Waves Physics Lab Notebook

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&

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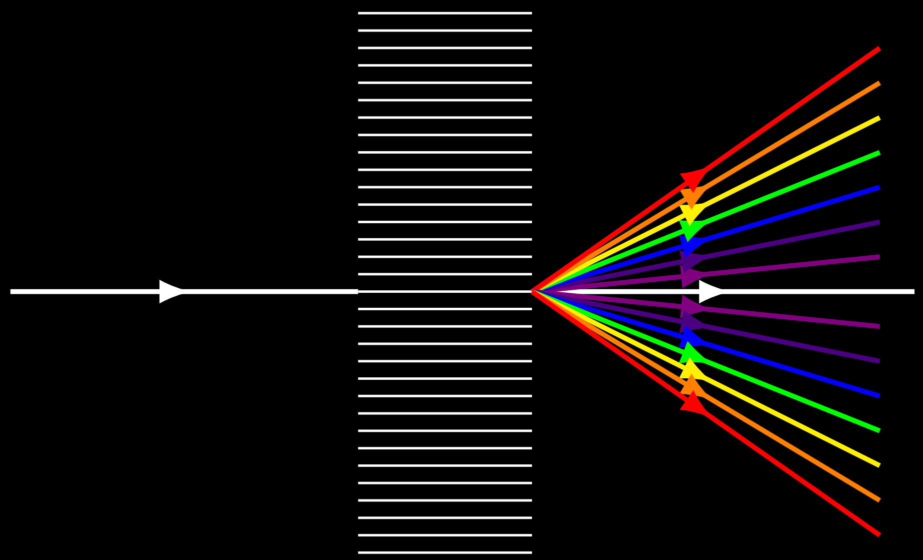
Under the Supervision of Prof. Bandar Al-Asbahi



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“One does not become enlightened by imagining figures of light, but by making the darkness conscious.”

-C.G Jung, Psychology and Alchemy

Contents

Introduction

The experiments, observations, and analyses carried out in **Waves Physics Lab** are fully documented in this notebook. Keeping a thorough and structured notebook is essential for students in the Waves Physics Lab to record their work and ensure experiment reproducibility.

It's critical to keep a uniform structure and follow proper scientific procedures in order to ensure the efficacy of your notebook. Each record should include the date, experiment, a brief explanation of the goal, the tools and supplies used, step-by-step instructions, measurement of error, thorough observations, and results. Keep track of any adjustments you made to the experiment, any unexpected observations you made, any difficulties you ran into, and any prospective improvements you can make in the future.

On the Reproducibility of Experiments

It is important to acknowledge that the experiments you are about to carry out have been conducted by hundreds of students before you. While this fact might initially seem unexciting, it is, in fact, the essence of the scientific method.

By comparing your data with that of past groups, you can gain valuable insights into the accuracy of the device you are using and the reliability of the data you are gathering. This comparative analysis allows you to assess the consistency and validity of your results, providing a broader context for your findings. Therefore, rather than considering it tedious, viewing the work of previous students will enhance your understanding of the scientific process and contribute to the rigor and reliability of your own experiments. Embrace the opportunity to build upon the knowledge and efforts of others, recognizing the collaborative nature of scientific inquiry.

The Ideal Report

Figure 1 shows some reports -written by the authors- that encompass all the aforementioned requirements:

Diffraction Grating

Goals:

- Calculating the wavelengths of different colours of visible light.

- Understanding how diffraction grating works.

Equations:

$n\lambda = d\sin\theta$, $d = 1/N$.

n: Order of fringes

λ: Wavelength (m).

d: Distance between two slits (m).

θ: Angle of diffraction (°).

N: Number of slits per millimetre ($\frac{Grooves}{mm}$).

Experimental Steps:

1- Turn on the spectral lamp and ensure that the light is collimated by the lens and aligned perpendicularly to the slit of the grating.

2- Position the monocular in a way that allows you to precisely observe the white light at the perpendicular lines.

3- Once you have successfully centered the white light, you can now adjust the position of the monocular as needed to observe the visible spectrum from both sides.

4- Now, you need to observe the same colour from both sides and measure corresponding angles θ_R and θ_L.

5- Repeat step 4 for every visible colour.

For the first rank $n=1$:

Colour	θ_L (°)	θ_R (°)	Diffraction angle θ	λ (nm)
Purple	159.783	173.867	7.042	408.24
Indigo	159.016	174.433	7.708	446.86
Blue	158.333	175.75	8.709	504.19
Green	157.333	176.408	9.538	551.76
Yellow	156.725	177	10.14	586.12
Red	156	177.817	10.91	630.17

Calculation of error:

$\lambda = d\sin\theta \rightarrow \frac{\Delta\lambda}{\lambda} = \frac{\Delta d}{d} + \cot\theta\,\Delta\theta$

$\Delta\lambda = [(1/300 + \cot(7.042°)(8.33\times10^{-3})](408.24\,nm)$

$= 28.89\,nm$

$\bar{\lambda} = 408.24 \pm 28.89\,nm$ $\quad \frac{\Delta\lambda}{\lambda}(100\%) = 7.08\%$

التجربة 1 محزوز الحيود

* الهدف من التجربة:

- حساب الأطوال الموجية لألوان الطيف باستخدام محزوز الحيود.
- التعرف على ظاهرة الحيود.

* القوانين المستخدمة:

$n\lambda = d\sin\theta \rightarrow \frac{n\lambda}{d} = \sin\theta \le 1$

$d = \frac{1}{N} = \frac{1}{300\,lines/mm} = \frac{10^{-3}}{300}\,m = 3.33\times10^{-6}\,m$

شرح الرموز:

n) رتبة هدبة الحيود

λ) الطول الموجي (m)

d) المسافة بين شقين متتاليين (m)

θ) زاوية الحيود (°)

N) عدد الشقوق في المليمتر الواحد

$2\theta = |\theta_R - \theta_L|$

$\theta = \frac{|\theta_R - \theta_L|}{2}$

بأخذ الرتبة الأولى n=1

$\lambda = d\sin\theta$ (nm)	زاوية الحيود θ (°)	قراءة التدريج θ_L (°)	قراءة التدريج θ_R (°)	اللون
408	7.042	159.783	173.867	بنفسجي
447	7.7085	159.016	174.433	نيلي
504	8.7085	158.333	175.75	أزرق
552	9.5375	157.33	176.408	أخضر
586	10.1375	156.725	177	أصفر
630	10.9085	156	177.817	أحمر

* حساب نسبة الخطأ:

$n=1$, $d=\frac{1}{N}$

$n\lambda = d\sin\theta$

$\ln\lambda = \ln d + \ln\sin\theta$

$\ln\lambda = \ln\frac{1}{N} + \ln\sin\theta$

$\frac{d\lambda}{\lambda} = \frac{dN}{N} + \frac{d\theta\cos\theta}{\sin\theta}$, $= D = \frac{\Delta d}{d}$

* الخطأ الأعظمي: $\frac{\Delta\lambda}{\lambda} = \frac{\Delta N}{N} + \frac{\Delta\theta\cos\theta}{\sin\theta}$

$\Delta\lambda = \lambda[D + \Delta\theta\cot\theta]$

* نسبة الخطأ للون الأخضر:

$\Delta\lambda = \lambda[D + \Delta\theta\cot\theta] \rightarrow \theta = 9.5375°$

$\Delta\lambda = 10.94\,nm$

* الخطأ المطلق: $\bar{\lambda} = \lambda \pm \Delta\lambda$

$\bar{\lambda} = 552\,nm \pm 10.94\,nm$

* الخطأ النسبي المئوي: $\frac{\Delta\lambda}{\lambda}(100\%) = \frac{10.94\,nm}{552\,nm}$

$\frac{\Delta\lambda}{\lambda} = 1.98\%$

Figure 1: Ideal Reports

Experiment 1

Diffraction Grating

Objectives

1. Understanding how diffraction grating works.
2. Finding the wavelengths λ of the main colours of the visible spectrum.

1.1 Theory

A diffraction grating is an optical device made of glass or plastic that features a flat surface covered in a regular pattern of parallel lines or grooves. These lines or grooves are typically engraved or precisely spaced on the surface and can range in number from 300 to 600 per centimeter (or more).

Diffraction is a phenomena that happens to light when it passes through an aperture. When a wave contacts a slit or an aperture that is the same size as its wavelength, diffraction takes place. In a diffraction grating, the slits or apertures are represented by the grooves.

As shown in Figure 1.1, diffraction grating's dispersion effect causes white light, which is made up of a mixture of different wavelengths that correspond to distinct colours, to separate into its component. A spectrum is created when the various colours diverge at various angles. The resulting spectrum makes clear which specific wavelengths or colours make up white light. We can identify the precise wavelengths present and deduce the makeup of the white light by examining the locations and intensities of the various colours in the spectrum.

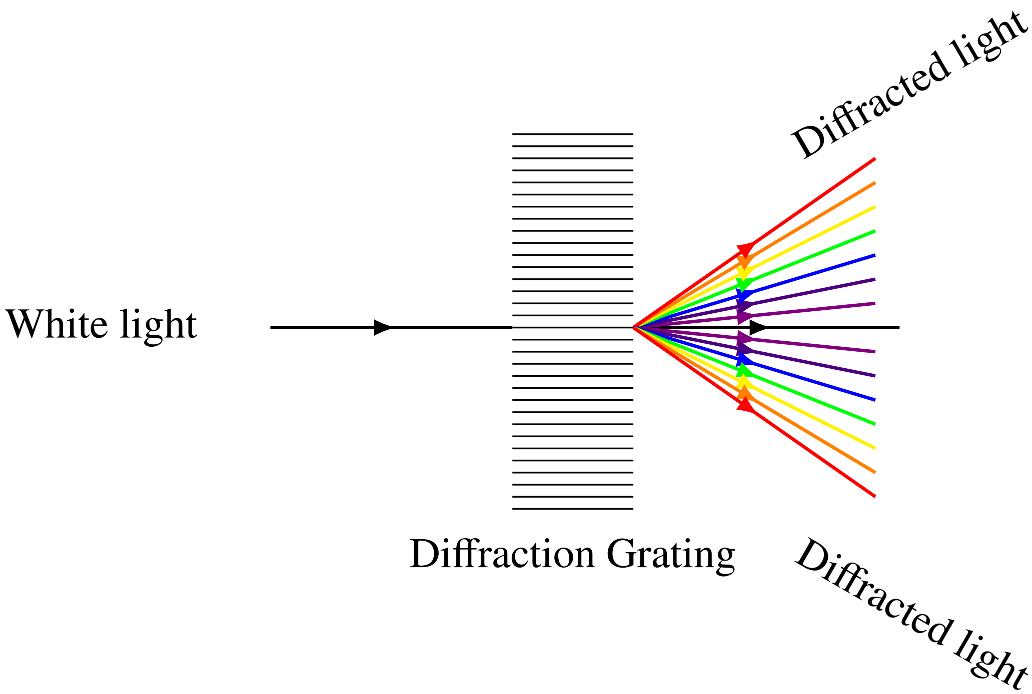


Figure 1.1: Grating disperses white light.

The grating constant d, conceptually, represents the distance between adjacent slits or lines on a diffraction grating. It determines the spatial arrangement and periodicity of the grating structure. It is given by

$$d = 1/N, \tag{1.1}$$

where N is the number of lines or slits per unit length.

A smaller grating constant implies that the slits or lines are closer to each other, resulting in a narrower spacing between the diffracted beams. Consequently, the angular separation between the diffracted beams will be larger. Conversely, a larger grating constant means that the slits or lines are spaced farther apart, leading to a wider spacing between the diffracted beams. This results in smaller angular separations between the diffracted beams.

The diffraction equation describes the relationship between the angles of incidence and diffraction, the wavelength of the incident light, and the spacing between the diffracting elements (such as slits or grooves). The equation is derived from the principles of wave interference and diffraction and it is given by

$$n\lambda = d \sin\theta, \tag{1.2}$$

where n denotes the order of diffraction, λ represents the wavelength, d the grating constant, and θ indicates the angle of diffraction.

You can also deduce the highest rank, n, by solving for $\sin\theta$ and finding the value that results in a number greater than 1, which is the maximum possible value of a sinusoidal function.

1.2 Experimental Setup

In this experiment, we use a spectrometer, a spectral lamp (white light), a voltage source, a collimating lens, and, most importantly, the diffraction grating. All of these tools are shown in Figure 1.2.

Figure 1.2: Setup of Diffraction Grating experiment.

1.3 Procedure

1. Turn on the spectral lamp and ensure that it is collimated by the lens and aligned perpendicularly to the slit of the grating.
2. Position the monocular in a way that allows you to precisely observe the white light at the perpendicular lines.
3. Once you have successfully centered the white light, you can now adjust the position of the monocular as needed to observe the visible spectrum from both sides.
4. Now, you need to observe the **same colour** from both sides and measure the corresponding angles θ_R and θ_L as shown in Figure 1.3.
5. Repeat step 4 for every visible colour, ensuring that you observe and record the angles θ_R and θ_L for each colour.
6. Fill your results in Table 1.1.

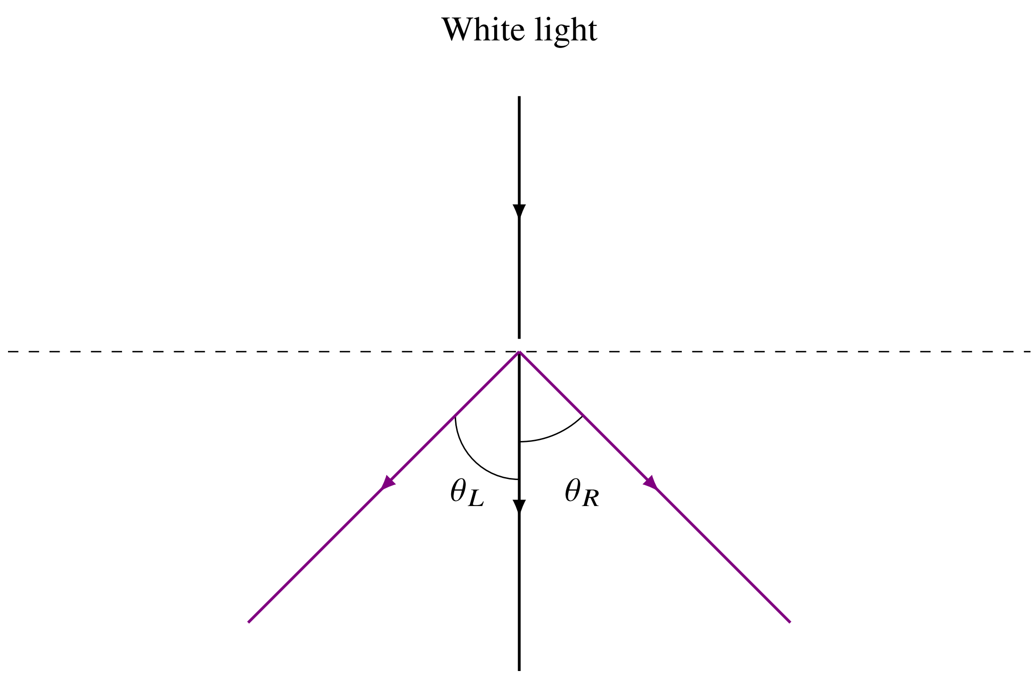


Figure 1.3: An abstracted view of the experiment.

1.4 Results, Tables and Measurement of Error

Write your results in a table, such as the following:

Colour	θ_R (°)	θ_L (°)	θ (°)	$\lambda = d\sin\theta$ (nm)
Purple				
Indigo				
Blue				
Green				
Yellow				
Red				

Table 1.1: Table of Diffraction Grating experiment ($n = 1$).

Referring to Figure 1.3, we can deduce the following relation, which is necessary to complete the table

$$\theta = \frac{|\theta_R - \theta_L|}{2}. \tag{1.3}$$

The instructor will explain to you how to calculate the error that arises because of the limitations of our setup. But here, we will only provide you with the expressions resulting from Eq(1.1) and Eq.(1.2) for the case when ($n = 1$):

$$\Delta\lambda = [\frac{\Delta d}{d} + \Delta\theta\cot\theta]\lambda; \tag{1.4}$$

$$\frac{\Delta d}{d} = \frac{\Delta N}{N}. \tag{1.5}$$

Conceptual Questions

Q1/:What is the purpose of the diffraction grating experiment?

A1:
1. To calculate the wavelength of the colours of the spectrum.
2. To investigate the phenomenon of diffraction.

Q2/ What is the difference between analyzing white light using a prism, and analyzing white light using a diffraction grating?

A2: Analyzing light with a prism occurs due to the refraction of light, whereas in a diffraction grating it occurs due to the diffraction of light.

Q3/ What is a diffraction grating made of?

A3: It consists of a glass or plastic plate, the surface of which has been scratched with a sharp tool in such a way that the slits are parallel and the distance between them is equal. The number of slits ranges from 300 to 600 lines per 1 cm. The distance between two consecutive slits is known as the diffraction grating constant d.

Q4/ Define the diffraction grating constant.

A4: It is the distance between any two consecutive slits in a diffraction grating.

Q5/ Calculate the diffraction grating constant for a grating with 300 lines per 1 cm.

A5: Using Eq(1.1):

$$d = \frac{1}{N} = \frac{1}{3 \times 10^4 \frac{lines}{m}} = 3 \times 10^{-5} m.$$

Experiment 2

Newton's Rings

Objectives

1. Observing Newton's rings.
2. Finding the wavelength λ of the monochromatic light source.

2.1 Theory

Newton's rings is an optical phenomenon that happens when a convex lens is placed on top of a flat glass surface, forming a thin air layer between them. As illustrated in Figure 2.1, when a monochromatic light source (in our case, sodium light) is focused onto the setup, some of the light is reflected from the upper surface of the air film while the remainder travels through the lens and is reflected from the lower surface of the air film.

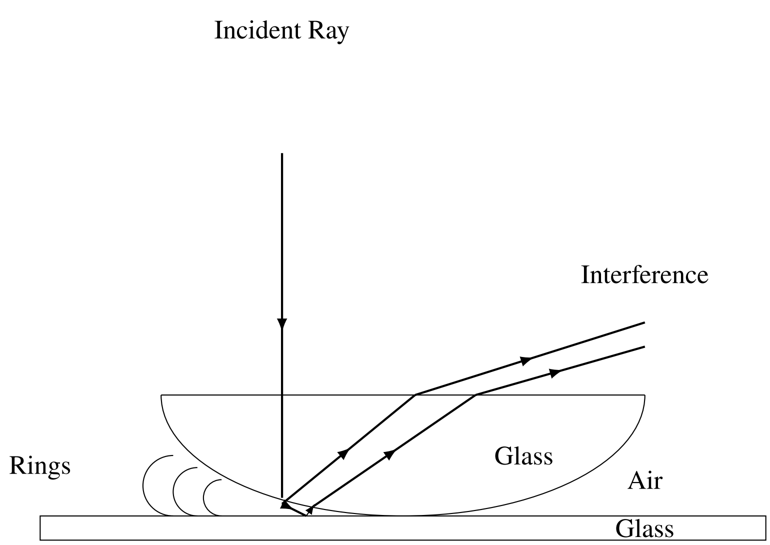


Figure 2.1: Formation of rings.

The light waves reflected from the two surfaces of the air film interfere with each other, resulting in a pattern of concentric circular rings. This interference occurs because the light waves travel different distances before recombining. The path difference between the waves determines whether constructive or destructive interference takes place.

Constructive interference occurs when the path difference between the waves is an integral multiple of half wavelength of the light (different mediums). At these points, the waves reinforce each other, creating bright fringes or rings. On the other hand, Destructive interference occurs when the path difference is a multiple of one wavelength. The waves cancel each other out, resulting in dark rings.

$$\text{Bright} : (n + \frac{1}{2})\lambda = 2t\cos\theta \tag{2.1}$$

$$\text{Dark} : n\lambda = 2t\cos\theta \tag{2.2}$$

where n is the rank of the fringe, λ the wavelength, t the thickness of the film (air) and θ is the angle of the incident ray. In our case, the angle will be perpendicular to the lens, meaning that $\cos\theta = 1$.

The pattern of Newton's rings consists of a central bright spot, called the central fringe, surrounded by a series of concentric bright and dark rings. The rings become larger in diameter as they move away from the central fringe, and the spacing between adjacent rings decreases. This pattern of rings can be observed and analyzed to determine various properties, such as the radius of curvature of the lens, the wavelength of the light used, and the thickness of the air film at different points.

To calculate λ, we first have to find t (thickness of air film). We do this by exploiting the geometry of the setup

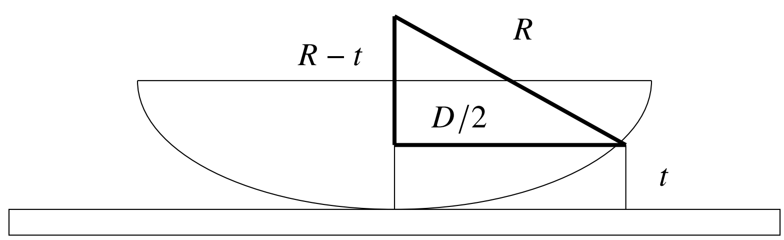


Figure 2.2: Geometry of Newton's rings.

By the Pythagorean theorem,

$$R^2 = (R - t)^2 + (\frac{D}{2})^2 = R^2 - 2Rt + t^2 + \frac{D^2}{4}. \tag{2.3}$$

Since t is extremely small, we have good reasons to neglect the square of it

$$2t = \frac{D^2}{4R}, \tag{2.4}$$

and by Eq(2.2) (the angle of the incident ray is $\theta = 0$),

$$\lambda = \frac{1}{4R} \cdot \frac{D^2}{n}. \tag{2.5}$$

2.2 Experimental Setup

As shown in Figure 2.3, we have a Newton's rings device that is composed of an optical microscope, a sodium light bulb with its voltage source, a convex lens with a focal length of 10cm, and a ruler from which we can take measurements.

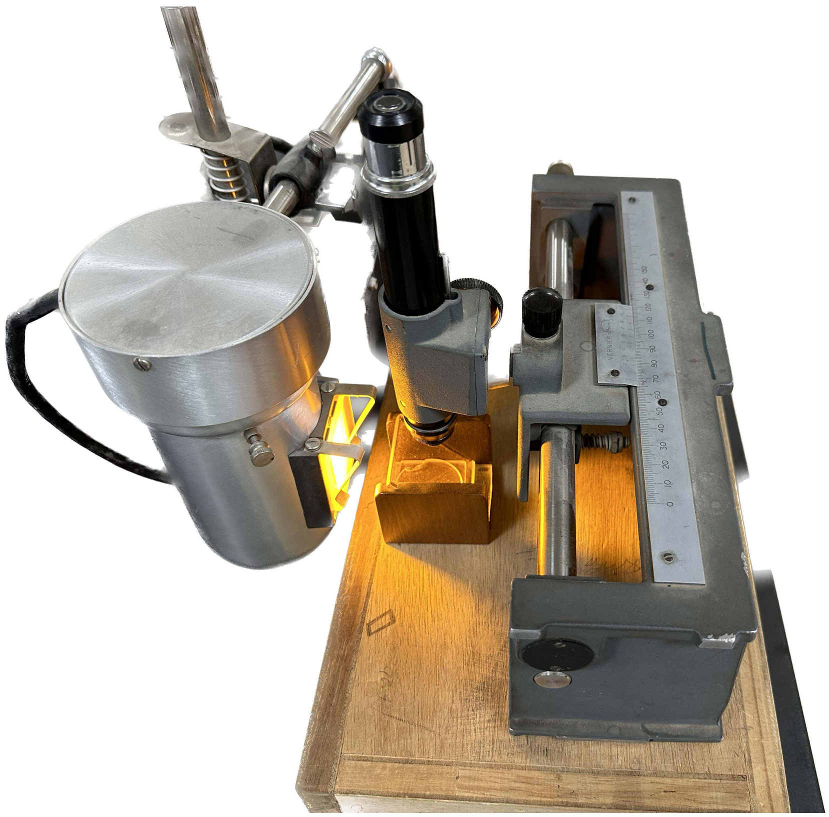


Figure 2.3: Setup of Newton's Rings experiment.

2.3 Procedure

1. To begin, switch on the sodium light source and carefully adjust the convex lens until you can clearly observe the interference rings. It is crucial to select either the dark or bright rings, as this choice will yield distinct outcomes in the experiment. Dark rings result from destructive interference, while bright fringes indicate constructive interference.
2. Using the microscope, ensure that the perpendicular lines are positioned in such a way that they intersect at the central fringe. This alignment is essential for accurate measurements and analysis.
3. Next, carefully shift the lines to the position of the 10th right ring (or left ring, depending on your preference). Take precise measurements of this fringe's position using a suitable measuring device such as a ruler or micrometer. This measurement will serve as a baseline for further calculations.
4. After measuring the position of the 10th right ring, decrease the distance between the lines by 2 units. Continue measuring and recording the distances until you reach the 10th left ring (or right ring, depending on your initial choice). These measurements will allow you to analyze

the interference pattern and make observations about the behavior of light waves. Make sure the measured distances are logical, and follow a decreasing/increasing pattern.
5. Fill your results in Table 2.1.

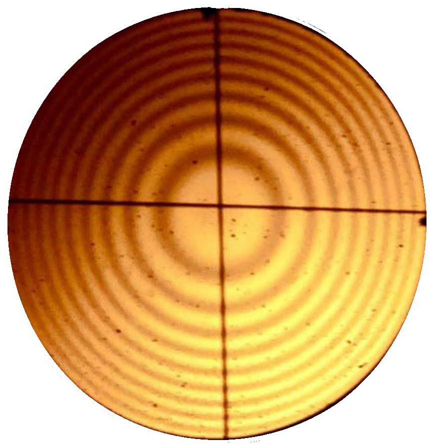


Figure 2.4: Apparatus of Newton's Rings in action.

2.4 Results, Tables, Graphs and Measurement of Error

In this experiment, the first column can change depending on the choice of rings. If you choose bright fringes, then by Eq(2.1), you will take $n + \frac{1}{2}$. Otherwise, it will be n as shown in the following table:

n	$D_L(mm)$	$D_R(mm)$	$D(mm)$	$D^2(mm^2)$

Table 2.1: Table of Newton's Rings experiment.

These will be the constants that you will use:

$$R = 500m, \quad \Delta R = 1mm. \tag{2.6}$$

You will use this data in Table 2.1 to draw a graph between n and D^2 as depicted in Figure 2.5 to calculate the slope.

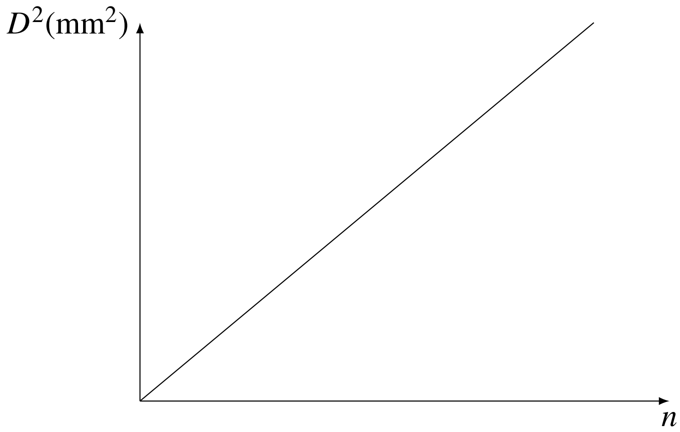


Figure 2.5: Linear relation between D^2 and n.

The purpose of using the slope is find the wavelength from Eq(2.5) that we deduced above.

$$\lambda = \frac{1}{4R} \cdot \frac{D^2}{n} = \frac{1}{4R} \cdot \text{slope}. \tag{2.7}$$

Just like in any experiment, it is essential to derive the expressions for the errors. However, instead of that, we will directly provide you with the resultant expression

$$\Delta\lambda = (\frac{\Delta R}{R} + 2\frac{\Delta D}{D})\lambda. \tag{2.8}$$

Conceptual Questions

Q1/ What is the purpose of the Newton's Rings experiment?

A1:
1. To calculate the wavelength of a monochromatic light.
2. To study the possibility of interference of light waves, reflected from two transparent plates (glass or plastic) separated by a thin layer (thin film) of air.

Q2/ Why do we get constructive interference when the path difference equals half an integer number of wavelengths, unlike what is normal ininterference experiments where we get constructive interference when the path difference equals an integer number of wavelengths?

A2:
This is because one of the interfering beams travels from a medium of lesser optical density to a medium of greater optical density, thus undergoing a phase shift of half a wavelength before interfering with the other beam.

Q3/ How are interference fringes obtained in the Newton's Rings experiment (explain in detail)?

A3: The incident rays on the convex lens are refracted and enter its convex surface, then some of it reflects and exits from the flat upper side after refraction. The other part of the rays penetrates through the convex surface to the varying thickness of the thin air layer, then reflects from the glass plate upwards, enters the lens through its convex face, and then exits from the flat surface to interfere with the beam that reflected directly from the convex surface.

Experiment 3

The Prism

Objectives

1. Studying how the coefficient of refraction n changes with the wavelength λ.
2. Calculating the minimum deviation angle δ_m of the main colours of the visible spectrum.
3. Calculating the ability of the prism to disperse light R.

3.1 Theory

In the 17th century, Sir Issac Newton demonstrated that white light is composed of a spectrum of colours. This astonishing fact was demonstrated with a simple glass in a shape of a pyramid that we call a prism. As shown in Figure 3.1, Prisms **disperse** white light into its components. The ability of a prism to disperse light depends on its refractive index n (i.e, the material) and the incident angle θ_i.

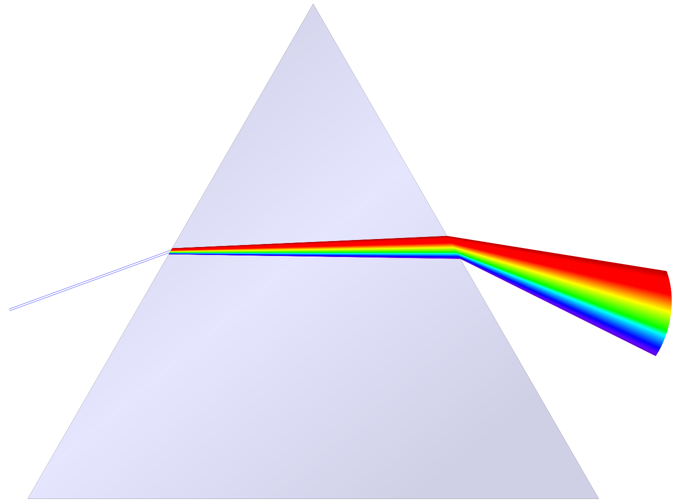


Figure 3.1: Dispersion by prism. **CC-BY-SA 4.0, Neutelings**.

Now, we will geometrically analyze the path of light as shown in Figure 3.2. First we will start with the total angle of deviation δ

$$\delta = \delta_1 + \delta_2 = (\theta_i - r_1) + (\theta_e - r_2) = \theta_i + \theta_e - (r_1 + r_2). \tag{3.1}$$

Since calculating the expression $(r_1 + r_2)$ every time is a waste of time, we can relate it to the apex angle $\angle$ BAC (or briefly, A) which is a constant quantity. By analyzing the triangle ΔPAQ, we find that

$$A + (90° - r_1) + (90° - r_2) = 180°, \tag{3.2}$$

and hence

$$A = r_1 + r_2; \tag{3.3}$$

$$\delta = \theta_i + \theta_e - A. \tag{3.4}$$

Eq(3.4) is an expression for the total angle of deviation δ that depends on two variables, namely, θ_i and θ_o. But we can make it depend on only one of them by applying Snell's law twice. If we do this, we end up with the monstrous expression

$$\delta = \theta_i + \arcsin\left[n \sin\left(A - \arcsin\left(\frac{\sin(\theta_i)}{n}\right)\right)\right] - A. \tag{3.5}$$

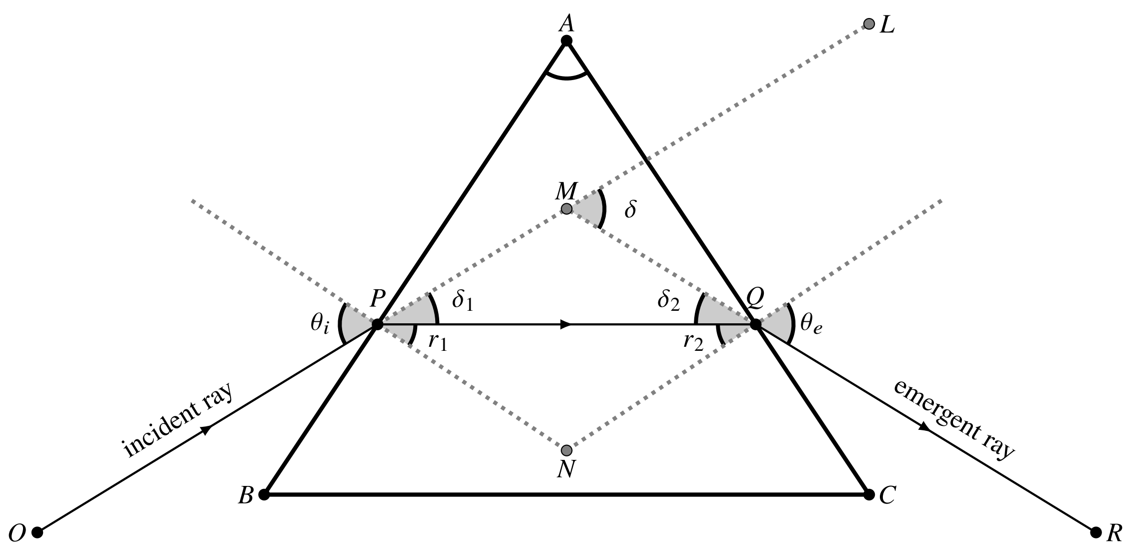


Figure 3.2: Analysis of the path of light through a prism. **MIT license**.

One of the goals of the experiment is to find the minimum angle of deviation δ_m and we have two ways to find it since we have Eq(3.5). We can either use direct calculus, or just look at the graph of the function. In any case, you will find that the minimum angle of deviation occurs when $\theta_i = \theta_e$. This will change Eq(3.1) in the following way

$$\delta_m = 2\theta_i - 2r_1, \tag{3.6}$$

and by Snell's law for the incident angle

$$n = \frac{\sin\left(\frac{A+\delta_m}{2}\right)}{\sin\left(\frac{A}{2}\right)}. \tag{3.7}$$

Along with Eq(3.7), you will need to use Eq(3.8) which is derived by analyzing Figure 3.3 in a similar way which we don't need to go through. Regardless, The final expression is given by

$$A = \frac{|\theta_R - \theta_L|}{2}. \tag{3.8}$$

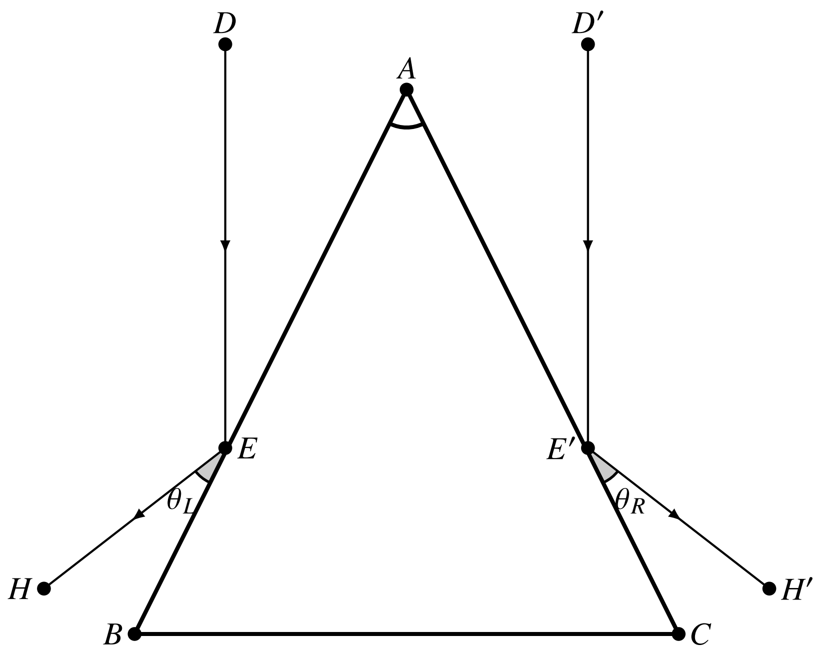


Figure 3.3: Two sources from above. **MIT license**.

3.2 Experimental Setup

Figure 3.4: Setup of The Prism experiment.

3.3 Procedure

1. Turn on the spectral lamp and place the prism so that its apex is facing the source of white light.
2. Rotate the monocular until you can see the passing white light at the centre. Denote this as θ_o.
3. Now, measure the angles θ_R and θ_L at the edges of the prism.
4. This is the critical part of the experiment: First, you have to rotate the monocular until you fully see the colours of the visible spectrum. Then, rotate the disk on which the prism is set in the clockwise direction until you see the colours stop moving and the white light rushing into them. The measured angle at this moment is the angle of deviation θ.
5. Measure the angle of deviation θ for every colour.
6. Fill your results in Table 3.1.

3.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following table:

Colour	λ (nm)	θ (°)	δ_m (°)	n
Indigo 1				
Indigo 2				
Blue				
Green				
Yellow				
Red				

Table 3.1: Table of The Prism experiment.

Graph the curve of n versus λ:

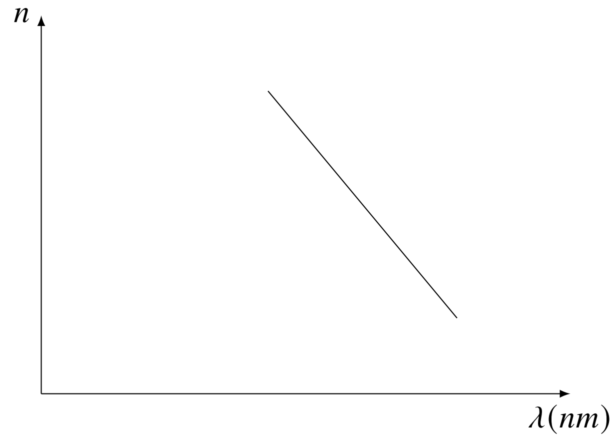


Figure 3.5: Linear relation between λ and n.

Use the value of the slope to find R which is given by

$$R = b\frac{dn}{d\lambda} = b \cdot \text{slope}, \tag{3.9}$$

where b is the length of the prism's base.

As always, you have to find the errors in measurements. For this experiment, you will use the following expressions:

$$\Delta D_m = \left(\frac{\Delta\theta}{\theta - \theta_0} + \frac{\Delta\theta_o}{\theta - \theta_0}\right)D_m; \tag{3.10}$$

$$\Delta n = \frac{1}{2}[\cot\left(\frac{A + D_m}{2}\right) - \cot\left(\frac{A}{2}\right)]\Delta A + \frac{1}{2}[\cot\left(\frac{A + D_m}{2}\right)D_m]n; \tag{3.11}$$

$$\Delta R = \left(\frac{\Delta\theta_R}{\theta_R - \theta_L} + \frac{\Delta\theta_L}{\theta_R - \theta_L}\right). \tag{3.12}$$

Conceptual Questions

Q1/ Why does light refract, when it falls on the surface of a prism?

A1:
Because the speed of light changes (directionally) when it moves from one transparent medium to another medium that differs in optical density.

Q2/ What are the conditions that are met, when minimum deviation occurs in a prism?

A2:
1. The refracted beam inside the prism becomes parallel to the base of the prism.
2. The angle of emergence becomes equal to the angle of incidence.

Q3/ Define the angle of minimum deviation.

A3:
1. It is the angle enclosed between the extension of the incident beam on the first face of the prism, and the extension of the emerging beam.
2. It is the smallest angle by which light deviates from its original path, after emerging from the other surface of the prism.

Q4/ What is the relationship between the angle of deviation and the angle of incidence?

A4:
When the angle of incidence is small, the angle of deviation is large. As the angle of incidence increases, the angle of deviation decreases until it becomes as small as possible, at this point it starts to increase again as the angle of incidence continues to increase.

Q5/ What is the purpose of the prism experiment?

A5:
1. To measure the angle of the prism's apex.
2. To measure the refractive index of light for the colours of the spectrum, using the method of minimum deviation.
3. To calculate the dispersive power of the prism.

Experiment 4

Abbe Refractometer

Objectives

1. Measuring the refractive index n of solutions with different concentrations.
2. Measuring the concentration C of different sugar solutions.

4.1 Theory

The Abbe refractometer is an optical device used to determine the refractive index of transparent substances. It functions by utilizing the critical angle θ_c. The refractometer gives the values of the concentration of the substance and its refractive index without the need to do any further calculations.

The device is composed of a light source, two prisms, sample cell, and observation system, the Abbe refractometer operates as follows: The light source, typically an incandescent lamp or LED, emits a beam of light that is focused onto the prisms. The prisms, made of a material with a high refractive index, such as glass, features a triangular shape, with one face forming the interface with the sample being analyzed. The sample is hold between the two prisms to ensure that refraction and total internal refraction take place.

The following Figure 4.1 shows the device in action. The dark spot represents the light that experiences total internal reflection, while the bright spot represents the light that undergoes refraction. The line that separates the two is, of course, the critical angle θ_c. We can also see the concentration of the used solution and its refractive index.

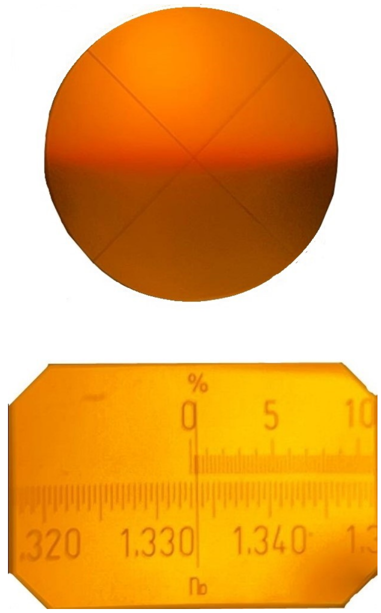


Figure 4.1: Dark and bright spots.

We will utilize all of this to find the refractive indices of a sugar solution with different concentration. To change the concentration of the solution, we use the law of dilution

$$C_1V_1 = C_2V_2, \quad C_1 = \frac{m}{V}, \tag{4.1}$$

where C_1 and V_1 are the concentration and volume before dilution, C_2 and V_2 are the concentration and volume after dilution and m is the mass of the initial solution.

4.2 Experimental Setup

In this experiment, we have Abbe refractometer, a light bulb, sugar, distilled water, a scale, a pipette, and a 100ml flask. All of these are shown in Figure 4.2.

Figure 4.2: Setup of Abbe's Refractometer experiment.

4.3 Procedure

1. Use the balance to precisely measure $40g$ of sugar.
2 .Place the measured sugar into an empty flask and add $40 - 60ml$ of water to it.
3. Vigorously shake the flask (or use a magnetic stirrer) until the sugar completely dissolves in the water. If the resulting solution does not reach a volume of $100ml$, add water until it does, aiming for an approximate 40% concentration.
4. Confirm the proper functioning of the refractometer by turning it on and using distilled water only. The refractive index reading should be around $n = 1.333$, indicating zero concentration.
5. Clean the area and carefully add a drop of the sugar solution between the prisms of the refractometer. Observe the change in concentration and refractive index by adjusting the monocular until the perpendicular lines align at the critical angle, midway between the dark and bright spots on the scale as shown in Figure 4.1. Record the corresponding n and C%, ensuring they align with the expected concentrations of the sugar solution.
6. For different concentrations, dilute the solution solution by adding water (use the law of dilution). Then, repeat step 5 for each dilution to measure the refractive index and observe the corresponding concentration.
7. Fill your results in Table 4.1. Note that C_p% is the prepared concentration, while C_s% is the measured one.

4.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following table:

$C_p\%(\frac{g}{ml})$	n	$C_s\%(\frac{g}{ml})$

Table 4.1: Table of Abbe's experiment.

These will be the constants that you will use

$$m = 40g, \quad V = 100m. \tag{4.2}$$

The graph of n versus $C\%$ will look like the following:

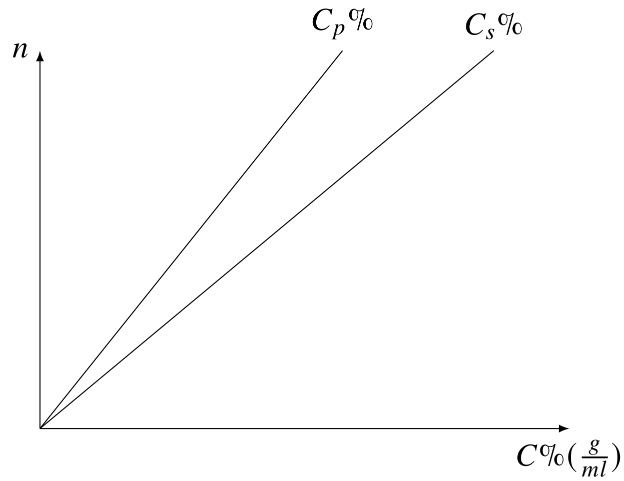


Figure 4.3: Linear relation between n and $C\%$.

The expressions of error are given by

$$\frac{\Delta C_1}{C_1} = (\frac{\Delta m}{m} + \frac{\Delta V}{V}); \tag{4.3}$$

$$\Delta C_2 = (\frac{\Delta C_1}{C_1} + \frac{\Delta V_1}{V_1} + \frac{\Delta V_2}{V_2})C_2. \tag{4.4}$$

Conceptual Questions

Q1/ What is the purpose of the Abbe Refractometer experiment?

A1:

1. To measure the refractive index of a solution.
2. To measure the concentration of the solution.

Q2/ What is the physical principle of the Abbe Refractometer?

A2:

It is based on the concept of the critical angle of light refraction.

Q3/ Define the critical angle

A3:

It is the angle at which light falls from a medium of greater optical density, to a medium of lesser optical density, such that it refracts parallel to the boundary surface between the two transparent media (i.e., the angle of refraction = 90 degrees).

Q4/ Explain in detail, how can we obtain a half-circle: one illuminated, and the other dark?

A4:

If light falls on the sugar solution placed between the two prisms at a 90-degree angle (such that it is tangent to the boundary surface between the prisms), it refracts at the critical angle and exits to the eyepiece, resulting in an illuminated half-circle. However, rays falling at different angles will not exit, leaving their space dark, thus resulting in a dark half-circle.

Experiment 5

Young's Double-Slit Experiment

Objectives

1. Finding the wavelength λ of the monochromatic light source.
2. Measuring the real distance between the two slits d.
3. Observing the distance between any two nearby fringes Δx.

5.1 Theory

Of all the experiments that you will undertake, this particular one holds immense importance due to its historical significance. It proves the wave nature of light, although this understanding is now considered incomplete. This experiment, accompanied by two other similar ones, demonstrates the phenomenon of light interference in three distinct ways. However, all of them require one important condition, which is making the light source coherent (i.e., using only one source). In this course, You will be asked to perform three similar experiments that show light interference, but with different principles. In the case of Young's experiment, we use the principle of **diffraction**.

When light passes through each slit, it diffracts and spreads, following Huygens's principle. These two new sources of light will have a path difference Δ, which determines how they will interfere with each other. Looking at Figure 5.1, we can deduce the relations that govern this behavior. For example, Eq.(5.1) provides the relation between d, which is the distance between the slits, Δ, which represents the path difference, and θ, which is the angle of the triangle.

$$\sin\theta = \frac{\Delta}{d}, \tag{5.1}$$

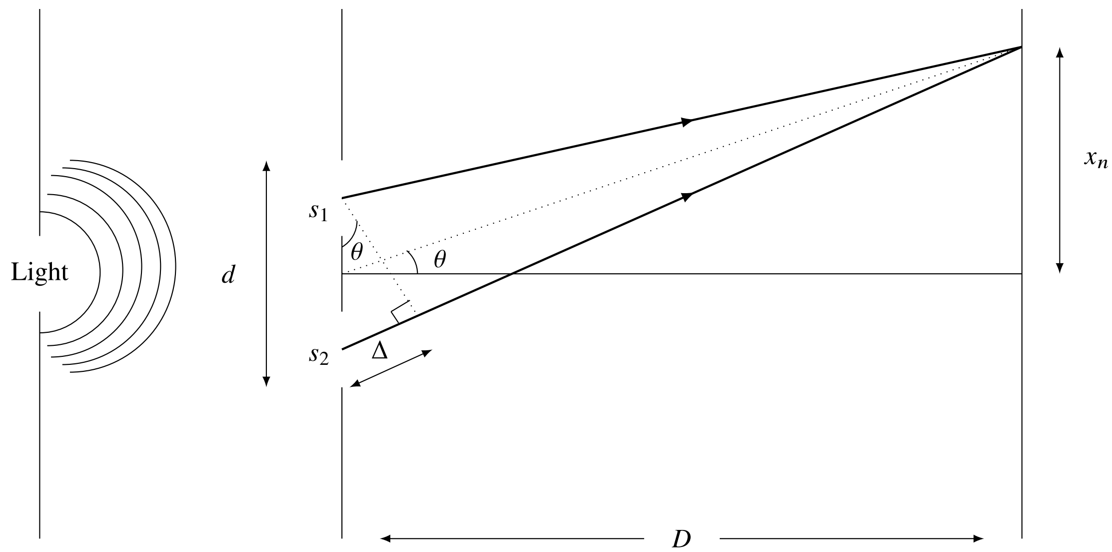


Figure 5.1: Double-slit interference.

Moreover, we see that we have similar triangles, and since for $\theta << 1$, we have $\sin\theta \approx \tan\theta$. Then,

$$\Delta = d\tan\theta = d\frac{x_n}{D}, \tag{5.2}$$

Where x_n is the the spacing of the n^{th} fringe and D is the distance from the slits to the screen (or the wall). Eq(5.2) is the essential equation in this experiment. We are left with two conditions:

$$\text{Constructive} \quad \rightarrow \quad \Delta = n\lambda; \tag{5.3}$$

$$\text{Destructive} \quad \rightarrow \quad \Delta = (n + \frac{1}{2})\lambda. \tag{5.4}$$

Assuming we have the first condition, we equate Eq(5.3) with Eq(5.4)

$$x_n = \frac{n\lambda D}{d}, \quad \Delta x = x_{n+1} - x_n = \frac{\lambda D}{d}. \tag{5.5}$$

Since our goal is to find the wavelength of light, we will manipulate Eq(5.5) to find a relation for the wavelength λ that will be included in the second table:

$$\lambda = \frac{\Delta x d}{D}. \tag{5.6}$$

Even with this relation, we still have a major problem, we don't know the value of d. To find its value, we must use a lens to project a real image of the slits on the wall, and use the law of magnification to find the value of d

$$d = d'\frac{u}{v}, \tag{5.7}$$

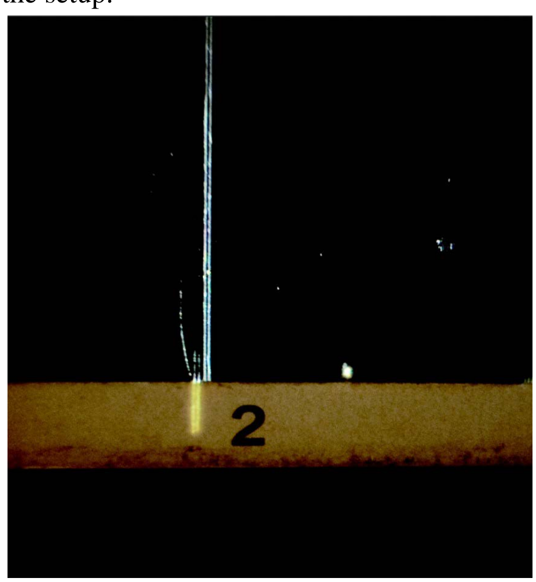
Where d' is the distance between the slits for the magnified image, u is the distance from the body to the lens and v is the distance from the lens to the screen.

5.2 Experimental Setup

In this experiment, we utilize a He-Ne laser, a magnifying lens, two slits, a convex lens, and a screen. All of these tools are shown in Figure 5.2.

(a) Overview of the setup.

(b) Slits apparatus.



(c) The two slits (Zoomed in).

Figure 5.2: Setup of Young's double slit experiment.

5.3 Procedure

Part 1: Determining the Distance between the Two Slits d

1. Activate the He-Ne laser and ensure that the emitted beam is effectively amplified by the positioned lens in front of the source.
2. Position the double-slits appropriately to allow the emitted light to pass through them.
3. Place a convex lens at a distance greater than its focal point from the slits to observe the image of the slits on the wall (or a screen). Measure and note down the distance from the slits to the lens as u.
4. Use a piece of paper to carefully trace the image displayed on the wall, which will help calculate the virtual distance between the slits d'.
5. Measure the distance from the lens to the image on the wall and record it as v.
6. Apply the law of magnification to calculate the actual distance between the slits d.
7. Repeat the above steps, incrementing the distance from the slits to the lens during each iteration (e.g, 20cm, 24cm).
8. Fill your results in Table 5.1.

Part 2: Calculating the Wavelength of the Light Source λ

1. Remove the convex lens to allow the emerging beams from the slits to interfere freely.
2. Use a movable screen and place it 55cm farther from the slits (or any distance of your choice that will make the fringes visible) to observe the interference behind the screen.
3. Using a paper and a ruler, measure the distance between nearby fringes by tracing the distance between 4-5 (or more) fringes. Divide the measured distance by (n-1), where n is the number of fringes.
4. Utilize all the previously measured quantities to calculate the wavelength of the light source.
5. Repeat the above steps increasing the distance between the slits and the screen by 5-10cm each time.
6. Fill your results in Table 5.2.

5.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following tables, respectively:

$u(cm)$	$v(cm)$	$d'(cm)$	$d = d'\frac{u}{v}(cm)$

Table 5.1: Determining the distance between the two slits d.

n	$D(cm)$	$x(cm)$	$\Delta x = \frac{x}{n}(cm)$	$\lambda = \frac{\Delta x \bar{d}}{D}(nm)$

Table 5.2: Calculating the wavelength of the light source λ.

Mathematical expressions of error:

$$\Delta d = (\frac{\Delta d'}{d'} + \frac{\Delta u}{u} + \frac{\Delta v}{v})\bar{d}; \tag{5.8}$$

$$\Delta \lambda = (\frac{\Delta(\Delta x)}{\Delta x} + \frac{\Delta d}{d} + \frac{\Delta D}{D})\bar{\lambda}. \tag{5.9}$$

Before proceeding to find the error, make sure that you calculate both $\bar{d}$ and $\bar{\lambda}$.

Conceptual Questions

Q1/ What is the purpose of Young's Double-Slit experiment?

A1:
1. To calculate the actual distance between the two slits.
2. To calculate the wavelength of monochromatic light (Helium-Neon laser light).
3. To observe interference fringes, and measure the distance between them.

Q2/ What is the fundamental condition, that must be met for interference to occur between light waves, from two light sources?

A2: The two light sources must be coherent, meaning they are emitted from a single light source.

Q3/ Why is there a path difference between the two light beams emitted from Young's double slits ?

A3: This occurs due to the diffraction of light, after it falls on the slits.

Q4/ What is the condition for the formation of bright, dark fringes?

A4:
Bright fringes form when the path difference equals an integer number n of wavelengths, and dark fringes form when the path difference equals a half-integer $n + \frac{1}{2}$ of wavelengths, where $n = 0, 1, 2, 3, \ldots$

Q5/ When calculating the distance between Young's double slits, why should the lens be placed at a distance greater than or equal to the focallength of the lens from the slits?

A5:
This is because we need to obtain a real image of the object in order to capture it on a screen. If the distance of the object from the convex lens were less than its focal length, a virtual image would form, which would be invisible and could not be captured on a screen.

Experiment 6

Photoelectric Cell

Objectives

1. Verifying the inverse-square law of light.
2. Finding the absorption factor μ for different plastic slabs.

6.1 Theory

The inverse-square law is a fundamental principle in physics that applies to various phenomena such as electromagnetic forces, gravitational forces, and sound intensity. In this context, we will specifically examine the inverse-square law as it pertains to the intensity of light at a given distance, denoted as r. This law can be expressed by the equation

$$I = \frac{P}{4\pi r^2}, \tag{6.1}$$

where I represents the intensity, P represents the power, and r represents the distance between the light source and the point of measurement. Figure 6.1 provides different ways to visualize Eq(6.1).

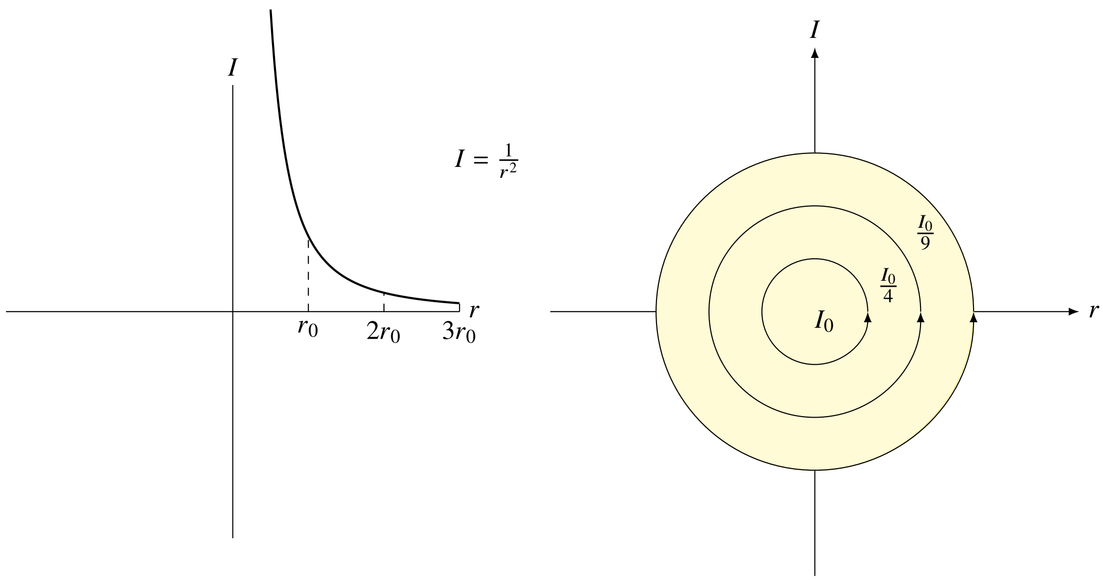


Figure 6.1: Different ways to visualize the inverse-square law.

In this experiment, we have two goals. First, we want to verify the inverse-square law by utilizing a photoelectric cell. Second, we will determine the absorption constant (propagation constant) of specific plastic slabs. Regarding the first goal, we aim to demonstrate that the inverse-square law holds by measuring the photoelectric current i generated by exposing the cell to light at varying distances. Therefore, we hypothesize the following relationship:

$$i \propto I \propto \frac{1}{d^2} \quad \rightarrow \quad i = k\frac{1}{d^2}, \tag{6.2}$$

where k is the proportionality constant. Now, if the graph between i and $\frac{1}{d^2}$ is a straight line, then our empirical formula holds.
The second part of the experiment will be devoted to finding the absorption constant of plastic slabs with different thicknesses by observing how the value of the current changes when the source of light is blocked by transparent slabs. The law that describes this phenomenon is called Beer-Lambert law and it is given by

$$I = Ie^{-\mu x} \quad \rightarrow \quad i = i_o e^{-\mu x}, \tag{6.3}$$

where i is the value of the current, i_o is the initial current (by choice), μ is the absorption factor and x is the thickness of the material (path).
We want to rewrite Eq(6.3) in a form that is easier to graph,

$$\ln\frac{i}{i_o} = \mu x. \tag{6.4}$$

Your task is to find the slope of the graph shown in Figure 6.4 between x and $\ln\frac{i}{i_o}$ since it will yield μ

$$\mu = \frac{\ln\frac{i}{i_o}}{x} = \text{slope}. \tag{6.5}$$

6.1.1 Photoelectric effect (Optional)

As illustrasted in Figure 6.2, when a metal surface is illuminated by light of a specific frequency f that surpasses the material's cutoff frequency f_c, photoelectrons are released, creating a photoelectric current that moves throughout the circuit.

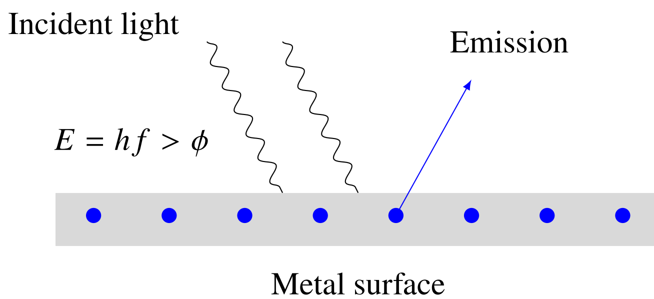


Figure 6.2: Photoelectric effect.

The formula that describes this phenomenon was developed by Planck and Einstein and it is given by

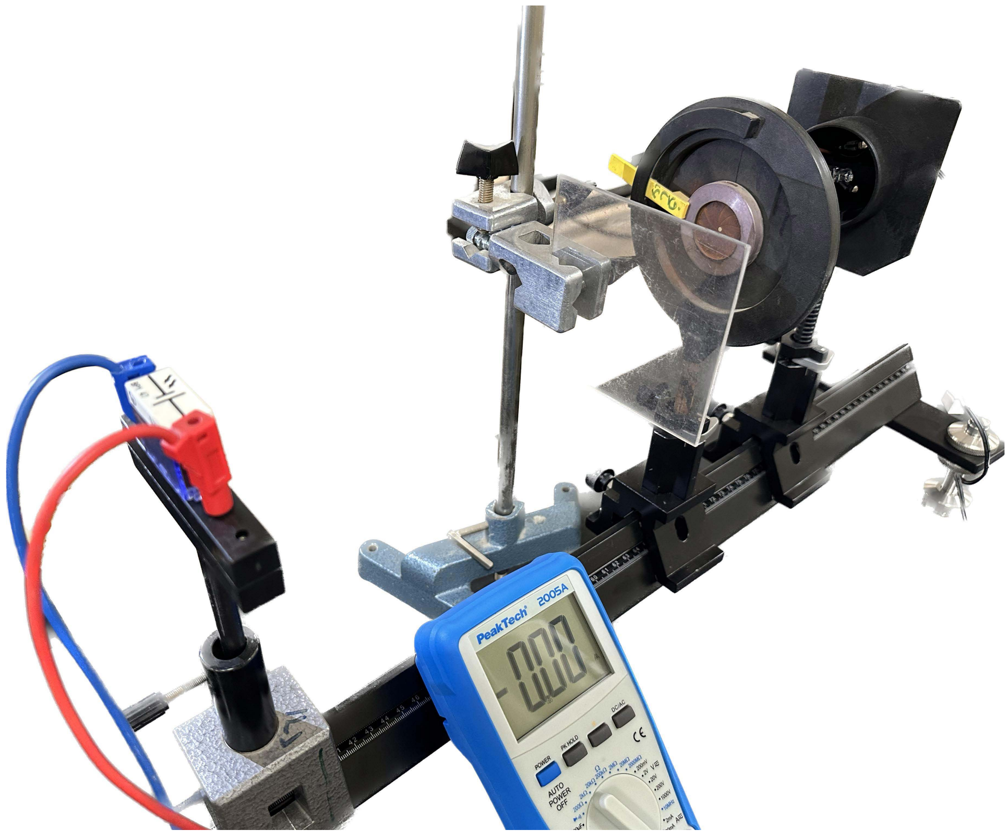
$$K_{max} = E_{photon} - \phi. \tag{6.6}$$

Given the work function ϕ, we can find the maximum possible kinetic energy K_{max} for the electrons (That is only the maximum, but in reality, not all electrons will have the same energy).

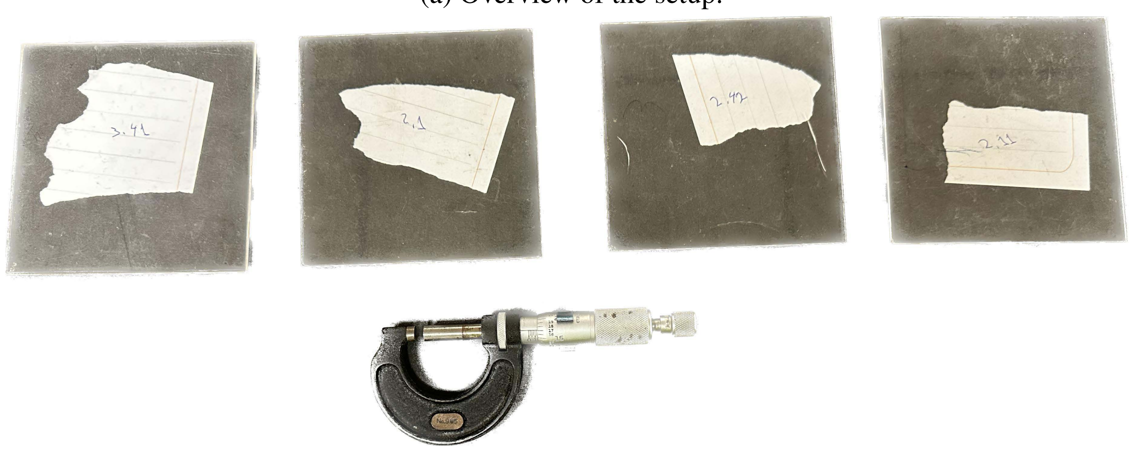
We agree that photoelectrons will be emitted if $f > f_c$, but how does this affect the value of the current at different distances? Here, intensity becomes a factor. By increasing the intensity of light, you expose the metal to a greater number of photons that can emit more photoelectrons. Therefore, it is expected that the value of the current will decrease as we increase the distance d between the light source and the cell in Eq(6.2).

6.2 Experimental Setup

As shown in Figure 6.3, we have a photoelectric cell, a light source, a circular aperture, a multimeter, a caliper, and plastic slabs.



(a) Overview of the setup.



(b) The caliper that is used to measure the thickness of plastic slabs.

Figure 6.3: Setup of the Photoelectric Effect experiment.

6.3 Procedure

6.3.1 Part 1: Verifying the Inverse-Square Law

1. Turn on the light source and make sure that it is being absorbed by the cell.
2. Check the value of the current and record it.
3. Repeat step 2, but at different distances d.
4. Fill your results in Table 6.1.

6.3.2 Part 2: Calculating absorption factor μ

1. Measure the thickness of five different slabs.
2. Choose fixed values for the distance d_o and current i_o.
3. Now, block the path of the light with a plastic slab and observe how the value of the current changes.
4. Repeat step 3, but add an additional slab each time.
5. Fill your results in Table 6.1.

6.4 Results, Tables, Graphs, and Measurement of Error

Write your results in the following tables:

$i(\mu A)$	$d(cm)$	$\frac{1}{d^2}(\frac{1}{cm^2})$

$x(mm)$	$i(\mu A)$	$\ln\frac{i_o}{i}$

Table 6.1: Tables of the Photoelectric effect experiment.

The graphs will look like the following:

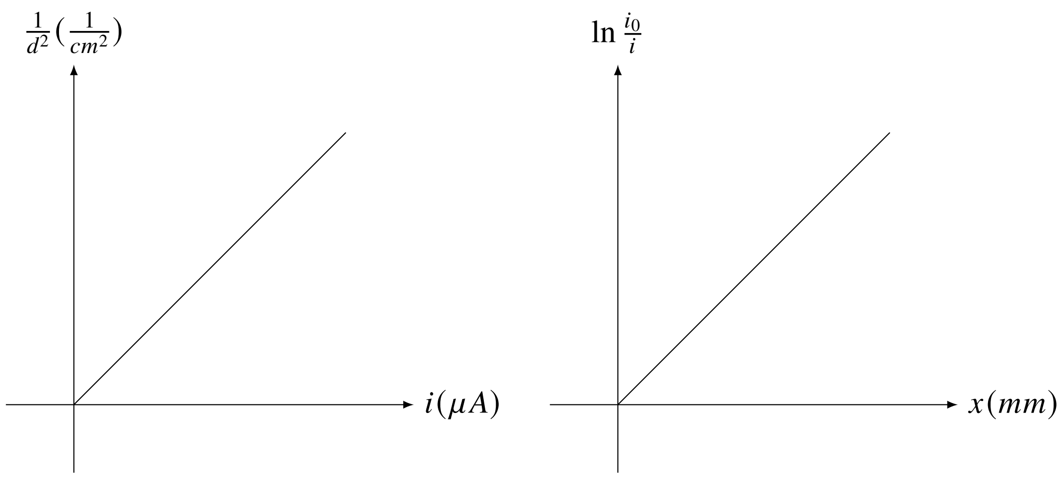


Figure 6.4: Graphs of intensity laws.

Finally, the expression for error of μ is given by

$$\Delta\mu = [(\frac{\Delta i_o}{i_o} + \frac{\Delta i}{i})\frac{1}{\ln\frac{i_0}{i}} + \frac{\Delta x}{x}]\mu. \tag{6.7}$$

Conceptual Questions

Q1/ What is the purpose of the photoelectric cell experiment?

A1:
1. To demonstrate the inverse-square law of light.
2. To calculate the light absorption coefficient of plastic.

Q2/ What is a photoelectric cell composed of?

A2:
It consists of a glass bulb evacuated of air, containing a light-sensitive surface that acts as the negative electrode, connected to a wire, which in turn is considered the positive electrode.

Q3/ Briefly explain the principle of operation of the photoelectric cell.

A3:
When light falls on the sensitive surface of the cell, electrons are emitted from it. These electrons move to the wire, which is connected to the positive pole of a battery (to attract the negative electrons).

Q4 What is the relationship between the current intensity measured by the galvanometer, and the intensity of light in the photoelectric cell experiment?

A4:
The greater the intensity of light falling on the cell, the greater the number of photoelectrons released from it, leading to a larger deflection in the galvanometer needle, hence measuring a higher current intensity.

Q5/ Define the inverse-square law of light.

A5:
The intensity of the electric current generated from the photoelectric cell is inversely proportional to the square of the distance of the cell from the light source.

Experiment 7

Melde's Experiment

Objectives

1. Understanding the phenomenon of standing waves.
2. Calculating the length, λ and speed v of the waves.
3. Calculating the frequency, f, of the electric current in Riyadh city.

7.1 Theory

One of the most effective ways to demonstrate the formation of standing waves is by conducting Melde's experiment. This experiment involves utilizing a string that is attached to a vibrator at one end and a pulley (or a tension string) at the other end. The vibrator induces a wave on the string, which propagates to the opposite end and undergoes reflection, resulting in the creation of standing waves, as depicted in Figure 7.1.

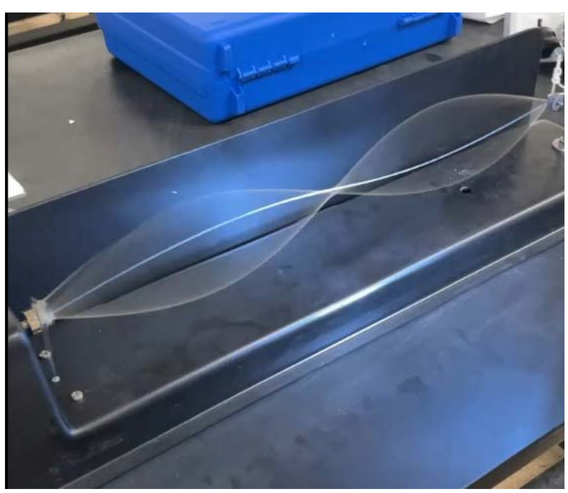


Figure 7.1: A student performing Melde's experiment ($n = 2$).

The controlled tension T on the string determines the number of nodes k and anti nodes n of the standing wave.

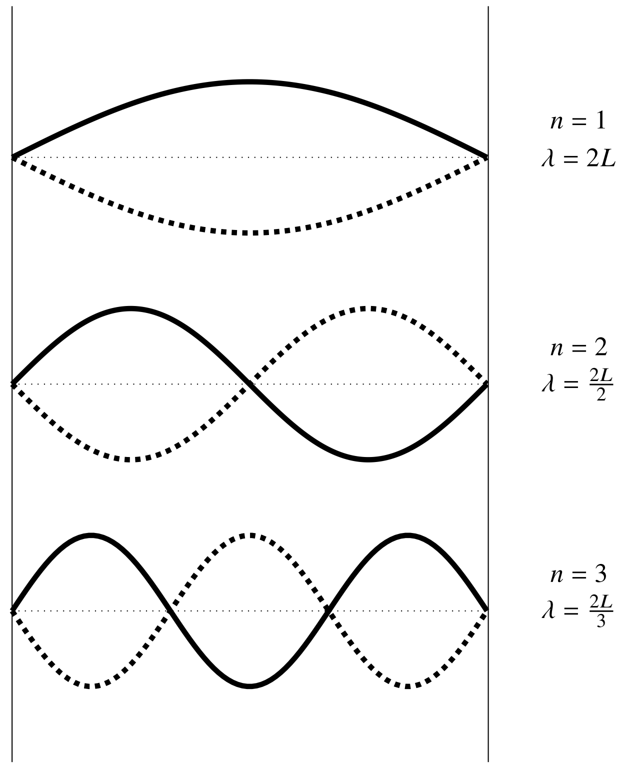


Figure 7.2: Pattern between nodes k and antinodes n

If you change the tension multiple times, you will find a consistent pattern as shown in Figure 7.2 between the nodes and antinodes from which we can derive the following formula by induction

$$\lambda = \frac{2L}{n} = \frac{2L}{k-1}. \tag{7.1}$$

We also want to utilize our knowledge in waves to experimentally determine the frequency of the electric current which is responsible for making the vibrator vibrate at a certain frequency which in turn makes the string vibrate at it! This might appear to be difficult, but we can make it endurable (and visually appealing) by using a stroboscope. The stroboscope, as shown in Figure 7.1, emits flashes light at frequencies that we control. Now, if the frequency of flashes matches that of the electric current, then the imaginary wave that we see in Figure 7.1 must stop! Perfect, now all we have to do is to use these laws for standing waves

$$v = \sqrt{\frac{T}{m}} = f\lambda; \tag{7.2}$$

$$f = \sqrt{\frac{T}{m\lambda^2}}; \tag{7.3}$$

Since we want the average frequency, we should make a graph of λ versus $\sqrt{\frac{T}{m}}$as shown in Figure 7.3 . The slope of this graph will give us our desired quantity

$$\bar{f} = \sqrt{\frac{T}{m\lambda^2}} = \frac{1}{\text{slope}}. \tag{7.4}$$

Moreover, we want to verify whether Eq(7.2) truly holds by graphing each quantity on a separate axis. Of course, the graph **must** be a straight line.

7.2 Experimental Setup

As shown in Figure 7.2, in this experiment we use a rope, a tension string, an electric vibrator, and a stroboscope.

Figure 7.3: Setup of Melde's experiment.

7.3 Procedure

1. First, find the mass per unit length m of the string by taking a length of $1m$ from the string and measuring its mass.
2. Determine the length L of the string that is attached to the spring by measuring it.
3. Switch on the rotator and observe how standing waves are formed.

4. For each different n, measure the frequency f and the tension T. Note that a stroboscope is utilized to find f.
5. Using the stroboscope, adjust the frequency of the device until the virtual wave appears to be stationary. This indicates that the frequency of the emitted light from the stroboscope matches that of the electric current. Record this frequency, denoted as f, for each different value of n.
6. Fill your results in Table 7.1.

7.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following table:

n	$T(N)$	$\lambda(m)$	$\sqrt{\frac{T}{m}}(\frac{m}{s})$	$f(Hz)$	$v = f\lambda(\frac{m}{s})$

Table 7.1: Table of Melde's experiment.

Use your results to graph the curves shown in Figure 7.4. The first one will show equality between measured and theoretical speeds, and the other will give you the frequency f of the electric current:

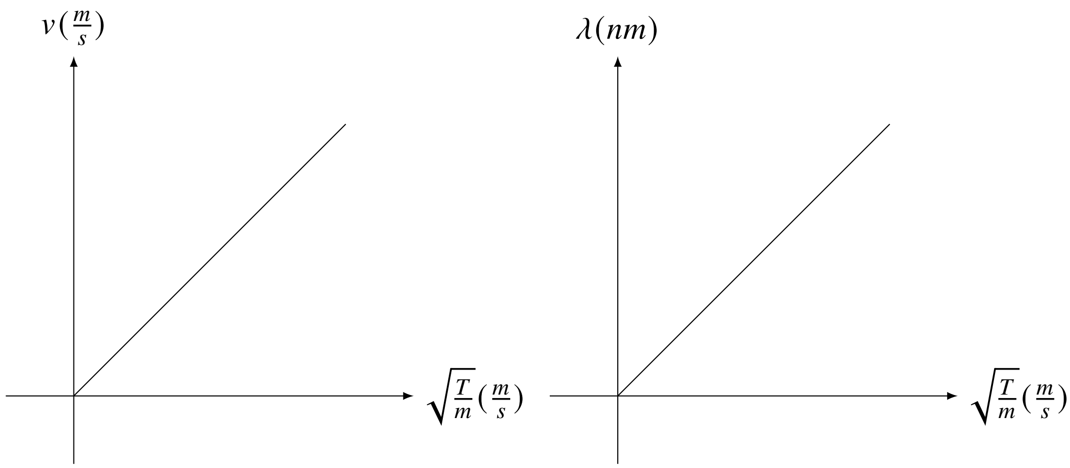


Figure 7.4: Relations between length and speed.

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As for the expressions of error, they are given by

$$\Delta f = \frac{1}{2}[\frac{\Delta T}{T} + \frac{\Delta m}{m} + \frac{\Delta \lambda}{\lambda}]\bar{f}; \tag{7.5}$$

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta L}{L}. \tag{7.6}$$

Since the frequency must be the same for all measurements, don't forget to calculate $\bar{f}$ first.

Conceptual Questions

Q1/ What is the purpose of Melde's experiment?

A1:
1. To calculate the wavelength of waves propagating in strings.
2. To calculate the frequency of the current of Riyadh city, using Melde's experiment.
3. To understand standing and stationary waves.

Q2/ Define standing and stationary waves.

A2:
These are waves composed of nodes and antinodes, resulting from the interference of outgoing waves and reflected waves from a fixed end, which have flipped from crest to trough or vice versa.

Q3/ Define nodes in standing and stationary waves.

A3:
Nodes are positions where the amplitude of vibration is the least possible (zero).

Q4/ Define antinodes in standing and stationary waves.

A4:
Antinodes are positions where the amplitude of vibration is the greatest possible.

Q5/ Define the wavelength of standing and stationary waves.

A5:
It is the distance between three consecutive nodes, with two consecutive antinodes separating them.

Q6/ What are the factors affecting the speed of waves propagating in strings?

A6:
1. The tension force in the string. The speed of the wave increases directly with the square root of the tension force in the string.
2. The mass per unit length of the string material (type of string material). The speed decreases inversely with the square root of the mass per unit length.

Q7/ How do we make a string vibrate at its fundamental frequency,
and what will be the length of the string then?

A7:
The string is plucked in the middle. At this point, two nodes form at its fixed ends, making the length of the string equal to half the wavelength.

Experiment 8

Fresnel's Biprism

Objectives

1. **Finding the wavelength λ of the monochromatic light source.**
2. **Measuring the real distance between the two prisms d.**
3. **Observing the distance between any two nearby fringes Δx.**

8.1 Theory

The Fresnel biprism experiment is a classic optical experiment that demonstrates the phenomenon of interference from two virtual sources. It was conducted by the French physicist Augustin-Jean Fresnel in the early 19th century as a variation of Young's double-slit experiment. The principle on which it relies is **refraction**.

In the Fresnel Biprism experiment, a thin prism with a wedge-shaped profile, known as a biprism, is placed in the path of a coherent light source (such as a laser beam, in our case). The biprism splits the incident beam into two separate beams as shown in Figure 8.1, which then propagate as if coming from two virtual point sources located behind the biprism.

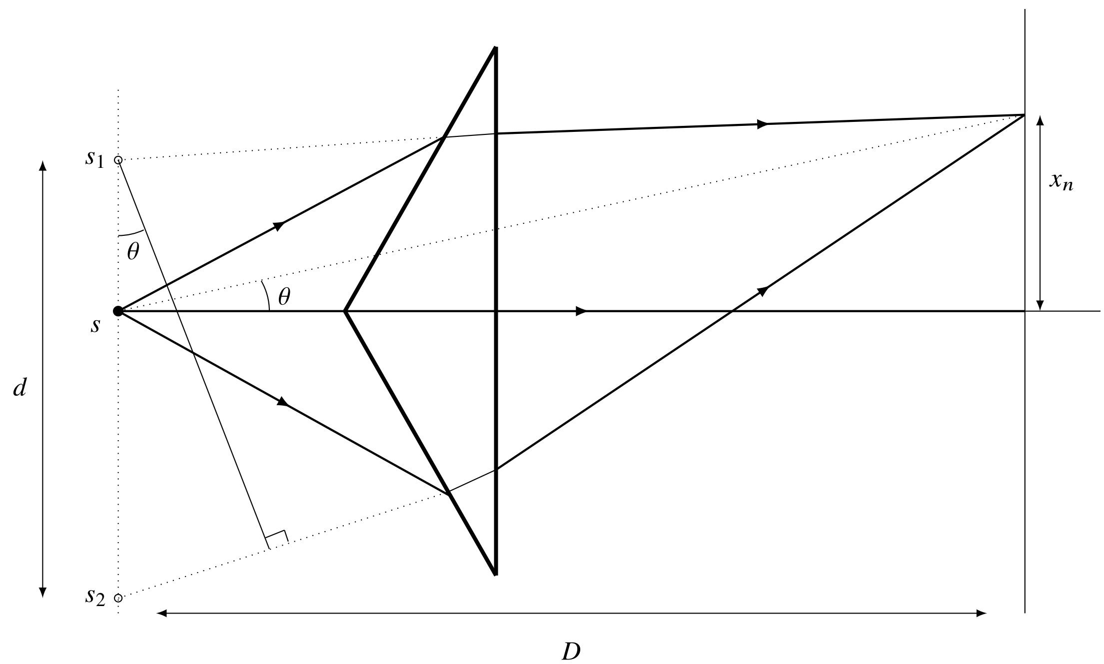

Figure 8.1: Interference resulting from diffraction using the biprism.

In Young's experiment, we have demonstrated how interference arises due to diffraction from two real sources. However, in this particular experiment, interference arises due to refraction from two virtual sources, as depicted in Figure 8.1. The analysis of interference is analogous, and it yields the same outcomes as discussed in Section5.1. Hence, we will only present you with the essential relationships without any additional deductions:

$$\text{Constructive} \quad \rightarrow \quad \Delta = n\lambda; \tag{8.1}$$

$$\text{Destructive} \quad \rightarrow \quad \Delta = (n + \frac{1}{2})\lambda; \tag{8.2}$$

$$\Delta x = x_{n+1} - x_n = \frac{\lambda D}{d}; \tag{8.3}$$

$$d = d' \frac{u}{v}. \tag{8.4}$$

8.2 Experimental Setup

In this experiment, we utilize a He-Ne laser, a magnifying lens, a biprism, a convex lens, and a screen. These tools are shown in Figure 8.2.

(a) Overview of the setup.

(b) Biprism on a holder.

Figure 8.2: Setup of Fresnel's Biprism experiment.

8.3 Procedure

Part 1: Determining the Distance between the Two Prisms d

1. Activate the He-Ne laser and ensure that the emitted beam is effectively amplified by the positioned lens in front of the source.
2. Position the biprism appropriately to allow the emitted light to pass through its middle.
3. Place a convex lens at a distance greater than its focal point from the biprism to observe the image of the distance between the two prisms on the wall (or a screen). Measure and note down the distance from the biprism to the lens as u.
4. Use a piece of paper to carefully trace the image displayed on the wall, which will help calculate the virtual distance between the two prisms d'.
5. Measure the distance from the lens to the image on the wall and record it as v.
6. Apply the law of magnification to calculate the actual distance between the two prisms d.
7. Repeat the above steps, incrementing the distance from the biprism to the lens during each iteration (e.g, 20cm, 24cm).
8. Fill your results in Table 8.1.

Part 2: Calculating the Wavelength of the Light Source λ

1. Remove the convex lens to allow the emerging beams from the biprism to interfere freely.
2. Use a movable screen and place it farther from the biprism to observe the interference behind the screen.
3. Using a paper and a ruler, measure the distance between nearby fringes by tracing the distance between 4-5 (or more) fringes. Divide the measured distance by (n-1), where n is the number of fringes.
4. Utilize all the previously measured quantities to calculate the wavelength of the light source.
5. Repeat the above steps increasing the distance between the biprism and the screen by 5-10cm (or any distance of your choice) each time.
6. Fill your results in Table 8.2.

8.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following tables, respectively:

$u(cm)$	$v(cm)$	$d'(cm)$	$d = d'\frac{u}{v}(cm)$

Table 8.1: Determining the distance between the two prisms d.

n	$D(cm)$	$x(cm)$	$\Delta x = \frac{x}{n}(cm)$	$\lambda = \frac{\Delta x \bar{d}}{D}(nm)$

Table 8.2: Calculating the wavelength of the light source λ.

Mathematical expressions of error:

$$\Delta d = (\frac{\Delta d'}{d'} + \frac{\Delta u}{u} + \frac{\Delta v}{v})\bar{d}; \tag{8.5}$$

$$\Delta \lambda = (\frac{\Delta(\Delta x)}{\Delta x} + \frac{\Delta d}{d} + \frac{\Delta D}{D})\bar{\lambda}. \tag{8.6}$$

Before proceeding to find the error, make sure that you calculate both $\bar{d}$ and $\bar{\lambda}$.

Conceptual Questions

Q1/ What is the purpose of the Fresnel's Biprism experiment?

A1:
1. To calculate the actual distance between the two slits.
2. To calculate the wavelength of monochromatic light (Helium-Neon laser light).
3. To observe interference fringes, and measure the distance between them.

Q2/ What is the fundamental condition, that must be met for interference to occur between light waves, from two light sources?

A2: The two light sources must be coherent, meaning they are emitted from a single light source.

Q3/ Why is there a path difference between the two light beams emitted from Fresnel Biprism?

A3: This occurs due to the diffraction of light, after it falls on the biprisms.

Q4/ What is the condition for the formation of bright, dark fringes?

A4:
Bright fringes form when the path difference equals an integer number n of wavelengths, and dark fringes form when the path difference equals a half-integer $n + \frac{1}{2}$ of wavelengths, where $n = 0, 1, 2, 3, \ldots$

Q5/ When calculating the distance between the virtual sources in the Fresnel Biprism, why should the lens be placed at a distance greater than at a distance greater than or equal to the focallength of the lens from the biprisms?

A5:
This is because we need to obtain a real image of the object in order to capture it on a screen (i.e., to see it with an eyepiece). If the distance of the object from the convex lens were less than its focal length, a virtual image would form, which would be invisible and could not be captured on a screen, meaning it could not be seen with an eyepiece.

Experiment 9

The Polarimeter

Objectives

1. Observing how polarization occurs.
2. Finding the specific rotation S of solutions with different concentrations.

9.1 Theory

At its core, light is an electromagnetic wave, which means it consists of oscillating electric and magnetic fields that propagate through space. Figure 9.1 shows how both fields propagate in sync to create light.

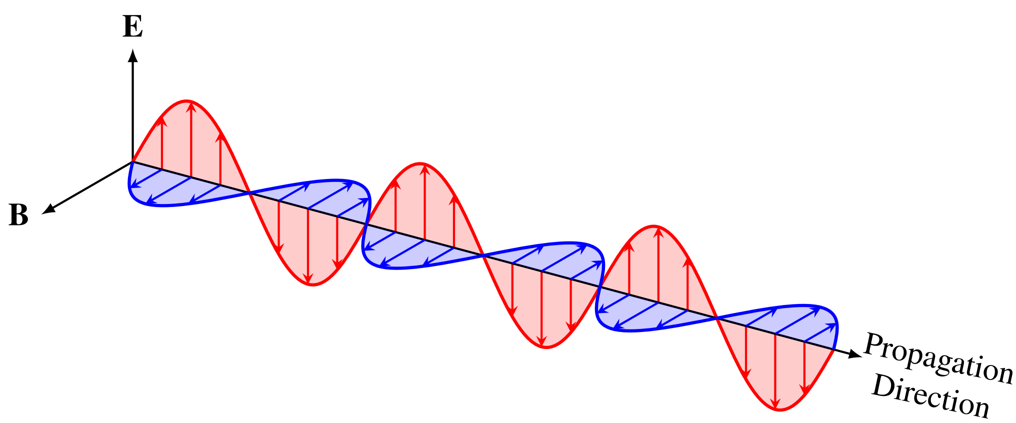

Figure 9.1: Light is an electromagnetic wave propagating in space. **MIT license**.

This electromagnetic wave will either be polarized, propagating in a certain direction, or unpolarized, propagating in all directions. The light emitted from an incandescent light bulb is an example of unpolarized light. Now, how can we filter out light in a specific direction from this unpolarized light? To achieve this, we use polarizers. As shown in Figure 9.2, polarizers and analyzers are optical devices that only allow light that matches their axis of polarization to pass through. By utilizing these devices, we can select the desired direction of polarization. In fact, this is essentially how sunglasses work!

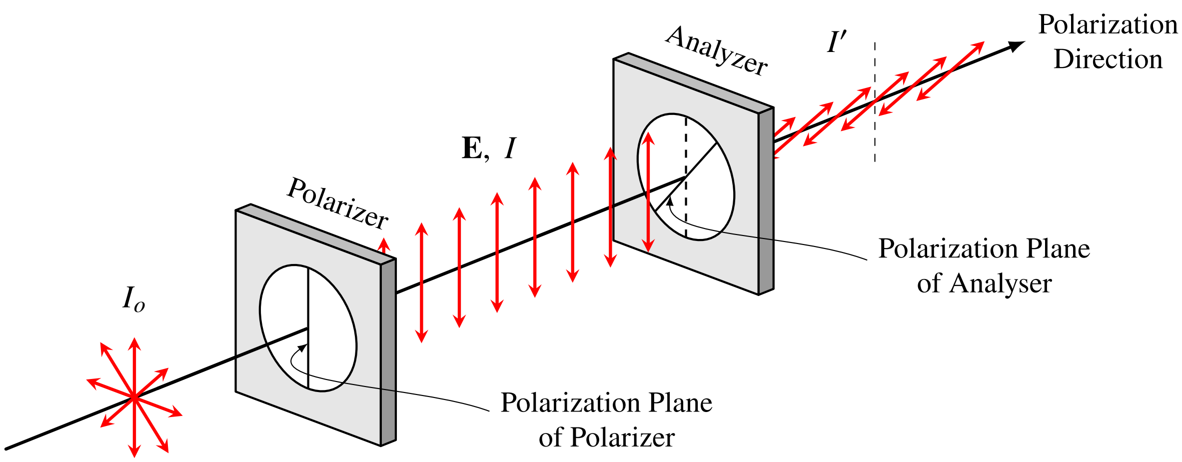

Figure 9.2: Unpolarized light under goes polarization. **MIT license**.

In this experiment, you will first observe and manipulate polarizers to understand how they filter light. Then, we will introduce a subtle change by placing an optically active material between the polarizer and the analyzer. When light passes through such materials, its polarization axis will undergo rotation by an angle θ. We can detect this rotation by examining the resulting polarized light using the analyzer. It is worth noting that each optically active material possesses a unique rotation factor S, which determines the extent of light rotation. Your task is to observe the rotation that occurs and determine the value of S for different concentrations of the sugar solution.

The relation between specific rotation S, length of the pipe L, concentration of the solution C, and rotation angle θ is given by

$$S = 10\frac{\theta}{LC}. \tag{9.1}$$

If we fix the length to be $10cm$, we can calculate S by finding the slope the graph in Figure 9.5 of θ against $C\%$. Hence,

$$S = \frac{\theta}{C} = \text{slope}. \tag{9.2}$$

9.2 Experimental Setup

In this experiment, we will use the polarimeter apparatus shown in Figure 9.3, a sugar solution, and a source of light (sodium light, in our case).

Figure 9.3: Setup of The Polarimeter experiment.

9.3 Procedure

1. Measure the length of the sample (pipe). It is approximately $10cm$.
2. Prepare a 40% sugar solution (similar to Abbe's experiment, read Section4.3).
3. To test the device, fill the sample with distilled water and observe the resulting change in the axis of polarization (it should be noted that pure water is not optically active). Find the equilibrium angle between the polarizer and analyzer ((c) in Figure 9.1), and record it as θ_o.
4. Repeat the previous step, using four different concentrations of sugar solution. Observe the changes in the polarization angle for each concentration, and use them to calculate the specific rotation S.
5. Fill your results in Table 9.1.

(a) High Contrast (b) High Contrast (c) Equal Contrast

Figure 9.4: Polarimeter in action with various angles.

9.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following table:

$C\%(\frac{g}{ml})$	$\theta(^\circ)$	$S(\frac{^\circ}{\frac{g}{ml}})$

Table 9.1: Table of The Polarimeter experiment.

The graph that you will draw to find the slope will look like the following:

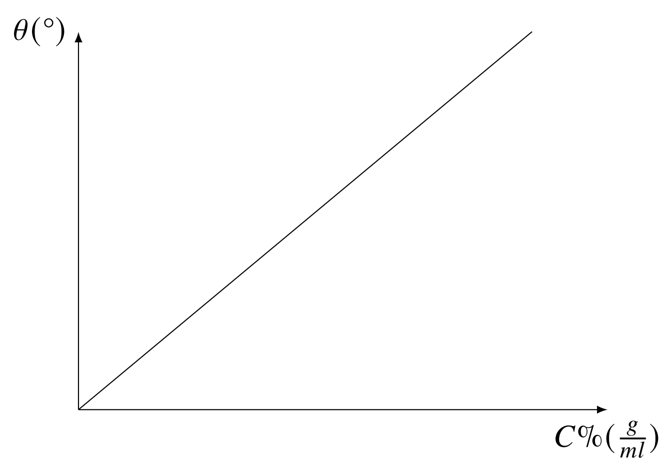

Figure 9.5: Linear relation between $C\%$ and θ.

Along with Eq(4.3) and Eq(4.4) from Abbe's experiment, the error can be calculated using the expression

$$\Delta S = (\frac{\Delta\theta}{\theta} + \frac{\Delta L}{L} + \frac{\Delta C}{C})S. \tag{9.3}$$

Conceptual Questions

Q1/ What does light consist of?
A1:
Light consists of electromagnetic waves, produced by two perpendicular fields, an electric field E and a magnetic field B, which propagate interchangeably in all planes.

Q2/ What is the difference between ordinary light and polarized light?
A2:
In ordinary light, the electric field component oscillates (vibrates) in all planes, whereas in polarized light, it oscillates (vibrates) in a single plane.

Q3/ How do we obtain polarized light?
A3:
There are naturally polarizing materials, and other polarizing materials can be manufactured. These materials allow light to pass through them in one plane, blocking it in all other planes.

Q4/ How do polarizing materials convert unpolarized light into polarized light?
A4:
These materials allow light to pass through them in the plane parallel to the length of the material's molecular vibrations (which is parallel to the length of the molecules), known as the polarization axis.

Q5/ What is a polarizing sheet, and what is an analyzer sheet?
A5:
1. A polarizing sheet is a sheet that polarizes ordinary light and only allows light parallel to its polarization axis to pass through.
2. An analyzer sheet is placed after the polarizing sheet along the path of polarized light. If the polarization axis of the analyzer: A. Is parallel to the polarization axis of the polarizer (i.e., the angle between the axes is zero), light passes through the sheet.
B. Is perpendicular to the polarization axis of the polarizer (i.e., the angle between the axes is 90 degrees), the analyzer does not allow polarized light to pass.
C. Makes an angle between zero and 90 degrees with the polarization axis of the polarizer, the intensity of light passing through it gradually decreases with the increase in the angle. This is the principle behind polarized sunglasses.

Q6/ What is the function of Nicol prisms?
A6:
Nicol prisms polarize ordinary light, with the first acting as a polarizer and the other as an analyzer. When a photoactive solution, like a sugar solution, is placed between them, it rotates the polarization plane of light by a certain angle, leading to a decrease in the light intensity passing through the analyzer. To restore the light intensity, the angle of the analyzer prism must be adjusted to equal the rotation angle of the solution.

Q7/ What is the purpose of the polarimeter experiment?
A7:
1. To calculate the specific rotation of a photoactive solution.
2. To study the factors that the rotation angle of photoactive substances depends on.

Q8/ Define photoactive materials.
A8:
These are materials capable of rotating the polarization plane of polarized light by a certain angle.

Q9/ What are the types of photoactive materials?
A9:
1. Dextrose: These materials rotate the polarization plane of light in clockwise direction.
2. Leaves: These materials rotate the polarization of light in counterclockwise direction.

Q10/ What factors does the rotation angle of the polarization plane of photoactive materials depend on?
A10:
1. Density of the material: Solid materials are more capable of rotating the polarization plane than solutions (direct relationship).
2. Concentration: The greater the concentration of the photoactive material in the solution, the greater the rotation angle (direct relationship).
3. Wavelength of the used light: The rotation angle is inversely proportional to the square of the wavelength of the used light.
4. Temperature: The rotation angle is directly proportional to the temperature of the solution.

Q11/ Define the specific rotation of photoactive materials.
A11:
It is the angle by which the material rotates the polarization plane, when light passes through a 10 cm thickness of a 1% concentration solution of the photoactive material.

Experiment 10

Lloyd's Mirror

Objectives

1. Finding the wavelength λ of the monochromatic light source.
2. Measuring the real distance between the two sources d.
3. Observing the distance between any two nearby fringes Δx.

10.1 Theory

Lloyd's experiment, also known as the Lloyd's mirror experiment, is a classic physics experiment that demonstrates the interference of two sources, one virtual and the other real, due to **reflection**, as shown in Figure 10.1. It was first conducted by Humphry Lloyd in the early 19th century.

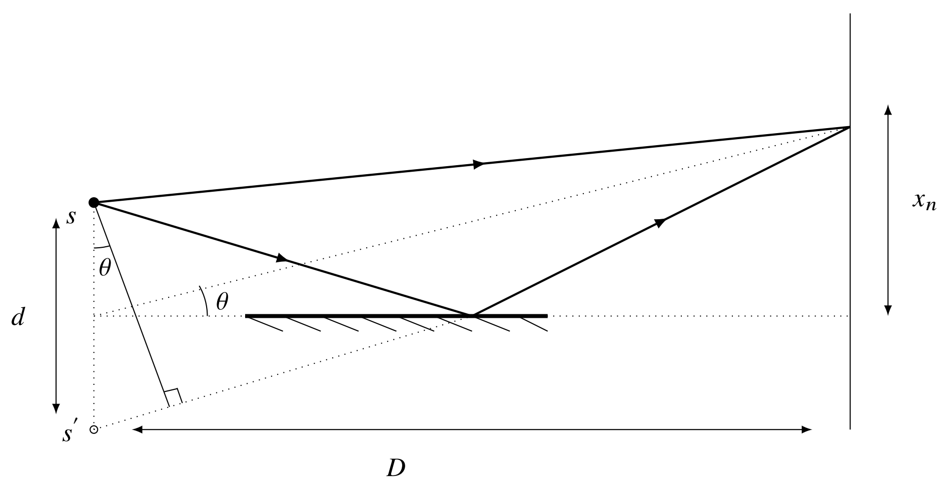

Figure 10.1: Interference resulting from reflection using Lloyd's mirror.

Previously, we have seen how interference can occur due to diffraction (Young) and refraction (Fresnel). However, in this experiment, we will explore how interference can occur due to **reflection** using Lloyd's mirror. The geometric analysis of Figure 10.1 will yield the same results as the last two interference experiments, but with the condition reversed (read Section5.1). Hence, we will leave the analysis to the reader and directly provide you with the necessary relations instead:

$$\text{Destructive} \quad \rightarrow \quad \Delta = n\lambda; \tag{10.1}$$

$$\text{Constructive} \quad \rightarrow \quad \Delta = (n + \frac{1}{2})\lambda; \tag{10.2}$$

$$\Delta x = x_{n+1} - x_n = \frac{\lambda D}{d}; \tag{10.3}$$

$$d = d' \frac{u}{v}. \tag{10.4}$$

10.2 Experimental Setup

As shown in Figure 10.2, we utilize a He-Ne laser, a magnifying lens, a mirror, a convex lens, and a screen.

(a) Setup.

(b) Lloyd's mirror on a holder.

Figure 10.2: Setup of Lloyd's Mirror experiment.

10.3 Procedure

Part 1: Determining the Distance between the Two Sources d

1. Activate the He-Ne laser and ensure that the emitted beam is effectively amplified by the positioned lens in front of the source.
2. Position the mirror appropriately to allow the emitted light to reflect.
3. Place a convex lens at a distance greater than its focal point from the mirror to observe the image of the two sources on the wall (or a screen). Measure and note down the distance from the source to the lens as u.
4. Use a piece of paper to carefully trace the image displayed on the wall, which will help calculate the virtual distance between the sources d'.
5. Measure the distance from the lens to the image on the wall and record it as v.
6. Apply the law of magnification to calculate the actual distance between the sources d.
7. Repeat the above steps, incrementing the distance from the source to the lens during each iteration (e.g, 20cm, 24cm).
8. Fill your results in Table 10.1.

Part 2: Calculating the Wavelength of the Light Source λ

1. Remove the convex lens to allow the emerging beams from the sources to interfere freely.
2. Use a movable screen and place it 55cm farther from the source (or any distance of your choice that will make the fringes visible) to observe the interference behind the screen.
3. Using a paper and a ruler, measure the distance between nearby fringes by tracing the distance between 4-5 (or more) fringes. Divide the measured distance by (n-1), where n is the number of fringes.
4. Utilize all the previously measured quantities to calculate the wavelength of the light source.
5. Repeat the above steps increasing the distance between the source and the screen by 5-10cm each time.
6. Fill your results in Table 10.2.

10.4 Results, Tables, Graphs, and Measurement of Error

Write down your results in the following tables, respectively:

$u(cm)$	$v(cm)$	$d'(cm)$	$d = d'\frac{u}{v}(cm)$

Table 10.1: Determining the distance between the two sources d.

n	$D(cm)$	$x(cm)$	$\Delta x = \frac{x}{n}(cm)$	$\lambda = \frac{\Delta x \bar{d}}{D}(nm)$

Table 10.2: Calculating the wavelength of the light source λ.

Mathematical expressions of error:

$$\Delta d = (\frac{\Delta d'}{d'} + \frac{\Delta u}{u} + \frac{\Delta v}{v})\bar{d}, ; \tag{10.5}$$

$$\Delta \lambda = (\frac{\Delta(\Delta x)}{\Delta x} + \frac{\Delta d}{d} + \frac{\Delta D}{D})\bar{\lambda}. \tag{10.6}$$

Before proceeding to find the error, make sure that you calculate both $\bar{d}$ and $\bar{\lambda}$.

Conceptual Questions

Q1/ What is the purpose of Lloyd's Mirror experiment?

A1:
1. To calculate the wavelength of the monochromatic source of light.
2. To understand the interference of light between two sources: one real and one virtual.

Q2/ How does interference occur in Lloyd's Mirror experiment?

A2:
Interference occurs when the two beams overlap: the beam that falls directly on the eyepiece (the real source) and the beam that falls on Lloyd's mirror and then reflects off it (the virtual source).

Q3/ Why do we get bright fringes when the path difference equals half an integer number of wavelengths?

A3:
Because the beam that falls on the mirror and then reflects (the virtual source) moves from a medium of lesser optical density (air) to a medium of greater optical density (the glass of the mirror). Therefore, it undergoes a phase change of 180 degrees, leading to a path difference of half a wavelength. As a result, we get: - Bright fringes: (constructive interference) when the path difference equals half an integer number of wavelengths. - Dark fringes: (destructive interference) when the path difference equals an integer number of wavelengths.

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