First name ....
Date ....

Last name ....
Degree program name ....

Exercise 158

Study of the diffraction phenomenon on a single and double slit

Wavelength of the laser, λ [nm]		Distance between slits and screen, l [m]	

The laser wavelength value is written on the laser housing.

Table I. Determination of the slit widths

Slit symbol			
Coordinate of the diffraction maximum	[mm]		
Coordinate of the diffraction minimum	[mm]		
Distance	[mm]	x'	x''
Average distance, x	[mm]		
Calculated slit width, a	[mm]		
Specified slit width, a_r	[mm]		
Relative percentage error, B_p	[%]		

Table II. Determination of the distance between the slits

Symbol for a pair of slits					
Coordinate maximum, $n = 0$	[mm]				
Coordinate maximum	[mm]	Order of maximum, $n = 1$		Order of maximum, $n = 2$	
Distance	[mm]	x_1'	x_1''	x_2'	x_2''
Average distance, x_n	[mm]				
Calculated slits distance, d_n	[mm]				
Calculated average slits distance d	[mm]				
Specified slits distance, d_r	[mm]				
Relative percentage error, B_p	[%]				

Please pay attention to the units when calculating! We recommend performing the relevant calculations in the laboratory – consultation with the tutor is usually needed.

158: Study of the diffraction phenomenon on a single and double slit

Purpose of exercise

The purpose of the exercise is to study the nature of light by the analysis the of diffraction phenomenon on a single and double slit. The diffraction phenomenon of light rays is closely related to the wave nature of light. It is based on the bending the of rectilinear course of light rays, encountering obstacles on their path.

Theory

Diffraction and interference of light

The phenomena of diffraction and interference of light rays indicate the wave nature of light. The light passing through slits with dimensions comparable to the wavelength, is deflected. This is by *Huygens' principle*, in which each slit becomes the source of a new wave and emits rays in all directions.

The phenomenon of wave deflection at the apertures or edges of the shutters is called *diffraction, i.e. deflection of the rectilinear course of rays***.** The deflected beams (possibly collected by a lens), reaching the same place on the screen, undergo interference. Interference *of waves* is called the overlapping of waves of the same frequency, causing amplification or attenuation of the resultant wave intensity. At those points on the screen where the deflected rays meet in compatible phases, the amplification occurs and bright interference fringes are formed.

The setup for diffraction and interference studies (Young's experiment) is shown in Figure 1.

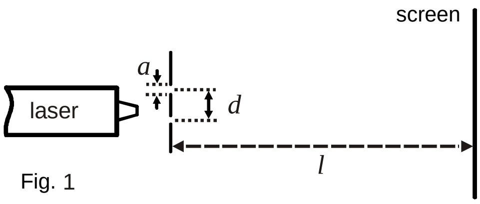


Fig. 1

Interference on two narrow slits ($a<\lambda$).

Light is an electromagnetic wave. The amplitude A of this wave, and therefore the electric field strength, depends on time t and the spatial coordinate r according to the formula below

$$A = A_0 \sin\left[2\pi\left(\frac{ct-r}{\lambda}\right)+\delta\right], \tag{1}$$

where: c – the speed of light, λ – wavelength, δ – initial phase.

If monochromatic (single-color) light is falling on a shutter with two slits (Fig. 2), then the intensity of the wave at point P on the screen is the sum of the intensities of the partial waves reaching P from B and D.

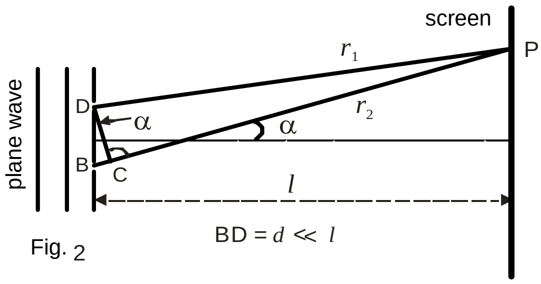


Fig. 2

The addition of two functions consistent with equation (1) indicates that the amplitude A_0' of the resultant wave is equal $A_0' = 2A_0$ at points, where the difference in the path of incoming rays satisfies the condition below

$$r_2 - r_1 = n\lambda, \quad n = 0, 1, 2, \ldots . \tag{2}$$

As a result of interference, we obtain *wave amplification* at those points on the screen for which the difference in the paths of the overlapping rays is equal to an integer multiple of the wavelength λ.

Zero value of the resultant wave amplitude $(A_0' = 0)$), namely, the extinction of the wave, can be observed, when the difference in paths of the rays equals an odd multiple of half of the wavelength,

$$r_2 - r_1 = (2n+1)\frac{\lambda}{2}, \quad n = 0, 1, 2, \ldots . \tag{3}$$

If the distance l between the screen and slits is much greater than the distance d between slits themselves, $(l >> d)$ then $r_2 - r_1 = \mathrm{BC} = d\sin\alpha$. Accordingly, the crucial conditions for the occurrence of interference maxima and minima are presented below :

$$d\sin\alpha_n = n\lambda \quad \text{— } n\text{-order maximum condition,} \tag{4}$$

$$d\sin\alpha_n = (2n+1)\frac{\lambda}{2} \quad \text{— } n\text{-order minimum condition.} \tag{5}$$

These conditions determine the angles of rays deflection at which, bright (gain) and dark (extinction) fringes are visible on the screen. The distribution of light wave intensities obtained on the screen is shown in Figure 3.

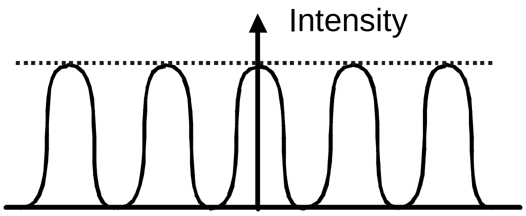


Fig. 3

Diffraction on a slit of width $a > \lambda$.

When a light wave falls on a single slit, a diffraction image composed of bright and dark fringes is created on the screen — however, in this case, the bright fringes are not of the same intensity, Fig. 4. The brightest fringe is the 0-order fringe, located directly opposite the slit. The fringes positioned to the right and to the left of this slit have lower intensity, decreasing with their order. Diffraction is caused by overlapping of waves coming from different areas of the slit.

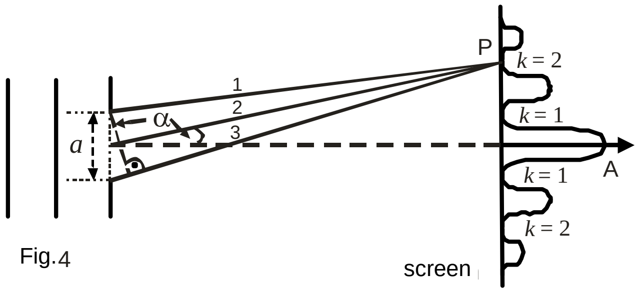


Fig. 4

The condition for the minimum occurrence in a diffraction image has the following form

$$a\sin\alpha_k = k\lambda, \quad k = 1, 2, \ldots, \; a - \text{slit width, } k - \text{minimum order} \tag{6}$$

According to this condition, rays 1 and 2 will be in opposite phases and there will be no light at point P — the ray passing through the upper half of the slit and the ray from the lower half, which is distant from it by $a/2$ will be neutralized by each other.

Lasers

For the diffraction and interference phenomena studies, laser light sources are highly desirable. The laser light beam has a low divergence (highly targeted), monochromatic (narrow spectra line) and highly coherent. *Coherence* can be defined as the stability of the wave phase in both space and time (the stability in space means an established phase relationship between separate waves, and the stability over time – phase invariability in a single wave). The mechanism of laser light formation process is discussed below.

The energy of an electron in an atom or molecule cannot be arbitrary — according to the quantum mechanics rules, only certain values are allowed. Electrons can only occupy specific energy levels in an atom or molecule. Luminosity of vapours and gases is related to the electrons energy change in atoms. When an electron transitions from one energy level to another, a portion (quantum) of energy ΔE is emitted or absorber. This energy determines the wavelength of emitted and absorbed radiation according to the formula:

$$\lambda = \frac{hc}{\Delta E}; \qquad c \text{ – speed of light,} \qquad h \text{ – Planck's constant.} \tag{7}$$

Under normal conditions, almost all gas atoms are in the ground state — electrons assume the lowest possible energies, which means they occupy the orbits closest to the nucleus.

When the radiation of the wavelength described by equation (7), falls on an atom with energy levels distant by ΔE , two situations should be considered:

1. The atom is in a lower energy state. The *absorption of radiation* and transition to a higher state is therefore possible, Fig. 6. After a certain period of time ($10^{-9} \div 10^{-6}$ s) a transition to state 1 occurs, combined with the emission of radiation.
2. The atom at the initial time is in a higher energy state. The influence of radiation with a wavelength corresponding to the energy difference of levels (1) and (2) can induce *a forced emission process*, Fig. 7. The radiation emitted at the transition to the lower state has precisely the same direction, frequency and phase as the incident wave. As a result, radiation passing through the medium is amplified.

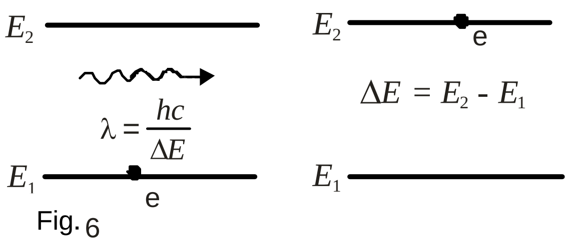


Fig. 6

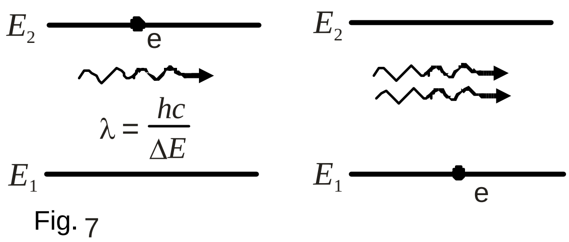


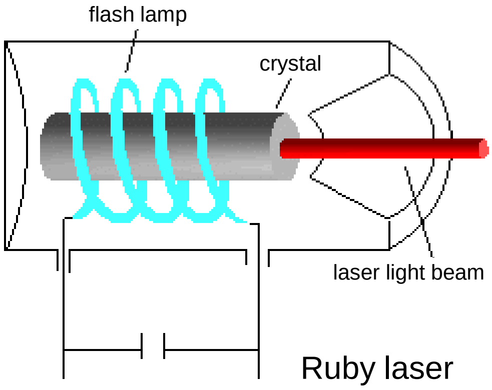
Fig. 7

The probabilities of absorption and forced emission are equal.. The resultant effect will be an amplification if, at the initial point, most of the atoms will be in a higher energy state, which means inversion (reversal) of energy level occupancies. *The laser* was originally developed and constructed in 1960. It is a device that uses the aforementioned occupancy inversion to generate a light wave. Excitation of atoms leading to occupancies inversion is called *optical pumping*.

A typical representative of a gas laser is *the helium-neon laser* (λ = 632,8 nm). The main part of this laser is a glass or quartz tube filled with a mixture of helium and neon, under very low pressure (partial pressures: $p_{He} \approx 130$ Pa, $p_{Ne} \approx 13$ Pa). The electrodes are soldered into the tube, to which a voltage is applied. The imposed voltage causes an electrical discharge resulting in the excitation of atoms inside the tube. Excited atoms spontaneously emit light (in all directions), seen as glowing laser tube. The occupancy of each level depends on the parameters of the discharge.

In neon, there is a pair of levels for which the discharge in the tube causes a greater occupancy of the upper level then the lower one. Radiation with a wavelength corresponding to the transition between these states is amplified when passing through the medium. The first portions of such radiation quanta, starting the process of forced emission, come from spontaneous emission. The radiation is amplified until it exits the laser tube — its intensity depends on the distance traveled inside the tube (the greater the distance, the greater the intensity). The best amplification conditions exist for radiation emitted along the tube. The presence of semi-transparent mirrors at the ends of the tube causes multiple transitions of radiation through the medium and increased its amplification.

Crystal lasers are also widely used, e.g. ruby laser, whose matrix is a sapphire crystal (Al_2O_3) doped with ions Cr^{3+}, (λ = 694,3 nm). The laser effect is achieved in a crystal in the shape of a cylindrical rod with a diameter of about 1 cm and a length of up to several cm. On the ends of the ruby rod the reflecting mirrors are applied. The „pumping" radiation is generated by a xenon-filled flash lamp placed around the crystal. The chromium atoms due to the green flash light absorption become excited.



Ruby laser

The laser effect is also observed in semiconductor p-n junctions, which glow due to the constant electric current flow through the junction in the conduction direction. The inversion of occupancy is observed in a thin layer of the p-type junction region. This means that more electrons can be found in the conduction band than in the upper levels of the valence band. Electrons that return to the valence band may be accompanied by the emission of electromagnetic radiation. Depending on the design of the diode and the current flowing through the junction, the light emitted by the junction source is either incoherent — we are then dealing with a light-emitting diode, or it is coherent — the source is then a junction laser. The best laser emission results are obtained in so-called heterojunctions, i.e. junctions formed at the interface of two layers with different chemical compositions (the base semiconductor material for heterojunction fabrication is gallium arsenide GaAs). Semiconductor lasers are characterized by high efficiency in the conversion of electrical to radiation energy, very long operating time, low power consumption and small dimensions.

EXERCISE MANUAL

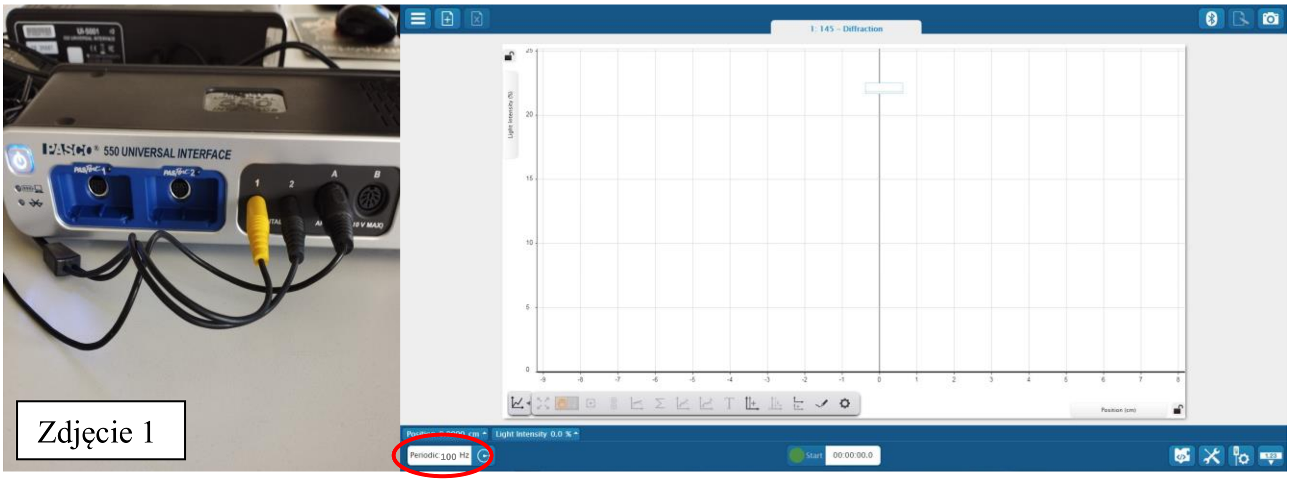
EQUIPMENT	• Optical bench, stands
• PASCO universal interface	• Optical fiber probe
• Rotary motion sensor	• Single-slit slide
• Laser	• Double-slit slide

ATTENTION! LASER LIGHT SOURCE IS USED IN THIS EXERCISE.
DO NOT POINT THE LASER IN THE FACE DIRECTION! RISKS EYE DAMAGE!

In the first part of the exercise the irradiance of laser light passing through a single slit will be measured using a fiber-optic probe. The second part will be similar, but the slit will be changed to a double one. The relative positions of the maxima obtained as a result of the laser light diffraction phenomenon will be determined using a rotating motion sensor. The *PASCO* software enables plotting of light intensity as a function of position.

SETTING UP THE MEASURING SYSTEM

1. Turn on the power of the table (see the dashboard of the table - by your left leg when sitting in front of the computer) - turn the red "knob" in the direction of the arrows (it should pop out), turn the key as in a car and let go.
2. Turn on in the following order: (1) PASCO universal interface, and then (2) computer.
3. Connect to the PASCO universal interface (if necessary): the force sensor to the analog channel A, and the position sensor to the digital channels: yellow tip - channel 1, black tip - channel 2. (Photo. 1).
4. To run the program, select profile **114** on the computer. Chart window ((Photo. 1) shows the dependence of force and velocity on time.



Zdjęcie 1

DIFFRACTION ON A SINGLE SLIT

EXPERIMENTAL RUN AND MEASUREMENTS RECORDING

1. Turn on the laser light source. Read the **wavelength of the laser light on the laser housing**.
1. Set the slide with a single slit in the path of light, at a distance ca. 10 cm from the laser.
2. Observe fringes of red light on a white sheet of paper placed perpendicularly in front of the fiber optic probe. Align the light source (laser) with respect to the slide with a slit to see clear and sharp fringes on the paper (screen).
3. Set the optic fibre tip in the laser light path at a distance of more than 150 cm from the slit slide. Pay attention to the proper alignment of the fibre optic front — at the height of the fringes visible on the paper sheet. The sensitivity of the light sensor can be adjusted — by the tutor.
4. Read the **distance of the slits from the screen *l*** (here: the tip of the fiber optic probe).
5. Press the **Start** button to start the measurement. (Check that the sampling rate (Periodic) is set at 100 Hz) (Photo 1)
6. Move the fibre optic tip slowly and smoothly by turning the motion sensor knob. Observe whether the fiber optic probe tip is within the laser light..
7. On the screen watch the light intensity change as a function of position in the graph window and select the appropriate speed of the fibre tip to achieve fairly continuous set of measurement points. The registered graph should reveal an intensity maximum for the zero order and much smaller maxima, corresponding to subsequent laser light amplifications (Figure 1).
8. Press **Stop** button when the experiment is finished (the fibre optic tip should be completely shifted to the opposite side)
9. In the program window, a record of data from the first measurement will be displayed on the graphs as "Run 1". You can repeat the experiment if the measurement is unsatisfactory. The program records successive measurement series and they are visible in the graph windows. You can select the best measurement data by marking the appropriate series in the window (Run 1, Run 2,...).

DATA ANALYSIS

Calculate the width of the slit *a*. According to the equation (6), for $k = 1$: $a = \lambda / \sin \alpha_1$.

Sine of the angle α_1, at which the first minimum is observed can be calculated from the following formula $\sin \alpha_1 = x / \sqrt{x^2 + l^2}$, where: x – average distance from the 0-order amplification centre to the first minimum, l – distance between the slit and fibre optic tip plane of motion.

1. To determine the positions of diffraction maxima and minima, mark on the **acquired graph** (as indicated below in Figure 1) the corresponding points and select the **precision cursor functions** (Photo 2).
2. The **coordinates (x and y)** of the cursor position will be displayed next to the marked point (Photo 3). Read the x coordinates (for minima and maxima, the y values should be the lowest and highest, respectively).
3. Calculate the width of the slit.
4. Compare the calculated slit width *a* with the real value a_r, shown on the slide frame. Calculate the relative percentage error for this purpose using equation given below:

$$B_p = \frac{a - a_r}{a_r} \cdot 100\% .$$

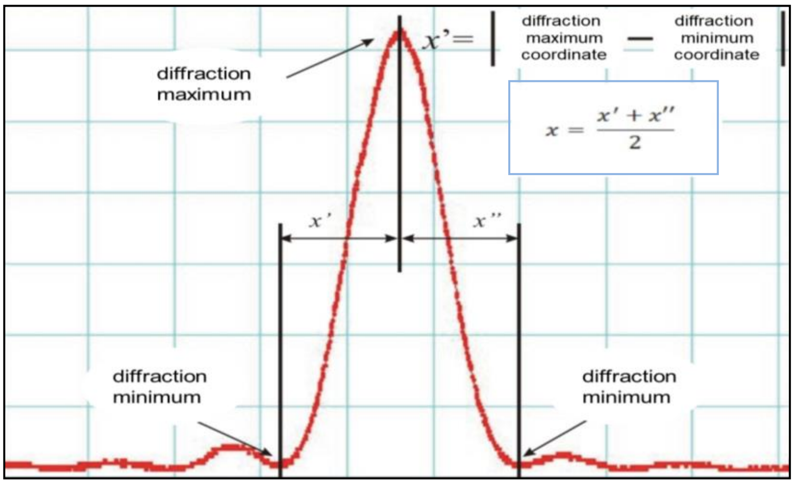
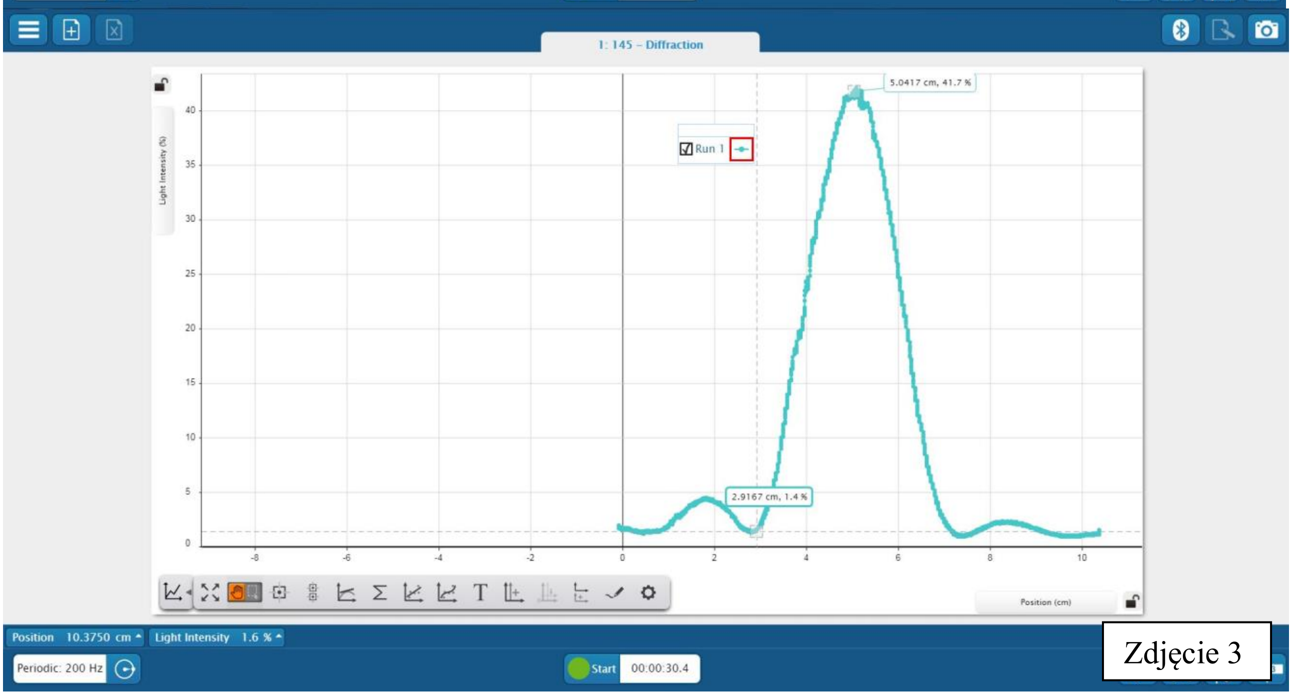


Fig. 1. Graph of maxima and minima of light intensity caused as a result of diffraction phenomenon.

Zdjęcie 2



Zdjęcie 3

DIFFRACTION ON A DOUBLE SLIT

EXPERIMENTAL RUN AND MEASUREMENTS RECORDING

1. Set the slide with a double slit in the path of laser radiation.
2. Repeat the measurements steps (3-9) previously described for a single slit.

DATA ANALYSIS

1. Use equation (4) to calculate the distance *d* between the slits: $d \sin\alpha_n = n\lambda$
   - Sine of *n*-order deflection angle expresses the following relations:

$$\sin\alpha_n = \frac{x_n}{\sqrt{x_n^2 + l^2}}$$

   - Determine the distance x_n using position coordinates of the maximum of zero order and subsequent n orders visible on the graph. To determine the positions of diffraction maxima and minima, mark the corresponding points on the **acquired graph** (as indicated below in Figure 2) and select the precision cursor function (Photo 4). Proceed as in the case of measurements for a single slit: the **x and y coordinates** of the cursor position will be displayed next to the marked point. Read the **x** coordinates (for minima and maxima, the y values should be the lowest and highest, respectively).
2. Compare the calculated slit distance *d* with the real value d_r, shown on the slide frame. Calculate the relative percentage error for this purpose using equation given below:

$$B_p = \frac{d - d_r}{d_r} \cdot 100\%.$$

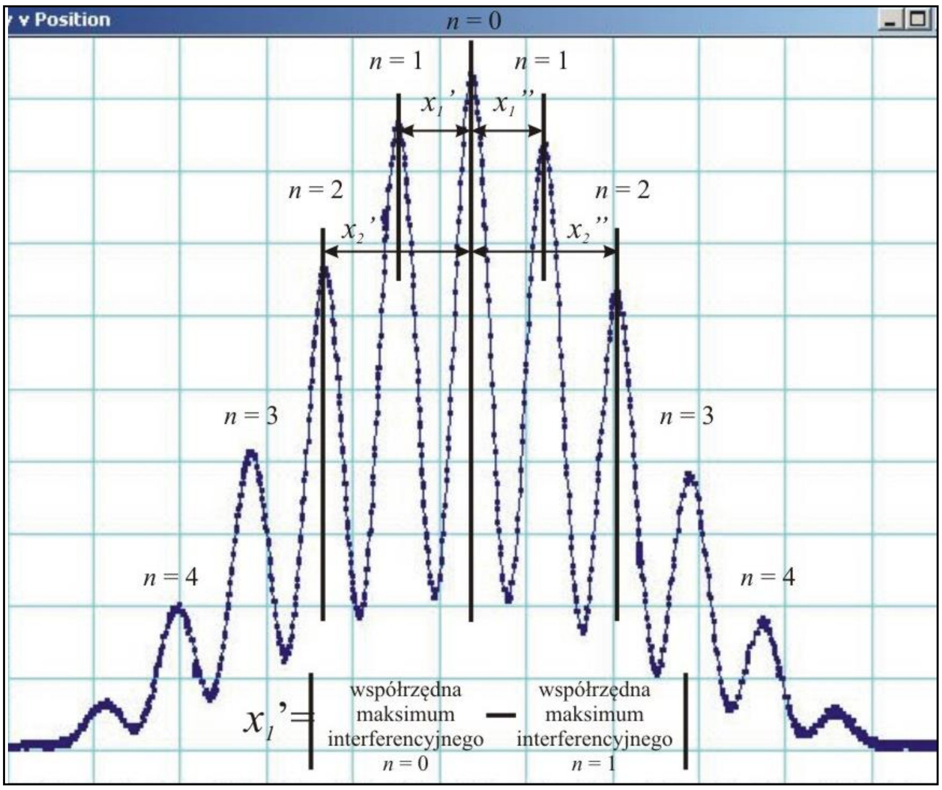


Fig. 2. Example of the registered light intensity changes for a double slit.

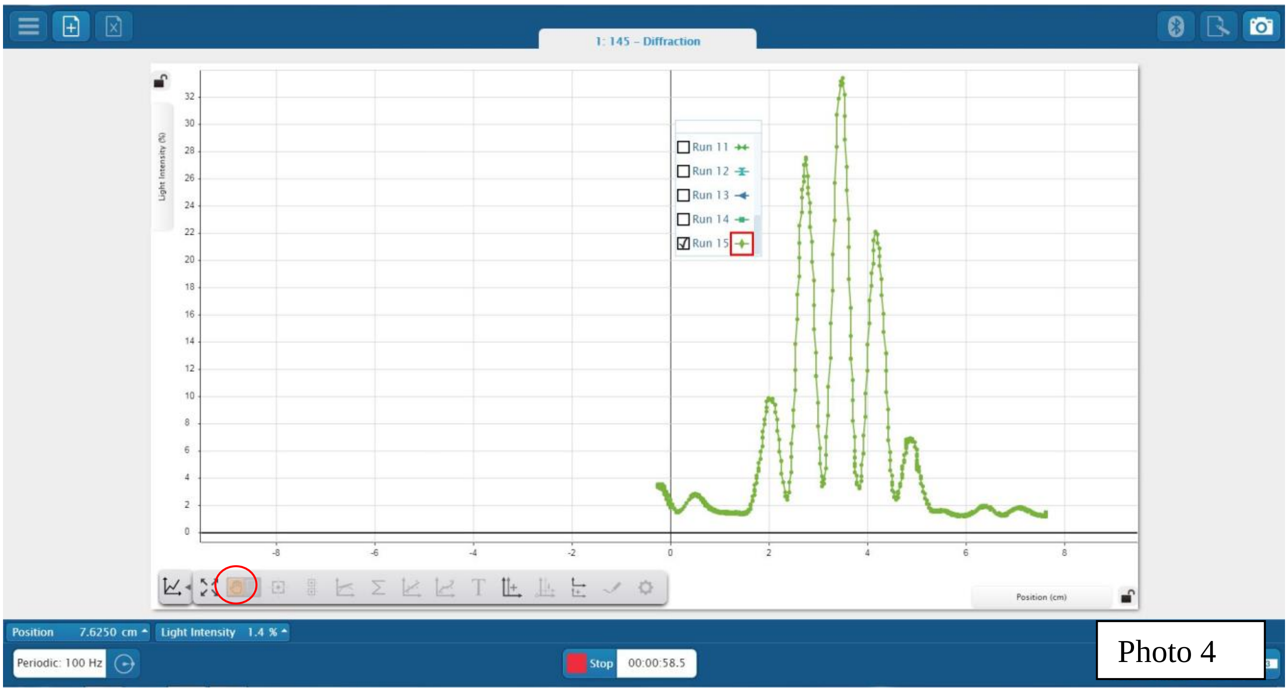


Photo 4

COMPLETION OF MEASUREMENTS

Turn off the PASCO universal interface, the computer and press the red "knob" on the table dashboard.