THE USE OF OPTICAL METROLOGY IN ACTIVE POSITIONING OF A LENS

Zheng Ji

Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

August 2014

APPROVED:

Shuping Wang, Major Professor
Elias Kougianos, Committee Member
Leticia Anaya, Committee Member
Robert Hayes, Committee Member
Enrique Barbieri, Chair of the Department of Engineering Technology
Costas Tsatsoulis, Dean of the College of Engineering
Mark Wardell, Dean of the Toulouse Graduate School

Ji, Zheng. The Use of Optical Metrology in Active Positioning of a Lens. Master of Science (Engineering Systems – Electrical Systems), August 2014, 53 pp., 4 tables, 35 figures, 41 numbered references.

Precisely positioned optical lenses are currently required for many highly repetitive mechanics and applications. Thus the need for micron-scale repetition between opto-mechanical units is evident, especially in industrial manufacturing and medical breakthroughs. In this thesis, a novel optical metrology system is proposed, designed, and built whose purpose is to precisely locate the center of a mechanical fixture and then to assemble a plano-convex optical lens into the located position of the fixture. Center location specifications up to ±3 μm decenter and ±0.001° tilting accuracy are required. Nine precisely positioned lenses and fixtures were built with eight units passing the requirements with a repetitive standard deviation of ±0.15 μm or less. The assembled units show satisfactory results.

ACKNOWLEDGEMENT

This thesis could never be done without the guidance and opportunity from Dr. Shuping Wang. I would like to express my highest appreciation to Dr. Shuping Wang for the continuous support of my degree study, research, and for her patience, motivation, enthusiasm, and immense knowledge. I could not have imagined having a better advisor and mentor for my study.

Besides my advisor, I would like to take this opportunity to express my thankfulness to the rest of my thesis committee members: Dr. Elias Kougianos, Dr. Leticia Anaya, and Dr. Robert Hayes, for their encouragement, insightful comments, and hard questions.

My sincere thanks also go to Sanmina for partially sponsoring this project, as well as their endless support in providing laboratory equipment and mechanical designs. In particular, I would like to thank Michael Gardner, director; Colleen Kimberly Davis, project manager; Mark Alt, opto-mechanical engineer; and John Yue Han, optical engineer.

I would also take this chance to thank our laboratory technician Bobby Grimes and department staff, for offering technical support to the optical laboratory. Also, I would like to thank Dr. Chi-Hao Cheng from Miami University of Oxford, in particular for enlightening me the first glance of research.

Last but not least, I would like to thank my family and all the people who continually showed their unending support. This thesis could not be completed without their contributions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

An optical lens is an optical component designed to transmit and refract light such as a laser beam. Some complex optical lenses consist of doublet or even triplet lenses being combined or molded together as one. Both basic and complex lenses could be used broadly for a variety of purposes including imaging, industrial, defense, medical, and life science applications.

Nowadays, accuracy and stability of lenses are essential in many highly precise applications, especially in industrial manufacturing and medical breakthroughs [1]. High resolution and accuracy applications have become possible due to the wide range of interferometer equipment now currently available. In order to further improve optomechanical applications for manufacturing stability, better equipment such as lenses are needed [2].

This thesis commenced from an industrial project to improve companies' manufacturing stability, which requires lens to be better positioned, in fact, centered, in a fixture, as a new and needed improvement to manufacturing processes. The accurately positioned lens will improve production systems by bringing them stabilization repeatability. In this thesis, the lens that the fixture requires, a plano-convex optical lens, is addressed as a unit lens.

In order to make possible the assembly of the unit lens, much highly precise equipment is needed for the alignment procedure. However, there is an upper limit on resolution and accuracy of applications. This upper limit is usually caused by environmental noises, errors, and degree of mechanical precision of equipment [3-5].

As a result, many applications demand even more precision and better control of environment conditions and factors [5].

To achieve even more exactitude in the positioning of a lens, this thesis aims to develop optical metrology to position a lens into a fixture, while incorporating some of the most advanced optical and mechanical technologies currently available within micrometer range. In addition, this metrology aims to precisely assemble not only the lens that are required, but also other lenses with different materials and with different optical devices. One of the main contributions of this thesis is the optical system design to perform the alignment of a unit lens. The other contribution is a method to stabilize system components.

1.1 Statement of Need

This thesis topic is a subset of a much larger effort to design an optimized industrial system. In order to improve the repeatability of the current manufacturing system, the optical application within will require optical lenses to have more rigorous specifications than their current design. This thesis develops the metrology system, which precisely positions a unit lens onto the center of a fixture.

The objective of the industrial project of this thesis is to design the optical metrology system to (a) locate the center of the fixture and align its axis to the optical-axis of the optical system and (b) accurately position the unit lens onto the center of the fixture. The following alignment specifications must be met:

1) The apex of the unit lens should be located at the center of the fixture with an error of less than ± 3 μm.

2) The plano surface of the unit lens should be perpendicular to the optical axis with an error of less than ± 0.001° (± 3.6 Arc-second).

1.2 Existing Methods and Studies Conducted

Since the given specification is very strict in regards to centering, to the position of the angle tip and the tilt of the unit lens, achieving precision measurement is challenging. Decentering of ± 3 μm is impossible for the naked human eye to detect. In order to confirm that the demanded specification can be attained, the study of existing methods, techniques, and technologies is conducted, while maintains position stability and repeatability of unit lens placement within the fixture as the main requirement.

Previous works mainly use mechanical systems as a solution. However, most mechanical systems do not meet the ± 3 μm decenter accuracy requirement; decentering is caused during the cutting and molding process of lens making, resulting in lenses having slightly different diameters from each other. Figure 1.1 shows two lenses of different shapes and, therefore, different diameters located at the same station. When these elliptical, not round, lenses are positioned in the fixture, and here positioned means situated utmost into the corner against the x and y apex, their centers are changed with respect to which direction the lenses are placed. Owing to shape and diameter difference, these lenses do not share the same center point.

This pure mechanical solution, in present use, of cornering the lens, shows unreliable position repeatability of lenses which results in a deviation of the output center point. Thus, it is crucial to have both position and angle references during the assembly process of the unit lens and fixture. Methods to include both references are studied through previous works, and optical methods resulted as being the most appropriate.

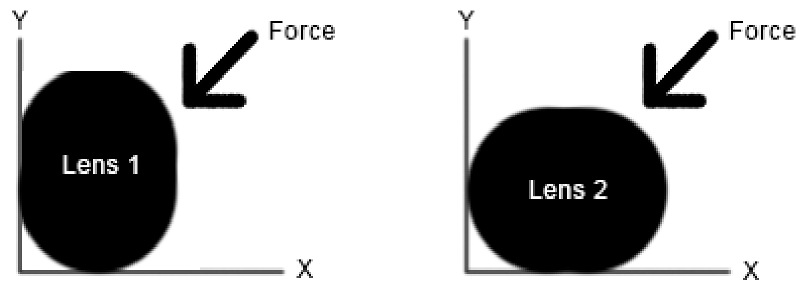


Figure 1.1 Example of mechanical solution error due to lens shape and diameter

Optical methods are commonly used to measure angle perpendicularity of a surface [6-10]. Perpendicularity is essential as a manufacturing requirement to ensure inerrant operation. Lens needs to be perpendicular during the process of inserting into the fixture for it to be perpendicular during its manufacturing use. As shown in Figure 1.2, the surface angle could be detected by comparing perpendicular vs. non-perpendicular alignment from the original laser beam with the reflected laser beam reflected off the plano side of the lens. In this thesis, since the surface happens to be the plano side of the unit lens, by obtaining the sent and received positions of the light emittance, the perpendicularity of the unit lens can be ascertained from formula 1.

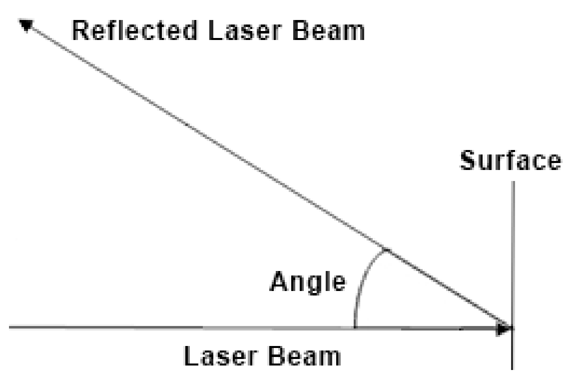


Figure 1.2 Surface perpendicularity detected through reflected laser beam

$$\theta = \tan^{-1}\left(\frac{\text{Distance From Laser Source to Surface}}{\text{Distance Between Original and Reflected Laser Beam at Laser Source}}\right) \quad (1)$$

Optical methods can also detect any decenter of the unit lens as shown in Figure 1.3. The theory is to send the laser beam through the unit lens, with the center of the unit lens to be aligned with the arriving incidence, or exact axis, of laser beam. The laser beam's resulting position should be the same as its starting position. On the other hand, if the resulting position is not on the axis of the laser beam, the beam has struck a decenter of the unit lens. In this thesis, the axis of the laser beam is addressed as the optical axis.

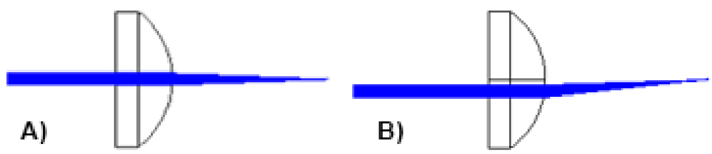


Figure 1.3 A) Unit lens is centered at optical axis and B) unit lens is decentered from optical axis

Optical metrology proves to be a reliable method. To measure both decentrality and perpendicularity between unit lens and the optical axis. However, mechanical methods are still required for assembly and repositioning of the unit lens. Thus optical and mechanical devices are required to build a qualified optical metrology system for the application.

1.3 Scope of Work

The scope of the thesis work focuses on both designs of the optical system and optical lenses to aid in this optical metrology. Several steps were taken in the development of this thesis and they are:

- Evaluated several mechanical and optical theories

- Procured and subsequently evaluated laboratory equipment for further experiments
- Assembled concept metrology system to evaluate it
- Verified the performance of the metrology system
- verified of build units and its results

Key point that assisted in the optical metrology system and its design, but is not covered within this thesis:

- Designed custom hardware that was used within the experiments
- Experimented with results for position sensitive device, since the specifications have noted that it does not meet system requirements
- Experimented with angle tip and tilt results because of the current technology and device accuracy have already satisfied the specification required

1.4 Content of Thesis

The chapters that follow are classified as:

- Device Overview and Challenges – In this chapter, introduction of optical systems and devices are presented along with their specifications. A list of potential challenges and errors for optical systems and experiments are also classified to include both environmental and mechanical errors
- Optical Metrology Design – This chapter contains an overview of the optical system and design, which is the main contribution of this thesis. It is then followed by an introduction of the design and simulation software used and then by the simulated result, to confirm the required specification of the system and devices
- Results and Analysis – Several experiment results are presented for device comparison, system setup, and the assembly of the unit lens. The experiment results are also analyzed in this chapter to validate both optical system reliability and built unit

performance. The validated build unit results are evaluated to determine if needed specifications for the build unit are met

- Conclusion and Future Work – The work results are summarized in this chapter. This includes evaluating the system as a whole and addressing matters found in optical metrology design and experiments

CHAPTER 2

DEVICE OVERVIEW AND CHALLENGES

From existing literature research it was determined to design an optical metrology system to position unit lens into fixture. This chapter describes an overview of available devices and technologies required for the system, and discuss potential challenges that might happen.

2.1 Optical Source

According to studies from previous chapter, laser source and beam have a crucial use in optical metrology systems, they could be used to help detect decentrality and perpendicularity of unit lens to the optical axis. The optical source is a required main component for the system.

Laser sources are ideal for high precision optical alignment. Laser beam pointing stability is critical for many practical applications, such as interferometry, laser material processing, and the application proposed in this proposal [11-14]. Ideally the laser source shoots out a straight laser beam as depicted in Figure 2.1A. However, the reality is that laser source is not as stable as the ideal case. Instead laser pointing occurs randomly within a specific angle as depicted in Figure 2.1B [15-21].

Many laser sources and types are available on market, including gas lasers, chemical lasers, dye lasers, metal-vapor lasers, solid-state lasers, semiconductor lasers, etc [22]. However, due to budget reasons, only a few laser sources that are already available were considered and studied within this section, then used to determine a suitable laser source for the optical metrology system.

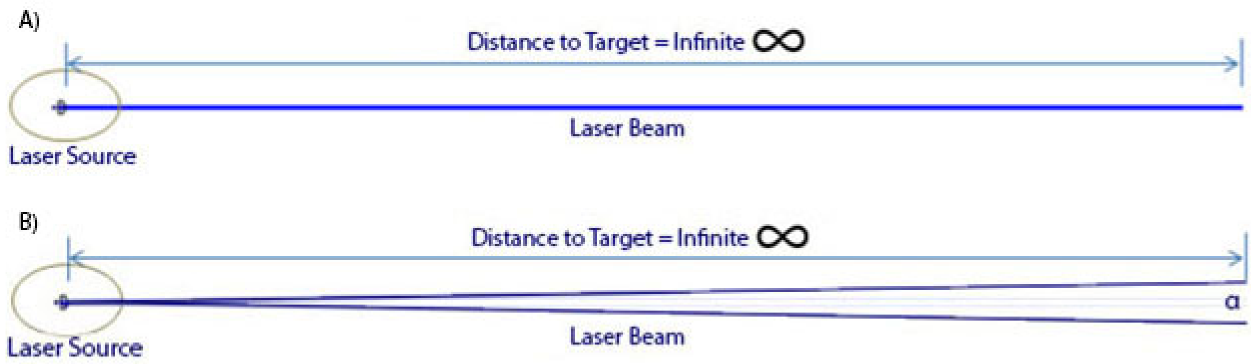


Figure 2.1 Laser pointing angle. A) ideal case with zero pointing angle and B) actual case with a pointing angle of α

2.1.1 Helium Neon Laser

Several helium neon (HeNe) lasers are already available in the optics and photonics laboratory. They were studied to confirm their specifications and reliability to determine if they should be included within the optical metrology application.

HeNe lasers are commonly used for industrial and scientific purposes due to their relatively low cost and ease of operation [22]. They are compared to other visible lasers producing beams of similar quality in terms of single mode Gaussian beam and long coherence length. HeNe lasers are also reliable and contain useful performance characteristics while having a broad range of laser output wavelength ranging from green through infrared as shown in Table 2.1. They can support a wide range of application purposes. Furthermore, they also have a relatively steady pointing stability and low output noise compared to other laser types.

Out of all the wavelengths given, the red color at 632.8 nm is the most popular and familiar wavelength of HeNe lasers. It is used mainly because of its high power and fast scanning abilities for testing and measuring applications that benefit from increased signal to noise performance. With its power range, it is also ideal for calibration, precision measurement, pointing, and alignment within applications.

Wavelength (nm)	Color
543.5 nm	Green
593.9 nm	Yellow
611.8 nm	Orange
632.8 nm	Red
1152.3 nm	Near Infra-Red
1523.1 nm	Near Infra-Red
3391.3 nm	Mid Infra-Red

Table 2.1 Wavelength and color of laser beam [22]

A HeNe laser is listed as a type of gas laser, which consists of a mixture of helium and neon gas within a glass tube, as shown in Figure 2.2. The laser energy is provided by an electrical discharge of several hundred volts between the anode and the cathode at each end of the tube. A specific range of current will also be required for a HeNe laser to have a continuous waveform output laser.

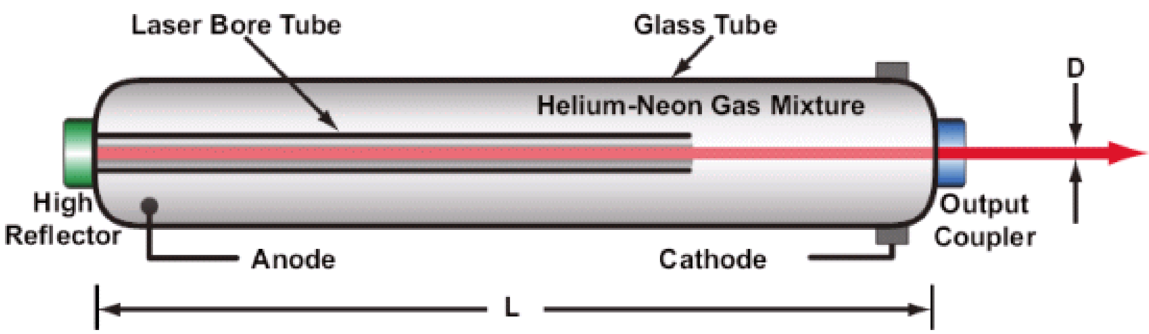


Figure 2.2 Theory of HeNe laser [23]

The used HeNe laser model is Thorlabs HRP 050 which is depicted in Figure 2.3. The HeNe laser system contains the HeNe laser and the power supply with an interlock circuit to be integrated with lab safety systems [24]. The actual setup is depicted in Figure 2.3, which is stabilized with three stabilizing rods to reduce environmental errors such as vibration.

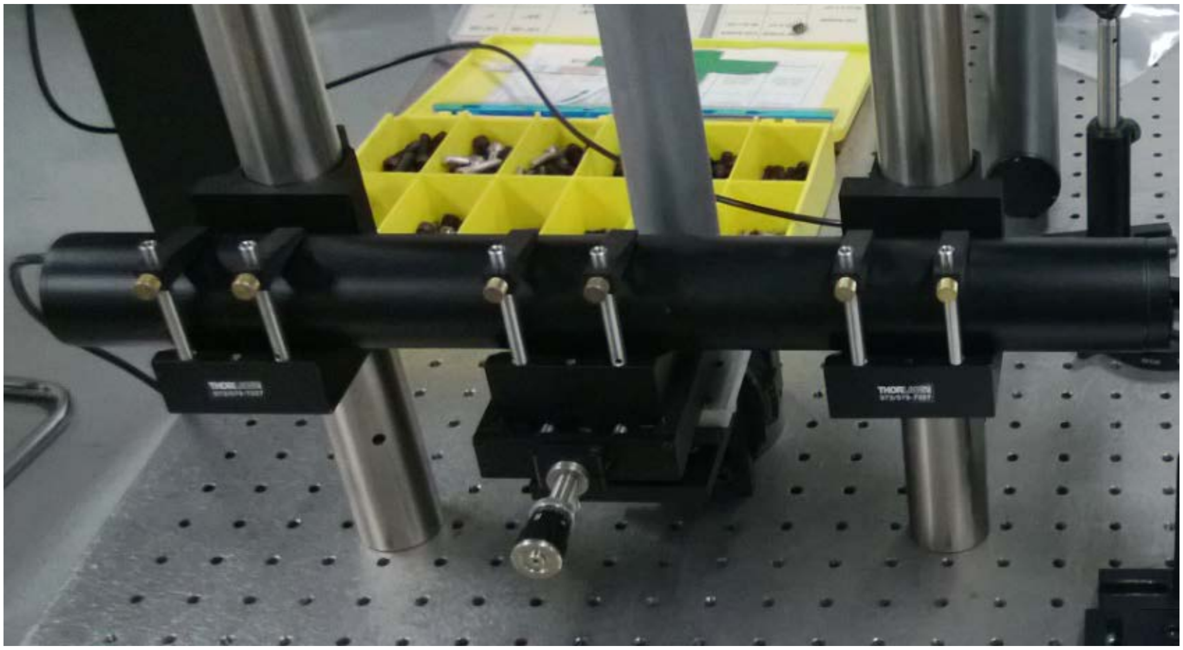


Figure 2.3 Thorlabs HRP 050 in actual laboratory setup

Most important specifications of the HeNe laser are listed in Table 2.2. From specification sheet, the Thorlabs HRP050 HeNe laser has 0.25 millimeters drift at 3 meters distance (0.0048°) and shows a lower angle pointing compared to typical lasers. Usually stabilized pointing has a performance of 0.2 mrad (0.012°) angle drifting at short period and a 0.05 mrad (0.003°) angle drifting at longer period [25-27].

Specification	Value
Wavelength	633 nm
Maximum Output Power	10.0 mW @ 633 nm
Minimum Output Power	5.0 mW
1/e2 Beam Diameter	0.80 mm
Beam Divergence	1.01 mrad
Beam Drift After 30 Minute Warm-Up	<0.20 mrad
Long Term Beam Drift	<0.05 mrad
Operating Voltage	2400 VDC
Operating Current	5.25 mA

Table 2.2 Specification sheet of Thorlabs HeNe laser HRP 050 [24]

2.1.2 Laser Diode Comparison to HeNe

Another laser source at the optical laboratory is a laser diode, which is included in the auto collimator device depicted in Figure 2.4. The laser diode within is an electrically pumped semiconductor laser, which is formed by a p-n junction.

Laser diode is also one of the most common types of laser produced since it has a broad variety of uses. These uses include fiber optic communications, barcode readers, laser pointers, laser printing, scanning, and etc. Thus, from the perspective of its low cost and commonness of the laser diode, it is considered as one of the laser source candidates.

Laser diode modules are usually smaller, more efficient, and more versatile comparing to most HeNe lasers. Because of their compactness and low power requirements, laser diodes have been used in many applications. However, these advantages are not required in this optical metrology.

On the other hand, HeNe lasers offers exceptional reliability and optical quality comparing to laser diodes, mainly because HeNe laser's output is well collimated. A well collimated output and stabilized position output is exactly the requirement for this optical metrology. Also, while comparing HeNe and laser diode pointing angles, the laser diode angle drift is more complex. The typical angle drifting for laser diode is 0.05mrad/°C to 0.2mrad/°C (0.003°/°C to 0.012°/°C) [26].

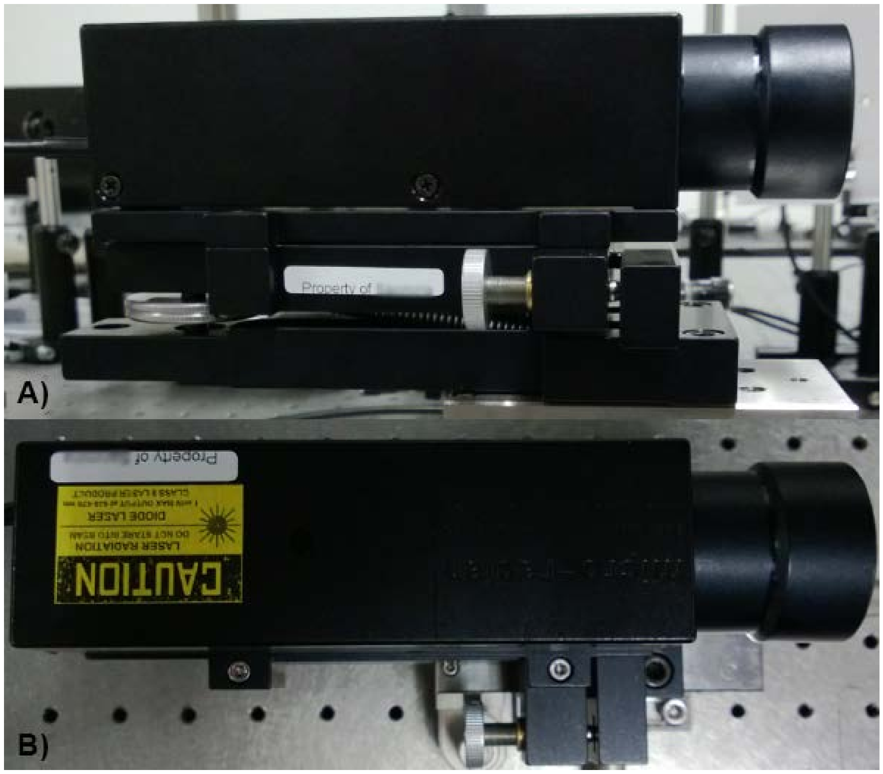


Figure 2.4 A) Side view of auto collimator and B) top view of auto collimator

2.2 Detector

A laser beam detector is required in order to detect a laser beam's position. Various position detectors are available but simulation results are needed to seek an appropriate detector. However, concerns still exist, especially on the sensitivity of detector to detect changes from unit lens decentering or tip and tilting. [28-34]

The other concern is the stability of the detector as shown in the previous experiment. Figure 2.5 shows results from different detectors and their results, and it is clear that the detectors are sensitive to temperature change [28, 35-36]. Thus if temperature caused drifting is more evident than actual laser beam position change, the detector is considered unreliable.

Three types of laser detectors had been included in Figure 2.5. In this section a position sensitive device/detector (PSD) and a laser beam profiler are compared.

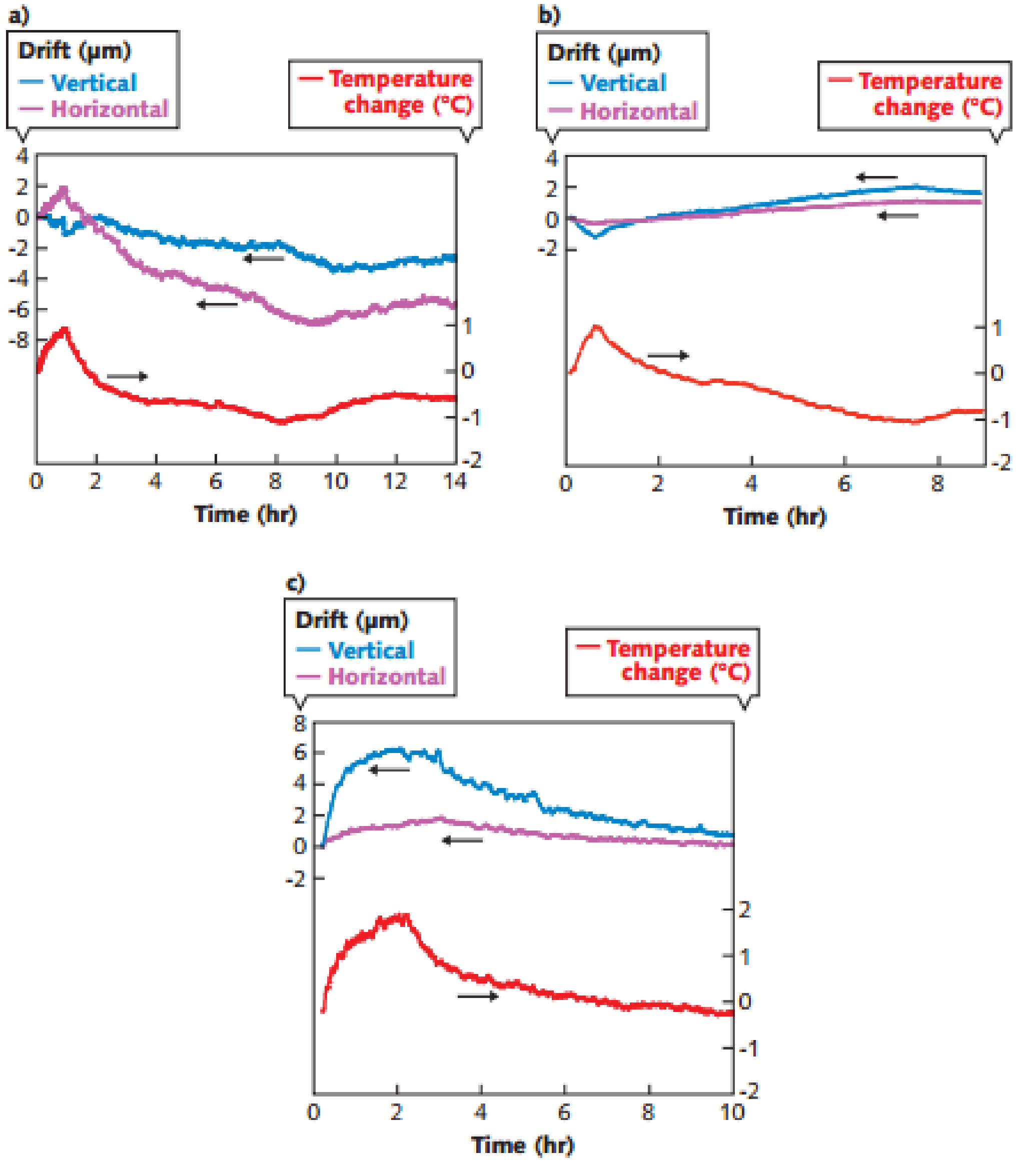


Figure 2.5 Measured beam drift using different detectors A) position sensitive detector B) quad cell C) camera [28]

2.2.1 Position Sensitive Detector

A PSD is an optical sensor to measure light spot position and returns a two dimensional (X and Y) reading of its position. The working theory of a PSD is to have many smaller sensors within, then the averaged position value of all the smaller sensors being hit by laser source is returned as depicted in Figure 2.6. In this case, the position reliability will also depend on the density of these smaller sensors, meaning if the distance between them is ± 10 μm then a ± 5 μm position, change will not be detected.

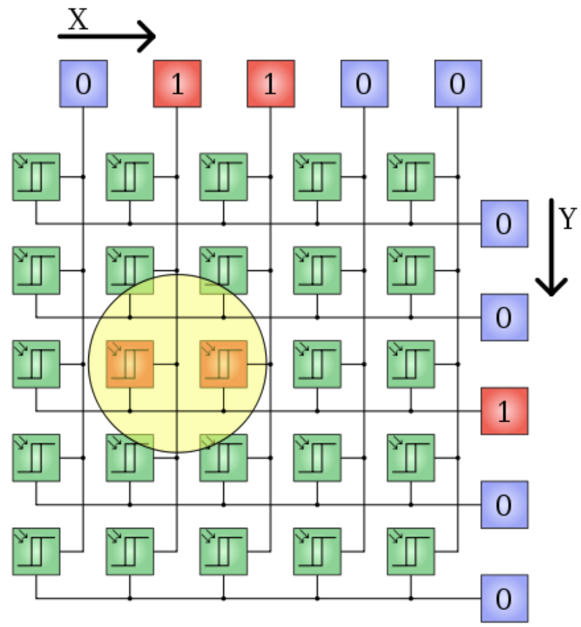


Figure 2.6 Schematic of a discrete PSD to show its working theory [37]

The actual experiment setup is shown in Figure 2.7. However, the experiment result will not be shown as the specification does not meet enough requirements. The speculated reason for this is that the distances between the smaller sensors exceeded the required distance.

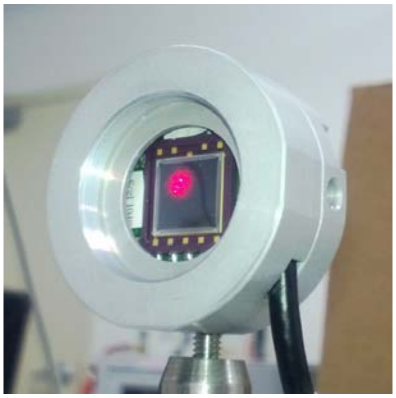


Figure 2.7 Actual PSD and laser beam

2.2.2 Scanning Slit Baser Beam Profiler

Another type of detector is Scanning Slit based Beam Profiler, which is addressed as the beam profiler. The beam profiler cannot handle every power level, pulse duration, repetition rate, wavelength, and beam size available since there are many types of lasers. However, the beam profiler has many more functions such as capturing and displaying the profile of a laser beam.

The working theory of the scanning slit based beam profiler is to analyze the laser beam that is going into the profiler. Then by using two slits in front of a linear photo detector, find the beam's current to generate the beam profile such as the one depicted in Figure 2.8. A digital encoder is used to detect the position the beam is hitting at. This device shows a 5.3nm – 18.3μm spatial sampling resolution in its specification [32]. Due to large variation between given values, preliminary works are required to confirm its accuracy.

The actual experimental beam profiler experimented is Ophir Nano Scan beam profiler, which is depicted in Figure 2.9. Since the claimed specification has met the required sensitivity, the beam profiler is used in the experiment, and the experimental results are shown in later chapter.

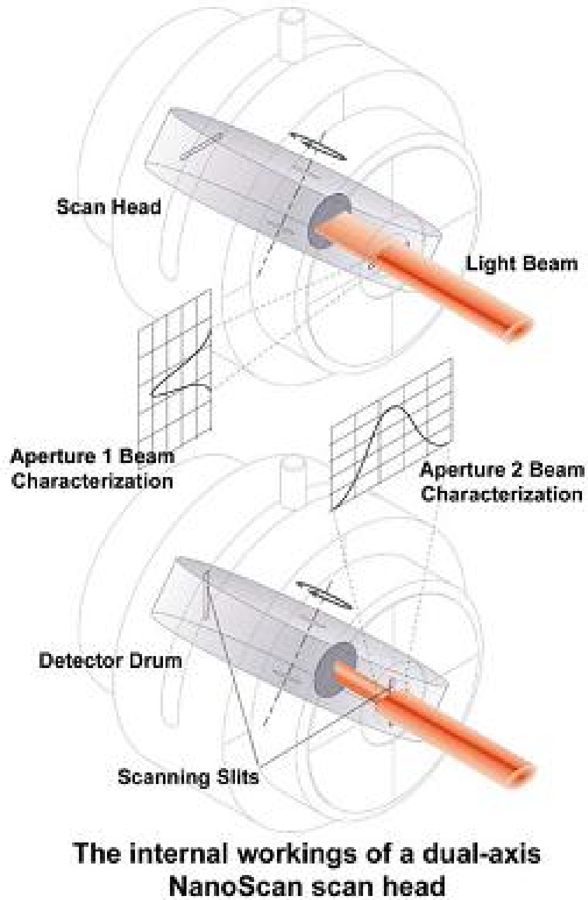


Figure 2.8 Working theory of scanning slit beam profiler [32]

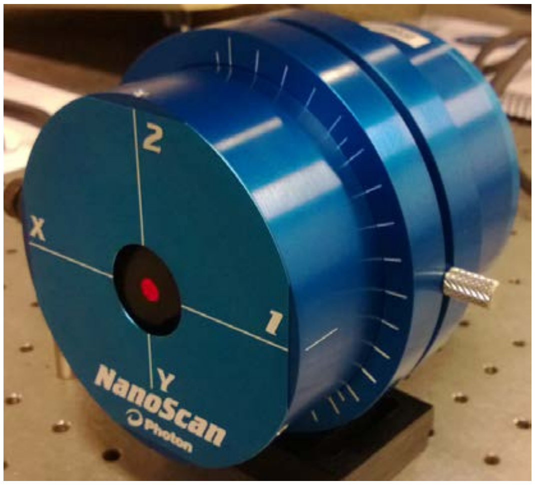


Figure 2.9 Ophir nano scan beam profiler

2.3 Auto Collimator

Auto collimator is an optical device for non-contact measurement of angles, which is previously depicted in Figure 2.4. Auto collimator is required because it is crucial to detect the angle tip and tilt of the unit lens. The theory of autocollimator is to project a beam image onto the unit lens and reads the reflected beam image. It returns a calculated angle change, as depicted in Figure 2.10. In this application, the autocollimator is used to align the unit lens by measuring the reflection returned.

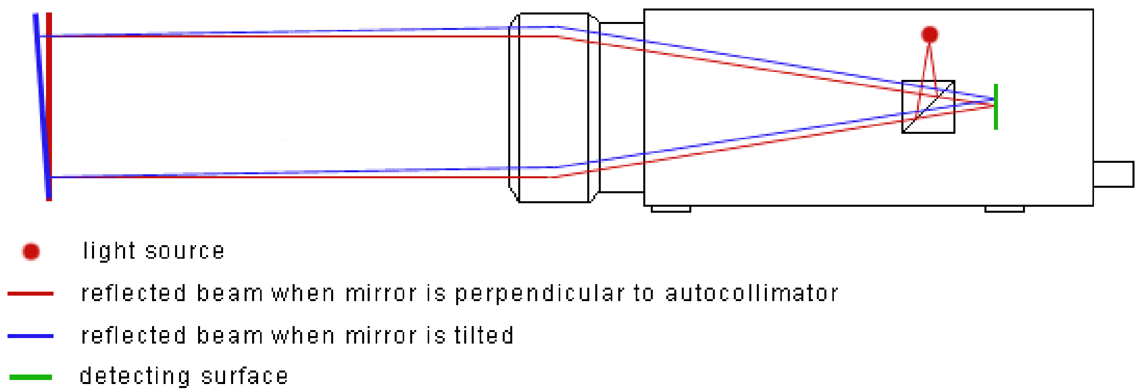


Figure 2.10 Auto collimator theory [37]

Autocollimators, in general, are very accurate, and electronic autocollimators can read up to 0.1 arc second (0.000028°) changes. This accuracy is sufficient for this optical metrology and specific application. As noted previously, the experimental angular results will not be shown in this thesis because of the maturity and accurateness of the technology [37].

2.4 Automated Translation Stage

An automated translation stage is a precise motion system to help move an object in a single axis of motion. A motorized translation stage Aerotech ALS 130 is used for the purpose of this thesis. The system has a resolution of 10nm and repeatability of 100nm, which satisfies the required performance of this thesis. Figure 2.11 depicts the experimental setup of the translation stage, which includes a motorized translation stage lying over another translation stage. Thus results in possible movement of both X and Z positions within the optical metrology system.

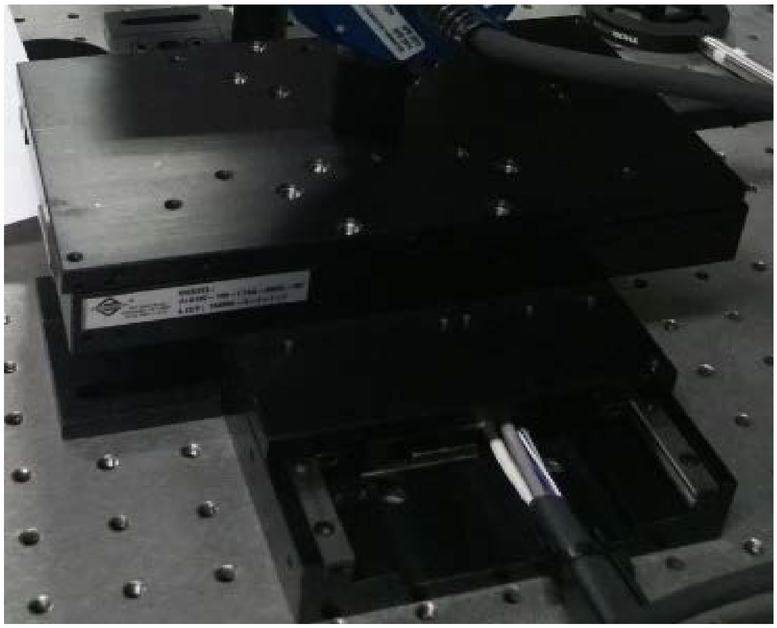


Figure 2.11 Setup of two automated translation stage for both X and Z axis

CHAPTER 3

OPTICAL METROLOGY DESIGN

The optical metrology is divided into several parts to be designed, with the main focus of having a stabilized system in order to position and assemble the unit lens into the required fixture. In this chapter, brief explanations are provided for the optical system design, for the optical software simulations and for results used to determine tolerance values. The optical metrology system overview is shown after simulations have provided reasonable values.

3.1 Optical System Design

The optical design process includes a myriad of tasks that needed to be performed and considered in the process of optimizing the performance of the optical system. Other than primary key points such as robustness of the optimization algorithm and reduction of aberrations, several other factors will also be considered:

- All first-order parameters and specifications such as magnification, focal length, full field of view, spectral band, relative weightings, and others.
- To assure the optical performance is to be met, including image quality, distortion, vignetting, and others.
- To assure packaging and other physical requirements, including the thermal environment, is being taken into account.
- Assure that the design is manufacturable at a reasonable cost based on a fabrication, assembly, and alignment tolerance analysis and performance budget error.
- Consider all possible problems such as polarization effects, including birefringence, coating feasibility, ghost images and stray light, and any other possible problems.

As the key factors have been examined, another lens component is added within the optical system. The reasoning is because the unit lens's tip and tilt angle of ± 0.01°

can be detected using an autocollimator. However, to detect a ± 3 μm decentering of the unit lens from the optical axis is a challenge.

The light is focused at the focal plane of the unit lens and is defocused and diverged after passing through the focal plane as depicted in Figure 3.1. If the beam profiler is placed near the unit lens's focal plane, the accuracy of the beam profiler is not substantial enough to measure a change of ± 3 μm directly. The defocusing of the light keeps the position of the lens fixed as the increased beam spot size can exceed the aperture size of the beam profiler, and cause position measurement to be inaccurate. To overcome the difficulty of measuring decentrality of the unit lens up to the micron level, an optical lens component, addressed as multiplier lens, is designed using optical simulation and design software - Zemax.

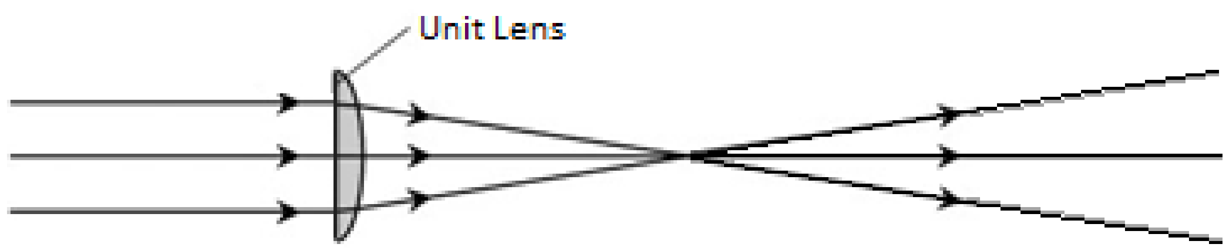


Figure 3.1 Beam source continuously diverging after going through unit lens

3.2 Zemax Software

Zemax is one of the industry's standard optical system design software packages. It works by modeling the propagation of rays, called ray tracing, through an optical system that consists of such optical elements as simple lenses, aspheric lenses, mirrors, and diffractive optical elements. Zemax produces standard analysis diagrams such as spot diagrams and ray-fan plots to help users better understand the system and further optimize the designs. It also has the capability of tolerance analysis of the effect of manufacturing defects and assembly errors. Zemax also allows for the importing/exporting of mechanical CAD drawings of the lenses to make the fabrication of lenses convenient.

In this thesis, the Zemax software is used in two important factors. The first factor is to design the lens component (multiplier lens) to solve the beam divergence problem. The second important use is to simulate the beam trend through each device and optical component. With Zemax's ray tracing function, it is possible to simulate the laser beam trend, profile, and position outcome.

3.2.1 Multiplier Lens Design

Since a laser beam shoots through the unit lens, the laser beam is focused and then diverges after it goes through the unit lens. The laser beam shooting through the unit lens is continuously diverging as function of distance, which is to be avoided, as divergence will cause beam aperture to exceed beam detector aperture at a specific distance. Thus, a multiplier lens is necessary to collimate the laser beam back as depicted in Figure 3.2 and to allow the detector to detect the same beam as was shot originally through the laser source. The multiplier lens also aids the system by further drifting (magnifying) the beam if decentering occurs, and thus allows easier detection of errors.

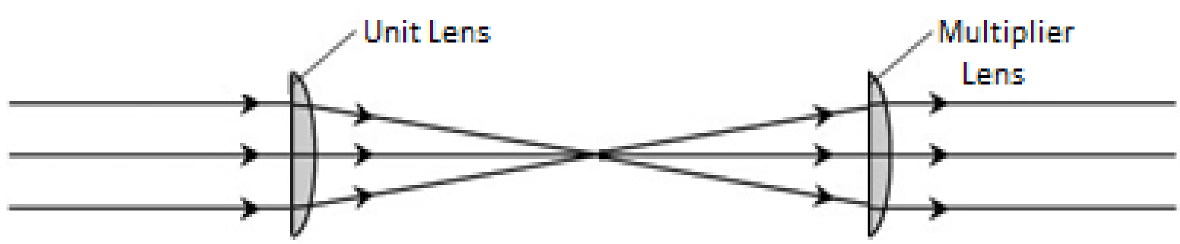


Figure 3.2 Beam source is being collimated

A plano-aspheric lens is designed as the multiplier lens. Its purpose is to (1) re-collimate the light that passes through the unit lens and to (2) magnify the amount of the decentering caused by the unit lens which helps improve the measurement accuracy at the beam profiler position. For example, a 1 µm decenter for unit lens may have result in 100 µm position change at detector position. The exact multiplying value requires simulation to be known, as it depends on both the multiplying lens and alignment conditions such as distance. The plano surface of the multiplier lens also serves as a reference plate for the system when conducting perpendicularity alignment. Thus, the plano surface must face the light source direction.

3.2.2 Optical System Tolerance Analysis

A Zemax [39] simulation representation of the optical system is depicted in Figure 3.3. The collimating light is used as light source for the simulation. The simulation is setup under the condition of 250 mm distance between the laser source and the unit lens and then 250 mm distance between the multiplier lens and the beam profiler (not shown). There is also a distance of 18.64 mm between the two lenses called the focal length. Two length is crucial as it will have great impact on the quality of the re-collimated laser beam.

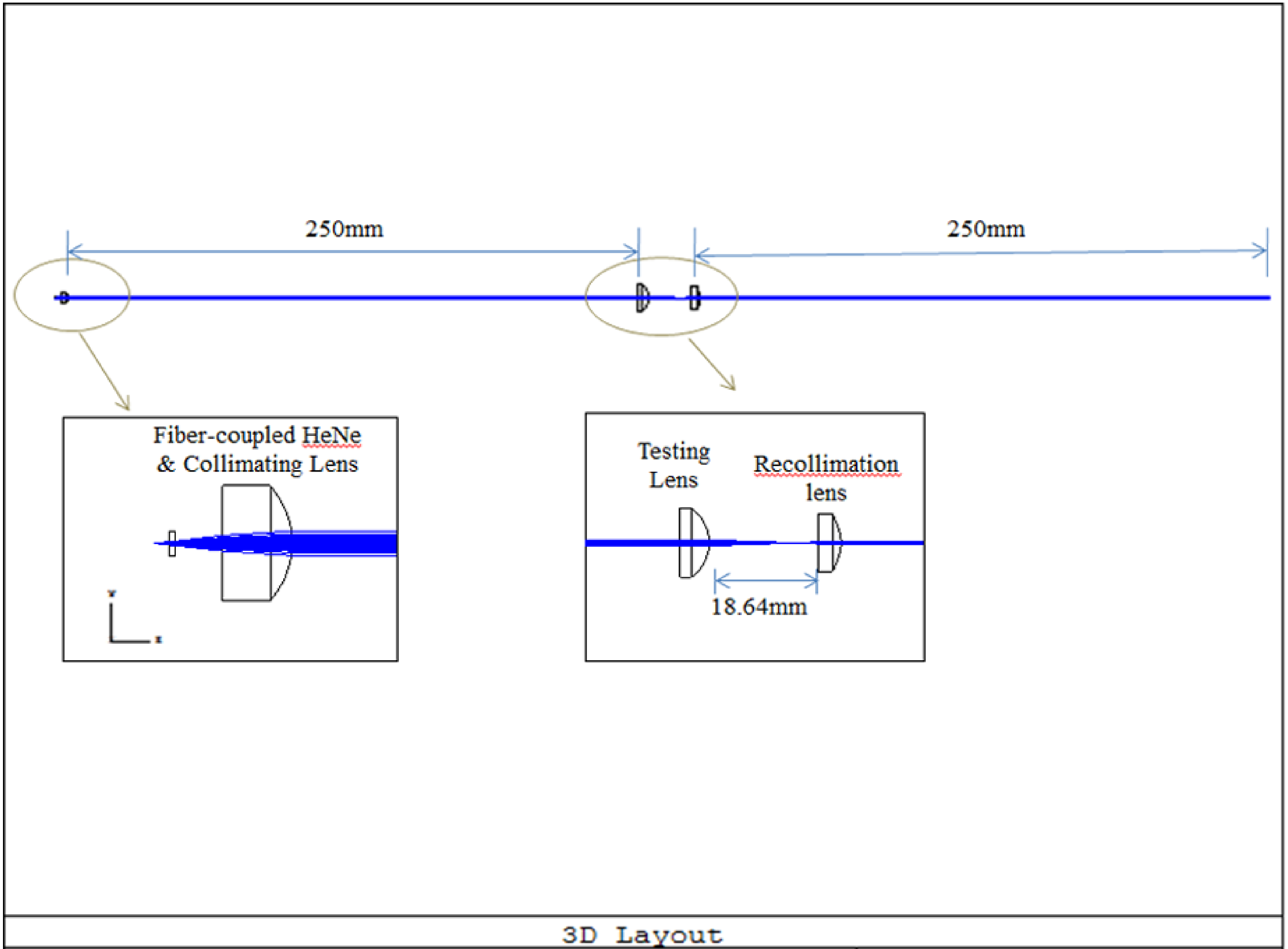
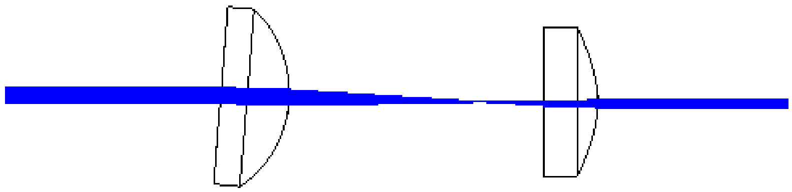


Figure 3.3 The optical system used to align the unit lens.

The first simulation is based on the angle tip and tilt and decenter of unit lens. Figure 3.4 depicts the simulation setup and the associated results to show the system sensitivity when (a) the unit lens is tilted, (b) the unit lens is decentered, and (c) the unit lens is tilted and decentered. The simulation results indicate that in order to detect a ± 0.5 µm decentering of the unit lens apex from the optical axis, an optical detector that is capable of detecting a position change of ± 18.0 µm is necessary. Since the position change has a linear relationship with the original laser position, to detect a ± 2.5 µm position change, a beam detector with sensitivity of at least 90 µm is required.

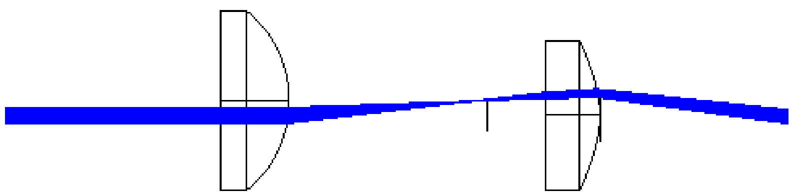
The second simulation is based on the angle tip/tilt and decenter of multiplier lens. Figure 3.5 depicts the simulation result to show how the multiplier lens affects the system alignment when (a) the multiplier lens is tilted and (b) the multiplier lens is decentered. The simulation result indicates the importance of position and angle tip-n-tilting between unit lens and multiplier lens. A ± 0.5 µm decenter at multiplier lens will cause ± 19 µm of position change at beam profiler. A ± 2.5 µm multiplier lens decenter will cause ± 47.5 µm position offset at beam profiler. To ensure the position and angle between are fixed, precise mechanical fixtures are required to keep the optical components and devices precisions.

Unit Lens Tilted	
Tilt (°)	Beam Profiler Position Shift (μm)
0.01	**1.0**



(a)

Unit Lens Decentered	
Decenter (μm)	Beam Profiler Position Shift (μm)
0.1	**3.6**
1.0	**36.0**



(b)

Unit Lens Tilted+Decentered		
Unit Lens Tilt (°)	Unit Lens Decenter (μm)	Beam Profiler Position Shift (μm)
0.01	0.1	**4.6**
0.01	1.0	**37.1**

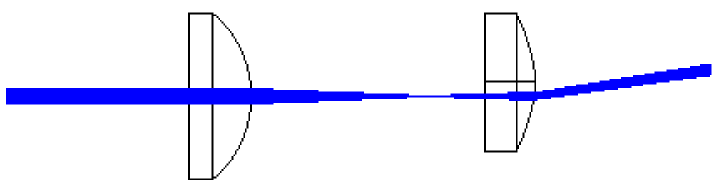
(c)

Figure 3.4 Simulation results to show the system sensitivity when (a) the unit lens is tilted, (b) the unit lens is decentered, and (c) the unit lens is tilted and decentered.

Recollimation Lens Tilt (°)	Beam Profiler Position Shift (μm)
0.001	**1.4**
0.01	**13.9**

(a)

Recollimation Lens Decenter (μm)	Beam Profiler Position Shift (μm)
0.1	**3.8**
1.0	**37.5**



(b)

Figure 3.5 Simulation results to show how the multiplier lens affects the system alignment when (a) the multiplier lens is tilted and (b) the multiplier lens is decentered.

The third simulation is based on the angle of the incoming laser beam. Figure 3.6 depicts the simulation result to show the system sensitivity to an angle of the incident light. The simulation results indicate that in order to have within ±9.2 μm reading at beam detector, a laser source within 0.001° pointing angle is required to be used.

Light Incident Angle (°)	Beam Profiler Position Shift (μm)
0.0001	**0.9**
0.001	**9.2**

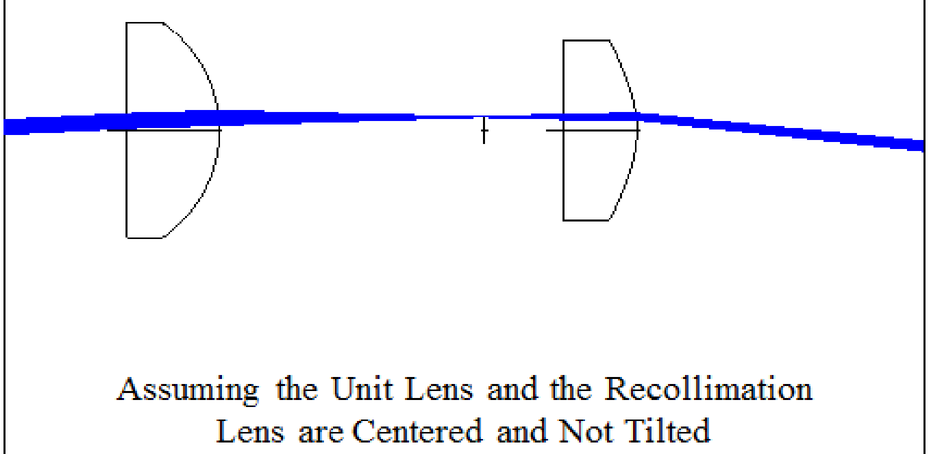


Figure 3.6 Simulation result to demonstrate system sensitivity to angle of the incident light

From simulation results above, the specification for optical source and beam detector has been confirmed. Angular pointing of optical source should be within 0.001° over time to ensure beam detector reading does not exceed 9.2 µm, which is the maximum value allowed by 0.25 µm decentering of unit lens. As explained previously, HeNe lasers have about 0.012° angular pointing and about 0.003° angular pointing for longer periods.

Although the angular pointing is not sufficient for this application, a fiber coupling cable can be used to couple the HeNe system in order to stabilize the laser beam outcome [40-41]. The outcome of the fiber coupled laser beam from HeNe is considered as a new optical source, which is a contribution of this thesis. Fiber coupled HeNe laser source is as depicted from Figure 3.7. However, any type of improvement cannot be proven until an examination is carried out of the findings in the next chapter, which presents the experimental results.

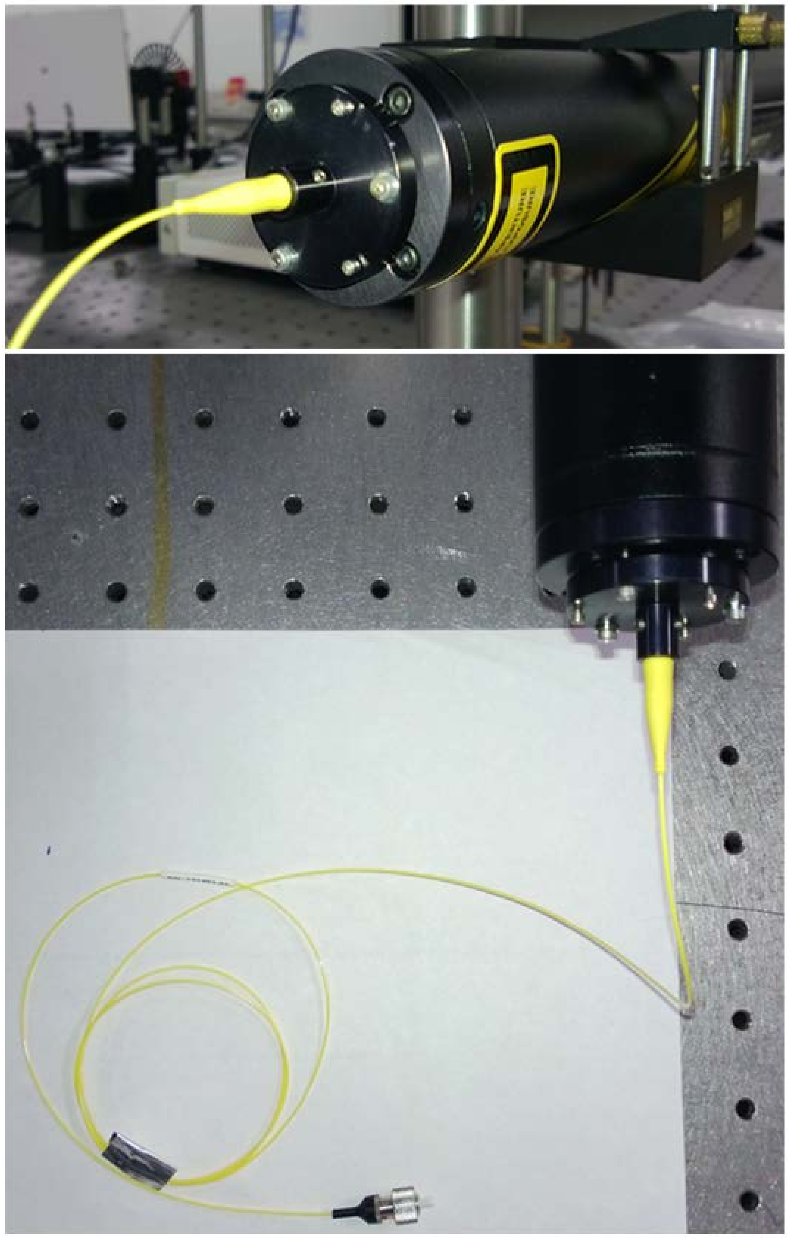


Figure 3.7 Fiber coupled HeNe laser source

Beam profiler should have sensitivity of at least 4 µm to ensure a reading of 0.1 µm decentering of the unit lens. Scanning slit beam profiler is expected to have 5.3nm – 18.3µm spatial sampling resolution. Thus, this beam profiler should be sufficient as a detector for this application. However, further experiments are required to test its sensitivity.

3.3 Optical System Overview

The optical metrology that has been designed for this project is a passive positioning design due to project cost restrictions. Because of the strict limits of the passive positioning technique, as well as the proven requirement in the optical simulation from optical system tolerance analysis section, specific mechanical and optical devices are critically needed to detect position accuracy.

With necessary components determined previously, a few metrology systems and setups were designed and evaluated. Those include:

- Single source, dual axis in which the optical beam is split such that the beams track each other.
- Single source in which the autocollimator was used as the reflective source for tip/tilt alignment and measurement as well as the through put source for X Y alignment and measurement.
- Dual source approach in which both sources were fixed and mirrors were used to bend the HeNe laser into the optical path.
- Dual source approach in which the HeNe was fixed and the autocollimator was put on a linear motorized stage.

However, because of the complex design, the complicated alignment procedure, and the high requirements to include even more devices and components, the metrology systems above will not be considered. An easier metrology system approach is designed and simulated.

The final alignment system is designed as depicted in Figure 3.8. The alignment system (Figure 3.8) is one of the main contributions of this thesis. The main characteristics of the metrology system are to:

- Use auto collimator to measure unit lens plano-surface tip and tilt to reference placed on a linear motorized stage.

- Use laser beam to provide reference vector to a detector for X Y measurement.

- Use a multiplying lens to increase the resolution of the system.

The step by step working theory of the metrology system is to:

- Align both laser source and auto collimator to target the optical axis

- Confirm that the motorized translation stage could allow the movement of the auto collimator, to enter or leave the optical axis freely.

- Confirm that beam profiler also detects both laser beams at the end of system and shows showing the same position (optical axis)

- Insert unit lens and confirm, that the beam profile center and direction is within the optical axis.

- Insert multiplier lens and confirm the resulting beam position of both laser source and auto collimator are on beam profiler.

- Theoretically, when perfect angle perpendicularity and no position change are happening at the beam detector, then the system is well aligned.

Each device and optical component of this metrology system is to be experimented in the next chapter to test its reliability and prove its specification. Then the actual build result of unit lens and its fixture, and its results.

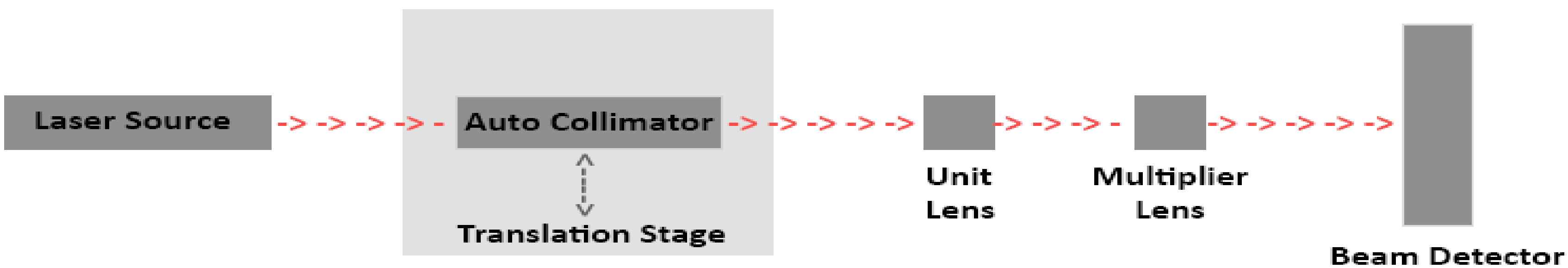


Figure 3.8 Block diagram of the optical metrology system

CHAPTER 4

RESULTS

In this chapter, each component is experimented to test their reliability and specifications, then to improve their performance if necessary. With each device and optical component, the optical system will then be aligned and tested. Unit lens are built into the mechanical fixtures and both provided by the same company. In the end of this chapter, a repeatability test will also be conducted to prove the build repetition and result.

4.1 Device Reliability

Fiber coupled HeNe (coupled HeNe) laser and scanning slit beam profiler (beam profiler) are the optical devices chosen from the simulation specification. The angular pointing and sensitivity of these devices are to be experimented on in order to determine their reliability. The targeted stability and sensitivity are not to exceed from the specification of the Zemax simulation. To ensure comparable results, most experiments are conducted under the same circumstances that include timing interval and distance of device setup.

4.1.1 Detector Sensibility Test Results

To verify the detection sensitivity to the lowest distance of the beam profiler, the detector is mounted onto a motorized translation stage as depicted in Figure 4.1. HeNe laser is impinged into the beam profiler that is shifted by 2 µm distance intervals. Angular pointing is excluded due to the proximal distance (15cm) between HeNe and detector.

Figure 4.2 depicts the detection of position changes measured by the beam profiler. Experiment result shows the trend of 2 µm movements which is as expected. From the experiment result it is safe to confirm that the detector has a sensitivity of at least 2 µm which is satisfactory for this application. Experiments with 0.5 µm and 1 µm distance intervals shifting were also been performed but results were unsatisfactory due to unclear gaps between shift intervals.

Figure 4.1 Detector sensitivity experiment setup

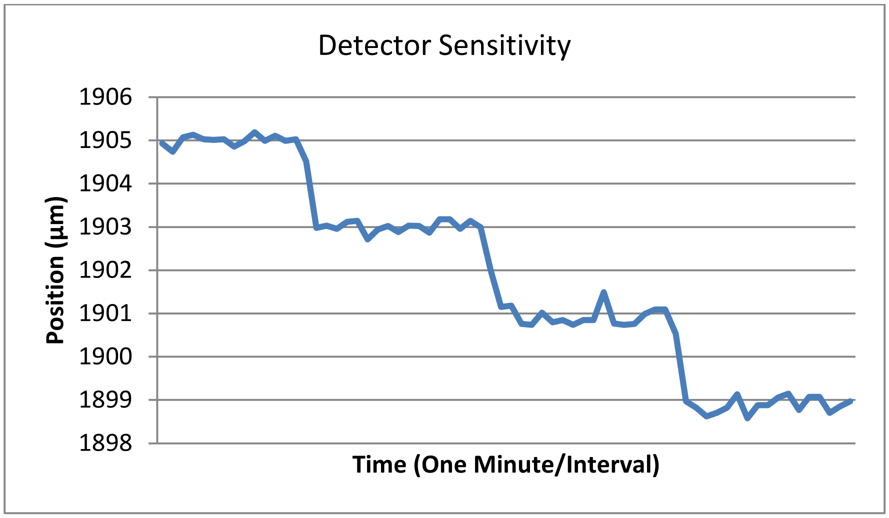


Figure 4.2 Beam profiler sensitivity test result showing 2 µm moving intervals

4.1.2 HeNe Stability Test Results

As the reference for stable positioning, a HeNe laser source was experimented to detect laser source pointing stability. Many experiments were conducted, and one of the results which is depicted in Figure 4.3 was for the setup under the condition of a one-meter distance between HeNe and beam profiler, and a length of ten hours. The ideal outcome was to have stability with less than 0.001° pointing angle.

Figure 4.3 HeNe stability experiment setup

Figure 4.4 depicts about a 180 µm position drift trend with no sign of stabilizing. A pointing angle of 0.103° occurred from the fluctuation of position drifting. The instability exceeded the ideal pointing angle, and it can be verified that HeNe laser source was unreliable and insufficient to be used as a positioning reference.

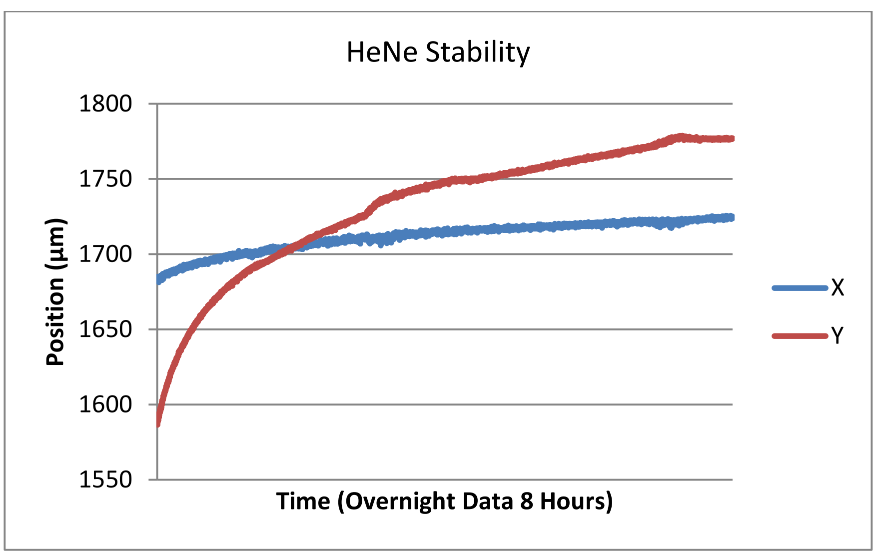


Figure 4.4 HeNe stability experiment result with 0.103° pointing angle

4.1.3 Fiber Coupled HeNe Stability Test Results

As the HeNe laser source was determined to be unreliable, a new laser source with better stability was required. Coupled HeNe is a method that contributed to the stabilization of the current laser source and reduced its pointing angle. This experiment is conducted at a one-meter distance between coupled HeNe and beam profiler for about ten hours as depicted in Figure 4.5.

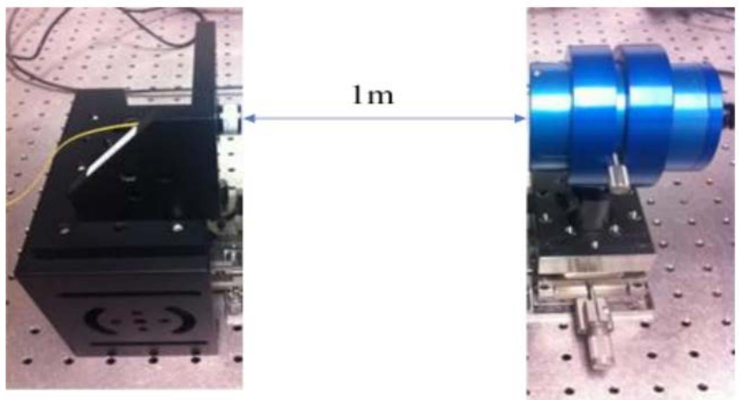


Figure 4.5 Coupled HeNe experiment setup

This experiment is to verify the stability of coupled HeNe laser and then to compare this stability to a non-coupled HeNe's position stability. Figure 4.6 depicts the stability of coupled HeNe which shows 20 µm drifting (0.001° pointing angle) for the whole period, and has about 10 µm drifting (0.0006° pointing angle) in the long-term condition, once stabilized.

For result comparison, it is clearly visible that coupled HeNe has less pointing angle than HeNe. Even though targeted pointing angle which is less than 0.001° has already been reached, further research are taken into consideration to continually improve the system stability. In order to further improve the stability, the cause of drifting needs to be studied. Temperature change is one of the concerns as explained in the challenges section.

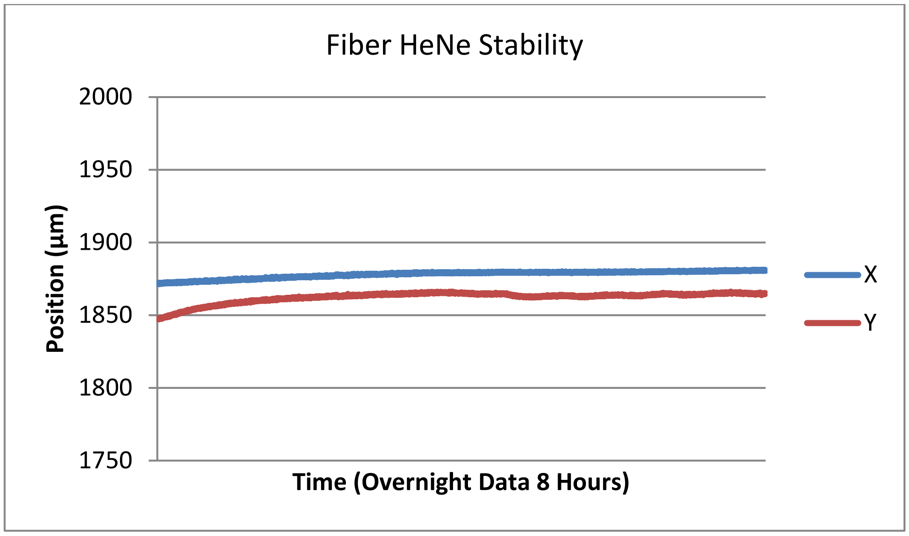


Figure 4.6 Fiber coupled HeNe stability result with 0.001° pointing angle

4.1.4 Stability Temperature Dependence

To confirm if temperature is the cause to drifting problems, coupled HeNe is experimented again under the same condition. Here, the experiment is conducted at one meter distance between coupled HeNe and beam profiler for about ten hours with a temperature logging device.

The result is expected, Figure 4.7A depicts the X and Y position drift while Figure 4.7B depicts temperature change over time. From the experimented result, it can be confirmed that there is a relationship between position drifting and temperature change. However, it is unknown if the position drift is caused by coupled HeNe or beam profiler.

4.1.5 Cause Identification

The purpose of setup is to identify coupled HeNe drifting at a shorter distance is to identify if coupled HeNe or beam profiler had contributed more to the position drifting above. An experiment is conducted by positioning coupled HeNe and beam profiler at one centimeter distance as depicted in Figure 4.8. If coupled HeNe drifting is the cause for position drifting, then position drifting at beam profiler should be reduced when the distance between them is reduced. On the other hand, if beam profiler is the cause for position drifting, then position drifting result should remain regardless of distance between coupled HeNe and beam profiler.

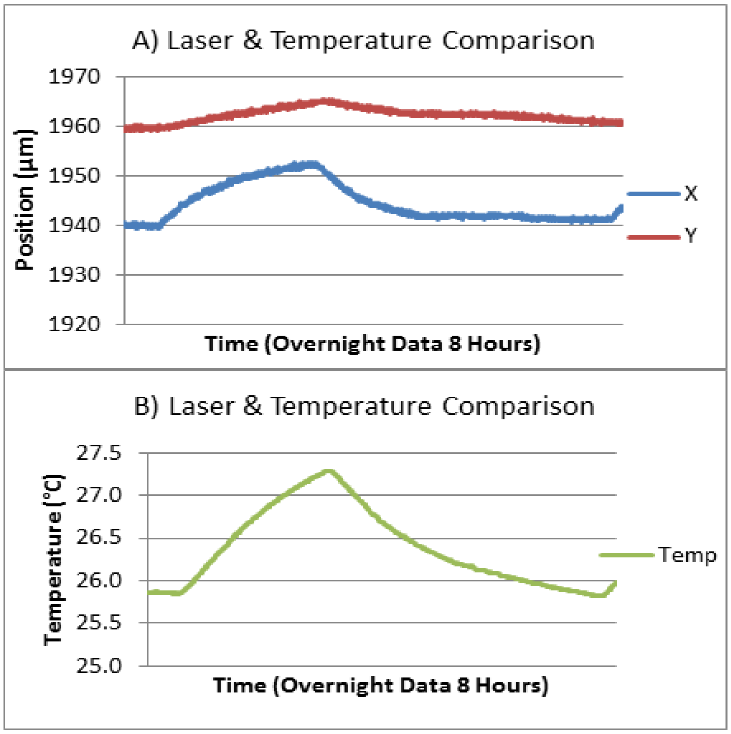


Figure 4.7 A) Position drifting and B) temperature change

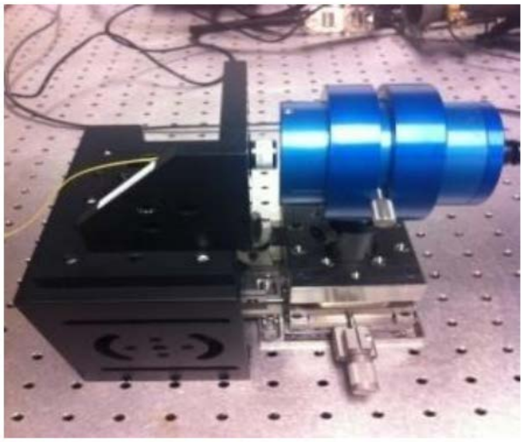


Figure 4.8 Cause identification experiment setup

The experimented result depicted in Figure 4.9A shows a stabilized outcome with less than 1.5 µm position drifting that is nearly independent from temperature as depicted in Figure 4.9B. From explanation above and experiment result, it is safe to speculate that coupled HeNe pointing angle is the reason for position drifting at beam profiler.

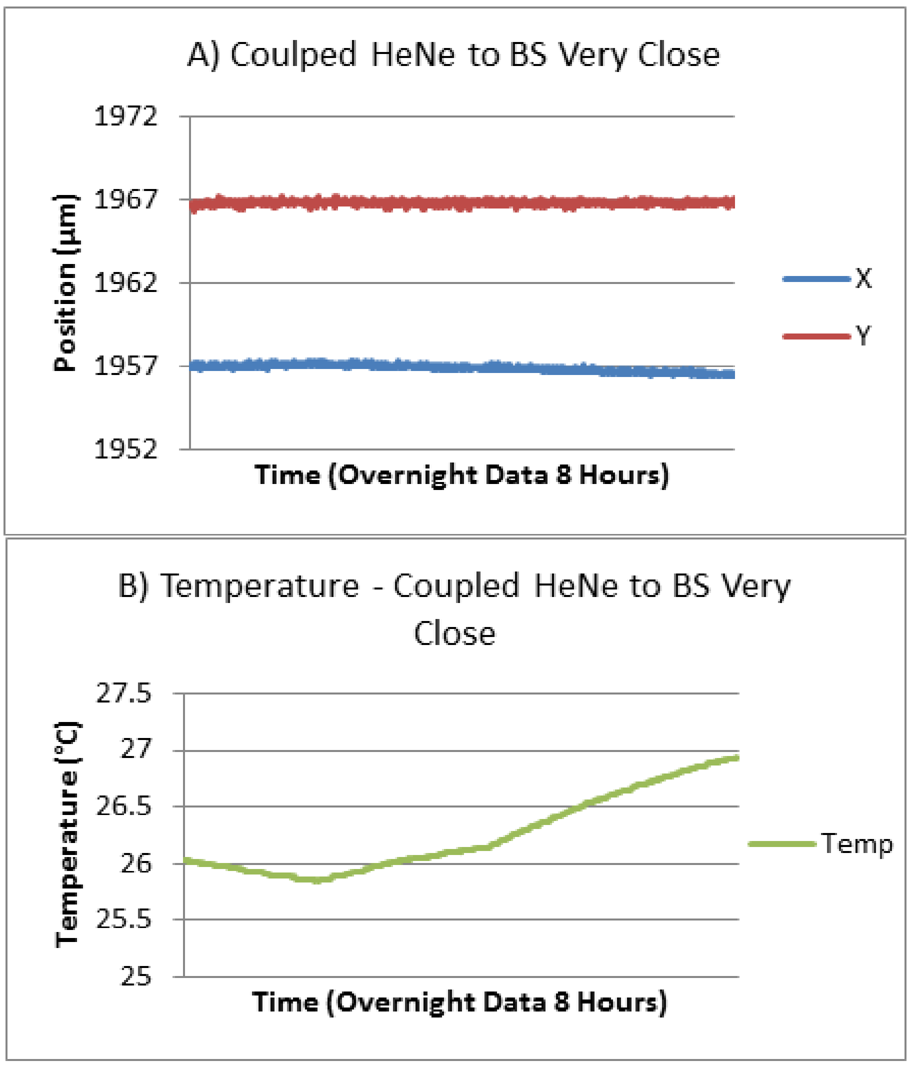


Figure 4.9 A) Position drifting B) temperature change

4.1.6 Isolated Coupled HeNe

In order to further stabilize coupled HeNe source, improvement is required to solve the cause of angle drifting, which is temperature. One practical method is to control the temperature of coupled HeNe. However, the result is unsatisfactory due to low but rapid temperature changes (0.1°C/10 minutes). The method adopted is to build an insulation box as depicted in Figure 4.10 to possibly isolate coupled HeNe from the room temperature. Although coupled HeNe is impossible to be completely isolated from temperature change, it can provide low and slow temperature variation of 0.1°C in 1 to 2 hours depending on room temperature or 0.4°C in 10 hours.

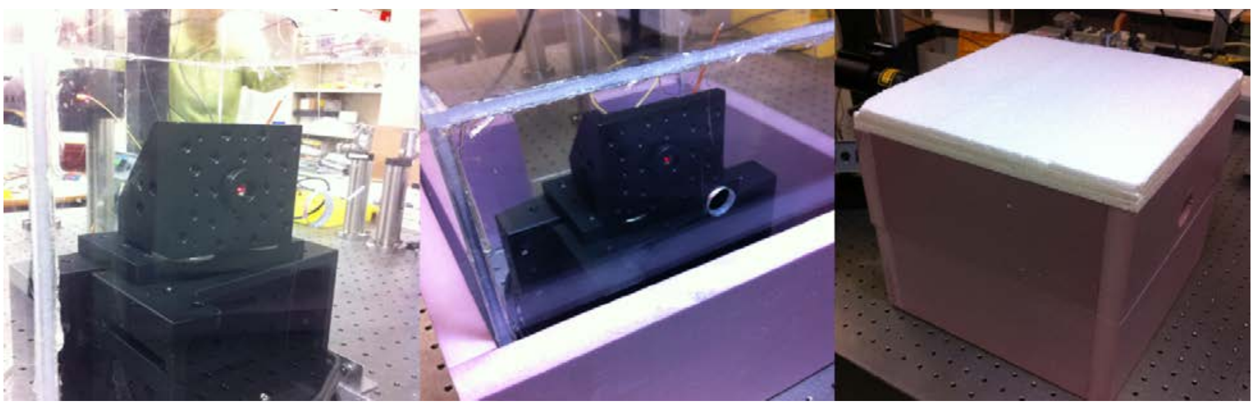


Figure 4.10 Isolated coupled HeNe laser source by building an insulation box

The experiment purpose is to conduct pointing angle testing for coupled HeNe covered in isolated box (isolated coupled HeNe). The experiment is conducted for ten hours with the distance of isolated coupled HeNe and beam profiler being one meter. This is the same condition as HeNe Stability and Fiber Coupled HeNe Stability tests.

The stability result depicted in Figure 4.11A has ±2 μm peak to peak with ±1 μm position drifting at one meter distance, which is equivalent to 0.00012° pointing angle. The pointing angle is satisfactory for this specific application, as it is only 1/10 of the targeted pointing angle, and it causes only 0.9 μm beam detector shift when unit lens and multiplier lens are centered and not tilted. By comparison of Figure 4.11A and Figure 4.11B, the pointing angle result is almost independent from temperature.

The device specification for this specific application requires 0.001° pointing angle for laser source, and 4 µm sensitivity for beam detector. Preliminary results had proven the performance of isolated coupled HeNe to have 0.00012° pointing angle, and beam profiler to have a sensitivity of 2 µm. The result shows satisfactory specification for both laser source and beam detector.

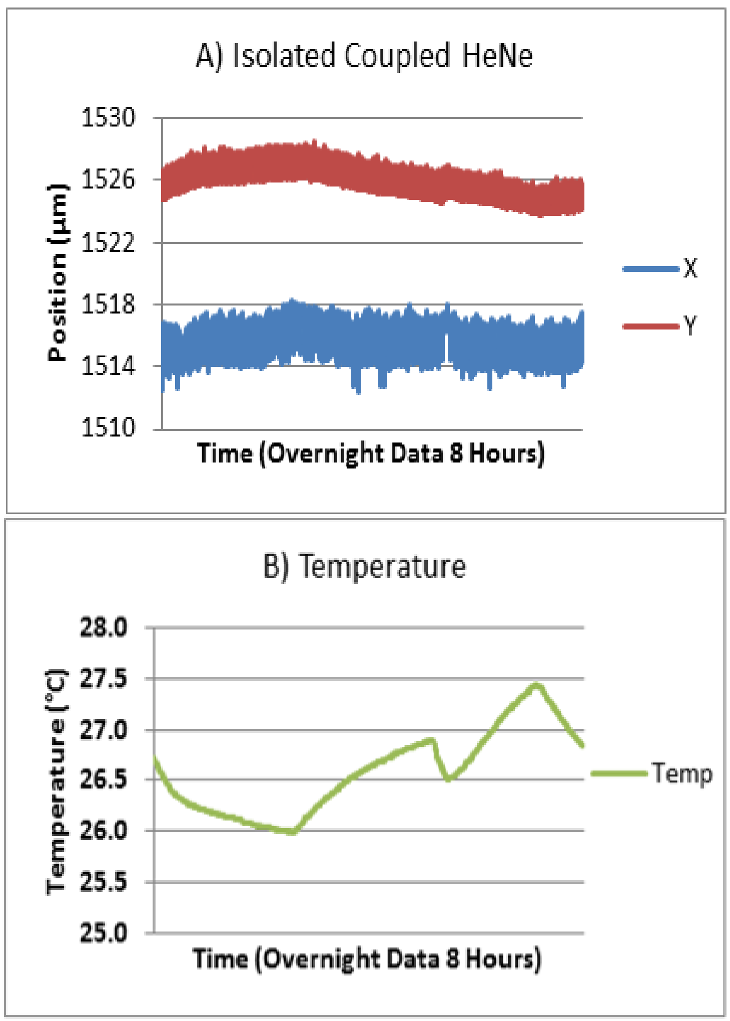


Figure 4.11 A) Isolated coupled HeNe pointing angle B) temperature change

4.2 System Test

With all of the devices proven that they each have enough performance, the optical metrology is aligned with all the necessary mechanical devices and optical components, and then tested for system stability. The experiment is to prove that the system is stabilized enough for the assembly process of unit lens.

Figure 4.12 depicts the system stability by showing both the X and Y position as function of temperature. The beam profiler detects a peak to peak position from the center of 40 μm, with normal temperature change in the room, and a stabilized temperature control of coupled HeNe laser. However, 40 μm is not the actual stability performance of the system, as the multiplier lens has magnified the instability by about 80 μm. Thus, the actual system stability is to divide the gained value by the magnified value, which yields 0.5 μm or ± 0.25 μm stability.

Since the required specification of the optical metrology system requires a decenter of less than ± 3 μm, a verified stability of ± 0.25 μm system is sufficient to continue the assembly process of unit lens and fixture. The units that are assembled in this step are addressed as build units.

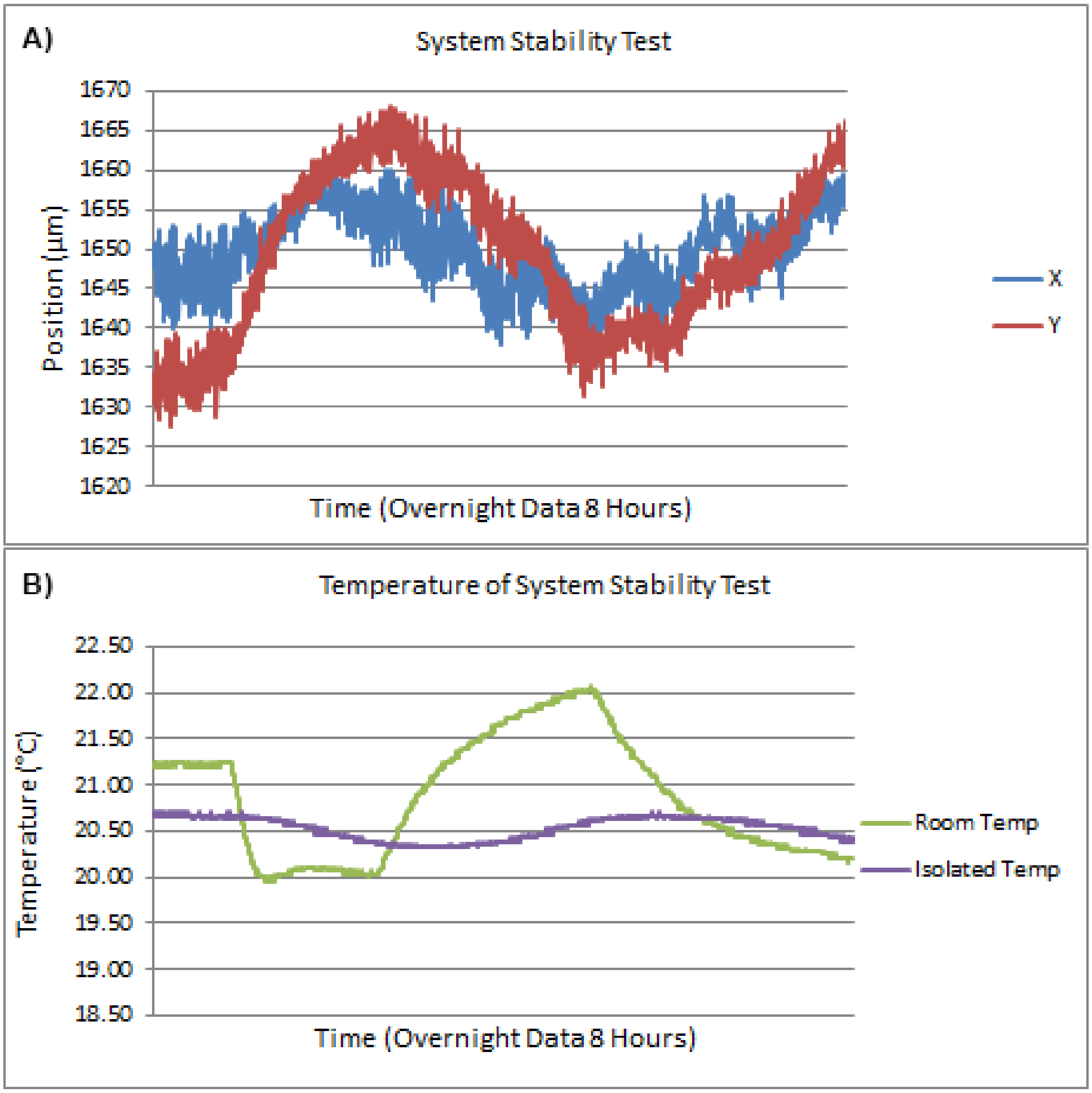


Figure 4.12 A) System stability showing both X and Y positions detected at beam profiler B) temperature change of room and isolated coupled HeNe temperature

4.3 Build Result

The optical devices and components are improved through multiple experiments, and the optical metrology system has reached satisfactory stability performance. The system has been used to assemble nine build units, with one golden unit used as a position reference.

The resulting position results are recorded for each build unit, and it is repositioned for five consecutive times to ensure the resulting repeatability. Table 4.1 shows the normalized value of each consecutive time the build unit is repositioned, which is compared to the result of golden unit and recorded as the actual off position instead of magnified off position.

A standard deviation value is also calculated within table 4.1 to show the repeatability of the build units being prepositioned. The value shows good repeatability with maximum value of 0.15 µm and a minimum of 0.01 µm. Repeatability experiment has proven most build units will not exceed 0.05 µm error for each repetitions.

Since values from table 4.1 shows results with each of them having mostly consistent repeatability, the average X and Y values are obtained for each build unit to calculate the distance off from center (golden unit position). The distance value is calculated from formula 2, which is the distance formula between two points with two coordinates (X and Y), and the center as zero value.

$$Distance = \sqrt{X^2 + Y^2} \qquad (2)$$

Unit 1		Unit 2		Unit 3	
Temp = 21.9 °C		Temp = 21.8 °C		Temp = 21.8 °C	
X	Y	X	Y	X	Y
0.44 µm	1.83 µm	2.01 µm	0.25 µm	0.63 µm	2.99 µm
0.38 µm	1.84 µm	2.05 µm	0.24 µm	0.55 µm	2.94 µm
0.33 µm	1.84 µm	2.03 µm	0.25 µm	0.58 µm	3.00 µm
0.38 µm	1.81 µm	1.99 µm	0.26 µm	0.65 µm	3.00 µm
0.15 µm	1.46 µm	2.05 µm	0.31 µm	0.66 µm	2.99 µm
Standard Deviation		Standard Deviation		Standard Deviation	
0.10 µm	0.15 µm	0.02 µm	0.02 µm	0.04 µm	0.02 µm

Unit 4		Unit 5		Unit 6	
Temp = 21.8 °C		Temp = 21.9 °C		Temp = 21.8 °C	
X	Y	X	Y	X	Y
1.59 µm	0.90 µm	1.35 µm	2.38 µm	0.39 µm	0.09 µm
1.56 µm	0.86 µm	1.31 µm	2.38 µm	0.35 µm	0.13 µm
1.58 µm	0.84 µm	1.34 µm	2.31 µm	0.40 µm	0.10 µm
1.58 µm	0.93 µm	1.26 µm	2.30 µm	0.39 µm	0.13 µm
1.61 µm	0.90 µm	1.29 µm	2.31 µm	0.31 µm	0.10 µm
Standard Deviation		Standard Deviation		Standard Deviation	
0.02 µm	0.03 µm	0.03 µm	0.04 µm	0.03 µm	0.02 µm

Unit 7		Unit 8		Unit 9	
Temp = 21.8 °C		Temp = 21.9 °C		Temp = 21.8 °C	
X	Y	X	Y	X	Y
1.30 µm	2.00 µm	0.58 µm	2.01 µm	1.06 µm	1.03 µm
1.33 µm	2.01 µm	0.58 µm	2.00 µm	0.95 µm	1.00 µm
1.06 µm	1.99 µm	0.59 µm	1.91 µm	1.10 µm	1.05 µm
1.26 µm	2.01 µm	0.45 µm	1.99 µm	1.04 µm	1.04 µm
1.39 µm	2.01 µm	0.53 µm	2.03 µm	1.01 µm	1.08 µm
Standard Deviation		Standard Deviation		Standard Deviation	
0.11 µm	0.01 µm	0.05 µm	0.04 µm	0.05 µm	0.03 µm

Table 4.1 Recorded raw data for each unit

The distance from each unit to the center is shown in Table 4.2. The distance values in green color shows the build units that are within specification and the values in red color shows the build unit that did not meet the requirements. It is clearly shown that eight out of the nine build units have passed, with the defected build unit to only have 0.05 µm off than required specification.

Unit 1	
X	Y
0.33 µm	-1.76 µm
Distance to Golden Unit	
1.79 µm	

Unit 2	
X	Y
-2.03 µm	-0.26 µm
Distance to Golden Unit	
2.04 µm	

Unit 3	
X	Y
-0.61 µm	-2.98 µm
Distance to Golden Unit	
3.05 µm	

Unit 4	
X	Y
-1.58 µm	0.89 µm
Distance to Golden Unit	
1.84 µm	

Unit 5	
X	Y
1.31 µm	-2.34 µm
Distance to Golden Unit	
2.67 µm	

Unit 6	
X	Y
0.37 µm	-0.11 µm
Distance to Golden Unit	
0.36 µm	

Unit 7	
X	Y
-1.27 µm	2.01 µm
Distance to Golden Unit	
2.39 µm	

Unit 8	
X	Y
-0.54 µm	-1.99 µm
Distance to Golden Unit	
2.07 µm	

Unit 9	
X	Y
-1.03 µm	-1.04 µm
Distance to Golden Unit	
1.48 µm	

Table 4.2 Average X and Y coordinates, and the distance of each unit from center point

To clearly represent the relationship of passed build units, defected build unit, and the required specification, Figure 4.13 has distributed the resulting build unit positions. From Figure 4.13 it can be seen that although the defected unit does not meet the requirement, it is extremely close to the specification required. Thus is also represented in table 4.2.

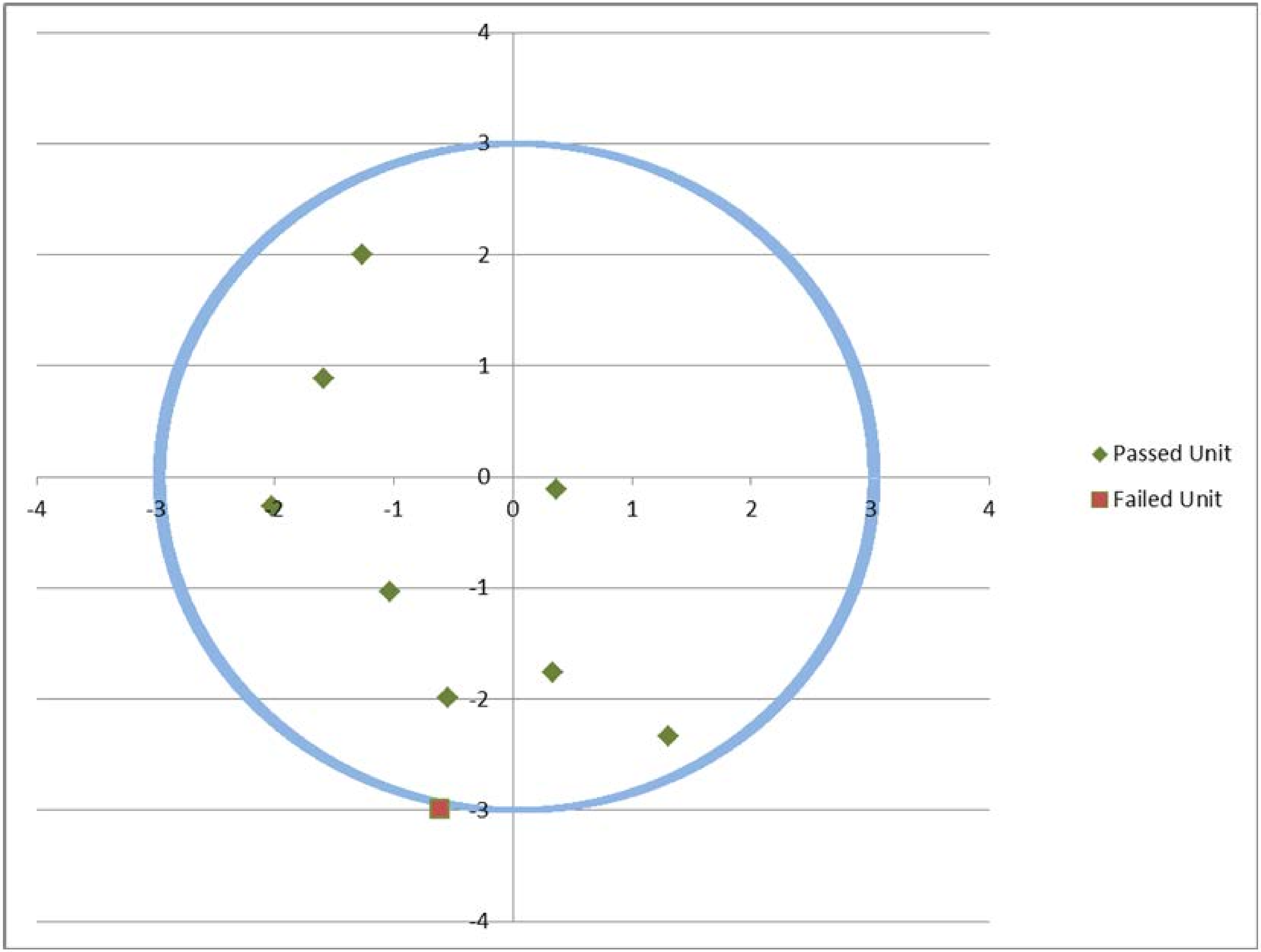


Figure 4.13 Distributed plot for passed and rejected build

CHAPTER 5

CONCLUSION

This thesis has described issues and challenges of positioning and assembling optical components using mechanical fixtures up to microns units of accuracy. This has been achieved by reviewing current metrologies, followed by a discussion about available optical instrumentations and custom designed optical components. Overall system consistency, especially laser source position drifting was discussed subsequently. Finally the relationship between position stability and temperature was identified based on experimental observations. Finally, the optical source was stabilized through temperature control.

Eight out of nine build units have met specifications, and the build unit that has not met specification is 0.05 µm off from ±3 µm decenter requirement or only 1.16% off from the required specification. For conclusion, the optical metrology system utilized to assemble the build units possesses satisfactory stability and repeatability. Nearly 90% of the assembled build units fall within the required accuracy specification, with each build unit having a repeatability error no more than 0.15 µm.

For future work, continuous improvement to the optical metrology system will allow better precision for both positioning and assembling of the build units. Possible improvements include mechanical and environmental methods. For mechanical methods, equipment with better stability is preferred. For example, laser systems with either less pointing angle or with position feedback function are ideal for the improvement of position accuracy. Pressurized floating table is also helpful to reduce environmental vibration errors.

Environmental methods consist of surrounding controls, for ambient temperature and for ambient brightness of the experiment setup. Better controlled ambient temperature is extremely helpful to reduce laser drifting, and controlled ambient brightness will result in less background lightning being exposed to the setup, which will eliminate random noises from the beam profiler.

REFERENCES

[1] H. Schwenke, U. Neuschaefer-Rube, T. Pfeifer, and H. Kunzmann, "Optical Methods for Dimensional Metrology in Production Engineering," CIRP Annals - Manufacturing Technology, Volume 51, Issue 2, Pages 685-699, 2002.

[2] H.N. Hansen, K. Cameiro, H. Haitjema, and L. De Chiffre, "Dimensional Micro and Nano Metrology," CIRP Annals - Manufacturing Technology, Volume 55, Issue 2, Pages 721-743, 2006.

[3] W. A. Plummer and H. E. Hagy, “Precision Thermal Expansion Measurements on Low Expansion Optical Materials,” Applied Optics, Vol. 7, 825-831, 1968.

[4] T. H. Jamieson, “Thermal effects in optical systems,” SPIE, Conference Vol 0193, 1979.

[5] B. Light, "The Sum of All Errors," SPIE Proceedings: SPIE Vol. TD03, 2009.

[6] R. S. Sirohi and M. P. Kothiyal, "Optical Components, Techniques, and Systems in Engineering."

[7] T. Yoshizawa, "Handbook of Optical Metrology: Principles and Applications."

[8] K. J. Gasvik, "Optical Metrology."

[9] K. Fischer, "Optical System Design."

[10] B. Dorband, H. Muller, and H. Gross, "Handbook of Optical Systems, Metrology of Optical Components and Systems."

[11] M. Mori, A. Pirozhkov, M. Nishiuchi, K. Ogura, A. Sagisaka, Y. Hayashi, S. Orimo, A. Fukumi, Z. Li, M. Kado, and H. Daido, "Development of Beam-Pointing Stabilizer on a 10-TW Ti:Al_2O_3 Laser System JLITE-X for Laser-Excited Ion Accelerator Research," Laser Physics, 2006, Vol. 16, No. 7, pp. 1092–1096.

[12] T.Kanai, A.Suda, S.Bohman, M.Kaku, S.Yamaguchi, and K.Midorikawa, “Pointing stabilization of a high-repetition-rate high-power femtosecond laser for intense few-cycle pulse generation,” Appl. Phys.Lett. 92, 061106 (2008).

[13] N. O. P´erez-Arancibia, J. S. Gibson and T. Tsao, “Laser Beam Pointing and Stabilization by Intensity Feedback Control,” 2009 American Control Conference, St. Louis, MO, USA, June 10-12, 2009.

[14] F. Breitling, R. S. Weigel, M. C. Downer, and T. Tajima, " Laser pointing stabilization and control in the submicroradian regime with neural networks," Review of Scientific Instruments 72, 1339 (2001); doi: 10.1063/1.1334624.

[16] C.W.Siders, E.W.Gaul, M.C.Downer, A.Babine, and A. Stepanov, “Self-starting femtosecond pulse generation from aTi:sapphire laser synchronously pumped by a pointing-stabilized mode-locked Nd:YAG laser,” Rev. Sci. Instrum. 65, 3140 (1994).

[17] T.Kanai, A.Suda, S.Bohman, M.Kaku, S.Yamaguchi, and K.Midorikawa, “Pointing stabilization of a high-repetition-rate high-power femtosecond laser for intense few-cycle pulse generation,” Appl. Phys.Lett. 92, 061106 (2008).

[18] N. O. P´erez-Arancibia, J. S. Gibson and T. Tsao, “Laser Beam Pointing and Stabilization by Intensity Feedback Control,” 2009 American Control Conference, St. Louis, MO, USA, June 10-12, 2009.

[19] F. Breitling, R. S. Weigel, M. C. Downer, and T. Tajima, " Laser pointing stabilization and control in the submicroradian regime with neural networks," Review of Scientific Instruments 72, 1339 (2001); doi: 10.1063/1.1334624.

[20] J. Gray, P. Thomas, and X. D. Zhu, "Laser pointing stability measured by an oblique-incidence optical transmittance difference technique," Review of Scientific Instruments 72, 3714 (2001); doi: 10.1063/1.1394187.

[21] M. Mori, A. Pirozhkov, M. Nishiuchi, K. Ogura, A. Sagisaka, Y. Hayashi, S. Orimo, A. Fukumi, Z. Li, M. Kado, and H. Daido, "Development of Beam-Pointing Stabilizer on a 10-TW Ti:Al_2O_3 Laser System JLITE-X for Laser-Excited Ion Accelerator Research," Laser Physics, 2006, Vol. 16, No. 7, pp. 1092–1096.

[22] S. M. Goldwasser, "Sam's Laser FAQ," SPIE Proceedings: SPIE Vol. TD03, 2009. [Online]. Available: http://www.repairfaq.org/sam/laserfaq.htm#faqtoc Retrieved: January, 2014

[23] Thorlabs, “Theory of HeNe Laser,” [Online]. Available: http://www.thorlabs.com/, Retrieved: Nov, 2013.

[24] Thorlabs, "Red HeNe Laser Systems (High Power) Operating Manual," [Online]. Available: http://www.thorlabs.com/thorcat/12100/HRP050-Manual.pdf Retrieved: January, 2014

[25] Power Technology Incorporated, “HeNe gas lasers vs. laser diode modules,” [Online]. Available: http://www.powertechnology.com/PDFs/WP_HeNe-vs-diodelaser.pdf, Retrieved: Nov, 2013.

[26] BEST Medical Company, “HeNe Lasers and Diode Lasers specification sheet,” [Online]. Available: http://www.cnmcco.com/treatment/PDFdocs/lasers/CNMC_hene_diode.pdf, Retrieved: Nov, 2013.

[27] J. Takahara, S. Yamagishi, H. Taki, A. Morimoto, and T. Kobayshi, "Guiding of a one-dimension optical beam with nanometer diameter," Optics Letters, Vol. 22, Issue 7, pp. 475-477, 1997.

[28] A. Cores and A. Davidson, “CMOS cameras allow robust active stabilization of laser beams,” Laser Focus World, Vol.47, Pages 73, 2011.

[29] K. Minoshima and H. Matsumoto, “High-Accuracy Measurement of 240-m Distance in an Optical Tunnel by use of a Compact Femtosecond Laser,” Applied Optics, Vol. 39, Issue 30, 5512-5517, 2000.

[30] A. Yacoot and N. Cross, “Measurement of picometre non-linearity in an optical grating encoder using x-ray interferometry,” 2003 Measurement Science and Technology, Vol. 14, 148, 2003.

[31] N. Massari, L. Gonzo, M. Gottardi, and A. Simoni, “High Speed Digital CMOS 2D Optical Position Sensitive Detector,” ESSCIRC. 2002.

[32] Newport, “NanoScan Beam Profiler Catalog,” [Online]. Available: http://www.ophiropt.com/laser/register_files/beam-profilers-catalog.pdf, Retrieved: Nov 2013.

[33] Photonics, “Profiling Gets You the Right Beam, Every Time,“ [Online]. Available: http://photonics.com/Article.aspx?AID=47615, Retrieved Nov 2013.

[34] F. Siewert, T. Noll, T. Schlegel, T. Zeschke, and H. Lammert, "The Nanometer Optical Component Measuring Machine: a new Sub-nm Topography Measuring Device for X-ray Optics at BESSY," AIP Conf. Proc. 705, 2004.

[35] W. A. Plummer and H. E. Hagy, “Precision Thermal Expansion Measurements on Low Expansion Optical Materials,” Applied Optics, Vol. 7, 825-831, 1968.

[36] T. H. Jamieson, “Thermal effects in optical systems,” SPIE, Conference Vol 0193, 1979.

[37] N. Massari, L. Gonzo, M. Gottardi and A. Simoni, " High Speed Digital CMOS 2D Optical Position Sensitive Detector," ESSCIRC, Firenze, Italy , Sept. 2002.

[38] Micro Radian, “Principles of Auto Collimator,” [Online]. Available: http://www.micro-radian.com/Principles.html Retrieved Jan 2014.

[39] Zemax Official Website [Online]. Available: https://www.radiantzemax.com/en, Retrieved Nov 2013.

[40] W. J. Thomes, Jr. ; R. F. Chuska ; M. N. Ott ; F. V. LaRocca ; R. C. Switzer ; S. L. Macmurphy, "Fiber optic cable thermal preparation to ensure stable operation," SPIE Conf. Vol. 7070, Optical Technologies for Arming, Safing, Fuzing, and Firing IV, 2008; doi:10.1117/12.796977.

[41] A. Koch and R. Ulrich, "Fiber-optic Displacement Sensor with 0.02 pm Resolution by White-light Interferometry," Sensors and Actuators A: Physical, Volume 25, Issues 1–3, Pages 201-207, 1990, ISSN 0924-4247, http://dx.doi.org/10.1016/0924-4247(90)87032-E.