Geometrical Optics
Practical 2. Part I. BASIC ELEMENTS AND METHODS FOR CHARACTERIZATION OF OPTICAL SYSTEMS

`Equipment and accessories:` an optical bench with a scale, an incandescent lamp, matte, a set of lenses and objects, a screen.

Introduction

Geometrical optics is an approach considering the rectilinear propagation of light only. It simplifies development of optical systems accounting for refraction and reflection phenomena. The wave properties of light (which manifest themselves in such phenomena as interference and diffraction) are simply ignored[1]. In short, the *Geometrical optics* treats the controlled manipulation of wave-fronts (or rays) by means of the interpositioning of reflecting and/or refracting bodies, neglecting any wave effects. A ray of light gives the direction of propagation of light. In the absence of an obstacle, the rays advance in a straight line without changing direction. When light meets a surface separating two transparent media, reflection and refraction occur and the light rays bend.

Geometrical optics will help you to understand the basics of light reflection and refraction and the use of simple optical elements such as mirrors, prisms, lenses, etc.

For *the Practical* you need to know the laws of reflection and refraction, the formula of a thin lens and a spherical mirror (in the approximation of the paraxial rays).

Objective of Practical: to get acquainted with the elements of optical systems (lenses, mirrors, etc.) and measure their parameters.

The lens formula

A *lens* is a transmissive optical device that focuses or disperses a light beam by means of refraction. A simple lens consists of a single piece of transparent material, while a compound lens consists of several simple lenses (elements), usually arranged along a common axis.

In optics, a *thin lens* is a lens with a thickness (distance along the optical axis between the two surfaces of the lens) that is negligible compared to the radii of curvature of the lens surfaces. Lenses whose thickness is not negligible are sometimes called *thick lenses*. The thin lens approximation ignores optical effects due to the thickness of lenses and simplifies ray tracing calculations.

Diverging lenses are thinner at the center and tend to advance that portion of the wavefront, causing it to diverge more than it did upon entry.

Converging lenses are thicker at the center and tend to decrease the radius of curvature of the wavefronts. In other words, the wave converges more as it traverses the lens, assuming that the index of the lens is greater than that of the media in which it is immersed.

[1]Which is physically justified by approaching the wavelength λ to 0.

The lens formula in Gaussian form is:

$$\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}, \tag{1}$$

where d_1 is the object distance, d_2 is the image distance, and f is the focal length of the lens. Also, the sign rule should be used:

1) for *real* objects and images, $d_{1,2}$ are **positive**,
2) for *virtual* objects and images, $d_{1,2}$ are **negative**,
3) for a *converging* (also referred to as *positive* or *convex*) lens, the *focal length* is **positive**,
4) for a *diverging* (also referred to as *negative* or *concave*) lens, the *focal length* is **negative**.

However, in many practical cases, *Cartesian*[2] sign convention is used:

1) the lens formula is written as:
$$-\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}. \tag{2}$$
2) The origin of the Cartesian coordinate system coincides with the centre of the lens, and the light traverses along the X-axis, e.g., all figures are drawn with light travelling from left to right.
3) All distances are measured from a reference surface, such as a wavefront or a refracting surface. Distances to the left of the surface are negative.
4) The refractive power of a surface that makes light rays more convergent is positive. The focal length of such a surface is positive.
5) The distance of a real object is negative. The distance of a real image is positive.
6) Heights above the optic axis are positive. Angles measured clockwise from the optic axis are negative.

The mirror formula

A *mirror* is an optical device that reflects the light. There are plain and curved mirrors. The simplest curved mirror is a spherical mirror for which the following equation is applied:

$$\frac{1}{d_{ob}} + \frac{1}{d_{im}} = \frac{1}{f}, \tag{3}$$

with d_{ob} and d_{im} being the distance to the object and image from the mirror, respectively, and f the mirror focal length.

Note, that either *Gaussian* or *Cartesian* sign convention must be used for mirrors as well.

[2] *Cartesian* means of or relating to the French philosopher René Descartes — from his Latinized name *Cartesius*.

The *Gaussian* sign convention, *aka* 'real is positive' is:

1) focal length (f) and radius of curvature (R) are both positive for concave mirrors,

2) distances to real images and real objects are positive,

3) distances to virtual images and virtual objects are negative;

The *Cartesian* sign convention is:

1) The mirror is placed at the origin of the XY-coordinate plane,

2) The light direction is from left to right,

3) Any ray starts at origin, it is positive to the right, negative to the left. Hence, concave mirror has negative focal length and negative radius of curvature.

Experimental setup

The experimental setup (Figure 1) includes an optical bench with optical elements: a light source (a lamp), lenses, prisms, mirrors, etc. The lens and mirror holders are equipped with adjusting screws that allow setting optical elements along a straight line, the optical axis of the system. Performing the experimental tasks, it is necessary to achieve the coaxial position of all optical elements.

Every experimental task must be accompanied with a diagram of the ray paths, illustrating a real conversion of a light beam in a given optical system.

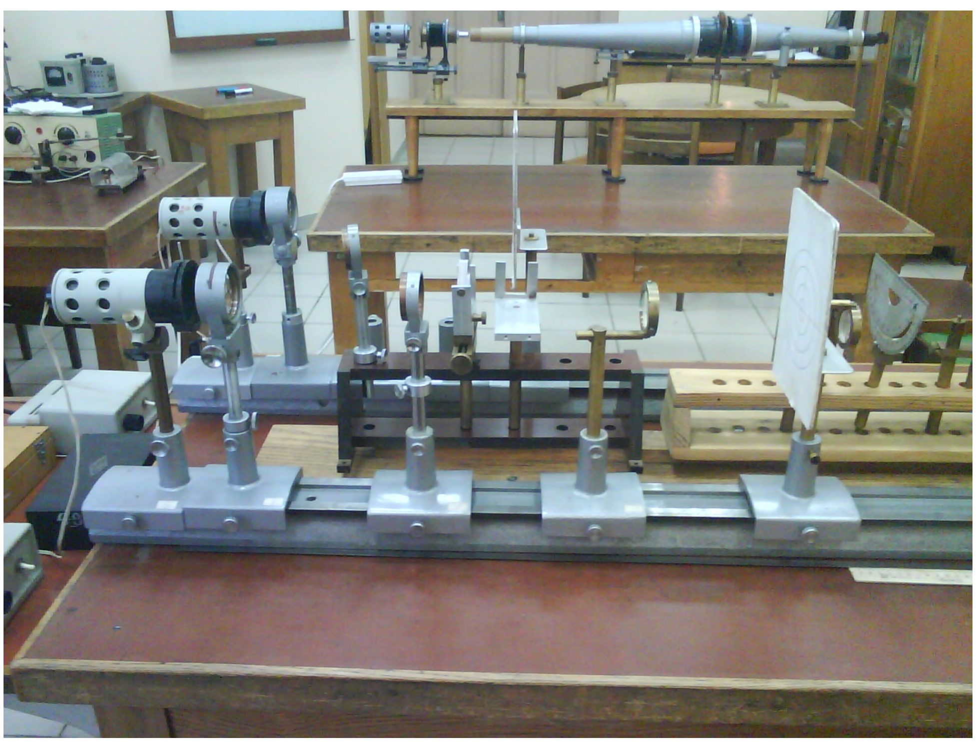

Figure 1: Experimental setup

Measurements and data processing

Task 1. Obtaining a divergent light beam

Create a "point" light source using a diaphragm in front of the filament of the lamp, and obtain a divergent light beam. Adjusting the position of the light source, make sure that the ray axis is perpendicular to the screen. If the elements achieve the coaxial position, the boundary of the light circle on the screen will coincide with one of the concentric circles on the screen.

Task 2. Obtaining a parallel light beam

Guess, how a convex lens should be positioned in respect to the "point" light source in order to obtain a parallel light beam. Using the Lens number 1 (referring further *Lens 1*), perform necessary measurements and calculations. As an object, the luminous element (e.g., filament of the bulb) of the light source can be used. Repeat the measurement three times, and find the averaged result. Place the *Lens 1* at the desired position on the optical bench and verify that the achieved light beam is a parallel one by moving the screen by 30 - 50 cm away from the lens. If the light forms the parallel beam, the diameter of the illuminated circle should not increase, and the center of the illuminated circle should not move relatively to the center of the screen.

Task 3. Obtaining a converging light beam and measuring the focal length of the lens

Place *Lens 2* into the previously prepared parallel beam. Make sure that optical axis of the lenses coincide with each other. Obtain a light spot located exactly at the screen's center. Adjust the spot to the smallest size. It will correspond to a converging light beam. Using basics of the geometrical optics, find the focal length of *Lens 2* for two positions of the screen and lens. Draw a diagram illustrating the rays paths.

Task 4. Obtaining an image of an object on the screen.

Insert a *matte* (also referred to as frosted glass, or ground glass, or milk glass) and an object (a plate with the letter 'F') into the slit in front of the lamp. Obtain (if possible) an image of the object in case:

1. the object is between f and $2f$,
2. the object is farther than $2f$,
3. the object is between the lens and f.

Draw the ray paths for the cases. Measure the distances that are necessary for calculation of the focal length of the *Lens 1*. Calculate the magnification of the lens.

Task 5. Experiment with a diverging lens

Remove the *Lens 1* from the bench and take the object out of the slot. Take a diverging lens (the *Lens 4*), put it between the lamp and the screen. Obtain a shadow image of the lens on the screen.

Sketch the ray paths diagram and explain why an image looks like a dark circle surrounded by a light ring (this optical effect is usually called a halo).

Task 6. Transformation of a parallel beam into a diverging one

Obtain a parallel beam (Task 2). Use a diverging lens to turn a parallel beam into a diverging one. Make sure that the beam axis passes exactly through the center of the screen.

Task 7. Measurement of the focal length of the diverging lens

Put the frosted glass and the plate with the letter 'F' into the slit in front of the lamp. Place the diverging on the bench and make sure that it is impossible to obtain an image of the object on the screen with a single diverging lens at any position of the lens and screen.

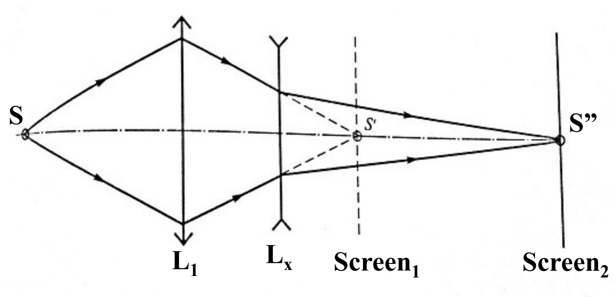

Figure 2: Measurement of the focal length of the diverging lens

Remove the diverging lens and put the converging lens instead. Obtain an image of the object on the screen. Add the diverging lens to the optical system again (see Figure 2). By moving the screen back and forward, obtain a clear image of the object on the screen. Figure 1 illustrates that the "old" image of the object (S) can be considered as an object whose "new" image is obtained with the diverging lens. Determine the focal length of the diverging lens by measuring the necessary distances of the optical system. Repeat the measurement three times, compute the averaged value and absolute error.

If it is appearing to be difficult obtaining a clear image by moving the screen only, adopt one of the two approaches:

1. Adjust position of the convex lens but keep the screen unmoved. Remember, that after the distances are measured, you are to remove the concave lens and adjust the screen so that a clear image is formed by the convex lens,
2. Keep the position of the convex lens but adjust positions of both the concave lens and the screen.

Task 8. Study of a cylindrical lens

Form a parallel beam and place a cylindrical lens into the optical system. Obtain a vertical strip and then a horizontal strip on the screen by rotating the lens in the frame.

Draw the ray path diagrams in two views: a top view and a side view. Think about the shape of the beam at a aome considerable distance from the lens. Make an assumption and check it experimentally.

Task 9. Measurement of the focal length and radius of curvature of a concave mirror

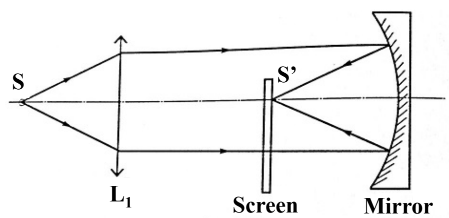

Figure 3: Measurement of the focal length of a concave mirror

Form a parallel beam. Place a concave mirror in the path of this light ray, obtain the image of the filament of the lamp on the screen (see Figure 3). Measure the distances between the elements, determine the focal length of the mirror.

Form a converging beam (see Figure 4). Receive the image of the filament of the lamp on the screen. Put the concave mirror behind the screen and move it until another image of the filament appears on the screen. In this case the autocollimation condition is said to be satisfied. After measuring the required distance, find the radius of curvature of the mirror.

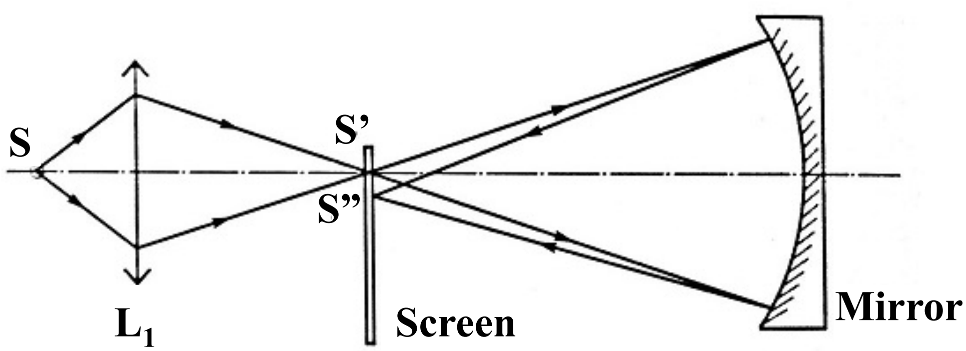

Figure 4: Measurement of radius of curvature of a concave mirror

Task 10. Experiment with a wrapping prism

Obtain a magnified inverted image of the object (letter *'F'*) on the screen with the converging lens (*Lens 1* or *Lens 2*). Place a right-angle prism between the lens and the screen and get a direct image of the object on the screen. The prism is oriented with its right angle down. Draw the ray path diagram. Explain why you need to shift the screen slightly.

Task 11. Measurement of the focal length of a lens by an autocollimation method

Assemble the circuit according to Figure 5 (the source is the filament of the lamp). Use *Lens 1* to obtain an image of the lamp filament on the screen. Place *Lens 2* (the lens under an investigation) behind a flat mirror. If the image is in the focus of *Lens 2*, the beam after *Lens 2* will be parallel. After the reflection from the mirror the light beam will again pass *Lens 2* and converge on the screen. It leads to formation of an another image of the lamp filament that almost coincides with the first image. This method is so called an autocollimation method.

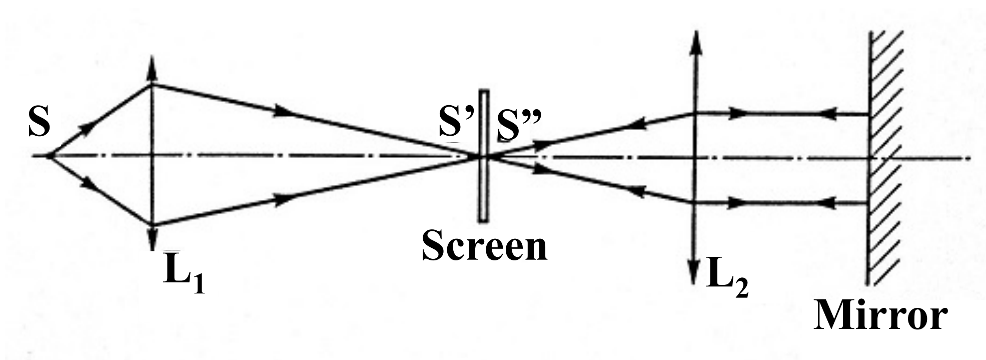

Figure 5: Measurement of the focal length of a lens by an autocollimation method

Moving *Lens 2* along the optical bench and slightly turning the mirror, achieve the described situation and find the focal length of *Lens 2*.

Task 12. Measurement of the focal length of a convex mirror

Think about how you can measure the focal length of a convex mirror. Draw the ray path for the proposed method and check the solution experimentally.

Questions

1. Is it possible to obtain a strictly parallel light beam?
2. What image of the object, real or virtual, can you see on the screen?
3. Is it is possible, by using a converging lens, to obtain: a) a direct actual image of the object; b) a direct magnified image; c) a direct minified image.
4. Is it possible, by using a diverging lens, to obtain: a) a real image of the object; b) an magnified image; c) a direct image.
5. In what practical cases is it beneficial to use a cylindrical lens?
6. Will the effect of the right-angle prism be improved if its the largest side is silvered?
7. Is it possible to measure the focal length of the diverging lens by the autocollimation method?
8. What images (difect, inverted, enlarged, etc.) can be obtained with the help of a concave mirror?
9. What images can be obtained with a convex mirror?