

ELECTRICAL ENGINEERING SENIOR PROJECT REPORT

WAVELENGTH-SCANNING FIBER OPTICS

CONFOCAL MICROSCOPY

FOR LENS' THICKNESS MEASUREMENT

Submitted to

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March 18, 2005

## Abstract

This report presents a non-contact optical method for absolute measurement of thickness of optical transparent media such as eye glasses and camera lenses. The method is based on a fiber-optic confocal microscopy technique. It includes a confocal channels consisting of an identical apertureless fiber-optic-type confocal microscope constructed by use of a single 2x2 fiber coupler. A geometric-ray model is used to obtain the provides high accuracy in spatially locating the specific imaging points that correspond to the back-reflected intensity peaks of the confocal responses. Thus, a measurement of the sample thickness is achieved.

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## Chapter 1

### Introduction

The standardization of lens industry recommended every lenses must be inspected which included lens' thickness measurement. Typical technique for measuring lenses could be caused a scratch to the lens, some errors and it took too much time. So, there is a new technique that has been used to measure the lens' thickness, it is non-contact laser scanning microscopy lens' thickness measurement. However, if the scanning technique can be eliminated, it will be more accuracy because scanning technique caused the vibration to the system.

This project proposes to develop a new lens' thickness measurement technique which eliminate the scanning technique. The varying wavelength technique is designed in this project. The author has used the simple idea that different wavelength of light can be caused the different focusing on the lens. Therefore, the database and calibration curves will be built by finding the relationship between focus and wavelength. Furthermore, to find the suitable objective lens is needed.

In this project is first to study the concepts of confocal microscopy technique, all the required equipment. Next, find the relationship of focal length of objective lens of different wavelength. Finally, use computer to control the wavelength scanning and demonstrate how the lens thickness will be achieved by using software.



## Chapter 2

### Literature Review

#### 2.1 Confocal

Although conventional light allows the examination of both fixed and living specimens, and thus the observation of dynamic processes as they actually occur, certain problems do exist with these techniques. One of the main difficulties faced is out-of-focus light. Out of focus information often obscures important structures of interest, particularly in thickness. In a conventional light microscope set-up, not only is the plane of focus illuminated, but much of the specimen above and below this point is also illuminated and imaged at the same time.

##### 2.1.1 The Principle of Confocal Microscopy

The basic optical principle is to scan specimen with an illuminating spot, and at the same time have a small photodetector aperture follow that illuminating spot. This is usually achieved by having a laser as illumination source and a small aperture in front of the photodetector.

From Figure 2.1, the laser beam is first focused to a spot by the microscope objective by passing through the beam splitter. An illuminating spot is formed in the focal plane of the objective. The laser beam is traveling back through the objective. Most of the laser beam is reflected by the beam splitter. The light from defocal plane

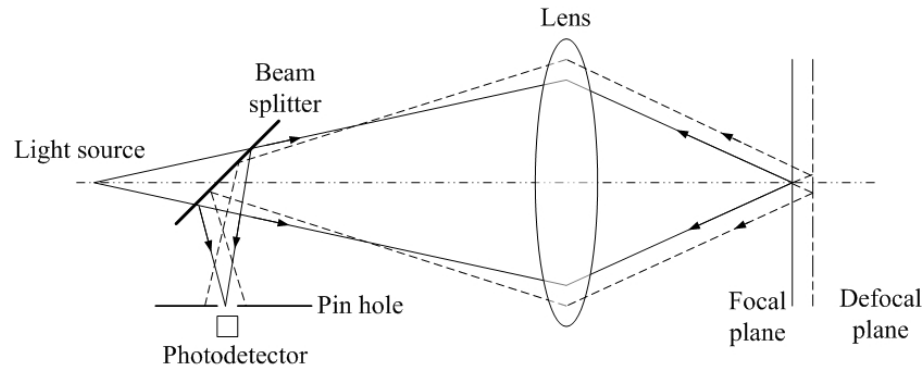


Fig. 2.1. The Arrangement of Equipments of Confocal Microscopy.

will be focused at a plane behind the pinhole such is blocked away by the pinhole plate. The light from defocal plane will be focused before the pinhole and is blocked away by the pinhole too. Only the light from focal plane is just focused at the pinhole thus can reach the image photodetector. The ray-path indicated with dashed lines shows how light from out-of-focus objects are propagated through the optical system. The illuminating spot is defocused, thus illumination a larger area with a weaker intensity. This is indicated to the left with the dotted focal position within the specimen.

### 2.1.2 The Advantage of Using a Confocal Microscope

By having a confocal pinhole, the microscope is really efficient at rejecting out of focus light. Also, a similar effect happens with points of light in the focal plane, but not at the focal point emitted light from these areas is blocked by the pinhole screen. So a confocal microscope has slightly better resolution horizontally as well as vertically.

## 2.2 Optical Fiber

Understanding the characteristics of different fiber types aides in understanding the applications for which they are used. There are two basic types of fiber: multimode fiber and single-mode fiber. Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance. Single-mode fiber is best designed for longer transmission distances, making it suitable for long-distance telephony and multichannel television broadcast systems.

### 2.2.1 Multimode Fiber

Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance. This fiber type has a much larger core diameter, compared to single-mode fiber, allowing for the larger number of modes, and multimode fiber is easier to couple than single-mode optical fiber. Multimode fiber may be categorized as step-index or graded-index fiber.

#### 2.2.1.1 Multimode Step-index Fiber

Figure 2.2 shows how the principle of total internal reflection applies to multimode step-index fiber. Because the core's index of refraction is higher than the cladding's index of refraction, the light that enters at less than the critical angle is guided along the fiber. Three different light waves travel down the fiber. One mode travels straight down the center of the core. A second mode travels at a steep angle and bounces back and forth by total internal reflection. The third mode exceeds the critical angle and refracts into the cladding. Intuitively, it can be seen that the second mode travels a longer distance

than the first mode, causing the two modes to arrive at separate times. This disparity between arrival times of the different light rays is known as dispersion, and the result is a muddled signal at the receiving end. It is important to note that high dispersion is an unavoidable characteristic of multimode step-index fiber.

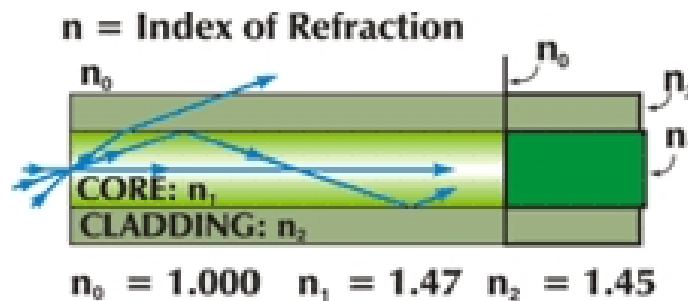


Fig. 2.2. Multimode Step-index Fiber

### 2.2.1.2 Multimode Graded-index Fiber

Graded-index refers to the fact that the refractive index of the core gradually decreases farther from the center of the core. The increased refraction in the center of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same time, reducing dispersion. The principle of this fiber is shown in Figure 2.3. The core's central refractive index ( $n_A$ ) is greater than that of the outer core's refractive index ( $n_B$ ). The core's refractive index is parabolic, being higher at the center. As Figure 2.3 shows, the light rays no longer follow straight lines; they follow a serpentine path being gradually bent back toward the center by the

continuously declining refractive index. This reduces the arrival time disparity because all modes arrive at about the same time. The modes traveling in a straight line are in a higher refractive index, so they travel slower than the serpentine mode. These travel farther but move faster in the lower refractive index of the outer core region.

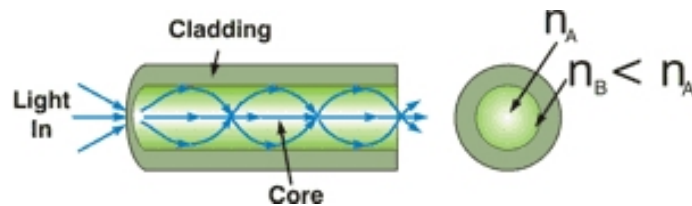


Fig. 2.3. Multimode Graded-index Fiber

### 2.2.2 Single-mode Fiber

Single-mode fiber allows for a higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes. Single-mode fiber also enjoys lower fiber attenuation than multimode fiber. Thus, more information can be transmitted per unit of time. Like multimode fiber, early single-mode fiber was generally characterized as step-index fiber meaning the refractive index of the fiber core is a step above that of the cladding rather than graduated as it is in graded-index fiber. Modern single-mode fibers have evolved into more complex designs such as matched clad, depressed clad and other exotic structure. This single-mode fiber has disadvantages. The smaller core diameter

makes coupling light into the core more difficult. The tolerances for single-mode connectors and splices are also much more demanding. Figure 2.4 shows the single-mode fiber.

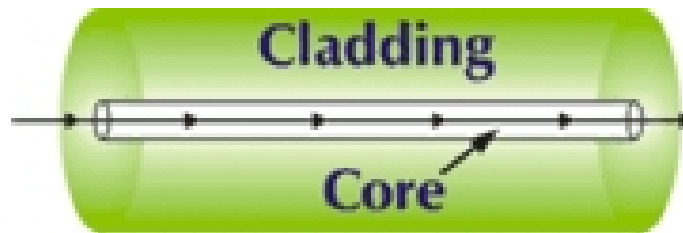


Fig. 2.4. Single-mode Fiber

### 2.3 The 2x2 50/50 Fiber Coupler

The 2x2 50/50 fiber coupler first provides effective launching and delivery of the input light emission. Second, it divides the input light power (50/50 coupling ratio) between the two confocal channel where the fiber tips act as intensive point light sources. Third, the fiber tips serve as objects for projecting and as highly sensitive confocal point receivers. Fourth, one of the output coupler fibers serves as a common optical output of the confocal arrangement. It delivers the confocal optical signal from the confocal microscopes to the detector system.

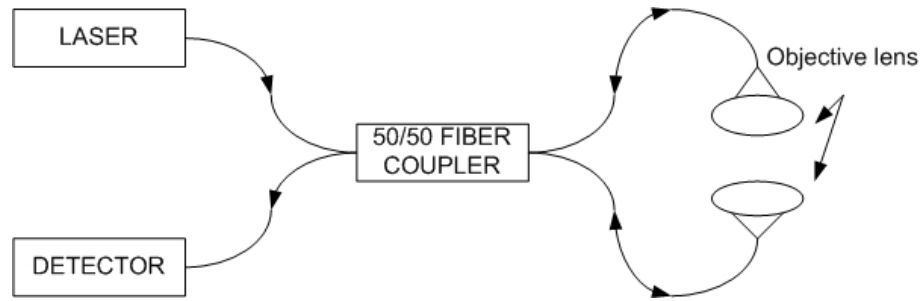


Fig. 2.5. The 2x2 50/50 Fiber Coupler

## 2.4 Monochromator

The Ebert monochromator, also known as the Fastie-Ebert monochromator, since it was developed for practical use by Fastie, is a very simple design that uses a plane grating at or near the focal point of a spherical collimating mirror. As shown in the optical diagram below, polychromatic radiation is focused at the entrance slit of the monochromator and reflected by a folding mirror onto a spherical collimating/ focusing mirror. This mirror collimates and directs the radiation onto a grating, where it is dispersed. The dispersed radiation is directed back onto the collimating/ focusing mirror and the portion of it is focused at the exit slit via a folding mirror.

Scanning Digital Mini-Chrom Monochromators (SDMC) produced by Optometrics Group are designed to be manually operated monochromator that utilizes a dial for wavelength selection or controlled by a stepping motor driver of other calibrated drive unit and wavelength readout is provided. The unit utilized a lead screw/ sine bar mechanism to rotate the grating and dual photosensors that function as high or low limit

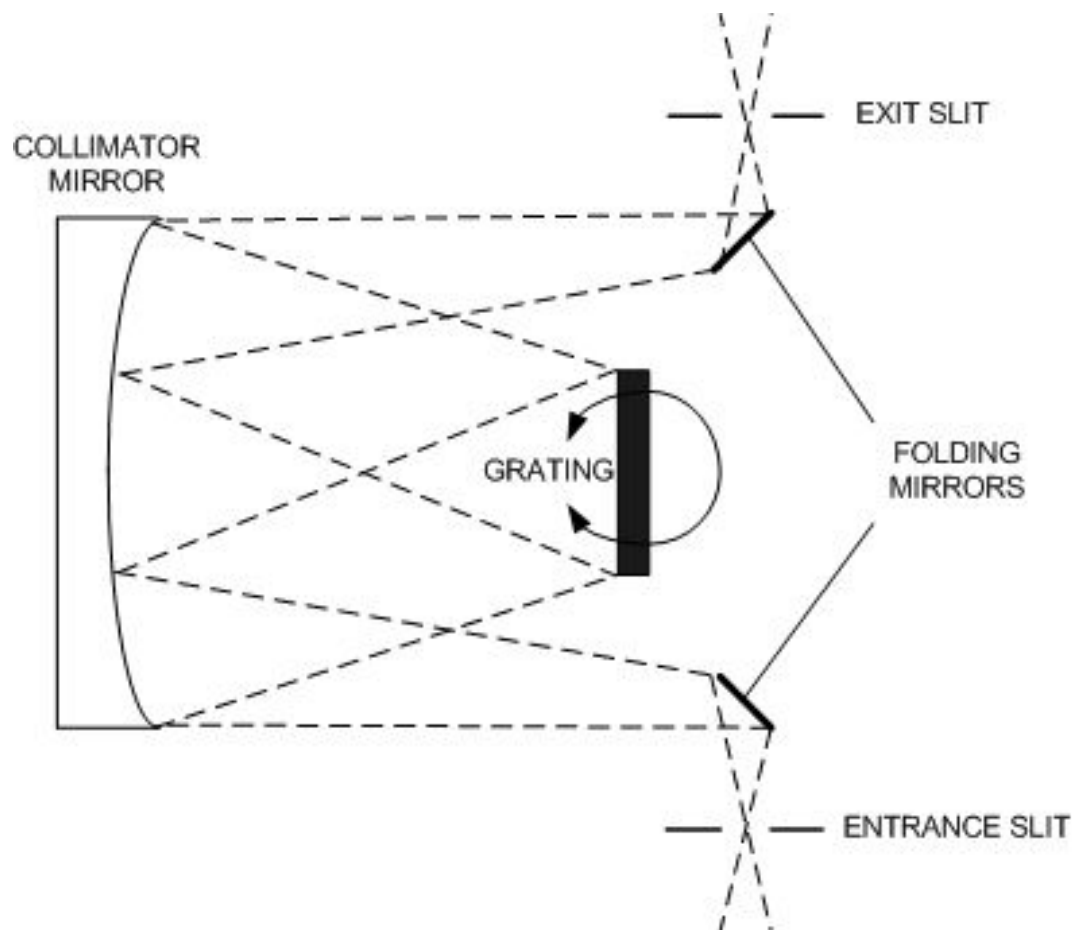


Fig. 2.6. Optical Diagram inside Monochromator



switches when operated by a stepping motor controller. Rotation of the drive shaft in clockwise direction increases the wavelength of radiation at the exit slit proportionately.

## Chapter 3

# Methodology

In "Wavelength-scanning fiber optics confocal microscopy for lens' thickness measurement", has the ideal concept as shown below.

From Figure 3.1, the wavelength scanning system generates the light in different wavelength (for example;  $\lambda_1$  to  $\lambda_4$  ) passing through fiber optics to the 50/50 fiber coupler, fiber coupler (acts as beam splitter) divides the input light power (50/50 coupling ratio). One of light transmits to objective lens which focused the light beam on to the lens. If the light is focused onto the surface, it will reflect and enter the fiber tip which acts as pinhole, the light transmits back to fiber coupler and divides the light power again, one go to the photodetector system and then the result is maximum intensity. Otherwise, if the light is out-of-focus on the surface, its light intensity will be less. In the Figure 3.1, the light at wavelength  $\lambda_2$  to  $\lambda_3$  are focused to the reflective sample surface and these two wavelength will result the confocal peaks. The sample thickness is proportional different between two wavelength (sample thickness  $\propto \Delta\lambda$ ).

### 3.1 Wavelength Scanning System

Wavelength scanning system used computer to control scanning digital monochrom monochromator (SDMC). Laboratory Virtual Instrument Engineering Workbench

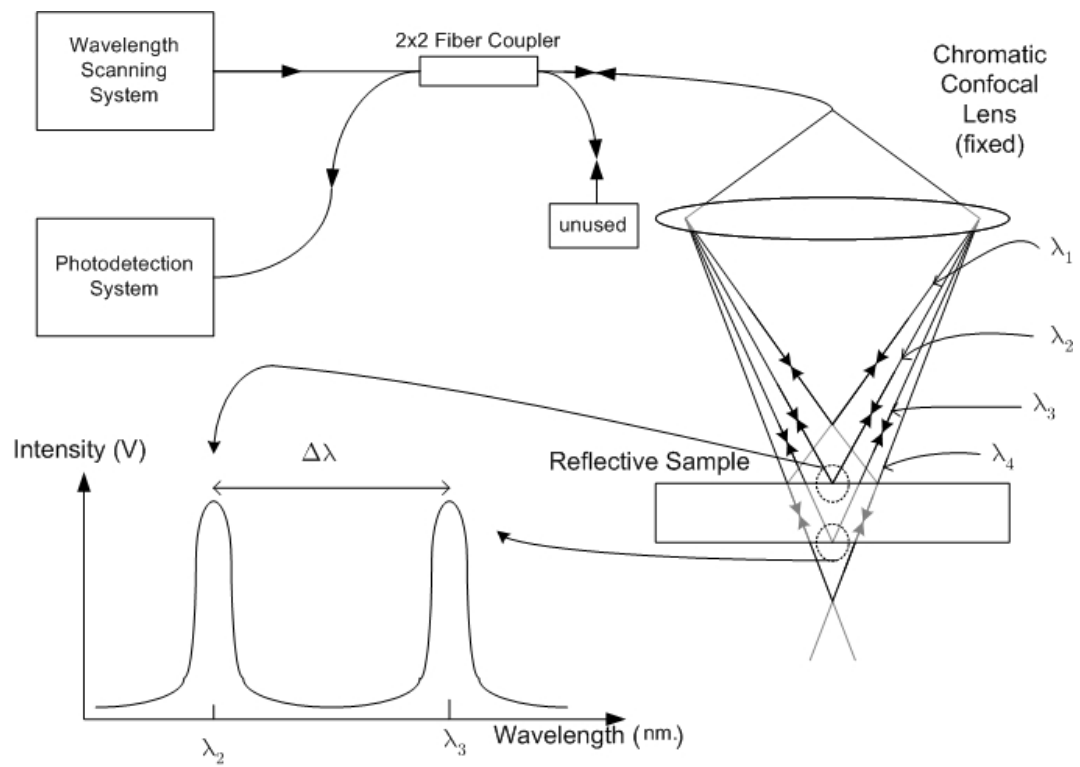


Fig. 3.1. Diagram of Wavelength-scanning Fiber Optics Confocal Microscopy for Lens' Thickness Measurement

or LabVIEW is a program developer which is used to build Virtual Instrument of VI for commanding stepping motor controller. The block diagram of system is shown below.



Fig. 3.2. Wavelength Scanning System Block Diagram

### 3.1.1 Stepping Motor Controller CB-3

Scanning digital mini-chrom monochromator (SDMC) is controlled by stepping motor controller model CB-3 produced by Optometrics Group. The CB-3 is a microprocessor based controller and motor driver designed for use with the Optometric Group SDMC. It can be program via a computer through an RS-232 interface and provides over 200 bytes of non-volatile memory to store complex motion control programs.

The user can perform over 25 different commands including move distance, initial and final velocities, ramp slope, time-out pauses, half or full step operation, etc. with stepping speeds which range from 5 steps per minute to 15,000 steps per second. Data can be sent or received at any time, even while driving a stepping motor. Stand alone operation is also possible using the external "GO" button provided. External systems may also communicate with and control operation of the CB-3 through a general purpose I/O port.

### **3.1.2 The Communication in the System**

The communications are established with a terminal or computer through a standard RS-232 MODEM cable. The CB-3 is configured as DCE (Data communication equipment). Data transfer is of a 10 bit asynchronous format consisting of: 1 start bit, 8 data bits (1 mark), 1 stop bit, no parity. Baud rate is factory set at 9600, however other baud rates may be selected by installing a combination of jumpers inside the CB-3.

The CB-3 is designed to operate with simple ASCII character commands transmitted via RS-232. Commands consist of a single letter instruction code followed by 0, 1, or 2 decimal numbers used as data. Each line may consist of up to 12 character including spaces. Spaces are optional between the instruction character and the first number, however commands with two numbers need at least one space between numbers. A comma will serve the same purpose as the space in this case. The commands in detail are in Appendix.

### **3.1.3 Initial Calibration of the Monochromator**

When setting up the equipments it is necessary to initialize calibration of the monochromator. Firstly, the number of steps between the low limit and zero lambda (monochromator zero order) is needed to be measured. Although, the calibration data supplied with the monochromator contains the low limit to zero order position, slight differences in limit detection circuits may result in different limit trip point. To calibrate zero order, a source at the monochromator input and a detector with a readout (voltmeter or recorder) at the output are needed.

The calibration method is first turn on the motor current off with the E0 command and then manually rotate the monochromator drive counter-clockwise until the mechanical stop is reached, then rotate clockwise until the large signal is seen. This is the zero order of grating. Next, adjust the drive until the maxima is found and then turn the motor current on E-1. After that, Set position counter to zero - O0(set origin) and then issue find low limit lambda command - F120 1. Next, enter display position command - Z, Log the zero offset distance. For example, Z 128(position returned). The position value returned is the zero offset distance. After power up, the controller must be initialized to low limit home(F120 1). Set the origin to the zero offset distance (Example: O 128). Finally, issue a move to relative zero command - R0 will cause the controller to move the monochromator to zero order. All subsequent move commands can now be issued as relative moves by prefixing the step sign and value with R. This simplifies complex motion sequences because there is no need to keep track of the step taken. The monochromator can be reset to zero order simply by issuing R0. This calibration method is written to non-volatile memory.

#### **3.1.4 Laboratory Virtual Instrument Engineering Workbenches (LabVIEW)**

LabVIEW is produced by National Instrument. It is the program to develop the application program which is similar to Visual Basic, Visual C++,etc. but write in the format of Graphical-based Programming. LabVIEW is more preferred to interface with instruments or transducers that used for measuring physical signals. So, many industrials used LabVIEW for controlling and automation.

Program that developed by LabVIEW is called Virtual Instrument or VI. LabVIEW can be categorized into 3 parts including Acquisition which is used to receive input from the environment to system, Analysis which is for analyzing and calculating, Presentation which is used for displaying to user.

### **3.1.5 Monochromator Controlling Program**

This program used to control monochromator. It is similar to terminal program which is used for communicating between CB-3 and computer. The front panel of monochromator is shown below which has 3 main sections including top section, bottom section and simulation section.

The top section, Calibrate to Zero Order grating button is used for initial calibration of monochromator, Command text-input is used for putting the ASCII character commands that mentioned before, Send button is used for sending commands, Repeat button is used for repeating previous command, Exit button is used for exiting program. VISA resource name is used for changing communication port, and the last is History display is used for display input command(s).

The bottom section, Wavelength sliding button and GO button are used for rotating monochromator to desired wavelength Wavelength command as mentioned before, Speed sliding button and set button are used for setting the speed of monochromator scanning, Start, Stop, Step wavelength buttons and Auto Scan button are used for scanning the monochromator from start to stop wavelength, Current speed indicator is used for displaying the current speed of scanning, Clear history buffer button is used to clear history indicator.

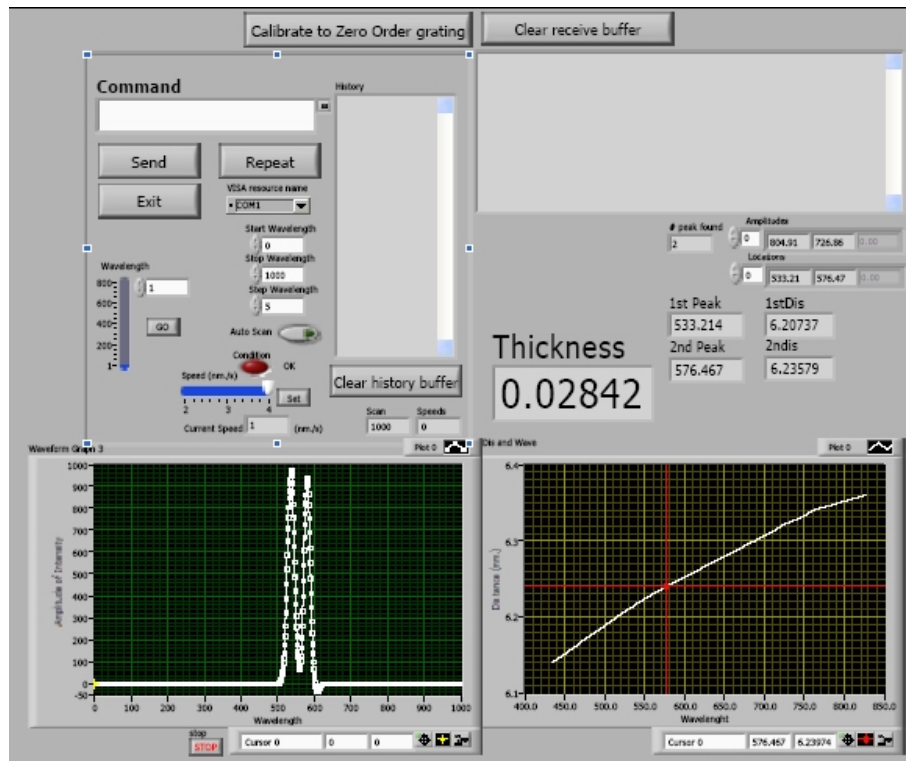


Fig. 3.3. Front Panel of Monochromator Controlling Program

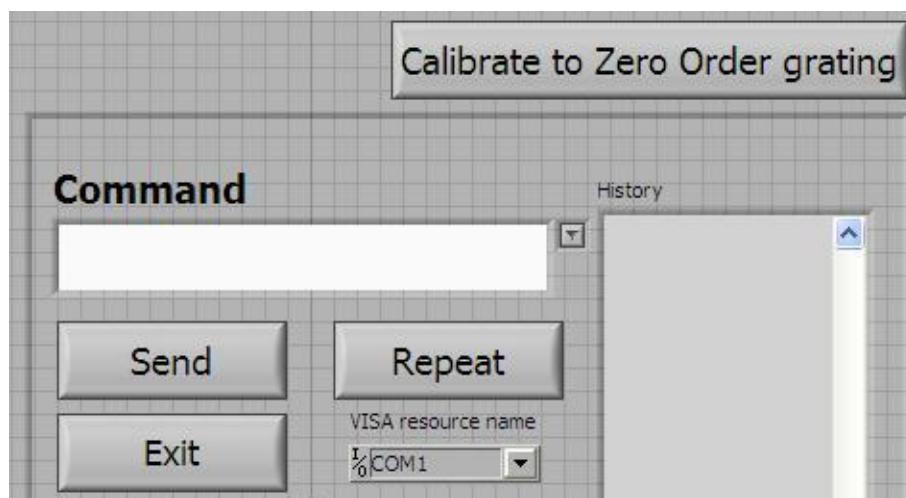


Fig. 3.4. The Top Section of Front Panel of Monochromator Controlling Program



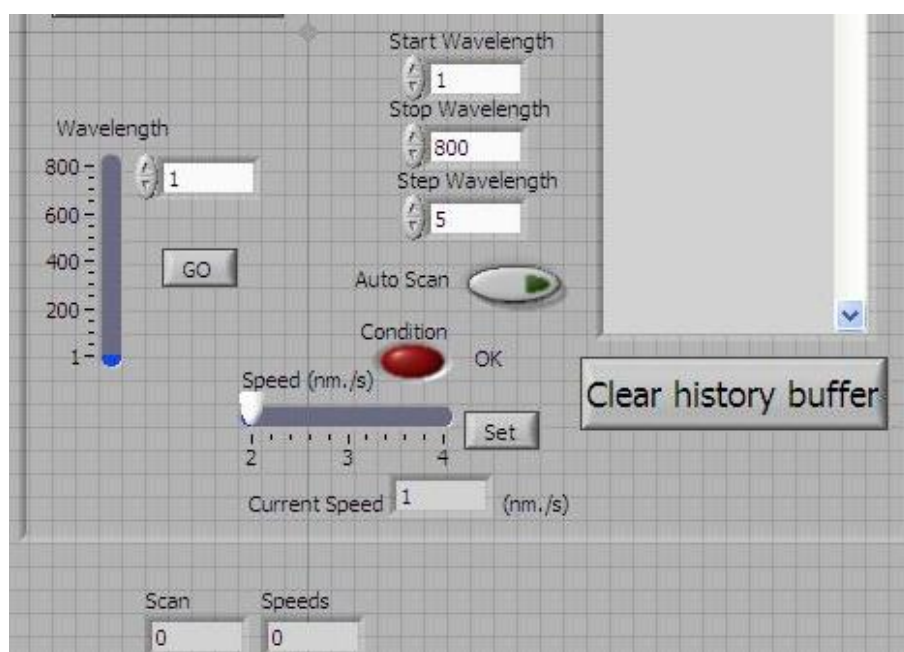


Fig. 3.5. The Bottom Section of Front Panel of Monochromator Controlling Program

The simulation section is to simulate scanning wavelength system. When the Auto Scan button is pressed, it starts to scan wavelength and read signal from photodetector system, simultaneously. The signal is plotted onto the graph on the left bottom side of front panel. After scanning and plotting is completed, the graph will be indicated the wavelengths of first and second peaks. These wavelengths will be used in the calibration curve which is at the right bottom side to calculate the thickness of sample.

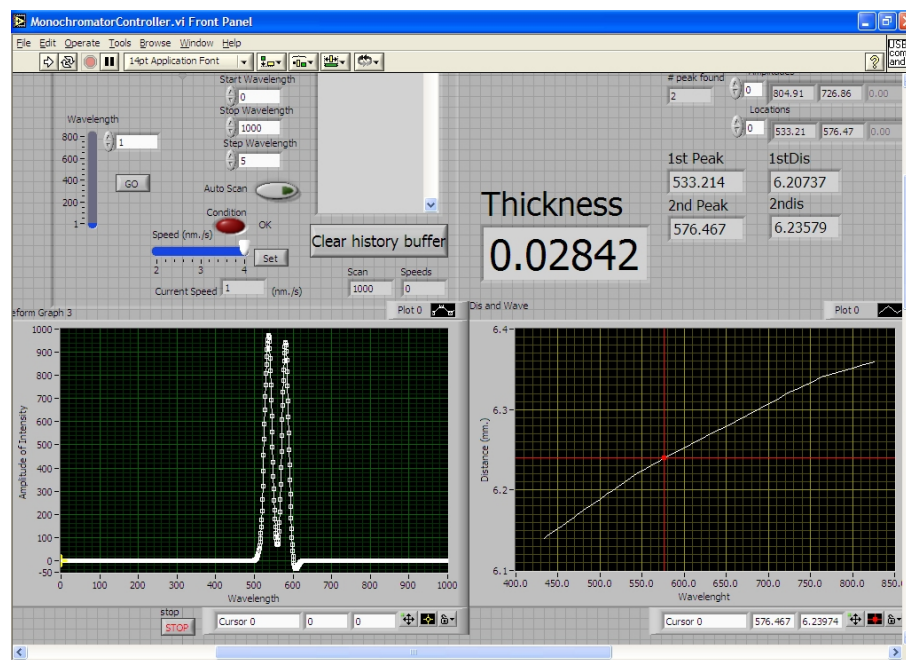


Fig. 3.6. The Simulation Section of Front Panel of Monochromator Controlling Program

## Chapter 4

### Experiment and Result

The main purpose of this chapter is to find the relationship of focal length of objective lens when the wavelength is changed. It is divided into two parts; the first part is to find the suitable wavelengths which have the peak of intensity in order to be used in the second part. The second part is to find the relationship between wavelength and distance of objective lens and highly reflective surface which will be further to achieve the main purpose of this chapter.

#### 4.1 To Find the Suitable Wavelengths of Light Source which have Peak of Intensity.

##### 4.1.1 Procedure

1. Set up the equipments as following Figure 4.1.

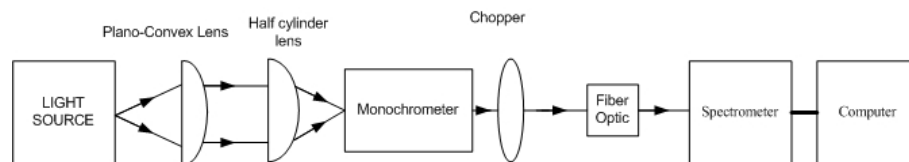


Fig. 4.1. Experimental Optical Setup for Observing Spectrum of Light

2. Turn on all equipments and then open spectra wizard program on the computer.
3. Select the 8 wavelengths which have high intensity as shown in Figure 4.2.

#### **4.1.2 Result and Discussion**

From the graph that shown in spectrometer program, there are 8 selected wavelengths which are wavelength at 433.5 nm., 543.0 nm., 576.0 nm., 762.0 nm., 827.0 nm., 833.5 nm., 857.5 nm. and 870.5 nm.

### **4.2 To Find the Relationship between Wavelength and Distance of Objective Lens and Highly Reflective Surface**

#### **4.2.1 Procedure**

1. Set up the equipments as following Figure 4.3.
2. Using 10x objective lens, turn on all equipments.
3. Adjust the monochromator to wavelength 433.5 nm.
4. Vary the distance between objective lens and highly reflective surface by using distance sensor. Record the light intensity in voltage and distance between objective lens and highly reflective surface as shown in Table 1 and Table 2 in Appendix A.
5. Repeat step 3 and 4 but adjust the monochromator to wavelength 543.0 nm., 576.0 nm., 762.0 nm., 827.0 nm., 833.5 nm., 857.5 nm., and 870.5 nm, respectively. Then record the values of distance and intensity .
6. Plot the graph of distance between objective lens and highly reflective surface versus the light intensity in different wavelength.

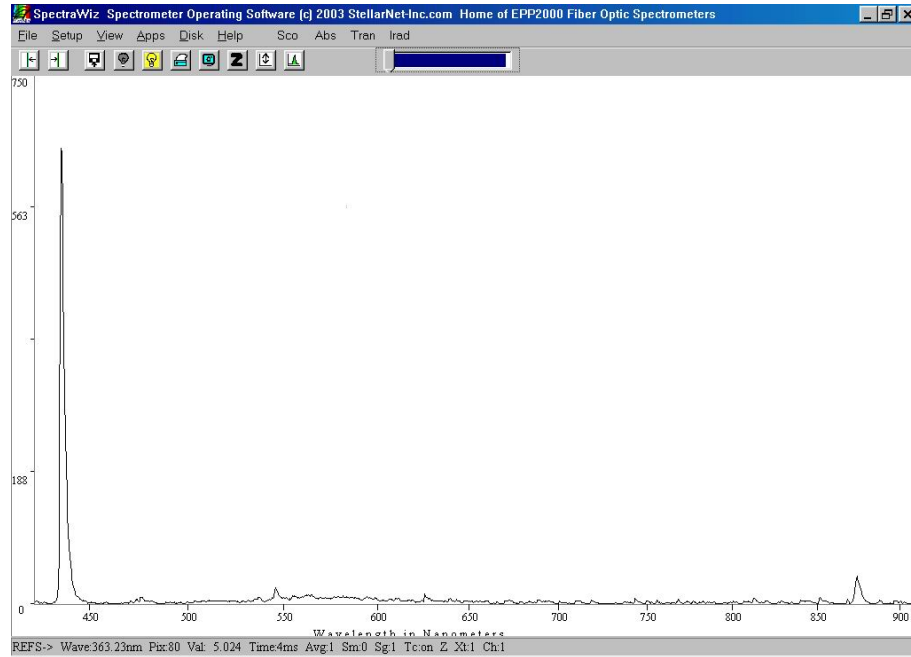


Fig. 4.2. Spectrum of Light

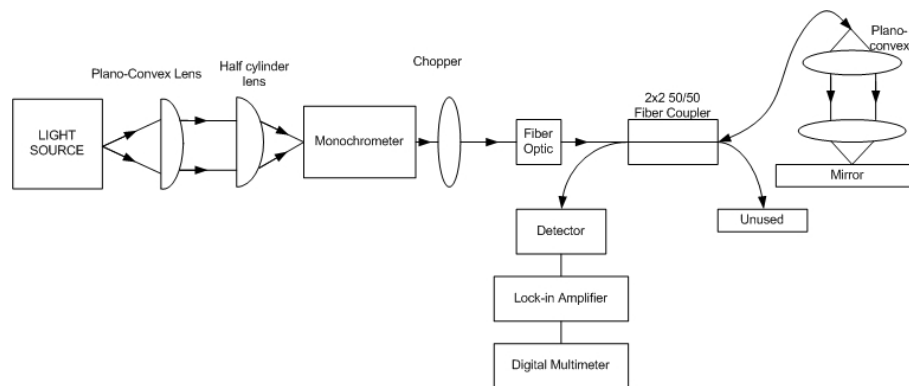


Fig. 4.3. Experimental Optical Setup for Finding the Relation between Wavelength and Distance of Objective Lens and Highly Reflective Surface

7. The maximum intensity of light of different wavelength and distance between objective lens and highly reflective surface are determined from the graph at step 7. Then plot the graph of wavelength versus focal length.

8. Repeat step 3 to 7 but change the objective lens from 10x to 20x. Record the value.

#### 4.2.2 Result and Discussion

After the light intensity in voltage and distance between objective lens and highly reflective surface of various wavelengths are recorded. The graph of distance between objective lens and highly reflective surface versus the light intensity of various wavelength has been plotted as shown in Figure 4.4 for 10x objective lens and Figure 4.5 for 20x objective lens.

From Figure 4.4 and Figure 4.5, it could be seen that the graphs of 20x objective lens are narrower than the graphs of 10x objective lens. For 10x objective lens the peaks of various wavelengths are on the longer range compared with 20x objective lens.

Each peak of the intensity of the graph is the focal length of each wavelength. Therefore, the graph of wavelength versus focal length has been plotted as shown in Figure 4.6 for 10x objective lens and Figure 4.7 for 20x objective lens.

From Figure 4.6 and Figure 4.7, the ranges of focal length is around 0.20 millimeters and 0.07 millimeters, respectively. It could be seen that when the change the objective lens from 10x to 20x the range is of focal length is decreased. Those graphs of two specifications of objective lens are slightly increase from wavelength 433.5 nm. to wavelength 833.5 nm. and the rapidly decrease from wavelength 857.5 to 870.5 nm.

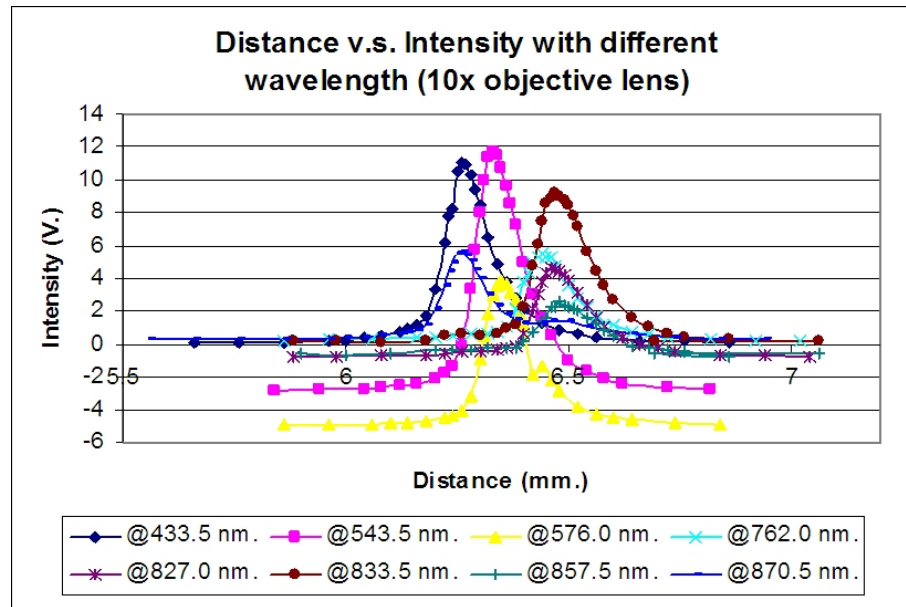


Fig. 4.4. Graph of Distance between Objective lens and Highly Reflective Surface versus the Light Intensity of Different Wavelength of 10x Objective Lens

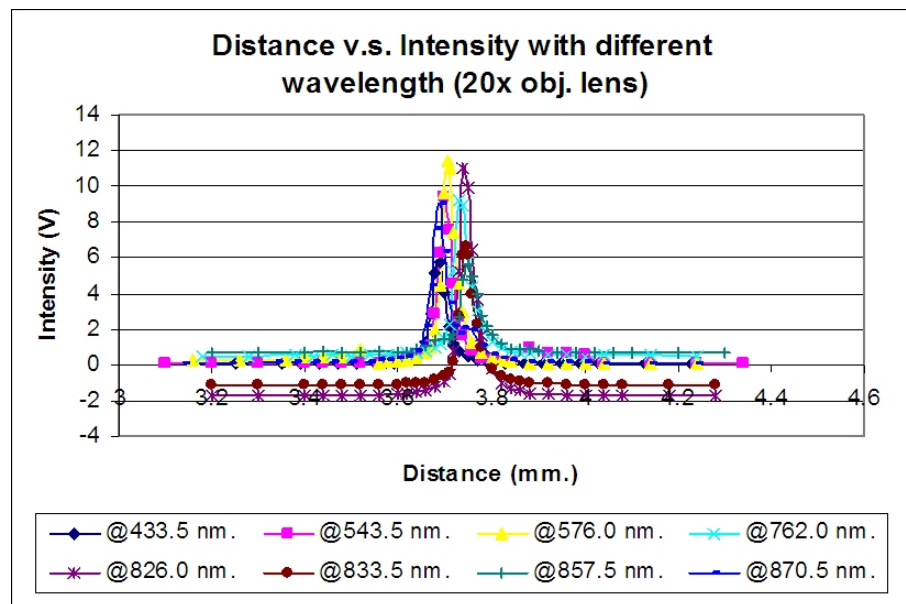


Fig. 4.5. Graph of Distance between Objective lens and Highly Reflective Surface versus the Light Intensity of Different Wavelength of 20x Objective Lens



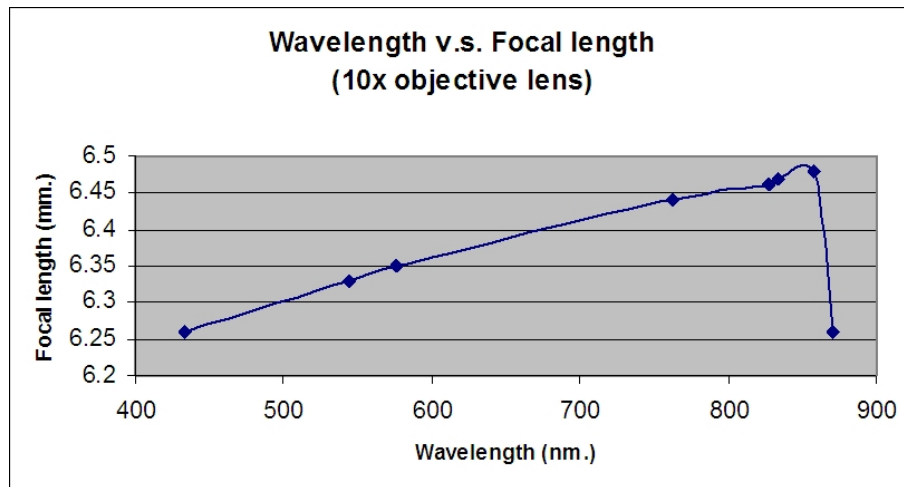


Fig. 4.6. Graph of Wavelength versus Focal Length of 10x Objective Lens

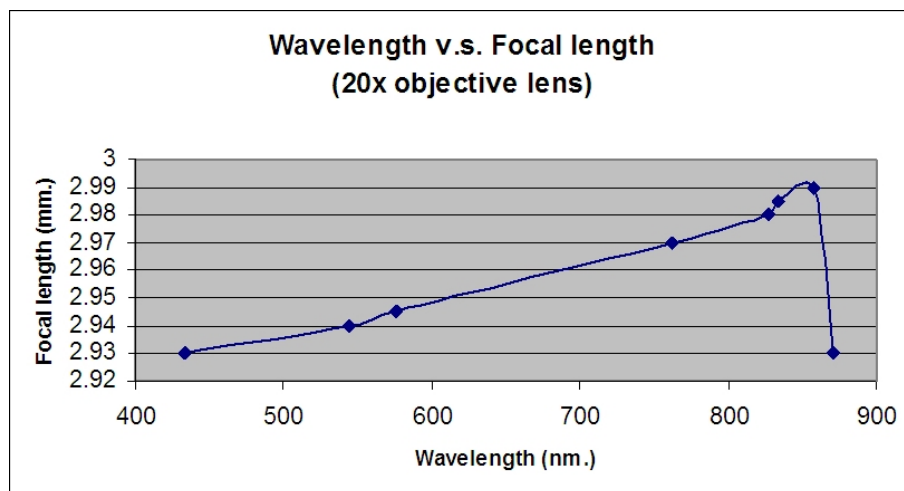


Fig. 4.7. Graph of Wavelength versus Focal Length of 20x Objective Lens

## Chapter 5

### Discussion and Conclusion

At different wavelength, the confocal peak has the different distance of objective lens and reflective sample (focal length). The focal length slightly increase when the wavelengths are increased from wavelength 433.5 nm. to 833.5 nm. and then it rapidly decrease from wavelength 857.5 nm. to 870.5 nm. The focal length range of 10x objective lens was wider than 20x objective lens, so when increase the objective lens's specification to 30x or more it will result in the smaller focal length range. However, the graph showed that the 20x objective lens gave shaper graphs than 10x objective lens. It could be said that 20x objective lens's focal length was more accurate compared with the 10x objective lens'.

This project presented the overview of the non-scanning fiber optics confocal microscopy for lens' thickness measurement system. The thickness of sample can be achieved by applying the technique that different wavelengths cause different focal length of objective lens. The calibration curve of focal length and wavelength was built. The monochromator can be control by computer through stepping motor controller via RS-232. LabVIEW is used to develop the program to control the monochromator and simulate the lens' thickness measurement.

From this project, the authors have gained a lot of experience and knowledge such as confocal microscopy technique, optical fiber, fiber coupler, monochromator and

stepping motor. They also have gained skill in real world application. They have applied and used appropriate information, as well as the demonstration of time management and problem solving. They have known how to divided up the work and share responsibilities with partner to deliver working project.

## Appendix A

### CB-3 Stepping Motor Controller Commands

- PORTS 1-5 SET/INCREMENT/READ.....A (n)

Binary data(n) in the range 0-31 is complimented and appears at ports 1 through 5 on the "I/O PORT", with port 1 being the least significant bit. At hardware reset, all ports are set off (high).

- CLEAR/INITIALIZE.....C (b)

NV memory is restored to the most recently stored initial parameters and program modes. Using a 1 as the datum prompts complete memory initialization including reversion to original default values and erasure of all NV program memory.

- DIVIDE BY N.....D (n)

All speeds encountered during ramping and slewing are divided by "n" which ranges from 1 to 255. The default value is 1.

- ENABLE/ DISABLE PHASES.....E (b)

When the datum is 0 (DISABLE), all motor phases are disabled until a move command is implemented. The phases are then automatically energized. Upon completion of the move command, the phases will be de-energized after a period equivalent to 255 steps at the present initial velocity. If the datum is 1 (ENABLE), all motor phases will be continuously energized. During a reset condition (using

the command C0 or the "RESET" button), phases are enabled as determined by the previously saved conditions. The default value is 0.

- FIND UPPER/ LOWER LIMIT.....F (n,b)

Upper and lower limits of the controller can be used both to prevent mechanical overtravel and to find a reference point from which additional moves can be indexed. The number "n" indicates the speed at which the limit will be approached during a "Find" command, and the bit "b" indicates the direction of the search.

- GO FROM ADDRESS, TRACE.....G (ap,b)

The user program starting at memory location "ap" is executed. Default for "ap" is 0. A "b" value of 1 implements the TRACE option which results in the display of each command as it is executed in the program run mode. Note that this form of the trace option is effective for only one program execution.

- HALF STEP/FULL STEP.....H (b)

Selection of two different phase sequences is possible. A "b" value of 1 will select the half-step sequence: one phase on/one phase off. When "b" is 0 the full step sequence is selected: two phase on/two phases off. Note that no parameters will be changed causing slew rate in half-step mode to be half that of the rate in full-step mode. Therefore initial and final velocities will need to be adjusted.

- INITIAL VELOCITY.....I (ww)

Initial velocity is set to the datum value is steps per second. As with all velocity parameters, this speed is divided by the divide factor D.

- ORIGIN SET.....O (sw)

The internal 16 bit position counter is set to the specified value. Zero position for the relative mode is 0, and a hardware RESET results in an origin value of 0 (see also "RELATIVE MOVE")

- PROGRAM FROM SPECIFIED ADDRESS...P (ap)

Program mode is entered at the address "ap" allowing the user to enter instructions for execution by the GO command or GO button. Existing program may also be edited in this mode. Upon completion of entering the instructions, and ESCape will allow exit to the command mode without insertion of an end of program marker, leaving the rest of the previous program intact. Entering an additional "P" followed by a carriage return will insert an end of program marker and exit the user to command mode. The instructions are stored in the NV memory and can be saved using the STORE command.

- RELATIVE MOVE.....R (sw)

Instructs the motor to move a specified number of steps (sw) relative to the origin set with the "O" command. Each move to the specified relative location is performed under the present control parameters and the sign of "sw" corresponds to the direction of shaft motion.

- STORE PARAMETERS/PROGRAM.....S (b)

b = 0 Stores the user program presently located in NV memory along with the following parameters:

I - Initial Velocity K - Ramp Slope V - Final Velocity E - Phase Enable T - Trip Point D - Divide Factor H - Half/ Full Step b = 1 Stores user program and parameters.

- FINAL VELOCITY.....V (ww)

Sets the final slew velocity in steps per second. This speed is used in relative or absolute moves and is always divided by the divide factor D.

- WAIT N MILLISECONDS.....W (ww)

Puts the controller in a wait state for the indicated number of milliseconds. In command mode, the wait will be executed after completion of the move. While in the program run mode, execution halts for the wait period, after which the next command is executed.

- EXAMINE PARAMETERS.....X

Present motion parameters are displayed in the following format:

F/H, K=kk (nnn), I=ii, V=vv

Where:

F/H = Full or Half Step Mode

kk = Ramp Factor

nn = Acceleration Ramp Distance (steps) ii = Initial Velocity (divided by "D") vv = Final Velocity (divided by "D")

- DISPLAY POSITION.....Z

Displays the current position counter value. This value will vary positively or

negatively dependent upon the direction of travel. The position counter is programmable via the "O" origin command.

- ABORT.....ESC

Terminates any present motor indexing without deceleration and returns the controller to COMMAND mode. The position counter update halts. Motor drivers and output ports are not affected.

- SOFT STOP.....@

Allows termination of present motor indexing, including deceleration, as controlled by the present motion parameters. When in the program run mode, program execution will terminate after deceleration is complete.



## Appendix B

**Light Intensity In Voltage and Distance  
between Objective Lens and Highly Reflective Surface  
of Different Wavelength of 10x and 20x Objective Lens**

Wavelength (nm.)							
433.5		543.5		576.0		762.0	
Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)
6.86	0.13	6.82	-2.79	6.84	-4.91	7.02	0.18
6.76	0.17	6.72	-2.67	6.74	-4.83	6.92	0.23
6.66	0.25	6.62	-2.36	6.64	-4.64	6.82	0.34
6.56	0.46	6.58	-2.11	6.6	-4.5	6.72	0.43
6.52	0.62	6.54	-1.67	6.56	-4.22	6.68	0.58
6.48	0.86	6.5	-0.95	6.52	-3.83	6.64	0.77
6.44	1.28	6.46	0.47	6.48	-2.87	6.6	1.14
6.4	2.18	6.44	1.58	6.46	-2.17	6.56	1.75
6.38	2.85	6.42	3.07	6.44	-1.28	6.54	2.22
6.36	3.76	6.4	4.98	6.42	-1.92	6.52	2.82
6.34	4.84	6.38	7.29	6.4	1.22	6.5	3.53
6.32	6.49	6.37	8.54	6.39	1.82	6.48	4.44
6.3	8.42	6.36	9.67	6.38	2.65	6.47	4.74
6.29	9.46	6.35	10.72	6.37	3.18	6.46	5.26
6.28	10.34	6.34	11.55	6.36	3.67	6.45	5.29
6.27	10.94	6.33	11.77	6.35	3.89	6.44	5.55
6.26	11.07	6.32	11.37	6.34	3.61	6.43	5.35
6.25	10.55	6.31	10.01	6.33	3.01	6.42	5.02
6.24	8.25	6.3	8.06	6.32	1.87	6.41	4.33
6.23	7.81	6.29	5.77	6.31	0.57	6.4	3.79
6.22	6.15	6.28	3.36	6.3	-0.89	6.38	2.14
6.2	3.37	6.26	-0.02	6.28	-3.15	6.36	1.04
6.18	1.76	6.24	-1.38	6.26	-4.02	6.34	0.79
6.16	1.22	6.22	-1.8	6.24	-4.33	6.32	0.68
6.14	0.94	6.2	-2.04	6.22	-4.46	6.28	0.58
6.12	0.78	6.16	-2.36	6.18	-4.66	6.24	0.51
6.08	0.5	6.12	-2.51	6.14	-4.75	6.2	0.4
6.04	0.37	6.08	-2.62	6.1	-4.81	6.16	0.36
6	0.25	6.04	-2.7	6.06	-4.86	6.06	0.27
5.96	0.22	5.94	-2.79	5.96	-4.92	5.96	0.26
5.86	0.13	5.84	-2.85	5.86	-4.95	5.86	0.21
5.76	0.12	-	-	-	-	-	-
5.66	0.09	-	-	-	-	-	-

Wavelength (nm.)							
827.0		833.5		857.5		870.5	
Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)
7.04	-0.76	7.06	0.17	7.06	-0.57	6.94	0.27
6.94	-0.72	6.69	0.21	6.69	-0.58	6.84	0.34
6.84	-0.64	6.86	0.26	6.86	-0.78	6.74	0.42
6.74	-0.47	6.76	0.43	6.76	-0.46	6.64	0.58
6.7	-0.28	6.72	0.64	6.72	-0.38	6.54	1.03
6.66	-0.06	6.68	1.04	6.68	-0.21	6.5	1.34
6.62	0.37	6.64	1.65	6.64	-0.15	6.46	1.43
6.58	1.07	6.6	2.7	6.6	0.56	6.44	1.29
6.56	1.65	6.58	3.56	6.58	0.83	6.4	1.27
6.54	2.34	6.56	4.41	6.56	1.29	6.38	1.47
6.52	3.17	6.54	5.67	6.54	1.59	6.36	1.83
6.5	3.91	6.52	7.12	6.52	2.06	6.34	2.32
6.49	4.25	6.51	7.77	6.51	2.16	6.32	3.03
6.48	4.47	6.5	8.42	6.5	2.27	6.3	4
6.47	4.55	6.49	8.76	6.49	2.35	6.29	4.52
6.46	4.61	6.48	9.04	6.48	2.55	6.28	5.05
6.45	4.38	6.47	9.23	6.47	2.28	6.27	5.42
6.44	3.77	6.46	8.89	6.46	2.21	6.26	5.63
6.43	2.97	6.45	8.53	6.45	1.63	6.25	5.55
6.42	2.13	6.44	7.47	6.44	1.36	6.24	5.02
6.4	0.62	6.43	6.08	6.42	0.73	6.23	4.43
6.38	-0.12	6.42	4.72	6.4	0.18	6.22	3.57
6.36	-0.27	6.4	2.27	6.38	-0.24	6.2	2.17
6.34	-0.38	6.38	1.18	6.36	-0.29	6.18	1.22
6.3	-0.43	6.36	0.92	6.32	-0.21	6.16	0.87
6.26	-0.51	6.34	0.68	6.28	-0.31	6.14	0.76
6.22	-0.57	6.3	0.53	6.24	-0.38	6.12	0.62
6.18	-0.67	6.26	0.68	6.2	-0.32	6.08	0.51
6.08	-0.68	6.22	0.52	6.1	-0.58	6.04	0.43
5.98	-0.77	6.18	0.22	6	-0.7	6	0.42
5.88	-0.77	6.08	0.14	5.9	-0.57	5.96	0.34
-	-	5.98	0.2	-	-	5.86	0.31
-	-	5.88	0.24	-	-	5.76	0.29
-	-	-	-	-	-	5.66	0.26
-	-	-	-	-	-	5.56	0.27

Table B.1. Light Intensity In Voltage and Distance between Objective Lens and Highly Reflective Surface of Different Wavelength of 10x Objective Lens

Wavelength (nm.)							
433.5		543.5		576.0		762.0	
Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)
3.47	0.05	3.58	0.05	3.48	0.04	3.48	0.5
3.37	0.04	3.48	0.08	3.38	0.03	3.38	0.55
3.27	0.04	3.38	0.048	3.28	0.04	3.28	0.53
3.23	0.04	3.28	0.05	3.24	0.05	3.24	0.52
3.19	0.05	3.24	0.58	3.2	0.06	3.2	0.54
3.15	0.06	3.2	0.66	3.16	0.09	3.16	0.58
3.11	0.07	3.16	0.71	3.12	0.098	3.12	0.63
3.07	0.1	3.12	0.95	3.08	0.17	3.1	0.69
3.05	0.13	3.08	0.14	3.06	0.23	3.08	0.73
3.03	0.17	3.06	0.18	3.04	0.36	3.06	0.95
3.01	0.25	3.04	0.27	3.02	0.63	3.04	1.28
2.99	0.44	3.02	0.41	3	1.25	3.02	2.12
2.97	0.81	3	0.75	2.98	2.95	3.01	3.02
2.96	1.18	2.98	1.65	2.97	4.55	3	4.33
2.95	2.14	2.97	2.66	2.96	7.4	2.99	6.25
2.94	4.1	2.96	4.55	2.95	10.98	2.98	8.91
2.93	5.71	2.95	7.56	2.945	11.4	2.97	9.25
2.92	5.11	2.94	9.42	2.94	9.67	2.96	5.26
2.91	2.89	2.93	6.24	2.93	4.46	2.95	2.23
2.9	1.26	2.92	2.83	2.92	2.01	2.94	1.5
2.89	0.69	2.91	1.1	2.91	0.99	2.93	1.2
2.87	0.34	2.9	0.7	2.9	0.67	2.92	0.98
2.85	0.21	2.88	0.38	2.88	0.38	2.9	0.74
2.83	0.12	2.86	0.25	2.86	0.24	2.88	0.7
2.81	0.11	2.84	0.18	2.84	0.19	2.86	0.64
2.79	0.09	2.82	0.14	2.82	0.14	2.84	0.57
2.75	0.07	2.8	0.11	2.8	0.11	2.82	0.55
2.71	0.06	2.76	0.08	2.76	0.9	2.78	0.54
2.67	0.05	2.72	0.07	2.72	0.5	2.74	0.52
2.63	0.04	2.68	0.06	2.68	0.5	2.7	0.55
2.59	0.04	2.64	0.05	2.64	0.5	2.66	0.52
2.49	0.05	2.54	0.05	2.6	0.24	2.62	0.53
2.39	0.04	2.44	0.05	2.5	0.3	2.52	0.52
-	-	2.34	0.05	2.4	0.23	2.42	0.51

Wavelength (nm.)							
827.0		833.5		857.5		870.5	
Distance (mm.)	Intensity (V)	Distance (mm.)	Distance (mm.)	Intensity (V)	Distance (mm.)	Intensity (V)	Distance (mm.)
3.52	-1.74	3.52	-1.15	3.54	0.71	3.48	0.1
3.42	-1.74	3.42	-1.15	3.44	0.64	3.38	0.1
3.32	-1.73	3.32	-1.14	3.34	0.65	3.28	0.12
3.28	-1.72	3.28	-1.14	3.3	0.64	3.24	0.13
3.24	-1.71	3.24	-1.14	3.26	0.7	3.2	0.14
3.2	-1.69	3.2	-1.09	3.22	0.72	3.16	0.17
3.16	-1.65	3.16	-1.05	3.18	0.69	3.12	0.19
3.12	-1.57	3.12	-1.02	3.14	0.82	3.08	0.26
3.1	-1.43	3.1	-0.96	3.12	0.86	3.06	0.39
3.08	-1.34	3.08	-0.84	3.1	0.87	3.04	0.55
3.06	-0.98	3.06	-0.65	3.08	0.92	3.02	1.05
3.04	-0.26	3.04	-0.23	3.06	1.15	3	1.94
3.02	1.7	3.02	0.98	3.04	1.62	2.98	2.1
3.01	3.62	3.01	2.25	3.03	2.15	2.97	1.81
3	6.41	3	4	3.02	2.74	2.96	2.21
2.99	9.92	2.99	6.17	3.01	3.95	2.95	3.42
2.98	11	2.985	6.68	3	4.91	2.94	6.33
2.97	5.22	2.98	6.18	2.99	5.66	2.93	9.03
2.96	0.78	2.97	2.78	2.98	4.72	2.92	7.66
2.95	-0.53	2.96	0.19	2.97	2.64	2.91	4.43
2.94	-0.88	2.95	-0.46	2.96	1.63	2.9	2.21
2.92	-1.25	2.94	-0.62	2.95	1.46	2.89	1.17
2.9	-1.45	2.92	-0.8	2.94	1.42	2.88	0.81
2.88	-1.55	2.9	-0.98	2.92	1.39	2.86	0.51
2.86	-1.58	2.88	-1.03	2.9	1.07	2.84	0.35
2.84	-1.64	2.86	-1.06	2.88	0.84	2.82	0.29
2.8	-1.69	2.84	-1.08	2.86	0.72	2.8	0.24
2.76	-1.71	2.8	-1.09	2.84	0.68	2.78	0.22
2.72	-1.71	2.76	-1.11	2.8	0.77	2.74	0.19
2.68	-1.73	2.72	-1.12	2.76	0.67	2.7	0.14
2.64	-1.73	2.68	-1.12	2.72	0.63	2.66	0.14
2.54	-1.74	2.64	-1.13	2.68	0.76	2.62	0.13
2.44	-1.74	2.54	-1.14	2.64	0.72	2.58	0.13
-	-	2.44	-1.14	2.54	0.69	2.48	0.11
-	-	-	-	2.44	0.72	2.38	0.1

Table B.2. Light Intensity In Voltage and Distance between Objective Lens and Highly Reflective Surface of Different Wavelength of 20x Objective Lens

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