# Reflected optical diffraction patterns from one-dimensional structures

**(Total marks: 12)**

## Introduction

This experiment is based on a recent discovery of a reflected high-energy electron diffraction phenomenon of a nanostructured Zinc-Selenide (ZnSe) surface that not only has a one-dimensional (1D) non-uniform modulation in nanoscale, but also has periodic atomic lattice spacing along the orientation of the 1D nanostructure (*Nanotechnology*, 20 (21), 215607(2009)). Figure 1 shows the cross-sectional image of the nanostructured ZnSe surface capped with a Au layer while the inset is an image of its surface without the Au cap.

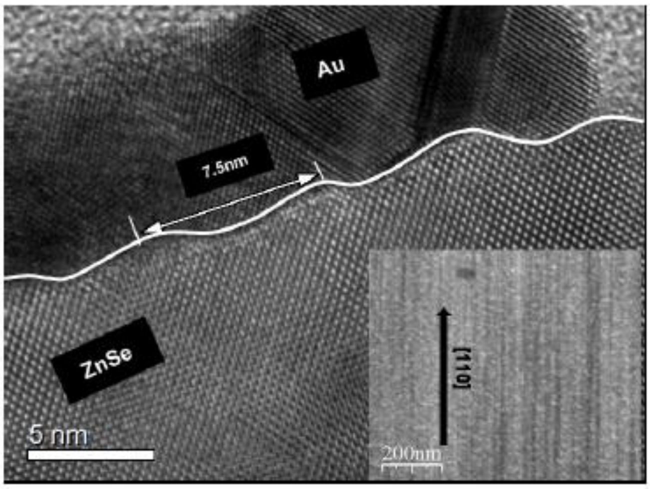


Figure 1: A cross-sectional image of the nanostructured ZnSe surface capped with a Au layer while the inset is an image of its surface without the Au cap.

## Objective

In this experiment, you are going to explore the optical analogy of this phenomenon for samples with 1D structure on a micrometer scale.

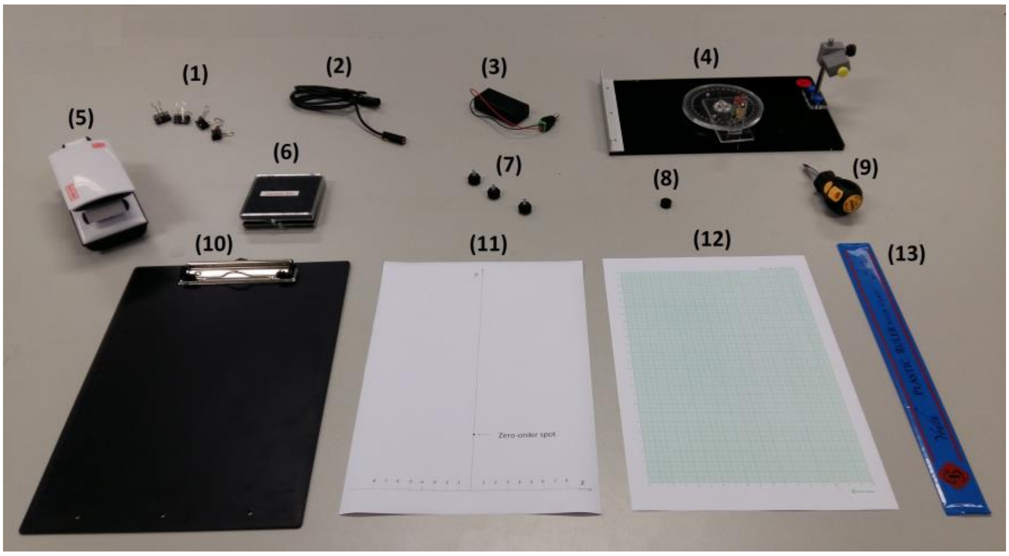


Figure 2: Apparatus and tools for this experiment

**List of apparatus and tools**

| | |
|---|---|
| [1] | 4 Paper clips |
| [2] | Laser diode |
| [3] | Battery pack with on/off switch |
| [4] | Optical platform with rotary disk, angular scale and laser-diode holder |
| [5] | LED lamp |
| [6] | Sample box containing Samples 1 to 5 |
| [7] | 3 screws for the observation board |
| [8] | Pinhole |
| [9] | Flat-head screw driver |
| [10] | Observation board |
| [11] | Alignment sheet |
| [12] | Graph papers |
| [13] | 30 cm ruler |

**Pictures of key apparatus and tools**

Figure 3: Observation board

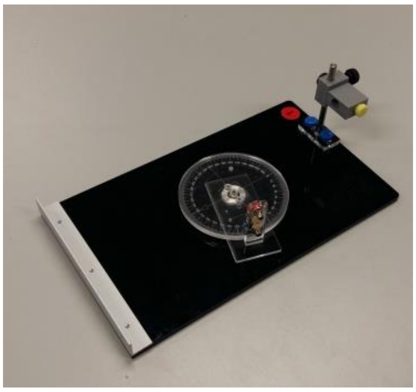

Figure 4: Optical platform with rotary disk, angular scale and laser diode holder

Figure 5: Pinhole

Figure 6: Laser diode with 0.5 mW output at wavelength of 650 nm (Class II).


Figure 7: Sample box containing samples labelled 1 to 5

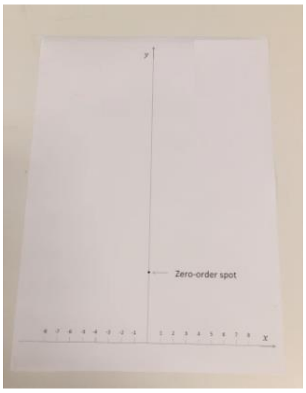


Figure 8: Alignment sheet

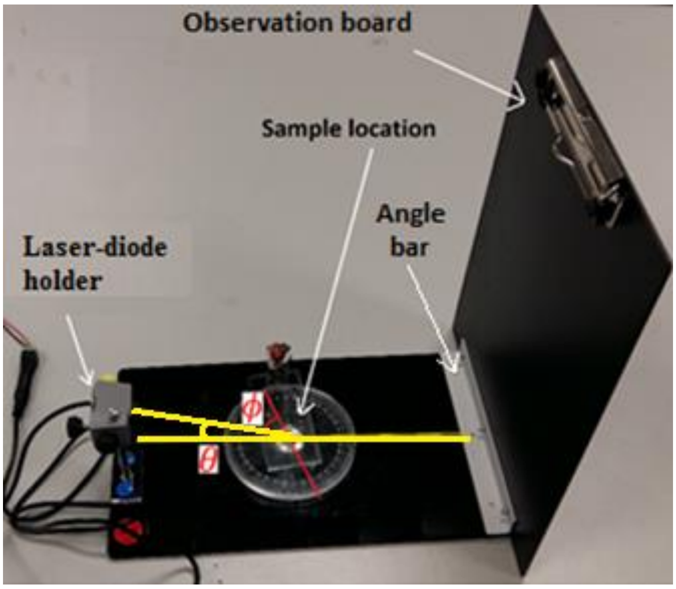


Figure 9: The setup used in this experiment. This shows how the observation board, the sample under test, the optical platform with rotary disk and the laser diode should be assembled. Angle $\boldsymbol{\phi}$ is the rotation angle of the sample. Angle $\boldsymbol{\theta}$ is the incident angle of the laser beam relative to the surface of the sample.

## Additional notes for items in the sample box

- All samples used in this experiment are squarely-shaped with dimensions of 1.5 cm × 1.5 cm. They are all labelled from 1 to 5 at one side of each sample holder.
- All sample holders have dimensions of 2.0 cm × 2.0 cm with a reference point marked as a triangle engraved near the center of one edge.
- Before placing each sample on the center of the rotary disk, you should ensure the tip of the arrow on the rotary disk is pointing to the $0^\circ$ mark of the angular scale. When placing a new sample, try to align it with the square marking on the rotary disk of the platform. The sample position at $\phi = 0^\circ$ (only refers to Samples 2 to 5) is defined when the reference point is aligned with and facing the $0^\circ$ mark on the angular scale.

| Sample | Description of the samples |
|---|---|
| 1 | A plane mirror. |
| 2 | A steel plate having straight scratch grooves parallel to two edges with non-uniform spacing. |
| 3 | A regular grating with the spacing between adjacent grooves equal to $a$, the grating constant. |
| 4 | Similar to Sample 2, but with non-uniformly spaced scratch grooves oriented at an angle of $\boldsymbol{\phi}^*$ with respect to the line joining the $0^\circ$ and $180^\circ$ marks on the angular scale of the rotary disk. |
| 5 | A steel plate that not only has straight scratch grooves with non-uniform spacing, but also has pre-made grooves with equal adjacent spacing $b$. These pre-made grooves lie perpendicularly to the straight scratch grooves with non-uniform spacing. |

## Safety precautions and general advice

1. **Caution: Do not stare into the laser beam directly!!**
2. Switch off the laser diode when it is not in use to avoid unnecessary draining of the battery.
3. Always keep the samples in an upright position. Avoid any contact with the surface of the samples.
4. Always hold the edges of the sample holder with your hands, when transferring the samples.

## Initial adjustments / procedures

1. Construct the experimental setup as shown in Figure 9. The observation board can be attached to the rotary disk using the three screws, as shown in Figure 10.

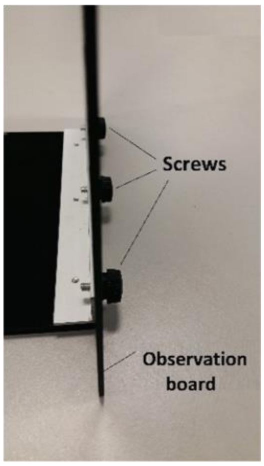


Figure 10: The observation board can be attached to the rotary disk using the three screws.

2. Mount the laser diode on the laser-diode holder. [*Note: Do not over-tighten the yellow screw when securing the laser diode to the holder; otherwise the laser diode may get damaged.*]

3. Connect the battery pack to the laser diode as shown in Figure 11.

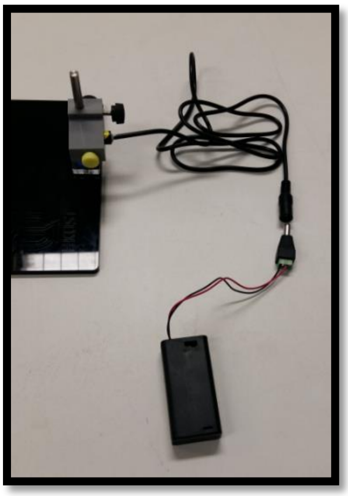

Figure 11: Laser diode connected to the battery pack.

4. Attach a piece of paper to the observation board to observe the light emitted by the laser diode, then adjust the aperture of the laser diode using a flat-head screw driver to obtain a beam spot of about 1 mm in diameter.

5. Place the laser diode in the laser-diode holder such that its head is about 5 to 10 mm out of the holder.

6. Attach the provided pinhole to the laser diode as shown in Figure 12, so that the size of the beam spot can be further reduced.

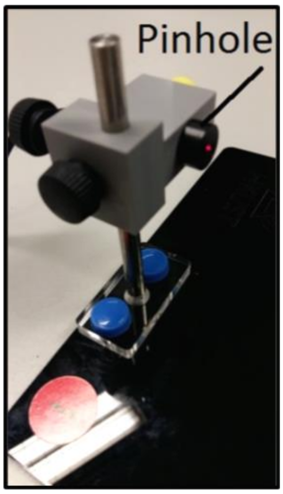


Figure 12: Laser diode with the pinhole attached.

**7.** This experiment requires that the horizontal projection of the laser beam must be aligned with the $0^{\circ}$ and $180^{\circ}$ marks on the angular scale and the laser beam must hit on the center of the sample being studied. These can be achieved by adjusting the location and tilting angle of the laser-diode holder with the screws as shown in Figure 13.

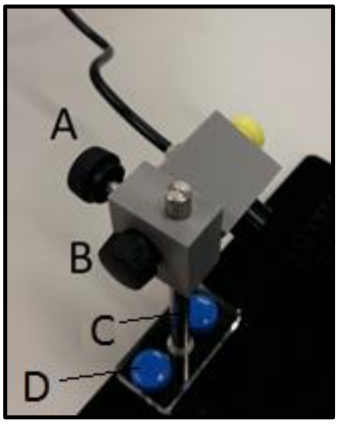


Figure 13: The location and the tilting angle of the laser-diode holder can be adjusted with the screws labelled. Screw 'A' allows the height of the laser beam to vary. Screw 'B' allows the laser beam to be tilted. Screws 'C' and 'D' allow the laser-diode holder to be adjusted horizontally.

# Experiment

## Part A: Alignment of the setup

Construct the experimental setup based on Figure 9. Note that the distance $D$ between the observation board and the center of the rotary disk has been fixed at 15 cm. Place Sample 1 at the center of the rotary disk following the procedure as described in the additional notes for items in the sample box (Page 3). Attach the alignment sheet to the observation board with the $x$-axis matching with the top edge of the angle bar holding the observation board (This can be done by folding the portion of the paper below the marked $x$-axis backward). The $x$-axis is defined in this way because the experimental setup is designed in a way that the surfaces of all the samples sitting on the rotary disk are aligned with the top edge of this angle bar. In addition, the origin of the $x$-axis must be aligned with the $180^{\circ}$ mark on the angular scale. In this experiment, the incident angle $\theta$ of the laser beam is fixed at a certain value. Adjust the height and tilting angle of the laser diode so that the laser beam hits the center of Sample 1 and the spot of the reflected laser beam overlaps with the "zero-order spot" marked on the alignment sheet.

| Tasks | | Mark |
|---|---|---|
| **A1** | Measure the height of the "zero-order spot" $h$, from the origin of the $x$-axis. Determine the incident angle $\theta$ of the laser beam from $D$ and $h$. Write down the values of $h$ in cm and $\theta$ in degrees to three significant figures in the corresponding table in the answer sheet. | **0.6** |

## Part B: Diffraction patterns from Sample 2

Replace Sample 1 with Sample 2 with the reference point on the sample holder aligned with and facing the $0^{\circ}$ mark, in which the direction of non-uniformly spaced scratch grooves of Sample 2 is parallel to the horizontal projection of the laser beam. The angle of rotation $\phi$ of the sample can be adjusted by turning the rotary disk and read from the angular scale.

Attach a graph paper to the observation board. Ensure that the bottom axis of the graph paper matches with the top edge of the angle bar holding the observation board (This can be done by folding the portion of the paper below its bottom axis backward). In addition, the origin of the $x$-axis must be aligned with the $180^{\circ}$mark on the angular scale.

| Tasks | | Mark |
|---|---|---|
| **B1** | Record the diffraction patterns on the graph paper for $\phi$ = $0^{\circ}$, $30^{\circ}$, $60^{\circ}$ and $90^{\circ}$ of the rotary disk and write down the corresponding angle of rotation $\phi$ next to each pattern. Write down "# 2" at the top of this graph paper. | **0.8** |

## Part C: Diffraction patterns from Sample 3

The experiments in this and the next tasks will help you to understand the physics behind the diffraction patterns observed in Task (B1). Remove Sample 2 from the rotary disk and replace it with Sample 3 with the reference point on the sample holder aligned with and facing the $0^\circ$ mark. For the starting position of Sample 3 (i.e. $\phi = 0^\circ$), the direction of the grating lines is parallel to the horizontal projection of the laser beam.

Attach a graph paper to the observation board. Ensure that the bottom axis of the graph paper matches with the top edge of the angle bar holding the observation board as described in Part (B). In addition, the origin of the $x$-axis must be aligned with the $180^\circ$ mark on the angular scale.

| Tasks | | Marks |
|---|---|---|
| **C1** | Mark the centers of the diffraction spots from Sample 3 for $\phi = 0^\circ$, $30^\circ$, $60^\circ$ and $90^\circ$ on the graph paper and write down the corresponding angle of rotation $\phi$ next to each pattern. Write down "# 3" at the top of this graph paper. | **0.8** |

After completing Tasks (B1) and (C1), you should have realized that the reflected diffraction patterns from Sample 2 are continuous while those from Sample 3 are discrete. The reason is that since the spacing between the neighboring straight scratch grooves of Sample 2 is non-uniform, so it is like a grating with its grating constant covers various values. Thus, its diffraction patterns follow the general shapes of the diffraction patterns from a regular grating (like those of Sample 3), however, the diffraction spots become broadened and form the continuous patterns as observed.

## Part D: Theory behind the reflected diffraction patterns from Sample 3

The origin of the reflected diffraction patterns from a regular grating like Sample 3 can be understood with geometrical optics. In this experiment, we define the $x$-$y$-$z$ coordinate system with the origin at the center of the sample as shown in Figure 14.

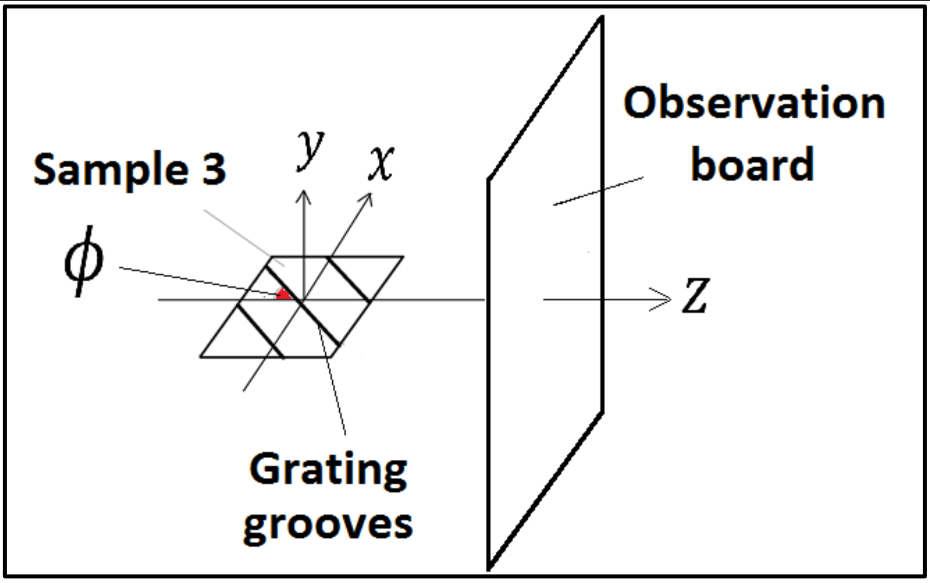


Figure 14: The definition of the ***x*-*y*-*z*** coordinate system used in this task, in which $\boldsymbol{\phi}$ is the rotation angle of the sample, with the observation board perpendicular to the *z*-axis.

Using geometrical optics, one can derive the following equations for the reflected diffraction patterns from Sample 3,

$$y^2 = \frac{(D\cos\phi + x\sin\phi)^2}{\cos^2\theta\,\cos^2\phi} - x^2 - D^2 \qquad (1)$$

$$x = \frac{Dm\lambda\cos\phi}{a\cos\theta - m\lambda\sin\phi} \quad , \qquad (2)$$

where $\lambda$ is the wavelength of the incident laser beam and $m$ is the order number of diffraction. One can predict the $x$ and $y$ co-ordinates of the diffraction spots as a function of $\phi$ using Equations (1) and (2), which can be demonstrated to be consistent with the observed patterns recorded in Task (C1).

Based on Equations (1) and (2), the diffraction spots for $\phi = 90^0$ should lie along the $y$-axis at $x = 0$ with their y-coordinates expressed by the following equation:

$$y = D\sqrt{\frac{a^2}{(a\cos\theta - m\lambda)^2} - 1} \qquad (3)$$

| Tasks | | Marks |
|---|---|---|
| **D1** | Equation (3) can be rearranged to obtain a quadratic equation for the grating constant $a$ of Sample 3, as<br>$$Aa^2 + Ba + C = 0. \qquad (4)$$<br>Derive the expressions for $A$, $B$ and $C$. Enter your results in the corresponding table in the answer sheet. | **0.9** |

| | | |
|---|---|---|
| **D2** | By solving this quadratic equation and using the measured $y$ values of the diffraction spots for Sample 3 at $\phi = 90^0$ (See Task (C1)), together with the known values of $D$, $\theta$ and $\lambda$, determine the grating constant $a$ of Sample 3 in meters to three significant figures for each diffraction order from the 1st order ($m$ = 1) up to the 6th order ($m$ = 6) [*Hints: These orders correspond to the six spots above the zero-order spot*]. Enter your results in the corresponding table in the answer sheet. | **1.8** |
| **D3** | Calculate the mean for the grating constant $a$ in meters to three significant figures and the standard error of the mean. Enter your results in the corresponding table in the answer sheet. | **0.8** |

## Part E: Determination of the unknown angle $\phi^*$ for Sample 4

Replace Sample 3 with Sample 4 with the reference point on the sample holder aligned with and facing the $0^\circ$ mark. In placing Sample 4 onto the rotary disk, the side of its sample holder close to the reference point should be perpendicular to the laser beam.

Attach a graph paper on the observation board. Ensure that the bottom axis of the graph paper matches with the top edge of the angle bar holding the observation board (This can be done by folding the portion of the paper below its bottom axis backward). In addition, the origin of the $x$-axis must be aligned with the $180^\circ$ mark on the angular scale.

| Tasks | | Marks |
|---|---|---|
| **E1** | Along the continuous diffracted curve of Sample 4 projected on the graph paper, measure the $y$-coordinates in cm for ten points starting from $x$ = - 1.0 cm to 3.5 cm with a step of 0.5 cm. Enter your results in the corresponding table in the answer sheet. | **0.6** |
| **E2** | Based on Eq. (1) given in Task (D), construct a linear equation in the form of<br>$$M(y,x,D,\theta) = I(D) + S(\phi^*)x\,. \quad (5)$$<br>Determine the functional forms for $M(y,x,D,\theta)$, $I(D)$ and $S(\phi^*)$. Plot $M$ against $x$, using the data recorded in E1. Determine the unknown angle $\phi^*$ in degrees from this graph. Write down all the functional forms and the value of $\phi^*$ in the corresponding table in the answer sheet. | **1.6** |

## Part F: Diffraction patterns from Sample 5

Replace Sample 4 with Sample 5 with the reference point on the sample holder aligned with and facing the $0^\circ$ mark. The geometry of Sample 5 is shown in Figure 15. For the starting position of Sample 5, the direction of non-uniformly spaced scratch grooves is parallel to the horizontal projection of the laser beam.

Attach a graph paper to the observation board. Ensure that the bottom axis of the graph paper matches with the top edge of the angle bar holding the observation board (This can be done by folding the portion of the paper below its bottom axis backward). In addition, the origin of the $x$-axis must align with the $180^{\circ}$ mark on the angular scale.

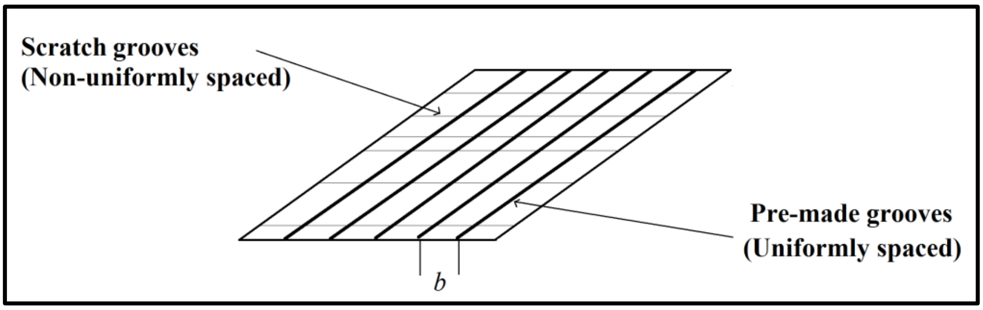


Figure 15: The structure of Sample 5, where the scratch grooves are non-uniformly spaced and the pre-made grooves are uniformly spaced. The adjacent spacing between the pre-made grooves is $\boldsymbol{b}$.

| Tasks | | Marks |
|---|---|---|
| **F1** | Record the diffraction patterns you observed for $\phi = 0^{\circ}$, $30^{\circ}$, $60^{\circ}$ and $90^{\circ}$ on separate graph papers for each value of $\phi$. At the top of each graph paper, put down '#5' and the corresponding $\phi$ value. It is expected that you could observe more than 10 diffraction orders. However, you are required to record only three relatively brighter orders on each graph paper. | **0.8** |

The sample structure of Sample 5 can be considered as a combination of Sample 2 and Sample 3, where the uniformly-spaced pre-made grooves are placed perpendicularly to the scratch grooves with non-uniform spacing. This is an optical analogy of the nano-grating as described in the introduction.

| Tasks | | Marks |
|---|---|---|
| **F2** | With this understanding, estimate the spacing $b$ in meters of the uniformly spaced pre-made grooves of Sample 5 using the recorded diffraction pattern for $\phi = 0^{\circ}$ from Task (F1). Enter the value of $b$ in the answer sheet.<br><br>[*Note that in estimating the value of* $b$, *you are only required to take the measured data of the first diffraction order and the estimated* $b$ *should be rounded up to three significant figures.*] | **1.6** |

## Part G: Determination of the lattice-plane spacing for ZnSe

As mentioned in the introduction, the above phenomenon was firstly discovered on the reflection high energy electron diffraction (RHEED) patterns of a nanostructured ZnSe surface. Such a surface has a one-dimensional (1D) modulation in nanoscale with non-uniform spatial separation, as well as having periodic atomic lattice planes perpendicular to these nano-grooves. Figure 16 shows the RHEED pattern of such a nanostructured ZnSe surface when the electron-beam is perpendicular to the nano-grooves with non-uniform spacing (Hint: With respect to the periodic atomic lattice planes, such a condition corresponds to $\phi = 0^{\circ}$)

Note that the spacing of the streaks in this figure, which can be measured using the given scale below the RHEED pattern, matches exactly with the actual diffraction pattern projected on the fluorescence screen (an analogy to the observation board used in this experiment).

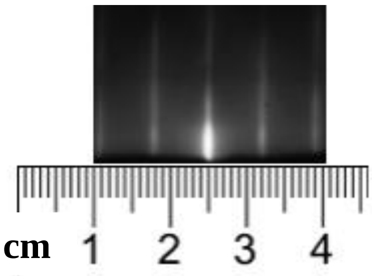


Figure 16: The reflection high energy electron diffraction (RHEED) pattern from a nano-structured surface of ZnSe, when the electron-beam is perpendicular to the nano-grooves with non-uniform spacing.

In taking the diffraction pattern shown in Figure 16, the accelerating voltage of the electron gun was set to be $V$ = 13,000 volts. The corresponding wavelength $\lambda$ of the high-energy electrons incident to the center of the sample surface can be calculated by

$$\lambda = \frac{12.247\times10^{-10}}{\sqrt{V(1+10^{-6}V)}}\,[\text{m}], \tag{6}$$

where the relativistic effect has been taken into account.

The incident angle of the electron beam to the surface of the ZnSe sample is $\theta \approx 0^{\circ}$ and the distance between the fluorescence screen and the incident spot of the electrons on the nano-structured ZnSe surface is $D$ = 26 cm.

| Tasks | | Marks |
|---|---|---|
| G1 | For the ZnSe sample, based on Figure 16 and the experimental conditions given above, determine the lattice-plane spacing $a^*$ of the periodic atomic lattice planes that are perpendicular to the nano-grooves with non-uniform spacing, in meters to three significant figures. Enter your result in the corresponding table in the answer sheet. | **1.7** |

**END**

# Reflection Phase Shift of Metal (Total marks: 8.0)

## Introduction

It is known that natural materials have refractive indexes ($n$) larger than that of vacuum ($n > n_o = 1$). However, meta-materials (artificial materials with nano-scale structures) can exhibit exotic phenomena, such as negative refraction which can be explained by considering negative effective refractive index. In general, the refractive index of a material, for instance metal, can also be a complex number when there is light absorption.

A simple method to study complex refractive index is by measuring the phase shift $\phi$ when a light beam is being reflected from the surface of a material. In optics, the phase shift due to reflection from a surface is important for many applications especially those in holographic measurements.

For ordinary glass, the reflection phase shift $\phi$ for normal incidence is $180^o$ (or $\pi$ in radian). However, $\phi$ can take different values for metals, depending on the absorptions of the metals. Phase measurement in optics is challenging and high precision is required. Many sophisticated techniques or methods have been developed for optical phase measurements. However, they are too complicated to be implemented for high school students. Here, we introduce a simple and inexpensive approach.

## Objective

To study the phase shift of light reflected from Titanium (Ti) surface using Fabry-Perot laser interferometry.

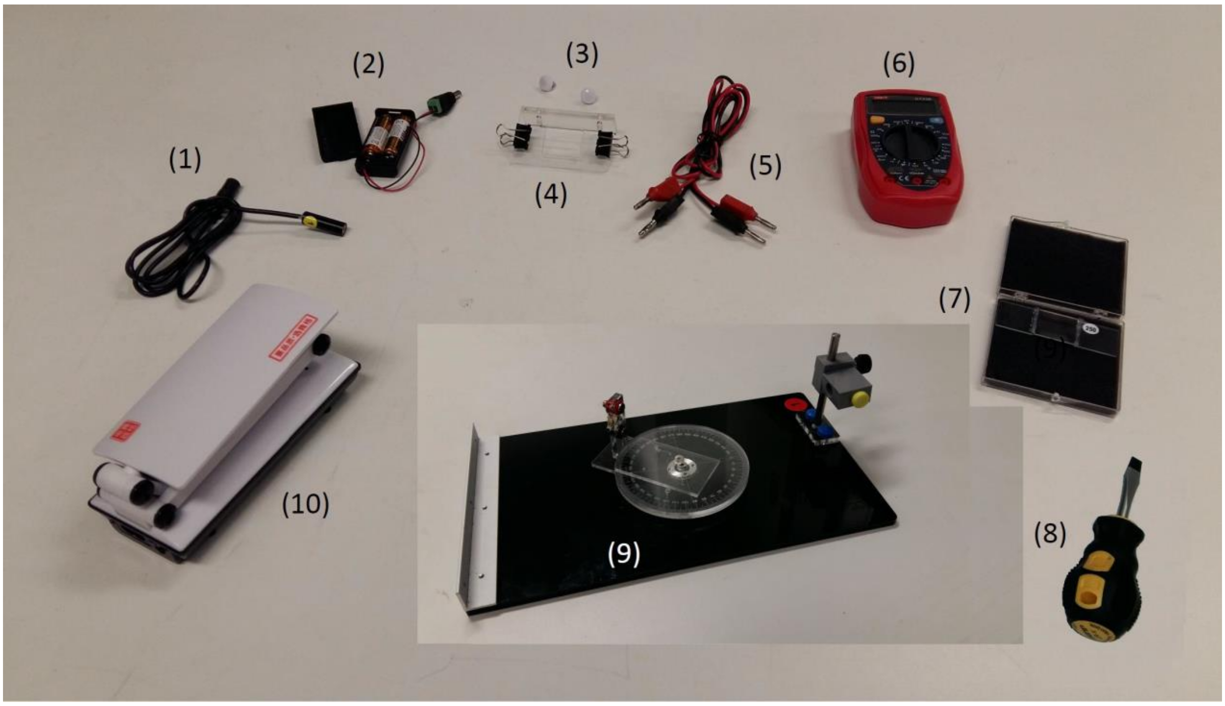


Figure 1: Apparatus for this experiment

## List of apparatus

| | |
|---|---|
| [1] | Laser diode |
| [2] | Battery pack with batteries for the laser diode |
| [3] | White-color-capped screws for sample holder |
| [4] | Sample holder with two paper clips |
| [5] | Wires with banana connectors |
| [6] | Digital multi-meter |
| [7] | Sample box with one Titanium (Ti)-coated Fabry-Perot etalon with specific sample number |
| [8] | Flat-head screw driver |
| [9] | Optical platform with rotary disk, turntable detector holder, fixed angular scale, and laser diode holder |
| [10] | LED lamp |

## Description of apparatus

Figure 2: Laser diode with 0.5 mW output at wavelength of 650 nm (Class II)

Figure 3: Battery pack with 2×1.5V AA batteries and outlet plug for the laser diode

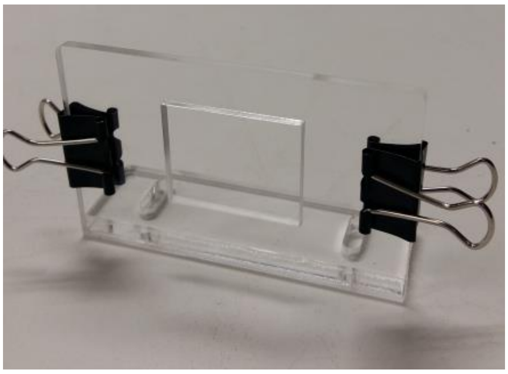

Figure 4: Sample holder with two paper clips

Figure 5: Digital multi-meter and wires with banana connectors


Figure 6: Sample box and one Ti-coated Fabry-Perot (FP) etalon (for illustration purpose, the sample number in this figure is #250)

Figure 7: Flat-head screw driver for adjusting the beam size of the laser diode

Figure 9: LED lamp for reading and writing

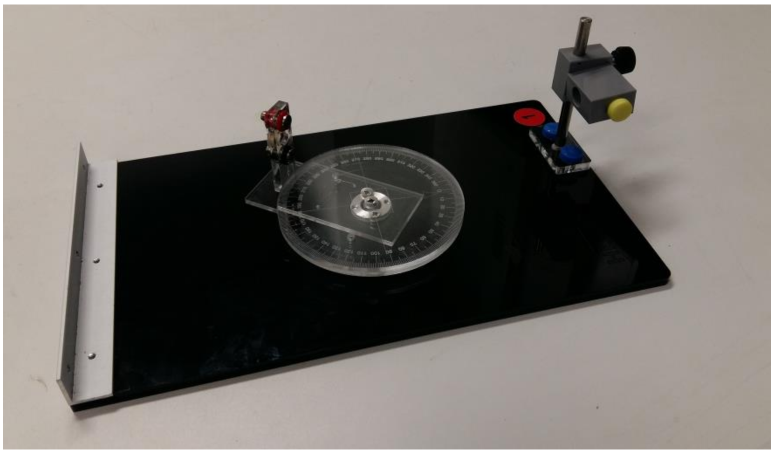

Figure 8: Optical platform consisting of a rotary disk, a turntable detector holder, a fixed angular scale, and a laser diode holder

## Theory

Consider an ideal air-gap Fabry-Perot (FP) etalon as shown in Figure 10. The etalon consists of a top thick glass plate (with refractive index $n_g$) and a bottom sample plate (with refractive index $n_s$) sandwiching a thin air-gap ($L$ ~ 5 micron) in-between.

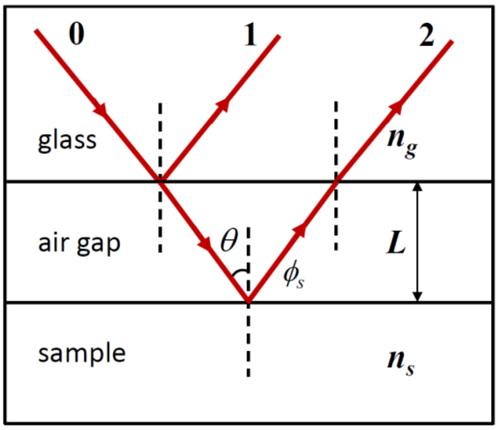


Figure 10: Light reflections from an ideal air-gap Fabry-Perot etalon consisting of a top glass plate and a bottom sample plate.

We use a two-beam interference approximation to model the air-gap etalon. A light beam (beam 0) incident on the top glass plate, neglecting the reflection from the air-glass interface of the top glass, is partially reflected (beam 1) and partially transmitted (refracted) at the glass-air interface. The transmitted (refracted) beam then gets reflected at the air-sample interface and then transmitted (refracted) through the top glass plate, which is labeled as beam 2 shown in Figure 10. For beam 2, the reflection at the air-sample interface picks up an additional phase shift $\phi_s$ while there is no phase shift at other interfaces. The resulting intensity of reflected light $I(\theta)$ for incident angle $\theta$ is the superposition of beams 1 and 2 given by:

$$I(\theta) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(2kL\cos\theta + \phi_s), \quad (1)$$

where $I_1$ and $I_2$ are the intensities of beams 1 and 2, respectively, $k = \frac{2\pi}{\lambda}$ is the wavenumber and $\lambda$ is the wavelength of the incident light. Equation (1) exhibits intensity peaks and troughs as a function of incident angle $\theta$ for fixed wavelength $\lambda$ and air-gap spacing $L$. In this experiment, we fix the polarization direction of the incident light and neglect polarization effects when the beam is reflected/refracted at the interfaces. Moreover, we use a Titanium (Ti)-coated glass plate as the bottom sample plate of the FP etalon.

## Preparatory procedures/adjustments

**1. If you have chosen to do experiment E1 first, remember to remove the observation board and also the pin hole for E1 before assembling the apparatus for this experiment E2.**

**2. CAUTION: DO NOT LOOK DIRECTLY AT THE LASER LIGHT OF THE LASER DIODE!!**

3. Install the laser diode into the circular hole of the laser holder as shown in Figure 11. Fasten the laser diode by using the yellow-color-capped screw. Make sure the body of the laser head is horizontal with the attached yellow label (see Figure 2 the laser diode with the yellow label) facing up (for setting the polarization of the laser light in the vertical direction). [*Note: Do not over-tighten the* (*yellow-color-capped*) *screw of the laser holder; otherwise it will damage the laser diode!*]

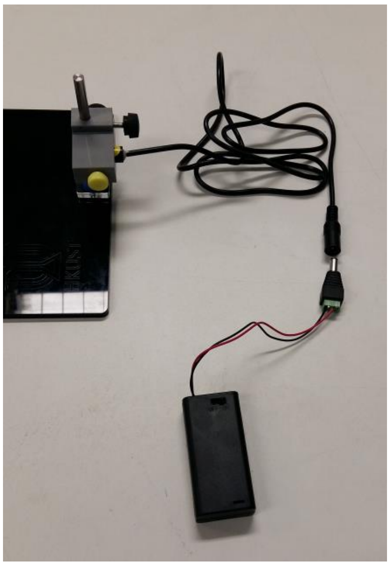

Figure 11: Laser diode mounted inside the laser holder

4. Connect the battery pack to the laser diode as shown in Figure 11 and switch on the laser diode.

5. It is desirable to have the laser diode to form a beam spot about 1 mm in diameter at a distance of 20 cm. To check the beam size, place a piece of paper at about 20 cm from the laser diode and observe the spot size of the laser beam emitted by the laser diode. Adjust the aperture of the laser diode using a flat-head screw driver to obtain a spot size about 1 mm in diameter if necessary.

6. Connect the output terminals of the photo-detector pre-mounted on the detector holder to the multi-meter **CAREFULLY** using the electric wires as shown in Figure 12. The photo-detector is a photodiode connected in parallel with a resistor such that the current produced by the photodiode when illuminated with light can be recorded by measuring the voltage across the resistor.

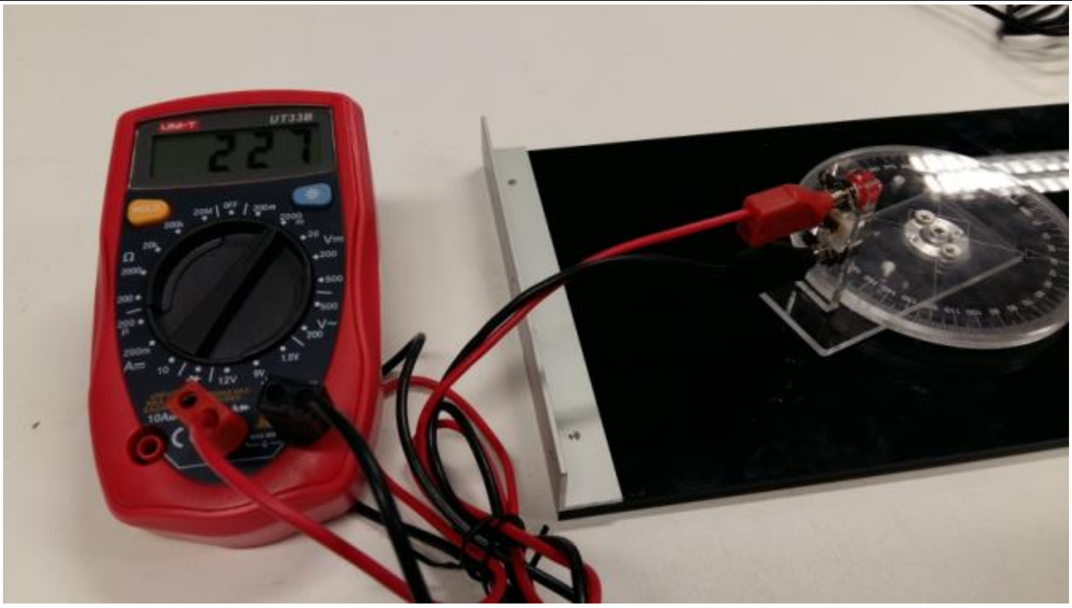

Figure 12: Photo-detector connected to the multi-meter

7. Adjust the position of the laser diode such that the laser beam shoots horizontally over the $0^o$ mark of the angular scale, crossing over the center of the rotary disk, and hits directly onto the detector positioned at the $180^o$ mark of the angular scale (as shown in Figure 13). You can turn on the multi-meter to monitor the intensity (in terms of voltage) of the laser beam to obtain an optimal condition. [*Note: Remember to turn off the laser diode when you are done with this step!*]

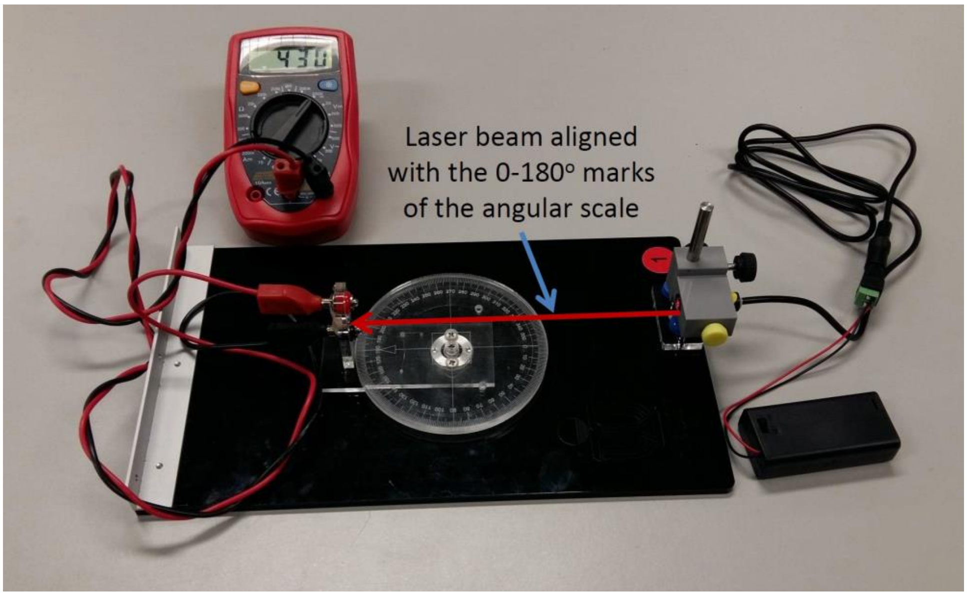


Figure 13: Alignment of the laser beam

8. Mount the sample holder to the rotary disk on the optical platform using the white-color-capped screws as shown in Figure 14.

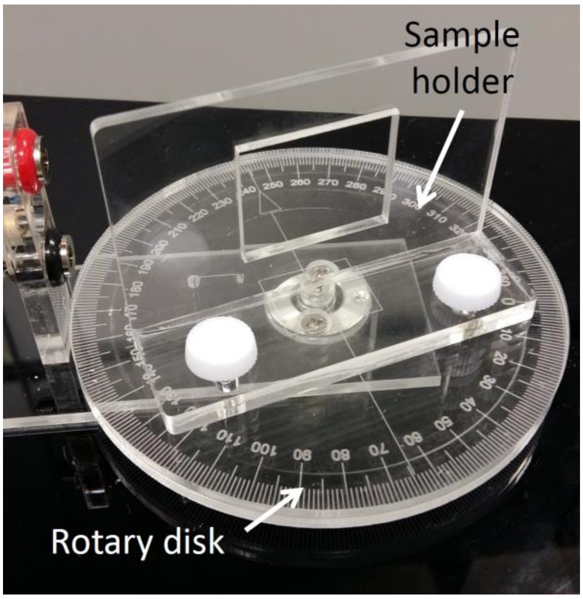


Figure 14: Sample holder mounted on the rotary disk

9. Then mount the Ti-coated etalon with the sample number (here #250) upright to the sample holder using the two paper clips provided such that the bottom glass plate of the sample is in contact with the wall surface of the holder as shown in Figure 15.

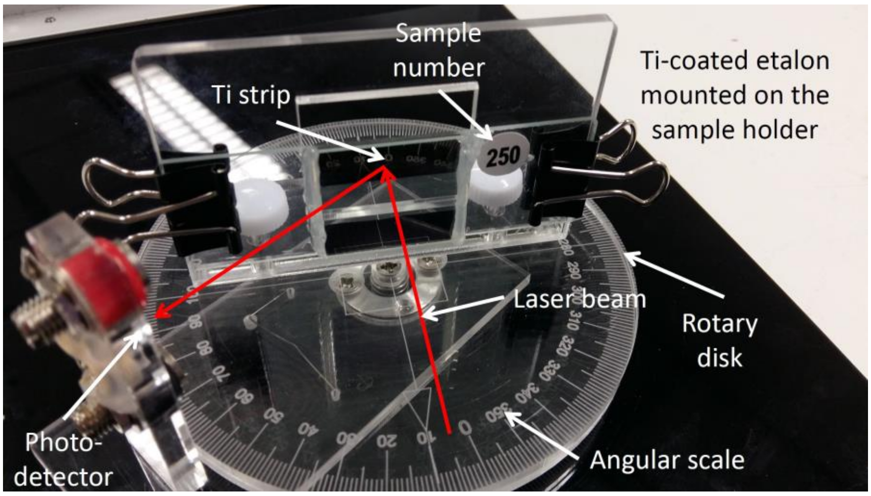


Figure 15: Sample mounted on the sample holder

10. Turn on the laser diode and adjust the vertical position of the etalon so that the laser beam shoots at the middle area of the top or the bottom Ti strip of the etalon and gets reflected to the photo-detector as shown in Figure 15. Then adjust the position of the photo-detector for maximum signal (in terms of the voltage measured by the multi-meter). Furthermore, you have to adjust the position of the sample holder using the two white-color-capped screws such that the Ti strip rotates with the same axis as the rotary disk, i.e. they are coaxial.

11. Now rotate the sample holder together with the mounted Ti-coated etalon such that the laser beam makes an incident angle $\theta$ with respect to the normal of the sample surface as indicated by the angular scale. Then move the photo-detector to an angle of about $2\theta$ and adjust the angular position of the photo-detector for obtaining a maximum signal from the multi-meter. After completing all the above steps/procedures, the setup is now ready for the experiment.

**Note: All numerical values and answers should have three significant figures.**

## The Experiment

| Tasks | Description | Marks |
|---|---|---|
| **1** | Measure the reflection intensity of the Ti-coated etalon in terms of voltage as a function of incident angle $\theta$ at fine enough angular steps, starting at $\theta \sim 4^o$ such that as many intensity peaks as possible are recorded. Enter your data in Table E2_1. | **1.0** |
| **2** | In order to reduce errors resulted from the mis-alignment of the laser beam with respect to the sample holder, and also with respect to the angular scale of the optical platform, carry out similar measurements for incident angles on the other side of the $0^o$ mark of the angular scale by first turning the sample to face the opposite side of the $0^o$ mark of the angular scale and then moving the photo-detector accordingly for measuring intensity of the reflected laser beam. Enter your data in Table E2_2. | **1.0** |
| **3** | Plot the reflection intensity as a function of incident angle $\theta$ on a graph paper using the recorded data in Table E2_1 and label the graph as 'Graph E2_1'. Plot a similar graph for the data in Table E2_2 on a different graph paper and label the graph as 'Graph E2_2'. Show the variation of the reflection intensity by drawing a smooth curve fitting the data points in Graph E2_1 as well as in Graph E2_2. | **0.9** |
| **4** | Identify the peaks of the reflection intensity and label them with sequential peak numbers in Graphs E2_1 and E2_2, starting with the peak having the largest incident angle. | **0.2** |
| **5** | Derive the condition for the reflection intensity peaks in terms of $L$, $\theta$, $\phi_s$, $\lambda$ using Equation (1). Label this condition as Equation (2). | **0.3** |
| **6** | Choose a suitable function of $\theta$, $X(\theta)$, as a new independent variable such that the reflection intensity peaks in Graphs E2_1 and E2_2 will be evenly spaced in a graph of reflection intensity vs $X(\theta)$. Then calculate the corresponding values of $X(\theta)$ and insert them, as a new column, to Tables E2_1 and E2_2. | **0.4** |
| **7** | Construct Table E2_3 consisting of the peak number and the corresponding incident angle for the data in Tables E2_1 and E2_2. You may label them with the notations of LHS (left-hand side) and RHS (right-hand side), respectively, i.e. $\theta_{LHS}$ and $\theta_{RHS}$ . Then, for each matched reflection intensity peak, calculate the average values of $\theta_{LHS}$ and $\theta_{RHS}$, and label the average as $\|\theta\|_{avg}$ and $X(\|\theta\|_{avg})$ and enter the results as new columns in Table E2_3. [Note: The peak numbers in Tables E2_1 and E2_2 can be different. Make sure you match the corresponding peaks obtained from Graphs E2_1 and E2_2.] | **0.6** |
| **8** | Plot a graph on a separate graph paper to show the relationship between the peak number vs. $X(\|\theta\|_{avg})$. Label this graph as 'Graph E2_3'. | **0.6** |

| | | |
|---|---|---|
| **9** | Draw a straight line through all the data points in Graph E2_3 and then determine the slope and $y$-intercept of this line. [Note: A graphical approach will also be accepted and error analysis is not required.] | **0.4** |
| **10** | Rewrite Equation (2) derived in Task 5 to give an expression of the interference order $m$ and the function $X(\lvert\theta\rvert_{\text{avg}})$ obtained in Task 6. Label this equation as Equation (3a). From Equation (3a), write down the expression of $m$ in terms of $L$, $\lambda$, and $\lvert\theta\rvert_{\text{avg}}$ as Equation (3b). Hence, express the normalized reflection phase $\phi_{\text{s,n}} = \phi_{\text{s}}/2\pi$ in terms of $L$, $\lambda$, and $\lvert\theta\rvert_{\text{avg}}$ as Equation (3c). Write down the range of $\phi_{s,n}$. Then determine the values of $m$ for the peaks from the results obtained in Task 7 and insert them as a new column in Table E2_3. | **1.2** |
| **11** | Plot $m$ vs. $X(\lvert\theta\rvert_{\text{avg}})$ on Graph E2_3, i.e. the same graph for the plot of peak number vs. $X(\lvert\theta\rvert_{\text{avg}})$. Draw a line through all data points for this plot. Hence determine the air-gap spacing $L$ of the etalon and also the reflection phase $\phi_{\text{s}}$ of the Ti. [Note: Again, graphical solution is acceptable and error analysis is not required.] | **1.4** |

**END**