Lab 18

Optical Experiments

A. Brief History in Optics

The property of light has been widely studied in all ages. In 1637, Descartes stated that light consists of small discrete particles called *"corpuscles"* that travel in a straight line with a finite speed and possess *impetus*. This *corpuscular theory of light* was accepted and greatly promoted by Isaac Newton, who notably elaborated upon the particle theory of light in the 17th century. Although this theory cannot explain diffraction as the wave theory of light proposed by Christiaan Huygens, before the 19th century, Newtonian optics was generally accepted for Newton's prestige and success in other areas of physics. It wasn't until the early 19th century, when Thomas Young and Augustin-Jean Fresnel studied the interference of light, that light's wave nature started to dominate the interpretation. The famous double-slit experiment conducted by Young showed the superposition property of light and shed new light on the entire study of physical optics. Later in the 1860s, James Clerk Maxwell successfully verified wave optics through his electromagnetic theory. The next development in optical theory, as is known to all, was started in 1899 by Max Planck who correctly modeled blackbody radiation by assuming the existence of quanta that allows discrete energy exchange between light and matter. From then on, light is said to possess wave-particle duality and a new door of physics is opened by quantum mechanics. This lab focuses on some basic optical phenomena.

B. Introduction

1. Focal length of a thin lens

Consider a parallel light beam propagating through a thin convex lens. The beam will focus on a point on the focal plane as Fig. 1 shows. The relationship between the object distance s_o, the image distance s_i, and the focal length f of the thin lens is

$$\frac{1}{s_o}+\frac{1}{s_i}=\frac{1}{f} \tag{1}$$

When a parallel light beam passes through a combination of a convex lens and a concave lens as shown in Fig. 2, the beam remains parallel if the focal points of the two lenses are at the same position. With this property, two useful applications are proposed:

(1) Measure the unknown focal length of a concave lens by a convex lens of a given focal length.

(2) Expand the beam size from a to b. The b/a ratio can be modulated by the focal length of the two lenses.

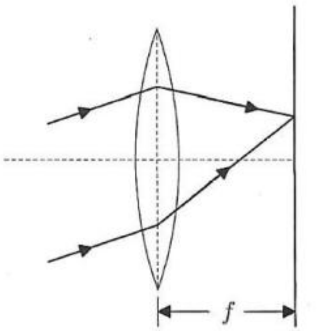


Fig. 1. The focal plane of a convex lens

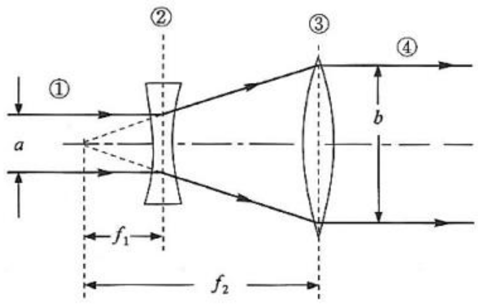


Fig. 2. Beam expander. ①incident light ②concave lens ③convex lens ④outgoing light

The area of a beam can also be expanded by passing through a glass plate due to the multi-reflections in the glass plate as Fig. 3 shows. In this experiment, you will first determine the focal length of a convex lens, and then use the idea of the beam expander to determine the unknown focal length of a concave lens.

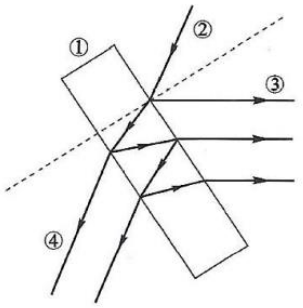


Fig. 3. Expansion of the beam size by a glass plate ①glass plate ②incident beam ③reflected beams ④transmitted beams

2. Index of refraction of dielectrics

When light crosses the boundary of separation between two contacting dielectrics of different indexes of refraction $(n_1 \,\&\, n_2)$, it will refract and the path of light follows Snell's law $(n_1 \sin\theta_1 = n_2 \sin\theta_2)$ as shown in Fig. 4. Note the index of refraction is equal to the ratio of the speed of light in vacuum to that in the medium.

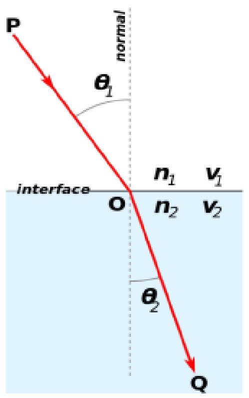


Fig. 3. Diagram of Snell's law.

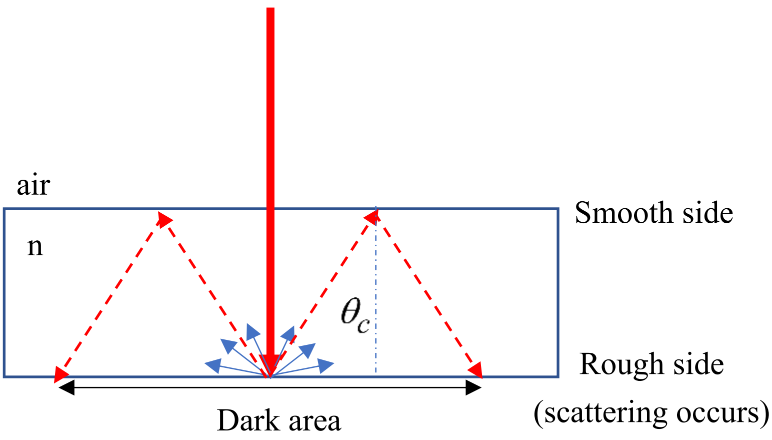


Fig. 4. Total internal reflection (TIR) between air and acrylic plate.

For the case of $n_1 > n_2$, there is a threshold for the angle of incidence θ_1, called the critical angle θ_c, at which the refracted light becomes parallel to the boundary surface and as $\theta_1 > \theta_c$, the conditions of refraction can no longer be satisfied. That is, there will be no refracted light but reflected light, and this condition is called the total internal reflection (TIR). The critical angle is governed by the index ratio of the two mediums and is described by

$$\theta_c = \sin^{-1}(n_2/n_1) \tag{2}$$

When laser light is incident on an acrylic plate with one rough side, TIR occurs and a dark circular area will be formed and one can determine the index of refraction n of the acrylic plate using eq (3).

$$n = 1/\sin\theta_c = \frac{\sqrt{d^2 + (R/2)^2}}{R/2} \tag{3}$$

C. Procedures

1. Pre-lab assignments (hand in before the experiment)
   (1) Install the app *"Light Meter"* to your phone, and make sure you know the working principle of the micrometer caliper.
   (2) Make a flowchart of this experiment and answer the questions below.
   (3) Prove the relation given in eq (1).
   (4) Explain the terms in your own words (with schematics)
      (i) Malus's law
      (ii) TE polarization and TM polarization
      (iii) Brewster's angle
      (iv) Babinet's principle
      (v) What is the difference between interference and diffraction?
   (5) Consider a beam expander as Fig. 2 shows. Find the relationship between the beam size ratio b/a and the focus lengths ratio f_2/f_1 of the two lenses. What would happen if one changes the order of the two lenses but still makes their focus at the same point?
   (6) Brewster's angle (also known as the polarization angle) is an angle of incidence at which ***the reflectance of the TE polarization is zero***. Therefore, when unpolarized light is incident at this angle, the reflected light is perfectly polarized. At Brewster's angle θ_b, ***the reflected beam is perpendicular to the transmitted beam***. Prove that the index of refraction of the acrylic plate can be determined by

   $$n = \tan\theta_b \tag{5}$$

   (7) To find the unknown wavelength λ of a laser beam by a double-slit experiment, given the distance between the center of the two slits is d,
      (i) Use a schematic to show the arrangement of the double-slit, the laser beam, and the screen. Label the physical quantities needed to be measured in the experiment.

(ii) Find the relationship between λ, d, and the quantities you mentioned.

(iii) After obtaining the wavelength λ of a laser beam, suppose now you are given a single-slit with unknown width a. Explain how to obtain the value of a.

2. In-lab activities (Don't forget to take pictures of your work.)

(1) Focal length of a thin lens

(i) Set up the experiment as Fig. 5 shows. Two intense parallel beams will be observed after the laser beam is reflected by the glass plate. **(Why two?)**

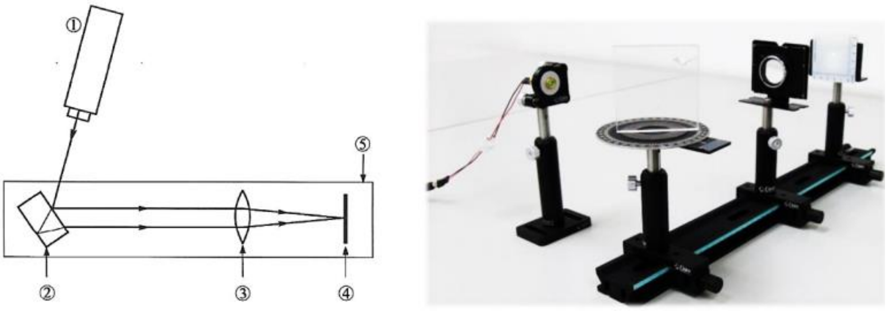


Fig. 5. Experimental setup of measuring the focal length of a thin convex lens.
① green laser ② glass plate ③ convex lens ④ screen ⑤ optical table

(ii) Move the screen behind the convex lens to make the two beams intercept at a point, where the distance between the lens and the screen is the focal length of the lens.

(iii) Re-do the step (ii) five times, and state the focal length f_1 in a standard form[1]

$$f_1 = f_{1,\text{best}} \pm \delta f_1$$

(iv) Change the experimental setup to Fig. 6, where a laser passes through a beam expander composed of a concave lens and a convex lens.

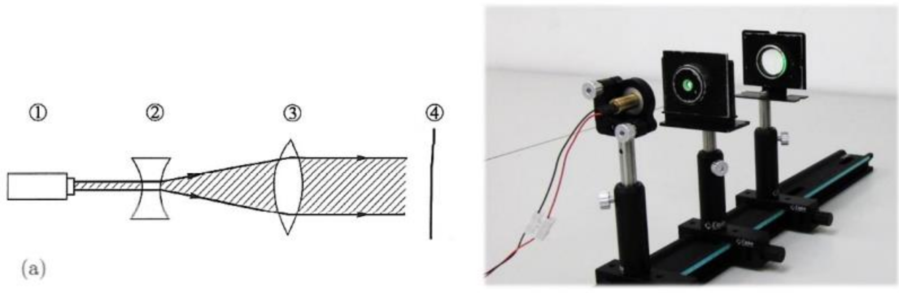


Fig. 6. Experimental setup of measuring the focal length of a thin concave lens.
① green laser ② concave lens ③ convex lens ④ screen

(v) Adjust the position of the concave lens to make the laser beam coming out from the convex lens collimated, where the focal length f_2 of the concave lens can be determined. **(How to tell whether the beam is collimated?)**

(vi) Re-do the step (v) five times and state the focal length f_2 in a standard form

[1] Don't forget to consider the type B uncertainty.

(2) Index of refraction of acrylic

(i) Acrylic plate with *one rough side* (Fig. 7(a)): A green laser beam is normally incident to the smooth side of the acrylic plate and **a black plate** is placed right behind the rough side of the plate.

(a) Observe and explain the phenomenon.

(b) Find the index of refraction n_1 of acrylic. (Hint: eq(3))

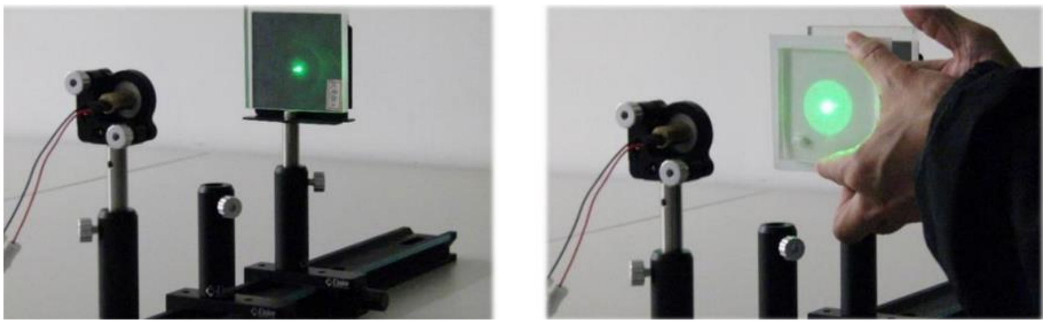
(ii) Acrylic plate with *two smooth sides* (Fig. 7(b)): A green laser beam is normally incident to the acrylic plate and **a white plate** is placed right behind the plate.

(a) Observe and explain the phenomenon.

(b) Find the index of refraction n_2 of acrylic. (Hint: eq(3))

(iii) Explain the similarities and differences between the two experiments.

(What's the difference if the laser beam is not normally incident to the plate?)



(a) acrylic plate of one smooth side (b) acrylic plate of two smooth sides

Fig. 7. Experimental setup of measuring the index of refraction of acrylic using TIF

(iv) Acrylic rectangular rod(Fig. 8): Use the laser rangefinder to obtain the index of refraction n_3 of acrylic by measuring the distance between the rangefinder and the wall with and without the acrylic rod.

(a) Explain how you obtain the result.

(b) Five different trials are needed and state the result in a standard form.

Fig. 8. Experimental setup of measuring the index of refraction of acrylic using a laser rangefinder

(v) Compare the results obtained by the three different experiments above with the reference value $n = 1.49$.

(3) Polarization

(i) Determine the polarization axis (or transmitting axis) for a linear polarizer

Take one linear polarizer. Observe the reflected light from the floor through the polarizer while rotating it. Explain how you determine the polarization axis for a linear polarizer by the intensity of the reflected light after the linear polarizer.

(ii) Verify Malus's law

(a) Fix two smartphones on the phone holders, with one being the light source and the other being the light intensity sensor. **The positions of the two phones should be fixed throughout the whole experiment.** Measure the light intensity I_0 via "Light Meter".

(b) Place a polarizer right against the light source and measure the light intensity I_1. Attach the second polarizer right against the first one. Record the light intensity I_2 with the angle between their polarization axes being $0°, 30°, 45°, 60°, 90°$, respectively. Compare the results with Malus's law.

(c) Adjust the two polarizers to the ***minimum*** light intensity. Place the third polarizer in the middle of the original two. Starting from the condition of minimum light intensity, rotate the third polarizer with the other two fixed by $0°, 30°, 45°, 60°, 90°$. Record the light intensity I_3 for each trial and explain the results by Malus's law.

(iii) Brewster's angle

(a) Set up the laser, acrylic plate, and the polarizer as shown in Fig. 9. Adjust the polarizer to make a horizontally-polarized beam. **(Why do we need a linear polarizer here?)**

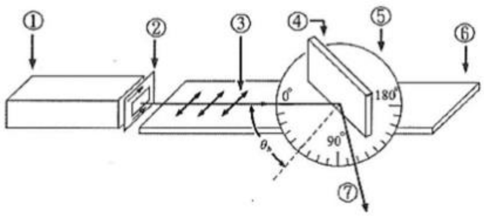
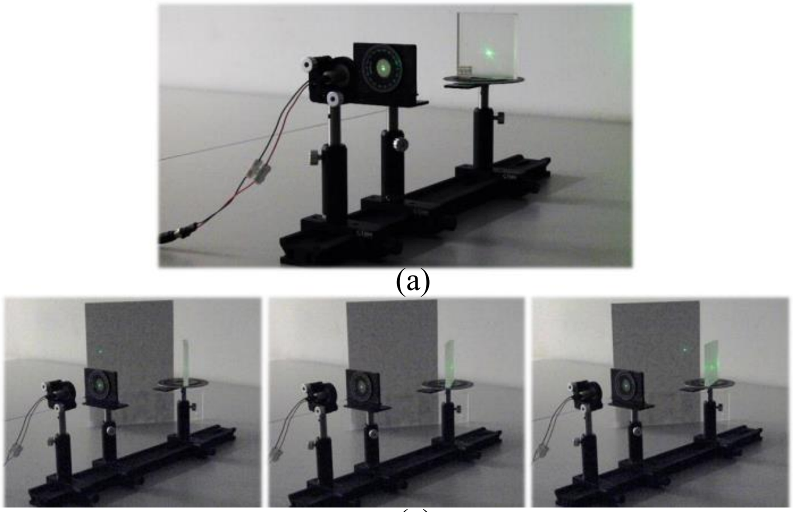


Fig. 9. Experimental setup of measuring Brewster's angle
①green laser ②linear polarizer
③horizontally-polarized light
④acrylic plate ⑤angle-adjusting table
⑥optical bench ⑦reflected light

(b) Rotate the angle-adjusting table to change the angle of incidence of the laser. When the intensity of the reflected light reaches the minimum, the angle of incidence is Brewster's angle θ_B. Record the value of θ_B, and determine the refraction of acrylic by it.

(c) Re-do the step (b) five times. Use eq (5) to determine the index of refraction of acrylic for each trial. Calculate the average value and compare it with the reference value.



(a)

(b) (c) (d)

Fig. 10. Experimental setup of measuring Brewster's angle.
(a) normal incidence (b) incident angle < Brewster's angle
(c) incident angle = Brewster's angle (d) incident angle > Brewster's angle

(4) Single-slit diffraction (slit width: 0.04 mm and 0.08 mm)

(i) Set up the experiment as shown in Fig. 11. Adjust the slit plate to make the laser beam normally incident to the single slit.

(ii) Adjust the holder of the slit plate to make a clear diffraction pattern on the screen. Observe the result and take a photo as a record.

(iii) Measure the physical quantities you need to determine the wavelength of the laser. Note that the width of the slit is indicated on the slit plate.

(iv) Compare the result with the laser wavelength $(\lambda = 532 \text{ nm})$.

(v) Replace the slit plate by one hair. With the laser wavelength, determine the diameter of the hair. Compare the result with the value obtained by the micrometer caliper.

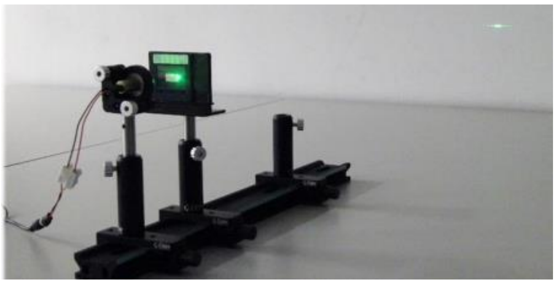


Fig. 11. Single-slit experiment

(5) Double-slit diffraction (A, C, and D)

(i) Set up the experiment as shown in Fig. 11. Adjust the slit plate to make the laser beam normally incident to the double slit in the plate.

(ii) Adjust the holder of the slit plate to make a clear diffraction pattern on the screen. Observe the result[2] and take a photo as a record.

[2] You will find out that the diffraction pattern is a combination of single-slit diffraction and double-slit interference.

(iii) Measure the width of the central bright fringe area due to the single-slit diffraction and the fringe spacing (the distance between two consecutive bright fringes) of the double-slit interference. Use the results to determine the width of the slit and the distance between the two slits. Compare the results with the values indicated on the plate.

(6) Multi-slit diffraction $(N = 2 \sim 5)$

(i) Set up the experiment as shown in Fig. 11. Adjust the slit plate to make the laser beam normally incident to the slit in the plate.

(ii) Adjust the holder of the slit plate to make a clear diffraction pattern on the screen. Carefully observe the results and take photos as a record. **Measure the width of the central bright fringe for each trial.**

(iii) Change the slit plate to the plate of different apperture shapes. Observe the diffraction patterns and take pictures as the record.

(iv) Describe the observations and explain in detail in your post-lab report.

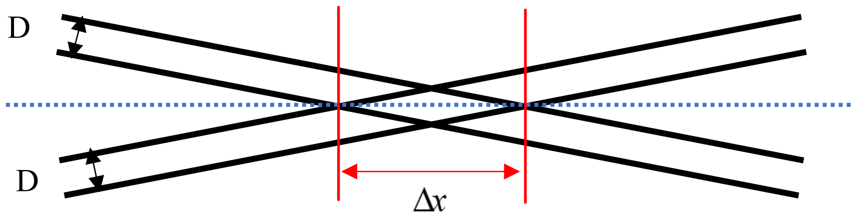
3. Post-lab report

(1) Recopy and organize your data from the in-lab tables in a neat and more readable form.

(2) Analyze the data you obtained in the lab and answer the given questions

E. Questions

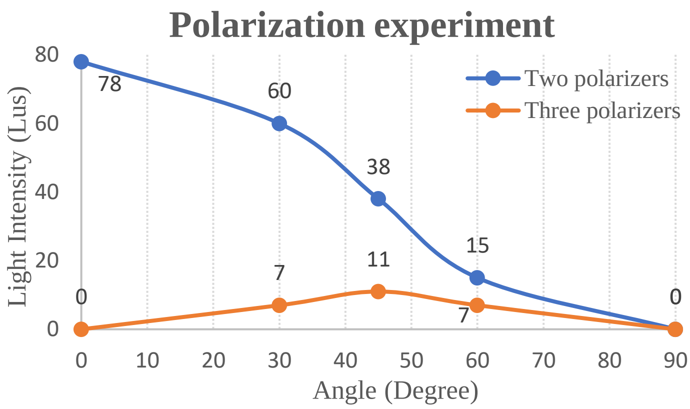
1. In the first experiment, if the laser beam was not parallel to the principle axis of the lenses, what would the result become?
2. In the first experiment, you were asked to measure the focal length of a thin convex lens by the distance between the lens and the focus of the two parallel beams. Suppose the beam width of the laser is D and the distance between the centers of two parallel beams before entering the convex lens is a. As the picture below shows, after passing through the convex lens, the refracted beams will have an overlapping area around the focus, which causes the uncertainty of the measurement. Estimate this uncertainty Δx by the given information. ($a \sim 0.5$ cm, $f \sim 15$ cm, $D \sim 0.1$ cm)



3. In the second experiment, you are asked to measure the index of refraction of acrylic by the bright circle due to the total internal reflection. If the laser is not normally incident to the acrylic, what will the results become? Will this affect the obtained value (index of refraction)? Explain in detail.

There are bright fringes with equal spacing and their intensity distribution is determined by the single-slit diffraction.

4. Consider the third experiment in this lab. Based on Malus's law, if the light source is fixed, then the light intensity right behind the first polarizer should remain the same. Suppose the maximum light intensity of the two-polarizer system is I_0. If the third polarizer is placed in the middle, the maximum light intensity should be $I_0/4$. Below is a graph plotted by real experimental data. The results, however, show that the ratio of the maximum light intensity between the two systems is not $1/4$ but around $1/7$. Explain the difference between the theory and the experiment, and try to modify the formula of Malus's law.



5. Sunglasses are made of polarized lenses. How to tell its polarization axis? Explain in detail.
6. The precise measurement of distance and the width of the central fringe is important for the single-slit experiment. Estimate the uncertainty of the obtained wavelength by the uncertainty of the measurement.
7. **(Optional)** Suppose you have a chance to write a letter to Isaac Newton. Based on the observations of this lab, try to convince him that the corpuscular theory of light is incorrect.

E. References

Ochoa, Romulo, Richard Fiorillo, and Cris Ochoa. "Index of refraction measurements using a laser distance meter." The Physics Teacher 52.3 (2014): 167-168.
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