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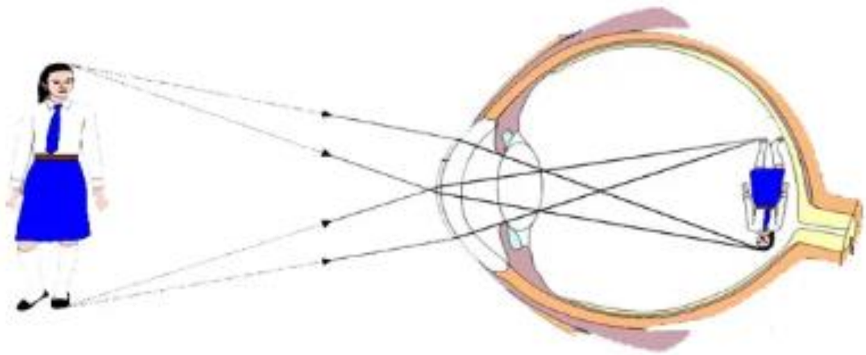
Handout for :

LABORATORY WORK: GEOMETRICAL AND PHYSICAL OPTICS



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Preface

This manual is intended for science students to develop practical skills through laboratory experiments in geometrical and physical optics.

It builds on the work of previous instructors and specialists who contributed to the design and improvement of these optics experiments. The present version has been organized and rewritten to match the university level and to align with students' prior knowledge of light and basic optical devices.

The manual includes a set of laboratory experiments, each with clear objectives and a theoretical background that supports understanding and guides the experimental work. It aims to help students grasp both the physical concepts and the practical procedures associated with each experiment. Short questions are included to enrich students' knowledge, strengthen their reasoning, and encourage analysis based on experimental observations and measured results. Each experiment also includes guidance on estimating experimental uncertainty, which is an essential part of scientific measurement.

This manual contains eleven experiments designed for second-year physics students in the Materials Science program.

I would like to express my sincere gratitude to everyone who contributed ideas and support to the preparation of this manuscript.

O. Haif Khaif

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Laser Hazards and Safety Precautions

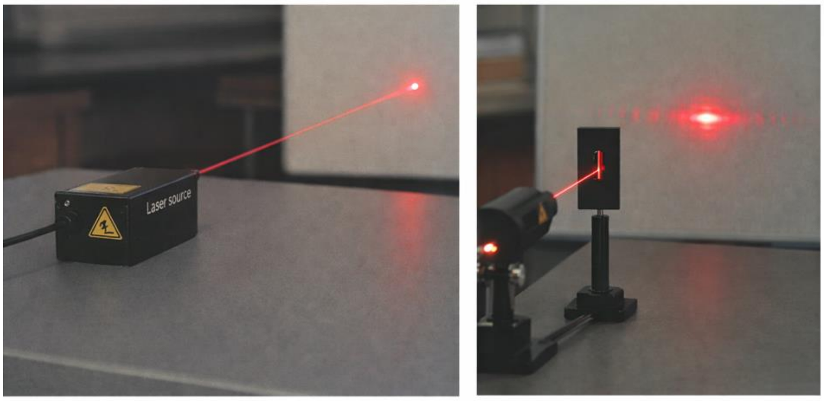
Laser Hazards

The laser produces an intense, highly directional beam of light. If directed, reflected, or focused upon an object, laser light may be partially absorbed, raising the temperature of the surface and/or the interior of the object, potentially causing an alteration or deformation of the material. In particular, direct or reflected laser beams can cause serious eye injury.

Safety Precautions

- Keep the laser ray box on your workstation.
- Avoid direct eye exposure to the laser beams from the laser ray box.
- Do not direct the laser beams toward other students.
- Turn the laser ray box off when it is not in use.

Never look directly into the beam or at specular reflections



Figurei. Typical laser setup used in the optics laboratory.

The Uncertainty of Measurements

1. Systematic and Random Uncertainty

We distinguish between two types of uncertainties: Systematic uncertainties, which are caused by poorly calibrated instruments or flaws in the measurement method, and Random (Accidental) uncertainties, which arise from the limited precision of the equipment and the observer's own sensory limitations.

2. Absolute And relative Uncertainty

In the case of a single direct measurement of a simple physical quantity (temperature, time, length, etc.), the absolute uncertainty ΔX is either specified by the manufacturer on the measuring device, or it is determined by the smallest unit the device is capable of displaying (the resolution). The precision of the measurement result is characterized by the ratio:

$$\frac{\Delta X}{X_{mes}} \rightarrow Relative\ Uncertainty \quad (1)$$

The smaller this ratio, known as the relative uncertainty, the more precise the measurement is.

3. Writing the Result

The final result of a measurement (X) must always be written with its absolute uncertainty (ΔX) and the corresponding unit. The standard form is:

measurement = (best estimate ± uncertainty) units

Example: When using a ruler with a precision of $0.1cm$, we measure a length L. Suppose the calculated value is $L_{mes} = 15.5\ cm$ and the absolute uncertainty is $\Delta L = 0.1\ cm$. The final result is reported as:

$$L = (15.5 \pm 0.1)cm \quad (2)$$

$$Relative\ Uncertainty = \frac{0.1}{15.5} = 0.0065 \rightarrow 0.65\% \quad (3)$$

4. Calculation of Absolute and Relative Uncertainties Using Partial Derivatives

Given that the quantity G is a function of the variables $a, b, c, \ldots$, a small variation in G can be obtained by differentiating the function $G = f(a, b, c, \ldots)$. Thus, we obtain the differential of G:

$$dG = \frac{\partial f}{\partial a}da + \frac{\partial f}{\partial b}db + \frac{\partial f}{\partial c}dc + \cdots \quad (4)$$

The absolute uncertainty ΔG is obtained by the following relation:

$$\Delta G = \left|\frac{\partial f}{\partial a}\right|\Delta a + \left|\frac{\partial f}{\partial b}\right|\Delta b + \left|\frac{\partial f}{\partial c}\right|\Delta c + \cdots \quad (5)$$

$d(ln\, G)$ is obtained according to the following relation:

$$d(lnG) = \frac{df}{G} = \frac{\partial lnf}{\partial a}da + \frac{\partial lnf}{\partial b}db + \frac{\partial lnf}{\partial c}dc + \cdots \quad (6)$$

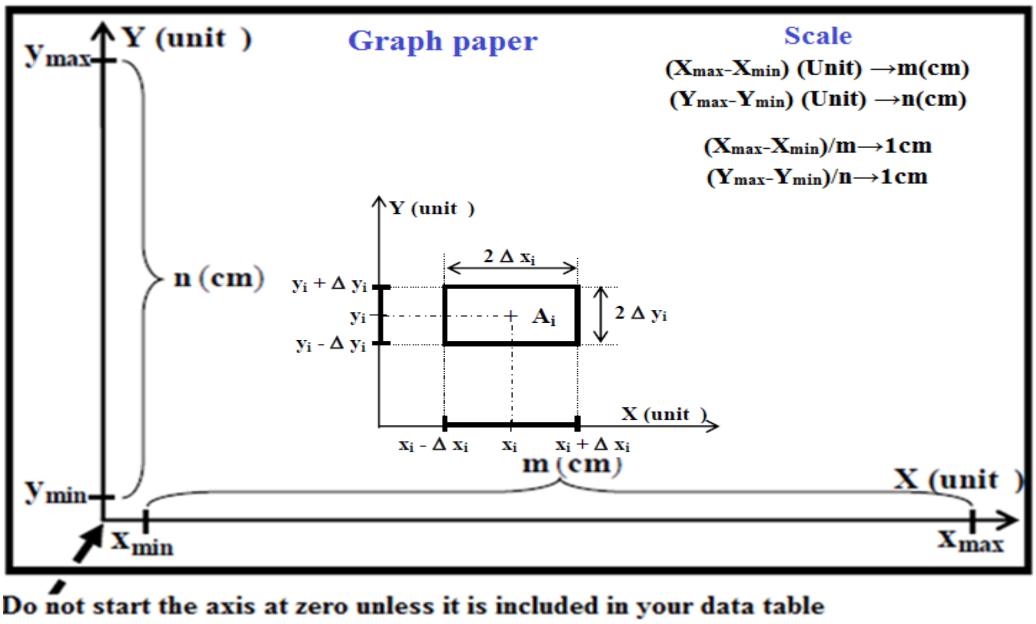
The relative uncertainty $\frac{\Delta G}{G}$ is obtained by taking each term of the sum as positive:

$$\frac{\Delta G}{G} = \left|\frac{\partial lnf}{\partial a}\right|\Delta a + \left|\frac{\partial lnf}{\partial b}\right|\Delta b + \left|\frac{\partial lnf}{\partial c}\right|\Delta c + \cdots \quad (7)$$

5. Graph Plotting

Plotting graphs is the best way to present and analyze your experimental data. For a perfect graph, follow these essential steps:

- **Descriptive Title:** (e.g., $Y = f(X)$).
- **Labeled Axes:** (Quantity and [Unit]).
- **Optimal Scale:** (Covers 75% of the paper).
- **Data Points:** (Marked with + or .).
- **Error Bars:** (ΔX and ΔY for each point).
- **Best-Fit Line:** (Passing through the average of points).



Figureii. Guide to Plotting and Data Representation

Lab Work N°1: Introduction: the different light sources and detectors

I. Objectives

- To study light sources and their main classifications.
- Exploring Optical Detectors: Learn about photonic detectors such as photodiodes, CMOS, and CCD, and understand how they convert light into electrical signals.

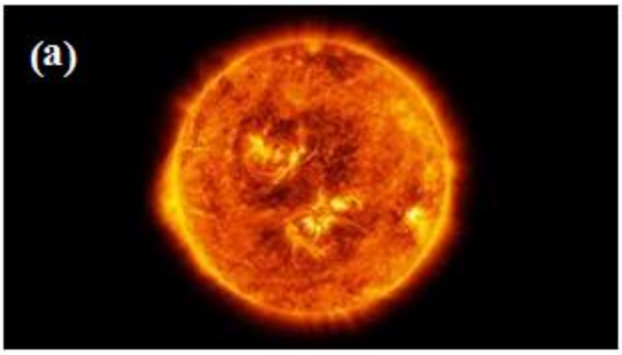
II. Light sources

Light is a form of electromagnetic waves that enables vision and supports the transmission of visual information from objects to the human eye and interacts with different media through reflection, refraction, and absorption. Understanding the nature of light and its sources is fundamental in geometrical optics, as it is crucial for analyzing shadow formation and image production using optical systems.

Light sources can be classified according to several criteria, the most important distinction in geometrical optics is:

1. **Primary light sources**: These emit light by themselves.

Examples (Figure1): the Sun (daylight), fire, flames, stars, lightning, fireflies, televisions, various artificial light sources, such as LED light bars, fluorescent tubes, neon lamps, and lasers, etc.



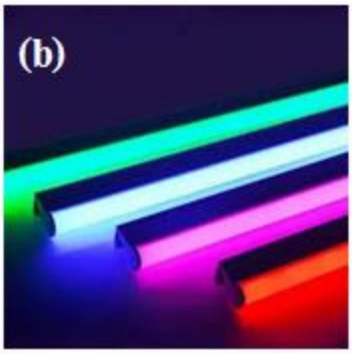


Figure1. Primary light sources, (a) The sun, (b) LED light bars

2. **Secondary light sources**: These do not generate light but become visible by reflecting the light falling on them.

Examples (Figure2):

- The Moon diffuses part of the light it receives from the Sun.
- The planets of the solar system.
- A cinema screen

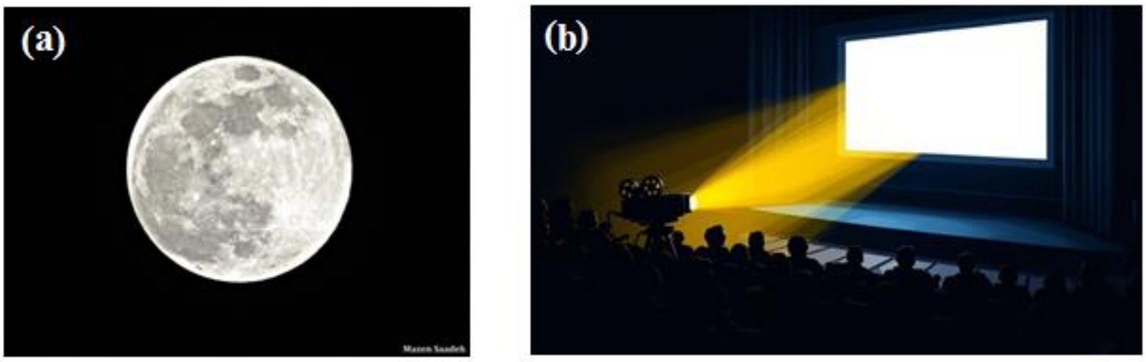


Figure2. Secondary light sources, (a) The Moon, (b) A cinema screen

They may also be categorized based on their size relative to the illuminated object into point sources, whose dimensions are negligible, and extended sources, which have appreciable dimensions. Furthermore, they can be divided by origin into natural sources, including the Sun and stars, and artificial sources, such as incandescent and LED lamps used in technological applications.

This classification provides a basis for practical studies in optics, enabling accurate modeling of light propagation and image formation in experimental setups.

III. Light detectors

III.1 Definition and categories

Optical detectors are devices that convert optical radiation, typically ranging from ultraviolet to infrared wavelengths, into electrical signals. They play a crucial role in modern technology and can be classified according to their main applications into five categories:

- **Imaging Detectors**: such as CCD and CMOS sensors, commonly used in photography, videography, and daily-life electronic devices.
- **Research Detectors**: specifically designed for scientific experiments and precise measurements in laboratories.
- **Industrial Detectors**: including photocells and photomultiplier tubes used in automation, manufacturing, and quality control processes.
- **Military Detectors**: employed for surveillance, target detection, and observation in terrestrial, marine, and aerospace environments.
- **Communication and Sensing Detectors**: essential components in optical communication networks and sensing systems, where they convert optical signals into electrical ones for data transmission, fiber optics, and environmental or biomedical sensing.

III.2 Characteristics

- Sensibility.
- Resolution.
- Faithfulness - Accuracy – Precision.
- Limit and extension of measurement.
- Hysteresis.
- Reproducibility or repeatability.
- Response time.

III.3 Classification

Two main types of detectors are identified according to the physical principles governing their response to light.

1. Thermal Optical Detectors

These detectors function by converting the absorbed light energy into heat within the detector material. This temperature rise leads to changes in its electrical properties, such as resistance (in bolometers), voltage (in thermocouples), or electric charge (in pyroelectric detectors).

Although less sensitive to individual photons, thermal detectors have a broad spectral response and are commonly used in infrared thermography and radiation measurement.

2. Photonic Optical Detectors

These detectors function through the interaction between photons and matter, generating charge carriers rather than heat.

They are mainly divided into:

- **Internal Effects**: such as photoconduction, photovoltaic, and photo electromagnetic effects, where light alters the electrical properties inside semiconductors.
- **External Effects**: based on photoemission, where electrons are emitted from the surface (as in photocells and photomultiplier tubes).

These detectors are highly sensitive and widely used in fields like optical communications, spectroscopy, and astronomy.

III.4 Principles of different detectors

1. Photodiode

When illumination is incident on a P ++N, junction, electron/hole pairs are released into the transition zone. The electrons thus created are immediately swept away by the electric fields to the zone N (and holes to the zone P ++), (Figure 3).

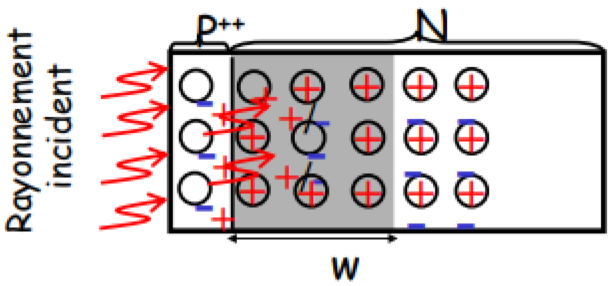


Figure3. Photodiode principle.

This results in a reverse photocurrent is given by:

$$I_{ph} = qA\eta\phi \quad (1)$$

Where A is the cross section of the photodiode, ϕ the luminous flux entering the structure, and η the quantum efficiency of the material.

Moreover if the diode is supplied with a voltage V, the total current is given by:

$$i = I_{sat}\left(e^{\frac{qV}{KT}} - 1\right) - I_{ph} \quad (2)$$

2. Image sensors CCD and CMOS

- **Optical Imaging Sensors**

Optical sensors, including technologies such as CMOS, CCD, MOS, BSI-CMOS, 3MOS, and Super CCD, are widely used in modern digital imaging systems, particularly in digital cameras.

These sensors operate based on the principle of converting incident light (photons) into electrical signals through photosensitive cells. Once the light is absorbed by these cells, the resulting electrical signals are then processed by an analog-to-digital converter. This process allows for the recovery of the final image, with color information captured through individual pixels. The processed data is subsequently handled by the imaging processor, which compiles the image. Finally, the resulting image is stored in the camera's buffer and later transferred to a memory card for further use or storage.

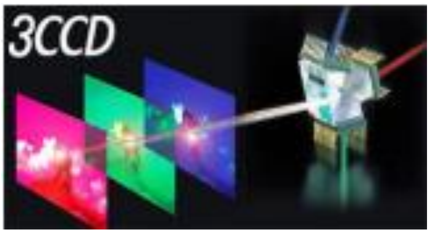


Figure4. 3CCD color sensor

- **CCD vs. CMOS Optical Sensors**

The operating principle of CCD (Charge-Coupled Device) optical sensors is based on an array of photosites small light-sensitive cells that individually accumulate light. The color information is determined through an analog filter (often a Bayer filter), which assigns color values based on the intensity of the received light. Typically, four photosites make up a single pixel in a color image.

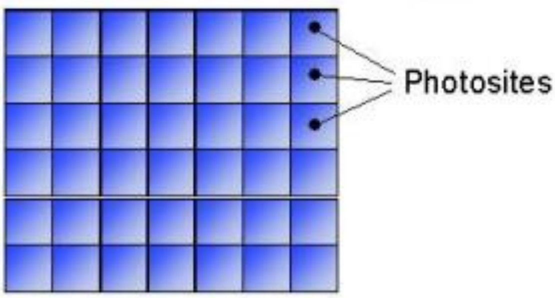


Figure5. Surface area of a CCD sensor

In contrast, CMOS (Complementary Metal-Oxide-Semiconductor) optical sensors operate using a photodiode array (PD), where each photodiode is sensitive to one of the primary colors (red, green, or blue). The sensor operates in a binary fashion, where each photodiode provides a "yes" or "no" response based on its light sensitivity. The final color of each pixel is determined by a combination of the output values (0 or 1) from each photodiode. The result is a pixel calculation matrix, which is often used in electronic imaging systems.

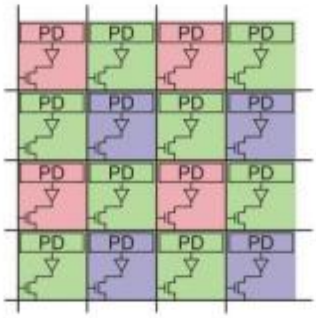


Figure6. Surface area of a CMOS sensor

IV. Student Activity

Identify the different light sources and detectors available in your laboratory. Classify each device and briefly describe its main characteristics and typical applications.

Lab Work N°2: Reflection (plane mirror, spherical mirror) and refraction (air/glass, glass/air)

I. Objectives

- To study the law of reflection.
- Use ray tracing to locate virtual images formed by mirrors.
- Form an image using a concave mirror and measure its magnification.
- To study the law of refraction (Snell's law) for air/glass and glass/air interfaces.
- To determine the refractive index of glass using experimental measurements.

II. Reflection

Reflection of light is the return of light rays into the same medium when they encounter a reflecting surface (such as a mirror). Figure (1) illustrates the reflection of a light ray. The ray that strikes the surface is called the incident ray, while the ray that leaves the surface after bouncing off is called the reflected ray. The normal is defined as the line perpendicular to the surface at the point of incidence.

The angle of incidence (θ_i) is defined as the angle between the incident ray and the normal, whereas the angle of reflection (θ_r) is the angle between the reflected ray and the normal at the point of reflection.

The law of reflection states that the angle of incidence is equal to the angle of reflection, and that the incident ray and the reflected ray all lie in the same plane (Figur1).

➲ Using the laws of reflection, draw ray diagrams to obtain the image by placing the object in different positions relative to the mirror.

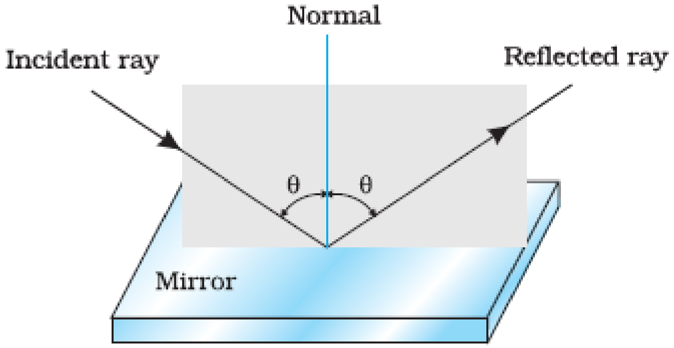


Figure1. Law of reflection.

➢ Materials

- Mirror.
- Light Source.
- Protractor.
- Ruler.

II.1 Plane mirror

- Images formed with plane mirrors

Images with mirrors are formed when many nonparallel rays from a given point on a source are reflected from the mirror surface, converge, and form a corresponding image point.

- laws of reflection

1. Place the mirror perpendicular to the paper so that the flat surface of the mirror is at the location indicated at the bottom of this paper.
2. Point the light source toward the mirror, assuring the incident ray (incoming ray) touches the center of the paper protractor (Figure 2).

➲ In which plane are the reflected beams located?

➲ Give the law that corresponds to this observation? (The first law of reflection).

3. Measure the angle of incidence of the incident ray. The angle between the normal line and in incident ray.
4. Measure the angle of reflection of the reflected ray. The angle between the normal line and the reflected ray.
5. Do this for 3 different angles of incidence and their respective angles of reflection and record your values in the table below.

Angle of incidence	Angle of reflection

- Can you give the second law of reflection?

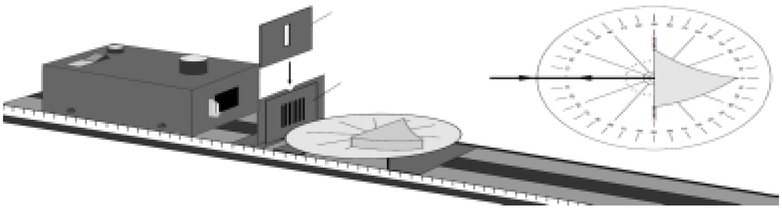


Figure2. Reflection experiment setup.

II.2 Spherical mirror

A spherical mirror consists of a reflective surface shaped like a spherical cap, with its center denoted as C, known as the optical center. The mirror's radius of curvature is represented by R. The optical axis is the axis of revolution of the spherical cap. The vertex of the mirror, marked as S, is the point where the optical axis intersects the mirror (Figure 3).

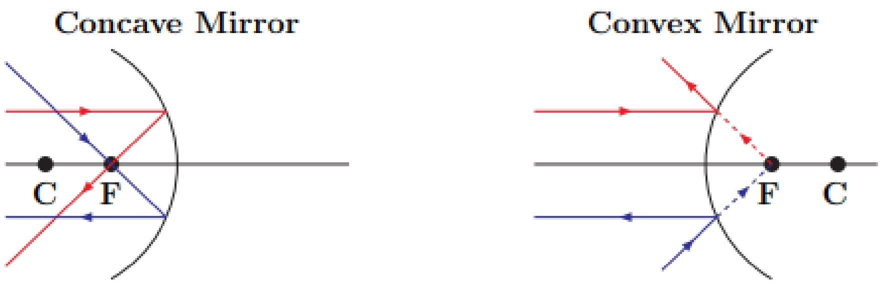


Figure3. Reflection in concave and convex spherical mirrors.

Figure 3, Illustrates the reflection of light rays in relation to a mirror's central axis and focal point. Parallel incident rays (red) reflect through the focal point, while rays incident along a line through the focal point (blue) reflect parallel to the central axis. In convex mirrors, the rays do not physically reach the focal point, but their reflected paths extend along lines that pass through it.

1. Experiment 1

Place the lighted candle in front of the concave mirror at different positions: very far from the mirror, near the center of curvature (C), at the center of curvature (C), between (C) and the focus (F), at the focus (F), and between (F) and the mirror. Record the position of the candle. Measure the distance x between the pole (P) of the mirror and the image of the candle flame, and record the other results in Table 1 (the part of concave mirror).

2. Experiment 2

Repeat the same experiment with a convex mirror, and record the results in Table 1 (the part of convex mirror).

Table 1

	Position of the object	Position of the image	Size of the object	Size of the image	magnification	Nature of the image
Concave mirror	**Beyond Center of Curvature ©**					
	At Center of Curvature ©					
	Between C and F					
	At Focus (F)					
	Between F and Mirror					
Convex mirror	**Beyond Center of Curvature ©**					
	At Center of Curvature ©					
	Between C and F					
	At Focus (F)					
	Between F and Mirror					

- **Questions**

  - How can you differentiate between a concave and a convex mirror?
  - What similarities and differences can be observed between the images formed by concave and convex mirrors?
  - Where the image is formed by a concave mirror when the candle is placed far from the mirror And what it type?

- Why is a screen used when working with a concave mirror, but not with a convex mirror?
- Why does a convex mirror form only virtual images?
- What are the practical uses of concave and convex mirrors in daily life?
- Why does a concave mirror sometimes produce a real image and sometimes a virtual image?

III. Refraction

If parallel light rays enter a transparent medium and then strike the surface of another transparent medium whose refractive index differs from that of the first medium, new light rays will be produced in the second medium, as shown in Figure2. We refer to the ray that appears in the second medium as the refracted ray, while the angle enclosed between this ray and the normal is called the angle of refraction (θ_t) (Figure4).

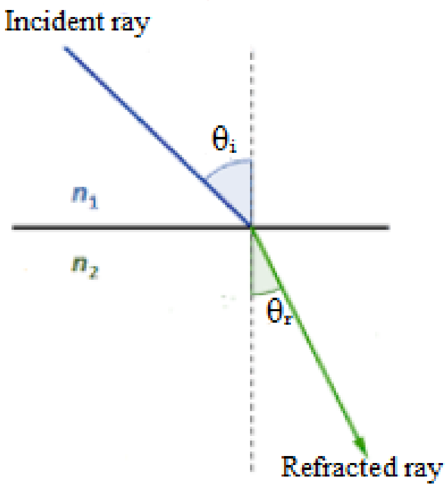


Figure4. Light refraction.

➢ Experiment

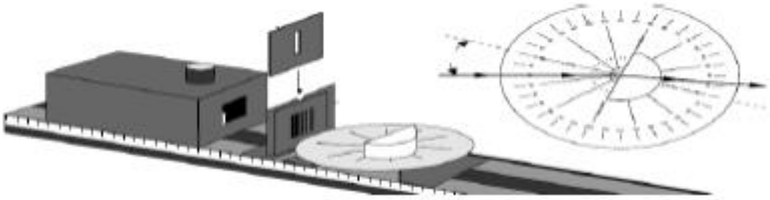


Figure5. Refraction experiment setup.

We keep the same experimental setup as before and replace the reflecting mirror with a glass half-cylinder placed in the same position, as shown in the adjacent figure 5.

A light beam is directed toward the flat face of the half-cylinder, and the angle of incidence (θ_i) is varied using the graduated disk. The corresponding angle of refraction (θ_r) inside the glass is then measured with respect to the normal to the interface.

This procedure is repeated for several values of the incident angle, and all measured results are recorded in the table below.

Angle of incidence (θ_i)	**Angle of refraction (θ_r)**	$sin\ (\theta_i)$	$sin\ (\theta_r)$

➢ Questions

- Plot the graph $sin\ (\theta_r) = f(sin\ (\theta_i))$
- What does the slope of the graph represent?
- Calculate the refractive index of the glass half-cylinder.
- Deduce the speed of light in the material of the half-cylinder.
- Identify experimental errors. What be the sources of these errors?
- Explain why a ray of light changes direction when it passes from air into glass.
- Determine the critical angle for the glass–air interface using your measured refractive index.
- If the experiment were performed with a different material (e.g., acrylic), how would the graph and slope change? Explain.

Lab Work N°3: Study of the prism: deviation

I. Objectives

- Study the deviation of light by a prism.
- Determine the angle of a prism
- Measurement the minimum angle of deviation for a prism and show how this angle can be used to determine the refractive index of a prism material.

II. Theoretical reminders

- **The fundamental relations of the prism**

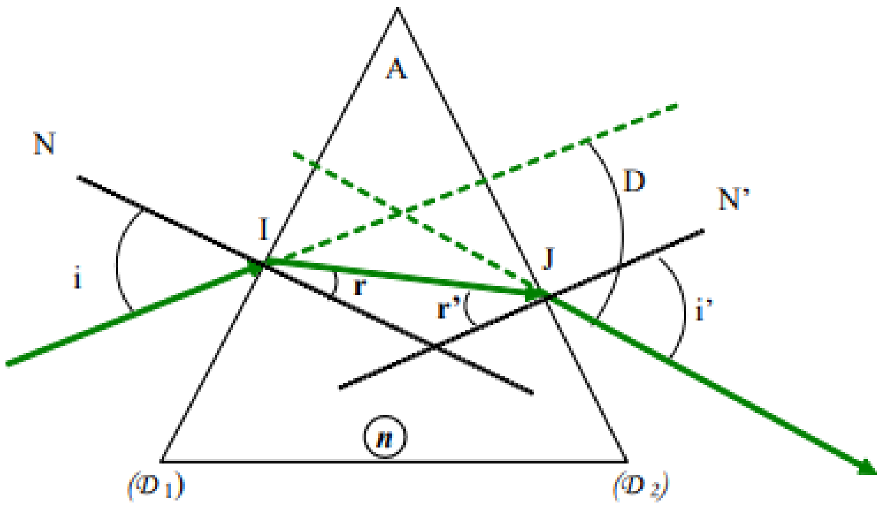


Figure1.Light deviation through a prism.

From figure 1:

$$\sin i = n \sin r \qquad (1)$$

$$\sin i' = n \sin r' \qquad (2)$$

$$A = r + r' \qquad (3)$$

$$D = i + i' - A \qquad (4)$$

Where:

i is the angle of incidence at the first face.

r is the angle of refraction inside the prism at the first face.

r′ is the angle of incidence inside the prism at the second face.

i′ is the emergence angle

D is the angle of deviation.

A is the prism angle.

When a prism is in the condition of minimum deviation, the angle of incidence i is equal to the angle of emergence i' (Figure 2). In this case we have:

$$r = r' = \frac{A}{2} \tag{5}$$

$$D_m = 2i - A \tag{6}$$

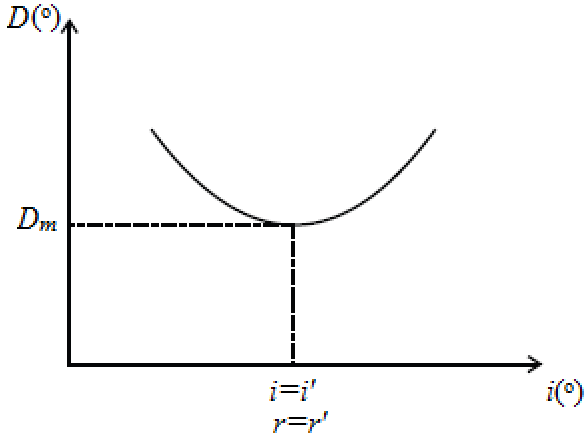


Figure2. Variation of the deviation angle with incidence.

III. Experimental determination of the angle of the prism

1. Place the prism on the turntable, so that the bisector of the prism is parallel to the rays of the beam coming from the collimator.

2. Part of the beam is reflected by face 1, the other part by face 2. Start by looking with the eye for the direction of the beam reflected by face 1 (Figure 3).

3. Refine the determination of the angular position of this first beam by replacing your eye with the telescope.

   ➲ Block the telescope in this position and read the value of the corresponding angle.

$$\alpha_1 = \cdots \dots \dots \dots \dots \dots \dots$$

4. Without touching the prism, look with the eye to the direction of the beam reflected by face 2.

5. Refine the determination of the angular position of this second beam by replacing your eye with the telescope.

   ➲ Block the telescope in this position and read the value of the corresponding angle.

$$\alpha_2 = \cdots \dots \dots \dots \dots \dots \dots$$

✓ **using the same vernier as that used for reading the angle α_1.**

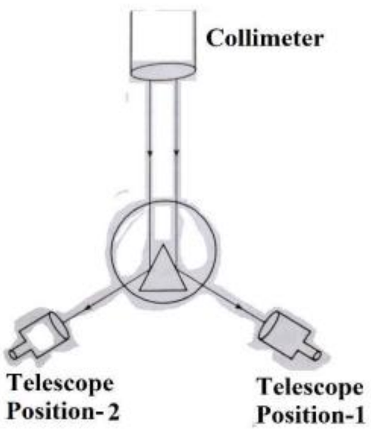


Figure3. Determination of the prism angle A.

- Calculate the angle $\alpha = |\alpha_2 - \alpha_1|$ which corresponds to the angle between the two beams reflected by surfaces 1 and 2 of the prism.

$$\alpha = \cdots \ldots \ldots \ldots \ldots \ldots \ldots \ldots$$

- Demonstrate that the angular deviation α between the two directions of the reflected beams is equal to $2A$.
- Deduce A.
- Estimate the uncertainty in A.
- Is it necessary to use a composite light to determine the prism angle? Why?

IV. Experimental determination of the minimum deviation D_m

1. Adjust the laser beam to obtain a narrow, well-defined ray, and align its image with the crosshairs of the telescope. Lock the telescope in position.
2. Set the prism table to (90°) using the vernier scale of the goniometer.
3. Place the prism on the table and secure it firmly.
4. Loosen the table clamp and slowly rotate the prism table until the reflected image of the slit coincides with itself on the first face of the prism. In this configuration, the angle of incidence is approximately (90°) (within the instrument's uncertainty). Tighten the table clamp.
5. Adjust the prism table to the required angle of incidence, $(i = 60^{\circ})$, taking into account the reading uncertainty.
6. Loosen the telescope clamp and rotate the telescope around the goniometer axis until the laser beam appears.
7. Record the angular position θ of the telescope corresponding to the laser beam.

✓ The deviation angle is then given by:

$$D = |\theta - i| \tag{7}$$

8. Vary the incidence angle from (60°) to (90°), and then from (60°) down to (25°). For each chosen incidence angle.

➢ Results and discussion

- Record all measurements in the table.
- Plot the graph $(D = f(i))$ and analyze its behavior.
- From the plotted curve, determine the minimum deviation angle (D_m).
- What are the critical angles in this experiment?
- What are your observations and conclusions?

i	θ	$D = \lvert\theta - i\rvert$	ΔD
25 … .90			

V. The prism refractive index

The minimum deviation condition is for the measurement of the refractive index n, the relation between n, the prism angle A, and the minimum angle of deviation D_m is given by:

$$n = \frac{\sin((D_m + A)/2)}{\sin(A/2)} \quad (8)$$

- Calculate the value of the refractive index n of the prism glass.
- Compare your experimental value of the refractive index with the theoretical value.
- Calculate the experimental uncertainty in the determination of the refractive index.
- Using your value of (n), calculate the critical angle for total internal reflection at the glass–air interface.
- Why is it necessary to use a monochromatic light source in this experiment?

Lab Work N°4: Study of the prism: Dispersion

I. Objectives

- Study the dispersion of light by a prism.
- To measure the minimum angle of deviation for a prism and show how this angle can be used to determine the refractive index of the prism material for a different wavelengths (spectral colors).
- To apply and verify Cauchy's law for the prism material.

II. Dispersion of light

Using a spectrometer to determine the refractive index of a material in the form of a triangular prism is a rapid procedure that typically provides higher accuracy than many alternative methods. With a properly aligned instrument, it is also possible to resolve the modest variation of refractive index with wavelength.

A prism deflects an incident light beam because refraction occurs at its two refracting faces. A spectrum is produced because the refractive index n of the prism material depends on the wavelength λ, this wavelength dependence is known as dispersion (Figure 1). Since the deviation introduced by the prism is governed by n, different wavelengths are deviated by different amounts and therefore emerge at different angles, separating the light into its spectral components. In practice, this effect is quantified by measuring the angle of minimum deviation Dmin for each calibration spectral line and applying the minimum deviation relation that links D_{min}, the prism apex angle A and the refractive index n.

$$n = \frac{\sin((D_m + A)/2)}{\sin(A/2)} \tag{1}$$

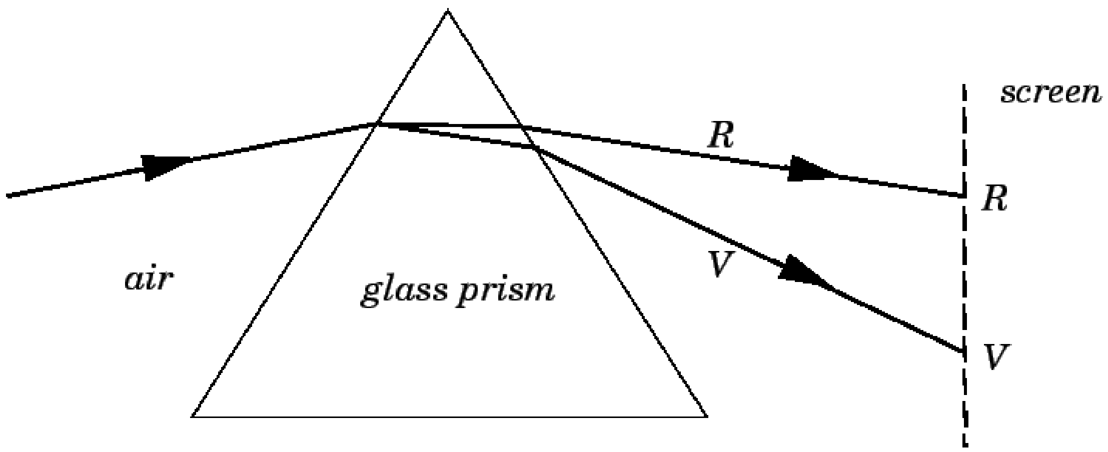


Figure1. Dispersion of light by a glass prism.

III. Reading Angles on the Goniometer

Angular measurements on the goniometer are obtained using two scales: the main (fixed) circular scale and the vernier (movable) scale. This vernier system improves the angular resolution and allows readings in arcminutes ($'$), where $1' = (1/60)°$.

The main scale provides the reading in degrees ($°$) and includes subdivisions (typically $1°$ and $10°$ marks). The vernier scale provides the additional minutes ($'$) reading. In this type of vernier, the smallest readable increment is $5'$. The angle is read in two steps (as shown in the figure):

1. Main-scale reading (degrees):

Locate the zero mark of the vernier and read the value on the main scale just to the left of this zero. In the figure, the vernier zero lies slightly beyond $131°$, therefore:

$$d = 131°$$

2. Vernier coincidence (minutes):

Identify the Vernier division that aligns exactly (coincides) with a division on the main scale . In the figure 2, the coincidence occurs at $20' + 15' = 35'$ on the vernier, hence:

$$m = 35'$$

Therefore, the measured angle is:

$$x = d + m = 131° + 35' = 131.58°$$

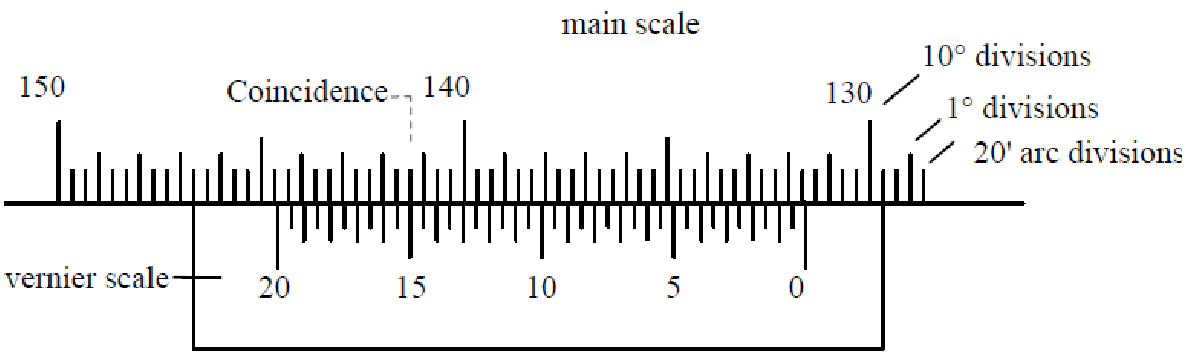


Figure2. Reading an angle with a vernier.

IV. Experimental determination of the minimum deviation D_m

For this manipulation, we are modifying the orientation of the prism relative to the incident ray (coming from the collimator). We will rotate the mobile plate which the prism is placed, not the prism. The angle of deviation depends on the wavelength. We make the manipulations by considering the yellow line of sodium (Na).

1. Orient the prism (by rotating the plate and not the prism) so that we get an incident ray on the first face of the prism ($i \sim \pi/2$).

2. Progressively reduce i by identifying the position of the yellow sodium line emerging from face 2 with the human eye. We identify the minimum deviation on the position which the apparent displacement of the yellow line changes it direction.

3. Refine the determination of the angular position of the minimum deviation by observing through the telescope.

4. Block the telescope on this position and read the value of the corresponding angle.

$$\theta_{1y} = \cdots \dots \dots \dots \dots \dots \dots \dots \dots \dots.$$

5. Repeat all the manipulation by using face 2 of the prism. We find a position symmetrical to the first with respect to the incident ray. Read the value of the corresponding angle (Figure3).

$$\theta_{2y} = \cdots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ....$$

✓ **Using the same vernier as that used for reading the angle $\boldsymbol{\theta_1}$.**

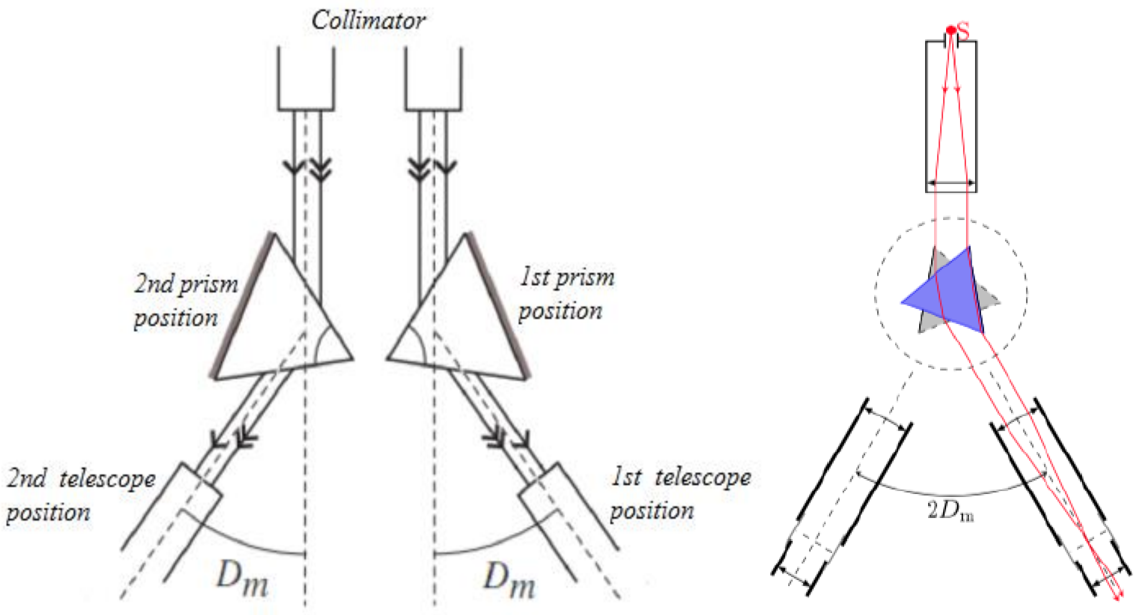


Figure3. Determination of the angle D_m of the prism

➲ Calculate the angle $\theta_y = |\theta_{2y} - \theta_{1y}|$.

$$\theta_y = \cdots \ldots \ldots \ldots \ldots \ldots \ldots ..,$$

➲ Deduce the value of the minimum deviation $D_{my} = \frac{\theta_y}{2}$ corresponding to the yellow sodium line.

$$D_{my} = \cdots \ldots \ldots \ldots \ldots \ldots \ldots ..$$

- Repeat the same procedure for other sodium spectral lines and put the results in the table below.

Color	θ_1	θ_2	θ	D_m

V. The prism refractive index

Experimentally, we determine the minimum deviation D_m of the prism for all the sodium spectral lines. Calculate the corresponding values of the refractive index n of the prism glass, Put the results in the table below.

Color	λ	D_m	$n(\lambda)$	$\Delta n(\lambda)$

- What do you observe?
- Which spectral color is deviated the most by the prism? Why?
- Using the refractive indices obtained for the different sodium spectral lines, calculate the dispersion of the prism glass.

- Compare the precision of the measurements across different wavelengths.
- Why does light split into its spectrum of colors in a prism?
- Why does light disperse through a shape such as a glass triangular prism however not something like a glass cube?

VI. Cauchy's law

The refractive index is modeled by Cauchy's formula:

$$n = \alpha + \frac{\beta}{\lambda^2} \quad (2)$$

Where, α and β are two constants (depends on the transparent medium) are called Cauchy's constants.

- Determine the values of α and β, from the experimental results of $n(\lambda)$.
- Compare the theoretical and experimental values of α and β.

Lab Work N°5: Study of the Grating: Dispersion

I. Objective

- To utilize a diffraction grating for the determination of wavelengths associated with various spectral lines.

II. Theory

When a beam of light is incident perpendicularly on a diffraction grating, it undergoes multiple coherent scattering from the equally spaced slits of the grating. The superposition of these emerging wave fronts gives rise to an interference pattern that can be observed either on a screen or directly on the retina when viewed from behind the grating.

The angular positions of the intensity maxima in this interference pattern correspond to constructive interference and are determined by the fundamental grating equation (Figure 1):

$$m\lambda = d sin\theta \quad (1)$$

Where:

m is the diffraction order,
λ is the wavelength of the incident light,
d is the distance between the lines on the grating,
θ is the angle at which the maximum intensity occurs. Angles are measured relative to the incident light direction.

- Prove that the angular dispersion of a grating can be written as: $D = tan\ \theta/\lambda$. Use the grating equation.

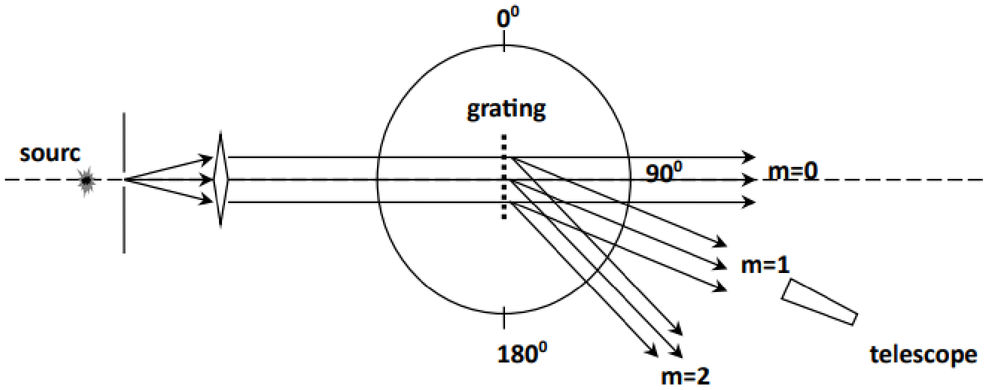


Figure1. Diffraction by a grating.

III. Experimental Procedure

- Adjust the collimator for parallel light, focus the objective on a distant object, and align the cross-hair on the image of the object, fixing the telescope so that it's zero position matches the body's zero position.
- Release the telescope to move freely, then carefully mount the diffraction grating on the spectrometer.
- Using the sodium lamp as the light source, determine the angular position of the first-order maximum for the yellow line on both sides of the center.
- Calculate the diffraction spacing (d).
- Using the discharge tube with unknown gas as the light source, determine the angles for all visible spectral lines.
- Calculate the wavelengths of the spectral lines and identify the gas using the table in Appendix A.
- Select two barely separated lines in the discharge tube spectrum to determine the angular dispersion of the grating.
- Use a white light source to determine the wavelength limits for visible light.

1. Determination of diffraction grating constant, d

The wavelength of the sodium spectral line is taken as 589 nm, and the theoretical grating spacing is $d_{th} = \cdots \dots \dots \dots \dots \dots \dots . (\mu m)$.

m	$\theta_{Left}(^o)$	$\theta_{Right}(^o)$	$\theta_{Ave}(^o)$	$d\ (\mu m)$	Error d (m)	Relative error (%)
1 ...						

- **Questions**

- Plot the graph of $sin(\theta_{Ave})$ as a function of the diffraction order m, Determine the slope of the line and use it to verify the value of the grating spacing d.
- What is the maximum number of orders that can be observed with the grating used in the experiment? Justify your answer.
- Why is it preferable to use a grating with a small d for accurate spectral analysis? Justify your answer.
- What is the origin of the Error d, and how can it be estimated?

1. Unknown discharge tube

Color	θ_{Left}	θ_{Right}	θ_{Ave}	$\lambda(nm)$

- **Questions**

- Calculate the angular dispersion of the diffraction grating. Comment on how dispersion changes with wavelength.
- Identify the gas contained in the Unknown discharge tube, using the measured spectral wavelengths.

Lab Work N°6: Focometry (determination of the focal length of a lens)

I. Objectives

- To determine the focal length of converging and diverging lenses using different experimental methods.
- Estimation of the experimental uncertainty.
- To compare the methods with respect to their speed, practicality, and accuracy.

II. Theoretical reminders

- **A lens:** is a piece of any transparent material with two faces, of which at least one is curved. Each surface of a lens is a part of a sphere. The center of the lens is called optical center (O). The line passing through the optical center of the lens is called principal axis or optical axis.
- **Type of lenses:** There are two main types of lenses: convex (converging) lenses and concave (diverging) lenses (Figure1). A convex lens is characterized by being thicker at the center and thinner at the edges, while a concave lens is thinner at the center and thicker toward the edges.

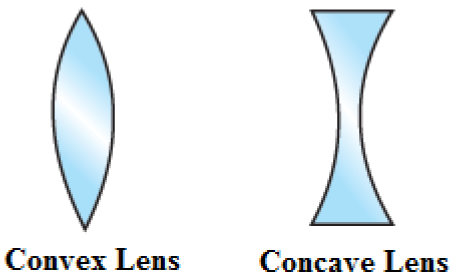


Figure1. Convex and concave lens.

- **The focal length of a lens**: is the distance from the lens to the point where rays that are parallel to the optical axis come together. If the lens is converging, the rays meet at a real focal point, giving a positive focal length. If the lens is diverging, the rays spread out and seem to originate from a virtual focal point on the same side as the incoming light, leading to a negative focal length (Figure2).

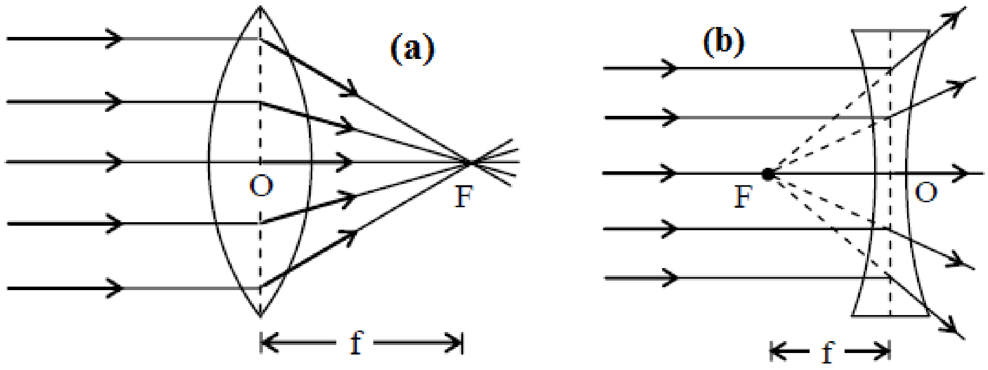


Figure2. Ray diagram showing the focal length of a lens, **(a)** converging lens, **(b)** diverging lens.

- **Thin Lens Equations and Magnification**:

$$\frac{1}{OA'} - \frac{1}{OA} = \frac{1}{f'} \quad (1)$$

$$M = \frac{OA'}{OA} = \frac{A'B'}{AB} \quad (2)$$

We define OA to be the object distance, the distance of an object from the center of a lens. Image distance OA' is defined to be the distance of the image from the center of a lens. The height of the object and height of the image are given the symbols AB and $A'B'$, respectively. Images that appear upright relative to the object have heights that are positive and those that are inverted have negative heights.

☑ **The focometry:** is the experiment for measuring a lens focal length.

➲ **Image Formation Activity by Converging Lens**: Completing the Table for Different Object Positions.

N°	Position of object	Diagram	Position of image	Nature of image
01	Infinity			
02	Between 2F and ∞			
03	2F			
04	Between F and 2F			
05	F			
06	Between F and optical center			

III. Experimental Part

III.1 Converging lens

In this part, we use a converging lens with theoretical focal length $f' = \cdots \ldots\ldots\ldots mm$.

1. Conjugate Points Method

We investigate a converging (convex) lens, with both the object and the image being real.

In this method, the experimental procedure consists in identifying the positions $OA = p$, and $OA' = p'$ of the image $A'B'$ formed by a thin lens (L) from a given object AB, by applying the thin-lens equation, the focal length f of the lens can be determined (Figure 3).

- Determine the image position $OA' = p'$ corresponding to an object AB placed at a distance $OA = p$ from the optical center of the lens (L), whose focal length is f.
- Repeat the same procedure for several different lens positions, adjusting the screen position each time to obtain a sharp image.

- Present the experimental results in tabular form, including the following quantities: p, p', $1/p$, $1/p'$, Δp, $\Delta p'$, $\Delta(1/p)$, and $\Delta(1/p')$.

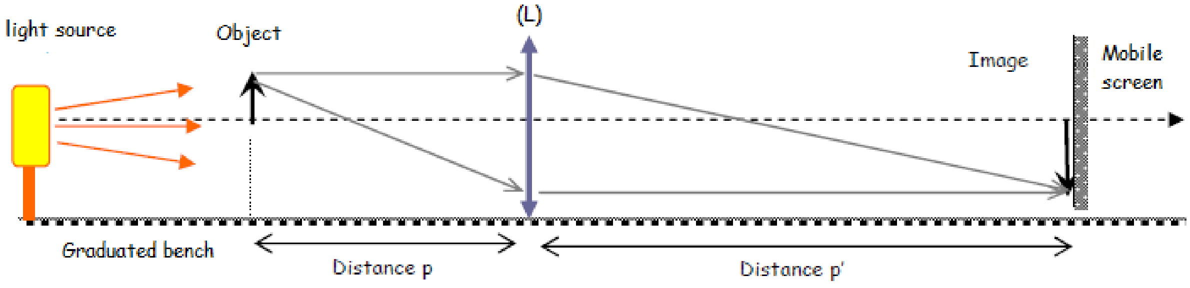


Figure3. Conjugate Points Method for Focal Length Determination of a Converging Lens.

- Plot the graph of $1/p'$ as a function of $1/p$
- Deduce the focal length of the lens (L).
- Compare the experimental results with the theoretical results.
- What are the different sources of error associated with the position of the screen? Do they depend on the position of the lens?
- What is your overall conclusion from this experiment?

2. Autocollimation method

The principle of the method is to place the object at the focal length of a lens.

- Draw the ray diagram.
- Write a Descartes relation that illustrates this method.
- Measure the focal length f' using the auto collimation method.
- Estimate the uncertainties resulting from this measurement.
- Briefly describe the steps of the experiment and Identify the best way to position the mirror to obtain precise results.

3. Bessel method

Bessel method is used to determine the focal length of a converging thin lens. the principal of This method is to imposing a distance D between an object O and a screen S and searching for the two position of the lens giving a sharp image of O on screen S. The difference between these two positions represents the distance l. The lens focal distance is calculated by measuring distances l and D,.

In this method we use: $D > D_{min} = 4f'$.

If $l = O_1O_2$ is the distance between these two positions of the lens, then:

$$f' = \frac{D^2 - l^2}{4D} \quad (3)$$

➲ Demonstrate Bessel's relation.

Where $D = 4f'$ is the case of Silbermann method and we obtain a single real image.

- Adjust the distance between the object and the screen to be large enough.
- Move the lens to get a real, aggrandize image on the screen. Determine the first of the two Bessel positions of the lens.

➢ **Measure**

$x_1 = O_1A = \cdots$ ……………..……………..………..….

$x_1' = O_1A' = \cdots$ ………………………..……..…..………

$\gamma_1 = \cdots$ ………………………………………..……………..…

- Move the lens again to get a real, diminutive image on the screen. Determine the second of the two Bessel positions of the lens.

➢ **Measure**

$x_2 = O_2A = \cdots$ ……………..……………..………..…

$x_2' = O_2A' = \cdots$ ………………………..……..……………

$\gamma_2 = \cdots$ ………………………………………..…………….

- Compare between $|x_1|$ et x_2' ‹$|x_2|$ et x_1' ‹γ_1 et γ_2.
- Deduce l.
- Calculate the uncertainty in the measurement of l.
- Deduce f'
- Calculate the uncertainty in the measurement of f'.

4. Silbermann method

The Silbermann position is the case where the object is located at a distance $\text{OA} = -2\text{f}'$ from the lens.

- According to the principle of the method, what is the position of the image relative to the lens? (Draw the ray diagram).
- Write a Descartes relation that illustrates this method.
- What is the magnification?
- Experimentally, Find the Silbermann position.
- Deduce the focal length f'.
- Estimate the uncertainty in the measurement of f'.
- Briefly describe the steps of the experiment and identify the best method for obtaining the Silbermann position.
- What are the experimental difficulties during this experiment?

III.2 Diverging lens

In this part, we use a diverging lens with theoretical focal length $f' = \cdots \ldots\ldots\ldots mm$.

1. Method of Lenses in Contact

Place a converging lens (L_1) of known focal length f_1' in contact with the diverging lens (L_2). Adjust the lens-screen distance until the image is sharp and has the same size as the object $(\gamma = -1)$, i.e., the Silbermann position (Figure 4).

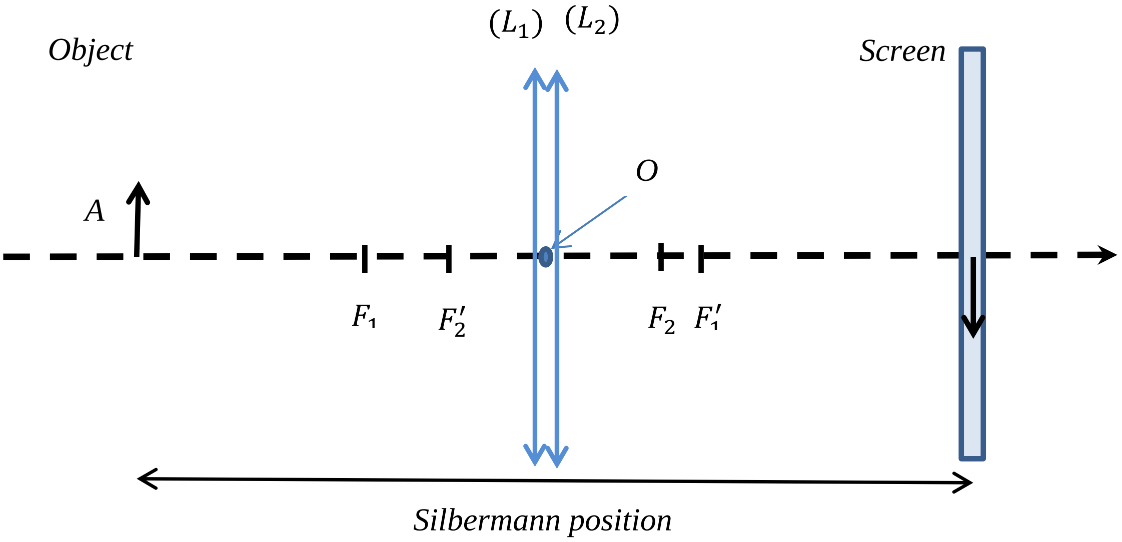


Figure4. Determination of the focal length of a diverging lens using the method of lenses in contact.

- Measure the distance from the lens pair optical center O to the object:

$$OA = \cdots \dots \dots \dots \dots \dots \dots$$

- Compute the equivalent focal length (Silbermann):

$$f'_{1,2} = \cdots \dots \dots \dots \dots \dots \dots$$

For two thin lenses in contact (same optical axis):

$$\frac{1}{f'_{1,2}} = \frac{1}{f'_1} + \frac{1}{f'_2}$$

- Calculate the focal length of the diverging lens:

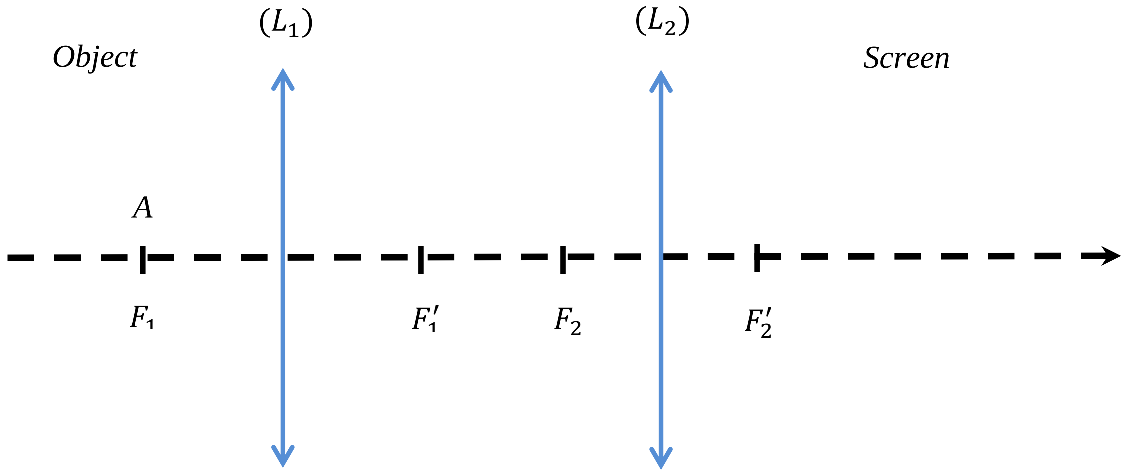
$$f'_2 = \cdots \dots \dots \dots \dots \dots \dots$$

- Calculate the uncertainty in the measurement of f'_2.

2. Badal method

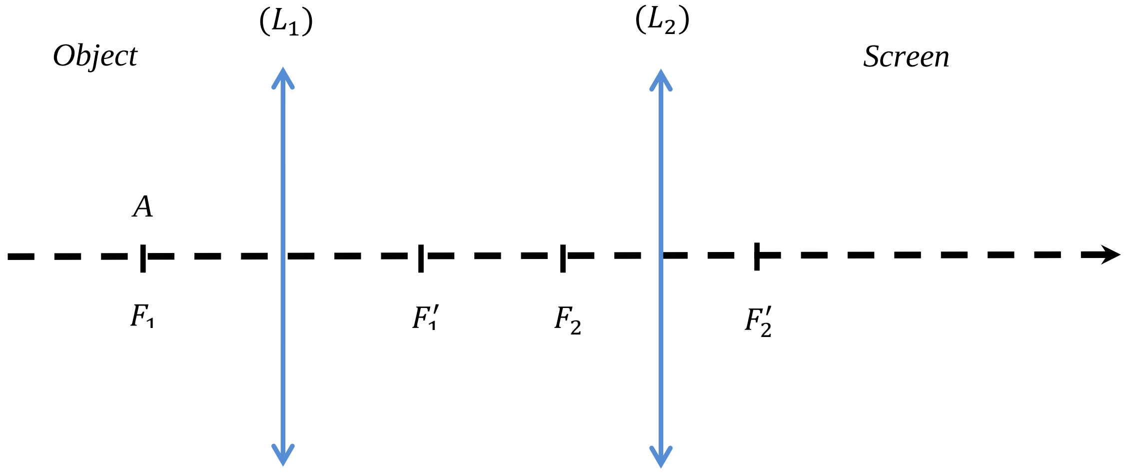
- To obtain a parallel beam of light, use a converging lens (L_1) and place the object at the focal point of (L_1) $(f'_1 = \cdots \ldots \ldots \ldots \ldots \ldots)$, lens (L_1) is called a "collimator".
- Form the image of the object on the screen, using a second lens (L_2) $(f'_2 = \cdots \ldots \ldots \ldots)$, lens (L_2) is called the "collector".

➢ Locate the screen position 1 on the following diagram:



- Insert the diverging lens of focal length f' into the focal plane of the collector lens (L_2) .
- Find the new image A'' of A by moving the screen a distance d and measure it.

➢ Locate the lens (L_2) and the screen position 2 on the following diagram:



Newton formula is given as:

$$F'A'.FA = -f'^2 \quad (4)$$

This formula is valid for all thin lenses.

- Using Newton formula applied to the converging lens (L_2), demonstrate that:

$$f' = -\frac{f'^2_2}{d} \quad (5)$$

- Find the focal length f' of the diverging lens.
- Calculate the uncertainty in the measurement of f'.

IV. General Summary

Give the advantages and disadvantages of each of the four methods.

Lab Work N°7: The microscope

I. Objectives

- Modelling the microscope and understanding how it works.

II. Theoretical reminders

The light microscope is a type of microscope that commonly uses visible light and a system of lenses to generate magnified images of small objects.

- **The principle**

The functioning of the light microscope is based on its ability to focus a beam of light through a specimen, which is very small and transparent, to produce an image. The image is then passed through one or two lenses for magnification for viewing. The transparency of the specimen allows easy and quick penetration of light.

- **Microscope lenses (Figure 1)**

1. **The objective lens** which can be modeled as a converging lens with a very short focal length, its role is to collect the light coming from the observed object and to form a real, enlarged intermediate image inside the microscope tube.

2. **The eyepiece (Ocular) lens** which can be modeled as a converging lens with a focal length on the order of a few centimeters, It is used like a magnifying glass to further magnify the intermediate image formed by the objective, so that the observer can see a larger virtual image.

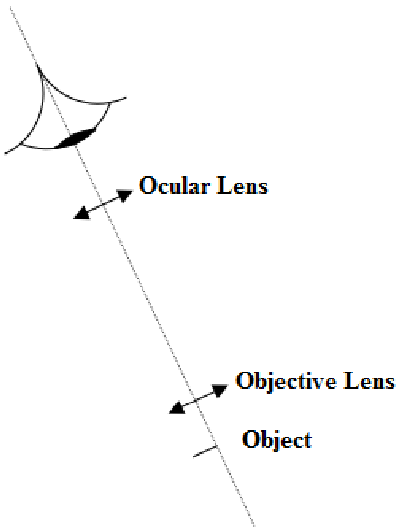


Figure1. Schematic Diagram of a Compound Microscope (Objective and Ocular Lenses).

- **The distance separating the two lenses**

We consider the distance between the image focal point of the objective lens and the object focal point of the eyepiece lens. This distance, called the **optical interval**, is denoted by Δ :

$$\Delta = F_1'F_2 \tag{1}$$

III. Calculation of the standard magnification G of the microscope

The standard magnification of the microscope:

$$G = |\gamma_1|G_2 = \alpha'/\alpha \tag{2}$$

Where:

$\boldsymbol{\gamma_1}$: The magnification of the lens (L_1),

$$\gamma_1 = A_1B_1/AB \tag{3}$$

$\boldsymbol{G_2}$: The standard magnification of the lens (L_2),

$\boldsymbol{\alpha}$: The angle which the eye sees an object located at $d_m = 0.25\, m$, (L_1). For α small, $tan(\alpha) = \alpha$.

In the right triangle O_1AB:

$tan(\alpha) = AB/d_m = \alpha$ with $d = 0.25\, m$, we obtain:

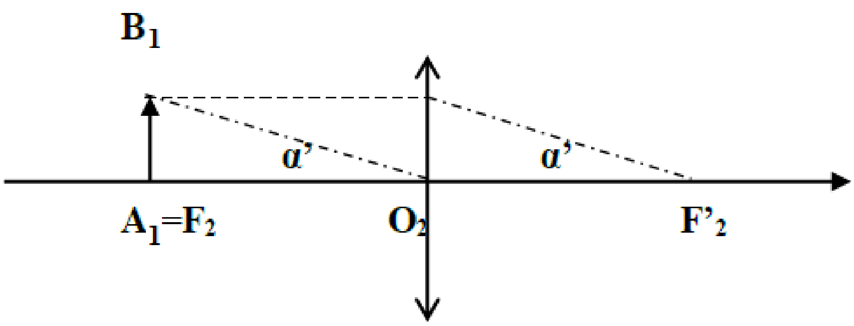
$$\alpha = AB/0.25 = 4AB\ (m)$$

$\boldsymbol{\alpha'}$: The angle which the eye sees an image located at infinity, therefore when the object of (L_2) is in the focal plane.

For α' small $tan(\alpha') = \alpha'$.

In the right triangle $O_2A_1B_1$ with $O_2A_1 = O_2F_2$ for find an image at infinity:

$$tan\ (\alpha') = \alpha' = A_1B_1/\ f_2{}'.$$



IV. Experimental part

We use an object AB of size $\overline{AB} = \cdots \dots \dots \dots .. \dots .. cm$

1. The objective Lens (L_1) has a focal length $f_1' \dots \dots . \dots .. \dots \dots cm.$

- Place the object at point 0 on the optical bench, and the (L_1) lens at $\dots \dots .... cm$ from the object.

$$O_1A = \cdots \dots \dots \dots \dots \dots . cm.$$

- Move the screen to obtain a clear image A_1B_1. Then measure the distance between the optical center O_1 of (L_1) and the image point A_1.

$$O_1A_1 = \dots \dots .. \dots \dots \dots .. cm.$$

- Calculate the uncertainty in the measurement of O_1A_1.

- We measure the size of the image:

$$A_1B_1 = \cdots \dots \dots .. \dots \dots \dots . cm.$$

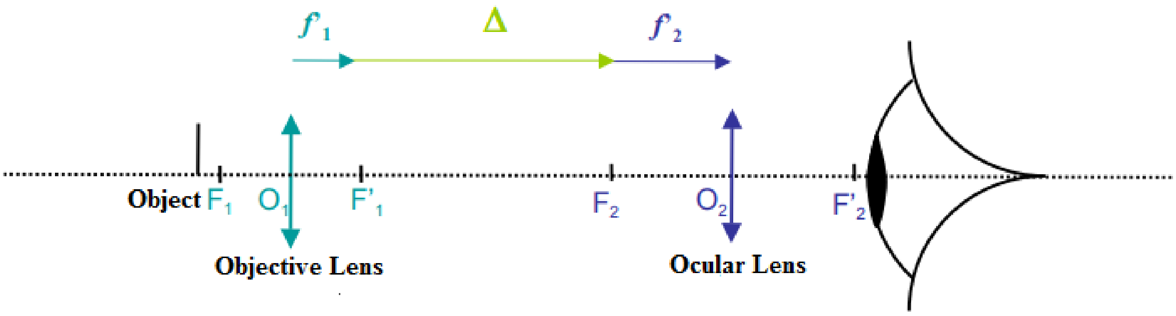
- Verify O_1A_1 and A_1B_1 using the ray diagram.
- Calculate the theoretical value of O_1A_1 using relation of Descartes, then compare it with your measured value.

  - Calculate the magnification of the objective lens using the two formulas.

2. The eyepiece (Ocular) lens (L_2) has a focal length $f_2' = \cdots \dots \dots \dots \dots \dots \dots cm.$

- The lens (L_2) is placed at a distance of $\dots \dots \dots .. \dots . \dots \dots$ cm behind the screen. A_1B_1 is in the object focal plane of (L_2).

  - Where is the image A_2B_2 formed?
  - If we move the screen behind the lens(L_2), do we see the image? Why?
  - Draw the ray diagram with the two lenses (L_1) and (L_2).



- **The eye** is modeled by a converging lens (L_3) with a focal length $f_3' = \cdots \ldots \ldots \ldots cm$. A_3B_3 is the image formed by (L_3). A_2B_2 is located at infinity, consequently, the rays arrive parallel to the lens (L_3), where is the image A_3B_3 formed?

$$O_3A_3 = \ldots \ldots \ldots \ldots \ldots \ldots cm.$$

  - Calculate the uncertainty in the measurement of O_3A_3.

➲ In this mounting, the lens (L_3) represents the crystalline lens, and the screen represents the retina.

➲ When we place the screen at a distance $d = \cdots \ldots \ldots \ldots \ldots \ldots cm$ from the lens (L_3), we observe a clear image. This is what happens when we look at an object through a microscope.

  - If we remove the lenses (L_1) and ((L_2), do you see a clear image on the screen?
  - Make the graph with the three lenses (L_1), (L_2) and (L_3).
  - Find that: $G_2 = 1/4f_2'$.
  - Demonstrate that: $= |\gamma_1|G_2$, use the relation: $G = \alpha'/\alpha$.
  - Write G as a function of Δ, f_1' and f_2'.
  - Calculate the values of γ_1, G_2, G and Δ, comment
  - Calculate the uncertainties $\Delta\gamma_1$, ΔG_2, ΔG and $\Delta(\Delta)$.

V. Conclusion

Lab Work N°8: Polarization of Light

I. Introduction

Light is considered linearly polarized when its oscillations are restricted to a single direction, with the direction of the electric field oscillation defining the polarization. Most natural light sources emit unpolarized light, meaning the light consists of multiple wave trains with randomly oriented oscillations. Light can be polarized by passing it through a commercially available material known as Polaroid. A Polaroid sheet allows only the component of light polarized in a specific direction to pass through while absorbing the perpendicular component.

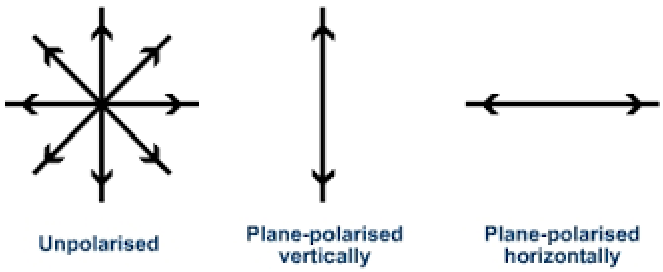


Figure1. Polarized light and unpolarized light.

II. Malus' law

Suppose we have a second piece of Polaroid whose transmission axis makes an angle θ with that of the first one. The electric field vector $\boldsymbol{E}$ of the light between the Polaroids can be resolved into two components:

1. **A component parallel** to the transmission axis of the second Polaroid.
2. **A component perpendicular** to the transmission axis of the second Polaroid (as shown in Figure 2).

If we denote the transmission axis direction of the second Polaroid as y', then:

- The parallel component to y' is:

$$E_{\parallel} = E cos\theta \tag{1}$$

- The perpendicular component to y' is:

$$E_{\perp} = E sin\theta \tag{2}$$

Here, E is the magnitude of the electric field vector before the second Polaroid. The light that passes through the second Polaroid will only be the parallel component $E_{\parallel}$, while the perpendicular component $E_{\perp}$ is blocked.

The intensity of light is proportional to the square of the electric field amplitude. Therefore, the intensity transmitted through both Polaroids can be expressed as:

$$I(\theta) \cong E_{\parallel}^2 = E^2 cos^2\theta \tag{3}$$

If $I_0 \cong E^2$ is The intensity of light between the two Polaroids and the intensity transmitted through both of them will be:

$$I = I_0 cos^2\theta \tag{4}$$

This relationship is known as **Malus's Law**, and it demonstrates how the transmitted light intensity depends on the angle between the polarization axes.

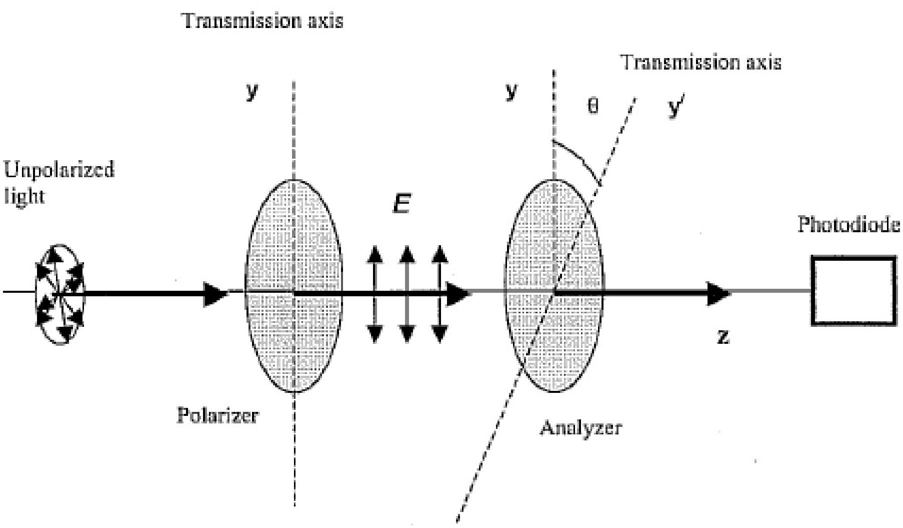


Figure2. Two Polaroids whose transmission directions make an angle θ with each other.

➢ Light polarization can be categorized into three main types (Figure 3):

1. **Linear Polarization**: The electric field oscillates in a fixed direction, remaining constant over time.
2. **Circular Polarization**: The electric field rotates uniformly, maintaining a constant amplitude, creating a circular path.
3. **Elliptical Polarization**: The electric field rotates with a varying amplitude, resulting in an elliptical path.

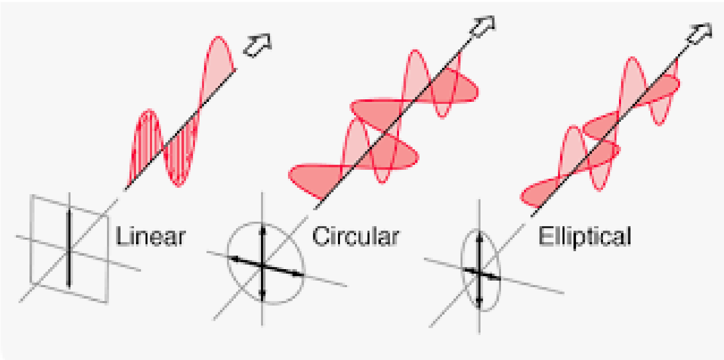


Figure3. Types of Light Polarization: Linear, Circular, and Elliptical.

III. Objectives

- ➢ Distinguish between polarized and unpolarized light.
- ➢ Determine the maximum transmitted intensity.
- ➢ Methods for analyzing polarized light.
- ➢ Explain different types of polarization using retarder plates (wave plates).

IV. Setup

Place the light source (laser or LED) on a stable optical bench to maintain alignment. Position the first polarizer in front of the light source to create linearly polarized light. Then, place the second polarizer, ensuring it can rotate freely to change the angle between its axis and the polarization direction. Finally, set up a photodetector behind the second polarizer to measure the transmitted light intensity.

Align the axes of both polarizers so that they are parallel ($\theta = 0^{\circ}$). This ensures that the maximum amount of light passes through the system. Record the initial intensity I_0 using the photodetector. This value represents the maximum intensity of the transmitted light.

Rotate the second polarizer (analyzer) in increments of $10^{\circ}(0^{\circ}, 10^{\circ}, 20^{\circ}, \ldots, 90^{\circ})$. At each angle, record the intensity I of the transmitted light using the photodetector.

Ensure that the light source remains stable and that the polarizers are properly aligned during the experiment.

The Angle θ	The intensity I	The intensity I (%)

- **Questions**

- Plot a graph of the transmitted light intensity I versus the angle($I = f(\theta)$).
- What is the general shape of the curve?
- What is the value of light intensity at $\theta = 0^{\circ}$?
- What is the value of light intensity at $\theta = 90^{\circ}$?
- How does the light intensity change at angles between 0° and 90°?
- What factors might influence the accuracy of the plotted curve?
- Plot a graph $I = f(cos^2\theta)$.
- Verify Malus' law by fitting $I = I_0 cos^2\theta$ and estimate I_0.
- Explain why a straight line passing through the origin is obtained.

Lab Work N°9: Reflection on a plate of a plane optical flat (E.M.O)

I. Objectives

- Study the phenomenon of reflection on smooth surfaces and understand the relationship between the angle of incidence and the angle of reflection, according to the law of reflection.
- Compare the behavior of light when reflected from different materials such as glass and acrylic, and study the impact of the reflecting material on the reflection phenomenon.
- Analyze and interpret the experimental results.

II. Theory

When light strikes the interface between two transparent optical media—such as air and glass, or water and glass, four possible outcomes can occur:

1. **Reflection**: A portion of the incident light can be reflected at the interface.
2. **Scattering**: The light can be scattered in various random directions at the interface.
3. **Transmission and Refraction**: Part of the light can pass through the interface and enter the second medium, undergoing refraction.
4. **Absorption**: Some of the light may be absorbed by either of the media.

In this lab work, we will focus exclusively on smooth surfaces that produce specular reflections (regular, geometric reflections), as shown in Figure 1a. We will ignore rough, uneven surfaces that lead to diffuse reflections (irregular reflections), as illustrated in Figure 1b.

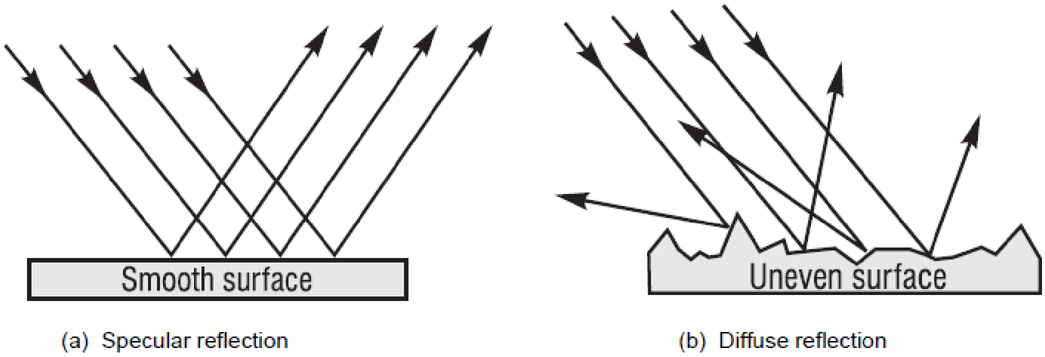


Figure1. Specular and Diffuse Reflections: Types of Light Reflection.

III. Experimental Procedure

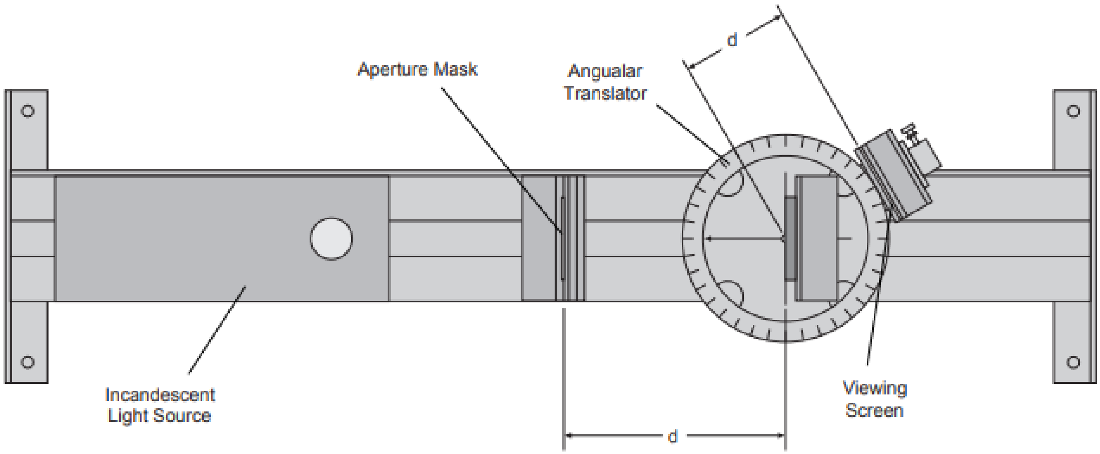


Figure2. Experimental Setup for the Experiment of Reflection from a Plane Optical Flat.

1. Place the incandescent light source at the left end of the optical bench.
2. Position the rotating table (or angular device) about 25 cm from the light source, Ensure that the 0° marks are aligned along a line parallel to the bench.
3. Adjust the rotating table so that the scored line passes through the center of rotation and is perpendicular to the bench, defining the plane of incidence.

4. Attach the aperture mask to the standard component holder and place it between the light source and the rotating table, Ensure that the mask is located at a distance $d \approx 6.5\ cm$ from the center of the rotating table. This distance corresponds to the separation between the device's center and the first analyzer holder on the movable arm (see Figure 2). This setup ensures proper alignment for reflection measurements on the plane optical flat.

5. Center the viewing screen of the special component carrier, designed for use with the rotating table, and place the assembly on the rotating table so that the front surface of the viewing screen coincides with the scored line on the table, which runs perpendicular to the optical bench. This ensures proper alignment of the screen with the plane of incidence.

6. Turn on the light source and adjust the position of the aperture mask (without moving the component carrier) until the full image is visible on the viewing screen.

7. Using the millimeter scale marked on the screen, align the image horizontally at the center.

8. Rotate the screen by 90° and align the image vertically at the center.
9. Now replace the viewing screen with the glass plate, taking care that the front surface of the glass coincides with the scored line.

10. Rotate the table until the glass plate is positioned at a convenient angle relative to the optical bench.

11. Move the arm until the reflected image becomes visible on the viewing screen.

   ➲ How many images of the rectangular aperture are observed? Why?

12. The brightest image (the one on the left) corresponds to the reflection from the front surface of the glass, Center this image on the screen and record the angle between the translator arm and the glass plate.

13. Repeat the procedure with the rotating table set at several different angles.

- What is the relationship between the angle of incidence and the angle of reflection?

14. Measure the height of the center of the reflected image.

15. Determine whether the incident ray, the reflected ray, and the normal to the glass at the point of reflection are all in the same plane.

16. Replace the glass plate with the acrylic plate and repeat steps 1–8.

- Does the law asserting the equality between the angles of incidence and reflection seem to vary with the material used as the reflecting surface?

IV. Conclusion

Lab Work N°10: Interferometry (Determination of Wavelength and the Refractive Index of a Parallel-Plate Sample)

I. Introduction

Interferometers are instruments used to analyze interference patterns generated by different light sources. They are broadly categorized into two primary types: those that operate based on the division of wavefront and those that function based on the division of amplitude.

Figure 1 shows a schematic diagram of a Michelson interferometer. A beam of light from the laser source hits the beam splitter, which is designed to reflect 50% of the incident light and transmit the remaining 50%. As a result, the incident beam splits into two beams: one is reflected toward mirror $M1$, while the other is transmitted toward mirror $M2$. Mirrors $M1$ and $M2$ reflect the beams back toward the beam splitter. Half of the light from $M1$ passes through the beam splitter to the viewing screen, and half of the light from $M2$ is reflected by the beam splitter to the viewing screen as well.

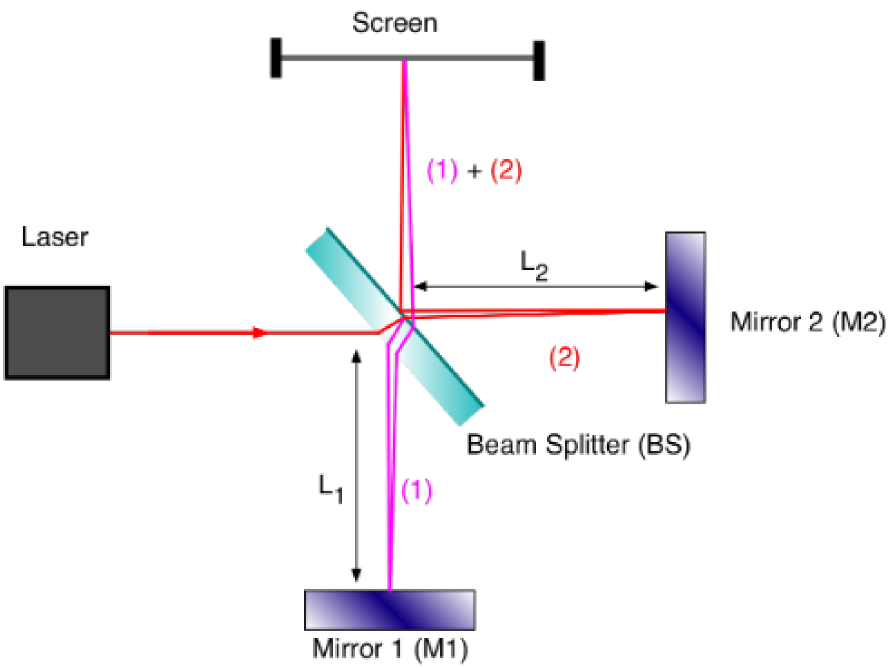


Figure1. Michelson Interferometer.

II. Initial adjustments, fringe pattern observation, and interferometer calibration

- Use the Michelson interferometer arrangement as described in the setup section.
- Position the sodium lamp in front of the diffusing screen holder (D) and insert the diffusing screen into the holder.
- Dim the room lights to improve visibility of the interference fringes and Look through the viewing opening, as close as possible for better visibility.
- You should observe dark fringes on a yellow/orange background. If no fringes appear, adjust the micrometer screw slowly until the fringes become visible.
- Adjust the calibration screws on mirror $M2$ to make it perpendicular to mirror $M1$. Proper alignment is achieved when you observe complete circular fringes, centered in your field of view.
- Locate the region where the optical path difference $(2d\ cos\ \theta)$ is nearly zero.
- For circular fringes, this region corresponds to the largest fringes, covering the entire field of view and For localized fringes, this region is where the fringes appear parallel to each other.
- It is easier to use localized fringes to find the zero path difference regions.
- Mark this position by noting the micrometer reading, which will help speed up the process in future trials.
- Switch the light source to white light instead of sodium light.
- Slowly rotate the micrometer screw to move through the zero path difference region.

- The white fringes should appear briefly, these are elusive and visible only within a narrow range ($\sim$20 degrees of micrometer rotation). The fringes are visible only when $2d\ cos\ \theta \approx 0$.

- Be sure to rotate the micrometer very slowly, as the white fringes are observed over a small range ($\sim$20 fringes wide).

- Switch the light source back to the sodium lamp.
- Adjust mirror $M2$ again until medium to large-sized circular fringes appear (Figure 2).

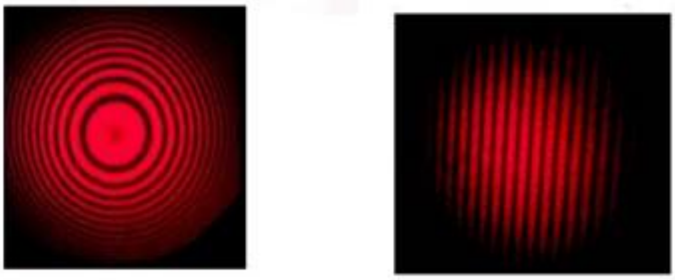


Figure2. The circular fringe interference pattern produced by a Michelson interferometer.

➲ To determine the relationship between the micrometer screw movement and the actual displacement of mirror $M1$, a calibration curve is needed.

➲ The micrometer screw is connected to the mirror carriage via a lever system, meaning not all micrometer movement directly translates into mirror displacement.

➲ Using equation $2d = m\lambda$, note that if the distance $2d$ changes by one wavelength (λ), one fringe will disappear from the field of view.

- Count the number of fringes that disappear as you move the micrometer by a known distance.
- Using this count and equation $2d = m\lambda$, calculate how much the mirror actually moved.

➲ This allows you to precisely relate the micrometer reading to the actual displacement of mirror $M1$, establishing an accurate calibration curve.

- Why must the optical paths be nearly equal for clear interference fringes to appear?

III. Measure of the wavelength of the sodium

- Position the photodiode to measure the intensity of an equal-thickness fringe. Use a lens to enhance the fringe magnification.

- Why is a laser diode chosen over an incandescent light source for this experiment?

- Move the adjustable mirror at a slow and steady pace. Use a Schmitt trigger and an electronic counter to count the number of fringes passing through the photodiode, aiming for approximately 10,000 fringes.

- Why is a Schmitt Trigger useful in fringe detection?
- Calculate the wavelength from:

$$\lambda = 2\,\Delta d/N \tag{1}$$

Where Δd is the change in position that causes N fringes to pass the photodiode.

- What do you understand by interference of light?
- What is a coherent light source?
- What is the role of coherence of the light source in the Michelson interferometer?
- What would happen if a thin-glass-slide of refractive index 1.55 (at 632.8 nm) and thickness 20 microns is introduced in one of the arms of the Michelson interferometer? Can you make an estimate of the number of fringes that collapse / appear?

- According to you, what could be the possible applications of studying interferometry?

IV. Determination of the Refractive Index of a Transparent Solid

A Michelson interferometer as shown in Figure 3 can be used to measure the refractive index of a transparent solid by placing it in the optical path of the beam directed at the movable mirror. This causes a shift in the interference pattern due to the change in optical path difference. By measuring this displacement, the refractive index of the material can be determined.

- How should the solid be positioned relative to the mirror, why?

Consider a thin parallel plate solid with a refractive index μ, having flat surfaces on both sides and being sufficiently transparent. We also assume it is homogeneous.

Before the solid is introduced, the optical path length across a region of air of length t with a refractive index of $\mu_{air} = 1$ is given by:

$$r_0 = 2t\,\mu_{air} = 2t \quad (2)$$

The factor of 2 is included because the beam travels the distance twice: once toward the mirror and once on its return.

After placing the solid in the beam's optical path, the new optical path length becomes:

$$r = 2t\mu \quad (3)$$

Thus, the path difference introduced by the solid is:

$$\delta = r - r_0 = 2t(\mu - 1) \quad (4)$$

This equation represents the increase in optical path difference due to the difference between the refractive index of the solid and that of air.

By using light with a known wavelength, along with the thickness of the solid and the number of displaced fringes, we can determine the refractive index of the solid by applying the following relationship:

$$\mu = \frac{m\lambda}{2t} + 1 \quad (5)$$

- Demonstrate this relation.

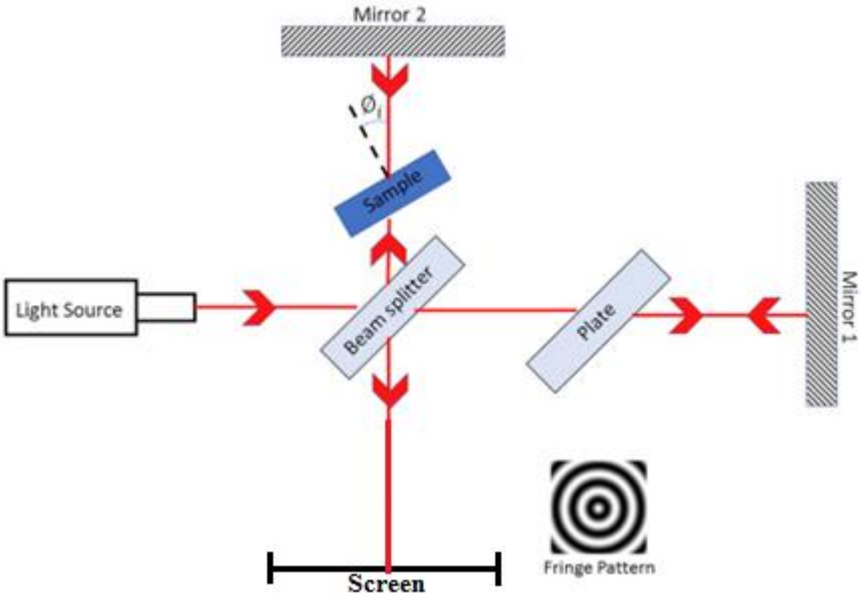


Figure3. Determination of the Refractive Index of a Transparent Solid.

In practice, it is slightly more complex, because the interference pattern transitions abruptly, it is not possible to count the fringes as they pass, as was done to obtain the calibration curve. Additionally, if a monochromatic light source is used, all the fringes become nearly indistinguishable. While they have different radii, determining the displacement of the interference pattern would be impossible without a precise scale.

Instead, we will proceed as follows: Similar to the previous part of this experiment, we first locate the white light fringes and record the micrometer reading. The fact that these fringes appear only within a narrow range of mirror positions will be advantageous in this case.

Once the solid is inserted into the optical path of the beam directed toward mirror $M1$, the interference pattern will shift, causing the white light fringes to disappear. However, by slowly moving the mirror carriage toward the observer (to compensate for the increased optical path length by reducing the geometric distance between the mirror and the beam splitter), the fringes can be relocated.

The difference between the two micrometer readings, before and after the shift, can be correlated using the calibration curve to the actual displacement of the mirror, which in turn can be linked to equation (4). Using equation (3) in the form:

$$2d = m\lambda$$

And noting that:

$$d = Mf$$

Where:

M represents the micrometer reading,
f is the conversion factor (the slope of the previously determined calibration curve),

We obtain:

$$\mu = \frac{Mf}{t} + 1 \quad (6)$$

To proceed, we need to measure the thickness of the plate and, once the fringe pattern is relocated, record the distance traversed by the micrometer.

However, finding the displaced fringes can be challenging. One approach is to estimate the refractive index of the microscope slide and use this value to define a range of distances to explore with the micrometer.

Be prepared for the possibility that locating the fringes may take some time. Once the approximate region is identified, it is advisable to mark its position on the micrometer. After repeating this process multiple times, the refractive index can be calculated using equation (6).

V. Conclusion

Lab Work N°11: Diffraction (Single slit, Monochromatic Laser Light)

I. Objectives

- Observe and interpret diffraction patterns produced by laser light passing through a single-slit aperture.
- Compare the effects of different slit.
- Determine the laser wavelength from the single-slit diffraction pattern.
- Determine the thickness of a human hair using laser diffraction, treating the hair as an inverse aperture.

II. Light, an electromagnetic wave

Light is an electromagnetic wave made of oscillating electric and magnetic fields that propagate through space at the speed of light. These two fields are perpendicular to each other and to the direction of propagation. An electromagnetic wave is characterized by its wavelength λ and frequency f.

Because light behaves as a wave, it can produce interference and diffraction patterns, which become clearly observable when coherent light such as a laser passes through narrow slits or apertures.

III. Light diffraction

Diffraction is a wave phenomenon that occurs when light encounters an obstacle or passes through an aperture whose size is comparable to its wavelength. Instead of traveling strictly in straight lines, the wavefront bends and spreads into the region beyond the opening. This spreading is explained by the Huygens–Fresnel principle: every point on a wavefront acts as a secondary source of spherical wavelets, and the observed pattern results from the superposition of these wavelets. As a consequence, light produces characteristic intensity distributions rather than a sharp geometric shadow (Figure 1).

In the case of a single slit of width a, the diffraction pattern on a distant screen (Fraunhofer diffraction) consists of a bright central maximum surrounded by weaker secondary maxima. The minima (dark fringes) occur when:

$$a sin\theta = m\lambda \qquad (m = \pm 1, \pm 2, \dots) \qquad (1)$$

Where λ is the wavelength and θ is the diffraction angle. The central maximum is the widest and most intense feature, and its width increases when the slit becomes narrower. This is why using a smaller slit produces a more spread-out pattern. Diffraction is therefore not only a clear demonstration of the wave nature of light, but also a practical tool for measuring the wavelength of a laser and, via Babinet's principle, estimating the diameter of thin objects such as a human hair.

To obtain stable and observable optical interference, several conditions are usually required:

- **Coherence**: the interfering waves must have a fixed phase relationship (in practice, they are obtained by splitting a single beam into two paths).
- **Monochromaticity**: the source should be monochromatic or quasi-monochromatic to ensure a long coherence length and well-defined fringes.
- **Limited path difference for broad spectra**: if the source is not monochromatic (e.g., white light), interference can still occur, but only when the optical path difference is very small (as in thin-film interference or near the zero path difference region in interferometers).

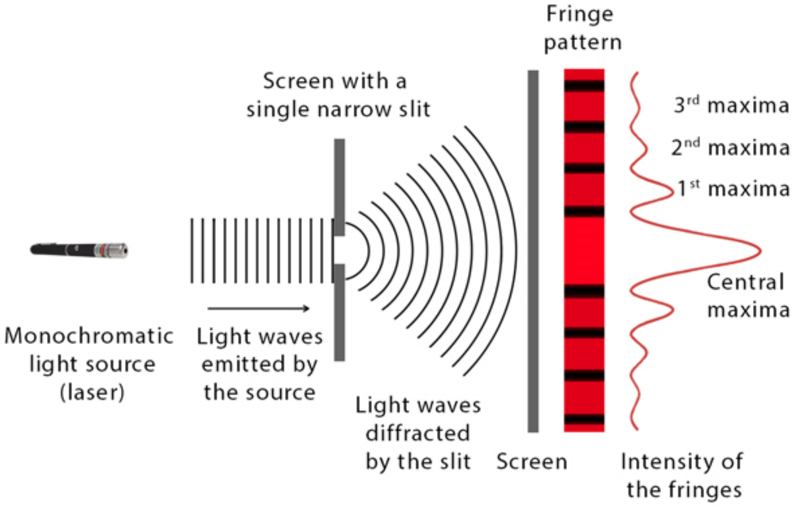


Figure1. Diffraction Phenomena in Monochromatic Light.

IV. Experimental Setup

1. Single Slit Diffraction

Turn on the He–Ne laser and place the screen at a distance slightly greater than 2 m from the laser, ensuring that the laser beam strikes the screen normally and near its center. Insert the single-slit slide into the holder and adjust its position so that the laser beam passes through the narrowest slit, producing a clear diffraction pattern on the screen. The diffraction pattern is best observed when the laser beam completely covers the width of the slit. Carefully adjust the slit position to obtain the clearest image (Figure 2).

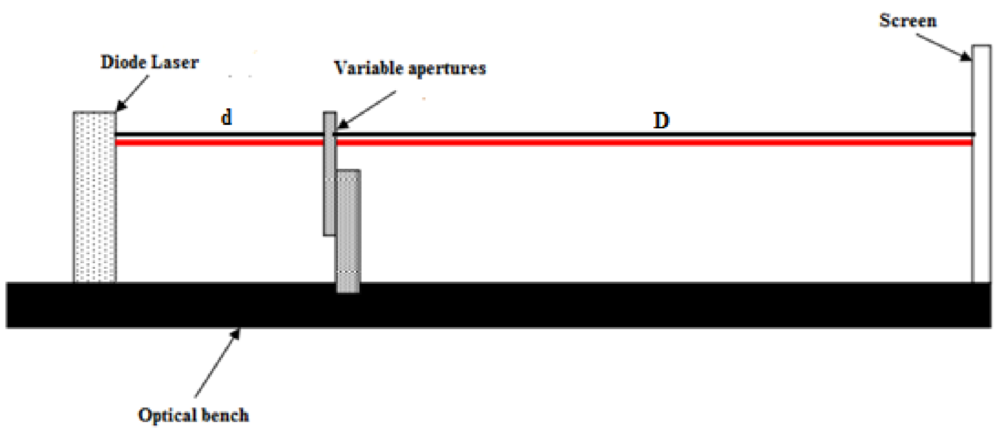


Figure2. Experimental setup for laser diffraction.

- Draw below the image obtained in 2 cases: when the slit is large and when it is small.
- Does the phenomenon of light diffraction appear? In which case?
- Compare the diffraction direction with the slit direction.

2. Diffraction by different objects

Realize the same experiment with different diffracting objects and draw the resulting images below.

- What do you observe between the geometry of the diffracting object and the image obtained? What do you observe about the slit and the wire?

3. The determination of the laser wavelength

Realize the same experiment.

- Register the wavelength λ of the laser light (value given by the manufacturer):

$$\lambda = \cdots \dots \dots \dots . \dots \dots nm$$

- For each slit of width a, register the width L of the central spot. Complete the table below.

a(m)						
L(m)						
1/a (m^{-1})						

- Plot the graph showing the evolution of L as a function of $1/a$.
- Are $1/a$ and L proportional?
- Deduce the experimental value of λ.

4. Measurement of Human hair thickness

Now we will measure the thickness of a human hair using laser diffraction, based on the same method used for the single-slit experiment.

- Fix a single human hair across the circular aperture using transparent tape. The hair should be vertical and stretched straight, without sagging.
- Place the screen at the same distance D as before (measure and record D).
- Align the laser so that the beam strikes the hair normally and a clear diffraction pattern appears on the screen.
- Measure the width L_{hair} of the central bright maximum (distance between the first dark minima on both sides). Repeat the measurement several times and take the average.

✓ Using Babinet's principle, the diffraction pattern of a thin wire (hair) is equivalent to that of a single slit whose width equals the hair diameter.

- Calculate the hair thickness a.
- Calculate the uncertainty Δa.
- Why can a hair be treated as an "inverse aperture"? (Babinet's principle)
- What are the main sources of uncertainty in measuring a?

V. Conclusion

If we redid these experiments with a blue laser instead of red, what changes would you have needed to make? Would it have affected the accuracy of the measurements?

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