Laboratory Practicum on General and Experimental Physics

Optics

Preface

This *Laboratory Practicum on General and Experimental Physics: **Optics*** is designed as a guide-book to experimental laboratory works which are presented in Moscow Pedagogical State University *(General and Experimental Physics Department, Institute of Physics, Technology, and Informational Systems)* and which have been used in the student training for many years. *The Practicum* is based on the "Laboratory Practicum on General and Experimental Physics" edited by E.M. Gershenzon and A.N. Mansurov [1], and written by the cooperation of the MSPU authors and staff.

Authors would like to appreciate the many-years-work by the physicists who have developed and created the Practicum and Labs, who have been responsible for building up and maintenance and have been teaching in the Practicum, who have polished the manuals and the book, all this is definitely considered as an invaluable contribution. We would like to thank our colleagues who have designed the "Physics in English" programme and by that provided us with prompt and stimulus for our creativity. And we are delighted to give acknowledgment to our colleagues from the General and Experimental Physics Department whose help and stimulating discussions were as much of the lead and help for us.

During our work on the English version of the Practicum all the possible efforts were given to enrich the description, whenever it was possible, provide additional tasks and comments. Especial gratitude is to our students who were using the Practicum for the first time, providing valuable comments and catching out misprints and "entangled" leads. We believe that our joint effort is still on its way and that future editions could be still improved, and for that any comments and suggestions are welcome.

The Authors

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[1]Laboratory Practicum on General and Experimental Physics, Textbook for universities. Educational Programme 032200 "Physics", 2004; edited by E.M. Gershenzon and A.N. Mansurov.

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Propagation of the Electromagnetic Waves

Practical 1.
STUDY OF THE ELECTROMAGNETIC WAVES
IN A TWO-WIRE TRANSMISSION LINE

Introduction

Electromagnetic wave can propagate in all possible directions in isotropic and homogeneous medium - free space, which contains no electrical conductors. To transmit the electromagnetic energy or information in a certain direction by mean of electromagnetic wave, one need to use leading systems such as wires, metallic pipes – waveguides, dielectric rods and so on.

One of the simplest system of such kind is a two-wire transmission line, which consists of two long cylindrical wires with wire diameter equal to r, and separated from each another by certain distance $h > r$.

The external field of such system is very small in comparison with the field between the wires, so we could say without loss of generality, that the electromagnetic wave will mainly propagate between the wires.

It can be shown, that the voltage U between the wires of an infinitely long line is defined by the wave equation:

$$L_0 C_0 \frac{\partial^2 U}{\partial t^2} = \frac{\partial^2 U}{\partial z^2} , \tag{1}$$

where z - is the cross section of the line under consideration, L_0 and C_0 - are an inductance and capacitance per unit length of the line.

The solution for the wave equation (1) defines the running wave of voltage:

$$u = U_m \cos \left[\omega \left(t - \frac{z}{v} \right) \right] , \tag{2}$$

PRACTICAL 1.
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where

$$v = \frac{1}{\sqrt{L_0 C_0}}, \tag{3}$$

Or one can think about the running wave of current in the line:

$$i = I_m \cos\left[\omega\left(t - \frac{z}{v}\right)\right], \tag{4}$$

and in the same way, about running waves of electric and magnetic E and B fileds in the line.

The running wave mode could be realized in the infinitely long line or in the actual one (line with a certain length), which is connected to a matched load. The resistance of such matched load is called the wave resistance of the line or the impedance of the line and is equal to:

$$Z_0 = \frac{U_m}{I_m} = \sqrt{\frac{L_0}{C_0}}, \tag{5}$$

To calculate the propagation speed of waves in the line, one need to use the relation between the L_0 and C_0 and the geometrical parameters of the line. Assuming that the conductors are in the vacuum:

$$L_0 = \frac{\mu_0}{\pi}\ln\frac{r+h}{r} \cong \frac{\mu_0}{\pi}\ln\frac{h}{r} \qquad \left(\frac{H}{m}\right), \tag{6}$$

$$C_0 = \pi\varepsilon_0\frac{1}{\ln\frac{h+r}{r}} \cong \pi\varepsilon_0\frac{1}{\ln\frac{h}{r}} \qquad \left(\frac{F}{m}\right) \tag{7}$$

Taking into account relations (3) and (6), (7) one can come to a very important result:

$$v = \frac{1}{\sqrt{L_0 C_0}} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = c, \tag{8}$$

This result states, that the propagation speed of electromagnetic waves in a line is equal to the one in a free space.

If the line is surrounded with a dielectric material, then the wave speed in such line will be reduced:

$$v_{aver} = \frac{c}{\sqrt{\varepsilon\mu}}, \tag{9}$$

Here ε and μ stands for the relative permittivity and permeability of a given dielectric material. For the majority of dielectric materials $\mu = 1$, which means that the relation (9) can be rewrite in the following way:

$$v_{aver} = \frac{c}{\sqrt{\varepsilon}}, \tag{10}$$

If an incoming wave, which propagates along the line, hits the conductive bridge ($Z = 0$), which shorts the wires of the line, a reflected wave will appear. Due to interference of the incoming and reflected waves, one can observe a peculiar interference pattern in the line, which is called a **standing wave**. One need to meet an obvious condition to observe a standing wave mode in the line. This condition sounds as following: an integer number of half wavelengths should be packed on the length of the line (or in relation to the experimental setup for this practical work - an integer number of half wavelengths should be packed on both sides from the conductive bridge).

Using the theory of oscillations for the oscillatory circuits with distributed parameters, one could say, that the resonant qualities of the circuit appears when the natural oscillation frequency f_0 of the line or its' harmonic overtones nf_0 ($n = 2,3,\dots$) match with the frequency of the driving force (frequency generator). As the result, the amplitude of the standing wave increases.

The latest case is used in this practical work. Two-wire transmission line is driven with a high frequency generator. Changing the length of the line and, as the result the set of its' natural frequencies, one can meet the conditions of the standing wave mode for the given line. Knowing the distance between two series resonances along the line, one can calculate the oscillation frequency ϑ of the generator:

$$\vartheta = \frac{c}{\lambda}. \tag{11}$$

where ϑ - is the oscillation frequency, c – is the speed of light in a free space or the speed of electromagnetic wave in the media, λ - is the wavelength of electromagnetic wave.

Experimental setup

The experimental setup is shown in Fig. 1. This setup employs the generator of decimeter waves. Its' oscillatory circuit doesn't include inductors and capacitors, which are typical for low frequency generators. The inductive and capacitive components in this generator are replaced with two metal pipes, which form the segment of the two-wire transmission line. Oscillation frequency from the generator is defined by the length and the distance between these metal pipes.

Two lines (long and short one), which are used in this work, have additional external segment with an incandescent lamp indicator. The short line is placed into the bath with water. Placing the external segment of the line above the generator (metal pipes segment of the generator), one can drive the forced oscillation in this line. The brightness of the incandescent lamp indicator allows to rate the amplitude of oscillations. The length of each line can be adjusted by changing the position of the conductive bridge.
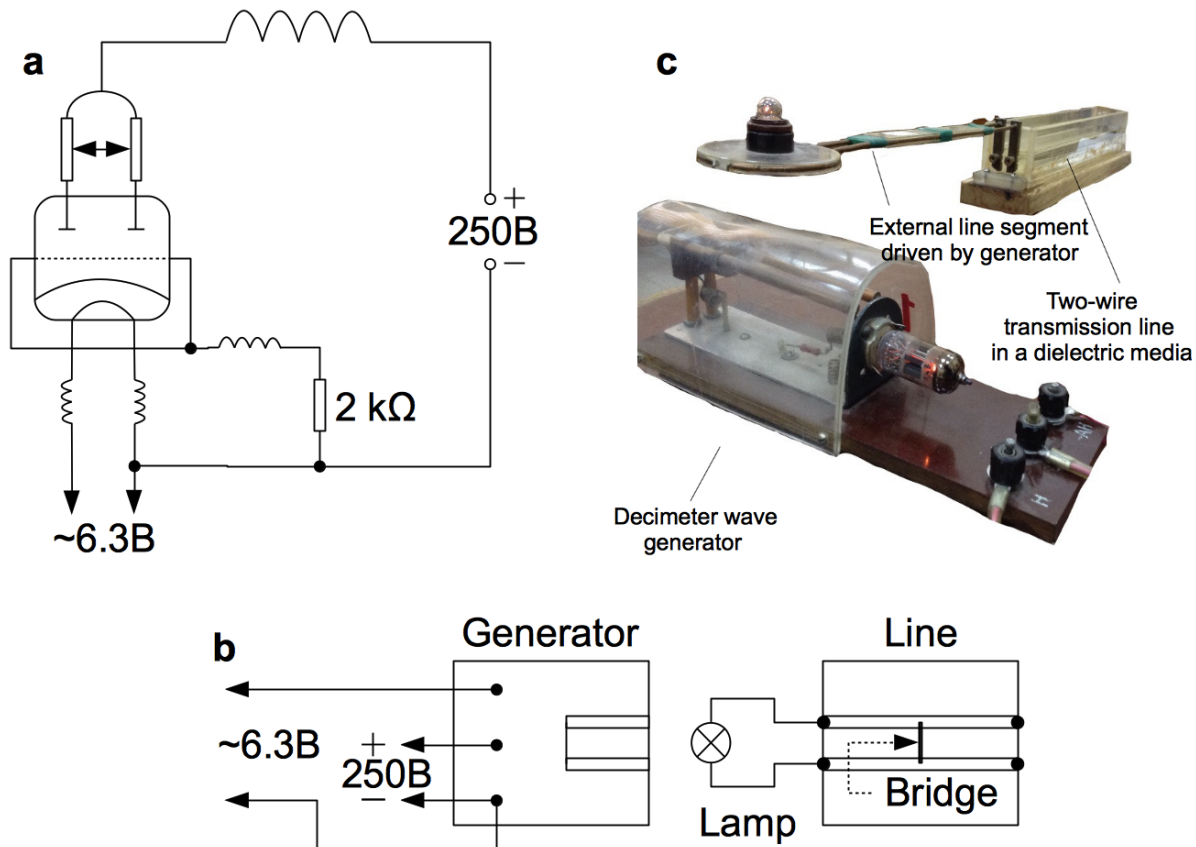

Figure 1: Experimental setup: a) biasing scheme of the lamp decimeter wave generator; b) position scheme of the elements of the setup; c) photos of actual elements of the setup.

PRACTICAL 1.
PROPAGATION OF   *STUDY OF THE ELECTROMAGNETIC WAVES*
THE ELECTROMAGNETIC WAVES   *IN A TWO-WIRE TRANSMISSION LINE*

Measurement and data processing

Task 1. Measurement of the wavelength of electromagnetic wave in the air

Turn on the generator and place it under the external segment of the long line. Moving the conductive bridge along the line, find two successive positions of the bridge, which associated either with the brightest glows of the incandescent lamp indicator or extinct states of the incandescent lamp indicator. Knowing the distance between two successive positions of the bridge, calculate the wavelength of the electromagnetic wave in the air. Calculate the oscillation frequency of the generator, which is used in this practical work.

Task 2. Measurement of the wavelength of electromagnetic wave in the dielectric media

Repeat the measurements from the first task, but with the short line dipped into water. Measure the wavelength in water. Calculate the permittivity of water from the data (wavelength in air/water), which were measured in both tasks. Consider the permeability of water equals to 1 in all your calculations.

Questions

1. What is the principal difference of electromagnetic waves propagation in a transmission line in comparison with a free space.

2. Draw field patterns for *E* and *B* fields in the line in case of running and standing waves in the given moment of time. How will these patterns change over time Δt, which is shorter than the period of oscillations.

3. Draw the direction of the Poynting's vector in different points along the line for two cases. The first case is the running wave mode in the transmission line. The second case is the standing wave mode in the transmission line.

4. What is the principal difference between the resonant phenomenon in systems with distributed parameters (a two-wire transmission line) from the one in the systems with lumped parameters (an oscillatory circuit)?

5. One could use either a glow neon lamp or a incandescent lamp to probe the amplitude of the electromagnetic wave in the line. To which parameter in the line is sensitive each of those indicators?

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[2]. 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.

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

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.

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*[3] sign convention is used:

1) the lens formula is written as:

$$-\frac{1}{d_1} + \frac{1}{d_2} = \frac{1}{f}. \tag{2}$$

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

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.

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.

PRACTICAL 2. PART I.
BASIC ELEMENTS AND METHODS   *GEOMETRICAL*
FOR CHARACTERIZATION OF OPTICAL SYSTEMS   *OPTICS*

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.
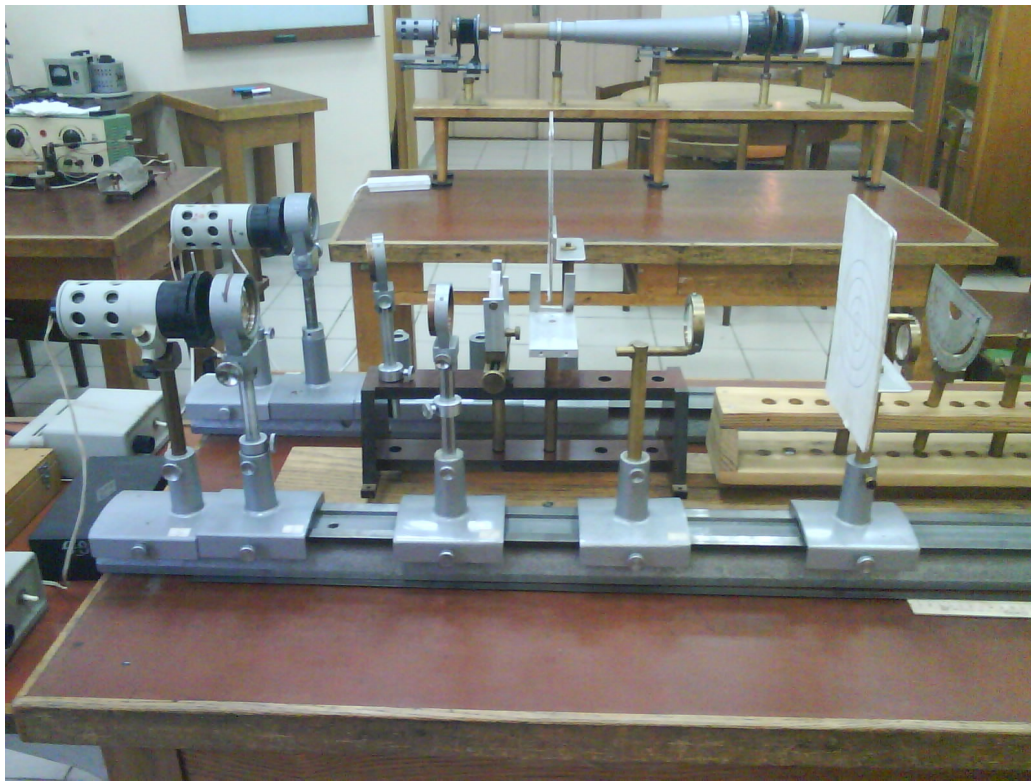

Figure 1: Experimental setup.

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.
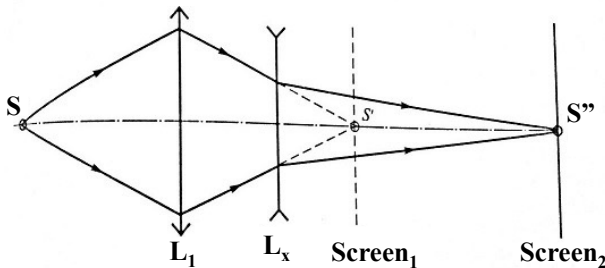

Figure 2: Measurement of the focal length of the diverging lens

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
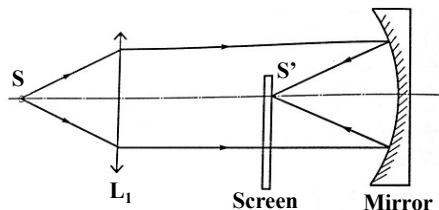

Figure 3: Measurement of the focal length of a concave mirror.

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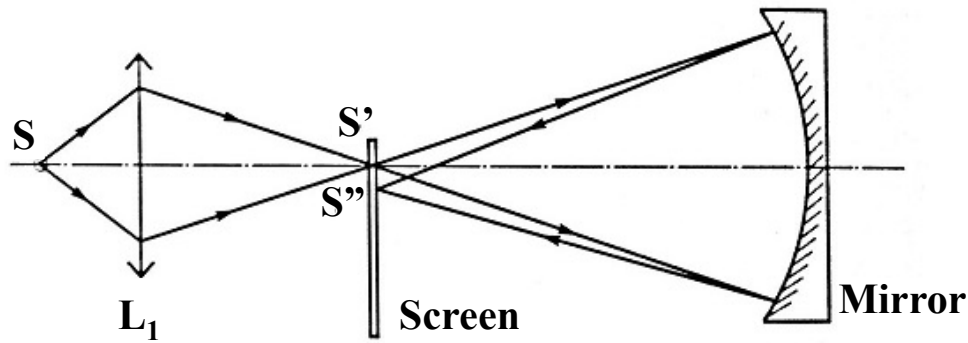
Figure 4: Measurement of radius of curvature of a concave mirror

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.
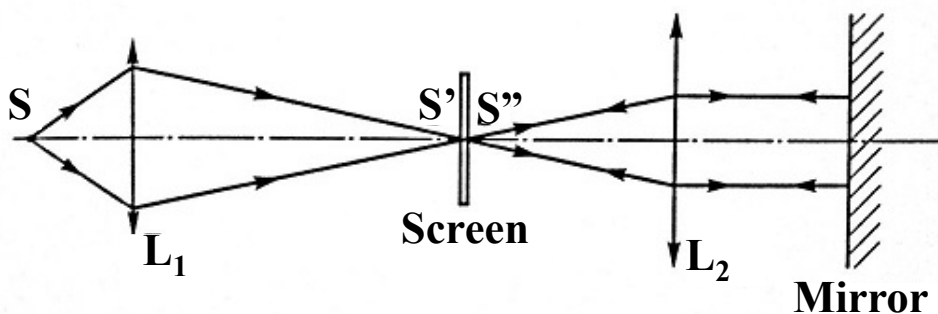

Figure 5: Measurement of the focal length of a lens by an autocollimation method

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?

Practical 2. Part II.
OPTICAL SYSTEMS

Introduction

Optical systems can consist of a one element (a one lens or a mirror, a magnifying glass), two or three lenses (an eyepiece, theatrical binoculars) and many lenses and mirrors (a telescope, a microscope, a spectrograph, etc.).

In *the Practical* the simplest optical systems are studied. The systems are the basic optical instruments: the telescope, the microscope and the slide projector.

Telescopic systems

Task 2.1 Study of the ray path in a telescopic optical system

Form a parallel light beam using *Lens 1* and the filament of a lamp as a source. Such an operation is often called collimation of a light beam, and a collimator is an optical system that supplies a parallel light beam.

Place the converging *Lens 3* at a distance of about 20 cm from *Lens 1* and get a beam converging at its focus (see Figure 1). Then put *Lens 2* into the path of the diverging beam. The focuses of the *Lenses 2* and *3* must coincide. Make sure that the parallel beam is still behind *Lens 2*.

The system of *Lens 2* and *Lens 3* obtained in this way is a special case of the telescopic system that transforms the parallel beam, entering into the system, into a parallel beam of a different diameter.
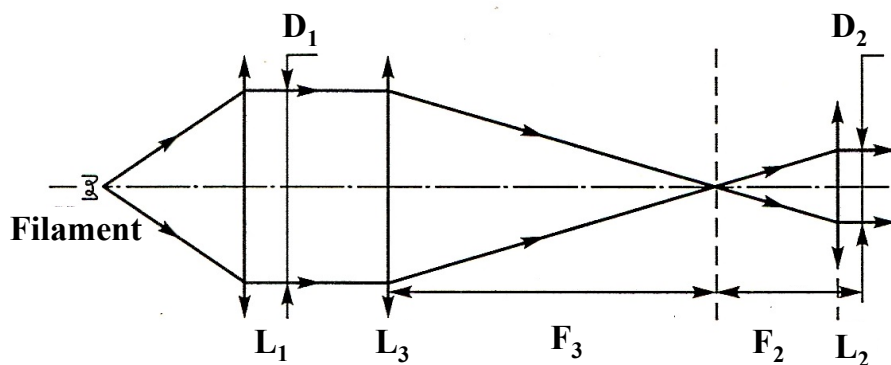

Figure 1: Implementation of the rays path in a telescopic optical system

The angular magnification of the optical system can be defined as:

$$N_{tel} = F_3/F_2, \tag{1}$$

or

$$N_{tel} = D_1/D_2. \tag{2}$$

Calculate the angular magnification of the given optical system using formulas 1 and 2. Compare the result. Draw the ray path diagram.

Task 2.2 Modelling Kepler's telescope

Form a parallel beam using the object (the letter 'F') as the object. Place a frosted glass and a plate with a letter into the slit in front of the lamp. Move the collimator *Lens 1* so that the source object is in the focus of the lens. Setting the object at the focus of the collimator lens is equivalent to removing the object to an infinitely large distance from the previously constructed telescopic lens system of *Lens 2* and *Lens 3*.

With a naked eye, observe the image of the object (letter) in the formed telescope. It is called Kepler's telescope. *Lens 3* in this case is called an objective, and the *Lens 2* is an eyepiece (or ocular).

Note that the length of Kepler's telescope is equal to the sum of the focal lengths of the objective lens and the eyepiece.

Draw the ray path diagram.

Task 2.3 Modelling Galileo's telescope

Replace the eyepiece lens (*Lens 2*) of Kepler's telescope with a concave one (use the *Lens 4*). The system should remain telescopic (see Figure 2). Observe a direct image of the object in the constructed telescope. It is called Galileo's telescope. Calculate the magnification. Draw the ray path diagram.
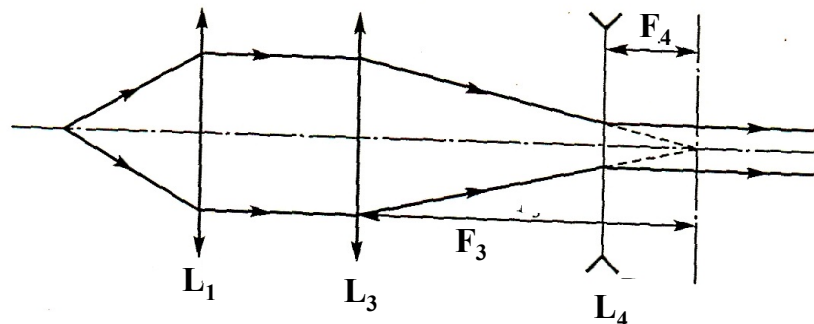

Figure 2: Modelling Galileo's telescope

The magnifying glass and the microscope

To observe an enlarged image of small objects, optical systems usually include one converging lens (in this case it is called a magnifying glass) or several lenses (it is typical for microscopes).

The magnification of the optical system is approximately calculated, knowing its focal length F, and the so-called best-sight distance L (that is equal to 250 mm for the average normal eye):

$$N = L/F = 250mm/F(mm). \tag{3}$$

In the simplest case the microscope consists of an objective with a focal length F_{ob} and an eyepiece with a focal length F_{ep}. The magnification of the microscope can be calculated with the distance of the best view of L and the distance between the focal points of the objective and the eyepiece (it is called the optical length of the microscope):

$$N_m = L/F_{ob}F_{ep}. \tag{4}$$

Both the magnifying glass and the microscope give virtual image of objects; it should be remembered that real image is always formed on the retina of the eye, with the help of the magnifying glass or the microscope.

Expressions (2) and (3) are not completely definite, since the magnification also depends on the parameters of the eye, in particular, on its optical force, which, as is known, varies when looking at objects located at different distances from the eye (the accommodation).

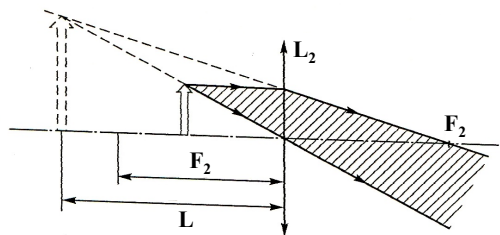**Task 3.1 Studying the magnifying glass and determination of its magnification.**

Figure 3: Studying the magnifying glass and determination of its magnification

As a magnifying glass, use the converging *Lens 2* (see Figure 3). Put in front of the lens a scale with millimetre divisions and observe an enlarged image of the scale. Knowing the focal length of the lens, calculate the magnification of the lens using expression (2).

Task 3.2 Modelling the microscope

Assemble the microscope system (see Figure 4). As an object, use the object-micrometer (with a scale 1 division = 0.1 mm) applied to a glass placed in a rectangular frame. Place the object-micrometer onto a table and insert a frosted glass into the slot in front of the lamp. Place *Lens 1* on the bench so that the distance between the object (that is in the frame) and the lens is slightly larger (by 2-3 cm) than the focal length of the lens.

Find the place where the actual enlarged image of the scale is formed. Place the eyepiece (*Lens 2*) at the end of the bench. You can use it as in a magnifying glass. You can see by a naked eye a real image of the scale (the entire field of view must be uniformly illuminated, and the scale divisions are extremely sharp).

Place a ruler below the axis in the focal plane of the eyepiece (ocular), observe both scales simultaneously and determine the subjective magnification of the microscope. To do this, you need to know the scale division of the object scale (1 division = 0.1 mm), the scale division of the ruler and the magnification of the eyepiece:

$$N_{mic} = N_{ob} \cdot N_{oc}, \tag{5}$$

with N_{ob} and N_{oc} being the objective and ocular magnification, respectively.
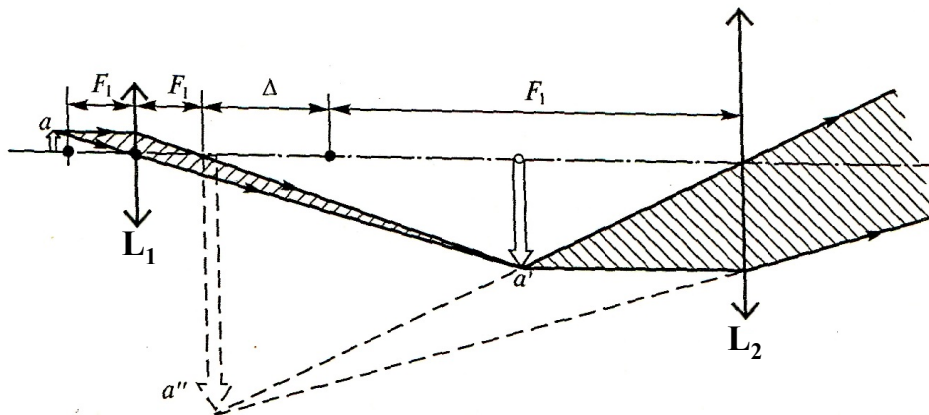

Figure 4: Modelling the microscope

Calculate the magnification of the microscope by measuring the optical distance of the microscope on the bench (see Fig. 4), knowing F_{ob} and F_{ep} and using expression (3).

Reduce the distance between the subject and the lens (do not forget that it should not be less than the focal length of the lens!). Using the procedure described previously, measure the new value of the subjective magnification of the microscope and compare it with formula (3).

The optical slide projector

A slide projector is designed to obtain an enlarged image of a transparent object (a slide) on the screen. In principle, one converging lens is sufficient for that; the object (a slide) must be at a distance slightly higher than the focus of the lens (see Figure 5):

Figure 5: A slide projector

Task 4.1 Modelling the simplest projector

Assemble the optical system as shown in Fig. 5 by placing a slide in the frame at some distance (10 - 15 cm) from the lamp and using the *Lens 2*. Obtain an image of the slide on the screen that is in 30 - 40 cm away from the lens.

Despite the possibility to obtain a sharp image (at least, its central part), the illumination of the image is very weak even when the filament of the lamp is heated intensively.

The fact is that the system is energetically inefficient: only a small fraction of the light flux passes through a relatively small part of the lens. To increase the energy efficiency of the optical system, the slide projector is supplied with a condenser. The condenser is a converging lens, installed between the light source and the object (see Figure 6). The condenser C directs the light flux of the source to the object, and the light beam continues to converge.

In a properly designed projector, the distance from the slide to the lens and from the lens to the screen remains almost the same as in the previous configuration.

Task 4.2 Increase in the energy efficiency of the slide projector

Assemble the optical system using the same lens as in 4.1.

In addition, place the condenser (*Lens 1*) as shown in Fig. 6. Make sure that the light is collected by the condenser and that the *Lens 2* is placed where the light is focused by the condenser. As a result you will get a bright and sharp image of the slide on the screen which now may be moved farther away.
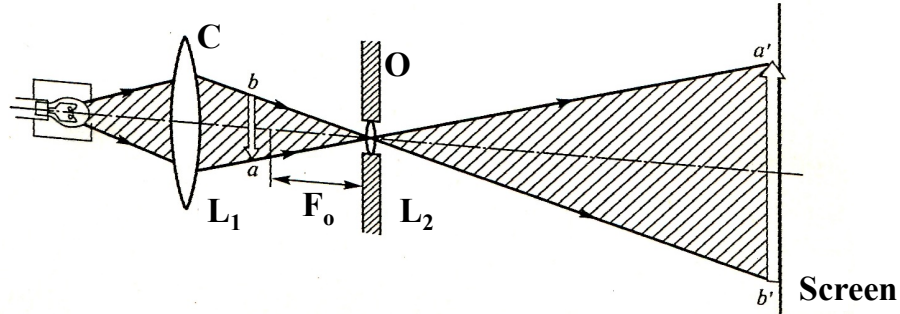

Figure 6: A slide projector with a condenser

All the tasks must be accompanied by ray path diagrams with the indication of the parameters of the optical elements!

Questions

1. What is the optical strength of a telescopic system?

2. Is there a linear magnification in the telescopic system?

3. Why is the beam coming out of the telescopic system sharply limited only in one place? Check it experimentally.

4. What physical considerations should be used in the practical choice of diameter for: a) Kepler's objectice? b) its eyepiece?

5. What elements should be introduced into Kepler's telescope to obtain a direct image? In which systems (or devices) does this configuration apply?

6. What devices use Galileo's optical system?

7. Is it reasonable to construct Galileo's telescope, in the field of view of which there should be a measuring grid (scale)?

8. How can you experimentally estimate the magnification of a magnifying glass without knowing its focal length?

9. Which image, direct or inverted, is observed with a microscope?

10. Can two microscopes that have the same lenses and the same eyepieces have different magnifications?

11. What part of the microscope - the object lens or the eyepiece - should be more free from aberrations of real lenses?

12. Is it possible to observe objects in an optical microscope whose dimensions are smaller than the wavelength of the light wave?

13. How should you insert a slide into the frame of the projector so that the image on the screen is neither upside down nor right-to-left?

14. What should be the minimum size of the condenser in a properly designed slide projector?

Practical 3.
FOCAL LENGTH MEASUREMENT OF THIN LENSES

Equipment and accessories: an optical bench with a scale, an incandescent lamp, a glass plate with a "mesh", a screen, an arrow, and a telescope.

Introduction

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.

   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*[4] 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.

Experimental setup

Experimental setup is assembled on an optical bench and includes a source of light which is an incandescent lamp; an object, which is formed by a glass plate with a "mesh". The image of the object is obtained on a screen with the help of lenses. All the required distances are measured using a centimetre scale. At the end of the optical bench a telescope is installed.

Measurement and data processing

Task 1. Measurement of a converging lens focal length by directly measuring distances d_1 and d_2

Turn on the lamp and move the lens along the optical bench until you get a clear image of the object on the screen. Measure the distances d_1 and d_2. Calculate the focal length using the lens formula (1) or (2) using an appropriate sign convention. Repeat the measurement three times, calculate mean value of the focal length and perform the error analysis. Fill out a table using your data. The final result should be written as $f = \overline{f} \pm \overline{\Delta f}$. Using a pencil and ruler make a drawing which demonstrates how the image was formed.

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

Task 2. Measurement of a converging lens focal length by displacement of the lens (the Bessel method)

Set the screen on the optical bench at a distance $D > 4f$ apart from the object. Now, moving the lens between the object and the screen one may always find two distinct positions of the lens, where a clear image of the object is formed. At one position of the lens, the image will be reduced, and at the other - enlarged. By measuring the distance b between these two positions of the lens and knowing the distance D it is possible to find the focal length of the lens, see a schematic in Fig. 1.

1) Derive the formula for the focal length of the converging lens using the lens formula (1) or (2) and distances D, b.

2) Repeat the measurement three times using the same lens. It is possible to change distances D, b.

3) Calculate mean value of the focal length and perform the error analysis.

4) Fill out a table using your data. The final result should be written as $f = \overline{f} \pm \overline{\Delta f}$.

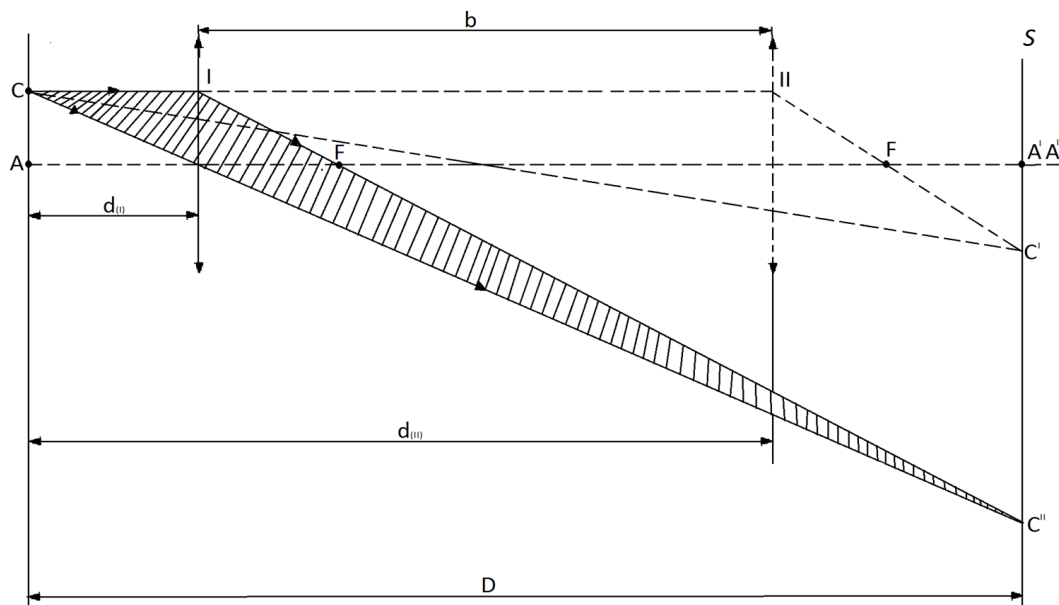5) Make a drawing which demonstrates how the image was formed.

Figure 1: Measurement of a converging lens focal length by displacement of the lens (the Bessel method).

Task 3. Measurement of a converging lens focal length using a spotter scope

The spotter scope, tuned to infinity is set at the end of the optical bench, against the object. By moving the lens along the bench, get a clear image of the grid in the scope's ocular. After that, having measured the necessary distance (please, find out what distance should be measured), find the convex lens focal length. Repeat the measurement three times.

Calculate f_{avg} using results of Task 1 - Task 3. Find the optical strength of the lens under study (in dioptres).

Task 4. Measurement of the concave lens focal length using a convex lens

Using the convex lens, obtain the grid image on the screen (S_1) which is placed at a distance l_1 apart from the convex lens (L_1). If a concave lens L_2 is placed on the optical bench between the screen and the lens L_1, the grid image on the screen disappears, but it can be resumed by moving the screen to position S_2 by a distance l_2 apart from the L_1. Using the lens formula, find the focal length of the concave lens for which the object distance is d_1 and the image distance is d_2. (See Fig. 2).

1) Repeat the measurement three times using the same lenses.

2) Calculate mean value of the concave lens focal length and perform the error analysis.

3) Fill out a table using your data. The final result should be written as $f = \overline{f} \pm \overline{\Delta f}$.

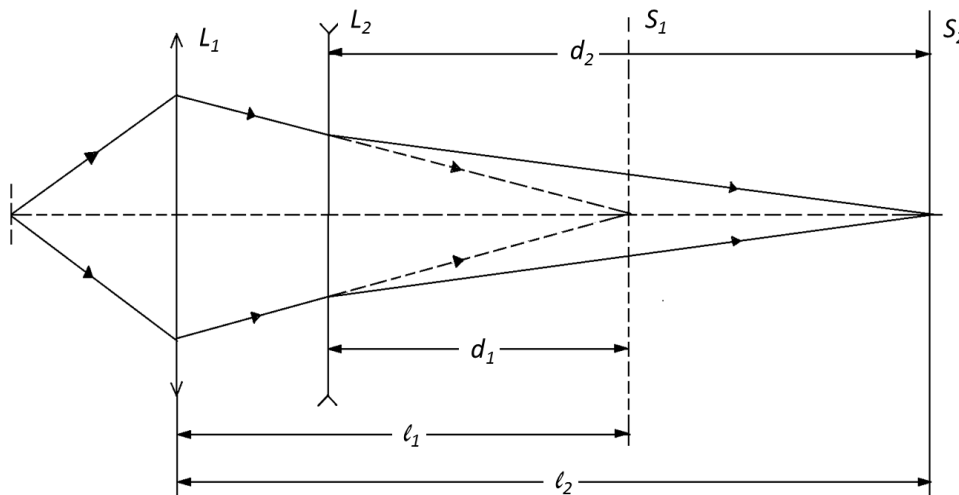4) Make a drawing which demonstrates how the image was formed.

Figure 2: Measurement of the concave lens focal length using a convex lens.

Task 5. Measurement of the concave lens focal length using a spotter scope

The spotter scope, tuned to infinity is set at the end of the optical bench, against the object. Place a convex lens and screen on the bench. Moving the lens and screen, obtain the grid image on the screen (note that the distance between the lens and the screen should be greater than the expected focal length of the concave lens). Note the positions of the lens and the screen on the scale. Between the screen and the convex lens, place the concave lens, and remove the screen. By moving the concave lens, obtain a distinct image of the grid in the scope's ocular. Find the focal length of the concave lens using reconstruction of the optical patch. Repeat the measurement three times.

Find f_{avg} for the concave lens using results of Task 4 and Task 5. Find the optical strength of the concave lens (in dioptres).

Questions

1. What is a thin lens?

2. Make a schematic drawing for measurement of the concave lens focal length.

3. Make a schematic drawing for measurement of the convex lens focal length.

4. Prove the lens formula considering the lens refractive index and the curvature of its surfaces.

5. One piece of glass has a refractive index of 1.5, and the other one - 1.7. Of both glasses, the biconvex lenses are made of the same size and shape. Find the ratio of the focal lengths of these lenses.

6. Prove all the formulas used in the practical.

7. Is it possible to determine the focal length of a concave lens using a spotter scope only?

8. Is there a biconvex lens which has a negative optical power?

Practical 4.
STUDY OF THE MICROSCOPE

Equipment and accessories: microscope, objective micrometer, ocular micrometer, mirror with a slit, millimeter scale on a vertical stand, diffraction grating, glass plate.

Introduction

A microscope is an instrument that allows one to to see objects that are too small to be seen by the naked eye. It is an optical system that provides an imaginary magnified image of an object located relatively close to the first lens of the system. In most cases, the microscope is used in conjunction with the eye; with the combined effect of these optical systems, a real image of the object is created on the retina of the eye, greatly enlarged compared to the image seen by the naked eye. The ratio of the above images determines the subjective magnification of the microscope. For different observers, in view of the difference in the optical power of the eye, this increase may be somewhat different. Using the average (for different eyes) value of the distance of the best vision, it is possible to express the angular magnification of the microscope through its optical parameters:

$$MA = \frac{D \cdot \Delta}{f_1 \cdot f_2}, \tag{1}$$

where D is the optimal (best) vision distance, Δ is the tube length (i.e., distance between objective back focal plane and the focal plane of the eyepiece), $f_{1,2}$ are the focal lengths of the objective and eyepiece (ocular) lenses correspondingly.

The most important characteristic of a microscope is its resolving power, that is, the ability to separately represent two points of an object. The resolving power of a microscope, like any optical device, is limited by the finite dimensions of the wavelength of the light wave.
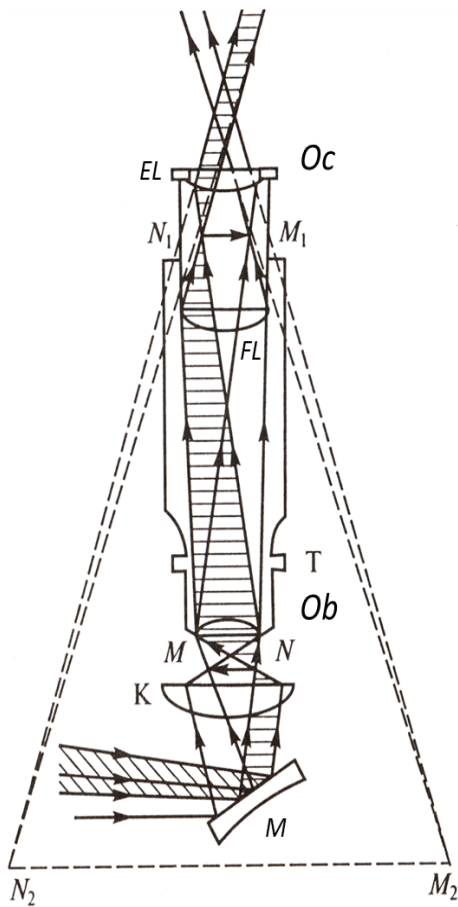
Description of the microscope

Figure 1: Schematic representation of an optical microscope.

The microscope (as shown in Fig. 1) consists of a tube *T*, in the lower part of which the objective lens *Ob* is located, and in the upper part an eyepiece (or ocular lens) *Oc* is installed. The objective lens is a system of lenses mounted into a single frame (in the figure shown as a single lens). The eyepiece consists of two collecting lenses mounted into a small tube. One of the lenses is called the field lens *FL*, and the other is called the eye lens *EL*. The tube of the microscope is located above the table, onto which the examined object *MN* is placed. Under the table is a mirror *M* so that the rays from any light source are directed through the condenser *K* to the object. The tube of the microscope with a screw is put in such a position, in which the object *MN* is located slightly further than the main focus of the lens. The real image of the object $M_1 N_1$ is formed at the other side of the lens. This image is viewed through the eyepiece of the eyepiece *EL*, which in this case works like a magnifying glass, creating an imaginary image $M_2 N_2$. Usually, a microscope has several objective lenses of different optical power; a convenient change of lenses is done with a turret device at the bottom of the tube. Accurate, calibrated movement of the tube is carried out using a micrometer feed.

Measurement and data processing

Task 1. Finding of the microscope subjective magnification

To determine the magnification of the microscope, place the objective micrometer on the microscope stage and adjust the focus that the micrometer scale is clearly seen. On the side of the microscope, place a vertical millimeter scale (25 cm apart). On the eyepiece of the microscope, place the inclined mirror with a slit so that you can simultaneously see the division of both the vertical scale and the objective micrometer. Counting the number of micrometer divisions that corresponds to a certain number of millimeters, find the desired increase (the scale of the objective micrometer scale is 0.01 mm).

Task 2. Determination of the ocular scale division value and the size measurement of a microobject

For measurements, between the eyepiece lenses, insert an ocular micrometer - a glass plate with a scale. Find the division value of this scale, using an objective micrometer (see the previous task). Further, place an object (for example, a diffraction grating) on the microscope stage instead of the objective micrometer and determine its characteristic dimensions.

Task 3. Measurement of the thickness of a glass plate

There are two marks scraped on the top and bottom surfaces of a glass plate. Focus the microscope so that you can see a distinct image of one of the marks (for example, on the bottom surface of the plate). Using a micrometric feed, move the tube and find a distinct image of the other mark. Find the translational movement of the tube using the micrometer feed scale. This translation corresponds to the optical thickness of the glass plate h_{opt}. The actual thickness h of the glass plate can be deduced knowing the refractive index of the glass n: $h = n \cdot h_{opt}$.

Questions

1. How to determine the lens magnification and the eyepiece magnification?

2. Why does the microscope objective usually consist of many (up to ten) lenses, and the eyepiece is usually made up of two lenses?

3. How should the ocular scale be positioned relative to the focal plane of the eyepiece and the image obtained with the lens?

4. Why is it impossible to determine the thickness of a glass plate, knowing only the movement of the tube?

5. Get an expression for the resolution of the microscope.

6. Indicate possible ways of increasing the resolution of an optical microscope.

Interference of Light

Practical 5.
NEWTON'S RINGS

Introduction

Placing a plano-convex lens on a polished glass plate, one can observe an interference pattern in the form of concentric rings, which are called Newton's rings after Newton, who initially observed such interference pattern. The radii of the rings can be related to the parameters of the interference scheme. Indeed, if the light falls normally to the surface of the glass plate, then the optical path difference Δ between the ray reflected from the spherical surface at the point *M* (Fig. 1.) and the ray passing through the point M after reflection from the plate is given by the following relation

$$\Delta = 2h_k + \frac{\lambda}{2} \tag{1}$$

where h_k - the thickness of the air gap in the given place (think about the reasons for the appearance of an additional path difference of $\lambda/2$).
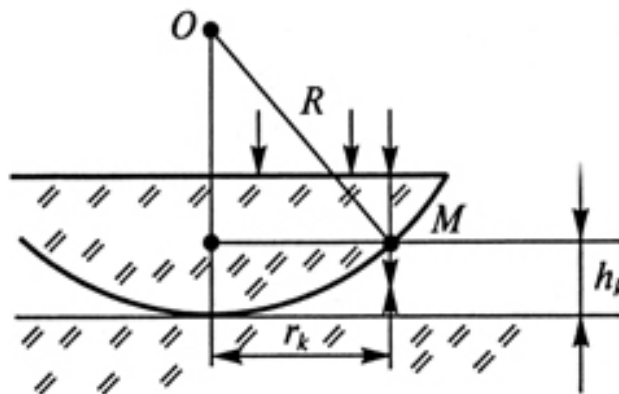

Figure 1: Formation of Newton's rings

Under the condition $R >> h_k$ one can derive the squared radius of the ring with the index *k*:

$$r_k^2 = 2Rh_k. \tag{2}$$

For a dark ring with index *k* (an interference minimum of the *k*-th order), the optical path difference at the point *M* is

$$\Delta = (2k-1) \cdot \frac{\lambda}{2}, k = 1,2,\dots \tag{3}$$

From equations (1), (2) and (3), one can obtain the radius of curvature of the lens as following:

$$R = \frac{\left(r_k^2 - r_i^2\right)}{\lambda \cdot (k-i)} = \frac{\left(d_k^2 - d_i^2\right)}{4\lambda \cdot (k-i)} \tag{4}$$

where *k* and *i* are the ordinal numbers of the dark rings in reflected light, which count from the center of the interference pattern (for the central dark spot *k* = 1).

Experimental setup

Experimental setup is depicted on the Fig. 2a. The experimental setup for the observation and measurements of Newton's rings was assembled on the basis of a microscope, the subject stage of which was replaced by a special holder 6 for mounting and moving the lens and the plate (Fig. 2b). The studied lens *1* is inserted into the movable round frame **5**. By changing the height of this frame above the stage with special screws **3**, it is possible to make the studied lens touch the glass plate in the holder. The displacement of the holder required for measurements is carried out with the aid of the screw **4**. The value of this displacement is measured on the scale of the micrometric indicator **7** with the accuracy of 0.01 mm. A small displacement of the table in the transverse direction (a precise tuning the microscope to the center of the interference pattern) is achieved with the help of the screws **2**. The picture of Newton's rings is observed in reflected light. To do this, use the so-called opaque illuminator - a translucent glass plate, mounted in the microscope tube.

The light beam from the light emission diode (LED) of a given wavelength falls on the vertical illuminator plate. Reflecting down from its translucent layer, the beam normally falls on the "lens-plate" system and is again reflected, thus ensuring the possibility of observing the interference pattern in the field of view of the microscope eyepiece.
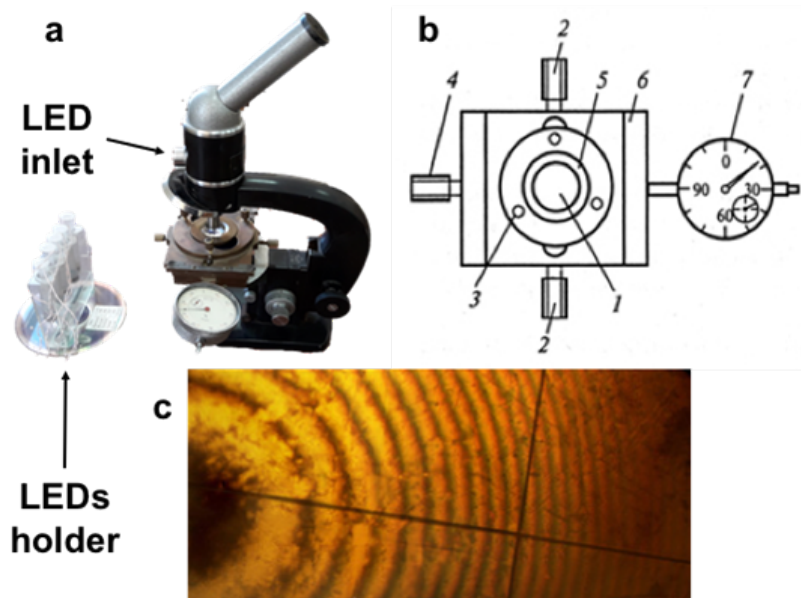
Figure 2: a – the image of the experimental setup; b – the schematic image of the lens holder; c – the interference fringes from the white light source with the cross pointer set to the k ring.

A cross pointer (Fig. 2c) of the eyepiece is placed in its focal plane, which makes it possible to determine the displacement of the certain point of the picture relative to the optical axis of the microscope. LEDs of different colors are used as light sources.

Measurement and data processing

Task 1. Setup adjustment

A key condition for correct measurements is a sufficiently bright and contrasting interference pattern. The following sequence of actions allows one to obtain such a picture. Rotating the screws 3, one can lower the frame so that the lens touches the glass plate (at the point of contact of the lens with the plate, one can see a small black spot - the central minimum of the interference pattern). Lowering the microscope tube with a micrometric screw, so that the objective lens of the microscope is ~ 5 mm above the lens, and adjusting the position of the LED source, ensure that the field of view of the microscope is uniformly and brightly illuminated. On the next step, gently (slowly!) raise the tube of the microscope until the interference fringes (Fig. 2c) appear in the field of view. First find the interference fringes, then tune position of the holder with screws 4 and 2, until you see the symmetrical interference pattern relative to the cross-pointer of the eyepiece. If the contrast of the picture is not sufficient, then one can play with the position of the LED holder in the microscope (this operation serves as an additional check of the correct position of the source).

One can proceed to the measurements of the radii of the rings, after checking that a sufficient number of interference rings is observable both to the left and to the right of the central interference minimum (with good tuning, at least 20 rings should be clearly observed). To reduce the relative error of measurements, it is recommended to measure the diameters of the rings by selecting rings of sufficiently large orders (at least 5-th order or higher), for example: $k = 10$, $i = 5$.

Task 2. Measurements of the radius of curvature of the lens

Measure radii and diameters of at least 15 rings for red (630 nm) and orange (590 nm) LEDs, for green LED (525 nm), blue LED (470 nm) and white light LED (440 – 640 nm) one need to observe the pattern of the Newton's rings and explain during the defense, why the measurements are done only for red and orange LEDs. After measuring the radii and diameters of the Newton's rings, one need to calculate the radius of curvature of the lens R using expression (4) for at least three different values of k and i and obtain the mean value of the radius of curvature R. The wavelength for the given LED is stated on the LEDs' holder. Record the results of measurements and calculations in a table. Estimating the errors of measurements of the radii of the rings, calculate the error of measurements for the radius of curvature of the lens R.

Questions

1. Under what condition will an interference maximum be observable in the reflected light at the point M (see Fig. 1.)?

2. How will the picture of Newton's rings, observed in the passing light, differ from the picture observed in the reflected light?

3. Compare the intensity of interfering light beams for two case: observations take place in passing light; observations take place in reflected light. In which cases will the picture be more contrast?

4. What will be observed if the lens is slightly raised above the glass plate? Check the answer experimentally.

5. Is it possible to use sufficiently long light sources in observations of Newton's rings?

6. How will the pattern of Newton's rings change, if one places the lens on the concave surface of the smaller curvature instead of the flat glass plate? Or if one places the lens on the convex lens with the same curvature instead of the flat glass plate?

7. How will the pattern of Newton's rings change, if the space between the lens and the plate be filled with water (the speed of light in the glass is lower than in the water)?

Practical 6.
STUDY OF TEMPORAL COHERENCE OF RADIATION

Equipment and accessories: a microscope, a lens in a special frame for the microscope objective, an incandescent lamp, gas discharge lamps (mercury lamp and sodium lamp), glass filters.

Introduction

To observe a steady-state interference picture, light waves must be coherent. Coherent light waves can be obtained from a light source with a thin glass plate. In that case an interference pattern is formed by two parts of a wave incident on a plate: a wave reflected from the first face of the plate and a wave reflected from the second face. However, an interference picture in a thin glass plate can only be observed in "white" light if the thickness of the plate is small enough, of the order of a few micrometers.

The radiation of any real light source does not represent an infinite sinusoidal wave. In that case it is convenient to use the concept of wave pulses of some finite length, the so called coherent wave trains. Individual trains are incoherent. In the case of a plate, interference is possible if two parts of the same train "meet", despite the difference in optical paths because of the thickness of the plate. The longer the train length, or the coherence length of the radiation, the thicker the plate that can be used to observe an interference pattern. In other words, the interference pattern can only be observed if the path difference does not exceed the coherence length of the radiation.

The coherence length is related to the spectral range of radiation. The narrower spectral range (the more monochromatic the radiation is), the greater the coherence length. In high precision optical measurements light is sufficiently monochromatic ($\Delta\nu \ll \nu$), and the coherence length:

$$l \approx \lambda^2/\Delta\lambda. \tag{1}$$

The corresponding propagation time is called the coherence time

$$\tau = l/c. \tag{2}$$

If you determine the optical path difference at which the interference pattern disappears, you can estimate the coherence length of the radiation, as well as the spectral range (the degree of its monochromaticity). These quantities characterize the temporal coherence of the radiation.

In Practical 6, it is proposed to use one of the classical interference schemes, Newton's rings (see the description of Practical 5). In contrast to the traditional scheme, the setup makes it possible to measure accurately the optical path difference between interfering light beams. Because of this, it is possible to estimate the temporal coherence of radiation produced by various light sources.

The objective of Practical 6: study the effect of temporal coherence of radiation from various light sources and estimate the spectral range of the radiation.

Experimental setup

Here, you need to use an incandescent lamp with a filter, a mercury lamp and a sodium lamp as sources of radiation.

It is necessary to become acquainted with the description of Practical 5 (Newton's rings). Referring to Fig. 1, the difference between the experimental setup, proposed in this Practical, and the traditional one is as follows. The lens L, from the lower surface of which the light wave 1 is reflected, is fixed in a special frame, which is put on the microscope objective. The glass plate II, on the surface of which wave 2 is reflected, lies on the stationary table of the microscope. After loosening screw B with the rim and lowering the lens before it comes in contact with the plate, it is possible to obtain a clearly visible interference pattern localized in the plane of contact of the lens and plate. After securing screw B and lifting the microscope tube with a micrometer screw, you can change the gap between the lens and the plate, Δ. Namely, this value Δ determines the optical path difference between interfering waves 1 and 2:

$$\Delta = 2h + \lambda/2. \tag{3}$$

If one neglects the additional path difference because of the difference in the reflection conditions of the waves at the glass-air and air-glass boundaries, it can be assumed that

$$\Delta \approx 2h. \tag{4}$$

Using the scale of the micrometer screw, it is possible to measure the gap size h and, consequently, the optical path difference Δ with a precision of 1μm.
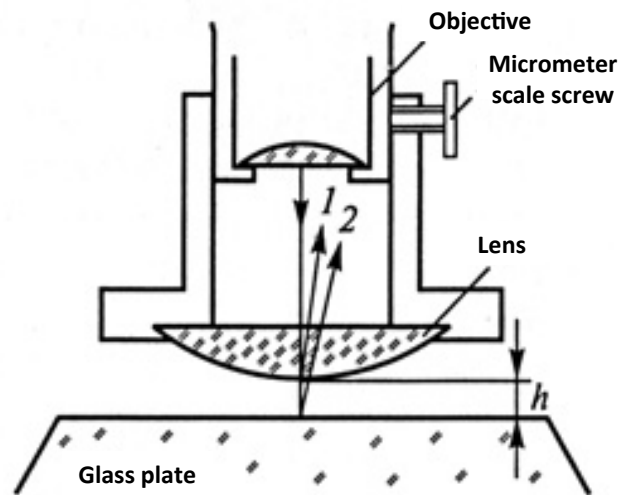
Figure 1: A schematic of the experimental setup

Measurements and data processing

Before proceeding with the measurements, you should adjust the experimental setup, following the procedures below:

1) Put the lens holder on the microscope lens, fix it with a screw and carefully move down the microscope tube until a very small (~ 0.5 mm) distance between the lens and the glass plate. After that, loosen the frame and let the lens slide down smoothly onto the plate.

2) Install the light source (an incandescent lamp) against the opaque-window and achieve uniform illumination of the field of view. It can be carried out conveniently without the eyepiece of the microscope. The correctness of the adjustment can be checked by changing the aperture of the diaphragm of the illuminator: this operation should not change the symmetry of the illuminated spot.

3) Without fixing the rims, gently move the tube of the microscope until the interference pattern appears in the field of view. Fix the position of the tube with a micrometer screw. If the contrast of the picture is not sufficient, the illumination from the incandescence lamp should be reduced. It can be changed by decreasing of the diaphragm aperture (the latter operation serves as an additional test of the correct position of the lamp).

4) When observing through the microscope, carefully fix the rim on the microscope objective not to knock down the achieved adjustment. Carefully move up the mi-

croscope tube with a micrometer screw. Upon this the rings of the interference pattern will "run", towards the center. Move down the tube and restore the original picture. After that start your measurements.

Task 1. Temporal coherence of the "white" light produced by an incandescent lamp

Obtain a picture of Newton's rings in "white" light. Use the incandescent lamp without a filter. Determine the gap at which the interference pattern disappears.

Task 2. Temporal coherence of the red-filtered "white" light produced by an incandescent lamp

Repeat measurements with a red filter.

What is the difference between the observed picture and the previous one?

Using the scale of the micrometer screw, measure the gap size h at which the interference pattern disappears.

Important remark: The assessment of situations "the picture is still visible" and "the picture is no longer visible" is quite subjective, so it is useful to repeat the procedure several times.

Calculate the coherence length l of the radiation under study and the corresponding width of the spectral range $\Delta\lambda$. The mean values of the wavelengths of the radiation sources are indicated in the specification.

Task 3. Temporal coherence of the light produced by the mercury and sodium lamps

Investigate the temporal coherence of the radiation of the mercury lamp with a filter and the sodium lamp in the same way (the parameters of the lamps: the current is of the order of $1A$).

The results of the measurements and calculations can be presented in the form of a table. The table must include the numbers of scale divisions n of the micrometer screw, the dimensions of the gap h, l and $\Delta\lambda$ for each source.

Draw a spectrogram in a suitable scale (about 1 mm = 1 nm). This spectrogram must show radiation bands in the spectrum of visible light that are occupied by the radiation of each of studied sources.

Questions

1. Derive the conditions of interference minima/maxima that appears at a given point of the field.

2. Is it possible to observe an interference pattern when you use a glass plate a few centimeters-thick and the best source in your experimental setup?

3. Can the light sources listed be considered coherent: (a) two incandescent lamps; (b) a lamp and its reflection in a mirror; (c) two slits illuminated by one lamp; (d) two lasers?

4. What are possible reasons for the difference in the level of temporal coherence of the radiation from an incandescent lamp and a gas-discharge lamp?

5. Estimate the maximum order of the interference maximum for the cases: (a) an interference pattern produced by an incandescent lamp (b) a mercury lamp.

6. What role does the spatial coherence of radiation play in the observation of interference patterns?

7. Propose a method that allows you to use the experimental setup in this practical for measurements of small displacements.

Practical 7.
YOUNG'S EXPERIMENT

Equipment and accessories: an incandescent lamp, a mercury lamp, glass filters, a diaphragm, lens, different double slits objects, glass plates, an eyepiece micrometer, an optical bench, polaroids.

Introduction

Referring to Fig. 1, two coherent light sources S1 and S2 produce an interference pattern on the screen parallel to the line connecting the sources. The distance between two successive interference maxima (or minima), usually called the fringe width Δx, can be calculated if the distance between the sources d and the distance from the sources to the screen L are known. Assuming that $L \gg d$ the fringe width Δx is

$$\Delta x = \lambda L/d, \tag{1}$$

where λ is the wavelength..

Figure 1: An interference pattern

In the case of real light sources, an interference pattern is not always observed. For example, two small electric light bulbs do not produce any interference picture. Even two very small slits illuminated by a single lamp does not guarantee an interference picture. One of the classical optical schemes that allow observing an interference picture is one proposed by T. Young. He used two small holes illuminated by a small or distant source. Using modern terminology, we would say that Young proposed a scheme that satisfies the conditions of spatial coherence.

Consider Young's scheme (Figure 2), in which the source is located at a relatively small distance from the two holes. Even in the case of an ideally monochromatic source, the interference pattern will only be observed if

$$b \cdot \sin(\omega) < \lambda/4, \tag{2}$$

where b is the spatial extent of the source (the size of the diaphragm), 2ω is characteristic parameter of the setup called the interference aperture.

Figure 2: Young's experiment

Practical 7 includes four parts. In *Part I* you study the dependence of the interference pattern on the parameters b and 2ω. The relationship between these parameters determines the level of the spatial coherence of the setup.

In *Part II* you study the influence of spatial coherence on the interference pattern.

Part III of Practical 7 is devoted to the effect of polarization of light waves on the interference pattern. It is usually assumed that the light waves under consideration are linearly polarized. However, even in the case of two linearly polarized waves, the result of their superposition depends substantially on the angle between the planes of polarization of these waves. It can be verified experimentally by covering the holes in Young's scheme with polaroids that convert natural light (incandescent lamps, gas-discharge lamps) into linearly polarized light of a given orientation.

In *Part IV* you study the effect of the degree of temporal coherence of radiation on the interference pattern. In the case of a real source, the interference pattern only will be observed if the optical path difference does not exceed the coherence length, L_c, of the radiation. As shown in Figure 3, if a glass plate of a thickness a and a refractive

index n is placed into the path of one of the light beams, an optical path difference is changed by

$$\Delta = a(n - 1). \tag{3}$$

In the case of a glass plate ($n \approx 1.5$), one obtains $\Delta = a(n - 1) \approx 0.5a$.
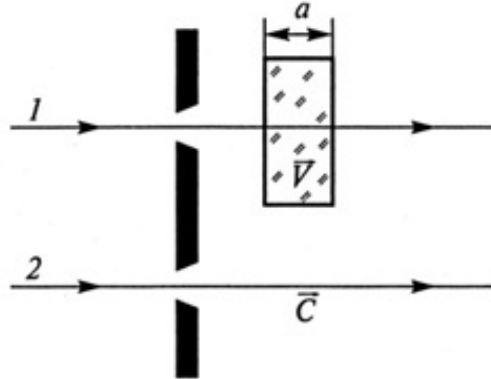

Figure 3: Study of the effect of temporal coherence on the interference pattern

The interference picture disappears when $\Delta > L_c$, which gives a value of the coherence time as $\tau_c = L_c/c$. As $\tau_c \sim 1/\Delta\nu$, one can estimate the spectral range of the radiation $\Delta\nu$, or $\Delta\lambda$ of different sources of radiation.

The objective of Practical 7: study of the dependence of an interference pattern on the parameters of the setup; estimate the degree of spatial and temporal coherence of radiation produced by different light sources.

Experimental setup

The experimental setup is presented in Figure 4. The light from an incandescent lamp or a mercury lamp (1) falls on the slit (2). The width of the slit b determines the size of the source and can be measured with a precision of 0.005 mm. To reduce the spectral range of the radiation between the source slit (2) and two slits (5), a glass filter (8) is placed. Two slits (5) are prepared in a photographic plate. The distance between the slits is indicated on the frame of the photographic plate. In front of the slits a Lens (4) is placed. The Lens (4) converges the light beams from the two slots to the observation point (6), located at a distance L from the slits. You should be able to observe the interference pattern by means of an eyepiece micrometer (7) with a precision of 0.01 mm. The slits objects, glass plates and polaroids are installed on an optical bench. The distance from the slit source to two slits l and from the slits to the observation point L is measured with an ordinary ruler.

Figure 4: Experimental setup

Ocular micrometer

An ocular micrometer is a glass disk that fits in a microscope eyepiece and has a ruled scale, which is used to measure the size of magnified objects (Fig. 5). The physical length of the marks on the scale depends on the degree of magnification. In this Practical a scale of a fixed glass plate consists of divisions which are equal to 1 mm. In the same plane there is a second glass plate (movable) with the cross K and the tics P. Rotating the micrometer screw, you can move the cross and the ticks relative to the fixed scale in the field of view of the eyepiece.

One complete turn of the micrometer screw is 1 mm. When you rotate the screw drum through one complete turn, the cross and the tics in the field of view of the eyepiece will move by one scale division, 1 mm. For counting the hundredths of a millimeter, the scale of the micrometer screw must be used. One division on the micrometer scale corresponds to 0.01 mm.

As an example, assume that the tics in the field of view are located between the 6th and 7th scale divisions of the ocular micrometer and the micrometer screw scale correponds to 21 divisions on the scale. In this case, the total reading is $6 + 0.21 = 6.21$ mm.

Figure 5: A schematic of the ocular micrometer

Measurements and data processing

Study of the dependence of the interference pattern on the parameters of the optical setup and determination of the radiation wavelength

Put the incandescent lamp in front of the source slit so that there is a bright image of the filament in the plane of the slit. With a source slit of a width of ~ 0.5mm and the lens, obtain an image of the slit on an auxiliary screen (for example, a sheet of white paper). Place the eyepiece micrometer at this point. You need to obtain a contrasting and bright image of the slit.

Install a filter behind the source slit, and observe the interference pattern behind the lens and a frame with two slits. If the contrast of the picture is not good enough, adjust the brightness and contrast of the picture by reducing the width of the source slit.

Measure the fringe width Δx and the distance L. For better accuracy, measure the width of several fringes and divide the result by their number. Perform similar measurements using another pair of slits ($d_2 > d_1$), and then change the distance L. *Why does the change of the two slits need to be accompanied by a change of the position of the Lens (4)?*

Task 1. Observation and study of the interference patterns

Calculate the mean value of the wavelength of the radiation transmitted through the filter in all cases. The results of the measurements and calculations must be presented in a table. The table must contain readings of the micrometer, the calculated values of Δx and λ for different values of L and d. You should also estimate the measurements errors Δx, d, L and $\Delta \lambda$.

Spatial coherence on the interference pattern

To perform this part of Practical 7, you need to know the parameters that affect the degree of spatial coherence, i.e. the width of the source slit b and the interference aperture 2ω. The width of the slit can be measured with a scale on the slit frame. The interference aperture can be determined from the distance between the source slit and two slits l (see Figure 4) and the distance between the slits d. If $d \ll l$, one can take $\sin(\omega) \approx \omega \approx d/2l$.

  You should perform the measurements according to the following procedure. Obtain a clear interference pattern with an object with a small (~ 0.5 mm) gap between the two slits. The distance l should be ~ 30 cm. Measure the values of l, b, d. Tracing the change in the form of the interference pattern, increase the width of the slit to the value at which the picture disappears completely. Record the corresponding gap width b. Move aside the frame with two slits from the source, it will result in an increase of the spatial coherence of the radiation incoming on the slit. Observe the changes in the picture and write down the position of the object (a new distance l), at which the picture becomes clearly visible. After that, without changing the width of the source slit b, increase the distance between two slits d and again make the picture disappear.

Task 2. Study of the influence of spatial coherence on the interference pattern

Write down all the measurements of l, d and b in the table and calculate for each case $b \cdot \sin(\omega) \approx bd/2l$. Compare the obtained values of $b \cdot \sin(\omega)$ with the previously calculated value $\lambda/4$ and formulate the criterion of observing the interference pattern in the experiment.

Influence of the polarization on the interference pattern

For this task you need an object with a large enough distance between the two slits ($d \sim 3$ mm). Obtain a clear visible interference pattern as in the previous tasks. Insert the polaroids into the frame of the object table. The orientation of the polaroid axes is indicated on the frame.

Task 3. Study of the influence of the polarization on the interference pattern

Closing the slits with the polaroids (first close slits with differently oriented polaroids, and then both slits with one polaroid), observe the change in the picture. Record the results for cases with different polaroid orientations.

Estimation of the degree of the temporal coherence of the radiation from various light sources

In this experiment, the same optical setup is used as in the previous task, but instead of the polaroids, the slits (first one slit and then both slits) are covered with a glass plate of a known thicknesses.

Task 4. Coherence length of the incandescent lamp

Find the thickness of the plate at which the interference pattern disappears, and estimate the coherence length of the incandescent light with a green filter.

Task 5. Coherence length of the mercury lamp

Replace the incandescent lamp by the mercury lamp with a filter centered at $\lambda = 546$ nm. Repeat the same procedure as in Task 4, estimate the coherence length of the mercury lamp.

Questions

1. How will you achieve the necessary degree of spatial and temporal coherence in the following interference schemes: (a) Fresnel's double mirrors (b) Fresnel's double lens (c) Newton's rings (d) a plane-parallel plate (e) Michelson's interferometer?

2. Is it possible to change the degree of spatial coherence of radiation without changing its spectral range?

3. Why are rainbow rings visible only in the case of very thin films (for example, gasoline on water)?

4. Are there radiation sources with a coherence length of a few kilometers?

5. Estimate the coherence length of the radiation produced by a radio source if its relative frequency stability is $\Delta\nu/\nu \approx 10^{-6}$, and $\lambda = 30$ m.

6. State possible reasons of the observed difference in the coherence lengths of two sources.

Practical 8.
YOUNG'S EXPERIMENT WITH A LASER

Equipment and accessories: a helium-neon laser, an incandescent lamp, a red light filter, a $40\times$ microlens, a lens with f=20 cm, an objective with f=10 cm, a table with frames for objects, glass plane-parallel plates, polarizers, a measuring microscope, an ocular micrometer, a set of objects slits, a set of pinholes).

Introduction

Figure 1: General setup of Thomas Young's Experiment.

Young's interference experiment, also referred to as Young's double - slit interference, was the original version of the modern double-slit experiment. A general schematic of the double-slit interference experiment is shown in Fig. 1. The experiment was originally performed by Thomas Young in the beginning of the nineteenth century providing an immense support for the wave nature theory of the light.

Using an initial pinhole *a* as the primary light source, Young created a spatially coherent beam that could identically illuminate the two apertures *b* and *c* which are spaced apart by a gap *d*. As a result, a system of alternating bright and dark bands (referred to as the interference fringes) was observed on a screen *F*. Denoting the distance between the two coherent light sources and the screen as *L*, and separation between the bright (or dark) fringes on the screen as Δx, one finds that for a given wavelength of the light λ:

$$\Delta x = \frac{L\lambda}{d}. \tag{1}$$

Figure 2: Experimental setup

   The first part of the Practical involves calculation of the wavelength of the laser by measuring the distance between the interference fringes. In the second part of the Practical, the effect of the polarization of light waves on the result of their superposition is investigated. The third part is devoted to a comparative evaluation of the temporal coherence of radiation from various light sources: a filament lamp with a red filter and a helium-neon laser given that the average wavelength of the radiation from these sources is approximately the same.
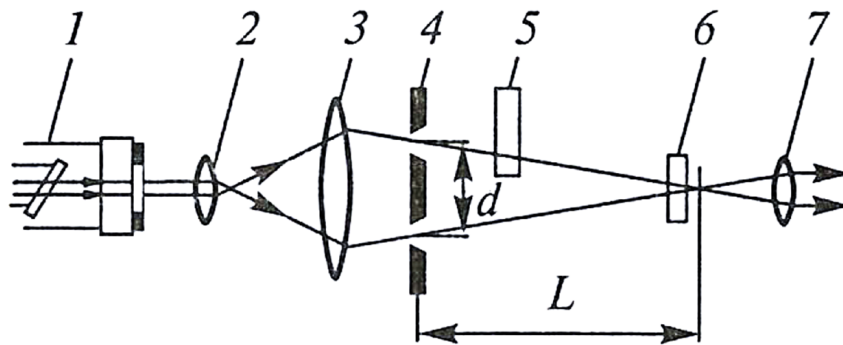
Experimental setup

The experimental setup is assembled onto an optical bench and is depicted in Fig. 2. As the light source, a helium-neon laser *1* is used. The laser beam is widened by a lens-system which includes a micro-objective *2* providing $40\times$ magnification and objective *3* an with a focal length *f = 110 mm* . Directly behind the lens is placed a table with a frame for objects *4* (which are pinholes in a foil or black paper). The table is followed by a pair of polarizers with the polarization angle adjustable by a rotating frame. A piece of glass *5* may be introduced into either of the two optical patches. The interference pattern is observed with the aid of an ocular equipped with a micrometer *7*, which makes it possible to measure the necessary distances with an accuracy of 0.01 mm. Ocular micrometer is depicted in Fig. 3.
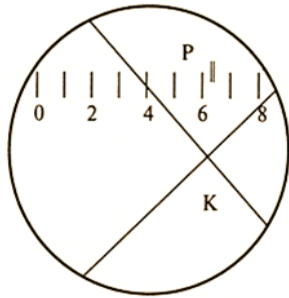
Figure 3: Ocular micrometer.

Ocular micrometer measures the size of the image of an object. In the focal plane of the eyepiece of the micrometer is located a fixed glass plate with a scale, each division of which is equal to 1 mm. In the same plane is placed a second - movable - glass plate with the cross *K* and the parallel risks *P*. With the rotation of the micrometer's thimble, the cross and the risks move in the field of view of the eyepiece relative to the fixed scale. One complete revolution of the thimble corresponds to rectilinear movement of 1 mm. One division on the circular scale on the thimble is 0.01 mm. Hence, the rectilinear displacement should be read using both scales.

To reduce the brightness of the observed patterns, an additional polarizer *6* is placed in front of the ocular micrometer. (The minimum of light transmission corresponds to the lower position of the red dot on the frame).

For the third part of the practical, an auxiliary setup assembled on the same table is used. It includes an incandescent lamp, a red filter, a slit, an objective, a table with a frame for objects and an ocular micrometer.

Attention! When working with a laser, the following precautions should be taken:

1. Do not turn the laser *on* or *off* by yourself. **The laser is always on!**

2. Never look at the laser beam by a naked eye as it may be extremely dangerous for the eye.

3. Before you start the observations with the ocular micrometer make sure that the pinholes are installed into the laser beam and that the intensity of light transmitted by the polarizer *6* is minimal (using a sheet of paper placed in front of the ocular).

4. Before removing the object *4* or altering its position, make sure that no one is looking into the micrometer eyepiece.

Measurement and data processing

Task 1. Determination of the laser wavelength

1. Check on the setup. Observe a bright and uniformly illuminated circle with a diameter of ~ 20 mm using a piece of paper placed behind the lens **3**. Moving the paper away from the lens, make sure that the light beam converges to a point approximately in the focal plane of the ocular.

2. Using a microscope, measure the distance d between the pinholes.

3. Insert the object into the frame **4** and make sure that the position of the polarizer **6** corresponds to the minimum of light transmission. Observe the interference pattern. If the brightness of the picture is insufficient, increase it rotating the polarizer.

4. Measure (for the selected pair of pinholes, e.g., object #*1*) the distance between the interference fringes Δx and the distance from the pinholes to the observation point L which is the ocular micrometer frame facing the light. In order to improve accuracy of the measurement, measure the width of *N = 10, 20, 30* fringes and then calculate Δx. Repeat the measurements by placing the micrometer at a different distance from the object.

5. Perform similar measurements by taking another pair of pinholes (object #*2*) with a different distance between them.

6. Knowing d, L, and Δx, calculate the wavelength of the laser for all cases. Tabulate the measurement results. Estimate the measurement error $\Delta \lambda$.

Task 2. Investigation of the wave superposition depending on their relative polarization angle

Use a pair of pinholes separated by ~ 10 mm. Set a pair of polarizers onto the optical bench after following the pinholes so that the light beams emerging from the pinholes pass through different polarizers. Rotating their frames, observe the change in the intensity of the beams, find the position in which the beam intensities are maximal (the polarizers' axes are parallel to the direction of the electric field of the laser beam). After this, it is useful to verify that the laser radiation is linearly polarized: when the polarizers are rotated by $90°$, the intensity of the beams should become minimal.

Attention! For all further observations, the installed pinholes **MUST NOT** be removed from the optical bench!

Rotating the polarizers (one clockwise and the other counter-clockwise), note the difference in the pattern for cases where the angle between the polarizers' axes is $0°$, $30°, 50°$, and $90°$. Investigate the observed pattern dependence on the orientation of the third polarizer placed in front of the eyepiece.

Task 3. Study of the temporal coherence of light irradiated by different sources

Turn on the incandescent lamp and observe the interference of the radiation transmitted by the red filter. Here, the Young scheme with the two slits is implemented because of a comparatively low brightness of the source. Nevertheless, this does not alter the experiment principally. In the path of light after the slots, place the thinnest glass plate. Overlapping one slit first, and then both, observe the changes in the interference pattern.

Knowing the thickness and refractive index of the plate, and taking into account that the optical path length (OPL) or optical distance is the product of the geometric path, and the index of refraction of the medium (i.e., $OPL = \ell_{geom} \cdot n$), estimate the coherence length of the radiation transmitted by the red filter.

Perform similar operations using the former setup. Use glass plates of different thicknesses (up to 40 mm). Estimate the coherence length of the laser radiation and compare the result with that of the incandescent lamp. Compute the temporal coherence for both of the sources.

Questions

1. What kind of interference pattern will there be from two coherent point sources if one observes it on a screen whose plane is perpendicular to the line connecting the sources?

2. What will be the picture if the plane of the screen is parallel to this line?

3. Estimate the size of the source, which makes it possible to observe the interference pattern from two holes spaced 20 mm apart and located 10 cm from the source.

4. Is it possible to observe the interference of laser radiation by applying a plane-parallel plate several centimeters thick?

5. Estimate the coherence length of the laser radiation if the obtained interference pattern ceases to be clearly visible when the path difference of the interfering beams reaches 10 m.

6. Is it possible, using the radiation of a heated body, to achieve the same degree of spatial coherence as in the case of laser radiation?

PRACTICAL 9.
DETERMINATION OF THE WAVELENGTH   *INTERFERENCE*
OF THE LIGHT WITH SPLIT LENS AND DOUBLE PRISM   *OF LIGHT*

Practical 9.
DETERMINATION OF THE WAVELENGTH
OF THE LIGHT WITH SPLIT LENS AND DOUBLE PRISM

Introduction

To observe interference of light, a number of schemes are used. Such schemes usually divide a light beam from one source into two beams (by means of reflection or refraction) and forced those beams to meet again after they have travelled along different optical paths. Such interference schemes are based, in particular, on Billet split lens and Fresnel double prism.

Split lens is a thin positive lens, cut in half. Half-lenses are displaced (in the plane of the lens) relative to each other so that two spatially separated optical centers are obtained. In this case, half-lenses give two imaginary or real images of the source S, which serve as coherent light sources S_1, and S_2 (Fig.1a).

Double prism consists of two prisms with small refractive angles, which located very close to one another. The light beam incident on the double prism from the slit, due to refraction in the double prism, is divided into two intersecting beams, as if emanating from two imaginary images of the slit S_1, and S_2, (Fig. 1b). In the region of intersection of the beams behind the prism, an interference pattern will be observed.

Knowing the distance between the sources d, the width (bandwidth) of the interference fringe x and the distance from the sources to the screen L, one can determine the wavelength of the light in accordance with the known formula:

$$\lambda = \frac{\Delta x \cdot d}{L}, \ \ (L \gg d). \tag{1}$$

Experimental setup

On the optical bench, the illuminator (incandescent lamp with condenser) and the slit diaphragm playing the role of the source are arranged in series. The small width of the slit provides the necessary spatial coherence. A sufficiently high degree of temporal coherence of radiation is achieved by means of a light filter that cuts out a relatively narrow frequency interval from the emission spectrum. The frame with replaceable filters is located directly behind the slit diaphragm. Split lens or double prism in the frame, allowing for the necessary adjustment and adjustment, is installed into a special holder. To observe the interference pattern, as well as to measure the bandwidth and distances between coherent sources, an ocular micrometer is used. In the case of working with a double prism, an auxiliary convex lens is placed in front of the micrometer. The distances between the plane of the source images and the plane of observation of the picture are measured using a ruler.
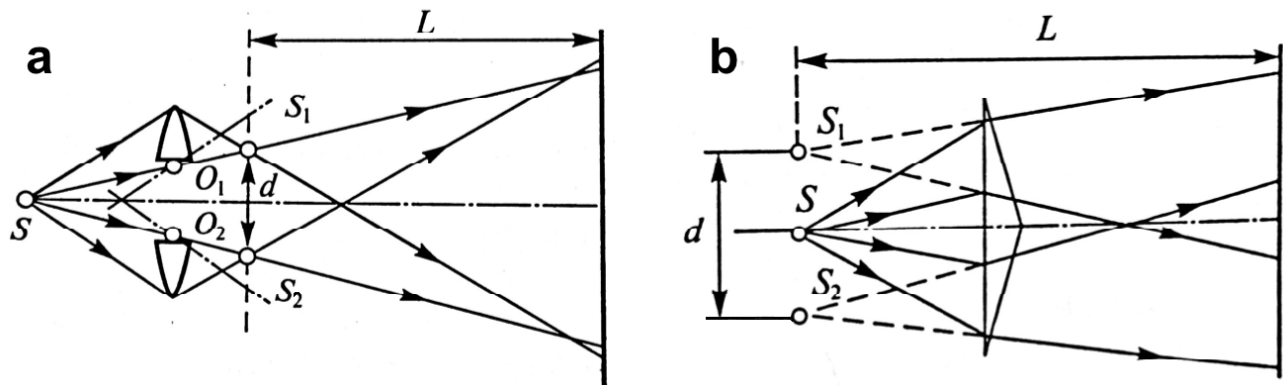

Figure 1: a - Ray tracing using the Billet split lens; b – Ray tracing using the Fresnel double prism.

Measurement and data processing

Task 1. Split lens setup adjustment

Observation of an interference pattern using split lens (see Fig. 1a) requires careful tuning of the experimental setup. To observe an interference pattern, one needs to ensure that the optical system is centered: the slit diaphragm should be located along the diameter of a bright and uniformly illuminated circle - the cross section of the light beam; the axis of the light beam must pass exactly between the halves of the split lens and through the ocular micrometer.

To obtain valid images of the source slit, the split lens should be placed at some distance (usually larger than 2F) from the slit.

After preliminary alignment of the system, adjusting the position of the lenses in the frame with the appropriate screws, one should get two symmetrically arranged (relative to the vertical) and equally bright images of the slit on the auxiliary screen (a piece of paper).

At the point where the actual images of the sources are obtained, install the eyepiece micrometer and observe the enlarged images of the two sources (the distance between them should be measured after the interference pattern is obtained and the bandwidth is measured).

Move the ocular micrometer until the images of the slits overlap each other. If, in this case, no characteristic interference fringes appear in the field of view, then keep observing, while gently adjust the position of the half-lens with the screw at the top of the rim. The contrast of the resulting picture can be increased by decreasing the width of the slit. If the interference fringes are too narrow, the micrometer should be moved away or the images of the slit should be moved together with a careful rotation of the screw located on the side of the split lens frame.

Once a distinct interference pattern is obtained, the bandwidth should be measured. To improve the accuracy of the result, it is advisable to determine the length of a segment containing several bands on the micrometer scale, and by dividing the obtained value by the number of bands, find the width of the strip x.

One should move the cross pointer of the ocular micrometer very gently, since strong pressure on the micrometer body can easily lead to a shift in the field of view. During this measurement, the micrometer drum (knob) rotates only in one direction.

After recording the position of the ocular micrometer on the centimeter scale, move it to the place where the sharp images of the sources are visible, and, observing the precautions listed above, measure the distance d between them.

The distance between two positions of the micrometer (in one of which the images of the sources are considered, and in the other the interference pattern) is obviously equal to *L*, that is, the distance between the coherent sources and the location of the interference pattern.

Task 2. Determination of the wavelength of the light with the split lens

Repeat the measurements of *x* several times and determine the average value of the bandwidth. Change the light filter and repeat the same set of measurements for another average wavelength of the light.

Put down the measured data of *d* and *L* in the table and, using the expression (1), calculate the required average wavelengths 1 and 2 for measurements with two difference light filter. Estimate the relative error and write the measurement results in the form: $\lambda_{exp} = (\lambda_{aver} \pm \Delta\lambda)$ nm.

Task 3. Double prism setup adjustment

If the interference pattern is observed with the help of a double prism (see Fig.1b), two imaginary images of the slit S_1 and S_2 serve as coherent sources. Due to small values to refractive angle of each of the prisms, which form the double prism, we can assume that the images S_1 and S_2 lie in one plane with a slit. This circumstance makes it easy to determine the distance from the sources to the place of observation. The optical system (a slit, a double prism, a micrometer) is centered in the same way as a system with a split lens. One need to pay attention to the position of the double prism, which should be parallel to the source slit. To get the necessary parallelism, one need to observe the source slit through the double prism (with a bare eye) and adjust the position of the rim of the double prism around the horizontal axis, until the desired parallelism is achieved (the images of the slits should be located symmetrically with respect to the vertical). The interference pattern is observed with a micrometer. If the picture is not clearly enough, slightly turn the frame of double prism. The contrast of the picture depends, of course, on the width of the slit. Measurement of the width of the strip *x* is carried out in the same way as in the **task 2** of the work.

To measure the distance between the sources, a convex lens is used. Using this lens, we obtain real images of the sources and measure (as in the **task 1**) the distances between them on the scale of the ocular micrometer. The distance between the imaginary sources *d* can be calculated by measuring the distances from the slit to the lens and from the lens to the focal plane of the micrometer (it is recommended to draw a picture, which traces the beams according to the laws of geometric optics).

PRACTICAL 9.
DETERMINATION OF THE WAVELENGTH   *INTERFERENCE*
OF THE LIGHT WITH SPLIT LENS AND DOUBLE PRISM   *OF LIGHT*

Task 4. Determination of the wavelength of the light with the double prism

Make the necessary measurements to determine the wavelength. Put down the results of two series of measurements (for two light filters) into the table. After evaluating the error, record the results of two series of measurements in the form:
$\lambda_{exp} = (\lambda_{aver} \pm \Delta\lambda)$ nm.

Questions

1. Where should one look for an interference pattern, if the lens is cut into halves and those half-lenses are separated from each other?

2. How should one locate half-lenses to make an interference pattern unobservable?

3. Is it possible to use a lens with a strip of black paper pasted over its diameter as the split lens?

4. Give several examples of interference schemes in which the dimensions of the source can be relatively large.

5. Compare the interference patterns obtained with the proposed setups, equipped with light filters, with the interference patterns obtained in the white light.

6. What means provide a sufficient degree of spatial coherence in experiments with double prism and split lens?

7. How can one simplify the experimental setup with double prism (split lens), if radiation of a very high degree of coherence (laser radiation) is used?

Diffraction of Light

Practical 10.
FRESNEL AND FRAUNHOFER DIFFRACTION

Introduction

The difference between Fresnel diffraction (near-field diffraction) and Fraunhofer diffraction (far-field diffraction) is determined by the position of the observation point with respect to the object at which diffraction of light occurs (diaphragms, screens, etc.). Let's consider a diffraction of light on an aperture of radius R, as depicted in Fig. 1. If the observation point O is located relatively close to the hole, or more precisely, if

$$b \leq \frac{R^2}{\lambda}, \tag{1}$$

(b is the distance from the aperture), then one says that the conditions for observing the Fresnel diffraction are satisfied. In this case, at least one Fresnel zone is placed in the hole:

$$R \geq \sqrt{\lambda \cdot b}, \tag{2}$$

$((\lambda b)^{0.5}$ is the radius of the first Fresnel zone under condition: $a \to \infty$).
In case when

$$b \gg \frac{R^2}{\lambda}, \tag{3}$$

for which the radius of the first Fresnel zone $(\lambda b)^{0.5}$ is much larger than the radius R of the aperture, then one speaks of the Fraunhofer diffraction.

Part 1. Fresnel diffraction

Figure 1: Schematic of the diffraction

In the first part, the diffraction of light waves on a circular aperture is studied, while the choice of the observation point satisfies condition (1).

$$n = \frac{R^2 \cdot (a + b)}{\lambda \cdot a \cdot b}. \tag{4}$$

Calculating the number of zones n (from the diffraction pattern) and measuring the distances a and b, one can calculate the wavelength λ of the light wave.

Experimental setup

The scheme of the setup is shown in Fig.2. Light from the source (a mercury lamp *1*) with a light filter *2* is converged by means of a condenser *3* into a very small circular hole *4*, which acts as a point source *S*. The hole *4* is made in aluminum foil and installed in a special frame on the tube. A cover *5* with a circular diffraction aperture of radius *R* is put on the opposite end of the tube.

The positions of the lamp, condenser and tube on the optical bench are fixed while tuning the setup, so one can not change them during operation. The diffraction pattern is observed with the help of the eyepiece *6*, which can be moved along the optical bench. The eyepiece holder has a pointer that allows measuring the distance *b* along the ruler (with accuracy up to 1 mm).
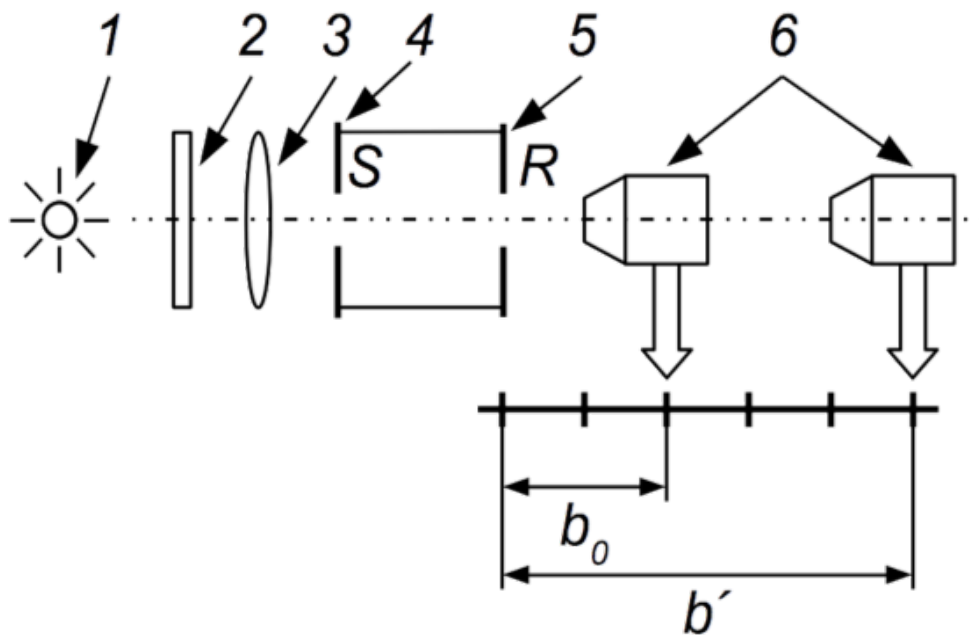

Figure 2: Observation of the Fresnel diffraction

Measurements and data processing

Turn on the mercury lamp, following the proper procedure, which should be familiar to the student from ***practical 6***. Put a light filter in the path of the light beam, which allows to extract from the emission spectrum a known wavelength λ; the value of λ is indicated on the light filter. Put a diffraction aperture **5** of radius R on the end of the tube, moving the eyepiece along the optical bench, observe the change in the diffraction pattern.

First, move the eyepiece to the end of the optical bench and then push it closer to the aperture; mark the position of the eyepiece at which the dark point (two Fresnel zones are open) appears for the first time in the center of the picture. Pay attention to the individuality of each picture

Task 1. Determine the radius of the diffraction aperture

Using previously defined values of b' and b_0, one need to calculate the values of $b = b' - b_0$ which correspond to all observed patterns. Knowing a, λ and the number of open zones n, one can calculate for each n the radius R of the aperture from the equation (4). The value of a is indicated on the setup.

Task 2. Determination of the passband of the light filter

Using the light filter with the unknown passband (the wavelength, which passes through the filter) and the radius R from task 1, one need to repeat the set of measurement from task 1 and determine from the equation (4) the passband of the filter. Put down the results in a table. The report must contain drawings of the observed patterns corresponding to two, three, etc. open Fresnel zones.

Part 2. Fraunhofer diffraction

Experimental setup

The scheme of the setup is shown in Fig. 3. The light source *1* is the same mercury lamp as in the Part I. The filter *2*, the condenser *3* and the inlet *4*, which plays the role of a point source, are made in a very similar way. To obtain a parallel light beam, the inlet *4* is located exactly in the focus of the lens *5* mounted at the end of the tube. Various diffraction objects can be placed on the lens rim *6*: a circular aperture, a rectangular slit, a set of circular apertures, etc. Diffraction patterns are viewed through the telescope *7*, tuned to infinity. The visual tube of the telescope is equipped with an ocular micrometer *8*, which makes it possible to measure the necessary distances while observing diffraction patterns. The displacement of the cross-pointer of the micrometer can be measured on its' scale with an accuracy of 0.01 mm.
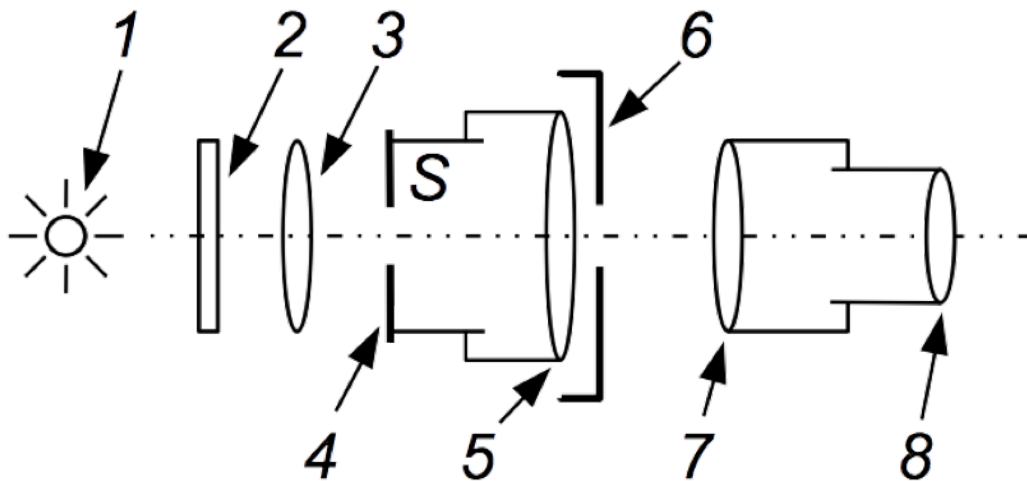

Figure 3: Observation of the Fraunhofer diffraction

Measurements and data processing

Tighten the telescope *7* in the stand mount so that a bright and sharp image of the inlet is visible in the center of the field of view. Make sure that the cross-pointer of the micrometer can be placed by rotating the drum exactly on the image of the inlet. The collimator - the tube with an inlet *4* and a lens *5* is already tuned to infinity and can not be adjusted.

Task 1. Observation of diffraction for a single circular aperture

Place a light filter in front of the condenser *3* and mount the iris diaphragm on the lens rim. Gradually changing the aperture opening, observe how the image of the inlet changes due to the light beam restriction. Put a cover with a single circular aperture on the lens rim and draw the observed picture into the notebook. Repeat the same procedure with a rectangular slit. Indicate the orientation of the rectangular slit, next to the diffraction pattern. The comparison of the figures should show which side of the rectangle slit corresponds to the high alternation frequency of the diffraction maxima.

Task 2. Observation of diffraction on a set of circular apertures

Put a cover with a lot of randomly located round apertures on the lens rim - the usage of such an object will allow observing a diffraction pattern, almost identical to the picture from a single circular aperture, but with much greater illumination.

Tune the cross-pointer of the micrometer to the different parts of the diffraction pattern and measure the positions of the maxima and minima of light illumination by recording the corresponding number of divisions on the ocular micrometer scale. Using the proper equations for the case of diffraction of plane waves on a circular aperture, one need to determine the wavelength of the light wave transmitted through the light filter from the mercury lamp emission spectrum:

for minima:
$$R \cdot \sin\left(\varphi\right)\big|_{\text{min}} = 0.61\lambda; 1.12\lambda; 1.68\lambda, \tag{5}$$

for maxima:
$$R \cdot \sin\left(\varphi\right)\big|_{\text{max}} = 0; 0.81\lambda; 1.33\lambda; 1.85\lambda. \tag{6}$$

The ocular micrometer allows one to measure the linear dimensions of a picture lying in its' focal plane. To find the sine of the diffraction angles, one needs to take the ratio of the displacement of the cross-pointer Δx to the focal length of the objective lens of the telescope:

$$\sin(\varphi) \approx \tan(\varphi) = \frac{\Delta x}{f}, \tag{7}$$

The radius of the aperture R and the focal length f of the telescope objective lens are indicated on the setup. Record the results into a table.

Questions

1. Is it possible to observe diffraction patterns on apertures of radii of the order of several centimeters?

2. How will the diffraction pattern change, if an opaque obstacle with an aperture of radius R in a Fresnel's setup is replaced with a transparent obstacle with a black circle of the same radius R?

3. How many Fresnel zones have been opened after an aperture, if the bright spot appeared in the center of the pattern for the first time after the dark point?

4. Why is the telescope used in the Fraunhofer diffraction setup instead of the eye-piece?

5. How will the diffraction pattern change if the telescope, which is tuned to infinity, is moved away from the lens?

6. How will the diffraction patterns differ for apertures of different radii?

7. Carefully examine the diffraction pattern from a set of apertures and comparing it with the diffraction pattern from a single aperture, one can notice some difference in those patterns (besides a significantly different in illumination). What is the difference between those patterns? How can one explain this difference?

Practical 11.
DIFFRACTION OF LASER RADIATION

Equipment and accessories: For *Part I* - a helium-neon laser, concave lenses, a set of different objects for observing diffraction.
For *Part II* - a collimator, a cylindrical lens, an objective, a telescope, a polaroid, an ocular micrometer, a set of various objects.

Introduction

The high degree of coherence of laser radiation gives us an excellent opportunity to study diffraction phenomena. The results of experiments with lasers are very clear and easily reproducible. In this case it is easy to overcome the limitations related to the size of the source, the size of the diffraction object in comparison with the distances at which a diffraction pattern can be observed.

In the case of diffraction of a plane wave on a single slit of width b (Fraunhofer diffraction), interference (diffraction) minima are observed in directions determined by the condition

$$\sin \phi_{min} = \lambda/b; 2\lambda/b; .. \tag{1}$$

In Fig. 1, the dashed line shows the intensity distribution in diffraction at one slit for the central part of the picture (between the minima of the first and the minus first order).

The intensity distribution in diffraction on two parallel slits of width b with centers located at a distance d, is presented in Fig. 1 by a solid line.

The maxima of diffraction on two slits are observed along the directions determined by the distance between the slits:

$$\sin \phi_{max} = \lambda/d; 2\lambda/d; .. \tag{2}$$

The number of minima M, that cover the central maximum of diffraction on one slit, is equal to

$$M = 2[d/b]. \tag{3}$$

The number of maxima observed in the region of this central maximum exceeds the number of minima:

$$L = M + 1 = 2[d/b] + 1. \tag{4}$$

In the case of diffraction by three or a greater number of slits (at constant d), the position of the maxima determined by expression 2 remains unchanged, so they are called the main maxima. An increase in the number of slits results in the appearance of additional maxima and minima between the main maxima. The number of maxima increases in proportion to the number of slits N.

Practical 11, *Part I* proposes the study of diffraction of laser radiation by objects of simple forms (a slit, a circular hole, etc.). In *Part II*, you will observe a change in the number of additional maxima, as well as the width and intensity of the main maxima with an increase in the number of slits. The final experiment is the observation of a diffraction pattern by a diffraction grating.
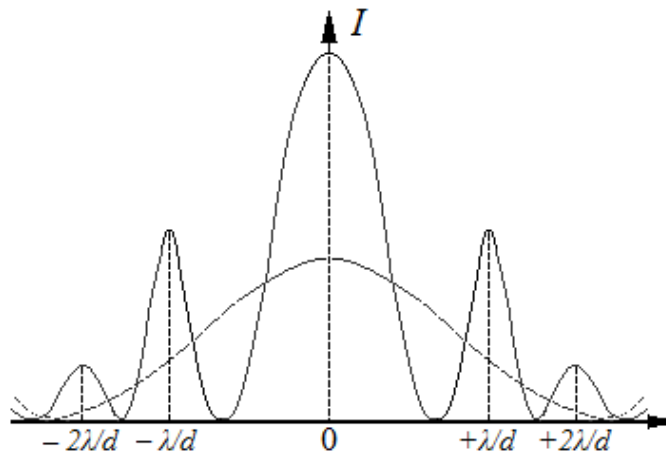
The objective of Practical 11: Observation of diffraction of laser radiation by objects of the simplest configurations.

Experimental setup

A schematic of the experimental setup used in *Part I* is shown in Figure 2. The helium-neon laser is used as a source. To observe Fraunhofer diffraction, the laser beam is used without any additional transformation. To observe Fresnel diffraction, the beam is made divergent by means of the Lens *2*. Diffraction patterns are observed on the Screen *4*. The Lenses, the Screen and the Holder *3* for diffraction objects are installed on the optical bench in rheaters. The rheaters can be moved along the optical bench for achieving the best observation conditions.
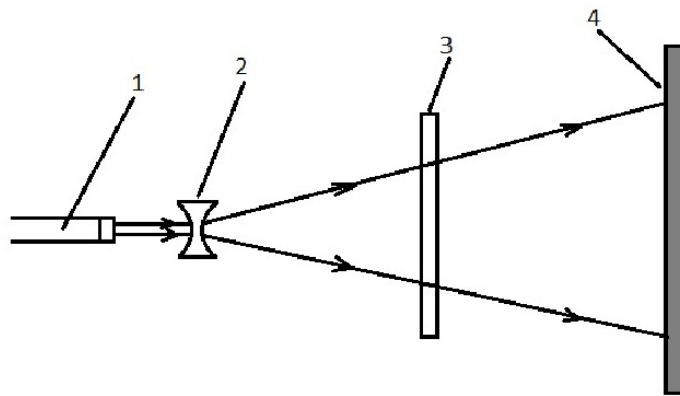
Figure 2: A schematic of the experimental setup for observation of diffraction by simple objects

A schematic of the experimental setup used in *Part II* is shown in Figure 3. A laser beam with a collimator *2* (a telescope is set to infinity) is converted into a wide parallel beam. To investigate diffraction phenomena at slit-type objects, you should use a cylindrical lens *3* and an objective *4*. It allows to obtain a "narrow" light source parallel to the slit. After the Collimator *2*, the plane front of light waves is transformed by the Lens *3* into a cylindrical one. In the focal plane of this lens, the light beam is compressed into a narrow vertical strip, which serves as a source. It is useful to verify the conversion of the light beam by moving a sheet of white paper between Lens *8* and Lens *4*. Using a cylindrical lens allows you to dispense with a real slit diaphragm. Behind the cylindrical lens *8*, you should place Lens *4* at a distance equal to the sum of the focal lengths of the lens and the objective (the positions on the bench of the lenses are fixed). At some distance from Lens *4* the beam is converged into a narrow horizontal strip. Here, you should place the diffracting object *5*. Since in this position a small area of the slit or grating is illuminated and the object defects do not affect on the quality of the diffraction pattern.
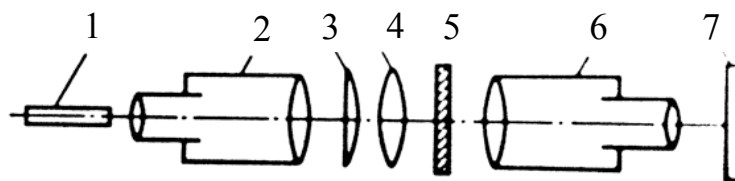

Figure 3: The experimental setup for observation of Fraunhofer diffraction on two or more slits

A diffraction pattern is observed in the telescope b with an eyepiece micrometer. For example, you can obtain the diffraction pattern from the slit (or from the grating) in the field of view of the tube by measuring the distances between the maxima. If you know the focal length of the tube objective and the width of the slit (or the grating period), you can determine the wavelength of the light.

To reduce the intensity of linearly polarized laser radiation, you should use the polaroid **7** fixed on the eyepiece of the telescope **6**. It is forbidden to start observations in the telescope without checking first that the polaroid is installed at an angle that ensures the minimum of light passing. When changing of a diffraction object, you should temporarily stop observations in the telescope. Before observations with a new object, you should again check the polaroid setting for minimum illumination.

The laser can only be switched on and off by a lab assistant or a teacher.

Measurements and data processing

Task 1. Observation of Fraunhofer diffraction patterns produced by a single slit

Obtain on the screen a diffraction pattern from the slit. You should remove the diverging Lens **2**, place the slit in $30 - 40$ cm from the source, and set the screen at the end of the bench. Changing the width of the slit, observe the changes in the diffraction pattern. Draw features of the pattern for wide and narrow slits and indicate how the width of the slit affects the distance between the diffraction peaks.

Task 2. Study and description of diffraction patterns produced by diffraction gratings

Obtain a diffraction pattern from a one-dimensional diffraction grating. The configuration of the optical set-up is the same as in Task 1. Observe diffraction patterns for the vertical and horizontal arrangements of the grating. Then obtain a diffraction pattern for a two-dimensional grating.

Calculate the periods of the two-dimensional grating in horizontal d_1 and vertical d_2 directions. To do that, use the relations $d_1 \sin\phi_1 = m_1\lambda_1$ and $d_2 \sin\phi_2 = m_2\lambda_2$, which determine the directions along which the principal maxima are observed. Here, m_1 and m_2 are integers that determine the order of the maximum.

Determine the values of λ_1 and λ_2 from the relations $\sin\phi_1 \approx \Delta x/L$ and $\sin\phi_2 \approx \Delta y/L$, where Δx is the distance from the zeroth-order maximum to the maximum of the order m_1 in the horizontal direction, Δy is the corresponding distance from the zeroth-order maximum up to a maximum of the order m_2 in the vertical direction, L is the distance from the grating to the screen, and λ the wavelength of the laser radiation ($\lambda = 633$ nm).

The results of your measurements and calculations (L, Δx, Δy, m_1, m_2, d_1 and d_2) should be written down into a Table.

Task 3. Observation of Fresnel diffraction patterns from different obstacles in a slightly divergent beam

Using the Lens *1*, obtain on the screen a diffraction pattern from a circular obstacle, the steel ball of a diameter of $4 \sim 6$ mm.

Moving the object between the screen and the lens, observe the changes in the pattern and draw a picture after a light spot appears in the center of the shadow, the so-called Poisson spot.

Obtain a diffraction pattern from a narrow long strip (a wire, or a pin, etc). Draw pictures of the diffraction patterns for the cases when the diffraction object is (a) near the screen (b) near the lens (c) at some middle position.

Task 4. Observation of Fresnel diffraction patterns produced by a circular hole with use of a divergent beam

To obtain a diffraction pattern produced by the circular hole, use the Lens *2* that provides a greater beam divergence than the Lens *1*. Moving the hole relative to the Lens, obtain the diffraction pattern corresponding to two, three, four, five and six (or more, if possible) Fresnel zones that are cut out of the wavefront by the hole.

Task 5. Study of diffraction pattern by a single slit and determination the light wavelength

Place the diffraction object (slit) behind the lens at the narrowest point of the beam. Obtain the diffraction pattern produced by one slit and calculate the light wavelength, knowing the width of the slit b (it is indicated in the specifications).

For calculations use the minima condition for diffraction by one slit (Eq. 1), assuming that $\sin\phi_m \approx x/f$, where f is the focal length of the telescope (in this Practical $f = 40$ cm), Δx is the distance from the center of the diffraction picture to a minimum of the m-th order. You should determine Δx by means of the ocular micrometer.

The measurements will be more accurate if you determine $2\Delta x$, the distance between two minima of the same order to the left and to the right of the center of the picture, instead of Δx.

Record the results of measurements and calculations in a Table ($2\Delta x$, f, $\sin\phi_m$, λ).

Task 6. Study of diffraction pattern produced by two slits

A plate with two slits is equipped with a special curtain, which allows cover the slits separately.

Observe the pictures from each slit separately, and then from both slits together. For the diffraction pattern produced by the two slits, calculate the number of minima and maxima arising in the region of the central maximum due to diffraction by one slit, and make a conclusion about the relation between b and d for a given slits (see relations (3) and (4)).

Then calculate $2b/d$ by measuring b and d with the ocular. Compare the results obtained by direct measurement, $2[d/b]_{meas}$, and from the diffraction pattern, $2[d/b]_{dif}$.

Record the results of measurements and calculations in a Table (b, d, $2[d/b]_{meas}$, $2[d/b]_{dif}$).

Task 7. Study of diffraction pattern produced by several slits

Using a set of plates with several slits, obtain diffraction patterns produced by N slits (N changes from 2 to 9). Note that the number of additional maxima corresponding to the given number of slits N.

Put down the results of your measurements and calculations in to a Table. Draw different diffraction patterns from 2, 3, 4 and 5 slits.

In the report, indicate how the number of additional maxima and minima depends on the number of slits, and whether the position of the main maxima changes when moving to a larger number of slits. It can be determined by marking the maximum position by means of the cross threads in the field of view of the ocular micrometer.

Task 8. Study of diffraction pattern produced by the diffraction grating as the number of slits changes

Install a diffraction grating between the lens and the tube. Also set just before the grating a sliding slot. Obtain a picture from the diffraction grating (with the gap of the sliding slot being maximally extended). By reducing the effective number of grating slots with the help of a sliding slit, observe changes in the diffraction pattern. Find out how the distance between the main maxima, their sharpness, and the ratio between the intensities of the main and additional maxima change with an increasing number of slits.

Task 9. Study of diffraction pattern produced by a rectangular and circular holes

To obtain a diffraction pattern by a rectangular hole, a source in the form of a gap is non-effective. You should remove the cylindrical lens *8* and the objective lens *4* from the bench.

Obtain diffraction patterns by the square with a side a, by the square with a side b and by the rectangular hole with sides a and b.

Draw all three diffraction patterns. Find out the dependence of the diffraction pattern on the rectangle orientation.

Obtain and draw a picture of the diffraction pattern by a circular hole. Note how the observed pattern differs from the diffraction patterns by the circular aperture observed with the use of Fresnel method.

Questions

1. Formulate the Huygens-Fresnel principle.

2. What is the difference between the conditions of observation of Fresnel diffraction and Fraunhofer diffraction?

3. What is the significance of the degree of coherence of the light used to observe diffraction patterns?

4. Why is it expedient to use laser radiation for observation of diffraction produced by two or several slits?

5. Why is it expedient to use a diverging lens of a small optical power for observation a diffraction pattern produced by a round object (ball)?

6. How is the beam of laser radiation formed between the collimator and the telescope in the experimental setup?

7. Draw the path of the rays in the vertical and horizontal cross-section of the beam.

8. How will the observed pattern change if a slit or a grating (in Tasks 5-7) is moved across the beam?

PRACTICAL 12.
DIFFRACTION   *STUDY OF THE DIFFRACTION OF LIGHT*
OF LIGHT   *BY THE SINGLE SLIT, DOUBLE SLIT, AND MULTIPLE SLITS*

Practical 12.
STUDY OF THE DIFFRACTION OF LIGHT
BY THE SINGLE SLIT, DOUBLE SLIT, AND MULTIPLE SLITS

Equipment and accessories: a mercury lamp, a light filter, two lenses, an ocular micrometer, a set of plates with a different number of slits.

Introduction

Diffraction is a phenomenon in which the wave deviates from the rectilinear propagation. The effect is a general characteristic of wave phenomena occurring whenever a portion of the wavefront is obstructed in some way. If in the course of encountering an obstacle, *either transparent or opaque*, a region of the wavefront is altered in amplitude or phase, diffraction will occur. The various segments of the wavefront that propagate beyond the obstacle interfere, causing a characteristic energy-density distribution referred to as the *diffraction pattern*.

The **Fraunhofer** *or* **far-field** diffraction occurs when both the incoming and outgoing waves may be considered *plane*[5], which can be formulated mathematically as:

$$R \gg \frac{a^2}{\lambda},\tag{1}$$

where a is the characteristic size of the obstacle, λ is the wavelength, R is the smaller of the two distances: from the light source S to the diffracting obstacle Σ and from the latter to the point of observation P, as depicted in Fig. 1.

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[5]On the other hand, when the curvature of the incoming and outgoing wavefronts is not negligible, the **Fresnel** *or* **near-field** diffraction is observed.
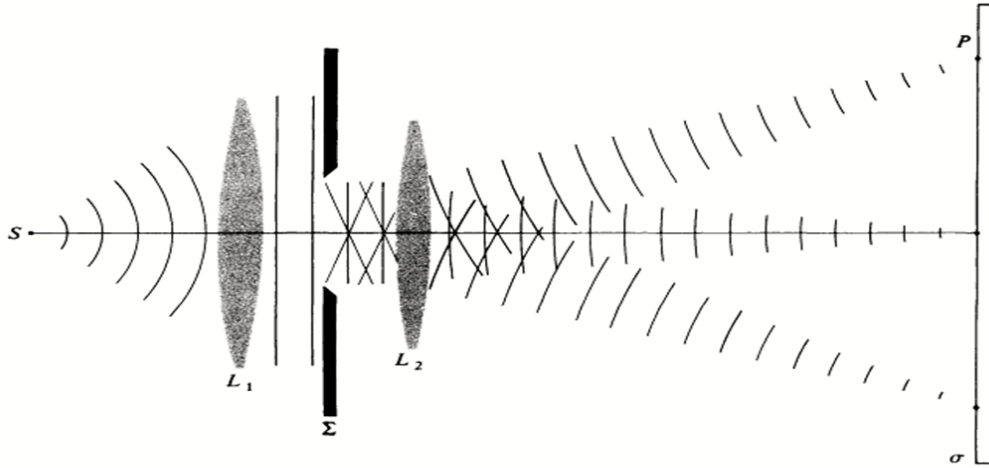
PRACTICAL 12.
STUDY OF THE DIFFRACTION OF LIGHT   *DIFFRACTION*
BY THE SINGLE SLIT, DOUBLE SLIT, AND MULTIPLE SLITS   *OF LIGHT*

Figure 1: A practical realization of the Fraunhofer diffraction, where both S and P are effectively at infinity, which is achieved by positioning the light source S at the principal focus of lens L_1 and the plane of observation at the second focal plane of lens L_2.

The diffraction patterns obtained with a single slit and a double slit are shown in Fig. 2. The principal minima and maxima of the diffraction pattern are given by:

$$\begin{cases} a \cdot sin(\theta) = \pm m \cdot \lambda, & \textit{m = 1,2... - min} \\ a \cdot sin(\theta) = 0, \pm(2m - 1) \cdot \frac{\lambda}{2}, & \textit{m = 1,2... - max} \end{cases} \tag{2}$$

here a is the *width* of the single slit.

With the use of the double slit, the intensity follows the so-called *single-slit envelope*, whereas newborn minima and maxima are formed due to the interference of the waves produced by the two slits. Recalling that for the interference maxima:

$$d \cdot sin(\phi) = \pm k\lambda, \tag{3}$$

where d is the distance between the two slits, and k - the interference order, one can find that in the double slit diffraction experiment the number of maxima and minima within the single-slit envelope, denoted as N_+ and N_-, are:

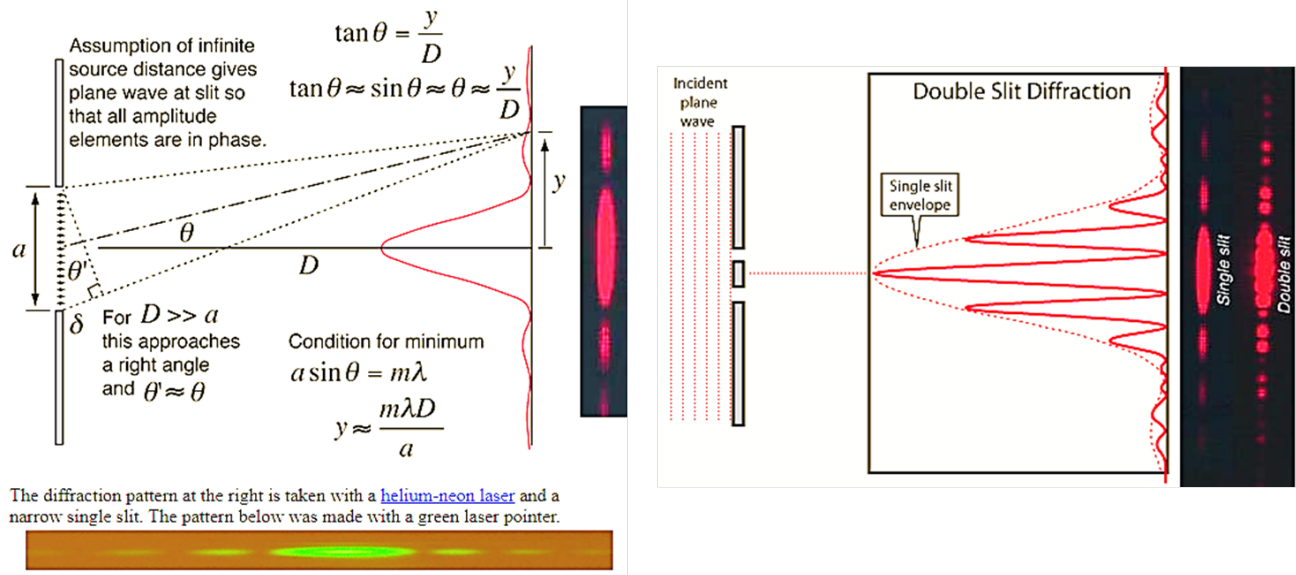$$\begin{cases} N_+ = 2d/b + 1 \\ N_- = 2d/b \end{cases}. \tag{4}$$

Figure 2: A diffraction pattern obtained with a single slit (left) and a double slit (right). Adopted from http://hyperphysics.phy-astr.gsu.edu/

Experimental setup

A schematic of the experimental setup is shown in Fig. 3. Light emitted by the mercury lamp *1* is collected by the condenser *2* and directed to the slit *3*, which is located at the focal plane of the objective *4*. The plane wave formed (i.e., a parallel beam of rays) illuminates the object *5* - the two slits in the figure, each with the width b separated by the distance d. The objective lens *6* forms a diffraction pattern at a distance F (in the focal plane). The picture is observed through the ocular micrometer *7*, which makes it possible to measure the required distances with an accuracy of 0.01 mm. In order to narrow the spectral interval of the mercury lamp, a light filter is used. The focal length of the objective is $F = 30\ cm$. The diffraction angles can be calculated from the distance Δx measured from the center of the diffraction pattern to the corresponding maximum (or minimum) and the focal length of the lens:
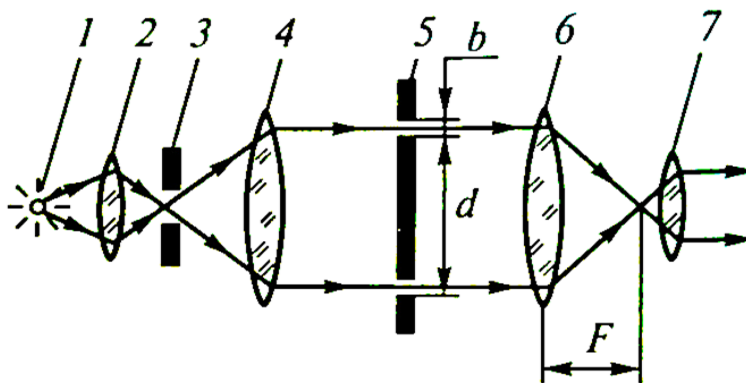
$$sin(\theta) \approx \Delta x / F. \tag{5}$$

Figure 3: Experimental setup.

Measurement and data processing

Task 1. Observation of the diffraction pattern using a single slit and calculation of the wavelength of the incident light

Place the diffracting obstacle - the single slit behind the lens at the narrowest point of the beam, and obtain a diffraction pattern. Calculate the wavelength of light, knowing the width of the slit b (it is indicated on the slit frame) and using (2) and (5).

To improve the measurement accuracy, measure the distance between the two minima of the corresponding order to the left and to the right of the center of the diffraction pattern rather than the distance between the center and one of the minima itself. Write down your data into a table. Perform the error analysis.

Task 2. Observation of the diffraction pattern using a double slit

The double slit is equipped with a special curtain, which allows one to alternately shut off the slits.

Observe the pictures using each slit independently, and then using the double slit. Having obtained the diffraction pattern using the double slit, calculate the number of minima and maxima arising in the region of the central maximum (the one due to diffraction pattern formed by the single slit). Make a conclusion about the relation between b and d for a given pair of slits (see eq. (4)).

Then calculate $2b/d$ by measuring b and d with a microscope, and compare the results obtained by direct measurement and observing the diffraction pattern. Write down your data into a table, including the values of b, d, $2 \cdot [d/b]_{meas}$ and $2 \cdot [d/b]_{calc}$.

Task 3. Observation of the diffraction pattern using multiple slits

Using a set of plates with multiple slits, obtain diffraction patterns for different number of slits N from 2 to 7. Write down in a table the number of additional maxima corresponding to the given number of slits N, and sketch the diffraction patterns observed.

Questions

1. What is the difference between the conditions for observing Fresnel diffraction and Fraunhofer diffraction?

2. What is the distribution of the light intensity in the diffraction pattern from a slit whose width b is equal to the wavelength of the radiation used?

3. How does the fraction of the energy pertaining to the main maxima change with the transition to a larger number of slits?

4. What diffraction pattern would be observed if the number of slits is large enough (of the order of hundreds)?

5. How will the diffraction patterns observed change if the light source is an incandescent lamp without a filter?

Practical 13.
STUDY OF THE DIFFRACTION GRATING

Equipment and accessories: a goniometer equipped with the objective and ocular tubes, a slit, neon-glow lamp, gas-discharge mercury lamp, incandescent lamp, diffraction gratings, a dispersive prism.

Introduction

Diffraction is a phenomenon in which the wave deviates from the rectilinear propagation. The effect is a general characteristic of wave phenomena occurring whenever a portion of a wavefront is obstructed in some way. If in the course of encountering an obstacle, *eitherent or opaque*, a region of the wavefront is altered in amplitude or phase, diffraction will occur. The various segments of the wavefront that propagate beyond the obstacle interfere, causing the particular energy-density distribution referred to as the *diffraction pattern*. As the *diffraction angle* depends on the wavelength of the diffracted light beam, the spectral composition of the latter can be easily determined by measuring the diffraction angles of individual spectral components. In practice, a *diffraction grating* is used which is a repetitive array of diffracting elements, either apertures or obstacles, that has the effect of producing periodic alterations in the phase, amplitude, or both of an emergent wave.
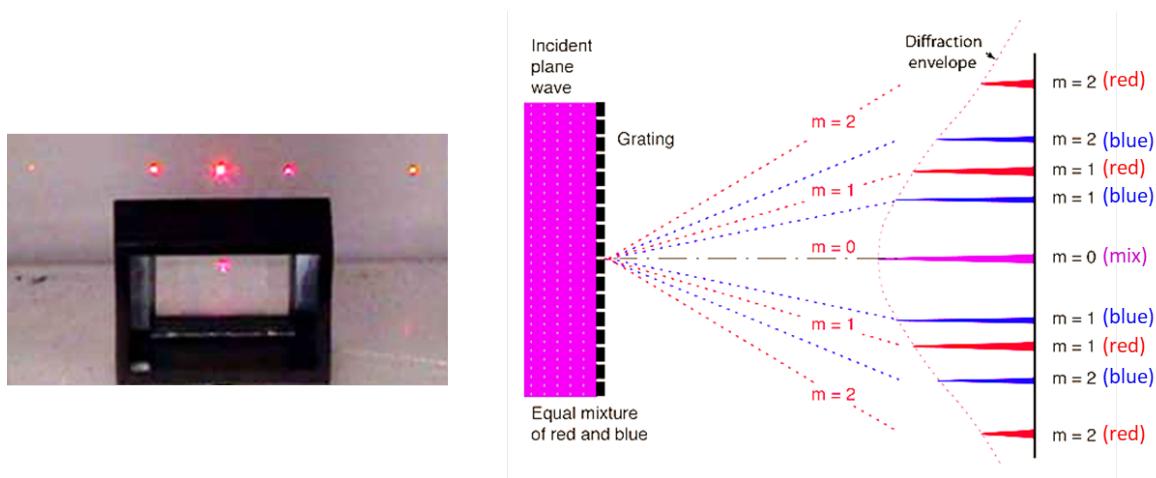

Figure 1: Left: The helium-neon laser beam diffracted by a transmissive diffraction grating. Right: Dispersion of the spectral components by a transmissive diffraction grating. Adopted from http://hyperphysics.phy-astr.gsu.edu/

A periodically changing parameter can be, for example, transparency (for amplitude grating) or geometrical thickness or refractive index (for phase grating). In Fig. 1 (left panel) a laser beam diffracted by a transmissive diffraction grating is shown. Fig. 1 (right panel) demonstrates how the spectral components of the light beam are separated depending on their wavelength. Large number of slits makes the intensity maxima very sharp and narrow, providing the high resolution for spectroscopic applications. The wavelength, diffraction grating constant and diffraction angle are connected through the *grating equation*:

$$d \cdot sin(\alpha) = \pm m\lambda, \tag{1}$$

with m being the order of the diffraction spectra. There is no spectral dispersion at the central diffraction maximum ($m = 0$), and a mixture of all the components is observed.

Experimental setup

Experimental setup is depicted in Fig. 2. In the work a transmission grating is used, which is a glass plate with a series of parallel lines applied by means of a ruling machine with a special diamond cutter. The dispersion angles are measured with use of a *goniometer*. The goniometer consists of a telescope tube T, collimator C, and table. Angular position of the telescope tube can be precisely measured using the angular scale equipped with a vernier. The collimator creates a parallel beam of light. It consists of an outer tube and an internal tube with an entrance slit S installed in the focal plane of the lens.
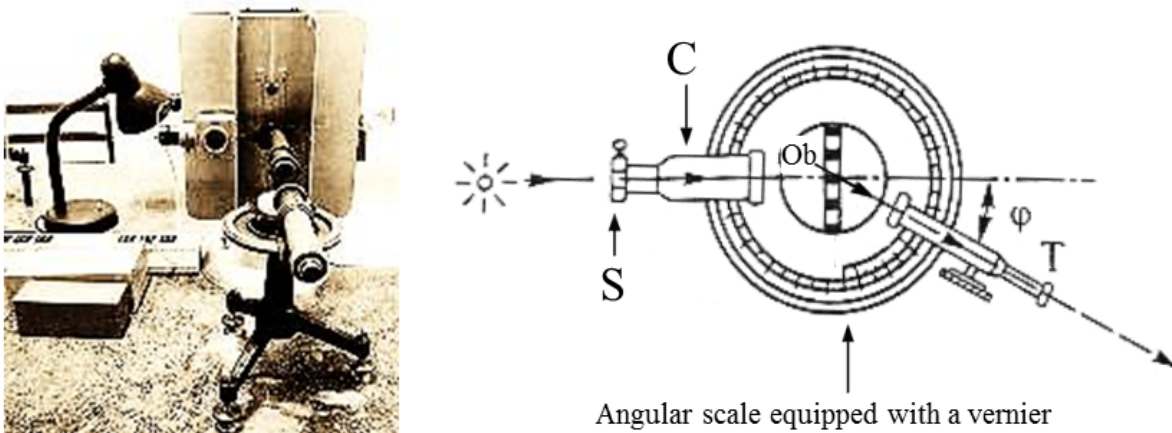

Figure 2: Photograph of the experimental setup (left) and schematic of the goniometer (right).

A plane wave (a parallel beam) of light emerges from the collimator and irradiates the diffraction grating. The light beams are collected by the telescope objective lens Ob at the focal plane of which the actual images of the collimator slit are formed. In the field of view of the eyepiece, a cross-marker and the actual image of the slit (the diffraction maximum) are simultaneously visible.

Measurement and data processing

Task 1. Determination of the diffraction grating constant using a well-known spectral line of the incident light source

In the task, a well-known line of the neon spectrum (yellow line, $\lambda = 585\ nm$) is used to determine the grating constant. The diffraction grating should be placed on the goniometer table so that its lines are vertical and the beam of light emerging from the collimator is normal to the grating. Rotate the telescope until the eyepiece marker is aligned with the first left image of the slit (maximum of the 1st order), note the angular position α_{left}. Rotate the telescope until the marker is aligned with the first right image of the slit and also note the angular position α_{right}. Using these values, find the diffraction angle ϕ. Repeat the measurement but now measure the diffraction angle of the second diffraction maximum, $m = 2$. Using formula (1), calculate the grating constant d. Tabulate the results. Estimate the measurement error.

Task 2. Study of the mercury lamp spectrum

In this task, the brightest lines in the mercury emission spectrum are measured. Point the goniometer to the mercury lamp and obtain a sharp image of the slit. In the same way as in Task 1, measure the angles of deviation for all visible lines of the mercury spectrum (for 1st and 2nd orders of the spectrum). Calculate the wavelengths of the observed lines of the mercury spectrum. Tabulate the measured and calculated parameters.

Task 3. Determination of the diffraction grating angular dispersion

Determine the difference in deviation angles for the blue and violet lines in the spectra of the 1st ($\Delta\phi_1$) and 2nd ($\Delta\phi_2$) orders. Knowing the difference $\Delta\lambda = \lambda_b - \lambda_v$, calculate the angular dispersion of the grating for the spectra of the first and second orders as $D = \Delta\phi/\Delta\lambda$.

Using a piece of paper shield the side part and later the top part of the grating. Observe the changes introduced to the spectra observed. Make a schematic drawing of the observations. Find out if the angular dispersion of the shielded grating has changed.

Task 4. Observation of the emission spectrum of a heated body

Illuminate the goniometer slit with the light emitted by the incandescent lamp. Observe the spectra of the 1st and 2nd orders using the diffraction grating. Place a prism instead of the diffraction grating on the goniometer table, obtain the dispersive spectrum of the incandescent lamp, and compare it with the diffraction spectrum. Draw the spectra observed into the notebook using the coloured pencils.

Questions

1. What kind of diffraction is observed in the work: Fresnel diffraction or Fraunhofer diffraction?

2. Using the rules of geometric optics, construct the ray path in the goniometer (in the presence of a diffraction grating) from the light source to the eye for maxima of the 0th and 1st orders.

3. How is the position of the main maxima calculated if a parallel beam of light illuminates the grating at an angle $\alpha \neq 0$?

4. How can a "rough" ($d \approx 1\ mm$) diffraction grating be used to observe the diffraction of light?

5. How will the diffraction pattern change if the width of the slit is changed without changing the grating constant (the light source yields a line spectrum)?

6. What is the significance of the spatial coherence of radiation for the observation of interference patterns?

7. How will the diffraction patterns obtained from gratings with different constants differ, but with the same number of lines per millimetre?

Dispersion
of Light

Practical 14.
STUDY OF THE DISPERSION OF LIGHT
WITH A GLASS PRISM

Introduction

Dispersion is a phenomenon, consisting in the phase velocity of the wave depending on its frequency. In this practical you will have an opportunity to study dispersion of light in a glass prism. The refractive index of glass, the prism is made of, can be determined as

$$n = \frac{sin\left(\frac{\varphi+\delta}{2}\right)}{sin\left(\frac{\varphi}{2}\right)}, \tag{1}$$

where φ - is the refraction angle of the prism, δ - is the angle of least deviation of rays passing through the prism. By measuring φ and δ, one can calculate the values of *n* for visible light of different frequencies and thus find the dependence *n(ν)*.

Experimental setup

A goniometer is used (for more details see the description of practical 13), to measure the angles φ and δ. A parallel beam of light after the collimator is collected by the telescope objective (tuned to infinity) in its focal plane, forming a real image of the slit, which is observed through the eyepiece. If one places a prism between the collimator and the telescope, then the tube will need to be rotated relative to the previous position by some angle to observe the image of the slit. It can be measured on the scale of the limb with the help of the vernier scale. A mercury lamp is used as the source of light in the setup. The emission spectrum of the mercury lamp has a substantially linear nature in the visible region, which makes it possible to work with the emission lines of several definite frequencies. One can find those frequencies from the wavelengths of mercury emission lines in vacuum (the table of wavelengths is given below) and the speed of light in vacuum.
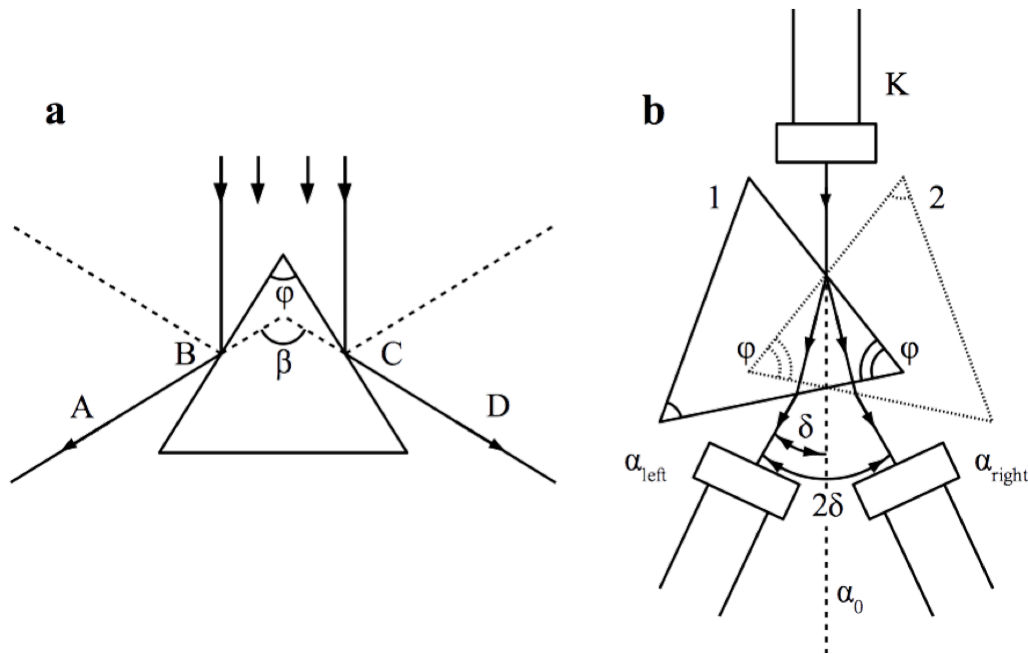

Figure 1: A schematic of the experimental setup: a – an initial position of the prism on the goniometer relative to the incoming light; b – two positions of the prism during the measurements.

Measurement and data processing

Task 1. Determination of the refraction angle of the prism

Place the prism on the goniometer table so that the bisector of the angle φ coincides with the axis of the collimator (see 1-a). The prism, which is used in this practical, has the base of an equilateral triangle. One should not forget that the angles of the prism cannot be exactly equal. Because of inequality of the prism angles, one needs to take all the measurements with the same defined refractive angle (the proper angle is marked on the prism). The beams reflected off the two faces of the prism form an angle β, as can be seen in Fig.1a. It can be shown that $\beta = 2\varphi$. The angle β is determined from the difference of measurements α_1 and α_2 corresponding to two positions of the telescope, at which the images of the slit formed by the reflected beams *BA* and *CD* are visible. Put down the results of measurements α_1, α_2, β and φ into table 1.

Task 2. Determination of the angles of minimal deviation and refraction indices for the characteristic frequencies of the radiation spectrum of a mercury lamp

To determine the angle of the least deviation of light of a particular frequency, place the prism on the goniometer table so that the refractive angle is equal to the angle, which was defined in task 1 (see Fig. 1b. - the prism in the position 1). Rotate the telescope to find a series of color images of the slit, which correspond to the individual frequencies of the mercury emission spectrum. Then, turn the table with the prism in such a direction that the images of the slit are displaced towards the undeflected beam (to the axis of the collimator). After selecting some image of the slit, continue turning the table while observing the image of the slit in the telescope. Keep turning the table until the image of the slot stops and, with the further rotation of the table in the same direction, does not begin to move back. The "stop position" of the image indicates that one has achieved the angle of least deviation for a given frequency (the angle δ in Fig.1b) by the prism. After the cross-pointer is positioned exactly at the "stop position" of the given line of the spectrum, record the angle α_{left} on the scale of the limb. To calculate the angle δ, it is sufficient to take the difference between the α_{left} and α_0 - corresponding to the undeflected beam (see 1-b); however, to increase the accuracy of measurements, it is recommended to turn the prism table to the position 2 and, once again measure the angle of least deviation α_{right} for the same line of the spectrum. As shown in Fig. 1b, α_{left} - α_{right} = 2δ. Measuring the values of α_{left} and α_{right} for five different spectral lines, calculate the angle δ and, using the refraction angle φ obtained in the task 1, find values of the refractive index *n* for the five characteristic frequencies of the mercury emission spectrum in accordance to the equation (1).

Put down the results of measurements and calculations into *Table 1*.

Table 1. Experimental results and data analysis

No.	Mercury spectral line	Wavelength in vacuum, nm	Frequency, 10^{14} Hz	α_1	α_2	β	φ	α_{left}	α_{right}	δ	n
1	yellow	579									
2	green	546									
3	blue	492									
4	dark blue	436									
5	violet	405									

Task 3. Plotting of the dispersion curve and calculation of the average dispersion

Using the obtained values of *n*, plot the dependence *n = f(ν)*. Find the average dispersion D_{avg} for a given glass type:

$$D_{avg} = \frac{n_{viol} - n_{yel}}{\lambda_{viol} - \lambda_{yel}}, \tag{2}$$

where n_{viol} and n_{yel} are the refractive indices for the violet and yellow lines of the mercury emission spectrum.

Questions

1. What are the main provisions of the classical dispersion theory?
2. What type of dispersion did you observe: normal or abnormal?
3. In what cases can one speak about abnormal dispersion?
4. How can one reduce the chromatic aberration of optical instruments?
5. How can one reconcile the change in the speed of light in a medium with the fact that the speed of motion of photons is constant and always equal to the speed of light in vacuum?

Polarization
of Light

Practical 15.
ELLIPTICAL POLARIZATION OF LIGHT

Introduction

Let a beam of linearly polarized light fall on a plane parallel crystal plate located so that its principal directions are perpendicular to the direction of light propagation. If the direction of the vector E in the incident beam propagates at any angle to one of the principal directions of the plate, then it is convenient to consider the oscillations of the vector E as the sum of two mutually perpendicular oscillations, expanding E along the principal directions of the plate (in the case of a plate of mica, these directions are called β and γ- directions).

Due to the anisotropy of the crystal, the propagation velocities of the components along these directions will be different and at the exit from the plate one will have two mutually perpendicular oscillations with a phase difference:

$$\Delta\varphi = \frac{2\pi * (n_\gamma - n_\beta) * d}{\lambda},\tag{1}$$

where d - is the thickness of the plate, λ - is the wavelength in vacuum, n_γ and n_β - are the refractive indices for the components of the corresponding directions.

Thus, after passing through the crystalline plate, the linearly polarized light becomes polarized elliptically: the tip of the light vector E in this case describes an ellipse, the direction of the axes and the shape of which depend on the thickness and material of the plate, and on the orientation of the vector E in the incident beam relative to the principal directions of the plate.

In laboratory practicals, the so-called "quarter-wave" and "half-wave" plates, for which the phase shift between the components of the vector *E* along the principal directions are equal to $\pi/2$ and π, respectively, are used very often. For example, passing through the quarter-wave plate, linearly polarized light becomes elliptically polarized, with the axes of the ellipse coinciding with the principal directions of the plate.

A crystal plate, placed in the path of linearly polarized light so that one of its principal directions coincides with the direction of the vector *E* of the incident wave, obviously does not introduce any changes into the state of polarization, and the light remains linearly polarized. The latter circumstance makes it possible to determine the main directions of the plate. To do that one needs to place the plate between two crossed polaroids and to orient it so that the intensity of light after the second polaroid again becomes minimal. A $\lambda/4$-plate can also be used as a phase difference compensator – one can convert elliptically polarized light into linearly polarized light with such a plate.

The goal of this practical is to give students an opportunity to determine the principal directions of the crystalline (mica) plate, to become familiar with the operation principal of $\lambda/4$ and $\lambda/2$ plates, and also to obtain elliptically polarized light and circularly polarized light using a $\lambda/4$-plate.

Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A beam of natural light from the illuminator *I* passes through the filter *F*, which passes a relatively narrow spectral interval, and falls on the polarizer *P*. Further in the path of the light beam, various mica plates (λ/4 or λ/2) can be placed. The light passes through the second polarizer, which acts as an analyzer *A,* after the plate. Between the polarizer *P* and the analyzer *A*, an auxiliary lens *L* can be placed. The photocell *PC* is used as the light detector, which is connected to a galvanometer (luxmeter - *LM*) calibrated in luxes (SI units: lx). The readings of the luxmeter are proportional to the intensity of light falling on the photocell. The photocell is closed with a special protective cover, which is removed immediately before the measurement starts. After the measurement is completed, the photocell must be closed with the cover.
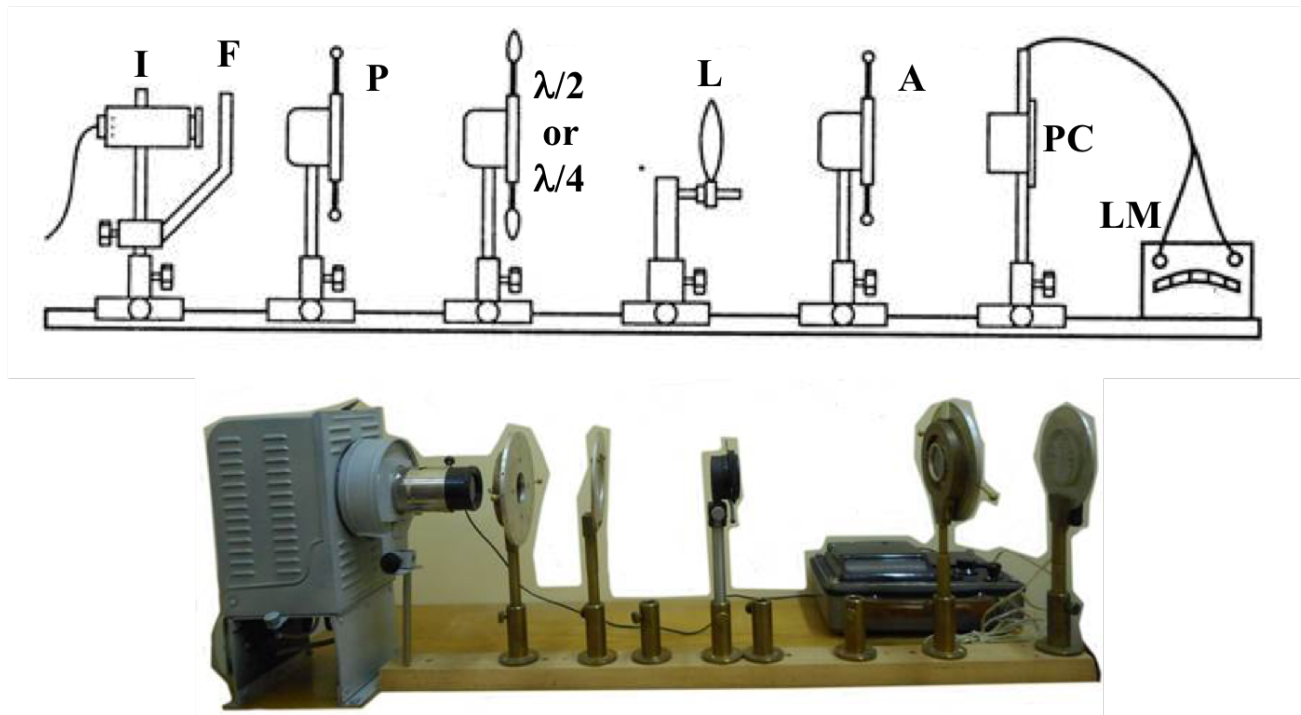

Figure 1: A schematic and an image of the setup

Measurement and data processing

Task 1. Determination of the principal directions of the crystalline plate

Place the filter corresponding to the plate under test in front of the illuminator, and get light polarized in the vertical plane, by rotating the polarizer. The polarizer is tightened in a frame so that this position corresponds to the division of the scale "0". Rotating the analyzer, one needs to achieve minimum illumination of the photocell. Recording the corresponding angle between the axes of the polarizers.

Place the $\lambda/4$ test plate between the polarizers and, rotating it, again achieve minimum illumination of the photocell. One needs to find four positions, which correspond to minimum illumination, record the corresponding scale divisions of the plate and find the angle between the principal directions of the plate.

Task2. Producing elliptically polarized light by means of a $\lambda/4$ plate.

Set the plate $\lambda/4$ so that one of its principal directions is at an angle $\varphi = 20°$ to the polarizer axis. Rotating the analyzer, measure the intensity of light passing through it, changing θ (the angle between the polarizer axis and the analyzer) from 0° to 360° with a step of 15°.

Do the same measurements for the other two values of the angle φ ($\varphi = 0°$ and $\varphi = 45°$) and plot the graphs in the polar coordinates

$I = f(\theta),\ \theta = 0°,\ 15°,\ 30°,\ \dots 360°$

for all the three cases, indicating on the graph the orientation of the polarizer axes and the principal directions of the plate. Note in the report what kind of polarization corresponds to each of the obtained curves.

Task 3. Determination of the polarization of light propagated through a plate

Do the measurements described in **task 2**, using the $\lambda/2$ plate for the selected filter, determining the principal directions of this plate in advance and orienting it so that one of the principal directions is at an angle of 45° with the polarizer axis.

Plot the graph of the $I(\theta)$ dependence, indicating the orientation of the principal directions of the plate and the axis of the polarizer. Note how the polarization of the light beam has changed after the $\lambda/2$ plate.
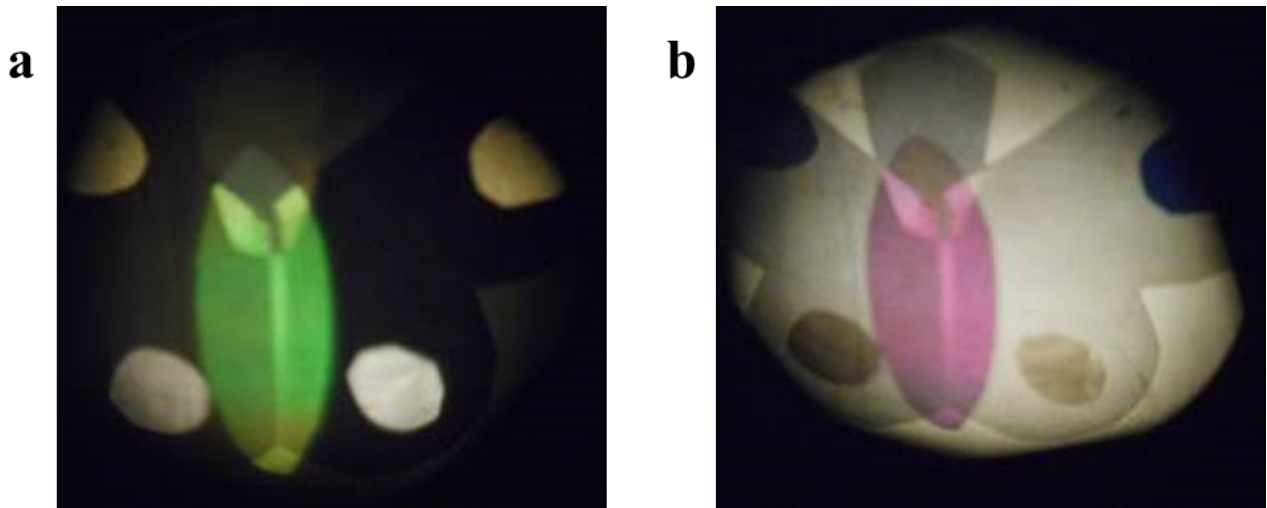
Figure 2: The examples of the observable images

Task 4. Producing color images of crystalline plates

When performing this task, one should use the illuminator without the filter. Put the screen instead of the photocell (**!** which must be covered with the protecting cover and removed), and insert a special plate, which is made of several overlapping mica leaves, between the polarizers. Using a lens, obtain a sharp image of the plate on the screen. Changing the orientation of the polarizer and the analyzer relative to the plate, one ought to trace the change in the color of the image, sketching the most specific cases and explain the change in the color of the image, while rotating the polarizers relative to each other and relative to the plate (as demonstrated in Fig. 2).

Task 5. Study of crystalline plates in monochromatic light

Put any filter and, rotating the analyzer, observe the distribution of illumination of the image of the plate on the screen. Explain the result of the observations. Draw an approximate distribution of the darkest areas of the image. Without changing the orientation of the elements of the setup, change the filter. Draw the position of the darkest areas once again, compare it with the first sketch and explain the result.

Questions

1. What curve will one get if one joins the tips of the vectors E of a linearly polarized plane wave at different points of space at the same instant moment of time? What about a wave polarized elliptically?

2. What material properties determine the thickness of a quarter-wave plate? What about the half wave plate?

3. How can one experimentally distinguish the circularly polarized light from the natural light?

4. How can one experimentally distinguish partially polarized light from elliptically polarized light?

5. How can one determine the direction of rotation of the light vector (E) in the case of elliptical polarization?

6. What is a polarizer?

Practical 16.
LINEAR POLARIZATION OF LIGHT

Part 1. Determination of permittivity of glass by the polarization method

Introduction

As is well known, the reflectance of linearly polarized light from a dielectric mirror depends on the angle of incidence and on the direction of the electric vector E of the light wave relative to the plane of incidence. If the electric vector E of the incident wave is perpendicular to the plane of incidence, then the reflectance is:

$$R_{\perp} = \left(\frac{E_{ref}}{E_{inc}}\right)^2 = \frac{\sin^2{(\varphi - \psi)}}{\sin^2{(\varphi + \psi)}}, \qquad (1)$$

where φ - is the angle of incidence, ψ - is the angle of refraction; reflection occurs at any angle of incidence.

If the electric vector E is parallel to the plane of incidence, then the reflection coefficient is:

$$R_{\parallel} = \frac{\tan^2{(\varphi - \psi)}}{\tan^2{(\varphi + \psi)}}, \qquad (2)$$

Expressions (1) and (2) are called Fresnel's formulas.

Using the law of refraction, one can easily find the angle of incidence at which the reflection in case (2) is absent:

$$\tan\varphi_{Br} = n, \qquad (3)$$

where n - is the refractive index of a given dielectric.

This relation is called Brewster's law and states that the angle of incidence φ_{Br} at which reflection is absent is called Brewster's angle or the polarization angle. Knowing the polarization angle, one can determine the permittivity of a given dielectric as follows:

$$\varepsilon = n^2 = \tan^2\varphi_{Br}. \qquad (4)$$

Experimental setup

Referring to Fig. 1, the experimental setup consists of the goniometer with the polarizer P mounted on the collimator C, which can be rotated relative to the optical axis of the collimator, and is used in the proposed practical to determine the angle of total polarization. The natural light becomes linearly polarized after passing through the polarizer. Rotating the polarizer, one can change the polarization of light emerging from the collimator. The dielectric mirror M is mounted on the stage of the goniometer. One can change the angle of incidence of the beam by rotating the mirror M relative to the vertical axis of the goniometer. The ray reflected from the mirror is observed through the telescope T, the position of which can be used to calculate the angle of incidence of the beam on the mirror. The radiation spectrum of the lamp L can be changed by means of the filter F.
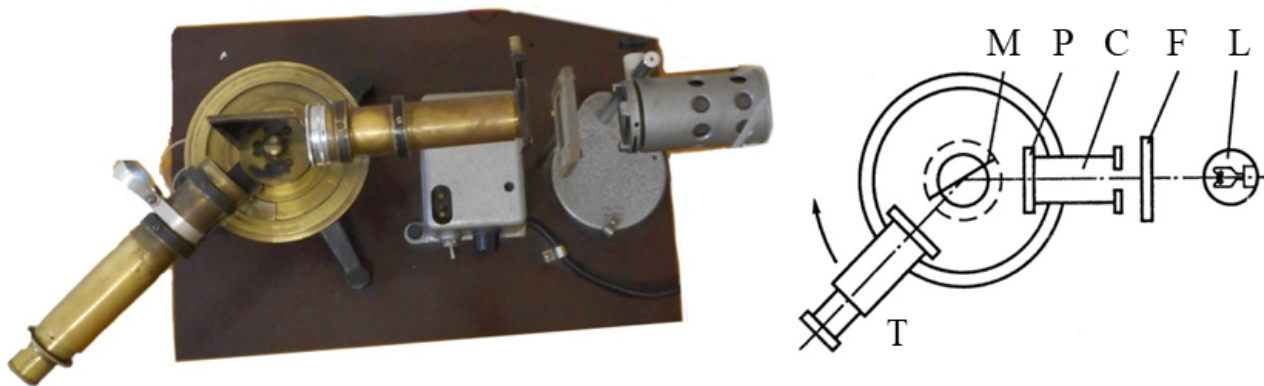

Figure 1: An image and a schematic of the setup

Measurement and data processing

Place the mirror *M* parallel to the optical axis of the collimator and, aligning the image of the slit with the cross of the threads in the pipe, determine the zero position of the telescope α_0 along the limb of collimator. Then turn the telescope through an angle of 10-15 degrees and tune the position of the mirror so that the image of the slit again coincides with the cross-pointer. Rotating the polarizer *P*, observe the change in the intensity of the beam reflected off the mirror. Do the same observations, increasing the angle of rotation of the telescope. When the brightness of the image of the slit begins to change appreciably, the angle of rotation of the telescope should be increased through smaller steps about 5 degrees. After reaching the values of α at which by turning the analyzer it is possible to achieve almost complete suppression of the reflected beam, reduce the step of change of the angle down to 1 degree or less.

Task 1. Determination of the permittivity of glass

In this task you need to find several close values of α for which the intensity of the reflected beam is close to zero at some position of the polarizer, calculate the average value of α_{aver} and calculate the polarization angle, starting from the following guess (as shown in Fig. 2): if the mirror is rotated by an angle β, then the image of the slit observed with the telescope is rotated by an angle 2β. Then the angle of incidence of the ray on the mirror will be determined as $\varphi = 90° - \beta$. Knowing the initial position of the telescope α_0, and the new position 2β, one can find φ:

$$\varphi = 90° - \frac{(\alpha_0 - 2\beta)}{2}. \tag{5}$$

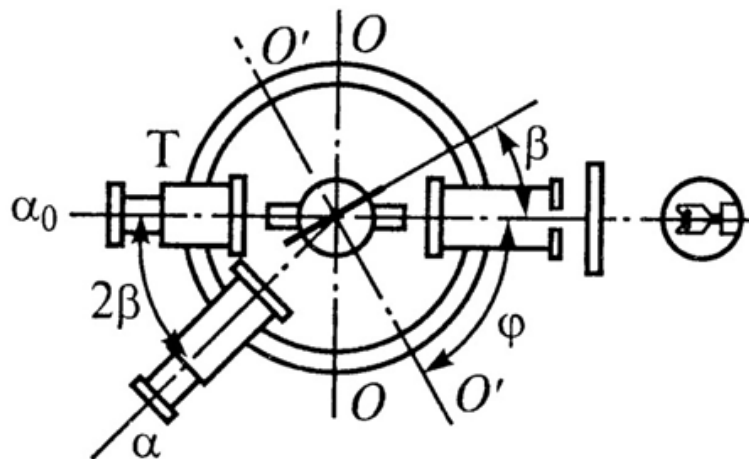Using expression (4), find the permittivity of glass the mirror is made of.

Figure 2: Measurement of the angles

Part 2. Determination of the transmission coefficient of the polarizers and validation of the Malus law

Introduction

If a beam of natural light passes through an ideal polarizer, then, because of the statistical symmetry of the oscillations of the vector *E*, the light intensity decreases by the factor of two, and the light turns into linearly polarized light. The intensity of light transmitted through two ideal polarizers is related to the initial intensity I_o as:

$$I = \frac{I_0}{2}\cos^2\theta, \tag{6}$$

where θ - is the angle between the transmission axes of the polarizers (Malus's law). The reflection of light off the surfaces of the polarizers is not taken into account in (6).

In the case of real polarization devices, the relation between I_0 and *I* will be somewhat different, first, because it is impossible to achieve strictly linear polarization, and secondly, because of the inevitable absorption of light by the material of each polarizer in addition to 50% of the natural light incident on the first polarizer.

It is proposed to investigate experimentally the change in the intensity of light passing first through one, and then through two polarizers. Changing the angle between the transmission axes of the polarizers, it makes possible to verify experimentally Malus's law (6).

The polarizers used in this practical are made of thin films of an anisotropic material (for example, polyvinyl covered with iodine).

The change in the intensity of light can be traced by the change in the illumination of the photocell, connected to a galvanometer. The scale of the galvanometer is often graduated directly in units of illumination - lux (in this case the device is called a luxmeter).

Experimental setup

The setup, which is used to determine of the transmittance coefficient of polarizers and validation of Malus's law, is shown in Fig. 3. It consists of the light source *5*, polarizer unit *6* with the scale *4* and the photocell *7*. A luxmeter photocell, which allows to measure the illumination directly in luxes, is used in this practical. The luxmeter has several measurement ranges, use the limit "0-100 lux" while measuring.

The polarizer unit consists of the supporting cylinder *1* and two reclining rings *2* with polarizers fixed in them. The upper operation position of the rings with polarizers is fixed by a ball lock. The polarizers can be rotated in their frames. The arrow pointer *3* is attached to the frame of one of the polarizers, which makes it possible to measure the rotation angle of the polarizer along the scale *4*.
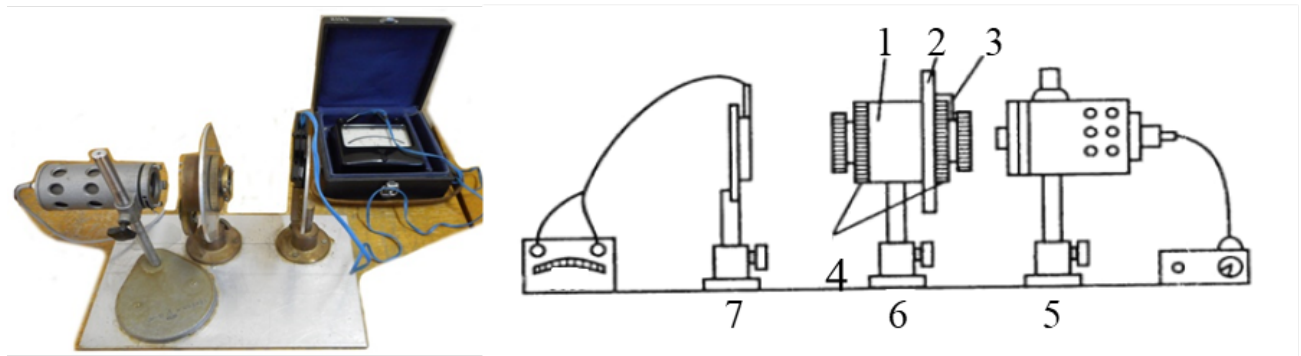

Figure 3: An image and a schematic of the setup

Measurement and data processing

Task 2. Determination of the transmittance of polarizers

Make sure that the lamp adjustment knob is in the extreme left position (turned home counter-clockwise). Mount the photocell on the stand *7*, put the switch of the luxmeter measurement range in the position "0 - 100 lx".

Move away both rings with polarizers, switch on the illuminator and, increasing the glow of the lamp, bring the illumination of the photocell to $E_0 = 80$ lx. It is convenient to use the diaphragm of the illuminator for accurate adjustment of illumination to a certain level.

After placing one of the polarizers onto the mount *6,* one needs to measure the illumination E_1, then put the second polarizer onto the other end of the mount *6* and measure the illumination E_2, while axes of both polarizers are parallel.

Repeat the same measurements, changing the order of the introduction of the polarizers and with a different value of the initial illumination. From these measurements, one can determine the transmittance of the polarizers – for a single one (E_1 / E_0) and for two polarizers together (E_2 / E_0).

Put down the measurement results into table 1.

Task 3. Validation of the Malus law

By adjusting the glow of the lamp and using the diaphragm of the illuminator, set the illumination of the photocell $E_{max} \approx 40$ lx, while the axes of the polarizers are parallel. This task can be performed at an arbitrary initial position of the polarizer parallel axes relative to the scale. But it is more convenient to orient the polarizers so that counting on the scale would directly give the value of the angle θ that appears in Malus's law.

Turning the polarizers, along the rim with an arrow, one needs to measure the illumination E_θ at ten different values of the angle $\theta = 0$; 10; 20; ...; 90°. Repeat the measurements by changing the angle θ from 90° to 0°. At the end of the measurement, it is necessary to close the photocell with a lid and put it into the case of the luxmeter.

Average the results over two series of measurements and calculate ten values of the ratio E_θ / E_{max}. E_{max} is the value of illumination, while the axes of the polarizers are parallel.

Put down the measurement results into the table 2. Plot the dependence $E_\theta / E_{max} = I_\theta / I_{max} = f(\theta)$. Add the theoretical curve $\cos^2(\theta) = f(\theta)$ on the same graph and compare the obtained curves.

Questions

1. What are the theoretical premises, which allow one to derive expressions (1) and (2)?

2. Indicate the polarization states of the reflected light beam off a dielectric if the angle of incidence is equal to Brewster's angle for several cases: natural light; linearly polarized light in the plane of incidence; linearly light polarized in the plane perpendicular to the plane of incidence.

3. How can one estimate the degree of polarization of partially polarized light?

4. How can one practically determine the plane of oscillations of the light transmitted for a given polarizer?

5. What is the operation principle of polarization prisms (Nicol prism, etc.)?

6. What is a polarizer?