M1")
nums = nums+80


x = np.linspace(nums, nums+80, np.shape(v)[0])
p1, = ax.plot(x, getv("M1") , label = "M1")
v = getv("M2")
nums = nums+80

x = np.linspace(nums, nums+80, np.shape(v)[0])

p2, = ax.plot(x, getv("M2") , label = "M2")
v = getv("M3")
nums = nums+80

x = np.linspace(nums, nums+80, np.shape(v)[0])
p3, = ax.plot(x, getv("M3" ), label = "M3")
v = getv("M4")
nums = nums+80

x = np.linspace(nums, nums+80, np.shape(v)[0])
p4, = ax.plot(x, getv("M4") , label = "M4")
v = getv("M5")
nums = nums+80

x = np.linspace(nums, nums+80, np.shape(v)[0])
p5, = ax.plot(x, getv("M5") , label = "M5")
```

```
v = getv("M6")
nums = nums+80

x = np.linspace(nums, nums+80, np.shape(v)[0])
p6, = ax.plot(x, getv("M6") , label = "M6")



ax.legend(handles=[p7, p1, p2, p3, p4, p5, p6], loc = 'best')


ax.set_xlabel("$\\Delta$ OPL")
ax.set_ylabel("Visibility")
ax.set_title("Initial System Results")
```

Appendix C: Customer Instructions

The purpose of our customer instructions manual was to provide the customer with a document that could explain how to set-up and operate the interferometer in case the system was ever in need of reassembly, as well as to clearly detail the procedure that our group followed when making the measurements provided earlier in this document. Depicted are screenshots of the manual that will be sent electronically to the customer along with the interferometer.

Coherence Length Measurement Device

Set-up and Operation Manual

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Purpose of Manual

The purpose of this manual is to assist in the future set-up and operation of the delivered interferometer and also to ensure that our team's operation procedure is documented and repeatable. These instructions are written with the understanding that the user possesses a strong optics background and therefore does not need to be provided with explicit details regarding generally known procedures.

Chapter 1: System Set-up

1.1 A Brief Note on Methodology

When assembling the interferometer, our group found the best approach to be first a "rough positioning" of the directly mounted components at their approximate position, followed by a more "precise positioning", once all optical components were placed in these mounts.

1.2 Rough Positioning of Mounting Components

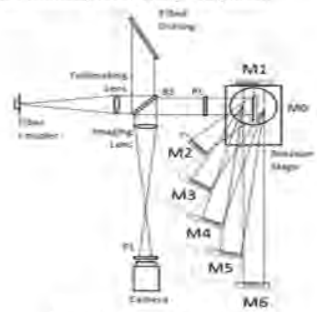

Figure 1. Complete system diagram for reference

1.2.1 Initial Optical Components

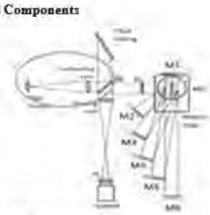

Figure 2: Circled in green are the initial optical components.

1. Fiber Coupler Mount
   a) Position and lock the post holder for the fiber coupler mount on the far left of the breadboard and approximately two-thirds from the bottom of the breadboard.

2. Collimating Lens Mount
   a) Measure **125 mm** to the right of fiber coupler mount and secure the post holder for the collimating lens.

3. Beamsplitter Mount
   a) Measure **85 mm** to the right of the collimating lens mount and secure the post holder for the beamsplitter.

1.2.2 Measurement Arm Components

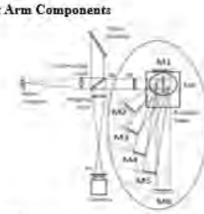

Figure 3: Circled in green are the measurement arm components.

1. Rotation Stage
   a. Take out the 20 M3 Washers and divide them into four stacks of five.
   b. Use the four stacks of M3 washers as spacers when attaching the two mounting brackets to the rotation stage.
   c. Take out the 16 M6 washers and divide them into four stacks of four.
   d. Measure **154 mm** to the right of the beamsplitter mount and place the center of the silver rotatable platform at this location.
   e. Use the four stacks of M6 washers as spacers when attaching the mounting brackets to the breadboard.

Note: It is important to orient the rotation stage such that the silver rotatable platform is towards the top of breadboard as indicated in Figure 3.

Figure 4: Circled in red is one set of five M3 washers. Circled in yellow is one set of four M6 washers.

2. Mirror 1 Mount
   a. Directly up from the rotation stage, measure **40 mm** and fix the post for M1.

Note: The knob of the M1 postholder should be very close to, but not touching the rotation stage.

3. Mirrors 2-6 Mounts
   a. Using the following table, fix the remaining mirror post holders.

Mirror	Angle Relative to Horizontal [deg]	Distance from Center of Silver Rotatable Platform [mm]
M2	30	80
M3	53	120
M4	68	160
M5	80	200
M6	90	240

Table 1: Value describing how to position mirrors 2-6

Note: For Mirrors 2, 3, and 6 be sure to place clamping forks in the direction of rotation stage, otherwise their will not be room for the detector.

4. Fixed Polarizer Mount
   a. Fix the postholder for the fixed polarizer where space permits between the beamsplitter and the rotation stage.

1.2.3 Grating Arm Component

Figure 5: Circled in green is the grating arm component.

1. Grating Mount
   a. Measure **144 mm** upward from the beam splitter and fix the post holder for the grating.

Note: Keep in mind that the grating will be at an angle. Therefore, the postholder should be shifted to the right so that the light will be incident on the tilted grating.

1.2.4 Imaging Components

Figure 6: Circled in green are the imaging components.

1. Imaging Lens Mount
   a. Approximately **58 mm** downward from the beamsplitter, secure the mount for the imaging lens.

2. Rotatable Polarizer Mount
   a. Measure **96 mm** downward from the imaging lens and secure the mount for the rotatable polarizer.

3. Detector Mount
   a. Measure **70 mm** downward from the rotatable polarizer and to the left of this point, fix the **tall (75 mm) post holder**.
   b. It is necessary to increase the height of the detector, which can be done, by place placing baseplates beneath the detector.

1.3 Precise Positioning of Components

The precise mounting of components depends upon using a light source to align the various components of the interferometer. For this alignment process our group used a fiber-coupled laser (λ=650 nm), but any visible laser source can be used.

1.3.1 Adding Optical Components to Mounts

With all components in their general position, the various optical elements can now be mounted, placed on posts, and added to the post holders. The following is a table of how elements should be mounted.

Component	Mount	Notes
Fiber Coupler	Fixed Circular 1" Diameter Mount	N/A
Collimating Lens	Fixed Circular 1" Diameter Mount	N/A
Beamsplitter	1" Rectangular Kinematic Mount	N/A
Fixed Polarizer	Fixed Circular 1" Diameter Mount	N/A
Mirror 0	1" Rectangular Kinematic Mount	Make sure that "L-Shape" of the mount is on the left side of the mirror when looking from behind. In this way, the mount will not hit anything when rotated. Be sure to use the mount that has had both knobs removed. Note that this mount is attached directly onto the silver rotatable platform.
Mirrors 1-5	1" Rectangular Kinematic Mount	Make sure that "L-Shape" of the mount is on the left side of the mirror when looking from behind. In this way, light going to the next mirror will not be clipped. For mirrors 2-5, be sure to use the mounts that have had one knob removed
Mirror 6	1" Circular Kinematic Mount	N/A
Grating	Grating Mount attached to 1" Circular Kinematic Mount	When inserting the grating, the arrow drawn on the long side of the grating should be pointing towards the beamsplitter.
Imaging Lens	Fixed Circular 1" Diameter Mount	N/A
Rotatable Polarizer	Rotatable Circular 1" Diameter Mount	N/A

Table 2: Description of how to mount all components.

Note: For the following section, when finely aligning the collimating lens and the beamsplitter, make sure that the light entering the measurement arm is centered on mirror 0. It is much easier to realign the fiber coupler, collimating lens, and beamsplitter, than to move the entire rotation stage.

1.3.2 Aligning the Collimating Lens

1. Position the collimating lens such that it is perpendicular to the light from the fiber adapter plate.
2. Use a shearing interferometer to test and improve the collimation of the light.

1.3.3 Aligning the Beamsplitter

1. Orient the beamsplitter at 45° relative to the collimated light. This angle will be known, when the light is both transmitted directly towards mirror 0 and reflected towards the grating that were roughly positioned earlier. When performing this alignment, it is best to remove the polarizers and set them aside until later.

1.3.4 Aligning the Mirrors in the Measurement Arm

1. Aligning Rotatable Mirror (M0)
   a. After aligning the collimating lens and the beamsplitter, the light should be incident on the center of M0.
   b. Make sure that M0 is in its home location perpendicular to the incoming light using the computer.
   c. Use the adjustment knobs of the M0 mirror such that light is reflected directly back into the output point of the fiber adapter plate.

Note: When adjusting M0 it is very likely that the rotation stage will be moved. Consequently, it is critical to readjust the rotation stage back to its home location when adjusting the knobs.

2. Aligning Secondary Measurement Arm Mirrors (M1-M6)
   a. Create a traditional Michelson interferometer
      i. To align M1-M6, it is best to first get an additional mirror and place it in the grating arm to create a traditional Michelson interferometer.
      ii. By leaving the rotation stage in the M0 configuration and in placing a piece of paper after the beamsplitter, the two dots created by the two arms can be seen. Align the mirror in the grating arm so that these dots overlap.

Notes: The following steps of b-d should be completed together for each mirror. To clarify, perform steps b-d for M1 and then perform steps b-d for M2, etc.

   b. Use the following table as a rough estimate for the starting rotation stage angle when beginning alignment. Then make fine adjustments to the rotation stage angle, until the entire beam is being reflected by the secondary measurement arm mirror.
   c.

Secondary Measurement Arm Mirrors	Angle relative to home position [deg]
M1	-45
M2	15
M3	26.5
M4	34
M5	40
M6	45

Table 3: Angles for initial rotation stage alignment.

   d. Make coarse adjustments to the secondary measurement arm mirror, such that all of the light reflected by this mirror, is also completely reflected by the rotating mirror.

Note: Be sure when making the coarse adjustments, that the distances between the rotating mirror and each of the secondary measurement arm mirrors remain the same as described in Table 1.

   e. Now seeing the two dots on the piece of paper after the beamsplitter, use the adjustment knobs of the secondary measurement arm mirror, to align the two dots.

Note: Since the mirror in the grating arm and M0 are already aligned, be sure not to perform any adjustments using these mirrors.

1.3.5 Aligning the Grating

1. Rotate the rotatable mirror to the M0 orientation and remove the mirror that was used in the grating arm.
2. Starting with the grating perpendicular to the light, rotate it approximately 63° clockwise, such that the arrow on the grating is pointing toward the beamsplitter and all light is hitting the grating.
3. Using a ruler, measure the distance from the center of the beamsplitter to the rotating mirror. Place the furthest part of the tilted grating at the same distance from the beamsplitter as the rotatable mirror.
4. Block the light coming from the measurement arm.
5. Make course adjustments to the grating angle by rotating the post until two bright dots can be seen hitting the paper (both of these dots are from the grating). Determine which of these dots is the brightest.
6. Uncover the light from the measurement arm and use the fine adjustment knobs of the grating mount to align the bright dot of the grating with the dot from M0.

1.3.6 Aligning the Imaging Lens

1. Position the imaging lens such that it is perpendicular to the combined beam from the two arms following the beamsplitter and focuses all the light.

1.3.7 Aligning the Polarizers

1. Reposition the polarizers, such that they are perpendicular to the beam and allow it to completely pass through.

1.3.8 Aligning the Detector

1. Align the detector such that it receives light that fills the whole detector array at some point after the focal point of the imaging lens.

1.3.9 Final Adjustment of Mirrors

1. Viewing the light from the two arms on the detector, it is possible to make a final fine adjustment of the mirrors.
2. Use the detector to view the fringe pattern on the computer and then adjust the tilt of M0-M6 to create the cleanest and most horizontal fringes as possible.

Chapter 2: System Operation

2.1 Measurement Procedure

2.1.1 Balancing the Two Arms

1. Before taking any measurements, use the rotatable polarizer to balance the light intensity from each arm.
2. This is best accomplished by incrementally adjusting the polarizer and then using a power meter to measure the power of the light until both arms have approximately the same power.

2.1.2 Capturing Images and Image Analysis

1. Image Capture
   a. Rotate the stage to the previously found angular values necessary to extended the path length and capture images at each of these locations.

2. Software analysis
   a. Once the image is collected, visibility is calculated by taking the Fourier transform of each grating line. The visibility of a fringe pattern can be determined by taking twice the amplitude of the fringe frequency and dividing it by the zero order frequency. The FFT of the system was obtained in python with the use of the numpy toolbox command FFT:

FringFft = np.abs(fft.fftshift(fft.fft(fft.fftshift(FringeArray))))

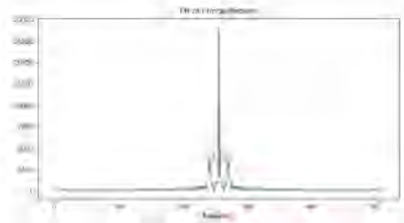

Figure 6. The fast Fourier transform of a 1-dimensional array along the line of the grating. Circled in orange is the shifted zero order frequency peak. Circled in red are the secondary peaks that correspond the fringes.

By calculating the visibility along each line of the grating and through calculating the grating line width we can plot the visibility as a function of optical path length.

3. Visibility Code

Note: To use the code attached, run the function gety(name), where name is the name of the image file. Be sure to set os to the current directory of the file.

```
import numpy as np
from numpy import fft
from PIL import Image
from scipy import ndimage
print(os.path.realpath(__file__))
os.chdir("/Users/pellegrinoconte/Desktop/310/53")

def gety(name):
  img = PIL.Image.open(name +".png") #.convert('LA')
  ar = array(img)
  v = np.empty(0, dtype = float)
  for each in np.transpose(ar)[::-1]:
  segm = each
  altimg =
  np.abs(fft.fftshift(fft.fft(fft.fftshift(segm))))
  m1 = (np.amax(np.abs(altimg[:int((altimg.shape[0]/2 -
  altimg.shape[0]/50 ))])))
  m2 = (np.amax(np.abs(altimg)))
  vis = 2*m1/m2
  v = np.append(v, vis)
  return v
```

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Appendix: Images of Assembled System for Reference

This section contains images of the interferometer from different angles that may prove useful in clarifying any questions with the system set-up.

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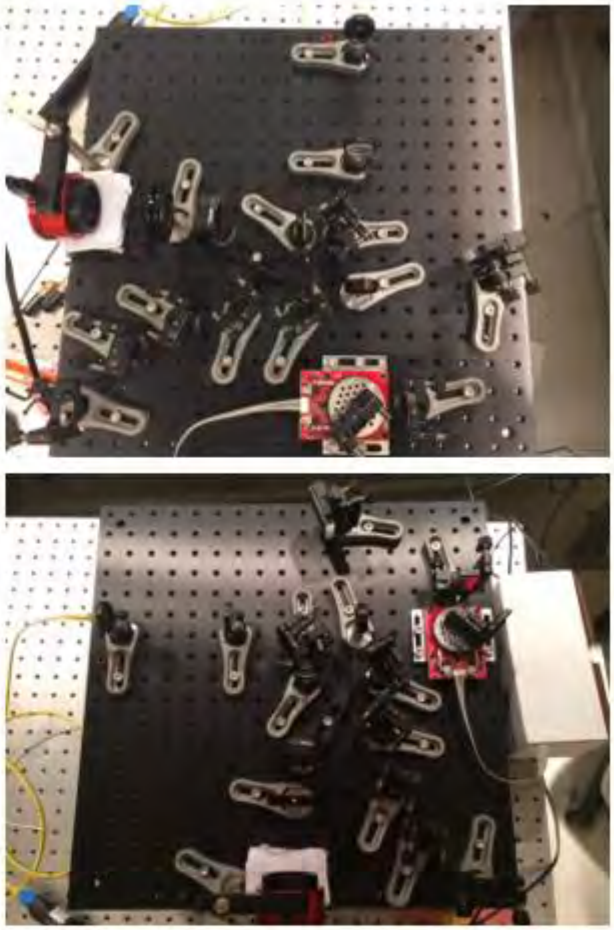

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[8] Vladimyros Devrelis, Martin O'Connor, and Jesper Munch, "Coherence length of single laser pulses as measured by CCD interferometry," Appl. Opt. 34, 5386-5389 (1995)